MIOCENE VOLCANIC ACTIVITY IN THE LOS ANGELES BASIN AND VICINITY

Thesis by

Gordon Pryor Eaton

In Partial Fulfillment of the Requirements

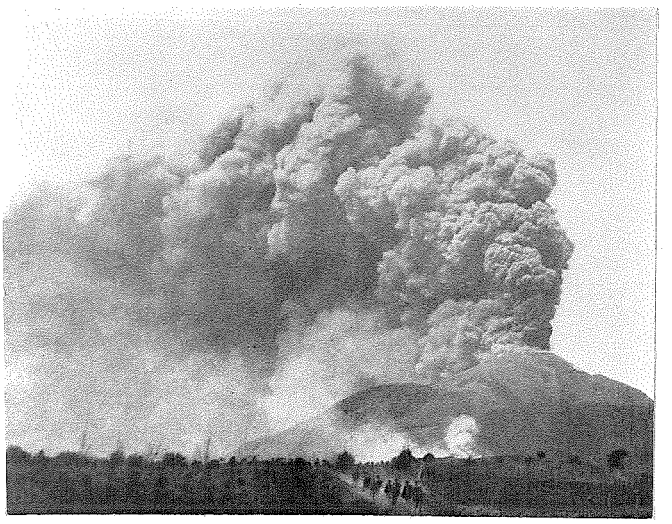
for the Degree of

Doctor of Philosophy

California Institute of Technology

Pasadena, California

1957



FRONTISPIECE. The effect of wind shear on a vertically-ejected ash cloud from Mt. Vesuvius. Photograph by F.A. Perret.

ACKNOWLEDGMENTS

In making the investigation upon which this report is based, the writer was aided by many persons who contributed pertinent data and suggestions. Two men are deserving of particular thanks in this connection. Professor R. H. Jahns originally outlined the problem and recommended some of the techniques that were brought to bear upon it. He followed the progress of various approaches made by the writer, and commented critically upon their usefulness and interpretation. Mr. W. H. Holman of the Standard Oil Company of California offered invaluable counsel concerning the stratigraphic aspects of the problem, and gave much time to the interpretation of critical well records and outcrop data, as well as to the identification of Foraminifera collected by the writer.

Several oil companies provided access to their records, thereby making possible the compilation of data presented in Plate VI. The cooperation of the following companies, and of their representatives who discussed the problem with the writer, is gratefully acknowledged:

Amerada Petroleum Corporation: L. K. O'Bert
Bandini Petroleum Company: E. S. Pickett
Continental Oil Company: R. B. Kelly
General Petroleum Corporation: B. C. Lupton
The Ohio Oil Company: R. R. Simonson
Richfield Oil Corporation: W. T. Rothwell, Jr. and R. L. Brooks
Seaboard Oil Company: V. F. Scurry
Signal Oil and Gas Company: R. E. Anderson
Shell Oil Company, Inc.: Paul See and G. H. Doane
Standard Oil Company of California: W. H. Holman, W. E. Hendrix, J. W. Ruth, J. W. Higgins
The Texas Company: G. E. Van Gundy and Frank Goodban
Tidewater Associated Oil Company: C. E. Sturz
Union Oil Company of California: B. C. Jones

Geologists of the Fuels Branch of the U. S. Geological Survey at Claremont also offered considerable assistance. Dr. A. O. Woodford discussed many aspects of the problem with the writer, and made available specimens collected by the group working under his direction. R. F. Yerkes, who is well acquainted with the petrographic aspects of the problem through his work with the volcanic rocks on the east side of the Los Angeles basin, gave freely of his time in discussions with the author. In addition, he

made available his manuscript report on the El Modeno volcanic rocks and a chemical analysis of an andesite from the San Joaquin Hills. J. E. Schoellhamer offered pertinent suggestions regarding the subsurface geology of the Los Angeles basin, and conducted the writer on a field examination in the Santa Ana Mountains, where exposures of the Santiago Peak and El Modeno volcanic rocks were visited. J. G. Vedder kindly examined a suite of megafossils collected by the writer, and offered suggestions concerning certain aspects of the geology of the San Joaquin Hills. The author has drawn heavily on the published reports of this group.

Dr. J. S. Shelton of Pomona College provided suggestions during the early phases of the work and kindly made available his specimens of the Glendora lavas for spectrochemical analysis. His detailed investigations of the Glendora rocks were the first of their kind in the area, and their importance to the present study can be judged by the number of references made to his published papers in the present report.

Professor Cordell Durrell of the University of California at Los Angeles facilitated the study in the northwestern part of the area by suggesting critical localities for the writer to visit, and by making available the manuscript maps from several unpublished M.A. theses. These maps were used as a basis for field checking the volcanic accumulations in the eastern Santa Monica Mountains and eastern Santa Susana Mountains, and are included in two of the compilation maps of the present report.

R. R. Wilson and David Campbell of the Field Engineering Division, Department of Water and Power of the City of Los Angeles, made available excavation maps and tunnel cross-sections of areas in the Verdugo Mountains and eastern Santa Monica Mountains, and conducted the writer on an examination of the Santa Monica Mountain sewer out-fall.

Harry Wexler and J. T. Williams of the U. S. Weather Bureau offered suggestions concerning the meteorological aspects of the problem dealing with the source of volcanic ash in the Los Angeles basin. W. J. Blake and William Otto assisted the writer by making quantitative analyses of the water content of several specimens of lava from the region.

Arthur Chodos, of the Division of Geological Sciences, California Institute of Technology, performed all of the spectrochemical analyses and helped in the preparation of artificially fused rock beads.

Of considerable benefit were discussions with various faculty and staff members and fellow graduate students at the California Institute of Technology. Among these men are Drs. T. H. McCulloh, L. C. Pray, J. A. Noble, L. T. Silver and G. J. Neuerburg, and Messrs. C. W. Burnham, J. J. W. Rogers, and G. I. Smith. Additional benefit was derived from discussions with the writer's colleague, Dr. J. L. Rosenfeld.

Special thanks are due the writer's wife, Virginia, who assisted in the preparation of the manuscript, and who offered field and editorial assistance, as well as continuing encouragement. Elspeth Cowie typed the preliminary manuscript and parts of the final manuscript, and helped in the final editing. Marian Haagen prepared the typescript. Dr. E. P. Lehmann assisted in the preparation of several of the plates and figures. Sincere appreciation is expressed to all of these people for their able assistance and for the time they spent in this work.

The studies were undertaken while the writer held a Fellowship in Geology from the Standard Oil Company of California. A research grant from this company made it possible to obtain most of the field data, the thin sections for petrographic work, and the analytical data that were used. The writer is deeply grateful for this generous support.

ABSTRACT

The Los Angeles basin is an elongate topographic depression on the southwestern coast of California. It marks the site of a former marine basin in which a maximum of about 30,000 feet of sediments accumulated during Tertiary times. Volcanic activity in this basin began during early middle Miocene (Relizian) time and ended during late Miocene (Mohnian) time. The products of this eruptive episode consist primarily of flows and tuff-breccias of olivine basalt, basaltic andesite, and hypersthene-augite andesite. Dacite and rhyolite were extruded locally in the northeastern part of the basin, but they constitute only a small fraction of the total volume of lavas and pyroclastic rocks of the region. Petrographically, the rocks are typical of the basalt-andesite-rhyolite association of the circum-Pacific volcanic belt.

An investigation was undertaken to determine, as closely as possible, the timing of the volcanism and the composition of the volcanic rocks in different parts of the basin, and to study criteria whereby correlations of the volcanic portions of the stratigraphic section might be achieved. To this end, field mapping and collecting were done in those parts of the basin in which the effusive rocks crop out, and data from wells which penetrated these rocks in the subsurface were compiled. Thin-section studies, wet chemical analyses, and spectrochemical analyses of selected specimens were made during the course of the study.

The results indicate that Tertiary volcanic activity in the Los Angeles basin was restricted wholly to the Miocene epoch. The first phases of this activity began simultaneously in the northwestern and southeastern parts of the area during Relizian time. Pyroclastic olivine basalt was thrown into the sea near the eastern end of the Santa Monica Mountains, northwest of Los Angeles, and olivine-bearing basaltic andesite was extruded subaerially near Sunland, 12 miles to the north, while flows and breccias of hypersthene-augite andesite accumulated in the vicinity of the San Joaquin Hills, 40 miles to the southeast. During the Relizian-Luisian transition interval (early to late middle Miocene), submarine flows of basalt and basaltic andesite were expelled near the city of Inglewood, southwest of Los Angeles. In the early part of the Luisian stage, peperites of hypersthene-augite andesite were injected into marine sediments accumulating in the vicinity of the Palos Verdes Hills, and at the

same time, volcanic activity broke out on a grand scale in the northeastern part of the basin. In rapid succession, flows and breccias ranging in composition from olivine basalt and hypersthene-augite andesite to rhyolite were deposited on and near the Miocene shore, in what is now the vicinity of Glendora and Pomona. Flows of olivine basalt were laid down on the sea bottom in the east central part of the basin at this time, and were followed by the deposition of pyroclastic rocks of similar composition. Near El Modeno, at the eastern margin of the basin, activity persisted until the end of Luisian time. Flows of olivine basalt, palagonite tuff, and breccias of basaltic andesite accumulated there. The dying phases of activity are represented by the Whittier diabase, an intrusive body of basaltic and dioritic composition that was emplaced in the Whittier fault zone, southeast of Los Angeles, during middle or late Mohnian time. Less well confirmed evidence of supposed Mohnian volcanism is represented by basaltic tuff-breccia beneath the Dominguez oil field, north of the Palos Verdes Hills.

In most of the areas, dikes and other small intrusive bodies were injected into the country rocks after surface manifestations of igneous activity had ceased. These intrusive bodies are less well dated than the lavas, but most are thought to be of approximately the same age as the associated flows. In the San Joaquin Hills, however, an augite andesite exposed near the coast is at least as young as Luisian, and possibly is even younger, whereas extrusive activity in this area took place during late Relizian time.

Between 400 and 800 square miles of lava are believed to underlie the Los Angeles basin proper. This represents only a small fraction of a much larger volcanic province that includes the western Santa Monica Mountains and Ventura basin to the northwest, and the continental shelf off the coast of California to the southwest. Miocene volcanic rocks are known to underlie large parts of all these areas.

Throughout the Los Angeles basin and surrounding region, beds of rhyolite tuff of various ages are interbedded with the Tertiary sedimentary rocks. Several of these tuffs were studied in detail, and it is concluded that most of them represent wind-borne products of volcanic activity in areas to the northwest (southern and central Coast Ranges) and/or southwest (present floor of the Pacific Ocean).

It was found that no one rock type in the area is restricted in time to a particular part of the Miocene epoch. As an example, olivine basalt of Relizian age occurs in the eastern Santa Monica Mountains, and identical rocks of Luisian age occur in the east central and northeastern parts of the basin. Similarly, hypersthene-augite andesite of Relizian age is exposed at the southeastern end of the basin, and Luisian lavas of like lithology are exposed in the northeastern part. A detailed study of the rocks reveals that the few distinctions that can be made on the basis of petrography are functions of geographic, rather than stratigraphic, differences. Rocks of andesitic composition are restricted primarily to the eastern and southern parts of the basin, and basalts predominate in the northwestern part.

Variation diagrams based on wet chemical analyses show a distinct contrast in chemical composition between the flows and breccias of the northeastern part of the basin and those exposed along the coast. The latter are richer than the former in FeO and MgO, and poorer in Al_2O_3. These differences are believed to be the result of assimilation of pre-Tertiary "basement" rocks beneath the floor of the basin by magma in the process of ascent. The coastal lavas occur entirely within an area underlain by the Catalina metamorphic facies, a chloritic schist accompanied by saussuritic gabbro and serpentine. The lavas in the northeastern part of the basin are underlain by "basement" rocks of granodiorite and quartz diorite. A series of calculations indicates that magmatic differentiation of the volcanic rocks in the Glendora area probably took place by crystal fractionation of early-formed ferromagnesian minerals and calcic plagioclase, accompanied by assimilation of granodiorite. Differences in composition arising in this manner cut across time boundaries, and thus hinder stratigraphic correlation of the rocks.

Quantitative spectrochemical analyses indicate numerous variations in the trace-element composition of the rocks. The sources of these variations include contamination of core samples, minor differences between neighboring flows of like composition, and large differences between various members of a single differentiation series. Differences in composition resulting from deuteric alteration of the rocks were found to be surprisingly small. If all of these variations are considered and the trace-element analyses of the rocks are compared, the only distinctions that can be made are geographic rather than stratigraphic. It is concluded that further attempts to

establish compositional criteria for the purpose of correlation would be unproductive and unprofitable.

Volcanic activity in the region coincided with profound tectonic unrest. The Los Angeles basin lies in the area of intersection of two major tectonic belts: the east-trending Transverse Ranges and Murray Fracture Zone, and the northwest-trending Coast Ranges and Peninsular Ranges. It is thought that deformation within, and at the base of, the earth's crust in this area was responsible for the localization of volcanic activity. The transverse Volcanic Province of southern Mexico is similarly located at the intersection of the east-trending Clarion Fracture Zone and the northwest-trending circum-Pacific orogenic belt. Tertiary subsidence of the Los Angeles basin was relatively slow until middle Miocene time. During the Relizian stage, rapid settling began concomitantly with the outbreak of volcanism.

TABLE OF CONTENTS

	Page
INTRODUCTION	1
The Problem	1
Historical background	1
The present approach	4
General Distribution of the Volcanic Rocks	4
Areal distribution	4
Stratigraphic distribution	7
Previous Work	8
General studies	8
Specific studies of volcanic rocks	11
Methods of the Present Study	11
Stratigraphic age determinations	11
Field investigations	13
Subsurface investigations	16
Petrography	18
Spectrochemical analysis	30
GEOLOGIC HISTORY OF THE LOS ANGELES BASIN	31
PRE-TERTIARY EPISODES OF VOLCANISM	34
SURFACE GEOLOGY OF THE MIOCENE VOLCANIC ROCKS	42
Sunland Area	42
Sunland North	44
Basaltic andesite breccia	45
Olivine-bearing basaltic andesite	52
Olivine basalt	55
Sunland South	63
The rocks	63
Pacoima Hills	67
Olivine basalt	68
Basaltic andesite breccia	69
Olivine-bearing basaltic andesite	70
Olivine diabase	73
Intrusive breccia	74
Tujunga Area	75
Summary of the Stratigraphic Relationships in the Sunland Area	76
Eastern Santa Susana Mountains	77
Olivine diabase	77
Eastern Santa Monica Mountains	83
Griffith Park	86
Olivine diabase	86
Massive basalts	87
Flow breccia	88

	Page
Basaltic agglomerate	89
Hypersthene basalt	91
Quartz-bearing basalt	92
Tuffs	95
Alteration of the rocks in the Griffith Park area	96
Epiclastic "volcanic" debris	96
Age of the volcanic rocks in the Griffith Park area	97
Cahuenga Pass to Laurel Canyon	99
Sideromelane tuff-breccias	99
Intrusive olivine basalt	106
Extrusive olivine basalt	107
Source of the eastern Santa Monica Mountain volcanic rocks	107
Significance of the interbedded fossiliferous limestones	109
Age of the volcanic rocks	112
Nature of the coarse-grained rocks of the upper Topanga formation	113
Palos Verdes Hills	115
Bluff Cove	116
Altered basalt (?)	116
Cross-cutting clastic dikes	119
Glassy andesite	120
Point Vincente	124
Hypersthene-augite andesite	124
Abalone Cove	132
Portuguese Bend	133
Porphyritic augite andesite	133
Olivine diabase	134
Whites Point	135
George F. Canyon	135
Contact Alteration Associated with the Miocene Volcanic Rocks	136
Summary and Age Relationships of the Volcanic Rocks in the Palos Verdes Hills	137
San Joaquin Hills	140
Augite andesite	141
Basic hypersthene-bearing andesite	143
Hypersthene-augite andesite	148
Epiclastic volcanic breccia	149
Age of the volcanic rocks in the San Joaquin Hills	150
El Modeno Area	152
Olivine basalt	153
Palagonite tuff and tuff-breccia	154
Basaltic andesite	155
Dike rocks	157
Summary of the age relationships of the volcanic rocks near El Modeno	158

Page

Glendora Area 159
Santa Catalina and San Clemente Islands 167
San Clemente Island 167
Hypersthene-augite andesite 167
Dacite 168
Rhyolite 169
Santa Catalina Island 169

SUBSURFACE GEOLOGY OF THE MIOCENE VOLCANIC ROCKS .. 171
Known and Inferred Extent 171
Thickness and Variations in Thickness 182
Lithologic Variations 184
General statement 184
San Fernando Valley 185
Inglewood oil field 186
Dominguez oil field 189
Puente and San Jose Hills 190
Intrusive rocks of the Whittier fault zone. 193
Extrusive rocks near the Whittier fault zone 196
The Leffingwell area 197
Anaheim-Santa Ana-Orange area 199
Southeastern Los Angeles basin 201
Age Relationships 203
Correlation with Outcrop Areas 212

DIKES IN THE PRE-TERTIARY BASEMENT COMPLEX POSSIBLY RELATED TO MIOCENE VOLCANIC ACTIVITY 215

RHYOLITIC TUFFS 218

ROLE OF VOLCANISM IN THE HISTORY OF THE LOS ANGELES BASIN 254
General Statement 254
The Time of Volcanism 255
The Locus of Volcanism 263

PETROLOGY 274
Mineralogy of the Rocks 274
Petrographic Data Bearing on the Mechanism of Magmatic Differentiation 291
Chemical Data Bearing on the Mechanism of Magmatic Differentiation 298
Trace-Element Composition of the Lavas 327
General statement 327
Methods of analysis 329
Variations in the trace elements of the lavas 349
Significance of Geographic Differences in the Trace-Element Composition of the Lavas . . . 366

SUMMARY AND CONCLUSIONS 370

		Page
BIBLIOGRAPHY	. . . . .	372
APPENDIX I.	Faunal suites from the Topanga sandstone north of Sunland, California	382
APPENDIX II.	Supplementary well data pertaining to Plate VIII	384

LIST OF FIGURES AND PLATES

Figure		Page
1.	Index map of area	5
2.	Stratigraphic column for the Los Angeles basin	14
3.	Silica-refractive index curve for the Miocene volcanic rocks of the Los Angeles basin	24
4.	Breccia of olivine-bearing basaltic andesite in Akens Canyon, north of Sunland	46
5.	Olivine basalt flow between Akens and Doane Canyons, north of Sunland	56
6.	Field sketch of olivine basalt contact on truck trail north of Sunland	60
7.	Hand specimen of basaltic andesite showing well developed flow banding	64
8.	Platy parting in basaltic andesite near Pacoima	71
9.	Large-scale flow banding in basaltic andesite near Pacoima	72
10.	Exfoliation of olivine diabase in the eastern Santa Susana Mountains	79
11.	Upper contact of olivine diabase sill in the eastern Santa Susana Mountains	81
12.	Basaltic agglomerate in Brush Canyon quarry, Griffith Park	90
13.	Sideromelane tuff-breccia in the eastern Santa Monica Mountains	101
14.	Relations of andesite sill north of Point Vincente, Palos Verdes Hills	121
15.	Upper contact of andesite sill at map station "B", Palos Verdes Hills	122
16.	Hand specimen of hypersthene-augite andesite from the Palos Verdes Hills	125

Figure		Page
17.	Andesite dike in the Monterey formation of the Palos Verdes Hills	129
18.	Contact between andesite sill and Monterey formation east of Point Vincente, Palos Verdes Hills	130
19.	Upper terminus of breccia dike in the Palos Verdes Hills	131
20.	View looking northeast from Shady Canyon, San Joaquin Hills	145
21.	Sample localities of volcanic rocks on the continental shelf	181
22.	Index map of the Mojave Desert	226
23.	Index map of the California Coast Ranges	228
24.	Isopach maps of wind-borne volcanic ash from six historic eruptions	232
25.	Wind directions over southern California	237
26.	Air pressure map, January and April	239
27.	Air pressure map, July and October	240
28.	Probable directions of seasonal winds near Los Angeles during the Cenozoic era	247
29.	Longitudinal profile of the geostrophic wind	249
30.	Downwind longitudinal profiles of volcanic ash from five Cenozoic eruptions	253
31.	Paleogeographic distribution of the Miocene volcanic rocks in the Los Angeles basin	257
32.	Post-Cretaceous subsidence and volcanism in the Los Angeles basin	260
33.	Inferred centers of eruption of Miocene volcanic rocks in the Los Angeles basin	271
34.	Diagram showing ranges in rock composition over which specific mafic minerals crystallized in volcanic rocks of the Los Angeles basin	284

Figure		Page
35.	Crystallization of olivine basalt in the eastern Santa Monica Mountains	296
36.	Silica-variation curves of the major oxides in the Miocene volcanic rocks of the Los Angeles basin	308
37.	Silica-variation curves of the major oxides in the Miocene volcanic rocks of the Los Angeles basin, plotted by area	313
38.	Differentiation diagram of the Miocene volcanic rocks of the Los Angeles basin	323
39.	Possible mode of magmatic differentiation of the Glendora volcanic rocks	328
40.	Silica-variation curves of minor elements in the Miocene volcanic rocks of the Glendora area	351
41.	Silica-variation curves of minor elements in Tertiary volcanic rocks from the Los Angeles basin and the Lava Mountains	368

Plate		
I.	Geologic map of the Miocene volcanic rocks near Sunland, California	In pocket
II.	Geologic map of the Miocene volcanic rocks in the eastern Santa Susana Mountains	"
III.	Reconnaissance geologic map of the Miocene volcanic rocks in the eastern Santa Monica Mountains	"
IV.	Sketch geologic map of the Miocene volcanic rocks in the Palos Verdes Hills	"
V.	Geologic map of the Miocene volcanic rocks in the San Joaquin Hills	"
VI.	Well data pertaining to the Miocene volcanic rocks of the Los Angeles basin	"
VII.	Structural relationships in the Los Angeles basin	"

Plate

VIII.	Thickness and extent of the Miocene volcanic rocks in the Los Angeles basin	In pocket
IX.	Age relationships of the Miocene volcanic rocks of the Los Angeles basin	"

LIST OF TABLES

Table		Page
1.	Bead fusion technique and reproducibility	5
2.	Percentages of phenocrysts in basaltic andesites south of Sunland, California	66
3.	Modal analyses of the basaltic rocks of the Griffith Park area	98
4.	Relations of Tertiary rhyolitic tuffs in coastal southern California	219
5.	Maximum height of ash-laden clouds from observed volcanic eruptions	235
6.	Micrometric analyses of Miocene volcanic rocks from the Los Angeles basin	275
7.	New chemical analyses of Miocene volcanic rocks from the Los Angeles basin	299
8.	Previously published chemical analyses of Miocene volcanic rocks from the Los Angeles basin	302
9.	Alkali-lime indices of rocks from the eastern circum-Pacific volcanic province	311
10.	Inferred composition of two country rocks in the northeastern Los Angeles basin	322
11.	Spectrochemical analyses of selected volcanic rocks from the Los Angeles basin	332
12.	Reproducibility of spectrochemical analyses	348
13.	Differences in trace element composition between neighboring flows of like gross composition	360
14.	Trace-element variations within a single flow	361
15.	Trace-element variations resulting from deuteric rock alteration	362
16.	Trace-element analyses of two drilling muds	364
17.	Comparison of the trace-element compositions of like, coeval lavas from different parts of the Los Angeles basin	365

INTRODUCTION

The Problem

Historical background.

In 1932 H. S. Gale and H. R. Gale, impressed with the great volume and broad distribution of Miocene volcanic rocks in the western United States, expressed the belief that the bulk of Tertiary volcanic activity had taken place during this epoch, and that other Tertiary episodes of eruption were in general of lesser consequence (Gale and Gale, 1932).

A decade later N. L. Taliaferro (1943a, p. 150) presented a table illustrating the time span and geographic distribution of effusive rocks in the region between Santa Barbara County and San Francisco Bay, California. In this table the earliest Tertiary volcanism is indicated as having occurred during the Eocene epoch, and later episodes are assigned to a time range from lower Miocene through Late Tertiary to Quaternary. Despite the apparent temporal continuity of the later volcanism, Taliaferro pointed out that the activity was most severe and extensive during the Miocene epoch and particularly during the middle and upper Miocene.

Reed and Hollister (1936) discussed evidence of a widespread middle Miocene transgression throughout much of

California, and they, too, characterized this time as "that of the most violent and widespread outbreak of volcanism during the Tertiary." Specifically they stated that in southern California this transgression was initiated by faulting, accompanied by rhyolitic and basaltic outbursts and followed by folding and volcanic activity that yielded rocks of andesitic composition.

Early geologic mapping in the vicinity of the Los Angeles basin suggested that the small and discontinuous patches of volcanic rocks exposed there also are restricted to the Miocene epoch, and Driver (1948), in summarizing the evolution of the basin, indicated that the major part of the volcanic activity occurred during the middle Miocene. This concept has become so firmly established in local geologic thought that the top of the volcanic section in the Los Angeles area now is often assumed to represent the top of the middle Miocene section. Yet no specific stratigraphic study of these volcanic rocks has been undertaken.

Shelton (1955) described in detail the exposures of volcanic rocks near Glendora, indicating that they are of upper middle Miocene age; although other rocks along the east side of the basin are lithologically similar, their age relationships have not yet been described. There remain also the volcanic rocks exposed in the San Joaquin Hills at the southeast end of the basin, those in the Palos Verdes Hills to the southwest, and others along the eastern flank

of the Santa Monica Mountains to the north. It seems remarkable that the bulk of these rocks should remain so long neglected in an area of such vigorous geologic study as the Los Angeles basin. The coastal plain and surrounding ranges have been mapped in detail in the search for petroleum, and some areas have been remapped several times. In addition many drill holes have penetrated the volcanic rocks at depth. But the primary objective in most of this geologic work has been the location of petroleum accumulations, and the volcanic rocks have elicited little interest.

Several published geologic reports indicate the local distribution of volcanic rocks, but they offer singularly brief discussions of the general nature and age of these rocks. Only three reports (Shelton, 1946, 1954, and 1955) are concerned chiefly with the volcanic rocks, and two of these are devoted almost exclusively to rocks in the Glendora area. In addition, the locally operating petroleum companies have an accumulation of pertinent data in their files, but little of this information has been published.

In some areas, where the rocks above and below the volcanic strata have not yielded the fossils commonly used in working out details of stratigraphy, the volcanic rocks could be of value in establishing stratigraphic correlations if they were accurately dated. The principal aim of the present investigation was to establish the age and basin-wide correlation of the volcanic rocks in the

Los Angeles area, and to examine critically the criteria whereby this correlation might be achieved.

The present approach

The early phases of the present investigation involved the field study of outcrop areas of volcanic rocks that had not been previously described in detail. Ages of the associated Tertiary sedimentary rocks were established through the kindness of paleontologists of several of the major petroleum companies. Geologic mapping was done in areas formerly mapped only in reconnaissance, and for other areas a compilation of available detailed maps was used as a basis for field checking the distribution and general nature of the volcanic accumulations. During the course of the work a representative sample suite of volcanic and intrusive rocks was collected from each area, and these were supplemented by a series of well cores from various parts of the basin. About 300 of the samples were studied in thin section, in order to classify them for purposes of petrographic correlation and to aid in selecting samples for wet chemical and spectrochemical analysis.

General Distribution of the Volcanic Rocks

Areal distribution

The area under discussion, as shown in Figure 1,

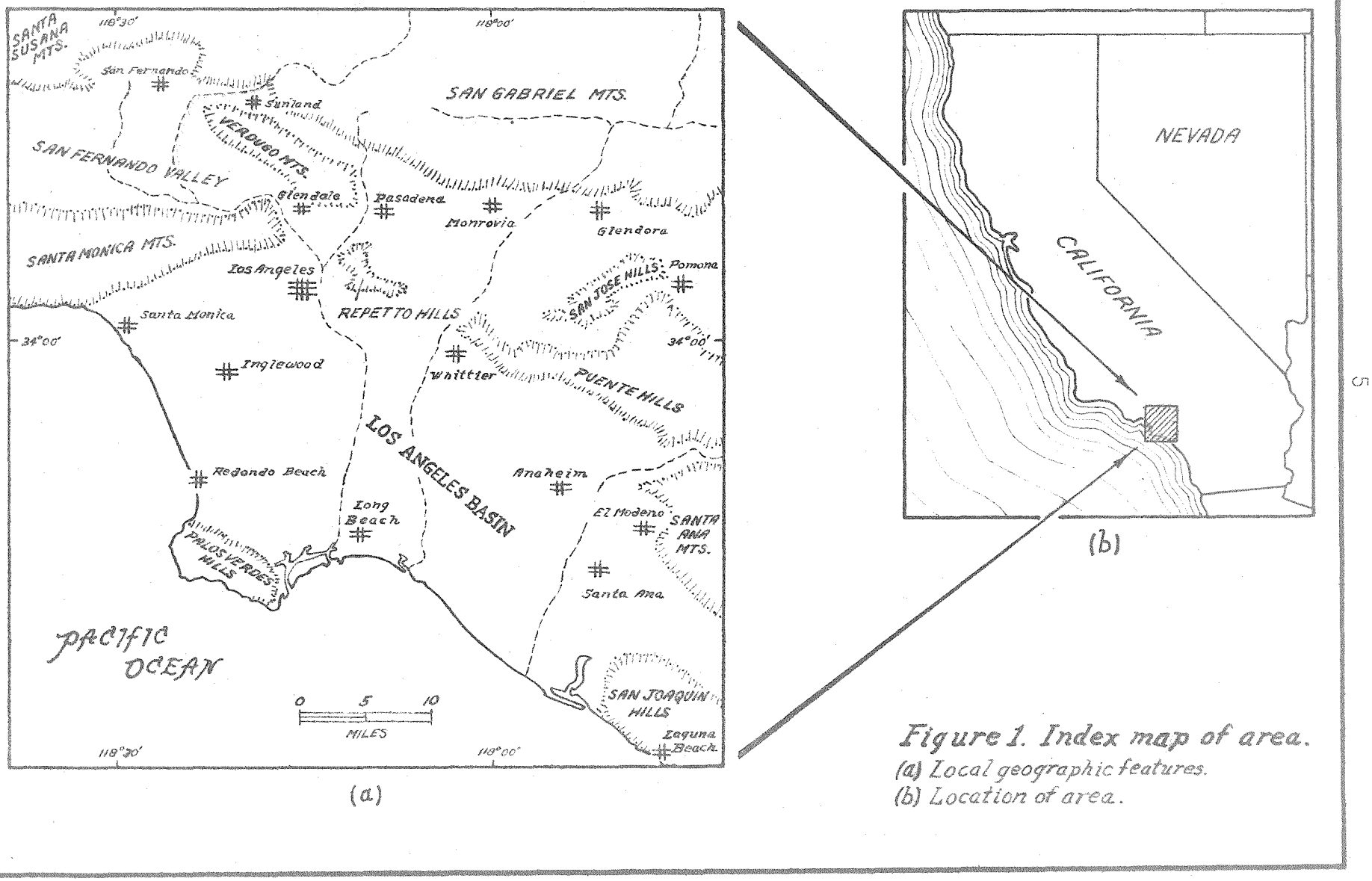


Figure 1. Index map of area.
(a) Local geographic features.
(b) Location of area.

includes the broad lowland commonly referred to as the Los Angeles basin, as well as a part of the eastern Santa Monica Mountains, the San Fernando Valley, and the eastern Santa Susana Mountains to the north, the foothills of the San Gabriel Mountains and the Puente and San Jose Hills to the northeast, the northwestern tip of the Santa Ana Mountains to the east, the San Joaquin Hills to the southeast, and the Palos Verdes Hills to the southwest. The studies were extended beyond the basin because only in the surrounding mountain areas are the volcanic rocks exposed at the surface. The choice of boundaries was arbitrary, and the area constitutes only a part of a much more extensive volcanic province that extends westward to the end of the Santa Monica Mountains and beyond to the Channel Islands.

Volcanic rocks have been recognized extensively in the subsurface along the eastern part of the basin, and have been encountered in deep wells in the Dominguez and Inglewood oil fields near the western side. Elsewhere in the western part, sedimentary rocks younger than the volcanics rest directly on pre-Tertiary crystalline "basement" rocks. Volcanic accumulations, if originally present, have been removed by erosion. If they are present in the deep central part of the basin, they lie at levels below those yet penetrated by wells. Only to the southeast, in an area immediately west of the San Joaquin Hills, is there stratigraphic

evidence indicating that the local absence of flows and pyroclastic rocks was due to non-accumulation, rather than to post-accumulation erosion.

In addition to these occurrences, in which the volcanic strata are intimately associated with Tertiary sedimentary rocks, numerous dikes, mineralogically similar to the volcanic rocks, cut the pre-Tertiary crystalline rocks of the San Gabriel, Santa Monica, and Verdugo Mountains. They conceivably may be related to the same episode of igneous activity.

Stratigraphic distribution

The bulk of the volcanic rocks in the Los Angeles basin is restricted to the Miocene portion of the stratigraphic section. The most noteworthy exception is a sequence of thin rhyolitic tuffs that are interbedded with sedimentary rocks ranging in age from early or early-middle Miocene to Pleistocene. These tuffs, to be described later, appear to have originated from a separate volcanic source. The volcanic rocks of principal interest consist of flows, pyroclastic accumulations, and minor intrusive masses that are predominantly basaltic and andesitic, and hence they differ from the tuffs in their composition as well as their age.

Previous Work

General areal studies

In describing the Puente Hills oil district, Eldridge and Arnold (1907) referred to a diabase dike that crops out northwest of Brea Canyon, and assigned to it a post-Puente (post-late Miocene) age. In a later discussion, English (1926) described this intrusive mass and also mentioned outcrops of flows and "agglomerates" in the San Jose Hills and northern Puente Hills. He concluded that the age of these extrusive rocks is intermediate between that of the lower Puente shale and middle Puente sandstone and tentatively referred the Puente formation to both the middle and upper Miocene.

In discussing the northwestern part of the Santa Ana Mountains, English described a "patch of intrusive rock" on the south side of Burruel Ridge and observed that it occurs along the contact between the Topanga and Puente formations. He likewise described outcrops of flows, "agglomerates," and tuffs in the "Tustin Hills" east of Orange, and considered them to be contemporaneous with Topanga sandstone (late middle Miocene). Inasmuch as the Puente shale overlies the Topanga formation throughout much of this area, the volcanic rocks in the "Tustin Hills" would appear to be older than those in the Puente and San Jose Hills to the north. Unfortunately, however, English

was working without the benefit of the close stratigraphic control provided by Foraminifera, and not all of his determinations of relative age have proved to be accurate.

At about the same time, Kew (1924) outlined the geology of parts of Los Angeles and Ventura Counties. The map accompanying his report shows volcanic rocks within the area of the present study near Sunland and Pacoima, as well as in the eastern Santa Susana Mountains. It also shows two wedges of volcanic rock in intimate association with "Modelo sandstone" along the San Gabriel fault zone near Gold Canyon. Field examination of the latter exposures by the present writer revealed that the rocks are conglomerates with well-rounded cobbles of silicified volcanic material, and that they are older than the Miocene rocks of the Los Angeles basin. Hill (1930) also outlined the distribution of volcanic rocks near Sunland and interpreted the wedges of rock in the San Gabriel fault zone as Cretaceous (?) or Eocene (?) sediments. He thus recognized their epiclastic origin.

In a report on the geology of the eastern Santa Monica Mountains, Hoots (1931) assigned the flows and volcanic breccias west of Cahuenga Pass to the middle Topanga formation (middle Miocene). East of the pass he found intrusive rocks in the upper part of the section and attributed these to later Topanga or post-Topanga igneous activity. Neuerburg (1953) more recently mapped the area east of the pass

and briefly outlined the complex structural relationships of the basalt and other rocks that occur there.

Three Oil and Gas Investigation maps of the U. S. Geological Survey include areas in which Tertiary volcanic rocks crop out. Map 23 (Woodford, Shelton, and Moran, 1944) shows the geology of the Puente and San Jose Hills and is accompanied by a brief descriptive text in which the volcanic rocks are tentatively assigned to the Topanga formation.

Map 63 (Shelton, 1946) is essentially concerned with the areal geology of the northeastern San Gabriel basin. In the text accompanying this map and in a later paper Shelton (1955) referred the volcanic rocks to the upper middle Miocene.

Map 154 (Schoellhamer et al., 1954a) deals with the geology of the northern Santa Ana Mountains, including the exposures of volcanic and intrusive rocks in the hills east of El Modeno and Orange (the "Tustin Hills" of English, 1926). These rocks are therein referred to as the "El Modeno volcanics"; according to the authors, they "probably straddle the boundary between middle and late Miocene."

Woodring, Bramlette, and Kew (1946) briefly described the "basaltic" sills that intruded the lower and middle part of the Altamira member of the Monterey shale in the Palos Verdes Hills. Some of the sills are as young as, or younger than, oldest middle Altamira (middle Miocene), but no upper age limit was assigned.

In addition to the published work described above, J. G. Vedder of the U. S. Geological Survey recently has completed a detailed geologic map of the San Joaquin Hills. This map outlines the distribution of the volcanic rocks exposed there.

Specific studies of volcanic rocks

Very few data and discussions devoted primarily to the Tertiary volcanic rocks of the Los Angeles basin have been published. Shelton briefly treated the whole of what might be called the "coastal southern California volcanic province" in a recent paper (1954), but his other papers (Shelton, 1946, 1955) are concerned only with the rocks near Glendora. Macdonald (1939) described the sills north of Pt. Vincente in the Palos Verdes Hills as pépérites, intruded beneath the sea floor under a thin cover of wet sediments. He outlined the general field relationships, the petrography, and the mechanics of intrusion of these rocks. Presumably they are of approximately the same age (middle Miocene) as the including sediments.

Methods of the Present Study

Stratigraphic age determinations

The ages assigned to the volcanic rocks in different parts of the Los Angeles basin are based on Foraminiferal

assemblages that occur in closely associated Tertiary sediments. Following R. M. Kleinpell's comprehensive work (1938) in subdividing the Miocene section of California, Wissler (1943) presented a detailed breakdown of the stratigraphic section in the Los Angeles basin. This has been revised only slightly since the time of his writing (cf. Natland and Rothwell, 1954). Kleinpell (p. 83) was careful to point out the ecologic limitations in the use of "Forams" in stratigraphic studies, and indicated that littoral faunas would be of limited value. In this regard, recent work by the U. S. Geological Survey has disclosed some serious stratigraphic problems in the Pliocene section of the Santa Ana Mountains. The difficulties apparently result from environmental effects on the distribution of the species in the various faunas (A. O. Woodford, personal communication, 1954). Although these troublesome occurrences might be ascribed to the location of the depositional area near the margin of the Los Angeles basin in Pliocene times, they cast some doubt on the dependability of index Foraminifera in other parts of the area.

Because the rocks of interest in the present study are almost wholly confined to the Miocene portion of the section, the dependability of Miocene index species is of particular relevance. Special interest centers about the recognition of the middle Miocene-upper Miocene boundary. Both shallow-water and deep-water facies of the Luisian

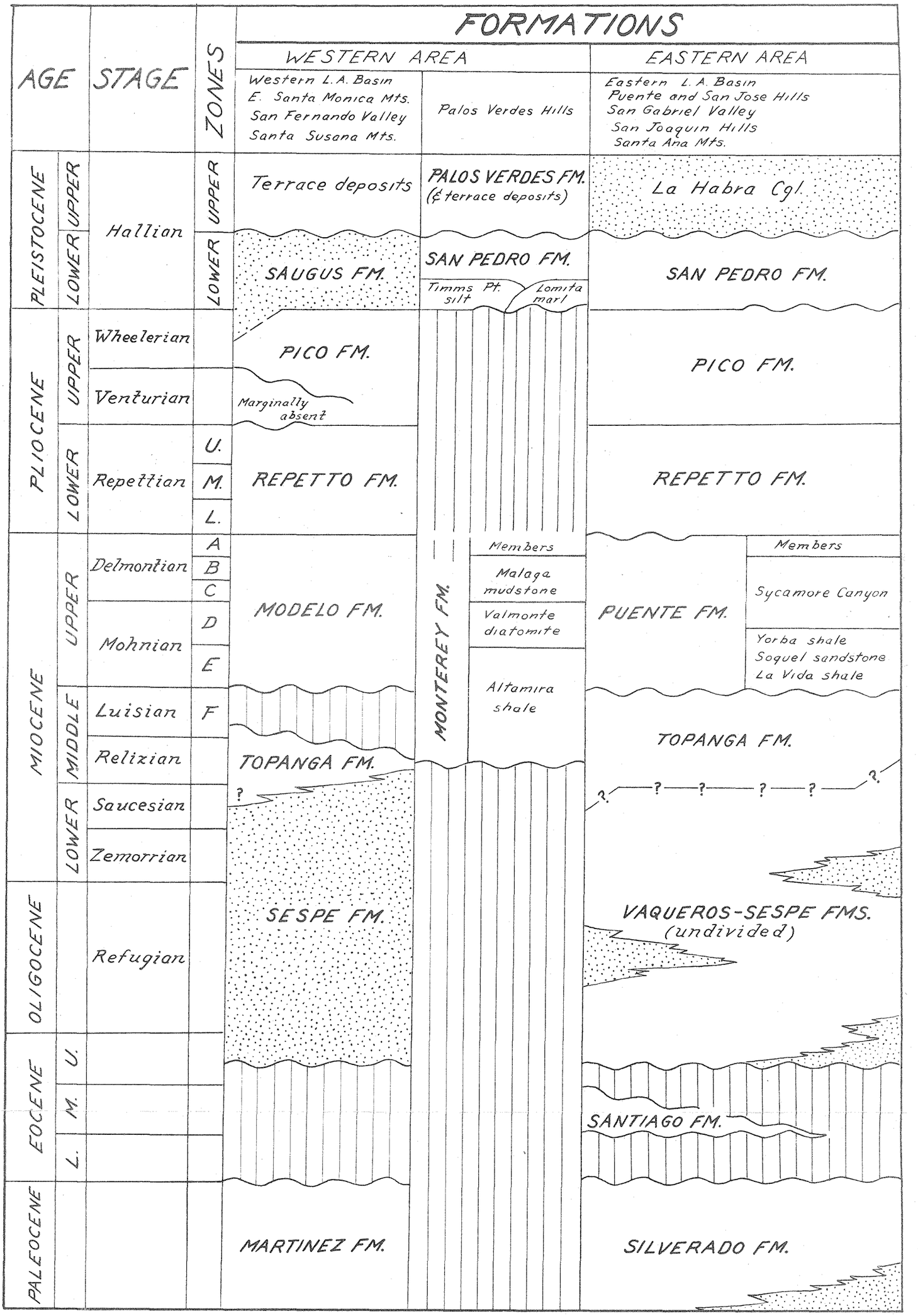
(late middle Miocene) and Mohnian (early late Miocene) are recognized, and are clearly distinguishable from each other and from those of earlier and later stages. Nowhere are Mohnian faunas succeeded upward or laterally by Luisian ones, regardless of alternations in the conditions of environment, and thus each stage defines a reliable time-bounded unit.

For the majority of occurrences, the individual age assignments made in this report are based directly upon the collections and interpretations of various petroleum-company paleontologists. For the remainder, where it was necessary for the writer to make fossil collections, the identifications and stratigraphic interpretations were made by W. H. Holman and W. E. Hendrix of the Standard Oil Company of California.

The stratigraphic relationships in the Los Angeles area are shown in Figure 2. These will be referred to throughout the remainder of this paper.

Field investigations

Despite the fact that surface exposures represent only a small fraction of the total known volume of volcanic rocks in the Los Angeles basin, their relationships were studied more intensively than those in the subsurface. Sampling of the subsurface rocks is limited to drill cores and other drill-hole data, and a small number of widely



Cenozoic Stratigraphy of the Los Angeles Basin & Vicinity

FIGURE 2

(Compiled from Wissler, 1943; Woodring et al., 1946; Natland and Rothwell, 1954)

spaced wells, like those involved in the current investigation, usually results in highly oversimplified interpretations.

The widely separated areas of outcrop were treated individually, and each was studied with a degree of detail judged to be most appropriate to its significance in the general problem. The Glendora area, mapped and described by Shelton (1946, 1955), was visited briefly for the collection of a representative suite of rocks and no further study was made. The exposures near Sunland were studied in detail, and were mapped on an enlarged topographic base (1:12,000) and on air photographs. The eastern Santa Susana Mountains were mapped in reconnaissance by Kew (1924) and in detail by Bishop (1950). Bishop's map, at a scale of 1:24,000, was utilized in the field study of the basaltic rocks exposed there.

Several maps of the eastern Santa Monica Mountains are available (Hoots, 1931; Neuerburg, 1953; Durrell, 1954), but in all of these the volcanic rocks are grouped together as "undifferentiated basalt." Furthermore, very little petrographic work has been done by previous investigators. The lack of map differentiation stems from a frustratingly heavy cover of brush, lack of distinctive marker units in the volcanic section, and the extremely complex structure of the range east of Cahuenga Pass. The region west of the pass is structurally simpler, but the

other difficulties are compounded by the presence of concordant intrusive masses of basaltic rock. Several textural and compositional varieties of volcanic rocks can be distinguished in roadcuts, however, and attention during the present investigation was directed at these.

The map of Woodring, Bramlette, and Kew (1946) served as an adequate base for studies in the Palos Verdes Hills. These investigators did not distinguish different varieties of volcanic rock, and certainly a field distinction is difficult even though variations are apparent under the microscope. During the present investigation, careful attention was given to the relationships of the volcanic rocks with the Monterey shale.

J. G. Vedder recently has completed a detailed map in the San Joaquin Hills, and no further mapping was regarded as necessary in that area. At Vedder's suggestion, several exposures of a significant nature were visited, however, and a suite of specimens was studied under the microscope.

The geology of the El Modeno volcanic rocks is described in a report to be published shortly by R. F. Yerkes (195_). Pertinent aspects of these rocks are discussed in the present report, but most of the data were taken directly from Yerkes' manuscript.

Subsurface investigations

Well data on the volcanic rocks were obtained through

the petroleum companies operating in the area, and through the Fuels Branch of the U. S. Geological Survey. Except in the instances noted, data relating to a particular well were acquired from the company operating it. It should be pointed out that some of the figures on thickness and depth listed in Plate VI do not agree with those published by Shelton (1954, 1955). These discrepancies are a result of differences in the interpretation of available records by the company geologists, Shelton and the writer. The detail and accuracy of available core descriptions vary greatly from well to well, and it was found necessary to re-examine many of the cores. Samples for thin-section study and spectrochemical analysis were collected from 35 of the 94 wells shown on Plates VII-IX. In addition, cores from other wells were sampled for megascopic study.

Many difficulties were encountered in compiling the subsurface data. To begin with, a large percentage of the wells in the Los Angeles basin bottom in the volcanic rocks, because most of the current production of petroleum is from higher stratigraphic zones, and hence drilling is ordinarily stopped before, or immediately after, the extrusive rocks are penetrated. Thus the subsurface samples represent only the upper part of the volcanic section. Fortunately, some exploratory wells that have been drilled to greater depths provide detailed information on the volcanic section. Several companies do not take cores of the volcanic rocks, however, and others core only at sporadic

stratigraphic intervals.

Coupled with these difficulties is the frustrating problem of distinguishing intrusive from extrusive rocks. Durrell (1953) emphasized this problem in discussing the volcanic rocks of the Santa Monica Mountains, and it applies to most of the Los Angeles basin as well. In the subsurface one is dealing essentially with a single dimension, and not only are discordant relationships frequently unrecognizable but other helpful details such as chilled margins and contact effects are obscured by gaps in the core records.

Petrography

A total of 300 thin sections was examined during the course of the laboratory work. The principal objectives were to classify the rocks, to determine the geographic extent of each of the various types, and to aid in selecting specimens for spectrochemical analysis. Rough modal estimates of most of the rocks were made by means of a grid ocular, and, after all of the thin sections had been examined, more accurate modal analyses were made with a point counter; 1200 to 1500 points were counted for each of 22 selected specimens. A comparison of the grid-ocular estimates with the results of the more detailed modal analyses showed that the grid estimates are accurate within $\pm$ 5 percent. In the descriptions that follow, the figures stated in ranges of 10 percent (e.g., 45-55 percent

labradorite) are those determined by the grid-ocular method.

In view of the currently unsettled problems of feldspar optics, the standard curves presented in the texts of Winchell (1951) and Rogers and Kerr (1942) were used for determining compositions of the plagioclase. Values of anorthite content were determined chiefly by extinctions on combined Carlsbad-albite twins in sections normal to (010), and less frequently by maximum extinction angles on albite twinning in zones normal to (010). Köhler (1949) stated that the use of these standard curves for determining the composition of volcanic plagioclases yields values of anorthite that are 10 or 15 percent too high. On the other hand, the optical data of Crump and Ketner (1953) show random scatters of up to $\overset{10}{\wedge}\pm$ percent anorthite in the region of An_{50}, a range which exceeds that supposedly due to the difference in optics between the so-called "high" and "low" temperature feldspars.

Thin-section study of chemically-analyzed holocrystalline rocks from the Los Angeles basin indicates that rocks that would be called "basalt" by most investigators on the basis of thin-section determinations of modal plagioclase composition, would also be called "basalt" on the basis of chemical composition. This stems from the fact that these two systems of classification (chemical and petrographic) were linked prior to the recognition of distinct "high"

and "low" temperature feldspars. Hence even if Köhler's contention is correct, and the anorthite values given in the present report are in need of correction, a comparison of the rocks and plagioclase feldspars described herein can be made with those of previous investigators with the assurance that the "basalt" of the writer is, in most respects, like the "basalt" described by others.

Universal-stage measurements were made of the optic angles of pyroxenes in approximately one-sixth of the thin sections examined. In the remainder, 2V was estimated visually from acute-bisectrix or optic-axis figures. The compositions of hypersthenes were determined by use of the 2V curve in Winchell (1951, Fig. 283).

In the petrographic descriptions of the rocks, the reader will note frequent reference to the presence of chlorophaeite, "fibro-chlorophaeite," or fibro-crystalline derivatives of chlorophaeite among the alteration products. Chlorophaeite and its mode of origin have been described by Peacock and Fuller (1928). This mineraloid substance is present in many of the volcanic rocks from the Los Angeles basin, but in most it has undergone evolution to tiny fibrous clusters of unidentified mineral(s). The latter are commonly pleochroic (yellow to green, yellow to brown, or light green to dark green), and have a moderate to high birefringence. Similar mineral(s) have been described by other investigators as "highly birefringent

chlorite." Inasmuch as true chlorite-family minerals are characterized by low to moderate birefringence (low in the common types), it seems inadvisable to continue to refer to the minerals under discussion as "chlorite." In certain specimens, where the chlorophaeitic substance is present as larger crystals, it was identified either as celadonite, or as a variety of nontronite (?). In a few specimens, both minerals seem to be present. The fine-grained varieties, however, will be referred to as chlorophaeite throughout the report.

With regard to textural nomenclature, the terms "phenocryst" and "microphenocryst" are used in a relative sense only. This is in contrast to the usage of others (cf. Wilcox, 1954, p. 291) who have established arbitrary dimensions for distinguishing microlites, microphenocrysts, and phenocrysts. This latter practice is occasionally misleading, as it may suggest to the reader the presence of two distinct size fractions when they are not apparent upon casual observation (e.g., as in a rock with seriate texture). Microphenocrysts are crystals that are too small to be seen by the unaided eye, but that present a distinct size contrast to the rest of the matrix.

The distinction between basalt and andesite was one of the more perplexing problems encountered. The usual practice of using the composition of plagioclase as a reliable index was found to be impracticable in most

instances. In the first place, the feldspar composition is far from uniform in any one lava. Differences between phenocrysts and microlites were observed in some rocks to exceed 30 percent of anorthite content. Similar differences between the cores and margins of normally zoned phenocrysts also were frequently encountered, and crystals showing strong oscillatory zoning defied determination by ordinary optical means. Some of the plagioclase microlites are so small that optical determinations of their compositions were impossible. In addition, the amount of glass is so great in many of the rocks that it is impossible to judge what the average composition of the plagioclase might have been if more complete crystallization had taken place. Consequently the determination of an <u>average</u> plagioclase was impossible.

Other investigators (e.g., Thayer, 1937) have used the presence or absence of olivine as an index to the composition of a lava, but olivine has been reported in volcanic rocks containing as much as 59 percent silica. Clearly, the mineralogical characteristics of some volcanic rocks are not practical indicators of their basic or intermediate nature.

Color index is a criterion of composition occasionally applied by petrographers, but it fails for partially glassy rocks. Its normative counterpart, the ratio of salic to femic minerals, is useful but probably no more so

than the chemical analysis from which the norm is calculated.

Shelton (1955) published a series of 14 analyses of the volcanic rocks near Glendora, and these were supplemented during the present investigation by new ones for seven rocks: 2 from the San Joaquin Hills, 1 from the Palos Verdes Hills, 2 from the eastern Santa Monica Mountains, and 2 from the vicinity of Sunland. In addition, R. F. Yerkes made available a recent analysis of a third specimen from the San Joaquin Hills.

Three of Shelton's analyses (S-438, S-669, and Jones 1) are not included here because they represent tuffaceous rocks. These rocks are not considered to be reliable indicators of primary lava composition because both the possible effects of sorting during transportation (mechanical differentiation) and the ease of alteration of ash are too great.

Inasmuch as chemical analyses are costly, additional analytical tools were sought to extend the study to other rocks in the basin, and in this connection the fusion technique described by Mathews (1951) was found to be useful. Its validity was checked by means of a curve established from the 19 analyzed rocks. Figure 3 illustrates the determined relationships between silica content and refractive index, and Table 1 indicates the procedure and reproducibility of the method used.

It should be pointed out that the silica-variation

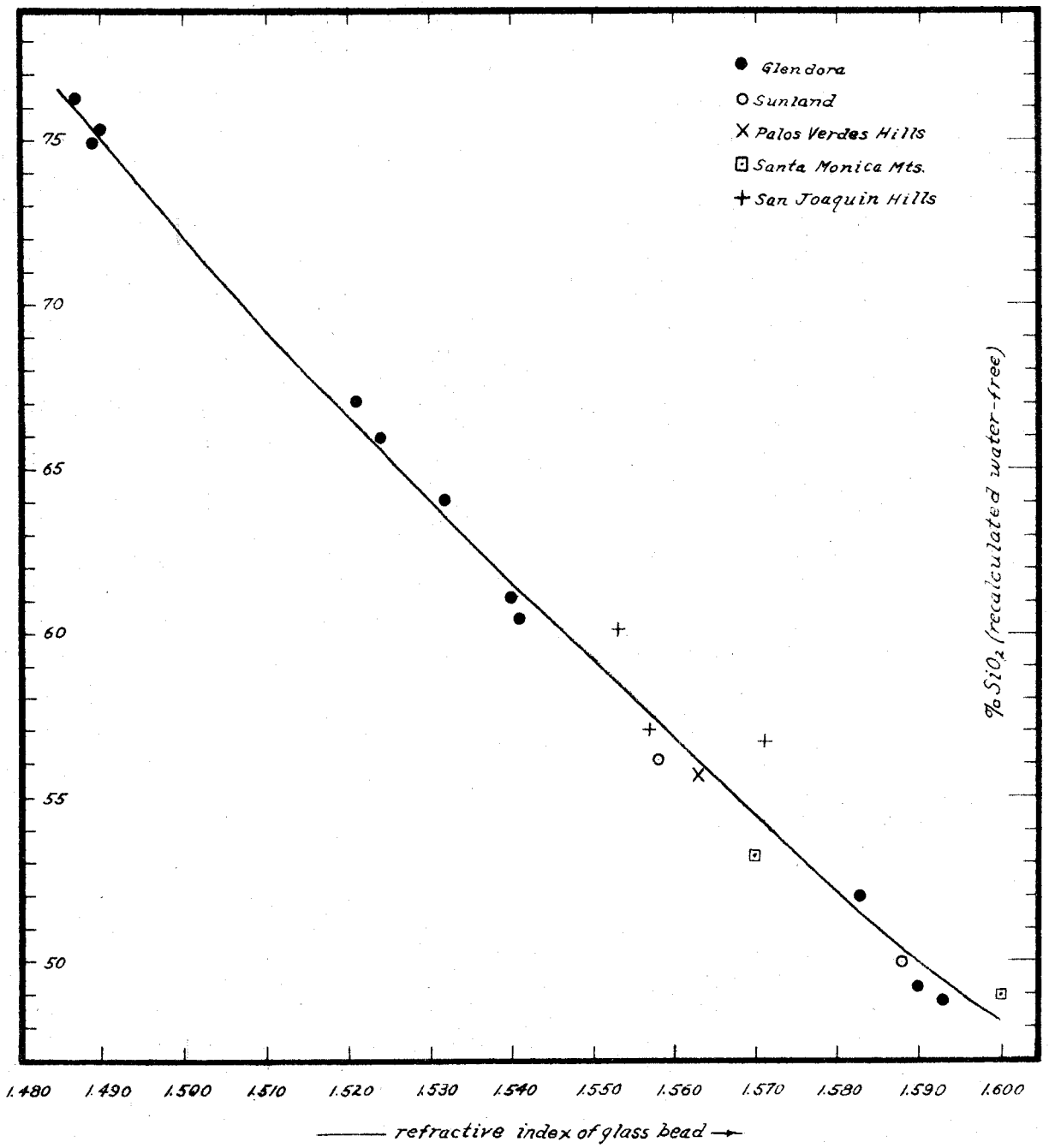


Figure 3. Silica-refractive index curve for volcanic rocks of the Los Angeles Basin.

Instrument: Jarrel-Ash spectroscope arc stand

Electrode spacing: 4 mm., adjusted during burn

Current: 6 amperes

Burn duration: 13 seconds (determined for optimum sample size by observing fluxing characteristics and time of differential volatilization[≈ 15-20 secs])

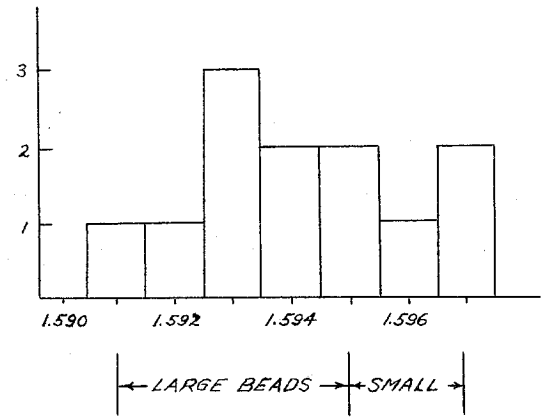
Matthews (1951) recommends shorter burns, but for smaller samples.

Determination of above conditions based on 14 runs with olivine basalt S-422.

Run	Sample size	Burn duration	R.I.
1	~30 mg	15 secs.	1.593
2	~30 mg	10	Lost
3	~10 mg	8	1.597
4	~30 mg	13	1.591
5	~10 mg	5	1.592
6	~10 mg	5	1.597
7	~30 mg	10	1.594
8	~30 mg	13	1.593
9	~30 mg	20	1.595
10	~10 mg	10	1.596
11	~10 mg	20*	1.608*
12	~10 mg	5	1.595
13	~30 mg	13	1.593
14	~30 mg	14	1.594

*Volatilization of major elements; not included in determination

TABLE 1: BEAD FUSION TECHNIQUE AND REPRODUCIBILITY



Mean for large beads: 1.593

Deviation for large beads: .002

Mean for small beads: 1.595

Deviation for small beads: .003

TABLE I (Continued)

Determination of values for curve in Figure 3 Each R.I. value = average of 3

Rock	R.I.	$\%SiO_2$ (recast water free)
BVD-3b	1.558	56.12
BVD-5	1.588	50.05
BVN-30	1.570	53.23
BVN-63	1.600	49.00
BVV-14b	1.563	55.68
BVJ-2	1.571	57.1
BVJ-7	1.553	60.09
BVJ-9a	1.557	57.05
S-422	1.593	48.77
S-347	1.590	49.26
S-615	1.583	51.97
$S-333_2$	1.541	60.34
S-339	1.540	61.04
S-345	1.532	64.09
S-519	1.524	65.93
S-468	1.521	67.03
S-597	1.489	74.90
S-673	1.490	75.41
S-496	1.487	76.30

TABLE I (Continued)

diagrams (Figure 36) of the major oxides show a fair degree of scatter. An explanation of this scatter is offered in the section on petrology, but it is important to note here that because of it, the results from the Mathews technique are not as precise as they are known to be in other areas. The maximum departure of the points for the analyzed rocks from the silica-refractive index curve is less than 1.7 percent. The refractive index curves for the other components generally show departures of no more than 2 percent, but their levels of concentration are considerably lower than that of silica, and the relative degree of error is therefore much greater.

It is noteworthy that the points representing two of the rocks from the San Joaquin Hills exhibit a marked tendency to fall above the curve. The analyses of these rocks indicate that their concentrations of MgO (for a given silica composition) are somewhat higher than others in the basin, and because an increase in this oxide is known to cause a corresponding increase in the refractivity of glass (George, 1924), this tendency might have been anticipated. The implication is that the San Joaquin volcanic rocks have had a magmatic origin somewhat different from the other volcanic rocks in the basin, and therefore the use of the silica-refractive index curve for determining their average silica composition must be tempered with caution. The curve seems directly applicable to other

rocks in the basin, however, regardless of their location, with the possible exception of rocks cored in wells near the San Joaquin Hills.

An arbitrary distinction between basalt and augite andesite was established on the basis of composition as determined from a bead evaluation of the silica content. A limit of 54 percent silica (dry) was selected on the grounds of the approximate statistical frequency of modal and normative labradorite in holocrystalline, medium-grained rocks in which plagioclase zoning is absent, and on the presence and composition of the pyroxenes. Those rocks with less than 54 percent silica are considered basaltic, those with more, andesitic. A second limit of 58 percent was selected from olivine-bearing rocks in which the plagioclase has a composition near, or less than, An_{50}. These are herein referred to as olivine-bearing basaltic andesites (after Williams, 1950). Rocks with a detectable amount of olivine, but with a silica content greater than 58 percent, are referred to simply as olivine-bearing andesites.

The use by Shelton (1955) of the name "calcic andesite" for one of the porphyritic hypersthene-bearing lavas of his Glendora suite is somewhat unfortunate. The name was earlier applied by Callaghan (1933) and Thayer (1937) to rocks in the western Cascade Range of Oregon, but the rocks they described are chemically quite different from those

of Shelton. His "calcic andesite" is more closely related in composition to the "pyroxene andesites" reported from other localities in the circum-Pacific volcanic belt. Among these are Crater Lake, Oregon (Diller and Patton, 1902), Newberry Volcano, Oregon (Williams, 1935), and Paricutin, Michoacan, Mexico (Williams, 1950). Shelton's use of the term apparently was adopted in part to distinguish the rock descriptively from other andesites of similar mineralogical composition in the area.

Spectrochemical analysis

Forty-six quantitative spectrochemical analyses were made in the hope that they would prove useful for the correlation of volcanic rocks extruded contemporaneously in different parts of the area. Trace-element variations between rocks of different age groups might indicate that there was but a single, homogeneous deep source supplying all of the vents, and that the concentrations of minor elements in the source magma were changing with time. The results of these analyses and a discussion of their significance are included in the section on petrology.

GEOLOGIC HISTORY OF THE LOS ANGELES BASIN

The geologic history of the Los Angeles basin has been outlined in the literature several times, and each successive summary has had the benefit of additional geologic data. The first comprehensive discussion was that of Reed and Hollister (1936), the second, Driver (1948), and the third, Woodford et al. (1954). In addition, the paleogeographic maps of Corey (1954) graphically portray the evolution of the region. A brief summary of the history is given here, in order to establish a framework within which to consider the volcanism.

The oldest unmetamorphosed sedimentary rocks in the area are of Upper Cretaceous age. They are exposed in the Santa Monica and Santa Ana Mountains, and at one time they may well have been continuous across the central part of the Los Angeles basin. In the Santa Ana Mountains the lower part of the Cretaceous section is nonmarine, and the upper part consists of shallow-water marine strata. At the close of Upper Cretaceous sedimentation, the region was gently folded and uplifted, and the Cretaceous strata were buried beneath nonmarine conglomerates of Paleocene age. Evidently a shallow and fluctuating transgression of the sea followed the deposition of these nonmarine sediments, for later Paleocene and Eocene rocks bear faunas indicative of limnetic or estuarine conditions.

Aside from the deformation that took place during Upper Cretaceous time, the post-Jurassic history of the region up to and including the early Miocene was one of alternating nonmarine and shallow-water marine conditions, with little or no deformation or notable transgressions.

Rocks of Oligocene (?) and lower Miocene age are perhaps not as well understood as others in the basin because of their subtle stratigraphic relationships. Nonmarine sandstones of the Sespe formation possibly were deposited from Eocene to lower Miocene times. They are overlain by, and intertongue with, the marine Vaqueros formation of lower Miocene age. The latter is composed principally of mollusk-bearing, shallow-water sandstones and conglomerates. The end of the lower Miocene marked the cessation of relatively quiescent conditions, and there may have been a mild transgression at this time. During early Relizian times (lower middle Miocene) the seas were generally shallow, and the continental shelf southwest of the Los Angeles basin was locally emergent. Neritic conditions evidently prevailed all along the coast. With the initiation of faulting in the southeastern part of the basin, accelerated subsidence began and a transgression of the sea followed during the Luisian (upper middle Miocene) period.

Middle Miocene sedimentation was interrupted and terminated by uplift and locally intense folding. The

truncation of middle Miocene strata that followed is well displayed in the eastern Santa Monica Mountains, where upper Miocene Modelo shale lies across bevelled middle Miocene Topanga sandstones with a pronounced angular discordance. Uplift at this time was localized however, for elsewhere in the basin the sea continued to deepen and spread inland during the Mohnian (upper Miocene) stage. During lower Pliocene time the sea contracted somewhat, but the basin continued to deepen. Only around the margins of the basin does sedimentation appear to have been interrupted.

Post-lower Pliocene time was one of gradual shallowing of the water, with more frequent interruptions of marginal sedimentation. The Plio-Pleistocene time-rock boundary is difficult to recognize locally, for there was no abrupt change in tectonic or depositional conditions at this time. The sea withdrew from the inland part of the basin, and marine sediments gave way to others of continental character. The older Pleistocene sediments in the Palos Verdes Hills are unconformably overlain by the upper Pleistocene Palos Verdes sand. This unconformity (middle Pleistocene) is major and widespread, and represents one of the latest deformations of the basin, but recent seismicity in the area suggests that tectonic activity is perhaps continuing today.

PRE-TERTIARY EPISODES OF VOLCANISM

Evidence of pre-Tertiary volcanic activity in coastal Southern California is widespread. Fragmentary sections of mildly metamorphosed flows and accumulations of pyroclastic material are exposed in the northern Peninsular Ranges between Los Angeles and San Diego, and clasts of volcanic rock are present in conglomerates ranging in age from Cretaceous to Miocene in many other parts of the region. This evidence indicates that the Miocene volcanic episode under discussion by no means constituted the only important phase of eruptive activity known to the area, nor were its products the most extensive.

The oldest local rocks of probable volcanic origin are interlayered with slaty rock of the Triassic Bedford Canyon formation near Elsinore and Temescal Hot Springs, on the northeast side of the Santa Ana Mountains. Larsen (1948) described them as metamorphosed andesitic flows. He also mentioned concordant bodies of amphibolite in a metamorphic terrane near Domenigoni Valley (45 miles east of Santa Ana). The host rocks are considered to be Paleozoic, but the masses of amphibolite probably represent sills rather than flows.

Unconformably overlying the Bedford Canyon formation in the Santa Ana Mountains is a section of Jurassic (?) volcanic rocks that extends discontinuously from points

immediately south of the Santa Ana River to San Diego, a distance of about eighty miles. Hanna (1926) first described these rocks and referred to them as the "Black Mountain volcanics." In the San Diego area, where he worked, they consist chiefly of andesitic agglomerates and breccias, with subordinate flows of andesite and trachyte. All are mildly metamorphosed.

Larsen (1948) later renamed the series the "Santiago Peak volcanics" from exposures in the Santa Ana Mountains to the northwest. According to him the rocks are predominantly andesitic and quartz latitic in composition. Flows, tuffs, and breccias alternate throughout the sequence and the total thickness is estimated to be in the neighborhood of several thousand feet.

In describing these rocks from their occurrence near San Dieguito, Jahns and Lance (1950) reported quartz latite and dacite breccias and agglomerates. Clasts of andesite in the volcanic breccias are mentioned, but they are apparently subordinate to the other lithologic types.

Exposures visited by the writer in the northern Santa Ana Mountains disclosed rocks of andesitic composition. Massive, medium dark gray porphyritic flow rocks form the freshest outcrops, and highly jointed, grayish-olive aphanitic rocks form the most severely altered ones. Plagioclase is the predominant phenocryst mineral.

The Santiago Peak volcanics appear to represent an

enormous outpouring of predominantly andesitic lavas during Jurassic (?) time. Their estimated thickness of several thousand feet and their present geographic extent of nearly eighty by fifteen miles indicate a volume at least equal to that of the rocks of the Miocene volcanic episode to be described.

Evidence of other Mesozoic (?) volcanic activity is suggested by the highly metamorphosed rocks of the Catalina schist on Santa Catalina Island. Bailey (1941), in a discussion of the glaucophane-bearing rocks of the island, recorded meta-andesites (?), meta-diabase, and meta-spilite, basing the identifications on relict textures and bulk composition. The age of these rocks is uncertain; although Bailey referred them to the Franciscan series (Jurassic (?) and Lower Cretaceous (?)), Taliaferro (1943b) suggested that they may be somewhat older. Certainly these rocks indicate that intermediate and basic lavas were extruded in southwestern California long before Miocene times.

Coarse-grained detrital rocks of Upper Cretaceous age are well exposed in the northern Santa Ana Mountains. The lower part of the section consists of two rather conspicuous boulder conglomerates, the Trabuco formation and the Baker Canyon member of the overlying Ladd formation. Popenoe (1941) described the lithologies of these conglomerates in detail, and stated that the predominant clasts comprise andesites and metamorphosed sedimentary

rocks, both strikingly similar to the rocks of the adjacent "basement complex," i.e., the Santiago Peak volcanics and the Bedford Canyon formation. He also mentioned subordinate "acidic lavas and porphyries," and in a later paper (Popenoe, 1942) referred to a "variety of types of volcanic...rock" in the Schulz member of the Williams formation, higher in the Upper Cretaceous section.

This reference to other volcanic types is significant. Abundant rounded cobbles of volcanic rock are present in conglomerates of early Tertiary age exposed in cuts along Santa Ana Canyon, and even a casual examination reveals that several different rock types are represented among them. These range from porphyritic rhyolites to dark-colored, apparently basic varieties. In addition to being well rounded, the cobbles are extremely tough, and many show a polish suggestive of mild silicification. Andesites like those of the immediately neighboring Santiago Peak volcanics seem to constitute only a small fraction of these clasts, and in places they are absent altogether.

Cobbles and boulders of rocks of lithologies similar to these are present in Tertiary conglomerates 50 miles northwest of Santa Ana Canyon. At the head of Gold Canyon, in the western San Gabriel Mountains, the writer examined cobble conglomerates in which the clasts are composed almost exclusively of red and gray porphyritic "metavolcanic" rocks. Pebbles and cobbles of plutonic rocks are so

subordinate that Kew (1924) originally interpreted these sedimentary accumulations as "Miocene volcanics." The same series crops out farther west in Little Tujunga Canyon, where R. H. Jahns (personal communication, 1954) collected invertebrate fossils indicating a Paleocene age.

In the Santa Monica Mountains are somewhat similar sandstones and conglomerates to which Popenoe (1942) assigned a Cretaceous age. These rocks may be traced as far east as Cahuenga Pass, where W. H. Holman (personal communication, 1955) found tiny calcite prisms evidently derived from shells of Inoceramus. An examination of these exposures revealed a high percentage of rounded cobbles of porphyritic rhyolites, andesites, and other intermediate varieties of volcanic rocks.

Soper (1938), in discussing the central Santa Monica Mountains, noted abundant clasts of "metavolcanic" rocks from middle Tertiary Sespe conglomerates. He mentioned meta-dacites, meta-rhyolite porphyries, and meta-quartz latites, and further remarked that these types are present in the middle Miocene Topanga formation in the same area.

Field examination by the writer disclosed cobbles of comparable rocks in the Topanga formation immediately west of Cahuenga Pass. In the lower part of the formation these volcanic or metavolcanic rocks constitute as much as 50 percent of the larger clasts, but this represents a decrease in abundance as compared with clasts in the older, Cretaceous

conglomerates nearby. A further decrease is evident in the upper Topanga formation. The gradual disappearance of clasts of these rocks from the younger parts of the section probably indicates that their source had either been completely consumed by erosion or that it had undergone subsequent burial by younger deposits.

It is interesting to note that L. F. Noble (1954) encountered well-rounded cobbles of metavolcanic rocks in the Eocene Martinez formation in the San Andreas fault zone. The Martinez beds he described are exposed in the Valyermo quadrangle, along the juncture between the northern part of the San Gabriel Mountains and the southwestern part of the Mojave Desert. If these cobbles are lithologically the same as those described above, it is possible that their source lay along the crest of the San Gabriel Mountains and that it contributed erosional debris to both the northern and southern flanks of the range.

During the course of the present study, clasts of similar rocks were noted in sediments of Quaternary age. They occur sporadically in the Pleistocene Saugus formation at the northeastern end of the San Fernando Valley, and also are present in remnants of high-level terraces along the south flank of the western San Gabriel Mountains. These occurrences in younger rocks probably represent second-cycle derivation, further attesting to the durability of the metavolcanic rocks.

The cobbles of metavolcanic rocks are readily distinguished from clasts of Miocene volcanic rocks by: 1) an extreme toughness and durability (compared to the soft and "rotten" nature of the cobbles of Miocene volcanic material), 2) a well-rounded and polished appearance, 3) a general scarcity of basaltic types, and 4) the presence, in at least small amounts, of porphyritic rhyolites or latites.

Several thin sections of cobbles from the lower Topanga formation of the eastern Santa Monica Mountains were examined. The rocks are porphyritic rhyolites and andesites (or dacites). Their most striking characteristic is the presence of abundant secondary quartz in the groundmass. It occurs in flamboyant growths, and also in tiny fractures and veinlets indicating secondary silicification. J. E. Schoellhamer (personal communication, 1954) noted the relatively uncommon mineral piedmontite in similar clasts from the Santa Ana Mountains, and A. O. Woodford (personal communication, 1956) found that the rocks contain a highly sodic plagioclase. It would appear either that they were originally rich in manganese and sodium or that these elements were introduced along with silica during metamorphism. O. E. Bowen (1954, p. 51) also encountered piedmontite in rhyolitic members of the Triassic (?) Sidewinder volcanics near Barstow (Figure 22). He commented (op. cit., pp. 51-52) that this mineral also is

present in cobbles and boulders of rhyolite and dacite in the Eocene Poway conglomerate near San Diego. If all of these rocks were not originally of an unusual composition, they have been rendered so by a somewhat unusual type of metasomatism, for they present a distinct compositional contrast to other metavolcanic rocks in southern California.

In the Santa Ana Mountains the oldest conglomerates (Upper Cretaceous) contain clasts of andesite that are strikingly similar to the Santiago Peak rocks exposed in that area (Popenoe, 1941), but the younger Tertiary sedimentary rocks contain types that are quite different. Either a new terrane of source rocks was available at the close of the Cretaceous period, or a compositionally distinct part of the Santiago Peak formation began to furnish clastic debris. If the latter were the case, the present concept of the former extent of the Santiago Peak formation must be modified, for the Sespe conglomerates of Soper (op. cit.) lie 60 miles northwest of the northernmost exposures of the Santiago Peak rocks.

SURFACE GEOLOGY OF THE MIOCENE VOLCANIC ROCKS

Sunland Area

The city of Sunland, California, occupies the northwestern end of a narrow structural trough that lies between the San Gabriel Mountains on the north and the Verdugo Mountains on the south. This trough opens westward into San Fernando Valley, an alluviated lowland underlain by a synclinorium of Miocene and Pliocene sedimentary rocks.

The core of the San Gabriel Mountains is composed of anorthositic, granitic, dioritic and gneissic rocks ranging in age from pre-Cambrian to Mesozoic. These rocks are cut by numerous faults. Along the northern margin of the range a thick section of variegated continental beds of Tertiary age is exposed. On the south, a sequence of predominantly marine sedimentary strata lies unconformably on the crystalline rocks, or is faulted against them. Paleocene marine beds are exposed as slivers in the San Gabriel fault zone in the southern part of the range.

The next youngest sedimentary rocks are middle Miocene marine conglomerates and sandstones of the Topanga formation. They are exposed as a narrow belt of rock in the Sierra Madre fault zone (Plate I, Figure A). The deposition of these rocks was followed by the deposition of

marine upper Miocene Modelo shale, and this in turn was followed by the deposition of Pliocene marine sediments. This Tertiary sequence was later capped by the lower Pleistocene Saugus formation, of continental origin. All of these rocks on the south side of the San Gabriel Mountains represent sediments that were deposited along the northern margin of the Tertiary Los Angeles basin.

The Verdugo Mountains are much smaller in geographic extent, and represent a tilted block of crystalline "basement" rock uplifted along major faults. Exposed at the northwestern tip of these hills are Miocene and Pliocene (?) sedimentary rocks similar to those on the south flank of the San Gabriel Mountains. To the west the isolated Pacoima Hills rise abruptly from the alluvial floor of the San Fernando Valley. Volcanic rocks of Miocene age are exposed in all three areas: the southern San Gabriel Mountains, the northwestern Verdugo Mountains, and the Pacoima Hills, as well as at the northern edge of the town of Tujunga, east of Sunland.

Folding, mild faulting, and uplift probably occurred several times during the Cenozoic history of the Sunland area, but the most intensive episode of deformation took place in mid-Pleistocene time, along with the last major uplift of the San Gabriel Mountains. The Sierra Madre fault zone, which forms the southern margin of the range, probably has been active since early Tertiary times or

possibly even longer. Tilted and dissected terrace deposits of Quaternary age possibly attest to continuing tectonic activity.

Although the volcanic rocks in each of the localities mentioned above are lithologically similar, general stratigraphic relationships differ from one locality to another, and the areas therefore are discussed individually. The geographic relationships and areal geology of these exposures are shown on Plate I.

Sunland North

On the south flank of the San Gabriel Mountains two miles north of Sunland, a belt of massive and fragmental volcanic rocks extends west-northwest toward Little Tujunga Canyon (Plate 1, Figure A). Except for some small canyons that cross this belt near its eastern end, the topographic relief is rather subdued.

The volcanic section is characterized by three principal rock units, a platy olivine-bearing basaltic andesite, a cliff-forming breccia of basaltic andesite, and a massive amygdaloidal olivine basalt. These rocks are faulted between quartz diorite (Wilson quartz diorite of Miller, 1934) and subordinate older metasedimentary rocks on the north, and conglomerates and shales of middle and late Miocene age on the south.

Basaltic andesite breccia

General statement. The basaltic andesite breccia appears to be the oldest of the three units. It is best exposed in the vicinity of Akens Canyon, where its resistant nature has resulted in the development of imposingly steep canyon walls. In general it is a sombre red, with individual clasts that range from dark gray to brilliant brick red. It is massive and structureless and no hint of stratification is suggested in vertical exposures of as much as 150 feet. The representation of block-sized fragments ranges from 20 to 75 percent, and in general is great enough to justify the use of the term "breccia" rather than "tuff-breccia."* Blocks exceeding 10 to 12 inches in diameter are not uncommon, and a few are as much as nine feet across. They are angular to subangular. Sorting is poor, and the breccia everywhere presents a chaotic appearance. Clasts protrude from the weathered outcrop surfaces and in time fall free of the matrix. Typical exposures are illustrated in Figure 4.

Clasts of several distinctive types appear to compose this unit. Some are brick red and scoriaceous, whereas others are dark gray and flow-banded, or massive, gray, and porphyritic. Under the microscope most of them are

---

*The terminology applied to the pyroclastic rocks in this report is that suggested by Wentworth and Williams (1932).



Figure 4a. Breccia of olivine-bearing basaltic andesite, Akens Canyon, western San Gabriel Mountains. Weathered outcrop reveals the poor sorting of the jumbled blocks. Brunton compass for scale.



Figure 4b. Close-up view of the breccia. Note partial rounding of many of the small blocks, suggesting mutual abrasion.

seen to be textural varieties of an olivine-bearing basaltic andesite. Krauskopf (1948) described a similar heterogeneity of textural types developing autoclastically at the margins of a flow, but the internal structure of the flow differs from that of the breccia under discussion, and it is probable that the latter originated through explosive eruptions or the development of mudflows or avalanches on the flanks of a block-strewn volcano.

Petrography. Mineralogically, the larger fragments in the breccia are composed of phenocrysts of labradorite, subordinate olivine, and augite in a fine-grained groundmass of plagioclase, clinopyroxene, magnetite, and a small amount of glass. The plagioclase phenocrysts constitute 3 to 11 percent of the rock and range from median to calcic labradorite, here and there showing weakly developed normal or oscillatory zoning. They are generally fresh, although minor replacements by calcite, analcite, and an unidentified clay mineral are not uncommon. Euhedral phenocrysts of olivine have been pseudomorphously replaced by iddingsite and magnetite, rarely accompanied by colorless serpentine or bowlingite. Even where fresh, the olivine composes less than two percent of the rock. The phenocrysts and microphenocrysts of augite are subordinate to the olivine. They are colorless or pale greenish yellow, and occur as subhedral prisms and rounded grains. A single rounded crystal of anorthoclase was noted in one section, and is

thought to be a xenocryst.

The groundmass of the clasts ranges texturally from hypo hyaline-hyalopilitic to holocrystalline-pilotaxitic. Microlites of plagioclase range from median andesine to sodic labradorite, and are fresh and clear. The clinopyroxene is too fine grained to be identified. It occurs as tiny rounded prisms and grains of pale yellow or greenish yellow color. In many of the brick-red clasts, clinopyroxene has been replaced by an unidentified brown prismatic mineral. Its optical properties are as follows: pleochroic from yellow brown to orange brown, apparent birefringence .010, negative elongation, variable extinction from approximately 0° to 20°, and moderate positive relief in balsam. Magnetite occurs as well-dispersed tiny euhedral crystals, and is altered here and there to hematite, imparting a red color to the clasts. Subordinate altered glass occurs as tiny irregular patches in intercrystalline areas. Most of the scoriaceous blocks are wholly glassy, and appear as extremely vesicular, dark reddish brown fragments with sporadic microphenocrysts of plagioclase.

Some of the fragments are vesicular or microvesicular. The vesicles are irregular and compressed, and some are lined with a scaley brown or green chlorophaeite derivative. Crystalline minerals filling these cavities include heulandite, stilbite, calcite, tridymite, and cristobalite,

although all of these do not occur within a single clast.

The matrix of the breccia is variable in composition. In general it is composed of ash-sized lithic fragments and less abundant crystals of plagioclase. The lithic debris is identical to the lapilli and blocks that compose the bulk of the breccia, and there is a continuous gradation of particle diameters from 0.03 mm. to those of lapilli size. Scoriaceous fragments are in evidence, and vitroclastic shards are common. The shards appear to be concentrated in small clusters, suggesting trituration of large pieces of scoria during transportation rather than originally explosive comminution of lithic debris, for the latter should lead to a more or less even distribution of shards throughout the matrix.

The fragments are generally bonded by crystalline calcite that locally composes as much as 12 percent of the rock. Much of this calcite has embayed, veined, and otherwise replaced the lithic and crystal fragments. In some instances only the ferromagnesian constituents remain. In some samples heulandite (?) is scattered throughout the calcite in euhedral crystals, and locally a pale green chlorite forms the bulk of the cement. Specular hematite and magnetite were found in a few specimens of the matrix, and in places are much coarser grained than the minerals of the lithic debris. In view of the fact that the breccia is cut by dikes of younger basaltic andesite, it is probable

that these ferric minerals have been derived from contact emanations, or perhaps they originated from fumarolic gases that permeated the breccia early in its development.

In some areas the breccia is bonded by lava which is similar to the clasts in mineral composition. It probably represents material that flowed over and through the breccia. This phenomenon has been observed at Paricutin by Krauskopf (op. cit.).

Origin. The maximum areal dimensions of the breccia in the vicinity of Akens Canyon are roughly 2,000 by 600 feet, with 200 feet of vertical section exposed in the canyon walls. Its original dimensions probably were much greater. The belt of outcrop is bounded on the north and east by faults, and westward it disappears beneath a cover of younger olivine basalt, although some small outcrops of breccia were noted farther west in Doane Canyon and the east fork of Ebey Canyon. This rock is everywhere uniform in lithology and appearance, and probably represents a single massive unit.

Patches of arkosic conglomeratic sandstone are exposed within the breccia near a longitudinal fault that crosses Akens Canyon. The contacts between this rock and the breccia generally are faults, but in the east wall of the west fork of Akens Canyon part of the arkose gives the appearance of having been deposited conformably on the volcanic rock. It contains, in addition to subangular clasts of plutonic

rock, pebbles and cobbles of red and gray basaltic andesite. Evidently it represents a break in the deposition of the breccia, during which time coarse debris derived from the "basement complex" was deposited.

Although fragments of scoria are present in the breccia, they constitute a much smaller fraction of material than do the non-vesicular clasts. There is no implication that an agent such as nuees ardentes was responsible for the formation of the breccia, because accumulations of pyroclastic debris deposited by nuees are usually composed of highly inflated and distended material. The variable textural nature of the breccia, as well as the absence of bombs and "bread-crusted" blocks tend to bear out this hypothesis.

Ultra-vulcanian explosions, followed by avalanching, might have been responsible for the development of the breccia. In this type of eruption, violent explosions shatter and eject non-incandescent material that previously formed part of the volcanic edifice. Chaotic deposits of unsorted angular pyroclastic debris result. Alternatively, these deposits might be considered to be the products of volcanic mudflows or lahars. However, no features indicating the presence of water as a mobilizing ingredient of the breccia could be found. Lahars have been known to flow for distances of as much as 30 or 40 miles from their

source, but dry avalanches are more restricted, owing to their notably lower degree of mobility. Because the location of the source of the Akens Canyon breccia is unknown, its former degree of mobility cannot be estimated.

According to Axelrod (1939), the middle Miocene Tehachapi floras (65 miles north of Sunland) were supported by 15 to 20 inches of rain annually, indicating that the climatic conditions of southern California were not unlike those of the present day. The nature of the precipitation was probably such that a single storm could have set mudflows into motion, just as happens in the most arid parts of California today.

Olivine-bearing basaltic andesite

General statement. A dark gray, porphyritic, olivine-bearing basaltic andesite is intimately associated with the massive pyroclastic breccia. Locally it exhibits a platy or slabby jointing that is parallel or nearly parallel to an apparent planar flow structure. A second facies of this rock is massive and shows random jointing. The platy structure is more conspicuous in similar rocks southwest of Sunland and in the Pacoima Hills (Figure 8). Generally the rock is rather resistant, and upholds steep shoulders on the divides between canyons. It yields blocky talus slopes because of well developed jointing, but the talus fragments are small and generally do not exceed

five inches in maximum dimension. Small phenocrysts of plagioclase are apparent in the hand specimen, and sparse equant crystals of iddingsite are prominent in the aphanitic groundmass.

Petrography. Petrographically the basaltic andesite is similar to the clasts of the above described breccia. Phenocrysts of sodic to calcic labradorite, ranging from .25 to 5.0 mm. in length, constitute approximately six percent of the rock. They occur in fresh euhedral and subhedral laths, and here and there they show a weak normal zoning with rims of median andesine. They are accompanied by phenocrystic olivine and augite, which form one to two percent of the rock. The olivine has been replaced pseudomorphously by iddingsite, magnetite, bowlingite (?), and subordinate serpentine. Generally it occurs with euhedral outlines, although resorption and embayment are apparent. Its maximum length is 2.3 mm.. Augite occurs in subhedral microphenocrysts with a maximum length of .50 mm. Measurements on the universal stage revealed optic angles of 48° to 50°.

The groundmass is fine grained and has a pilotaxitic texture, although in some specimens the flow alignment of the feldspar microlites is pronounced enough to give the rock a trachytic aspect. Tiny granules of magnetite and pale yellow prisms of clinopyroxene are set between clear

euhedral microlites of median to calcic andesine. Also present in the groundmass are colorless needles of apatite and ragged shreds of brown biotite. Glass is rare; where present it is nearly colorless, and has a refractive index of less than 1.54. The groundmass plagioclase composes 45 to 55 percent of the rock, clinopyroxene 25 to 30 percent, magnetite roughly 10 percent, and glass and alteration products approximately four percent. Vesicles are notably absent from this rock, but in some specimens tiny patches of cristobalite dot the groundmass. Here and there the cristobalite is accompanied by minor calcite and heulandite (?).

The modal analysis of a porphyritic facies of this rock is given in Table 6 (specimen BVD-3b), and its chemical analysis in Table 7.

Origin. The spatial relationships of the platy basaltic andesite and the massive breccia are not readily determinable. Where exposed, the contacts are razor-sharp and steeply inclined. Slickensides are apparent, but because the entire belt of volcanic rocks is essentially a fault wedge, these slickensides probably indicate minor adjustments between rock masses of slightly different competency. Mapping revealed that the platy andesite thins locally to tabular dike-like masses, and where contacts bend sharply the flow structure or platy parting conforms. In a few places the breccia is reddened near its contacts with the

andesite. These features are thought to indicate that the breccia was intruded by the basaltic andesite.

Olivine basalt

General statement. Flows of olivine basalt overlie the breccia on the west wall of the west fork of Akens Canyon. They extend from that point to the west end of the area, and, with the exception of minor exposures of breccia in Doane and Ebey Canyons, they make up the remainder of the outcrops of volcanic rock. They weather to a soft, drab-brown material that upholds a topography of gentle relief. Although individual flows can be distinguished locally, the extensive weathering and the heavy cover of brush make it impossible to trace individual units for a distance of more than a few tens of feet. Fumarolic activity has locally reddened the basalt, but the rock is black where it is fresh and unaltered. Partially altered facies are reddish or yellowish brown. Although the petrographic characteristics vary slightly from unit to unit, the rock commonly is porphyritic and is either amygdaloidal or vesicular. Figure 5 shows the highly vesicular, reddened top of a massive flow exposed between Doane and Akens Canyons.

Petrography. Diversity in the percentages of constituent minerals is characteristic of the olivine basalt.

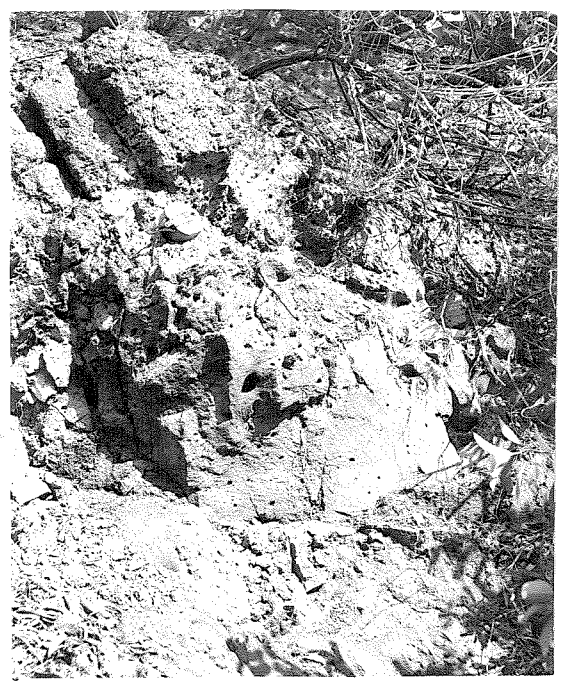


Figure 5. Upper part of olivine basalt flow between Akens and Doane Canyons, western San Gabriel Mountains. Highly vesicular, reddened flow top with crude columnar jointing overlies vesicle-poor, massive black interior.

Phenocrysts constitute from four to 25 percent of the rock, and they vary in abundance from flow to flow. They are principally plagioclase, constituting three to 20 percent of the rock, and olivine, constituting one to seven percent; diopsidic augite, with optic angles ranging from 50° to 53°, is present in small amounts. The plagioclase, in euhedral and subhedral laths with maximum length of 5.5 mm., ranges in composition from median labradorite to median bytownite. It exhibits normal or oscillatory zoning, with rims of calcic andesine, and in its outer zones contains abundant crystalline inclusions of the groundmass constituents or blebs of altered glass that may represent remelt patches.

Olivine is fresh in some rocks but wholly altered in others. Where fresh, it exhibits optic angles near 90°, suggesting a highly magnesian composition. Its alteration products show considerable variation. Iddingsite is the most common; it either partially rims fresh crystals or replaces them entirely. Other products include magnetite, hematite, bowlingite (?), xylotile, calcite, and microcrystalline derivatives of chlorophaeite. In some specimens these replacements are arranged in zones, possibly reflecting a compositional zoning of the original olivine crystals. The crystals of fresh olivine and their pseudomorphs have euhedral outlines modified by resorption. They range in length from 1.2 to 3.0 mm..

Several textures characterize the groundmass. These

include holocrystalline-intergranular, holocrystalline-subophitic, hypocrystalline-intersertal and hypocrystalline-hyaloophitic. Glass typically constitutes about five percent of the rock, although some specimens contain as much as 30 percent. The groundmass plagioclase ranges in composition from sodic to calcic labradorite, and composes 40 to 50 percent of the rock. It is present in tiny microlites .08 mm. in average length, and in laths as long as .60 mm.. Augite, with 2V of 49° to 53°, occurs either interstitially or molded about crystals of plagioclase. It is pale yellow or very pale brown, and in some samples is altered to hematite. Apparently it crystallized late, for in rocks containing as much as 30 percent of glass it is the only mineral that exhibits a sympathetic decrease in abundance. Normally it composes 15 to 25 percent of the rock.

Olivine not only forms phenocrysts but also occurs in the groundmass, where its percentage ranges from five to ten. The crystals are of varied sizes and are in most instances wholly altered. Opaque "ores" are present either as well developed crystals or as a highly dispersed dust in the glassy mesostasis. Distinctive octahedra of magnetite can be seen in some rocks, and lath-like crystals, apparently of ilmenite, are visible in others. These minerals form four to eight percent of the total volume of the rock.

Both celadonite and brown and green microcrystalline derivatives of chlorophaeite have replaced the interstitial glass in patches, and also occur as linings of irregular vesicles. Amygdules are most commonly composed of crystalline calcite or a soft, purplish, clay-like powder of iron oxides. Chalcedony is abundant where the basalt has been severely altered by fumarolic gases. Tangentially-oriented laths of plagioclase form rims around vesicles and amygdules, indicating partial crystallinity of the rock at the time of gas bubble formation. Near the west end of the area, ellipsoidal amygdules of calcite as much as two inches in diameter are accompanied by large calcite-lined pipes oriented normal to the flow structure. Two modal analyses of the basalt are presented in Table 6, and a chemical analysis in Table 7. Fused beads indicate that certain of the flows contain as much as 52 percent of silica.

Origin. Where exposed along the truck trail to Fascination Springs, in the western part of the area, the contact between the olivine basalt and Tertiary sedimentary rocks is apparently a fault. Both rocks are locally shattered, and they are separated by a zone of gouge. At the head of the next truck trail west, however, the contact appears to be intrusive in nature. Basalt butts irregularly against a massive, buff-colored arkosic sandstone, and at the contact the sandstone is discolored to a dark green (Figure 6). Immediately to the north the contact between

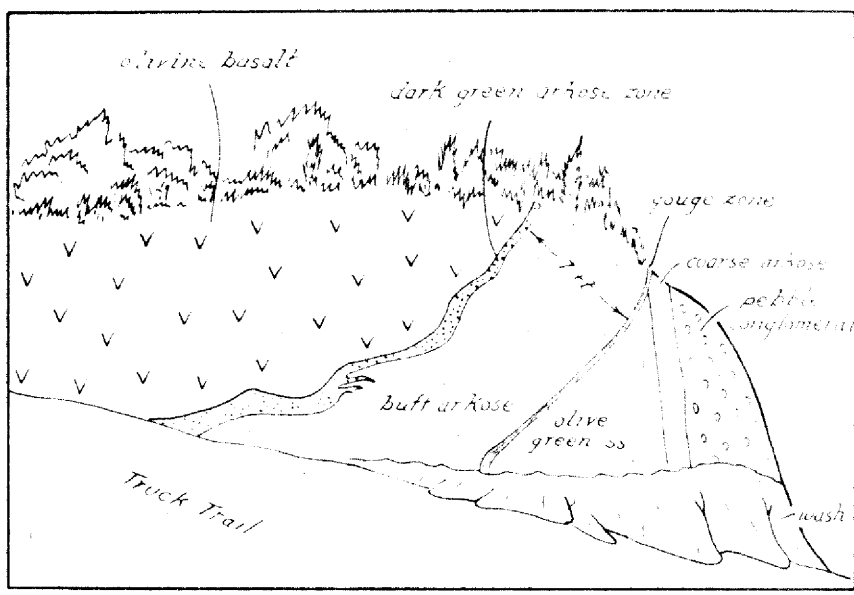


Figure 6. Field sketch (looking east) of truck trail cut south of Fascination Springs, western San Gabriel Mountains (Plate 1, Figure A). Olivine basalt butts irregularly against buff-colored arkose. Latter is stained dark green at contact, suggesting contact alteration.

this basalt and the "basement" rocks is overlain by an outlier of arkose. It has a pronounced vertical jointing, but the bedding dips gently southward. Either this arkose is younger than the basalt and lies unconformably across it and the older rocks, or it represents a remnant of sandstone resting depositionally upon the "basement" rocks at the crest of an eroded fold, the core of which has been intruded by the basalt. Trail construction activities have buried much of the contact between the arkose and basalt, but previous work by students of the California Institute of Technology (unpublished reports) revealed intrusive relationships with the base of the sandstone at this locality. The fact that part of the olivine basalt is intrusive, and therefore of post-arkose age, is further corroborated by three disconnected lenticular masses of this rock that apparently have risen along the fault bounding the southern edge of the volcanic rocks near Akens Canyon (see Plate I, Figure A). All three bodies lie in contact with the arkose on the south.

Age. The age of the intruded sedimentary rocks fixes a lower limit for the age of the intrusive portion of the olivine basalt. The Modelo shale lies immediately south of, and stratigraphically above, the arkosic sandstones and conglomerates. It is middle Mohnian in age, as established by Foraminiferal assemblages collected by Standard Oil Company paleontologists at the localities indicated in

Plate I, Figure A. Near Akens Canyon this shale is separated from the coarser epiclastic rocks by a fault, but west of Doane Canyon the contact appears to be depositional, and the arkose underlies the shale. Within the arkose are thin beds of highly indurated grayish brown sandstone and pebble conglomerate that contain abundant marine megafossils. A suite of poorly preserved fossils (Appendix I) was collected by W. H. Holman and the author, and was identified by Dr. L. G. Hertlein, who commented as follows:

> This group of species appears to be referable to the Topanga, Miocene. Species such as Oliva californica and Trophon kernensis are restricted to the Temblor or to beds of approximately equivalent age, such as the Topanga.

The presence of Aequipecten discus is significant, for a few miles to the west a shallow well encountered gray sandstones containing A. discus and a Foraminiferal fauna indicative of the Relizian-Luisian interval of the Miocene. One may assume, therefore, that the intruded arkose is middle Miocene in age. This date corresponds to an age determination in the eastern Santa Monica Mountains, where lithologically similar lavas were extravasated during Relizian time. There, as here, a later phase of intrusive activity followed the surface manifestations of volcanism and, although the small intrusive bodies cut rocks of middle Miocene age, nowhere were they observed to cut younger rocks such as the Modelo shale.

An exact determination of the age of the basaltic

andesite breccia is precluded by the lack of interbedded fossiliferous sedimentary rocks. Upper Miocene (Mohnian) conglomerates exposed near Big Tujunga Wash, to the south, contain clasts typical of the breccia, however, indicating that it is pre-late Miocene in age. In addition, the intruded arkosic sandstones and conglomerates contain no clasts of this rock type, indicating that the breccia probably formed contemporaneously with, or slightly later than, the arkose. Its age, therefore, would be middle Miocene.

Sunland South

The rocks

General statement. At the southwest edge of Sunland, along the north flank of the Verdugo Mountains, is another belt of similar volcanic rocks (Plate I, Figure B). The section is composed primarily of flows and breccias of olivine-bearing basaltic andesite, with a capping flow of vesicular olivine basalt. Individual flows of the andesite are readily distinguished by the nature and relative abundance of their phenocrysts. Most of the flows show a well developed platy parting (Figure 8) or a distinctive flow foliation (Figure 7). Where both features are discernible, the parting is either parallel to the foliation or inclined from it at a small angle. With the exception of the two



Figure 7. Hand specimen of olivine-bearing basaltic andesite, showing well developed flow laminae. Rocks of this type show a sub-trachytic texture in thin section. Specimen from northwestern Verdugo Mountains, near Sunland, California.

northernmost (uppermost) units, the flows are extremely irregular in cross section, thinning and thickening along the strike. As a result, the stratigraphic succession is not uniform throughout the area.

Locally the volcanic rocks are brecciated and reddened along their bases or tops. Some of the brecciation appears to be of tectonic origin, but most is suggestive of pyroclastic or autoclastic processes. Many of the fragments exhibit irregular flattened vesicles of the type ascribed by Macdonald (1953) to aa flows.

One of the fragmental units is 120 feet thick. It consists almost wholly of non-scoriaceous lapilli and blocks that are bonded with secondary clay. Immediately overlying it is a thin lens of arkosic sandstone, reddened along its upper margin. A similar lens occurs to the west at about the same stratigraphic position. Both lenses are overlain by flows of basaltic andesite.

The uppermost unit of olivine basalt is overlain by buff arkosic sandstone and conglomerate. Although clastic debris from the "basement complex" constitutes the larger part of these rocks, subangular pebbles and cobbles of olivine-bearing basaltic andesite and olivine basalt also are present. The contact between the sedimentary rocks and basalt is exposed at only two places and at both it is a fault. Nearby isolated outcrops of sandstone and conglomerates show anomalous dips and strikes that suggest deformation near the contact.

The nature of the southern (lower) contact is less obvious. The eastern half of the volcanic section rests on pre-Tertiary crystalline rocks, but to the west the section rests on a conglomerate of undetermined age. This conglomerate contains clasts of volcanic rock identical to those exposed nearby, which suggests that it is younger than the volcanic section which now overlies it. It may have gained its apparent stratigraphic position below the effusive rocks by faulting.

Petrography. The olivine basalt is petrographically similar to that exposed in the San Gabriel Mountains to the north. The olivine-bearing basaltic andesites show variation, however, and differences between flows are distinguished on the basis of phenocryst percentages (Table 2). These percentages are constant for distances of as much as one mile along the strike.

Plagioclase	Augite	Olivine	Magnetite	Remarks
Median labradorite				Microporphyritic
20%	6%	1%	3%	Total: 30%
Labradorite-bytownite				Porphyritic
18%	1%	< 1%	0%	Total: approx.20%
Median labradorite				Microporphyritic
13%	0%	1%	0%	Total: approx. 14%

Table 2. VARIATIONS IN THE PERCENTAGE OF PHENOCRYSTS IN FLOWS OF OLIVINE-BEARING BASALTIC ANDESITE NEAR SUNLAND, CALIFORNIA.

The groundmass, which varies little in composition from flow to flow, consists of 45 to 55 percent plagioclase (median andesine to andesine-labradorite), 15 to 20 percent clinopyroxene, 8 to 12 percent magnetite, and 0 to 3 percent glass (dark brown, n less than 1.54). Cristobalite and, rarely, tridymite are present in micro-vesicles, but neither is as common as derivatives of chlorophaeite or celadonite (?). Bead determinations indicate that the silica content of the bulk rock ranges from 56 to 58 percent.

Age. Sandstone and conglomerate overlying the volcanic rocks are succeeded upward by fine-grained sandstone and shale of early Mohnian age. The only locality where fossils were collected lies north of Sunland Boulevard at an undetermined stratigraphic distance above the fault-bounded volcanic section. The volcanic rocks, therefore, are probably of pre-lower Mohnian age.

Pacoima Hills

Pre-Tertiary crystalline rocks are exposed along the southern edge of the Pacoima Hills, approximately five and one half miles west-southwest of Sunland. To the north they are faulted against arkosic sandstones and conglomerates. The arkosic sediments consist chiefly of relatively thin beds of red color that grade upward into sharply bedded yellow and pink sandstones. Most of the larger clasts in the conglomerate are of granitic rocks, but

cobbles of gray and purplish gray basaltic andesite also are present, suggesting that volcanic rocks that were originally stratigraphically below the arkose have been cut out by the faulting that placed the arkose against the pre-Tertiary crystalline "basement."

Olivine basalt

General statement. The arkose is succeeded upward by two distinctive flows of olivine basalt that are about 40 feet in total thickness. They thin eastward and pinch out near the margin of the hills. On the map (Plate I, Figure C) they are indicated as a single unit, but in the field a lower, purplish gray, amygdaloidal flow can be distinguished locally from an overlying, less resistant, essentially non-amygdaloidal one. The arkose beneath them is reddened for a thickness of one or two feet.

Petrography. Under the microscope, rocks from the two flows are nearly identical. The non-amygdaloidal lava is characterized by phenocrysts of sodic bytownite, which constitutes two percent of the rock, and altered olivine, which constitutes ten percent, in a subophitic groundmass composed of 44 percent median labradorite, in laths .10 to .60 mm. long, 19 percent pale brown augite ($2V = 48^\circ$ to 50°), 12 percent altered olivine, 7 percent ore, and 5 percent chlorophaeite. Fused beads indicate that the silica content of the entire rock is 50 percent.

The amygdaloidal flow rock differs in the relative proportion of its phenocrysts. The amygdules are composed of calcite and subordinate quartz. The major alteration product of the olivine is unidentified. It is pleochroic with X = colorless or pale yellow, and Y and Z = amber yellow. N_x is less than 1.530, but N_y and N_z show a moderate positive relief in balsam. The birefringence is variable, with a maximum value of 0.070. The mineral is optically negative with a low 2V, and shows parallel extinction and positive elongation. It appears to be most closely related to biotite, but the X index is lower than that of biotite, the birefringence is slightly too high, and an X-ray powder pattern is totally unconvincing. It is accompanied by a little iddingsite and hematite. In all other respects, the rock is like the non-amygdaloidal lava described above.

Age. The flows of olivine basalt are overlain by a coarse-grained arkosic sandstone. The age of this arkose has been estimated to be somewhere in the interval middle-early to late-middle Miocene by R. H. Jahns (personal communication, 1954), on the basis of a poorly preserved oreodont ramus. Other geologists have long referred to this section as Topanga on the basis of its lithology.

Basaltic andesite breccia

A medium to grayish red breccia of basaltic andesite lies above the fossil-bearing arkose beds. It is only a

few feet in maximum thickness, and is locally absent where an overlying body of massive basaltic andesite is in direct contact with the arkose. The sheet-like dimensions of the breccia, as well as its poorly sorted nature, suggest a mudflow origin. Locally, the basal part of the unit appears to include volcanic sandstone (pyroclastic material reworked by water).

Olivine-bearing basaltic andesite

North of the breccia and stratigraphically above it is a massive olivine-bearing basaltic andesite, similar in composition to the volcanic rocks exposed in the Verdugo Mountains to the east. It is a thick unit, and although its lower contact is generally conformable with the underlying volcanic-sedimentary section, it locally lies between the breccia and arkose or cuts the breccia out altogether. The upper contact is not well exposed, but it does not appear to be parallel to the lower contact. South of the private road in the northern part of the map area, a thin screen of red and buff arkosic sandstone is exposed between this andesite and an olivine diabase to the north. The diabase plainly is intrusive into the arkose, but the andesite is too poorly exposed to give a suggestion of its relationship. In general, the andesite is massive and unbroken except for well developed platy parting and a locally conspicuous flow structure (Figures 8 and 9). The latter



Figure 8. Platy parting (jointing) in intrusive basaltic andesite, western Pacoima Hills. The parting is parallel or quasi-parallel to a discernible flow structure in the rock.

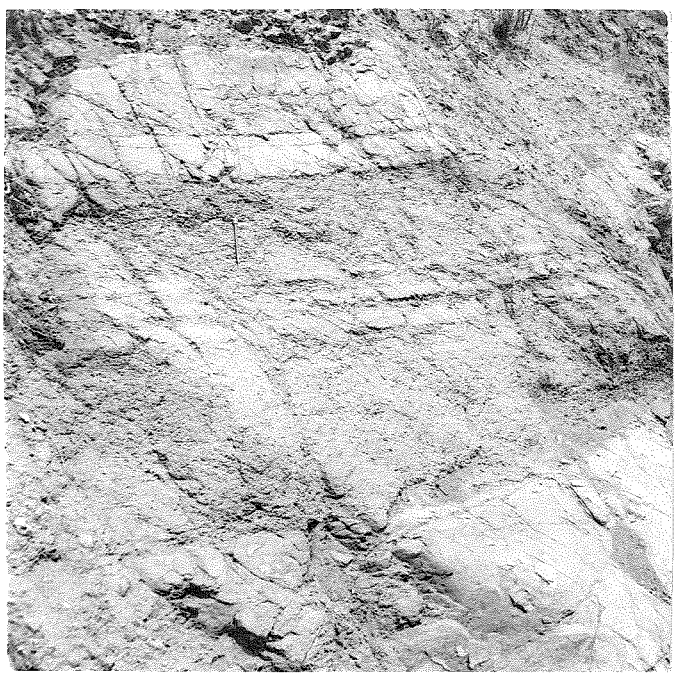


Figure 9. Large-scale flow banding in massive basaltic andesite, western Pacoima Hills. Bands consist of alternating vesicular and non-vesicular rock. The banding is thought to have resulted from a shearing out of volatile-rich portions of the magma. Pencil is five inches long.

is manifested in alternating vesicular and non-vesicular layers with a maximum thickness of two feet. Field evidence suggests that the basaltic andesite is intrusive, even though its uniformly fine-grained texture does not appear to support this interpretation.

Olivine diabase

The northernmost "volcanic" unit in the Pacoima Hills is an olivine diabase. It differs from the olivine basalt of the flows in having a relatively coarser, nonporphyritic texture and a higher percentage of plagioclase. Its modal analysis (BVP-6) is given in Table 6. On the south, this roughly tabular mass is bordered by the massive basaltic andesite and by a sliver of reddened arkose. On the north it is bordered by arkosic sandstones and conglomerates of the Topanga (?) formation and shale of the Modelo formation.

The Topanga (?) sandstone that lies above the volcanic section is conspicuously poor in fossils, but several pieces of charred wood and the vertebrae of a fish suggest a littoral facies of the formation. Foraminiferal faunas indicative of the lower Mohnian were collected from the Modelo formation by the writer and W. E. Hendrix at the localities indicated on Plate I, Figure C. In the eastern part of the hills, the sedimentary strata of these formations appear to butt against the diabase, suggesting that

the latter is intrusive into them, or that it is separated from them by a fault. The contact is knife-sharp, and at one place an apparent apophysis is exposed, indicating that the diabase is probably intrusive. Because of the general lack of parallelism of the beds above and below the diabase and basaltic andesite, it is probable that both of these intrusive bodies were emplaced along an older fault plane. Later deformation would account for the small amount of gouge that was noted along the contact.

According to R. H. Jahns (personal communication, 1954), a small intrusive plug of "dacite" was exposed during the excavation for the hilltop house north of the diabase exposures. It lies entirely within the sandstone and very close to the contact with the lower Mohnian shale.

Intrusive breccia

In addition to the rocks described above are scattered lensoid masses of clastic volcanic rock, indicated on the map as "intrusive breccia." In the westernmost quarry, platy basaltic andesite is in contact with one of these breccia masses. Near the breccia the platy parting is parallel to the contact, but farther away it dips outward on all sides, suggesting that the breccia has domed the andesite. Elsewhere these bodies are not well exposed and the interpretation of their intrusive nature is based on the steep contacts of the bodies and their occurrence at several

different stratigraphic horizons.

Under the microscope the matrix of the breccia consists chiefly of tiny angular fragments, .05 to .10 mm. in diameter, of highly vesicular to scoriaceous, reddish brown altered glass containing microphenocrysts of labradorite. In addition to the scoria fragments are free crystals and fragments of plagioclase and some larger clasts of a lithic nature. Locally this ash is cemented by opal and nontronite (?) and elsewhere by an unidentified clay mineral. The larger angular clasts give these breccias a strong resemblance to the mudflow breccia already described.

Tujunga Area

Tertiary volcanic rocks crop out as a small sliver along the margin of the San Gabriel Mountains northeast of Tujunga (Plate I, Figure D). In cuts near the corner of Rose Street and Pinyon Avenue both dark gray pyroxene andesite and a massive sombre red breccia are exposed. They are separated from crystalline "basement" rocks by a fault-bounded wedge of coarse conglomerate, the age of which is undetermined.

Summary of the Stratigraphic Relationships in the Sunland Area

The flows of olivine basalt near Pacoima are probably of middle Miocene age, but no distinction between Relizian or Luisian stages can be made. The sedimentary strata that lie below these flows contain clasts of olivine-bearing basaltic andesite, suggesting that flows of this rock type were extravasated earlier (i.e., before the flows of olivine basalt). This interpretation is substantiated in the Verdugo Mountains, where several flows of basaltic andesite, capped by olivine basalt, are present in a section that is probably pre-lower Mohnian in age. In both the San Gabriel Mountains and Verdugo Mountains, breccias of olivine-bearing basaltic andesite are locally intercalated with red arkosic sandstone that is lithologically correlative with strata interbedded in the volcanic sequence near Pacoima. Thus breccias and flows of basaltic andesite were succeeded by flows of olivine basalt, and together these rocks characterize the local middle Miocene episode of volcanism in the Sunland area.

In the Pacoima Hills and San Gabriel Mountains a later phase of intrusive activity resulted in the emplacement of olivine basalt and diabase. The intruded sedimentary rocks north of Sunland are middle Miocene in age, and those near Pacoima probably are of a similar age.

Eastern Santa Susana Mountains

The eastern Santa Susana Mountains lie immediately north of the western part of San Fernando Valley. The rocks exposed in and near the southern edge of these mountains range in age from Upper Cretaceous to Pleistocene, and include both marine and non-marine strata. The "volcanic" rocks are enclosed by medium-grained to coarse-grained clastic rocks of the Topanga formation.

The structure of the Santa Susana Mountains is essentially anticlinal. In the southern part of the mountains the Santa Susana thrust fault is exposed. This fault crops out for a strike distance of approximately 20 miles and represents a minimum of 8,000 feet of reverse dip-slip displacement. The northern block of the mountains has been thrust southward. At the surface the fault plane is nearly horizontal, but exploratory drilling has revealed that it steepens with depth. In the foothills, the footwall block is folded and broken by steeply dipping subordinate faults that strike roughly parallel to the thrust zone. The Santa Susana thrust continues eastward via a series of branches to merge with the Sierra Madre fault zone.

Olivine diabase

General statement. A concordant, sheet-like body of olivine-bearing basaltic rock is exposed near the top of

the Topanga sandstone immediately west of the Aliso Canyon oil field. It crops out at the heads of Browns and Mormon Canyons and is readily accessible along the western oil field roads (Plate II). Its maximum exposed thickness is nearly 120 feet, but it thins westward and appears to pinch out northwest of Browns Canyon.

It weathers typically to a reddish brown material, but in roadcuts it is dark brown, brownish black, or dark orange. Alteration, which is joint controlled, has resulted in the development of relatively fresh, subangular residual blocks in a friable earthy matrix (Figure 10). This is apparently a form of exfoliation, but the characteristic spherical bosses have not been developed.

Petrography. Under the microscope the rock has a subophitic texture, and slender laths of plagioclase, averaging .75 mm. in length, give it a diabasic appearance in the hand specimen, as well. The plagioclase, which constitutes 60 percent of the rock, is predominantly calcic labradorite showing transitional normal zoning. In most specimens it is fresh. Molded about the ends of the feldspar laths are grains of pale brown diopsidic augite ($2V = 51^{\circ}$ to 54°). They constitute 14 to 17 percent of the rock. Olivine is present as small, clustered crystals ranging in abundance from 17 to 21 percent of the rock. The remaining five percent of the rock consists of lath-shaped crystals of ilmenite. The amygdules are chiefly of

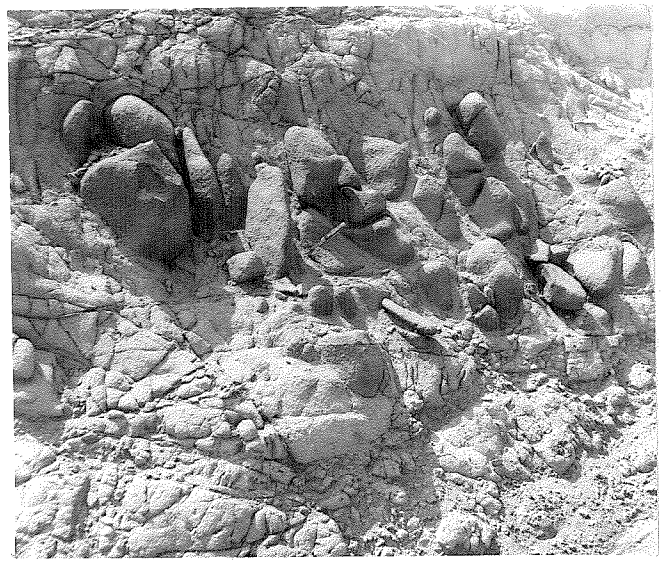


Figure 10. Unusual exfoliation in olivine diabase, Aliso Canyon oil field, eastern Santa Susana Mountains. Note the superficial resemblance of this rock to an agglomerate. Knife handle is 3 1/2 inches long.

calcite, although a fibrous zeolite was seen in several specimens. A study of samples taken from different horizons in the sill failed to indicate any striking or consistent variations in the mineral composition.

Origin. The nature of this tabular mass is most easily determined near the head of Mormon Canyon. Here the overlying Topanga sedimentary strata are conglomeratic, and the beds show a slight angular discordance with the upper surface of the igneous rock. In addition, apophyses of the latter project upward into the sediments (Figure 11). The body is clearly intrusive.

Near its base and upper margin the sill is amygdaloidal, but it lacks recognizable chilled selvages. Well developed amygdules were noted in several other intrusive bodies in the region. In addition, the sedimentary rocks in contact with the sill above and below show little or no baking or discoloration. This is characteristic of rocks in contact with the Tertiary volcanic rocks at most places in the Los Angeles area, the reddened sediments in the Pacoima Hills being an exception. This lack of contact effects might be attributed either to low temperatures of intrusion, lack of reactive volatiles, or to an advanced stage of crystallization in the lavas at the time of their emplacement. If crystallization had been advanced, it seemingly should have resulted in the development of flow structures, protoclastic structure, or a high percentage

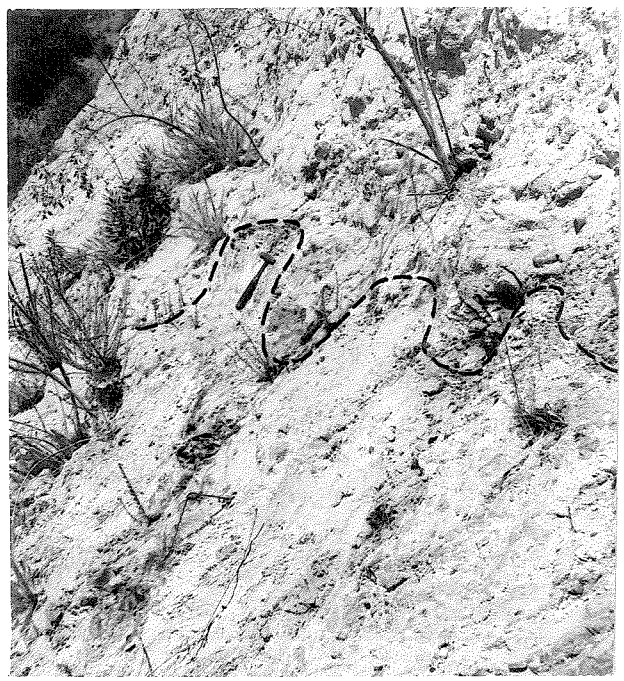


Figure 11. Upper contact of diabase sill near head of Mormon Canyon, eastern Santa Susana Mountains. Irregularity of contact between Topanga conglomerate and diabase, and inclusions of the Topanga formation within the diabase indicate an intrusive origin for this body.

of phenocrysts. None of these features was noted in specimens taken from the upper and lower contact zones. The presence of amygdules and vesicles is not necessarily indicative of a high content of volatile constituents, according to Verhoogen (1951), and thus the development of amygdules in this rock does not mean that the lava was rich in gases. There is no indication that the sill was emplaced at a low temperature. It may be that the nature of the sediments was such that the heat and volatiles were transferred rapidly away from the igneous body, thus preventing the development of recognizable contact effects.

Age. The Topanga sandstones and conglomerates in immediate contact with the sill have yielded no fossils. However, just below the Mohnian shale that rims the head of the canyon is a thin shale bed containing Valvulineria californica, an index species representative of the Luisian stage. The intruded rocks must therefore be Luisian or older, and the diabase must have been emplaced either during the middle Miocene or some time thereafter. It is possibly correlative with the intrusive olivine diabase and basalt at Sunland and in the eastern Santa Monica Mountains.

Eastern Santa Monica Mountains

The Santa Monica Mountains represent the southernmost member of the east-west trending Transverse Ranges, and extend from the Los Angeles River on the east to the Oxnard Plain on the west. Beyond the southeastern end of the Santa Barbara Channel, the Channel Islands rise from the Pacific Ocean as a westward structural continuation of the Santa Monica Mountains. Both the Cenozoic rocks and the principal structures of the islands are like those of the mountains to the east. The total exposed length of this tectonic unit is 125 miles, and it is three to thirteen miles wide.

The rocks that crop out in the eastern part of the mountains range in age from Triassic (?) to Pleistocene. The oldest rocks are Triassic (?) slates and schists that have been intruded by quartz diorite. These "basement" rocks are not exposed west of 118° 35' W. They are uncomformably overlain by unmetamorphosed Upper Cretaceous conglomerates correlative with lithologically similar rocks in the Santa Ana Mountains. Above these Mesozoic rocks is a Cenozoic section that includes the Martinez (Paleocene), Sespe (Eocene-lower Miocene), Vaqueros (lower Miocene), Topanga (middle Miocene), Modelo (upper Miocene), and Pico (Pliocene) formations. There are many unconformities in this section, and a few of them locally show high angular

discordances. Relevant to the present study are the unconformities that bound that part of the Topanga formation containing the volcanic rocks, and the pronounced angular unconformities within and at the top of the upper Topanga formation. According to Durrell (1954), "the Santa Monica Mountains represent a large part of a trough in which sediments younger than the Santa Monica formation (Triassic (?) slates) accumulated to an estimated thickness of nearly 50,000 feet."

Structurally, the eastern Santa Monica Mountains compose a faulted and broken anticline that plunges to the west. The south flank of this anticline is not exposed locally because of faulting or burial beneath Quaternary sediments. The fold underwent more or less continual evolution during late Mesozoic and Tertiary times. Many faults cut the range; the most persistent is the Malibu Coast fault, a steep northward dipping reverse fault that bounds the southern margin of the mountains. No comparable fault is exposed along the northern margin.

In the central part of the range, west of the area included in the present investigation, intrusive masses of diabase and basaltic breccia are exposed. Several of these masses occupy fault zones which they evidently utilized as channel-ways. This phenomenon is particularly striking where the faults branch or intersect other faults, for there the hypabyssal bodies branch also.

Still farther west, in the western Santa Monica Mountains and Conejo Hills, flows and interbedded pyroclastic

rocks of Miocene age reach a thickness possibly exceeding 12,000 feet. According to Shelton (1954, p. 33), these rocks include porphyritic hornblende andesite, breccias and flows of augite andesite, hypersthene basalt, and olivine basalt, as well as intrusive bodies of diabase and hypersthene diabase. Subordinate rocks comprise rhyolite and trachyte (?). This great pile of varied volcanic rocks suggests close proximity to one or more sources. Certain features of the volcanic rocks in the eastern part of the range suggest a closeness of source in that area also.

The area here designated as the eastern Santa Monica Mountains extends westward from the Los Angeles River to a point approximately half a mile beyond Laurel Canyon (Plate III). The geology of the eastern Santa Monica Mountains can be conveniently divided into two areas separated by the Cahuenga fault zone, which lies one half to three fourths of a mile east of Cahuenga Boulevard. In a general sense, the rocks cropping out in both areas are similar, but in detail they show striking differences. This is particularly true of the volcanic rocks.

West of the fault zone the strata dip steeply north in homoclinal fashion,* and are offset by northeast-trending transverse faults. To the east the structure is more complex and is characterized by high-angle faults that break

*North limb of the Santa Monica anticline of Hoots (1931).

the rocks of the Griffith Park area into several distinct blocks. According to Neuerburg (1953), some of these faults were active throughout the Tertiary history of the area.

Griffith Park

The volcanic rocks in the Griffith Park area show lithologic variations that are not present in the rocks west of Cahuenga Pass. Excellent exposures of these rocks can be seen in roadcuts along Vista del Valle and Mt. Hollywood Drives and in the old basalt quarries on the east side of Brush Canyon.

Olivine diabase

General statement. The most widespread unit is a fine-grained olivine diabase or ophitic olivine basalt. It weathers readily to a tan or brown material that has a soft, crumbly consistency. Alteration has been facilitated by the presence of abundant joints. In places the diabase is vesicular or amygdaloidal. Locally, it shows an intrusive relationship with the middle Miocene Topanga formation, but in most places its mode of emplacement cannot be determined. Neuerburg, who mapped the area in detail, states that "no massive flows of basalt were recognized" in the area, indicating that he considers this unit to be intrusive (Neuerburg, op. cit., p. 15).

Petrography. Plagioclase, olivine, titanaugite, and ilmenite are the characteristic minerals of the diabase. The olivine occurs as slightly rounded euhedral phenocrysts that constitute three percent of the rock, and as smaller, wholly altered groundmass individuals that constitute 18 percent. They are either rimmed or completely replaced by magnetite, chlorophaeite, celadonite (?), and the unidentified, highly birefringent, yellow mineral noted in the flows of olivine basalt in the Pacoima Hills. Euhedral laths of faintly zoned median to calcic labradorite compose 42 percent of the rock. They average .40 to .60 mm. in length, and are ophitically enclosed by a pinkish-brown titanaugite ($2V = 47°-50°$) that constitutes 19 percent of the rock. Laths of "ore", in places altered to hematite, make up nearly three percent. The remaining 14 percent of the rock consists of celadonite (?) and other fibrocrystalline derivatives of chlorophaeite that fill tiny interspaces between the principal minerals. The refractive index of a fused bead indicates that the rock contains approximately 48 percent of silica.

Massive basalts

Another massive intrusive body is exposed along the east wall of the main Brush Canyon quarry. It is medium dark gray in color, and porphyritic-aphanitic in texture, with phenocrysts of plagioclase and augite. Its appearance

is similar to that of the olivine-bearing basaltic andesites near Sunland, but the groundmass texture of the rock is typically that of a basalt. Plagioclase has been replaced by analcite, natrolite, subordinate calcite, and cloudy albite-oligoclase, but vestiges of the original mineral suggest that it was labradorite. Coarsely crystalline analcite lines joints and fractures. Here and there on a microscopic scale, the rock exhibits zones of a sheared or crushed nature, but this structure is not evident in the field.

Also exposed in the quarry is a massive, porphyritic, intergranular basalt that contains phenocrysts of sodic bytownite, neutral-colored augite, and altered olivine. This rock locally occurs as a coarsely brecciated facies in the immediate vicinity of the quarry, but in places it grades into a massive, non-fragmental rock. Its contact with the sedimentary rocks of the Topanga formation is nowhere exposed.

Flow breccia

The most conspicuous volcanic rock in the Griffith Park area is a brick red breccia that is well exposed in several roadcuts. It forms thin, irregular masses that are shown as a separate unit on the map (Plate III). Neuerburg (op. cit.) suggests that its exposures "... represent a stratigraphic marker in ... the Topanga formation." In

a few places, for example, stations "A" and "B", this breccia is underlain by a texturally-similar breccia that is medium dark gray in color.

The larger clasts that compose this rock are angular, and range from four to ten inches in diameter. Sorting is poor. Thin-section study reveals that specimens from different localities in the park are not lithologically identical, which suggests that all of the exposures of this rock may not constitute the same stratigraphic unit. Flow breccias, with angular fragments of holocrystalline basalt in a matrix of basaltic lava, and tuff-breccias, with a reddened matrix of highly vesicular lithic ash, are common. Some of the fragments in the breccia are highly porphyritic, with 32 percent of the volume consisting of phenocrysts. Plagioclase has been replaced by analcite, albite (?), subordinate calcite, and clay, and the ferromagnesian minerals have been altered to hematite.

Basaltic agglomerate

Olivine basalt occurs as breccia or agglomerate in several parts of the park. The most readily accessible exposures are at map station "C" (Plate III) on Mt. Hollywood Drive and along a topographic buttress projecting from the east wall of the main Brush Canyon quarry. Fragments of this rock are commonly subrounded or subangular, but in places they are well rounded. Figure 12 illustrates the

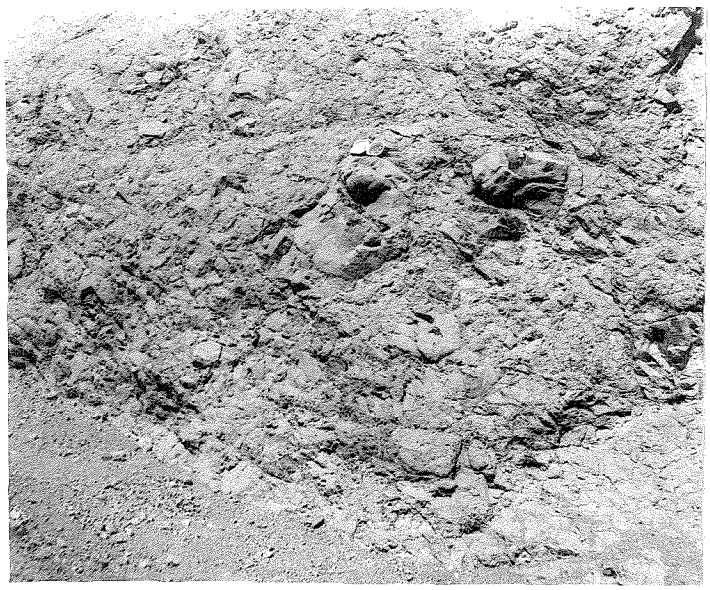


Figure 12. Agglomerate of olivine basalt in Brush Canyon quarry, eastern Santa Monica Mountains.

typical appearance of the rock. The clasts range from about one inch to three feet in diameter, and aggregates of the smaller ones serve as a matrix for the larger. Very little ash is present. The fragments are chiefly holocrystalline, and only a few are vesicular. Where contacts are well exposed, they suggest an intrusive relationship with the adjacent sedimentary rocks. In all probability the rock is auto-brecciated. Mineralogically it is identical to the extrusive rocks west of Cahuenga Pass.

Hypersthene basalt

At map stations "D" and "E", dark gray to olive gray, olivine-bearing hypersthene basalt is exposed. These occurrences represent the only outcrops of hypersthene-bearing rock in the northwestern part of the Los Angeles basin. Both are closely associated with a red volcanic breccia, and probably are parts of the same stratigraphic unit.

Under the microscope, the rock is composed of plagioclase (normally zoned from sodic bytownite to sodic labradorite), augite and olivine phenocrysts in a groundmass of labradorite, augite, hypersthene (En_{53-57}), "ore," glass, and accessory apatite. A micrometric analysis of this unit is given in Tables 3 and 6 (BVN-30), and a chemical analysis in Table 7.

Quartz-bearing basalt

General statement. From a petrologic standpoint, the most interesting volcanic rock in the Griffith Park area is a quartz-bearing basalt. It was noted at map stations "F" and "G", and is readily identified by its perfectly developed hexagonal bipyramidal phenocrysts of quartz. Locally accompanying the quartz are large laths of plagioclase, much coarser than the phenocrysts in neighboring flows and intrusive rocks. At station "G" the rock occurs as a sombre maroon breccia. Its typical color is brownish or purplish gray. The crystals of quartz are commonly mantled with a dull rusty material, but fresh glassy surfaces are exposed when the crystals are broken.

Petrography. In thin section the crystals of quartz are finely pitted or scalloped, and are characteristically rimmed by an opaque brown material (altered basaltic glass?) and finely crystalline clinopyroxene. The latter indicates that the quartz was not in equilibrium with the remainder of the system of which it was a part, despite its gross euhedral form. The groundmass is mineralogically similar to those of other basalts in the area, but is characterized by one textural peculiarity. The plagioclase (median labradorite, partly replaced by albite and analcite) has a stubby habit that in plane light gives the rock the appearance of nephelinite. In some specimens there appear to be three generations of crystals: phenocrysts of quartz and

plagioclase, stubby microphenocrysts of labradorite and euhedral microphenocrysts of a mafic mineral, and tiny microlites of plagioclase, clinopyroxene, and "ore." No orthopyroxene was found, but the crystal outlines of a thoroughly altered mafic mineral are suggestive of olivine, or possibly an amphibole.

From the modal analysis of this rock given in Table 3, it is apparent that the color index is only slightly lower than that of typical basalt. A fused head of the least altered sample indicates that the rock contains approximately 55 percent of silica. According to the classification employed in this report, the rock is a basaltic andesite, but because the quartz may be a contaminant, it is possible that the original lava was somewhat poorer in silica. The quartz does not occur evenly dispersed throughout the rock, but is sparse in some places and abundant in others.

Origin. Nowhere in the area are ordinary quartz-bearing lavas such as rhyolite or dacite exposed, and the euhedral form of the quartz rules out the possibility of derivation from the closely associated Tertiary sedimentary rocks or pre-Tertiary quartz diorite. Even if the quartz represents a mineral phase that had begun to separate from a rhyolitic or dacitic differentiate high in a local magma cupola, it could not have settled downward into an underlying melt of basalt because of its relatively low density. The density

of quartz is 2.65 and that of diabase glass ranges from 2.64 to 2.78. Although the density of a liquid diabase melt would be slightly lower than that of diabase glass, the density differential between the melt and quartz, and the probable viscosity of the melt, would tend to inhibit downward settling.

Laboratory studies of the systems forsterite-silica and diopside-forsterite-silica (Bowen, 1928, pp. 29-31, 49-53) indicate that silicate melts of basic composition are capable of yielding pyroxene and free silica if disequilibrium conditions are maintained. In some instances, small amounts of forsterite (olivine), pyroxene and silica are found together. The essential requirement is that early-formed forsterite be prevented in some way from reacting with the rest of the melt. Although the effects of other components on the system are not known, and the exact composition of the mafic minerals of the rock under consideration are likewise not known, it is possible that the quartz in the quartz-bearing basaltic lava of the Griffith Park area is primary, and therefore not a contaminant. Additional petrologic work would need to be done before such an interpretation could be considered conclusive.

Tuffs

In addition to the flows, intrusive rocks, and breccias described above, several rocks of tuffaceous aspect are present in the area. Neuerburg (op. cit.) described "alkali trachyte tuffs" which occur in the Topanga formation, and one of these is exposed at map station "F". It is pale red in color, and occurs as an irregular lens between two flows of basalt. Angular fragments of altered volcanic rock, with fluidal texture, are accompanied by tiny broken crystals of fresh oligoclase, quartz, and an unidentified opaque mineral. These components are not present in the associated basaltic rocks.

A second tuff examined under the microscope is rhyolitic or dacitic in composition. Its gross color is pale yellowish brown, but variegated lithic fragments are abundant. This tuff is essentially composite, consisting of vitric, lithic, and crystal debris that ranges from .30 to 2.50 mm. in diameter. The angular lithic clasts include pumice and basalt, and the crystal fragments comprise plagioclase, augite, magnetite (?), and quartz. These clasts are embedded in a mesostasis of tiny shards of nearly colorless glass, with a refractive index of approximately 1.504. The low index indicates that the glass contains approximately 70 percent of silica (George, 1924). The intimate association of acid and basic components suggests that the glass, and probably the pumice, represent juvenile material, whereas the basalt fragments represent accessory debris torn from the walls of the vent during an explosive eruption.

Alteration of the rocks in the Griffith Park area

Alteration of plagioclase and olivine is common in the volcanic rocks of the Griffith Park area. Olivine has been altered to, or replaced by, magnetite, hematite, calcite, chlorite, chlorophaeite, and the same pleochroic, yellow unidentified mineral as that in basalt from the Pacoima Hills. Spaces formerly occupied by plagioclase are now occupied by analcite, calcite, clay, and albite-oligoclase. Albitization and analcitization are common east of Cahuenga Pass, but relatively uncommon to the west. In addition to the mineralogical variation of the alteration products, the mineral matter filling vesicles, veins, and fractures in the rocks is also highly varied. Among the minerals noted are natrolite, calcite, quartz, nontronite, celadonite (?), coarsely crystalline analcite, and chlorophaeite. Neuerberg (op. cit.) reported heulandite, apophyllite, thomsonite, and prehnite as well.

Epiclastic "volcanic" detritus

At the close of volcanic activity, some of the rocks described above lay exposed at the surface before they were buried under arkosic debris from the neighboring ancestral Verdugo and San Gabriel Mountains. The time of exposure was sufficiently long for the weathering and erosion of these rocks and for the transportation and deposition of

sediments derived from them. Thick sections of volcanic sandstones and conglomerates, as well as massive, structureless mudflow deposits accumulated in the area. Neuerburg (op. cit., p. 22) measured 1400 feet of bedded volcanic sandstone at one locality. Where exposed along Mt. Hollywood Drive, these epiclastic sediments have the same drab brown color as their parental flows. Sandstones, siltstones, and conglomerates alternate throughout the sequence. The general scarcity of granitic material suggests that the crystalline "basement" rocks were not exposed at this time. The epiclastic "volcanic" rocks are typical of the "basaltic wackes" of Williams, Turner, and Gilbert (1954).

Age of the volcanic rocks in the Griffith Park area

Immediately overlying the epiclastic "volcanic" rocks are coarse, conglomeratic arkosic sandstones of the upper Topanga formation. The volcanic rocks thus must be of late middle Miocene or pre-late middle Miocene age. A more accurate determination of the age of these rocks, or rather of their stratigraphic equivalents, is given in the following section on the geology of the volcanic rocks west of Cahuenga Pass. The stratigraphic relationships in that area are more readily determined.

Minerals / Rocks	PHENOCRYSTS			
	Plagioclase	Pyroxene	Olivine	Quartz
Fine-grained olivine diabase[1]	----	----	(completely altered) 3.0	----
Olivine basalt breccia and agglomerate[2]	----	----	----	----
Intergranular porphyritic basalt[1] (average of two)	labradorite-bytownite 15.0	augite 2.6	altered 2.4	----
Hypersthene basalt[1] (average of two)	median labradorite 9.5	augite 2.6	(completely altered) 4.0	----
Quartz-bearing basalt[2] (average of two)	median labradorite 2-3	----	altered olivine(?) 2	as xenocrysts 2-3

1) Determined by point counter
2) " " grid ocular estimates

GROUNDMASS				
Plagioclase	Clinopyroxene	Orthopyroxene	Olivine	Ore
calcic labradorite 42.3	titaniferous augite ($2V=47-50^{\circ}$) 19.1	----	see below (miscellaneous)	in lath-shaped crystals 3.3
calcic labradorite 50-60	augite 15-20	----	(completely altered) 5-10	in lath-shaped crystals 3.3
median labradorite 40.8	augite(?) 24.8	----	altered 2.4	in lath-shaped crystals 4.0
median labradorite 49.1	augite ($2V=47^{\circ}$) 17.0	hypersthene (En_{55}) 6.8	----	magnetite 5.1
sodic to median labradorite 55-56	undetermined variety 20-25	----	----	magnetite 4-7

TABLE 3. MODAL ANALYSES OF THE BASALTIC ROCKS OF THE GRIFFITH PARK AREA, EASTERN SANTA MONICA MOUNTAINS
(Figures in percents)

GROUNDMASS

Glass	Miscellaneous	Texture
----	Olive green mineral derivatives of chlorophaeite, much of it (18.9?) derived from groundmass olivine, the rest filling interstitial space. 32.9	Holocrystalline, ophitic
----	Celadonite and other chlorophaeite derivatives 10-15	Holocrystalline, ophitic
----	Alteration products from undifferentiated sources 8.0	Holocrystalline, intergranular
altered to chlorophaeite 4.3	Trace of apatite	Holocrystalline, porphyritic-seriate, intergranular
----	----	Holocrystalline, intergranular

Cahuenga Pass to Laurel Canyon

Volcanic rocks west of the Cahuenga fault zone are characterized by a mineralogical simplicity that reflects the unvarying chemical composition of the lavas extruded there. The area is structurally less complex than that to the east, and numerous roadcuts clearly reveal the lithologic and stratigraphic relationships of the rocks.

It is noteworthy that the section near Cahuenga Pass is composed largely of massive basalt interbedded with basaltic breccias or fragmental rocks, whereas to the west the exposures are almost exclusively of breccia. This variation from predominantly massive rocks to predominantly fragmental rocks was also observed in the third dimension (down dip). Examination of the volcanic rocks exposed in the sewer tunnel recently driven through the Santa Monica Mountains east of Nicols Canyon reveals that the section at depth is almost exclusively fragmental also. If the rock strata were restored to their original horizontal position, the massive non-fragmental units would be seen to die out north and west of Cahuenga Pass.

Sideromelane tuff-breccias

General statement. The most abundant volcanic rock is a dark gray to black basaltic breccia or tuff-breccia. Hoots (1931), who apparently did not study these rocks in

thin section, suggested that they are flows that have been auto-brecciated by "cooling and tectonic stress." Their most striking feature, however, is the glassiness of the smaller fragments of the matrix on freshly fractured surfaces. Embedded in the coarse glassy lapilli and ash are large, dark brownish gray, angular and rounded blocks of olivine basalt, ranging from a few inches to several feet in diameter. Figure 13A shows the partially weathered outcrop surface of a typical exposure, and Figure 13B, the shape and size variation of lapilli from the matrix. In the western part of the area, zeolites and carbonate minerals occur as secondary cement in the interstices between the ash particles and lapilli, and the same material occupies numerous fractures and veins that transect the breccias. Locally, a crude stratification is apparent, but more commonly the rock is structureless.

Petrography of the matrix. Microscopic study reveals that the matrix of this rock consists predominantly of fragments of buff-yellow sideromelane (basaltic glass), in which microphenocrysts and crystallites of median labradorite and fresh magnesian olivine are present. The refractive index of the glass is approximately 1.574, and the ratio of glass plus palagonite (altered basaltic glass) to crystalline material is about 8.5 to 1. Surrounding each tiny fragment of sideromelane is a mantle of orange to yellow-brown palagonite or "fibropalagonite." Here and



Figure 13a. Sideromelane tuff-breccia, west of Cahuenga Pass, eastern Santa Monica Mountains. Glassy lapilli serve as a matrix for partially crystalline blocks of olivine basalt. Knife handle is 3 1/2 inches long.

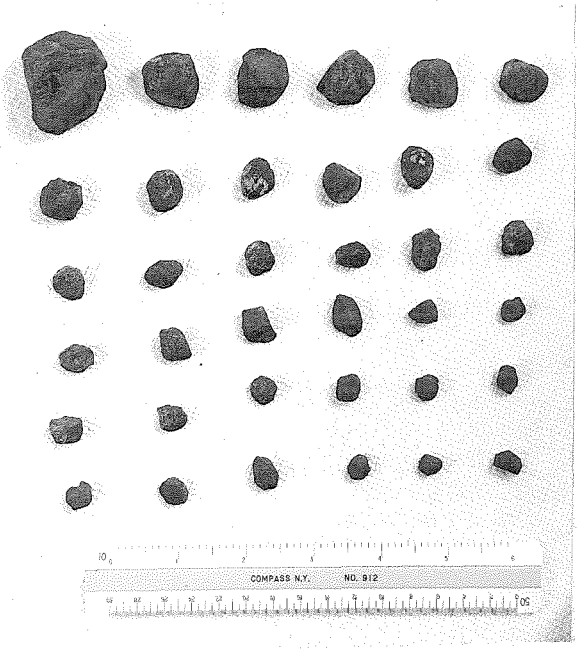


Figure 13b. Glassy and partially glassy lapilli from sideromelane tuff-breccia west of Cahuenga Pass, eastern Santa Monica Mountains. The degree of crystallinity of the fragments is roughly proportional to their size.

there the smaller fragments are completely palagonitized, but the gross aspect of the matrix is predominantly that of a fresh clear glass. The fragments and shards range in diameter from .50 to 4.50 mm..

Analcite and tiny rosettes of aragonite occur between the fragments. The white crystalline fracture fillings that can be seen in these rocks along Mulholland Drive near Laurel Canyon also consist of aragonite (and locally calcite) or, more commonly, natrolite. Analyses of ground water that percolated into the sewer tunnel through the breccia show a much higher content of soda than the water from the neighboring Topanga and Modelo sedimentary rocks or pre-Tertiary crystalline rocks (David Campbell, personal communication). This is additional evidence of the high percentage of sodium-bearing zeolites in the rock.

Petrography of the blocks. Some of the blocks embedded in the sideromelane tuff are as large as three feet in diameter. They are typically angular, but in approximately the middle of the section (exposed north of the junction of Laurel Canyon Boulevard and Mulholland Drive) they exhibit rounded or distorted shapes suggestive of bombs that may have been plastic during their flight and subsequent impact.

Petrographically these blocks and bombs differ from the enclosing sideromelane tuff in being more completely crystalline. Thin-section examinations of several fragments

of different size showed a range in the content of glass from 0 to 70 percent. The blocks are mineralogically typical of olivine basalt. Microlites and laths of median to calcic labradorite, commonly accompanied by microphenocrysts of labradorite-bytownite, are embedded in a dark brown glass that is heavily charged with finely disseminated magnetite dust. The index of refraction of this glass is greater than 1.54. Slightly altered magnesian olivine occurs with the plagioclase as microphenocrysts and microlites. The texture of the blocks is hyaloophitic.

Olivine has been replaced principally by the same unidentified mineral that occurs in the basalt flows in the Pacoima Hills; in the locality presently under discussion, it is pleochroic both in shades of yellow and in shades of olive green. Its maximum birefringence is higher than that of biotite, and its N_x index is lower. The writer has not examined specimens from the type locality of the mineral griffithite, but the optical properties of the unknown mineral appear to fit those of griffithite.

Augite was noted in a few specimens. Where present, it is pale yellowish to grayish brown in color and has optic angles of 54° to 55°. Fibrous natrolite occurs in vesicular cavities. The rock has a bulk composition characterized by approximately 48 percent of silica.

Origin. Thin beds or lenses of coquinoidal limestone are present locally along the base and top of beds of the

sideromelane tuff-breccia. They are lithologically similar to a lenticular limestone exposed in Griffith Park,* and one of the five horizons at which they were noted west of Cahuenga Pass is probably correlative with the horizon in the park. In the beds west of the pass, many of the shells are nearly intact. The presence of these beds indicates that the tuff-breccias are of submarine origin.

Further substantiation of this origin comes from specimens collected near the top of the pyroclastic section in the sewer-tunnel, approximately 1.4 miles north of the south portal. Here the greenish black tuff is intimately associated with a white, very fine-grained, compact limestone that contains numerous Foraminifera tests, the chambers of which are filled with pyrite. Fragments of hypocrystalline basalt embedded in the originally muddy lime are shattered, and the plagioclase is altered to analcite and albite (?). Fresh exposures of the tuff-breccia along the walls and back of the tunnel are of a grayish black color, but a pronounced reddening, clearly unrelated to surface stain, was noted at two horizons. These horizons may represent the upper surfaces of breccias that temporarily were

---

*Conspicuous co-planar lenses of sub-coquinoidal limestone are present between flows of basalt east of station "H" on M:. Hollywood Drive (Neuerburg, 1953, p. 21). They are composed almost exclusively of broken shell fragments, but no fossils of a time-diagnostic nature were found. The lensoid character of this rock may be the result of its formation in small marine pools atop partially submerged lava flows.

above sea level before they were submerged or buried by the next accumulation of pyroclastic debris.

At map station "I" on the east side of Cahuenga Boulevard, a coarsely fragmental brown breccia is exposed. It consists of vesicular, angular blocks of basalt in a yellowish white carbonate matrix. Under the microscope small fragments of both porphyritic basalt and shell-bearing limestone are visible in a finely crystalline calcite mosaic. Here and there small fragments of the basalt are enclosed by larger fragments of shell-bearing limestone. Partially crystalline blocks of basalt evidently fell into semi-consolidated mud, disrupting the bedding, and became thoroughly mixed with the mud.

These sideromelane tuff-breccias are very much like the sideromelane and palagonite tuffs of Iceland (Peacock, 1926) and Jamaica (Raw, 1943). The Icelandic rocks contain inter-fragmental analcite and calcite, the Jamaican rocks analcite, albite, and natrolite. Reportedly, palagonite is derived through the hydration of sideromelane, accompanied by oxidation of iron and loss of lime and soda (Peacock and Fuller, 1928). This loss of soda and lime by the glass might account for the source of analcite, natrolite, and calcium carbonate, but according to Raw (op. cit.), some of the Jamaican tuffs contain as much as 50 percent analcite by volume, which means that roughly seven percent Na_2O by weight would have to be freed from

the sideromelane during palagonitization. Inasmuch as calc-alkaline basalts do not contain this much soda, part of it must have come from another source. The corresponding figures for the rocks from the Santa Monica Mountains are much lower, and compositionally within reason, but because analcitization and albitization of plagioclase were noted in holocrystalline rocks of the Griffith Park area, it is probable that soda was derived from sources other than the sideromelane-palagonite reaction. Possibly the source was sea water.

Intrusive olivine basalt

Near Cahuenga Pass the section contains a large percentage of massive, non-fragmental basaltic rocks. Although some of these rocks are extrusive in origin, a large part are clearly intrusive. Evidence of the intrusive nature of these bodies is manifested in the inclusion of blocks of shell-bearing limestone along the upper margin of at least one sill, and in the mild contact metamorphism of the base of a fossiliferous siltstone overlying another. Commonly these bodies are amygdaloidal near their contacts, with ellipsoids of chlorophaeite, calcite, or chalcedony locally reaching two inches in maximum diameter. Mineralogically, these intrusive rocks are characterized by altered olivine, median and calcic labradorite, common augite ($2V = 50^{\circ}$) or subcalcic augite ($2V = 35^{\circ}$-45°), "ore,"

and glass. At one exposure on Mulholland Drive the rock is thoroughly spilitized. The plagioclase has been almost completely altered to an aggregate of analcite and oligoclase, and large, irregular patches of flamboyant penninite are cut by veins of chrysotile.

Extrusive olivine basalt

Massive extrusive rocks are less readily recognized. Pillow structure is evident locally (Cahuenga Boulevard; and Mulholland Drive north of the intersection with Woodrow Wilson and Laurel Canyon Boulevard), and elsewhere clastic dikes from overlying beds of arkose penetrate downward into dark gray flows. Mineralogically, these rocks are similar to the intrusive bodies. Sparse phenocrysts of sodic bytownite and altered olivine are embedded in a matrix consisting of euhedral and subhedral laths of median to calcic labradorite, pale brown augite ($2V = 45°-57°$ in different specimens), olivine, "ore," and brown or gray glass containing finely disseminated magnetite dust. Textures range from subophitic to intergranular. Table 6 lists the modal analysis of a typical specimen (BVN-63), and Table 7 a chemical analysis.

Source of the eastern Santa Monica Mountain volcanic rocks

The massive basaltic rocks west of Cahuenga Pass

decrease in proportion to pyroclastic rocks in a westerly direction and also down-dip (originally northward). Because airborne pyroclastic debris travels farther from the parent vent than associated lava flows during many eruptions, and also because some of the concordant bodies of massive basaltic rock near Cahuenga Pass are known to be intrusive sills, the variation in the proportion of massive to fragmental rock units suggests that these rocks were derived from a volcanic source to the southeast, in the general vicinity of Griffith Park. The large volume of intrusive diabase exposed in the park and the lithologic variations noted there tend to substantiate this interpretation. Further corroborative evidence is found in the sedimentary strata interbedded with the volcanic rocks. The limy oyster beds described above, occur chiefly in the area near Cahuenga Pass (from Griffith Park to Outpost Drive). They were not seen as far west as Laurel Canyon, but Foraminiferal strata were found in their place. This implies that deeper water overlay the Laurel Canyon area and that shallower water lay to the east. If the topography of the sea floor in the area was affected by the construction of a volcanic edifice, this edifice must have lain to the east, near Griffith Park.

As an additional check on this hypothesis, a series of measurements was made of the diameters of the lapilli in the sideromelane tuff-breccias. It was hoped that the

mean diameters of the lapilli would show consistent lateral variations, becoming larger as the source was approached. These measurements showed little or no consistency in size variation in any direction, however.

Although the contact at the base of the volcanic pile is an unconformity, that at the top is not clearly interpretable. Near the western end of the area the volcanic section is between 1500 and 2000 feet thick, and most of the rocks there are pyroclastic. The existence of such a thick section of pyroclastic rocks bears testimony to the tremendous explosive activity of the local volcanic vent(s). The general source either was sub-marine or lay close on shore, for the fragments of lava fell into the sea in an incandescent condition.

Significance of the interbedded fossiliferous limestones

Beds of arkosic sand and gravel occasionally were laid down between eruptions, indicating that the ancestral Verdugo and San Gabriel Mountains were exposed to the north. Where beds of shell-bearing limestone occur between layers of basalt and arkose, they invariably lie stratigraphically above the basalt and below the arkose. Evidently post-eruptive conditions of the water and the sea bottom were favorable for the development of oyster beds.

An interesting feature of the limestone beds is their total lack of clastic material other than shell fragments.

In the few strata in which the shells are still intact, they occur in such great abundance that the beds have the appearance of modern-day pelecypod "reefs." It is noteworthy that the deposition of the pyroclastic rocks was not responsible for the destruction of the pelecypod banks, but rather gave rise to the environmental conditions in which the animals lived and flourished. The later deposition of coarse epiclastic debris appears to have been the cause of their destruction.

Although specific faunal studies were not made during the present investigation, it was noted in the field that several of the limestone beds consist almost entirely of fragments of a single species, namely, a species of oyster. Pelecypods in general, and oysters in particular, are noted for their gregarious habits, and thus it is not surprising that paucispecific faunas should be found.

Ladd (1951) and Stenzel (1945) discussed the ecologic conditions under which modern-day oyster banks thrive, and from their work it is possible to gain some insight into the conditions that must have prevailed immediately after the eruptions of pyroclastic debris. Most members of the family Ostreidae live in shallow, brackish, near-shore waters, although a few species (e.g., Pycnodonte) are found in marine waters of normal salinity at depths in excess of 300 feet. Present-day "reef"-building oysters flourish most readily in water of salinity midway between

that of fresh water and normal sea water, and in all likelihood the oyster beds of the eastern Santa Monica Mountains represent a salinity condition that could be classified as "brackish." However, the salinity tolerance of the oysters must have been high enough for them to withstand the changes that ordinarily come with changing tides and currents, and fluctuating river discharge. A further prerequisite to the formation of oyster banks is that the rate of sedimentation be slow. That this was so, is apparent from the lack of other detritus within the shell beds and from their abrupt termination against the overlying arkosic conglomerates and sandstones.

Stenzel (op. cit., pp. 44-45) asserted that most brackish-water oyster beds are composed of very few species because the environment is highly specialized and the enemies which can penetrate it are few in number. If the latter is true, the brief field checks made during the present study indicate that the beds in question truly represent brackish-water oyster banks.

The simple deposition of sideromelane tuff-breccia would not have been adequate to desalify the waters of the Miocene sea, but it may so have changed the near-shore bottom topography that streams draining the adjacent land were partially impounded causing a mixing of fresh water and sea water. Furthermore, deposition of the breccias unquestionably caused a rapid local shallowing of the sea.

The development of shoals not only altered circulation, but furnished submarine banks that were free from the constant interruption by sand and gravel that elsewhere moved along the bottom. The free-swimming larvae probably settled on these shoals and found them favorable to growth. It is not known whether sedimentation was continuous throughout the area until the breccia falls were buried, or whether the intercalated arkosic sedimentary rocks represent sudden and rapid uplift of the neighboring granitic highlands.

Age of the volcanic rocks

Fossils collected by Hoots (1931, p. 124, locality 102) at map station "J" belong to the Relizian stage of the Miocene epoch. At the time of Hoots' work, Kleinpell (1938) had not completed his comprehensive subdivision of the Miocene section of California, but reinterpretation of Hoots' collection indicates that it is of Relizian age. Inasmuch as this locality lies near the top of the volcanic sequence, and sedimentary rocks typical of the Topanga formation underlie the sequence, volcanic activity in the eastern Santa Monica Mountains must have taken place during the lower middle Miocene.

Evidence of later intrusive activity is apparent in many parts of the area. Sills of olivine basalt were injected between extrusive flows and interbedded sedimentary

rocks, and also into the upper part of the Topanga formation (Hollycrest formation of Neuerburg, 1953). The youngest Topanga strata cut by intrusive basaltic rocks occur at map station "K". Foraminifera collected from localities east of Laurel Canyon Boulevard (Plate III) are representative of the Luisian stage, but the beds cropping out at the collecting localities are stratigraphically higher than those present at map station "K". It appears that the intrusive activity took place no later than the middle Miocene, and probably no later than the early middle Miocene.

Nature of the coarse-grained rocks of the upper Topanga formation

Core samples from holes drilled during early phases of the sewer-tunnel work revealed the presence of volcanic conglomerate at the top of the volcanic sequence. Highly rounded pebbles and cobbles of basalt and fragments of crystalline "basement" rocks are embedded in a poorly sorted sandy matrix. This conglomerate is stratigraphically equivalent to the volcanic wacke in Griffith Park, but its lithology is somewhat different. It represents a heterogeneous source (pre-Tertiary granitic "basement" rocks and Miocene basaltic rocks), whereas the volcanic wacke is essentially monolithologic.

In the arkosic sedimentary rocks higher in the section, crumbly boulders and cobbles of highly altered amygdaloidal

basalt are distributed sporadically among clasts of granite. They are badly decomposed, and it is doubtful whether or not they would have been capable of surviving long distances of transportation. Hoots (op. cit.) observed that green hornblende makes its first appearance as an accessory mineral in the sediments stratigraphically above the basalt, implying that this amphibole had its origin in the extrusive rocks. Hornblende was not observed, however, in any of 55 thin sections of volcanic rock from the eastern Santa Monica Mountains.

Palos Verdes Hills

The Palos Verdes Hills rise at the southwestern edge of the Los Angeles basin. They are thought to represent a land-tied former island because of their general geologic and topographic similarity to the islands off the southern California coast.

The Tertiary sedimentary rocks that crop out in the hills rest unconformably on an irregular "basement" of Catalina schist. They show a striking contrast to equivalent stratigraphic sections exposed elsewhere near Los Angeles (e.g., parts of the Santa Ana and Santa Monica Mountains), in that the Upper Cretaceous to lower Miocene parts of the section are missing, and the middle and upper Miocene strata (Monterey formation), as well as the Pliocene strata (Repetto formation), are considerably thinner. Even the Pleistocene rocks show a marked reduction in thickness compared to their basin equivalents.

The general structure of the hills is anticlinal, and a deeply buried fault to the northeast separates this fold from the Los Angeles basin proper. There is little evidence of tectonic activity during the Miocene epoch, and the most pronounced deformation evidently took place in late Pliocene times. An angular unconformity between lower and upper Pleistocene deposits, and 13 tilted marine terraces, capped by upper Pleistocene sediments, attest to

early Quaternary tectonic activity.

Woodring et al. (1946) described the Miocene igneous rocks of the Palos Verdes Hills as sills of basalt, intrusive into the Altamira member of the Monterey shale. Macdonald (1939) had reached the same conclusion earlier, but his study included only a small area north of Point Vincente. The contact relationships in that area suggest that the rocks formed as peperites, i.e., lavas intruded into thin, water-saturated sediments. Results of the present investigation revealed that the rocks are in large part andesites (with the exception of minor olivine diabase), and that lavas locally broke through to the surface as actual flows. The distribution of exposures is shown in Plate IV.

Bluff Cove

Altered basalt (?)

General statement. The northernmost outcrops of volcanic rock are exposed near Bluff Cove, at the northwest edge of the hills. They are readily observable along the cuts of Palos Verdes Drive West. The rock is typically rusty brown or orange where altered and olive gray where fresh. Along the sea cliffs southeast of Flatrock Point, it has been severely solfatarized to a material that is variously yellow, tan, pink, orange, or white. Small

bluish white amygdules and veinlets of chalcedony and opal are present, and are commonly accompanied by tiny crystals of a metallic sulfide mineral (probably pyrite).

The lower margin of the body of which these outcrops are a part is exposed on the beach road near Flatrock Point. The underlying sedimentary rocks consist of limestone and shale, commonly buff or yellowish gray in color, and containing abundant light brown chitinous fish scales. Within approximately 30 inches of the base of the igneous rock, the sediments are medium dark gray, and the fish scales are a lustrous jet black, apparently as a result of carbonization. In thin section this contact rock is composed of a nearly opaque opaline material with irregular patches of calcite, tiny scattered grains of plagioclase and quartz, and tests of Foraminifera or other microfossils. The Foram tests, originally composed of a carbonate mineral, have been partially replaced by chalcedony, and tiny composite veinlets of chalcedony, quartz and a carbonate mineral are common. At the upper contact of the igneous body, similar dark gray sedimentary rock is present, but it is interbedded with unaffected, buff-colored strata.

The contact relationships along the upper margin of the igneous mass can be seen readily at map station "A". The general discordant nature of the contact, as well as xenoliths of sedimentary rock enclosed by the basalt, are

evidence of the intrusive nature of this body.

Petrography. Under the microscope, the basaltic rock is severely altered, and fully 45 percent of the volume comprises olive green fibrocrystalline chlorophaeite, secondary dolomite, opal, chalcedony, pyrite (?), and quartz. The unreplaced patches of primary minerals reveal that originally about six percent of the rock consisted of spongy phenocrysts of sodic bytownite, 2.50 mm. long, with pronounced oscillatory and normal zoning, in a groundmass of euhedral median labradorite, nearly colorless augite ($2V = 50°$), lath-shaped ilmenite, and a little glass. The augite has been replaced largely by dolomite and chlorophaeite, but the abundance of chlorophaeite suggests that part of it has also replaced glass.

The amygdules are commonly zoned, and the following minerals occur in concentric shells: fibrocrystalline chlorophaeite, opal, quartz, chalcedony, and dolomite. Where all of these minerals are present in a single amygdule, they occur in the succession named, from the walls inward.

The labradoritic composition of the feldspar suggests that the rock is basaltic, but if most of the chlorophaeite represents the replacement of a glassy mesostasis, it is possible that complete crystallization of the lavas would have resulted in the development of a more sodic feldspar. The degree of alteration of this rock prevented the

determination of its silica percentage by the fused bead method. The rock is here referred to as altered basalt (?).

Cross-cutting clastic dikes

Two clastic dikes transect the igneous rock at the northern end of the cut at map station "A". Similar dikes are exposed elsewhere in the hills. They are medium light gray in color and consist of coarse, angular fragments of altered basalt (?) or andesite, dark gray limestone, and chert, ranging from one-fourth of an inch to eight inches in diameter, in a limy matrix. In thin section, the matrix appears as a clean granular mosaic of calcite, with scattered tiny angular grains of labradorite and pyrite, and vestiges of microfossils, partially obliterated owing to recrystallization of the calcium carbonate. The matrix material probably was derived in a plastic state from a limy marine bottom mud stratigraphically higher in the section. The sharp, angular boundaries of the clasts testify to the fresh, relatively brittle nature of the rocks at the time of brecciation.

Although most of the clastic dikes in the Palos Verdes Hills are vertical or quasi-vertical in orientation, and therefore strongly discordant to the intruded volcanic and sedimentary rocks, horizontal sill-like branches were observed at a few localities. Figure 14A shows several of these dikes projecting as low ridges above the more readily

wave-worn andesite. Figure 14B is a close-up view of one of the dikes, showing the size and angular nature of the clasts.

Glassy andesite

General statement. From Resort Point southward to station "C", the Miocene igneous rocks are represented by a medium (locally bluish) gray glassy andesite, that commonly has weathered or has been altered to a material that is dark rusty tan or deep orangish brown in color. The rock is vesicular to microvesicular, and locally exhibits a subtle flow banding manifested in the alignment of tiny vesicles. The discordant upper contact, exposed at map station "B", is shown in Figure 15.

Petrography. Microscopically, this rock consists of sparse euhedral phenocrysts of calcic labradorite, spongy with inclusions of secondary opal and pyrite, and normally zoned with narrow rims of median andesine, in a groundmass of smaller crystals and glass. In the average specimen, 40 percent of the rock is made up of microphenocrysts and skeletal microlites of median labradorite. The microphenocrysts are .20 to .40 mm. long. The feldspar is accompanied by anhedral grains of neutral-colored augite ($2V = 47^{\circ}$-50°), in amounts of as much as 15 to 20 percent, but commonly this pyroxene is lacking. Pyrite occurs as

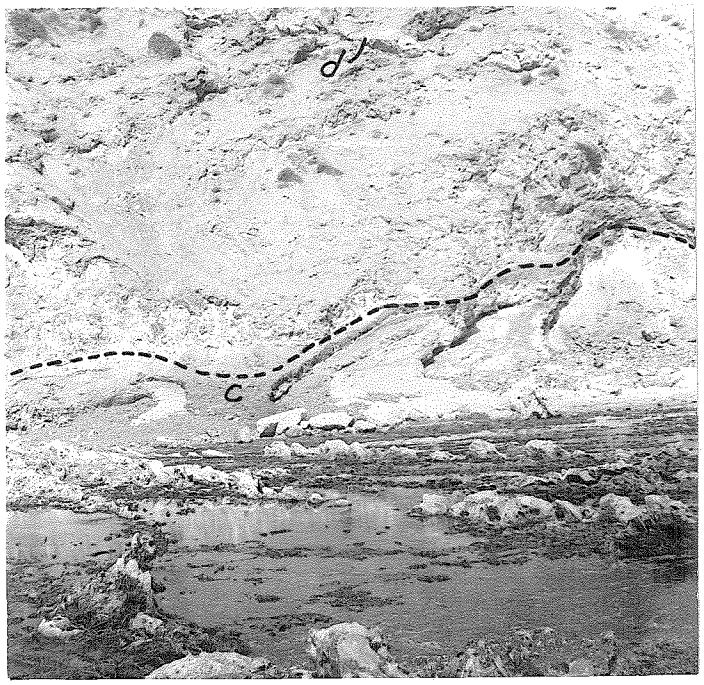


Figure 14a. Lower contact of andesite sill at foot of sea cliff, western Palos Verdes Hills. The contact, indicated by a dotted line, is underlain by a thin bed of black chert (c), dipping toward the observer. In the foreground are the erosional ridges of several clastic limestone dikes that cut the andesite. Another dike (d), trending from left to right, can be seen in the upper part of the photo.



Figure 14b. Close-up of a clastic dike showing angular fragments of andesite (dark) embedded in a limestone matrix (light).

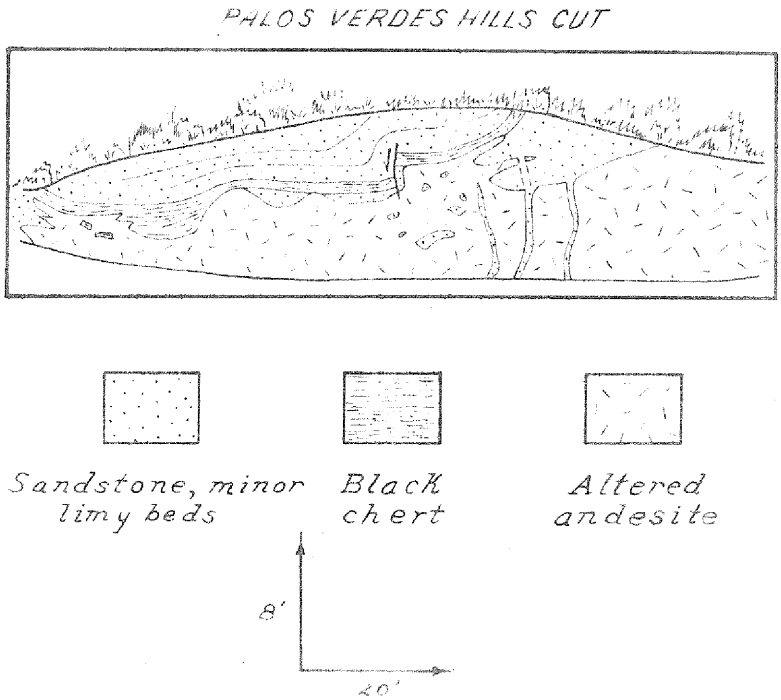


FIGURE 15. Field sketch looking east at map station B, Plate IV, Palos Verdes Hills. Upper contact of andesite sill in Monterey formation. Note irregularity of contact and inclusions of sedimentary rock in the andesite.

tiny cubes on vesicle walls, and as laths and rods in the glass. It apparently is secondary after ilmenite, and its average abundance is 15 percent. The remainder of the rock (30 to 40 percent) consists of a dark, smoky brown glass, rendered nearly opaque by an impalpable magnetite dust. The index of the glass is moderately less than 1.54. Near vesicles, the place of the glass has been taken by a very pale brown, isotropic substance of moderate negative relief that seems to grade almost imperceptibly into the vesicle linings. These vesicles are lined with colloform opal, and are either devoid of other mineral matter or are filled with chalcedony, dolomite, or pyrite.

Application of the Mathews fusion technique to a specimen from station "D" indicated that the rock has a total silica content of 62 percent. The rock is thus a glassy augite andesite. Its andesitic composition might have been anticipated from (1) the andesine rims developed on labradorite phenocrysts, and (2) the high percentage of glass that probably would have reacted with the labradorite microphenocrysts and skeletal microlites to form a more sodic feldspar, if crystallization had gone to completion.

Point Vincente

Hypersthene-augite andesite

General statement. The igneous rock exposed south of map station "C" shows several features that serve to distinguish it from the rock just described. On altered surfaces the color is dark brown or orange, but on fresh surfaces it is medium dark gray, and the rock is crudely marked by thin discontinuous streaks of a dark gray or black color, in which large, irregular drusy cavities, filled with crystalline dolomite and pyrite, occur. In addition, abundant tiny areas of light gray color reveal the presence of small angular inclusions. The rock is finely vesicular, and partly glassy. Figure 16 shows its appearance in a typical hand specimen.

Petrography. Thin-section studies and a chemical analysis indicate that this rock is a glassy hypersthene-augite andesite. Plagioclase phenocrysts constitute 14 percent of the rock by volume, and range in composition from median labradorite to sodic bytownite. They commonly exhibit normal or oscillatory zoning, and have rims of median to calcic andesine. They occur chiefly as euhedral and subhedral laths showing minor embayment or rounding. Tiny, zonally-arranged inclusions of dark brown glass and opal give the laths a spongy appearance. The glass may



Figure 16. Specimen of hypersthene-augite andesite from the southwestern Palos Verdes Hills. A crude flow banding, essentially parallel to the ruler, can be seen at the top, middle, and bottom of the specimen. It is marked by dark streaks within which are irregular, drusy vesicles lined with dolomite. Light colored, angular inclusions can be seen within the andesite, about one inch above the bottom of the specimen, just to the left of center. These inclusions are mineralogically similar to the enclosing rock, and are thought to be fragments of a chilled selvage.

represent points at which the plagioclase remelted, or it may represent droplets of quenched lava that were incorporated in the growing crystals of feldspar. Phenocrysts of hypersthene (En_{55-63}) constitute three percent of the rock. They occur as elongate prisms with inclusions of magnetite-charged glass and jackets of clinopyroxene. The latter mineral, which appears to be augite, also occurs as phenocrysts, composing approximately 0.5 percent of the rock. It exhibits optic angles of 46°- 47°.

The plagioclase of the groundmass is sodic to median labradorite. It constitutes 21 percent of the rock, and occurs both as microphenocrysts and as skeletal microlites. The crystals are fresh, and are free of inclusions. Like the larger laths, they are rimmed by a slightly more sodic feldspar. They are not arranged in felted fashion. Accompanying them are tiny granules of an unidentified clinopyroxene (8.5 percent) and slightly rounded prisms of hypersthene (two percent), both altered marginally to hematite. Ragged laths of ilmenite (one percent) have been altered, in part, to leucoxene. Additional "ore" is present as a finely disseminated phase that renders the enclosing glass (34 percent) nearly opaque. The texture of the rock is predominantly hyaloophitic, but in places it is hyalopilitic.

Inclusions. The small, light-colored inclusions seen in the hand specimen consist of angular fragments of a rock

that is mineralogically similar to the host (hypersthene-augite andesite). It differs from the host in being finer-grained and in having a greater content of pyrite. In addition, the glassy mesostasis has been replaced by an unidentified very pale brown isotropic material. In one thin section, these inclusions are enclosed by trains of vesicles. The writer believes them to be fragments of a chilled selvage that was finely brecciated by rapid quenching, and strewn throughout the lava.

The drusy, dark-colored bands that are apparent in the hand specimen are very prominent under the microscope. They are nearly opaque, and contain much less crystalline material than the remainder of the rock. The small amount that is present is very fine grained. Trains of opal-lined cavities filled with dolomite or pyrite occur within the streaks. These streaks are believed to represent local, volatile-rich portions of the lava that were sheared out during flow. Their richness in volatile constituents, as evidenced by the presence of drusy cavities, may have been due to the entrapment of water-saturated mud by settling fragments of the selvage. A chemical analysis of this rock (BVV-14b, Table 7) shows 1.20 percent of free carbon, and 3.49 percent of sulphur, suggesting that organic-rich mud was assimilated.

Origin. Not all of the exposures of glassy hypersthene-augite andesite represent a single tabular body. Some of

them represent lava that was intruded beneath the sea floor, but others indicate that lava broke through to the surface as submarine flows. In a roadcut northeast of Point Vincente, rounded pebbles and cobbles of altered andesite occur in a limy matrix, indicating reworking of the upper surface of the andesite body. Along the sea cliff just east of the point, however, the intrusive relationships shown in Figure 17 and 18 were noted. Figure 18 which shows inclusions of the overlying sedimentary rocks enclosed by andesite, verifies the interpretation of an intrusive igneous origin for at least one of the bodies. The partially-saturated sediments into which the andesite burrowed caused a rapid quenching of the lava that accounts for the glassy nature of the rock.

The thickness of the local sedimentary cover at the time of intrusion can be determined from Figure 19, which was sketched at map station "E". Two to three feet of consolidated chert and limestone, overlain by unconsolidated sand, were present on the sea floor when the andesite was injected. Later fracturing of the andesite and chert took place prior to the consolidation of the sand. This sketch also serves to illustrate the general mode of origin of the breccia dikes. The material composing most of these dikes originated in the section above the igneous rocks, but almost all of the dikes contain angular fragments of the local intrusive rock, suggesting that they have filled

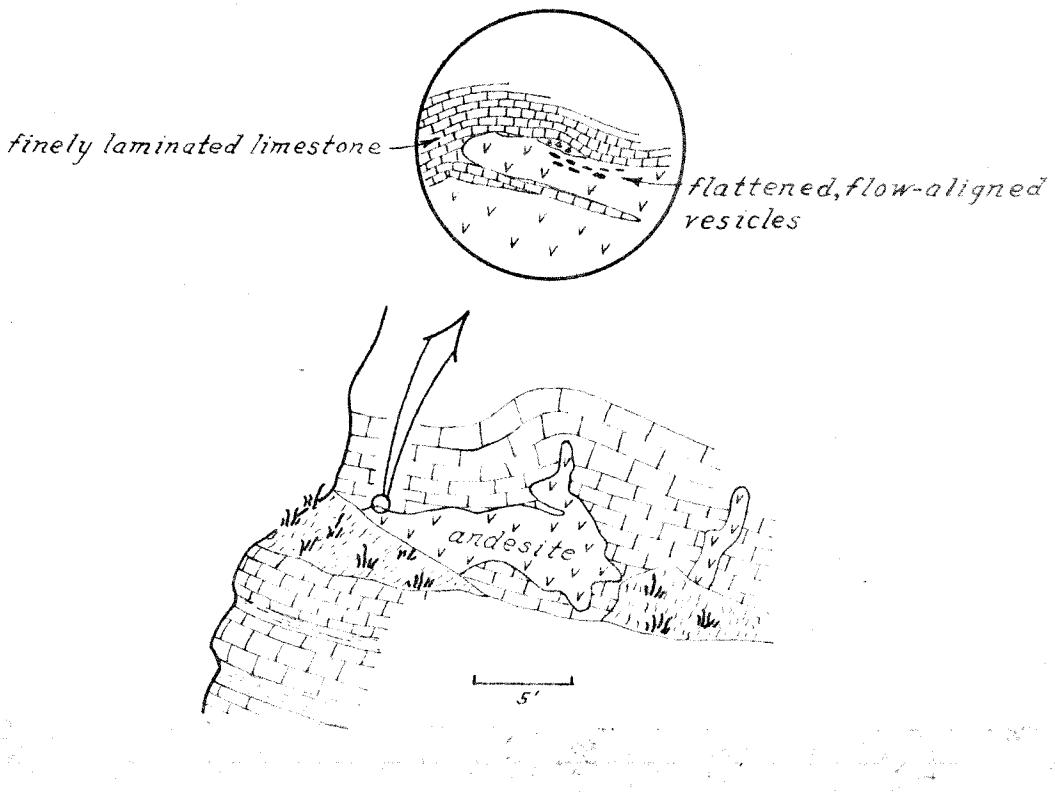


Figure 17. Andesite dike in Monterey formation, east of Point Vincente, Palos Verdes Hills.



Figure 18. Upper contact of andesite sill east of Point Vincente, Palos Verdes Hills; limestone and chert of Monterey formation above, andesite below. Within the andesite are several inclusions of limestone and chert; three of them occur in a line to the lower right of the hammer handle. The emplacement of the sill evidently was accompanied by minor stoping.

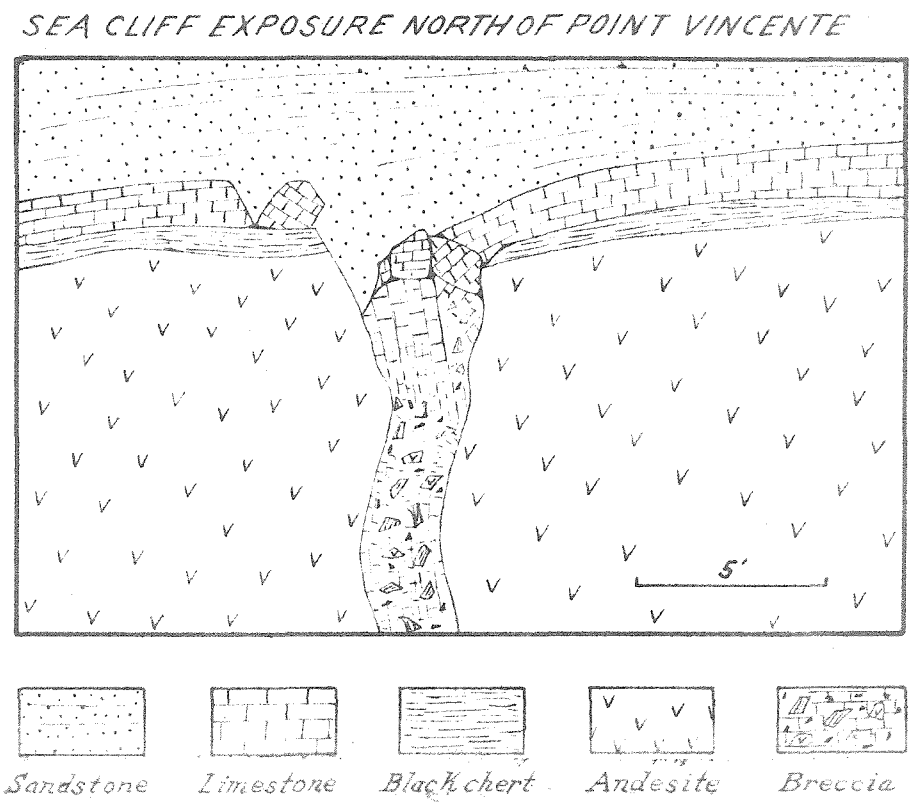


Figure 19. Field sketch of upper terminus of breccia dike in the Palos Verdes Hills. The dike cuts strata of limestone and chert and extends downward into the upper part of a thick andesite sill. Note relatively brittle behavior of the limestone, chert, and andesite, plastic behavior of the sand. About six feet from the top of the dike, the limestone forms a continuous matrix for the clasts of chert and andesite.

in situ brecciated zones of the rocks they transect.

The area near Point Vincente was subjected to faulting some time after the emplacement of the andesite bodies, and locally, the altered andesite has been visibly dragged (sheared) along the faults, giving rise to features that look like apophyses.

Abalone Cove

Several steeply dipping tabular bodies of igneous rock are exposed in the cliffs on the west side of Abalone Cove. They do not represent parts of a single body repeated by faulting, for they are composed of different rock types. One of them, a basalt, is petrographically similar to the sill at Bluff Cove, but it is much less altered here. Its texture is holocrystalline and subophitic, and it clearly exhibits the replacement of ilmenite by pyrite. The other bodies are composed of pyroxene andesite.

The Abalone Cove area has long been known for the presence of crystalline barite veins that cut both the Altamira shale and the associated igneous rocks. In this connection it is interesting to note that the abundance of barium in the local volcanic rocks is high, as compared with that in rocks from the Santa Monica Mountains and Sunland (Table 11).

Portuguese Bend

In the area northeast of Portuguese Bend, quarry operations by the Livingston Rock and Gravel Company have exposed in vertical section a composite sill that is more than 200 feet thick. Two quarries, near the center and the west end of this body, were excavated in olivine diabase and porphyritic augite andesite, respectively.

In the central quarry, exfoliation shells can be seen in the diabase nearly 100 feet below the present topographic surface. This rock is vesicular along its upper contact and is concordant with the overlying Altamira shale.

In the western quarry, where porphyritic augite andesite is exposed, the upper contact also is parallel to the overlying sedimentary rocks, but large slabs of shale and limestone engulfed by the andesite bear testimony to the intrusive nature of the body. This sill is present at the crest of a broad anticlinal fold, and although this is likewise true of the sill exposed on the coast north of Point Vincente, there is no evidence to indicate that the injection of the magma was the cause of arching of the overlying rocks, as suggested by Macdonald (op. cit., p. 329).

Porphyritic augite andesite

The andesite exposed in the western quarry is the most

highly porphyritic rock in the area. Approximately 35 percent of the rock consists of phenocrysts of sodic, median, or calcic labradorite, and these are accompanied by five to ten percent of phenocrystic augite. The augite has been altered extensively to microcrystalline derivatives of chlorophaeite and calcite. The groundmass constitutes approximately 55 percent of the rock, and comprises 10 to 15 percent of calcic andesine or sodic to median labradorite, approximately two percent of ilmenite and pyrite, and 15 to 25 percent of altered pyroxene and glass. Amygdules and irregular veinlets are composed of chlorophaeite with subordinate carbonate minerals or chalcedony. Large veins of both calcite and quartz were noted in the quarry, and the andesite is highly altered and discolored adjacent to them. A brecciated facies of the rock is present locally and in places irregular dikes cut the augite andesite. The dikes are lithologically similar to the andesite, but are darker in color.

Olivine diabase

In addition to the exposures of olivine diabase in the quarry, this rock also crops out north of Abalone Cove. At both localities it is characterized by partly altered subhedral olivine, fractured laths of calcic labradorite with thin rims of calcic andesine (.80 to 1.00 mm. in length), large, ophitic, pale brown (locally pink)

patches of titaniferous augite ($2V = 48^{\circ}-52^{\circ}$), and leucoxenized laths of ilmenite (Table 6, sample BVV -21). Both olivine and augite are altered to chlorite, pseudo-fibrous celadonite (?), and subordinate secondary green hornblende. Natrolite, in finely radiating clusters, occurs in irregular amygdules and interstices, and as a patchy replacement of labradorite.

Whites Point

A short distance west of Whites Point, tide-washed exposures of dolomitic limestone exhibit tiny, included fragments of andesitic volcanic rock (station "F"). Woodring et al. (op. cit., p. 108) suggested that this locality displays even better than Point Vincente the peperitic brecciation of mud-quenched lava. Microscopic study by the writer revealed the presence of at least two distinct textural varieties of andesite, and it is conceivable, therefore, that this locality represents an area where lavas actually were exposed on the sea floor during the Miocene epoch. Waves could have attacked these flows and distributed the erosional debris throughout the limy mud that later buried the flows.

George F. Canyon

Severely bleached and altered andesite (?) breccia

crops out as a series of irregular resistant knobs on the slopes west of George F. Canyon (map station "G"). This breccia overlies a coarse epiclastic breccia of greenish gray schist that is exposed in the canyon wall, and the schist breccia, in turn, overlies "basement" rocks of the so-called "Catalina schist." The andesite breccia ranges in color from pale reddish brown to grayish orange. Highly angular blocks, from one to ten inches in diameter, project from the weathered surface. In thin section, partly altered phenocrysts of andesine can be seen. Phenocrysts of an unidentified mafic mineral have been replaced completely by hematite.

Contact Alteration Associated with the Miocene Volcanic Rocks

Woodring et al. (op.cit., p. 108) noted that a thin black chert is nearly everywhere present at the base or top of the igneous rocks in the Palos Verdes Hills, and suggested that it is the product of mild contact metamorphism. Two types of evidence indicate that the presence of this dark-colored opaline rock at the top of a body of igneous rock is not a reliable indicator of the intrusive origin of the body. First, miscroscopic examination of specimens in immediate contact with the igneous rocks, and enclosed by them as xenoliths, showed little, if any, evidence of contact alteration. In general, the contact rocks

are composed of finely laminated impure opaline material, rendered almost opaque by an extremely fine-grained, highly disseminated organic substance. Microfossils composed of calcite or chalcedony are the only features that interrupt the monotonous appearance of the rock. Scattered angular grains of quartz are also present locally. No evidence of recrystallization or veining was noted in the specimens examined by the writer.

Second, beds of identical black chert were noted in the Altamira shale stratigraphically distant from any bodies of igneous rock, indicating that the dark color and resistant nature of the chert were imparted by processes other than contact metamorphism. The only apparent metamorphic effect noted during the course of the present investigation is the carbonization of chitinous fish scales.

Summary and Age Relationships of the Volcanic Rocks in the Palos Verdes Hills

Six types of volcanic rock were recognized in the Palos Verdes Hills: glassy hypersthene-augite andesite near Point Vincente; glassy hypersthene-free andesite north of station "C" (this rock may be a compositional equivalent of the hypersthene-augite andesite in an earlier-arrested stage of crystallization); severely altered andesite breccia near George F. Canyon; highly porphyritic augite andesite and olivine diabase northeast of Portuguese Bend;

and altered, subophitic, olivine-free basalt at Bluff Cove and Abalone Cove. The Portuguese and Miraleste tuffs are not considered to belong to the same episode of igneous activity, and are discussed in a later section on rhyolitic tuffs.

Without exception, the volcanic rocks in the Palos Verdes Hills lie between sedimentary strata belonging to the Siphogenerina branneri and S. reedi zones of the Altamira member of the Monterey shale (late Relizian and early Luisian stages, respectively). Field evidence described above suggests that some of the bodies of rock represent flows, and others represent intrusive units that burrowed beneath a cover of unconsolidated sediments. In the light of this evidence, these rocks are considered to be of approximately the same age as the enclosing sedimentary rocks. Two exceptions to this generalization about surface or near-surface sites of emplacement were noted: the sill of altered basalt (?) at Bluff Cove and the composite sill northeast of Portuguese Bend. In both instances the nature of the upper contact of the igneous rock and the large xenolithic blocks of sedimentary rock plucked from the overlying strata, suggest that the beds immediately above the igneous rock were consolidated or semiconsolidated. This means that there was a thicker cover of strata at the two localities in question than at those where the lava burrowed just beneath the surface. Either these

sills are younger than the others, having been injected after a greater thickness of Altamira shale had accumulated, or they are of approximately the same age, but were injected into a lower part of the section. Because the composite sill northeast of Portuguese Bend is intrusive into the lower Altamira shale (Siphogenerina branneri zone) and the sill at Bluff Cove is intrusive into the lower part of the middle Altamira shale (S. reedi zone), whereas the other bodies are intrusive into the middle part of the middle Altamira, the writer believes that the igneous rocks are all approximately contemporaneous, and therefore of lower Luisian age.

San Joaquin Hills

The San Joaquin Hills form a relatively isolated upland at the southeastern end of the Los Angeles basin. They are underlain by Tertiary sedimentary rocks that range in age from Upper Eocene (?) to Upper Pliocene. Structurally, the area lies at the northern edge of a southeastward projection of the Newport-Inglewood fault zone. The hills themselves are cut by a series of northwest trending faults that delimit three crudely parallel outcrop belts: Monterey shale near the coast, Topanga sandstone in the central part of the hills, and rocks of the Vaqueros-Sespe group on the northeast.

East of Laguna Canyon, in the southeastern part of the hills, middle Miocene San Onofre breccia and Monterey shale rest unconformably on the bevelled edges of rocks of the Vaqueros-Sespe and Topanga formations. This unconformity indicates pronounced tectonic activity during middle Miocene time, for at least 3,000 feet of middle Miocene Topanga sandstone was removed by erosion before the younger Monterey and San Onofre sediments were deposited.

Broadly speaking, the hills are anticlinal, with an axis trending northwest-southeast, but complications due to faulting have all but obliterated this structural feature. Of relevance to the matter under discussion is the fact that several of the fault zones within the hills have been intruded by andesitic magma of Miocene age.

The prominent headland jutting seaward from the foot of the San Joaquin Hills between Corona del Mar and Laguna Beach is known as Abalone Point. The rock underlying the point is a fine-grained augite andesite with well developed columnar jointing. This andesite is restricted areally to a number of small exposures of irregular outline near the coast.

Farther north, in the central part of the hills, massive sills and anastomosing dikes of a more basic composition crop out. They are coarse grained and less resistant to erosion than the augite andesite, and constitute the bulk of the igneous rocks in the hills.

At the northwest edge of the hills, near Bonita Reservoir, flows of vesicular, black, glassy hypersthene-augite andesite are exposed. Approximately 1,000 feet northwest of these flows are sedimentary strata belonging to the upper Topanga formation. They consist of a medium gray breccia that is composed predominantly of angular, glassy, volcanic debris. (See Plate V.)

Augite andesite

General statement. The augite andesite near the coast is a fine-grained rock, and is intrusive into Monterey shale (middle and upper Miocene). It is medium gray on fresh surfaces, but weathers to a drab brown or very dark gray. Specimens affected by deuteric alteration are medium

bluish gray in color. Near its contact with the Monterey shale the andesite is bleached and less resistant to erosion than elsewhere. The adjacent shale exhibits no effects of baking or other contact alteration. The columnar jointing is not everywhere as well developed as at Abalone Point.

Petrography. Under the microscope, the rock exhibits a pilotaxitic or trachytic texture. Here and there, the fluidal alignment of narrow plagioclase laths is interrupted at vesicles, where the laths are tangentially arranged. They consist principally of median labradorite, and have an average length of 0.25 mm.. Tiny equidimensional granules of colorless augite ($2V = 50^{o}$) occur between the laths of feldspar in intergranular fashion. They are accompanied by scattered grains of magnetite, and, rarely, by tiny microlites of an orthopyroxene. The remainder of the rock consists of an interstitial pale brown glass (n less than 1.54), altered in part to an olive green chlorophaeitic material. Where the rock has been subjected to deuteric alteration, irregular blebs of quartz and cavity-lining sericite are present. Their development was accompanied by an alteration of the augite, and a replacement of magnetite by pyrite. Table 6 gives a micrometric analysis of this rock (BVJ-9a), and Table 7, a chemical analysis.

Basic hypersthene-bearing andesite

General statement. Dikes of basic hypersthene-bearing andesite fan out in radial fashion through the central part of the San Joaquin Hills. Dikes with a north-northeasterly trend extend from the edge of the town of Laguna Beach to the northern margin of the hills, but those with a northerly and north-northwesterly trend terminate on the south against an upfaulted block of Vaqueros-Sespe sedimentary rocks (Upper Eocene to lower Miocene), two and one quarter miles north of the mouth of Nigger Canyon. In the field, these dikes are indistinguishable from the sill-like mass exposed west of Sand Canyon Reservoir, and those in the area between Coyote and Bommer Canyons, and between Coyote and Big Canyons (J. G. Vedder, personal communication).

The distribution pattern of faults and dikes in the hills is similar, and many of the dikes occupy fault zones. Evidently the magma ascended along these zones of fracture. At the intersections of two or more faults, the dikes branch in a fashion similar to those in the Santa Monica Mountains. Straight-line projections of the dikes and faults in the San Joaquin Hills intersect at a point offshore near Laguna Beach. The Newport-Inglewood fault zone also passes through this point. Analogous radial dike swarms and fractures occur in many volcanic regions of the world, and generally are centered about intrusive plugs or stocks.

In contrast to the fine-grained augite andesite near the coast, the phaneritic, locally porphyritic rocks of the dikes are less resistant to weathering than the sedimentary strata that enclose them. Thus they commonly underlie shallow topographic troughs or saddles. Examples of exfoliation are common.

Coarsely crystalline calcite occurs along the margins of the dikes and in the country rock adjacent to them. It is probably responsible for the abnormal induration of the sedimentary rocks bordering the dike east of Shady Canyon (Figure 20).

Petrography. Petrographic comparisons of specimens taken from several of the dikes revealed variations in their mineralogy. The dike represented by the chemical analysis in Table 7 (BVJ-2) is porphyritic. Phenocrysts of sodic to median labradorite constitute approximately ten percent of the rock, and phenocrysts of hypersthene (En_{68}) about 15 percent. The plagioclase shows pronounced oscillatory zoning, and has marginal shells of median or calcic andesine. The hypersthene occurs in stubby euhedral prisms, and is locally clustered in glomeroporphyritic clots. The groundmass consists of sodic labradorite, augite, ilmenite, and subordinate apatite. Impure green nontronite (?) and other secondary mineral matter fills the remaining space. The texture is predominantly intergranular, but in some specimens it is subophitic.

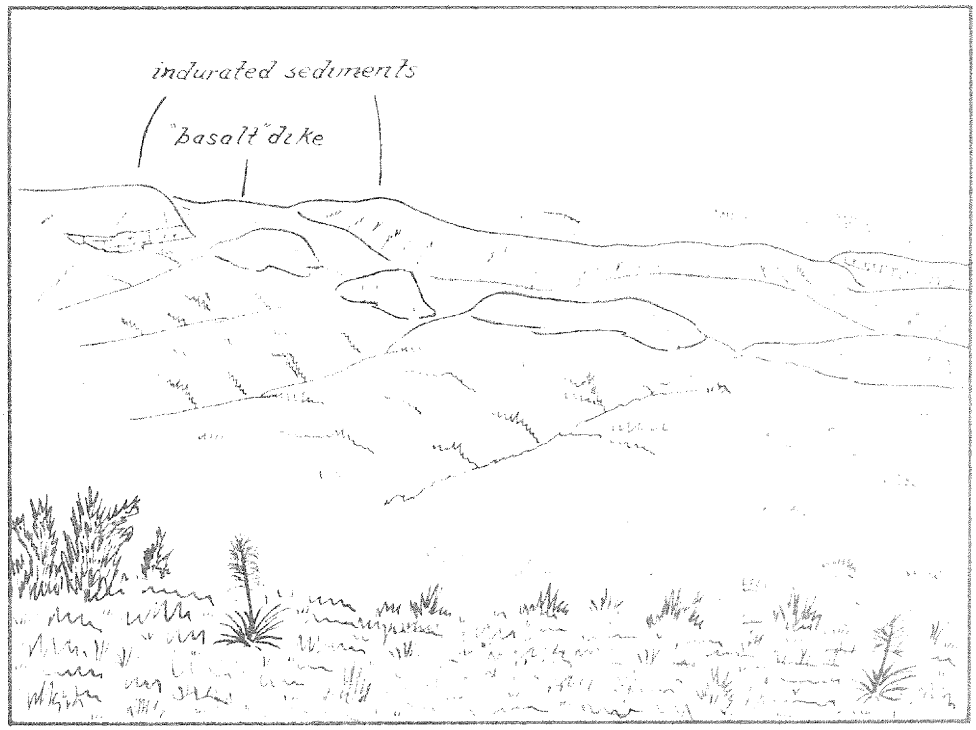


Figure 20. View looking northeast from vicinity of Shady Canyon, San Joaquin Hills. Dike of "basalt" underlies a shallow topographic trough flanked by ridges of highly indurated sandstone. The dike rock is actually a rather basic andesite. The induration of the sandstone is the result of contact alterations by the andesite magma.

The dike immediately west of northern Laguna Canyon is also porphyritic. Both augite and hypersthene occur as altered phenocrysts, constituting nine percent of the rock. They are accompanied by compositionally-varied plagioclase which composes 30 percent of the rock. The latter is principally sodic labradorite, but it shows complex zoning with outer margins of median andesine. Alteration of the mafic minerals has resulted in the development of biotite. The groundmass of this rock consists of andesine-labradorite, altered prismatic pyroxene, ilmenite, and colorless, acicular apatite in a brownish cryptocrystalline mesostasis.

Specimens from dikes at two other localities are hypersthene-free, but contain pigeonite. One of these specimens, from the ridge north of Signal Peak, exhibits a subvariolitic texture. Slender laths of sodic to median labradorite, arranged in crudely radiating bunches, are separated by both stubby and subacicular prisms of calcium-poor augite ($2V = 30^{\circ}-42^{\circ}$) and pigeonite ($2V = 10^{\circ}-18^{\circ}$). Partially altered magnetite constitutes the remainder of this rock. A fused-bead test indicates that the rock contains a total of 53 percent of silica.

Approximately half a mile east-northeast of the point where MacArthur Boulevard crosses Big Canyon, a low hill of igneous rock projects from the alluvial terrace at the foot of the hills. The rock is moderately coarse grained,

and is yellowish gray to light olive gray in color. It evidently represents a resistant intrusive plug. Approximately 50 percent of the rock comprises fresh euhedral and subhedral laths of plagioclase. Normal zoning of the plagioclase is common, and cores of sodic bytownite and calcic labradorite grade outward to margins of median and sodic labradorite, respectively. Both pigeonite ($2V = 0 - 12^{o}$) and augite ($2V = 47^{o}-48^{o}$) are present, and they ophitically enclose the plagioclase. Ragged skeletal crystals of "ore" constitute the remainder of the primary minerals. Altered glass (?), with swallowtail microlites of plagioclase, and a brilliantly iron-stained carbonate mineral are present in the intercrystal areas.

The chemical analysis of the dike rock presented in Table 7 (BVJ-2) shows a striking contrast to that of the augite andesite collected near the coast (BVJ-9a). The two rocks are alike in their percentages of all major oxides except Al_2O_3, FeO, and CaO. With respect to these oxides, BVJ-2 differs from the other Miocene volcanic rocks in the basin as well. The lower alumina and higher iron content of the rock suggest a basaltic composition, but most of the basalts in the basin contain at least 16 percent of alumina. A further departure of this rock from the compositional mean of the other volcanic rocks in the basin can be seen in Figure 3. The anomalous composition of BVJ-2 is thought to be due to the assimilation

of more basic material at depth (see section on Petrology). For want of a better term, the rock is herein referred to as "basic hypersthene-bearing andesite."

Hypersthene-augite andesite

General statement. Glassy flows of hypersthene-augite andesite are exposed northeast and southwest of Bonita Reservoir. They are fresh and resistant, and are medium gray to black in color. In places, the glassy surfaces exhibit a pitchy luster, and show discernible flow-banding. Locally the rock is vesicular.

Petrography. Megaphenocrysts of plagioclase range in composition from calcic andesine to median labradorite, and show reversed zoning. Tiny inclusions or remelt patches of glass commonly are arranged in zonal fashion within the plagioclase, giving it a sieved or spongy appearance. Phenocrysts of hypersthene (En_{57-60}) occur as fresh euhedral prisms, locally with narrow jackets of clinopyroxene. Augite ($2V = 45^{\circ}-46^{\circ}$) phenocrysts are characterized by fresh, stubby subhedral individuals. Microphenocrysts and swallow-tailed microlites of feldspar range from sodic to median labradorite in composition. Microphenocrysts of hypersthene are compositionally identical to the megaphenocrysts, but jackets of clinopyroxene are more commonly in evidence. Grains of monoclinic pyroxene are too small to be specifically identified.

The glassy mesostasis constitutes fully half of the rock. It is brownish black and opaque, presumably because of a disseminated, impalpable magnetite dust. Modal and chemical analyses of this unit (BVJ-7) are given in Tables 6 and 7, respectively.

The rock represents the only extrusive body in the San Joaquin Hills, and constitutes but a small fraction of the total area of igneous rock exposed there. Mineralogically and petrographically it resembles the rocks near Point Vincente in the Palos Verdes Hills.

Epiclastic volcanic breccia

Northwest of Bonita Reservoir, exposures of part of the upper Topanga formation reveal a gray, epiclastic breccia composed predominantly of pyroclastic debris. This unit is exposed northeast and southwest of Bonita Creek. Microscopic study of the fine-grained matrix of this rock reveals tiny angular (vitroclastic?) fragments of opaque brown glass and orange palagonite, accompanied by broken crystals of median labradorite. Within the glass are microphenocrysts of labradorite and an unidentified substance that evidently has replaced pyroxene. Clasts of these constituents are thoroughly mixed and poorly sorted; particle sizes range from 0.10 to 3.00 mm.. The rock has the appearance of a pyroclastic breccia, but according to J. G. Vedder (personal communication) it locally has an

arkosic matrix, and therefore probably represents reworked pyroclastic debris.

Age of the volcanic rocks in the San Joaquin Hills

Microfaunas collected from the Topanga formation near Bonita Reservoir indicate a late Relizian age for the strata overlying the glassy flows of hypersthene augite andesite. Diatomaceous beds of the lower Monterey formation, stratigraphically above these Topanga strata, contain Foraminifera characteristic of the Luisian stage. The volcanic activity represented by the glassy flows thus took place late in the Relizian stage of the middle Miocene epoch.

According to J. G. Vedder and R. F. Yerkes (personal communication, 1955), the youngest strata cut by the dikes of basic hypersthene-bearing andesite contain faunas indicative of the Relizian stage. As none of these dikes are known to transect beds of Luisian or younger age, it is possible that the dikes were emplaced during Relizian time. The massive andesite sill west of Sand Canyon Reservoir is cut by a fault that trends southeastward across the hills and disappears beneath an unconformity at the base of the Monterey formation east of Laguna Canyon. The basal Monterey strata in that area have yielded a Luisian Foraminiferal assemblage, and because these strata truncate a fault that post-dates the sill, the sill must be

pre-Luisian in age. On the other hand, branches of this same fault have been intruded by basic andesite west of Laguna Canyon. On the basis of this evidence, the writer believes that the dikes and sills of basic hypersthene-bearing andesite are approximately of late Relizian or transitional Relizian-Luisian age.

The age of the intrusive augite andesite exposed near the coast has not been determined conclusively. The andesite cuts shale belonging to the Monterey formation, but this formation ranges in age from late middle Miocene (Luisian) to late Miocene. The andesite must be at least as young as Luisian, and it may be even younger. It therefore was emplaced some time after the other Miocene igneous rocks in the hills.

El Modeno Area

Severely altered volcanic rocks of Miocene age are exposed in the foothills of the Santa Ana Mountains east of Orange and El Modeno (the "Tustin Hills" of English, 1926). The distribution of these rocks is shown on U. S. Geological Survey Oil and Gas Investigations Map No. 154 (Schoellhamer et al., 1954a), and a detailed petrographic study of the rocks was recently completed by R. F. Yerkes (195_, in press).

In a general sense, the Santa Ana Mountains represent a faulted anticline. The axis of this anticline trends and plunges to the northwest. To the southeast it passes approximately through Santiago Peak, type locality of the Jurassic metavolcanic rocks described earlier in this report. These ancient volcanic rocks, together with metasedimentary rocks of the Triassic Bedford Canyon formation, constitute the core of the anticline. Resting unconformably upon this core is a section of conglomerates, sandstones, and siltstones that range in age from Upper Cretaceous to Pliocene.

Miocene volcanic rocks are exposed on the south limb of the anticline, where they lie between middle Miocene Topanga sandstone and the La Vida shale member of the upper Miocene Puente formation. They consist, from their base upward, of olivine basalt, palagonite tuff and tuff-breccia, and flows and flow-breccias of andesite. On the

north limb of the fold (Burruel Ridge) they are represented by only a thin, discontinuous mass of olivine basalt.

The following description of the Miocene volcanic rocks is based on personal discussions with Yerkes, a study of his preliminary manuscript, several visits to the area, and an examination of thin sections of the principal rock types.

Olivine basalt

General statement. The thickness of the basal basalt ranges from 0 to 200 feet. It is massive, and seemingly constitutes a single, rather extensive flow. Crudely ellipsoidal pillows with inter-pillow siltstone imply, at least locally, a submarine origin. This interpretation is confirmed by the presence of a thin bed of marine limy siltstone overlying the basalt. Where the flow rock is jointed, the central parts of the joint blocks are bleached and altered, but near the joints the rock is fresher and less affected. This phenomenon probably is the result of retention of reactive volatiles within the central parts of the joint blocks during cooling of the rock. It was not observed elsewhere in the Los Angeles basin.

Petrography. A thin-section study of the flow rock revealed phenocrysts of plagioclase and a severely altered mafic mineral in a groundmass of plagioclase, augite, "ore," and fibrocrystalline derivatives of chlorophaeite. The

phenocrysts of plagioclase consist chiefly of normally zoned calcic labradorite, with margins as sodic as calcic andesine. The plagioclase is generally fresh, but is cut by abundant fractures that are seamed with secondary alteration products. Chlorophaeite and calcite have replaced the unidentified mafic mineral. According to Yerkes (personal communication, 1955), this mineral was olivine.

The feldspar of the groundmass ranges in composition from median to calcic labradorite. Pale brown augite occurs ophitically about the ends of euhedral laths of the labradorite. Much of the augite has been replaced by brown, fibrocrystalline chlorophaeite. In addition to tablets of "ore," colorless needles of apatite and interstitial chlorophaeite are present.

Age. On Burruel Ridge, three miles north of the El Modeno area, an erosional remnant of this olivine basalt is overlain by a 20-inch bed of light gray claystone containing a silicified Foraminiferal fauna representative of Kleinpell's Siphogenerina reedi zone (early Luisian stage). This bed is stratigraphically equivalent to the limy siltstone that rests on basalt in the El Modeno area. The siltstone contains fish scales of middle Miocene age.

Palagonite tuff and tuff-breccia

The palagonite tuff and tuff-breccia are characterized by interbedded tan or grayish buff, fine-grained, well

sorted tuffs, and poorly sorted, coarse angular breccias of augite andesite. They rest in apparent conformity on the limy siltstone. These rocks range in thickness from 125 to 450 feet, and their average thickness is between 200 and 300 feet. The palagonite tuff occurs in thick sequences of finely bedded rocks that locally display cross-bedding. Tiny pieces of amber or black vesicular palagonite constitute a fragmental matrix for larger fragments of plagioclase (andesine or labradorite), subordinate pyroxene, quartz, and lithic basalt. The tuff alternates both vertically and laterally with layers of unsorted breccia consisting of angular blocks of light gray, vesicular augite andesite in a tuffaceous matrix. The larger fragments range from less than one inch to ten inches in diameter.

Basaltic andesite

General statement. On the basis of labradoritic plagioclase, Yerkes referred to the uppermost volcanic unit near El Modeno as "calcic andesite." His use of this term conforms to that of Shelton (1946, 1955), but the "calcic andesite" of the El Modeno area differs from the Glendora "calcic andesite" in the absence of hypersthene and in a lower total silica content, as determined by means of fused beads. Both rocks differ in their chemical composition from Callaghan's (1933) "calcic andesite."

According to the classification employed in the present report, the El Modeno rock is a basaltic andesite.

Interbedded red and gray vesicular flows of this andesite alternate with flow breccias and minor tuff-breccias. Parts of this sequence crown nearly every hill in the area. The flows locally are scoriaceous or dense and blocky. Some of them exhibit well defined pillow structure. The breccias consist of angular, vesicular blocks, some as large as six feet in diameter, in a matrix of severely altered fine-grained andesite, or andesitic (?) tuff.

Petrography. Under the microscope the basaltic andesite exhibits phenocrysts of calcic labradorite and a chlorophaeitized mafic mineral with outlines suggestive of olivine. The groundmass is composed of normally-zoned median labradorite, colorless prisms and grains of clinopyroxene, lath-shaped crystals of ilmenite, and yellowish brown fibrous chlorophaeite. The texture is porphyritic-intergranular. Micrometric analyses of several different specimens by both Yerkes and the writer revealed considerable variation in the mineral composition of this unit. Spindle-shaped calcite amygdules are common, and Yerkes reported secondary calcite, tridymite, and phillipsite, as well.

Age. Immediately overlying the andesite is the basal La Vida member of the Puente shale, containing a Foraminiferal fauna indicative of the Mohnian stage. The

palagonite tuff and basaltic andesite therefore are bracketed stratigraphically by Luisian rocks below and Mohnian rocks above.

Dike rocks

Dikes of both olivine basalt and pyroxene andesite are present in the area. The basaltic dikes comprise dense, black rocks that are non-vesicular and highly porphyritic. They are composed of median to calcic labradorite, olivine, augite, and magnetite. These dikes cut both the Santiago formation (middle Eocene) and the Topanga formation (middle Miocene).

The andesite dikes are mineralogically similar to the youngest flows and breccias of the area. Locally they are vesicular, and the vesicles are filled with calcite and an unidentified zeolite. These dikes cut both the palagonite tuff and the flows of basaltic andesite.

Yerkes (195_) made the interesting observation that certain petrographic features of the El Modeno rocks make it possible to distinguish between intrusive and extrusive bodies. The intrusive rocks reportedly are characterized by a lack of vesicularity (to which there are a few exceptions), apparent freshness, coarser grain size, ophitic texture, and the presence of hydroxl-bearing secondary minerals such as chlorite and biotite. The extrusive rocks are characteristically altered to soft, crumbly

masses and certain abundant chlorophaeite or its fibrocrystalline derivatives. These criteria are of questionable value for the volcanic rocks in other parts of the Los Angeles basin. This is particularly true of the degree of alteration, the presence or absence of vesicles, and the grain size. If applied to the region in general, they could be highly misleading.

Summary of the age relationships of the volcanic rocks near El Modeno

Inasmuch as Luisian strata overlie the basal olivine basalt, and it, in turn, rests on the upper Topanga formation, the basalt must be of Luisian (late middle Miocene) age. The palagonite tuff and basaltic andesite members of the volcanic sequence lie between Luisian and Mohnian beds and are therefore younger than the basalt. They probably were extravasated near the close of the Luisian stage. On the basis of the local stratigraphic relationships, the horizon dividing the Mohnian and Luisian stages might be placed at the top of the andesite, at the bottom of the palagonite tuff, or at the boundary between the two. On the basis of regional stratigraphic relationships however, most geologists would probably place it at the top of the andesite, thereby restricting the entire volcanic section to the Luisian. Additional evidence bearing on this problem is presented in the section concerned with subsurface data.

Glendora Area

The extrusive rocks referred to as the "Glendora volcanics" crop out in three upland areas northeast of the Los Angeles basin: the Puente Hills, the San Jose Hills, and the southern foothills of the San Gabriel Mountains between the cities of Azusa and La Verne. Well logs indicate that these rocks also are present in the subsurface beneath the floor of the eastern San Gabriel basin. This basin lies south of the San Gabriel Mountains and extends from the San Jose Hills on the east to Pasadena on the west. A discussion of the subsurface data appears in a later part of this report.

The Puente Hills are crudely triangular in plan, and are bounded on the south by a major northwest-trending fracture zone known as the Whittier fault. Part of the northeastern margin of the hills is similarly bounded by the Chino fault. Both of these faults dip steeply, and along part of their lengths show evidence of reverse movement, with the northeast side having moved up. Within the hills, the structure consists of broad, gentle folds.

Rocks exposed at the surface range in age from pre-Upper Cretaceous to Pliocene. Clastic sedimentary rocks of Miocene and Pliocene age predominate, but at the southernmost edge of the hills a small exposure of Sespe (?) sandstone (Oligocene to lower Miocene) has been found. These sedimentary strata rest unconformably on a pre-Upper

Cretaceous "basement complex" of quartz dioritic and granodioritic plutonic rocks that crop out at the northern tip of the hills.

In the southern part of the hills, west of Rodeo Canyon, small exposures of diabase have been encountered. These exposures represent the upper part of a large, branching body of diabase that is essentially parallel to the Whittier fault.

The San Jose Hills lie north of the Puente Hills, and are separated from them by the valley of San Jose Creek. Folds in the San Jose Hills are somewhat tighter than those in the Puente Hills, and they are locally overturned to the south. They trend east-northeast, parallel to the margins of the upland.

The sedimentary rocks that crop out in the San Jose Hills are similar to those in the Puente Hills with the exception of minor differences in lithologic facies. Outcrops of the Topanga formation (encountered only at depth in the Puente Hills) make up the core of the San Jose anticline. The eastern end of the hills consists entirely of outcrops of the Glendora volcanic series and subordinate exposures of the crystalline "basement complex." Included in the latter is the Mountain Meadows dacite, assigned by Shelton (1955) to an interval between early Cretaceous and middle Miocene times. Clasts of this dacite are found embedded in the basal Glendora volcanic rocks.

The area between the San Jose Hills and the foothills of the San Gabriel Mountains is buried beneath coarse unconsolidated alluvium of Quaternary age. The structural complexity of the belt bordering the frontal slope of the San Gabriel Mountains can be seen from the cross-sections of Shelton (1955). There is a predominance of moderately to steeply dipping reverse faults. Shelton (1946) expressed the belief that "at least part of the Late Tertiary and post-Tertiary uplift of the San Gabriel Mountains has taken place along (these) faults..."

The volcanic rocks have been described in detail by Shelton (1946, 1954, and 1955) and need only be mentioned here. The discussion that follows is largely a summary of his work. As a group, the Glendora volcanic rocks are more acid in composition than the extrusive rocks exposed elsewhere in the Los Angeles basin. Lithologic types ranging from olivine basalt to rhyolite are present, but the average composition is close to that of andesite, with a silica content of between 60 and 65 percent.

As mentioned above, the "calcic andesite" of the Glendora suite is mineralogically a porphyritic hypersthene-augite andesite. Its chemical analysis differs from that of the "calcic andesite" or "labradorite andesite" of Callaghan (1933) in having more silica and alumina and less iron and lime. Other pyroxene andesites in the Los Angeles basin (Sunland, Palos Verdes Hills, San Joaquin

Hills, and El Modeno) have a lower content of silica.

Not only do the average Glendora lavas have a more acid composition than others described in this report, but they also show a wider range in both mineralogical and chemical composition. Rocks such as rhyolite, dacite(?), biotite andesite, and hornblende andesite are not exposed outside the Glendora area, although cores from Standard Oil Company's Baldwin-Cienega No. 105 well near Inglewood and Irvine No. 1 well north of Newport Lagoon yielded specimens of soda rhyolite and hornblende-bearing pyroxene andesite, respectively. Evidently the conditions and nature of magmatic differentiation in this area northeast of the Los Angeles basin differed from those elsewhere in the basin.

The total thickness of the Glendora volcanic rocks (approximately 3,800 feet) is much greater than the average thickness of the volcanic section in the Los Angeles basin. Only in the western Santa Monica Mountains are more impressive volumes of lava encountered.

Rhyolitic felsophyre and a breccia of spherulitic rhyolite glass, accompanied by subordinate biotite andesite and fine-grained basalt, are present at the northern tip of the Puente Hills, west-southwest of Pomona. The body of glassy breccia appears to be an eroded vent-filling, for the flow-foliation in the surrounding felsophyre dips away from it quaquaversally. Sedimentary strata of the

upper Miocene Puente formation rest directly on the volcanic rocks, indicating that the area was topographically higher than the surrounding country during the early upper Miocene. The age of these volcanic rocks has not been determined, but because middle Puente sandstone rests unconformably upon them, there is reason to believe that they are temporally equivalent to the volcanic rocks to the north and northwest.

In the eastern San Jose Hills, the volcanic rocks in the areas northwest and southeast of Puddingstone Reservoir show pronounced contrasts in their petrographic and structural characteristics. Southeast of the reservoir an extensive flow-breccia of hypersthene andesite, with a maximum thickness of 800 feet, rests on Mountain Meadows dacite and rocks of the "basement complex," and is overlain by nearly 500 feet of fine-grained, porphyritic hypersthene-bearing basalt. No stratigraphic correlative of either of these units is found in the complex narrow belt of volcanic rocks northwest of the reservoir. Instead, one finds breccias of vesicular olivine basalt, flows of platy biotite andesite, finely laminated felsitic rhyolite, lenses and pipes of perlitic tuff, flows and breccias of hornblende andesite, andesitic tuff-breccia, palagonite tuff, and epiclastic volcanic conglomerates. A breccia pipe, filled with fragments of perlite and banded glassy rhyolite, crops out downstream from Puddingstone Dam and

probably represents the site of a former conduit or vent.

On Way Hill, north of San Dimas, tuff-breccias and tuffs of altered vitric(?) andesite and flows of fine-grained andesite and red basaltic tuff are in contact with middle Miocene (probably Luisian) sandstone and shale. In the South Hills, southeast of Glendora, sedimentary rocks of the Topanga formation are interlayered with altered hornblende andesite flows and breccias, fine-grained flows of basaltic andesite (?), coarse basaltic breccia, dacite (?), and andesitic tuff. Sedimentary strata at the western end of the hills have yielded Foraminifera characteristic of the Luisian stage of the Miocene epoch. On the basis of correlations between the isolated exposures of Glendora volcanic rocks, Shelton believes that these flows are among the youngest in the area.

In the foothills of the San Gabriel Mountains, east of Glendora, a structurally complex belt of Miocene volcanic rocks is exposed between pre-Tertiary crystalline "basement" rocks on the north and sandstone and shale of the Puente formation on the south. Although a general stratigraphic section has been established for the extrusive rocks, many of the units are so irregular in shape that the detailed sequence is quite complex. Certain lithologic types are repeated several times. Locally, the oldest unit resting on the pre-Tertiary crystalline "basement" is what Shelton called "fine-grained andesite."

It is an aphanitic, partly glassy augite andesite. It is variously overlain by "calcic andesite," Johnstone Peak tuff-breccia, or basalt. The "calcic andesite" is one of the most abundant rock types in the area. Certain facies of it have been interpreted as autoclastic breccias.

The Johnstone Peak tuff-breccia is a chaotic, structureless deposit of fragments and blocks of hypersthene andesite, ranging from less than one inch to more than ten feet in diameter, embedded in a matrix of crystal-vitric tuff. From the abundance of blocks exhibiting radial cooling cracks, the notable lack of bedding, and the high percentage of tuff matrix, Shelton has interpreted this unit as a product of nuées ardentes.

The basalt that locally overlies the "fine-grained andesite" commonly contains a small amount of hypersthene, and subordinate olivine. One mile northeast of Azusa similar basalt is interbedded with Topanga sandstone that reportedly has yielded Luisian Foraminifera.

Also present in the foothills area is a breccia or tuff-breccia of hornblende andesite, and several dikes and other intrusive masses of both basalt and dacite. A steep-walled, roughly cylindrical mass of dacite breccia, with several associated dacite dikes, crops out southeast of Johnstone Peak, and another breccia-filled pipe (?) is exposed north of the junction of Mystic and Big Dalton Canyons.

At the east end of Sierra Madre Avenue, northeast of Glendora, outcrops of Topanga sandstone and shale have yielded Foraminiferal fauna typical of the Luisian stage. The sedimentary rocks lie in close proximity to volcanic rocks, but the stratigraphic relationship between the two is indeterminable.

In addition to the established Luisian ages listed above, cores from a neighboring well (the Texas Company's Covina 27-1) have revealed a thick section of Luisian sedimentary strata overlying flows and pyroclastic rocks that are lithologically similar to the Glendora volcanic rocks. Apparently, most of the volcanic activity in the Glendora area was restricted in time to the late middle Miocene (Luisian), but it terminated before deposition of Luisian sediments ceased.

Santa Catalina and San Clemente Islands

The volcanic rocks of Santa Catalina and San Clemente Islands (Smith, 1897 and 1898) are petrographically similar to the volcanic rocks near the coast of the Los Angeles basin. Volcanic rocks of Tertiary age also crop out on the Channel Islands to the north, but less is known of these rocks. Any comments regarding their nature and occurrence properly belong under a discussion of the western Santa Monica Mountains, of which the Channel Islands are structurally a part.

San Clemente Island

The emerged part of San Clemente Island consists almost entirely of volcanic rocks of Tertiary age. Hypersthene-augite andesite predominates, but dacite and rhyolite are present also. Marine sedimentary rocks crop out here and there. They do not appear to be interbedded with the volcanic rocks, but instead rest upon them. They are of middle Miocene age (W. H. Holman, personal communication, 1955). None of the rocks are severely deformed. According to Smith (1898) the gross structure of the island is anticlinal.

Hypersthene-augite andesite

The hypersthene-augite andesite is porphyritic, with

phenocrysts of normally-zoned plagioclase, and, commonly, of augite and hypersthene. The plagioclase phenocrysts contain zonally-arranged inclusions of pyroxene and glass, and the crystals of hypersthene show overgrowths or jackets of augite. As in the rocks of the San Joaquin Hills and the subsurface to the west, the hypersthene is a non-pleochroic variety and the augite is very pale green.

The groundmass texture ranges from holocrystalline to holohyaline. Crystalline components include andesine, hypersthene, augite and magnetite.

Smith (1898) described platy jointing in this rock that is similar to that exhibited by the basaltic andesites at Sunland. Jointing of this type is relatively common in rocks of andesitic composition in the circum-Pacific volcanic belt (see, e.g., Anderson, 1941).

Dacite

The dacite occurs as purplish gray, porphyritic flow rocks. Phenocrysts include andesine, hypersthene, and, less commonly, augite. Flow banding is manifested in the alignment of oligoclase microlites and laths in the partially glassy groundmass. Quartz is present in what Smith (op. cit.) referred to as "micropoecilitic" structure. The latter, combined with the over-all mineralogical composition of the rock, gives it a strong resemblance to Shelton's (1955) breccia of "hypersthene andesite" (S-468)

which contains micropoikilitic quartz.

Rhyolite

The proportion of rhyolite, relative to the other rocks on San Clemente Island, is small. The rock occurs in very light gray units that locally show flow banding. Phenocrysts of andesine (?) are common, and phenocrystic quartz can be seen in some specimens. The groundmass consists of alternating bands of glass and aggregates of quartz and potash feldspar.

Rhyolite flows were the last to be extruded. They were preceded by dacite, and, at an earlier date, by hypersthene-augite andesite.

Inasmuch as the volcanic rocks of San Clemente Island are similar to those of the Los Angeles basin, both in composition and in age, it seems very likely that they are genetically related.

Santa Catalina Island

Volcanic rocks of Miocene age are exposed in an irregular east-west belt just south of the center of Santa Catalina Island, and at the southern tip and along the northeastern shore of the island as well. Hypersthene-augite andesite predominates. The other volcanic rocks, described by Smith (1897) and Bailey (1941), include

rhyolite and basalt. The andesite is lithologically similar to the pyroxene andesites of San Clemente Island, the San Joaquin Hills, and the Palos Verdes Hills. It is composed of phenocrysts of labradorite, hypersthene, and augite in a groundmass of andesine microlites, pyroxene, and smoky glass.

The rhyolite bodies are small in size, and are considered by Bailey (op. cit.) to be intrusive in origin. The basalt is composed of labradorite (phenocrysts and groundmass individuals), augite, magnetite, and olivine, the last chiefly altered to iddingsite.

The flows and breccias of Santa Catalina Island are interbedded with marine sedimentary rocks that reportedly are late Miocene in age (Bailey, op. cit.). According to W. H. Holman (personal communication, 1955), however, the age of these strata is in need of further study.

Chemical analyses of the volcanic rocks from both of the islands can be found in Table 8 of this report. They are old analyses, performed principally by Smith (op. cit.), and probably are not as accurate as the others included in the table.

SUBSURFACE GEOLOGY OF THE MIOCENE VOLCANIC ROCKS

Known and Inferred Extent

The general surface distribution of the rocks under discussion and the locations of wells that have penetrated these rocks in the subsurface are indicated in Plate VII. A tabular summary of subsurface data pertaining to these rocks is given in Plate VI.

Exposures of Tertiary volcanic rocks or kindred intrusives occupy only 19 of the approximately 2,200 square miles of land shown on Plate VII. If one includes the areas surrounding groups of wells in which these rocks were encountered, however, approximately 200 square miles are added to the surface exposures, bringing the total known extent to 220 square miles, or approximately ten percent of the entire area. Even this last figure is a conservative estimate, for it is almost certain that the volcanic rocks extend into the central parts of the Los Angeles, San Gabriel, and San Fernando basins. They occur at such depths in these basins, however, that their presence has not been verified by drilling.

Some idea of the basinward slope of the Tertiary section can be gained from the structure contours drawn on the top of the volcanic rocks. The contours are necessarily generalized, but they serve to illustrate the fact that where the volcanic rocks have been penetrated in the

areas of deepest drilling, they are present at depths of from 7,000 to 12,000 feet subsea. The groups of wells shown near the southwestern edge of the basin are located not over the central deep, but over the Newport-Inglewood uplift which is structurally high.

The inferred subsurface extent of the volcanic rocks is indicated in a less conservative manner in Plate VIII. The location of parts of the buried margin of these rocks is largely conjectural, for pertinent information is meager or lacking. Petroleum production in the basin is currently obtained from zones stratigraphically above the volcanic rocks, and only in rare instances have operators drilled deeply enough to outline the extrusive rocks in a definitive manner.

Southwest of the Newport-Inglewood uplift, upper Miocene sedimentary rocks rest unconformably on a corrugated surface of the Catalina schist. The highest point on this surface (excluding the Palos Verdes Hills) occurs beneath the Playa del Rey oil field at 5,300 feet subsea (Schoellhamer and Woodford,1951). Five miles northeast of this point, Standard Oil Company's Baldwin-Cienega No. 105 well (No. 55 on Plate VIII) penetrated more than 4,000 feet of middle Miocene sedimentary and volcanic rocks without reaching schist. This rather abrupt pinching-out of a thick middle Miocene section takes place in a distance of

only three miles, for well No. S-32* penetrated schist immediately below upper Miocene sedimentary strata. A similar occurrence has been observed twelve miles to the southeast, where approximately 1,300 feet of strata, including volcanic rocks, pinches out between wells No. 51 and S-26. Two deep wells (Nos. S-20 and S-21) in the Long Beach oil field entered pre-Tertiary schist directly from upper Miocene (Mohnian) beds, indicating that in this area the margin of the middle Miocene volcanic rocks lies somewhere down the northeast flank of the Newport-Inglewood arch.

The general areal extent of the irregular elongate "ridge" of buried schist over which the extrusive rocks are missing is indicated in Plate VIII by the wells along the coast prefixed with the letter "S" (see also Appendix II). Exposures and wells in the Palos Verdes Hills indicate that the sills and subordinate flows that are present there pinch out toward this "ridge" from the southwest.

Near Newport Lagoon, and along the coast for a distance of 8½ miles to the northwest, several deep wells have passed through middle Miocene sedimentary rocks

---

* Data pertaining to wells prefixed with the letter "S" can be found in Appendix II.

ranging in "penetrated thickness" * from 400 to 3,500 feet without encountering volcanic rocks. The presence of a volcanic-free Relizian sedimentary section only 2½ to 10½ miles west of Relizian volcanic rocks in the San Joaquin Hills, indicates that flows and pyroclastic rocks probably were never present in this area.

The location of the subsurface margin of the Miocene volcanic rocks along the northern edge of the Los Angeles basin is conjectural. The Seaboard Oil Company of Delaware drilled two wells on the north side of Los Angeles (Nos. S-17 and S-18, Plate VIII) that penetrated Santa Monica slate in the core of an anticlinal ridge, and neither encountered volcanic rocks. Well No. S-17 passed directly from upper Miocene sedimentary strata into slate, and No. S-18 passed through 15 feet of rocks of questionable middle Miocene age before entering slate. Evidently middle Miocene rocks lap out on this "basement high," just as they do to the southwest, but whether or not they include lavas and pyroclastic rocks is not known.

Four miles to the west-northwest, 1,200 to 1,700 feet of basalt is present in the Griffith Park area, and evidence

---

* In this report, "penetrated thickness" refers to the apparent thickness of a given formation or group of rocks encountered in drilling, without regard to the attitude of the rocks or the orientation of the well. The term "stratigraphic thickness" refers to the thickness of the rocks measured perpendicular to their bedding surfaces; it represents a trigonometrically corrected "penetrated thickness."

discussed earlier supports the hypothesis that a volcanic vent lay close by. There is thus a possibility that volcanic rocks are present in the subsurface south of the Santa Monica Mountains. On this rather tenuous basis, the margin has been drawn just south of, and parallel to, the general anticlinal arch of the Repetto Hills. None of the wells drilled in the Montebello-Whittier Narrows area has been deep enough to penetrate a section that might include volcanic rocks, and thus it is uncertain as to where the subsurface margin of the volcanic field lies in this area.

Flows and breccias may exist beneath a large part of the San Gabriel basin, or they may thin from a maximum of 3,840 feet in well No. 77 to a feather-edge in mid-basin. Those wells indicated on the map by crosses represent the bulk of the subsurface exploration north of T2S and west of R10W, and all of them are too shallow to have reached the upper part of the middle Miocene section.

Data from Shelton (1955) indicate that in the area east of exposures of the Glendora volcanic rocks, and north of well No. 50, crystalline "basement" rocks lie directly beneath the alluvial gravel of Quaternary age. Evidently Tertiary volcanic rocks are not present in this area.

To the south, in T3S, R8W, Honolulu Oil Company's Santa Ana Valley Irrigation Co. No. 1 (S-8, Plate VIII) penetrated more than 1,000 feet of middle Miocene (Luisian

and Relizian) sedimentary rocks with 40°-dips and bottomed in them at a depth of 2,220 feet without encountering volcanic rocks. This evidence is in essential agreement with the data from areas to the north, and with the facts as indicated in the area to the south by the map of Schoellhamer et al. (1954b). A generalization concerning the eastern boundary of the Miocene volcanic rocks can therefore be made: these rocks are not present beyond a line two miles east of the north-south boundary between Ranges 8 and 9 W.

In townships 5 and 6 S, this margin lies farther west, probably as indicated on the map, although the well data are meager. Well No. S-25 entered lower Miocene Vaqueros beds directly from Pliocene rocks at a depth of 1,750 feet. This suggests that the moderately thick middle and upper Miocene sections (possibly containing volcanic rocks) had been removed by erosion before Pliocene deposition began. To the southeast, well No. S-2 encountered identifiable upper Miocene (Mohnian) sedimentary rocks and, deeper in the section, strata of possible Cretaceous age, but an examination of ditch samples from zones between these two units failed to reveal the presence of extrusive rocks. In the San Joaquin Hills, several intrusive bodies occur east of the supposed eastern margin of the volcanic rocks, but they are not accompanied by related flows.

It is probable that this boundary represents the

original eastern margin of the Miocene volcanic field, for well data in the Puente Hills indicate a pronounced thinning of the lavas in an eastward direction. In addition, a study of the sedimentary rocks flanking the west and northwest sides of the Santa Ana Mountains suggests that the range was topographically high during most of the Tertiary period (Corey, 1954), and nowhere have plugs or dikes, indicating former conduits of Miocene age, been found within it. In T5S, R8W, a thin middle Miocene Topanga section lies with apparent conformity between upper Miocene Puente and lower Miocene Vaqueros rocks. Volcanic rocks are absent.

The absence of volcanic rocks in the southern part of T3S, Ranges 9 and 10 W probably indicates a post-upper Miocene erosion interval. Stratigraphic studies of well data from the southern edge of this area indicate that Pliocene sedimentary rocks lie unconformably across the bevelled edges of upper, middle, and lower Miocene rocks, including flows and pyroclastic units. The exact location of the northern margin of this volcanic-free area is not known because of the great depth at which the relevant horizons occur. Union Oil Company's Chapman No. 29 well (No. 89 on Plates VII-IX), the deepest well in the vicinity (10,496 feet), did not encounter volcanic rock until a depth of 7,955 feet had been reached (7,662 feet subsea).

The present northern boundary of the Miocene lavas in the area of the San Gabriel and San Fernando Valleys is the southern face of the San Gabriel Mountains or, more specifically, the Sierra Madre fault zone. Farther west, beyond the limits of the present study, the Santa Susana and Oak Ridge faults bound the northern edge of the westward extension of these extrusive rocks. Whether or not this chain of faults was the northern boundary of the volcanic field during Miocene times is not known with certainty, but indirect evidence suggests that it was. The studies of Edwards (1934) and Woodford, Moran, and Shelton (1946) both indicate that the San Gabriel Mountains behaved as a positive tectonic element throughout most of Miocene time, for they furnished abundant clastic debris to the subsiding basin on their south. Both the megafossils collected from Topanga conglomerates near Sunland, and the presence of carbonized wood fragments in the accompanying sandstones suggest that these rocks represent a nearshore facies of the Topanga formation. Shelton (1955, p. 71) found similar corroborative evidence to the east. Evidently the southern edge of the San Gabriel block has shifted very little since early Tertiary time (cf. Corey, 1954).

It is possible, however, that some of the lavas were expelled from vents or conduits within the mountain block itself, and have since been removed by erosion. Both the

mass of volcanic rocks in contact with the "basement complex" northeast of the city of Glendora (Shelton, 1946, 1955) and the small slide of basaltic debris resting on Wilson quartz diorite east of Doane Canyon near Sunland (Plate I, Figure A) indicate that there may have been a source or sources within the mountains, but no rocks of similar character have been noted north of the San Gabriel fault, either as flow remnants or as dissected plugs or stocks. Miller (1934) mapped a number of small diabase dikes farther north in the San Gabriel Mountains, and although these dikes are discussed in a later section of this report, it is improbable that they once served as feeders for volcanoes.

Less is known of the subsurface geology of the San Fernando Valley. Wells that have penetrated volcanic rocks in this area indicate that these rocks dip generally to the east and thicken in the same direction. They are missing in Richfield Oil Corporation's Pertusati well (No. S-16), which suggests that they pinch out unconformably between it and well No. 30. The structure of the northern edge of the eastern Santa Monica Mountains indicates that the post-Jurassic stratigraphic section dips under San Fernando Valley in a northward direction, and it is thus conceivable that the flows and breccias of the eastern Santa Monica Mountains were once continuous with those encountered in the valley wells.

In summary, if Miocene volcanic rocks underlie the deeper parts of the Los Angeles basin and San Fernando Valley, as indicated on Plate VIII, their total areal extent is approximately 800 square miles. If, however, the major centers of eruption were confined primarily to belts near the principal zones of fracture (as suggested later in this report), it is possible that parts of the basin and valley floors never were covered by these extrusive rocks. Under the latter hypothesis, a reduction of the estimate to 400 or 500 square miles becomes necessary.

If the area of Miocene volcanic rocks on the continental shelf and in the western Santa Monica Mountains is added to the estimate for the Los Angeles basin, a total of nearly 20,000 square miles is obtained. Figure 21 shows offshore localities at which samples of volcanic rocks were dredged from the sea bottom. These rocks are predominantly basalt or andesite, and in most places they are associated with sedimentary rocks of Miocene age (Emery and Shepard, 1945). At present there is no means for determining how much of the shelf area is, or was at one time, continuously underlain by volcanic rocks, but in view of the fact that some of these rocks (i.e., those on San Clemente and Santa Catalina Islands) are lithologically similar to others from the Los Angeles basin, there is every reason to believe that the area constitutes a single, rather large petrographic-volcanic province.

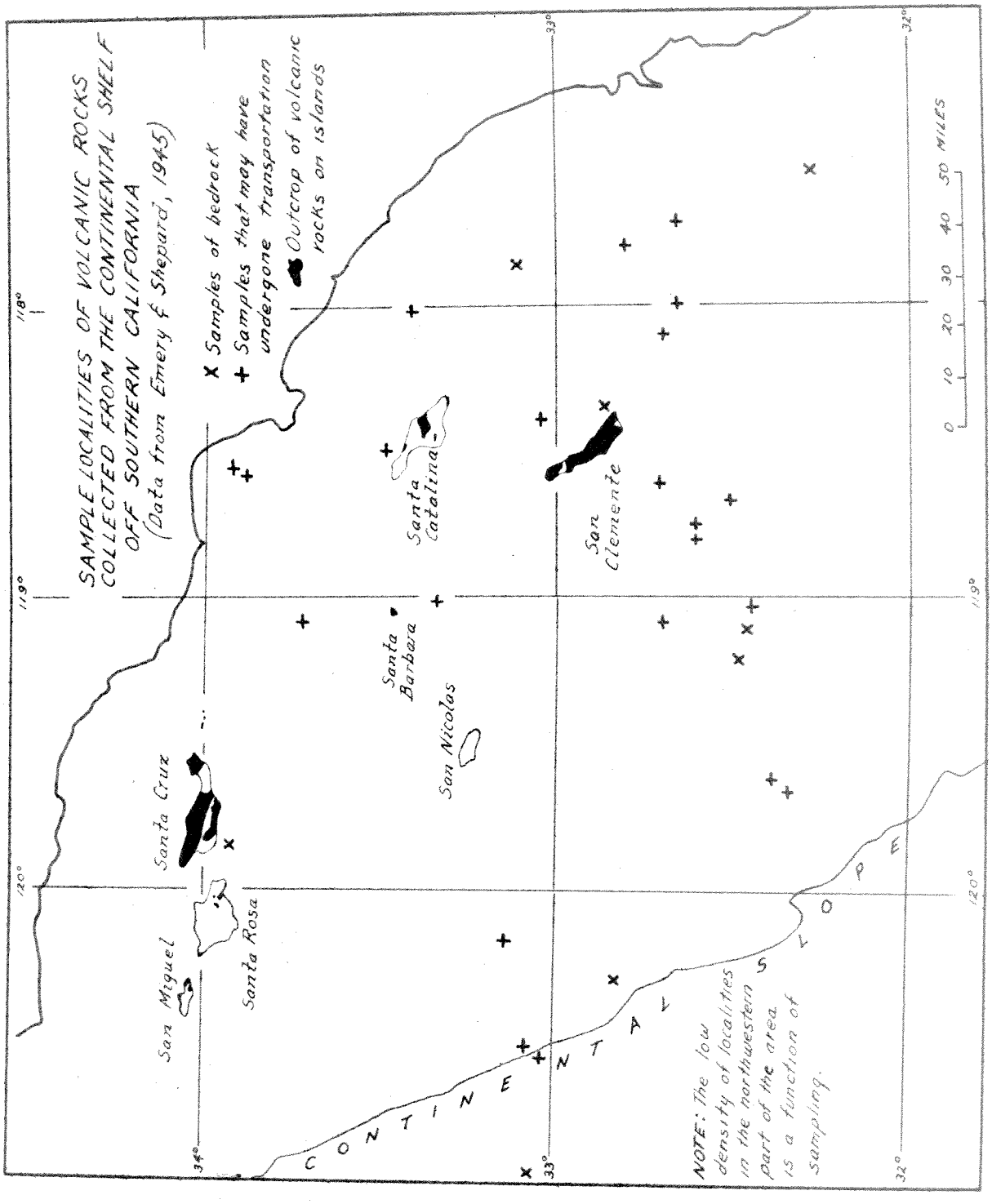


Figure 21. Map showing localities from which samples of volcanic rock were dredged from the continental shelf off southern California.

Thickness and Variations in Thickness

The thickness of volcanic rocks within and marginal to the Los Angeles basin is highly variable, as implied in the previous discussion. A maximum thickness of 3,840 feet was encountered in the Puente Hills during the drilling of the Texas Company's Covina 27-1 well, and a minimum thickness of 40 feet was penetrated near Huntington Beach in Seguro Petroleum Company's Seguro No. 1 well. (Areas in which the rocks are absent are not included.) Unfortunately, most of the wells shown on Plate VIII did not completely penetrate the volcanic section. Even in instances of total penetration, the thicknesses encountered may not represent the total original thickness of the extrusive rocks, for in several areas erosion has bevelled the volcanic pile.

Local variations in the thickness of volcanic rocks are open to any one of the following interpretations: 1) variations due to irregularities of the topographic surface upon which the lavas or pyroclastic materials were deposited; 2) variations due to the growth of cone-like or other volcanic edifices; and 3) variations due to differential erosion or dissection of the volcanic accumulations.

From a consideration of surface and subsurface data collected in the Los Angeles basin, an approximate average thickness of 550 feet was derived for the rocks under

discussion. This is considerably less than Shelton's estimate (1954) of 1,000 feet, but his figure included the unusually thick section (greater than 12,000 feet) in the western Santa Monica Mountains, and, in some instances, applied to "penetrated" thicknesses rather than stratigraphic thicknesses. The estimated thickness of 550 feet, coupled with the areal extent indicated on Plate VIII, leads to an approximate volume of 85 cubic miles. The inclusion of the volcanic rocks in the western Santa Monica Mountains and off the southern California coast increases the average thickness considerably, and expands the figure for the estimated total volume by a factor of 50 or 100.

Local variations in thickness, where accurately known, aid in defining probable centers of eruption. The striking subsurface increase in thickness of the volcanic rocks in the general area of the San Jose Hills, the diversity of rock types occurring there, and the presence of exposed vent-like structures all suggest that this area and the area east of Glendora were at one time sites of impressive volcanic edifices.

Variations in the thickness of the volcanic section in T3S, R11W, indicate that either a volcanic cone formed in the area during the latter half of the Miocene epoch, or that the pre-volcanic topography was such that a thick section of pyroclastic debris accumulated as a valley filling. Independent stratigraphic evidence suggests that at

least part of the thickening was consequent upon the local topography, but the source of the pyroclastic material could not have been far away, for well No. 58 penetrated the greatest thickness of volcanic strata on the east side of the basin south of the Puente Hills.

Elsewhere in the basin, data are insufficient to outline probable eruptive centers. At Dominguez oil field there appears to be an increase in thickness toward the southeast, and near Newport Beach there seems to be an increase toward a possible volcanic center north-northwest of the lagoon, but neither of these "centers" is very well defined.

Lithologic Variations

General statement

As noted in the introduction, the cores from different wells in the basin were studied in varying detail by the writer, depending upon the location of the well, the degree of alteration of the volcanic rocks, their continuity and representation of the volcanic section (as determined from a study of well logs), and the apparent composition of the rocks as determined from well-log descriptions and preliminary hand-specimen examinations.

With the exception of the rhyolite encountered in Standard Oil Company's Baldwin-Cienega No. 105 well, the

volcanic and hypabyssal intrusive rocks in all of the wells in the Los Angeles basin were found to be basalts or andesites of a fragmental or massive nature. It would be inappropriate to list here the detailed description of each hand specimen and thin section examined during the course of this study, and the interested reader is referred instead to Plate VI. The following discussion is limited to general remarks concerning the broader aspects of the lithologic variations.

San Fernando Valley

Cores from wells in San Fernando Valley indicate that the volcanic rocks that occur there are basaltic in composition. In this respect they are similar to the sill exposed in the Santa Susana Mountains to the north, and to the breccias in the eastern Santa Monica Mountains to the southeast. Two textural varieties of the rock were noted: 1) massive, dark gray, phaneritic, amygdaloidal basalt, composed of tiny laths of calcic labradorite, chlorophaeite, and partly altered augite, and 2) basaltic conglomerate, composed of well rounded pebbles and cobbles of dark gray basalt in a coarse, sandy, basaltic, calcite-cemented matrix. Phenocrysts of sodic bytownite were seen in some thin sections, and amygdules of chalcedony were noted in others. The conglomeratic facies probably represents a reworked portion of the underlying massive

flows. The Topanga sedimentary rocks underlying the volcanic rocks contain both ostracods and Turritella ocoyana s.s., indicating a lagoonal environment of deposition. The lavas probably were expelled on the shallow floor of a warm sea. Unlike the eruptions taking place 10 or 15 miles to the southeast, these apparently involved little or no explosive activity.

Inglewood oil field

A study of cores recovered at Inglewood oil field (T2S, R14W) indicates that the volcanic section encountered in well No. 55 is far greater in aggregate thickness than the sections in the other four wells shown on the map. The simplest interpretation (e.g., see Woodford et al., 1954, Plate IA) is that the volcanic rocks in this area are interbedded with thick sedimentary rocks, and that well No. 55 is the only one of the group that penetrated the entire volcanic section. Additional stratigraphic information indicates that some of the rocks may be intrusive in origin, as outlined farther on.

Examination of the uppermost rocks in the series (those encountered in all five of the wells) shows that they are altered basalts or basaltic andesites. Their color ranges from light gray to medium bluish or medium dark gray, depending upon the extent of the alteration. The lighter-colored rocks are the most highly altered,

the color being a function of their high content of carbonate minerals, clay, and pyrite.

Rocks from parts of the section are highly amygdaloidal, with tiny spherical amygdules of calcite, whereas others contain large phenocrystic tablets of glassy plagioclase. The groundmass feldspar in these rocks is chiefly median labradorite. Most of the groundmass is severely altered to chlorophaeite, clays, and pyrite. The last-named mineral also occurs conspicuously in veinlets. Part of the groundmass was originally glassy, and is densely speckled with finely disseminated magnetite or ilmenite. Bead tests of the freshest specimens of this rock indicate that it has a silica content of 53 percent.

It is interesting to note that the observers who first described the cores from wells Nos. 55 and 69 mentioned intrusive relationships with the associated sedimentary rocks. The specific cores in which this phenomenon was observed are no longer available, but other facts seem to bear out this interpretation. In well No. 55 the top of the basalt lies 35 feet below the base of the lower Mohnian "Nodular shale," whereas in well No. 61, less than one mile away, igneous rock was reached only at a distance of 255 feet below this marker unit. Regardless of these criteria, however, it seems unlikely that the entire upper part of the section of "volcanic" rocks is intrusive, for fully 135 feet of it (in well No. 55) is aphanitic in

texture, and the groundmass is partially glassy. An intrusive body of this thickness would probably not be glassy in its central part, even if it were rapidly quenched.

Altered rhyolite from this area was first described by Schoellhamer and Woodford (1951) in their discussion of cores from Standard Oil Company's Baldwin-Cienega No. 105 well (No. 55, Plates VII-IX). These investigators did not make it clear whether the rock represents an intrusive body of Miocene age or part of the "basement complex," because it was found near the base of the well. During the present study, light-colored cores from a point higher in the hole (11, 425 feet) were examined in thin section and found to be similar to the rocks at 12,110 feet, referred to as "greatly altered soda rhyolite porphyry ?" by Schoellhamer and Woodford. Inasmuch as sedimentary rocks of the Topanga (?) formation lie between the horizons at which this rock was encountered, it seems unlikely that it represents part of the crystalline "basement." The rocks at 11,425 feet are composed of phenocrysts of severely altered albite and embayed quartz in a groundmass of subordinate microlites of acid plagioclase and an allotriomorphic-granular mixture of quartz and potash (?) feldspar. Whether or not this rhyolite had an extrusive origin must remain unanswered until further information is available.

None of the volcanic rocks encountered in the Inglewood

field is fragmental in nature; all are massive and generally very fine-grained. Flow banding was noted in cores from two of the wells; it is manifested in color streaks and in the alignment of trains of amygdules.

Dominguez oil field

The volcanic rocks at Dominguez present a distinct textural contrast to those at Inglewood. The rocks penetrated in wells Nos. 88 and 91 are wholly pyroclastic. The thick sequence encountered in well No. 51 consists of massive, amygdaloidal, porphyritic flows, interlayered with coarse tuffs and tuff-breccias. Most of these rocks are basalt, with the possible exception of a few subordinate andesite (?) flows.

Inasmuch as all three of the wells in this area are thought to have penetrated the volcanic section completely, the flows of basalt encountered in well No. 51 must pinch out to the northwest, for they are missing in the other two wells. The volcanic section thins in that direction also. These facts suggest that a volcanic source lay to the southeast, possibly along the Newport-Inglewood uplift. Shales interbedded with the volcanic rocks indicate that, during the period of eruption, the area lay beneath the sea.

The tuffs and breccias range in color from medium bluish gray to dark greenish gray, and are considerably

altered. Under the microscope they are composed of angular lapilli of basaltic glass with microlites of median to calcic labradorite. The glass has been replaced by olive-colored chlorophaeite, and much granular pyrite is present. Few of the fragments are vesicular. Many of them show flow alignment of the feldspar microlites, suggesting that the lava had partially congealed before explosive eruption took place.

The massive flows, which indicate occasional quiet effusions of lava, range in color from medium gray to black, but altered samples are greenish gray. They consist principally of basalt that is amygdaloidal and locally porphyritic. Secondary calcite and pyrite are common.

Puente and San Jose Hills

The greatest thickness of volcanic rocks encountered by drilling in the vicinity of the Los Angeles basin was found in the San Jose Hills. Because of the close proximity of these rocks to outcrops of the Glendora volcanic series, Shelton studied and described them in detail (Shelton, 1955, Table 3, pp. 82-87). His descriptions reveal that their lithologies are similar to those of the Glendora volcanic rocks exposed to the north and east: "calcic andesite," "fine-grained andesite," hornblende andesite, augite andesite, basalt, and tuffs and tuff-breccias of similar composition. Additional data were

compiled during the course of the present investigation from areas to the southeast and southwest (wells Nos. 34, 49, 50, 79, 80, and 81).

Wells Nos. 79, 80, and 81 are located at the southern edge of the San Gabriel Valley. All of them bottomed in volcanic rocks, and the few cores that were recovered indicate that the youngest rocks in the section are basaltic andesites or basalts. They are medium to olive gray, porphyritic flows and breccias. Phenocrysts of calcic labradorite predominate, although areas of pyrite-rimmed calcite suggest the original presence of ferromagnesian phenocrysts as well. The groundmass is predominantly a smoky brown glass with finely disseminated "ore" and crystallites of plagioclase. Bead tests of one specimen indicate that the rock has a total silica content of 55 percent. The breccia facies is finely amygdaloidal, and is cemented by coarsely crystalline calcite.

Approximately ten miles to the east, wells Nos. 34, 49, and 50 encountered basalt. In the two wells that penetrated the volcanic section completely, the entire sequence was found to consist of this rock. In all three wells, a small percentage of basaltic breccia was noted, but for the most part the section comprises fresh, massive flow rocks that are aphanitic, locally porphyritic, and amygdaloidal.

The flows are commonly dark gray to grayish black,

though some are greenish gray and a few are dark red. They are composed of calcic labradorite, augite, ilmenite, and altered olivine. Phenocrysts, where present, consist of altered olivine, labradorite, or both. Amygdules comprise calcite, chlorophaeite, and natrolite (?). Bead tests of one flow indicate that the rock has a total silica content of 48 percent. Mineralogically and texturally, these rocks bear a strong resemblance to the olivine basalt of the eastern Santa Monica Mountains.

The breccia is dark gray to pale olive gray, and consists of angular fragments of basaltic glass with microphenocrysts of altered median labradorite. Amygdules and portions of the original glass have been replaced by fibrocrystalline chlorophaeite.

Although wells Nos. 34, 49, and 50 lie within four miles of outcrops of volcanic rock in the northern part of the Puente Hills, the cores which they yielded show a striking compositional contrast to the rocks exposed there. The predominant lithology of the outcrop area is rhyolite, although Shelton (1955, p. 56) mentioned a subordinate fine-grained basalt that crops out at the western edge of the area. The cores from wells Nos. 79, 80, and 81 consist of basaltic andesite and to the south, well No. 27 passed successively through an intrusive body of diabase, some underlying middle Miocene sedimentary rocks, and a thick section of basalt believed to be extrusive in origin.

These data indicate that the predominantly andesitic rocks of the Glendora volcanic series give way southward to more mafic rocks of equivalent age.

Intrusive rocks of the Whittier fault zone

It is interesting to note that the first Tertiary igneous body to be described in the literature pertaining to the Los Angeles basin is the one that has received the least attention in subsequent years. Since the original mention of diabase near Brea Canyon by Eldridge and Arnold (1907), only English (1926) and Woodford et al. (1944) have referred to it in print. This diabase is exposed at the surface and encountered in wells along a belt extending for a distance of 15 miles parallel to the Whittier fault, north of the cities of Whittier, La Habra, and Yorba Linda.

Outcrops of this rock occur near the western edge of Brea Canyon, where they consist of altered vesicular diabase. This diabase is dark in color, and locally exhibits a chilled margin approximately 14 inches wide. Vesicles are arranged in zonal fashion parallel to the contact. Elsewhere, in the subsurface, the rock is coarser grained, and ranges in composition from gabbro to augite diorite. The name Whittier diabase is herein proposed to include all of these bodies and their minor lithologic variations.

Surface exposures of the diabase occur near well No. 45, the highest point on the irregular branching body. The local structural disregard of the diabase for the stratification of the sedimentary rocks is noteworthy. In certain places it is concordant and sill-like, but elsewhere it cuts across the bedding structure.

The close geographic relationship between the steeply dipping Whittier fault and the wells in which diabase was encountered is illustrated in Plate VII and Figure 33. Well No. 29, south of the fault, also penetrated diabase. The dense spacing of wells that yielded cores of diabase and the parallelism of trend between this group of wells and the Whittier fault, coupled with the fact that bodies of diabase were not encountered farther north or south, suggest that the diabasic magma utilized the lower part of the fault as an access-way during its emplacement. At shallower depths, where the load of superincumbent rocks was less, the magma was able to spread laterally in the form of sills between strata of upper Miocene (Mohnian) age.

Several of the wells encountered brecciated and altered diabase within the zone of the fault. Brecciation probably took place during renewed (Pliocene or post-Pliocene) movement along the fault.

The utilization of pre-existing faults by magma in the process of ascent has been noted elsewhere in the

region (Plate V; Durrell's map, 1954; and Plate I, Figure A). This relationship is not surprising, particularly in the instance of faults with root zones that extend deep into the crust. It is noteworthy that the other major fault zone of the region (Newport-Inglewood) is geographically associated with most of the other wells that encountered rocks of intrusive origin (see Plate VII). This string of wells extends from the San Joaquin Hills to the Inglewood oil field, and includes wells Nos. 6, 2, 21, and 39, in addition to those in the Inglewood field that reportedly penetrated discordant bodies of igneous rock. The spacing of these wells is not as close as it is along the Whittier fault and thus the sampling of the rocks is not as good, but their principal mode of emplacement was probably the same.

Of the twelve wells along the Whittier fault from which stratigraphic information is available, seven indicate that the diabase intrudes Mohnian sedimentary rocks. Well No. 3 encountered upper or middle Mohnian Foraminifera in strata immediately above an intrusive body, and thus a lower age limit of middle Mohnian is established for the period of intrusion. An upper limit has not been determined, but considering the fact that post-intrusive movement took place along the fault, and that lower Pliocene breccias south of the fault include fragments of upper Miocene Puente sedimentary rocks (Woodford et al., 1954,

p. 75), it is possible that the diabase is no younger than Pliocene. Nowhere does it cut rocks as young as Delmontian. In all probability it was emplaced during the Mohnian stage of the Miocene epoch. In this respect it has the distinction of being the only igneous body of undisputed post-middle Miocene age in the region.

The Whittier diabase is chiefly dark gray to greenish gray in color, and is composed of calcic labradorite, augite, and ilmenite. Locally it is porphyritic. In well No. 53, rocks that contain partially altered olivine, subordinate red hornblende, and small amounts of biotite were encountered. The hornblende and biotite are interpreted as alteration products of titaniferous augite that is also present. In the interval between wells Nos. 53 and 46 the igneous rock is coarser grained and varies in composition from augite diorite to gabbro. It consists of plagioclase (calcic andesine or labradorite-bytownite), augite (altered in part to chlorite, nontronite (?) and biotite), magnetite or leucoxenized ilmenite, and apatite.

Extrusive rocks near the Whittier fault zone

Associated with the group of wells in which the Whittier diabase was encountered are several wells that penetrated rocks of apparent extrusive origin. There is a large tract of land in T2S, Ranges 9 and 10 W, where no deep wells have been drilled, but it is assumed that the

volcanic rocks are continuous from the area of wells Nos. 50, 34, 78, and 81 to wells Nos. 93, 7, 20, and 90.

Well No. 20 penetrated tuffs and tuff-breccias described by Shelton (1955, Tables 1 and 2) as palagonite-bearing. Cores from well No. 93 are medium dark gray in color, and severely altered. They are basaltic or andesitic in composition, and altered remnants of labradorite (?) phenocrysts were seen in thin section. No samples from well No. 7 were available.

Twelve miles to the southeast, well No. 90 penetrated both diabasic intrusive rocks, and two thin units of volcanic (?) rock interbedded with middle Miocene sandstones. The latter igneous rocks are tentatively considered to be extrusive, on the basis of a high percentage of glass. The upper unit consists of microlites of sodic labradorite in an altered vitric groundmass, and the lower unit consists of phenocrysts of augite and altered olivine (?) in a groundmass of median labradorite, altered glass, and ilmenite.

The Leffingwell area

The wells of the Leffingwell area lie immediately west of the Coyote Hills, near La Mirada Creek. They represent one of the most important groups of wells in this study, for they are closely spaced and furnish good stratigraphic control. Most of them penetrated the entire

volcanic sequence. Despite these favorable factors, however, the age of the upper part of the sequence involves some questions.

Wells of the southwestern part of this group (wells Nos. 12, 13, 14, 15, and 16) encountered volcanic rocks of the lowest part of the sequence only. These rocks include bluish gray to olive black flows of glassy or phaneritic, amygdaloidal olivine basalt, and dark bluish to greenish gray breccias. Many of the rocks are altered, and veinlets and vesicle fillings of calcite are common. The breccias are restricted primarily to the base of the section, indicating that volcanic activity in the area began explosively and later changed to more quiet effusions.

The other wells in the group (wells Nos. 56, 57, 58, 59, 63, 66, and 71) penetrated basaltic rocks that are principally fragmental. Paleontological data suggest that at least the lower part of the section in these wells is stratigraphically equivalent to that in the wells just described (Nos. 12-16) despite the textural contrast displayed by the rocks. Only the dark greenish gray olivine basalt in well No. 63 is non-fragmental, and like the rocks in the wells to the southwest, it appears to be older than the volcanic strata in the immediately adjacent wells.

Well No. 57 yielded the most complete set of cores,

although it bottomed within the volcanic section. It penetrated olive gray to greenish black, altered, pyritiferous, olivine-bearing basaltic breccia and tuff-breccia. A subordinate facies of olive gray-amygdaloidal basalt, or basaltic andesite, also was encountered, but it represents only a small fraction of the section. The lithic fragments of the breccia are composed of calcic labradorite, augite, ilmenite, and wholly altered olivine. Vitric fragments have been altered to chlorophaeite or a fibrocrystalline derivative of chlorophaeite. Part of the cementing material of the breccia is analcite, and part is calcite. The rocks are surprisingly similar to those of the eastern Santa Monica Mountains. They indicate that basaltic lavas are as liable to violent gaseous distention as acid or intermediate lavas, although statements to the contrary frequently appear in the literature.

Anaheim-Santa Ana-Orange area

The wells in the Anaheim-Santa Ana-Orange area are scattered between outcrops of the El Modeno volcanic series and wells of the Leffingwell area, described above. Without exception they lie south of the probable location of the sub-alluvial trace of the Norwalk fault (see Plates VII and VIII). The group includes wells Nos. 1, 24, 36, 43, 65, 67, 68, 72, 73, 74, 82, 84, 85, 87, 89, and 92.

The wells in T4S, R10W encountered olive and dark

gray basaltic tuffs, tuff-breccia, and fine-grained flows. These rocks are in places amygdaloidal. The angular fragments of the breccia attain a maximum diameter of 3½ inches. Locally, the basaltic tuffs are palagonitic, but generally they are altered to a soft, olive green material that is partly chlorophaeitic. Thin-section studies of the ash fragments showed them to be highly vesicular. The freshest of the massive flows are dark gray in color and contain small phenocrysts of olivine, altered to pyrite, and an impure iron-bearing clay. Some of the rocks have the composition of olivine basalt, but the plagioclase in others indicates that they are basaltic andesites.

The wells in T4S, R9W penetrated rocks similar to those that crop out in the El Modeno Hills east of Orange. Cores of the volcanic rocks from this area are few in number; the most complete sequence was collected at well No. 67 (Standard Oil Company's Taft Community No. 1-1). The lowest part of the sequence consists of medium olive gray basaltic tuff, like that encountered in wells five miles to the west. The tuffaceous material is vesicular to frothy, and consists of altered basaltic glass, cemented by analcite and other zeolites. It is overlain by flows of amygdaloidal, porphyritic volcanic rock, breccia, and shale. The flows consist of medium dark gray olivine-bearing basaltic andesite ("calcic andesite" of Yerkes, 195_). Phenocrysts of calcic labradorite, augite, and

altered olivine occur in a glassy groundmass that contains microphenocrysts of hypersthene and an unidentified clinopyroxene. The interbedded sedimentary rocks are Foraminiferal brown shales, which indicate that the volcanic rocks are submarine in origin. These shales also were encountered in other wells in the area.

The relatively coarse-grained texture of the olive gray basalt and diabase encountered in wells Nos. 72 and 87 is suggestive of an intrusive origin. Basaltic dikes were noted by Yerkes (op. cit.) in the El Modeno Hills, and it is possible that these rocks are genetically related to the dikes.

Southeastern Los Angeles basin

The rocks in the southeastern part of the Los Angeles basin show lithologic variations that are surpassed only by the Glendora volcanic rocks to the north. Wells in this area encountered flows and breccias of basalt, hypersthene-augite andesite, and hornblende-augite andesite. Breccias composed of mixed volcanic and "basement" material also were found. The hypersthene-bearing rocks are strikingly similar to the rocks that crop out in the neighboring San Joaquin Hills, and there is little doubt of their original continuity. Cores were available from only four of the 17 wells that penetrated extrusive rocks, but original well-log descriptions from the others indicate that

rocks of a similar nature were encountered.

Well No. 60 is one of the few that passed through the entire volcanic section. Near the base of the sequence are dark gray, amygdaloidal flows, interbedded with bluish gray tuff and breccia, but the major part of the section consists of medium gray to light bluish gray andesite breccias and tuff-breccias. Fine-grained fragmental rocks grade upward into coarser ones. The andesite fragments are of two types: hypersthene-augite andesite and hornblende-augite andesite. Both rocks are composed of nearly 64 percent of silica. The hornblende is a basaltic hornblende, and the augite is pale green in color. Both of these features are common in this part of the basin only. Interbedded diatomaceous shales and sandstone in the lower part of the sequence indicate a submarine accumulation of the volcanic rocks. One core of tuffaceous sedimentary rocks encloses a large fragment of carbonized wood.

Approximately 2¼ miles to the northwest, well No. 4 encountered the same sequence: massive, dark gray flows of hypersthene-augite andesite overlain by bluish gray andesitic tuff-breccias. North of these wells, wells Nos. 8 and 18 penetrated more basic rocks: dark gray to reddish brown breccias, palagonite tuffs, and minor flows of basalt. Marine sedimentary rocks are interbedded with the volcanic rocks, and testify to their submarine origin. In well No. 8, sandstones directly overlying the volcanic

rocks contain fragments of the latter, indicating a reworking by waves.

To the west, wells Nos. 22 and 41 penetrated rocks reported to be "dark gray-green basalt" and "light gray tuff." Well No. 62, between Huntington Beach and Seal Beach, encountered a section consisting entirely of light bluish gray to medium gray hypersthene-bearing andesite breccia and tuff-breccia, identical with the rocks encountered in well No. 60. Here and there, these fragmental volcanic rocks contain sporadic clasts of schist, and it is possible that part of them represent Miocene mud flows. It has been suggested that some of this material is equivalent to the San Onofre breccia of Woodford (1925). The latter is composed primarily of clastic debris from the so-called "Western Bedrock complex," an area of glaucophane-bearing schist that at one time was emergent off the present coast of southern California.

Age Relationships

Variations in the age of the volcanic rocks encountered in the subsurface and exposed in correlative outcrop areas are shown in Plate IX. This plate summarizes the present state (1955) of stratigraphic knowledge concerning each well and outcrop, and groups together the areas in which igneous activity was contemporaneous. The grouping is not the product of age data alone, but includes

correlations based on lithological and chemical data as well. It represents one of the principal goals of the present investigation.

It is not the writer's intent to summarize in this section all of the data relating to the determination of the time of volcanism in the Los Angeles basin, but rather to point out some of the problems and characteristics peculiar to this determination as approached through the use of subsurface information.

A total of 94 wells is included in Plate VI. Of these wells, 28 encountered rocks known or thought to be intrusive, either wholly, or in part. With respect to the wells that penetrated known or probable extrusive rocks, 32 passed entirely through the volcanic sequence and bottomed in underlying sedimentary rocks or pre-Tertiary "basement" rocks. Of these, 22 encountered rocks above and below the lavas for which it was possible to determine an age, either on the basis of paleontologic or lithologic data. Nothing is known of the age of the sedimentary strata immediately overlying and underlying the volcanic rocks in eight other wells.

A total of only nine wells encountered Foraminiferal strata interbedded with the volcanic sequence (wells Nos. 7, 8, 12, 16, 17, 18, 57, 67, and 91). Three of these (wells Nos. 7, 67, and 91) present stratigraphic problems that preclude an exact determination of the age of the

volcanic rocks. Well No. 7 penetrated zones of gouge in the vicinity of the extrusive rocks, indicating the probable presence of a fault. Well No. 67 passed through sedimentary rocks (within the volcanic section) typical of the La Vida shale member of the Puente formation, and although this shale contains arenaceous Foraminifera, they are not diagnostic as to age. Well No. 91 penetrated beds definitely identified as Mohnian by the Union Oil Company, and although this age assignment has previously been incorrectly referred to well No. 88 by other investigators, there still is a general reluctance on the part of some geologists to accept the determination at face value, for the Foraminifera on which it is based reportedly were partially crushed.

The range in age between the sedimentary strata overlying and underlying the volcanic rocks in the Los Angeles basin varies from well to well. In well No. 28, for example, the rocks beneath the volcanic section are Mesozoic in age, whereas those above it are Luisian. At the other extreme, the basaltic breccia in well No. 58 is underlain by Luisian beds and overlain by Mohnian beds. Data from exposures and wells in which the age of the volcanic rocks was determinable within close limits enabled the writer to make an appraisal of the age of the lavas encountered in those wells in which the stratigraphic section exhibited significant gaps. Interpolations of age were based on the proximity of control points (wells or surface exposures)

to the wells in question, and on careful lithologic correlations of the volcanic rocks. The results of this work are shown in the age groupings of Plate IX; all of these groupings are believed to be internally consistent as to age. They indicate that, although the stratigraphic data from certain wells (i.e., those that encountered unconformities) are open to several interpretations regarding the age of the volcanic rocks, extrusion of most of the lava in the Los Angeles basin took place during middle Miocene time, or at the latest, during the early part of late Miocene time.

There has been considerable reluctance on the part of many geologists working in the Los Angeles basin to accept the existence of Mohnian or younger volcanic activity. During the last few years, several examples of supposed Mohnian volcanism have been pointed out, but in almost every instance there has been enough ambiguity in the stratigraphic data to warrant serious questioning of their reliability. Two examples of unquestioned post-middle Miocene igneous activity are the Whittier diabase and a thin bed of basaltic tuff that is present in the lower part of the Puente formation in Brea Canyon. The diabase is known to have intruded Mohnian sedimentary rocks, and therefore must be Mohnian or younger in age. The tuff, which is exposed just north of the Orange County-Los Angeles County line, is interbedded with Mohnian

sedimentary rocks, and, interestingly enough, crops out only a mile or so northeast of the wells in which the diabase was encountered (Woodford et al., 1944).

The data from well No. 67 (Standard Oil Company's Taft Community No. 1-1) are typical of an example of igneous activity of questionable late Miocene age. Immediately overlying the volcanic rocks in this well is a dark brownish gray, laminated shale containing fish scales and arenaceous and calcareous Foraminifera. The calcareous Forams indicate conclusively that the shale is of Mohnian age. From both its lithology and its faunal assemblage, it is recognized as the La Vida member of the upper Miocene Puente formation, and it occurs above volcanic rocks in several neighboring wells. At approximately 10 feet, and also at 30 feet below the top of the volcanic pile, an identical brownish gray shale is interlayered with the extrusive rocks. At these horizons the shale contains fish vertebrae and scales, and arenaceous Foraminifera like those in the strata overlying the volcanic rocks. Lithologically it is identical with the La Vida shale, but it contains no calcareous Foraminifera indicative of the Mohnian stage. According to W. H. Holman (personal communication, 1954), arenaceous Foraminifera are not uncommonly found in Mohnian and younger rocks in the Los Angeles basin, but they are practically unknown in strata of Luisian and Relizian age. One might infer therefore, that

the uppermost flows of volcanic rock in this well are Mohnian in age. The number of examples of middle Miocene (Relizian or Luisian) volcanic activity encountered elsewhere in the basin weighs heavily against this inference, however. Proponents of the "middle Miocene school of volcanism" can point to the lack of diagnostic Mohnian faunas in these intercalated shales, but it should be noted that there are no diagnostic Relizian or Luisian faunas in the beds, either. Inasmuch as sediments of identical composition were deposited both during the period of volcanic activity and afterward, during a period of time known to be Mohnian, and inasmuch as similar arenaceous Foraminifera and fish scales are found in both these sedimentary sections, the writer believes that the dying phases of volcanism may well have continued until early Mohnian time.

The data from well No. 57 (Standard Oil Company's Emery No. 87) pose a similar problem. A short distance below the top of the volcanic sequence, siltstones interbedded with the volcanic rocks have yielded Luisian Foraminifera. In well No. 58, nearby, sedimentary rocks underlying the basaltic breccias also have yielded a Luisian fauna, which indicates rather clearly that at least the lower three-fourths of the volcanic sequence is Luisian in age. The sedimentary strata overlying the volcanic pile are indicative of the Mohnian stage, and thus the age of the upper part of the sequence could be either

Luisian, Luisian-Mohnian transitional, or Mohnian. Wells Nos. 63 and 16, to the east and southwest of well No. 57, respectively, encountered Luisian strata overlying extrusive rocks, which suggests that the upper part of the volcanic sequence is also Luisian. However, further investigation has revealed that the volcanic rocks in wells Nos. 63 and 16 are lithologically dissimilar to those in well No. 57. In the first two wells, flows of olivine basalt predominate; in the latter, the principal rock is pyroclastic basaltic breccia. Furthermore, detailed electric-log correlations indicate that the position of the upper part of the basaltic breccia in well No. 57 is correlative with the lower Puente sandstone in well No. 63 (J. W. Higgins, personal communication, 1955). This correlation is based on strata above and below the volcanic rocks, both in the wells under consideration and in others to the east, in which the effusive rocks are absent but in which the sedimentary section is complete. This would appear to indicate a Mohnian rather than Luisian age for the upper part of the basaltic breccia in well No. 57. Unlike most sedimentary rocks, however, a moderately thick section of volcanic rocks can accumulate in an infinitesimally short period of geologic time, and hence an electric-log correlation based on the stratigraphic position of a volcanic unit does not uniquely define its age in terms of the sedimentary strata overlying or underlying it.

None of the evidence bearing on the age of these volcanic rocks is clearly definitive.

Three other wells encountered volcanic rocks that might be interpreted as being of Mohnian age. If zones of gouge are indicative, well No. 7 (Continental Oil Company's Buehler No. 1) encountered Miocene volcanic rocks in the vicinity of a fault. The stratigraphic sequence in this well was found to be, in descending order: Mohnian sedimentary rocks-volcanic rocks-Mohnian sedimentary rocks-Luisian sedimentary rocks-volcanic rocks-Relizian sedimentary rocks. According to the interpretation of Daviess and Woodford (1949), a low-angle normal fault cuts these strata, and the upper volcanic rocks represent a slice within this fault, and hence are not necessarily of Mohnian age. Well No. 20 encountered Mohnian sedimentary strata above and below volcanic rocks that are sheared and severely altered. According to J. S. Shelton (personal communication, 1954), however, the lower surface of these rocks is bounded by a fault. Well No. 93 penetrated dark brown shales below moderately altered volcanic rocks, and although this shale is lithologically similar to the upper Miocene La Vida member of the Puente formation, no microfossils of Mohnian age were found in it.

In the Dominguez oil field, well No. 91 (Union Oil Company's Hellman No. 58) penetrated beds of black shale in the middle of a section of altered basaltic tuff and

breccia. Mohnian Foraminifera reportedly were recovered from this shale, but in view of the weight of evidence of middle Miocene volcanic activity elsewhere in the region, the determination of the age of these microfossils has been discounted by some investigators. It is difficult to evaluate this criticism, or to defend the original determination. If other, clear-cut examples of local Mohnian volcanism were known, there undoubtedly would be less scepticism in this instance, as well as in the others described in the preceding paragraphs. So far as the writer is aware, there is no obvious physical reason why the closing phases of volcanic activity in the Los Angeles basin could not have continued until the beginning of the Mohnian. The existence of the Whittier diabase indicates that the basaltic magma was ascending toward the surface as late as the middle Mohnian, or perhaps even later. It is thus conceivable that there were surface manifestations of igneous activity at this time also.

In the five other wells in which fossiliferous strata were found to be interbedded with the volcanic rocks, middle Miocene Foraminifera were recovered. This evidence, together with the fact that many other wells in the region encountered Luisian or Relizian Foraminifera in the sediments overlying the effusive rocks, indicates clearly that most of the activity in the basin took place during the middle Miocene. It is almost certain that none took place earlier

in the Tertiary (with the possible exception of the eruption of Mountain Meadows dacite) and certain, also, that none occurred later than the Mohnian, excluding from consideration the thin-bedded rhyolitic tuffs discussed in a later section of this report.

Correlation with Outcrop Areas

An interpretation of the descriptive data included in the foregoing pages is presented graphically in Plate IX. The volcanic rocks have been divided into seven geographic groups. San Fernando Valley, and the mountains to the north, east, and south, constitute one of these groups; the area around Inglewood constitutes another; that near Dominguez, a third; the Palos Verdes Hills a fourth; and the general area along the southwestern coast, including the San Joaquin Hills and the region near Costa Mesa, a fifth. The volcanic rocks in the northeastern area of the basin are divided into two parts by the Whittier diabase, north of the Whittier fault. The area to the south comprises that of the El Modeno volcanics, the region near Santa Ana, Orange, and Anaheim, and the western end of the Coyote Hills. The area to the north includes the Puente and San Jose Hills, and the foothills of the San Gabriel Mountains near Glendora. Inasmuch as the rocks in these two areas differ in lithology as well as age, their division by the Whittier fault and associated

diabase is of real significance.

The volcanic rocks of the San Fernando Valley and the surrounding mountains are uniformly basaltic in composition. Olivine basalt crops out in the Santa Susana Mountains, the eastern Santa Monica Mountains, the Pacoima Hills, and the area near Sunland. The rocks beneath the valley floor are basaltic also, but they do not contain modal olivine. Other rocks in the group include olivine-bearing basaltic andesite and subordinate hypersthene-bearing basalt. The age of these rocks is Relizian, but in the Santa Monica Mountains and near the town of Sunland as well, later intrusive activity followed the eruption of lavas. The time of this later activity has not been satisfactorily established, but nowhere do the dikes and sills cut strata younger than those of the middle Miocene Topanga formation.

The volcanic rocks encountered at depth in the Dominguez and Inglewood oil fields differ from one another in lithology (non-fragmental rhyolite and basalt or basaltic andesite at Inglewood; tuffs and breccias of basalt at Dominguez) and apparently also in age. Sedimentary rocks underlying the volcanic strata and interbedded with them at Inglewood are of a transitional Relizian-Luisian age, whereas those at Dominguez are reportedly Mohnian.

A characteristic lithologic feature of the volcanic rocks near the coast is the presence of the mineral

hypersthene. Hypersthene-augite andesite crops out in both the Palos Verdes and San Joaquin Hills, and also was encountered in several wells in the intervening area (e.g., wells Nos. 4, 60, and 62). Volcanism in the San Joaquin Hills and adjacent areas to the west began during the late Relizian and continued until the beginning of the Luisian. The shallow intrusive pépérites of the Palos Verdes Hills were emplaced during the early part of the Luisian.

Rocks of the El Modeno volcanic series are related to the extrusive rocks encountered in the subsurface to the west and northwest. Close to the Santa Ana Mountains these buried rocks are lithologically similar to the El Modeno rocks (olivine basalt and basaltic andesite), but farther west and north they grade laterally into breccias of basalt. Sedimentary strata of Luisian age are interbedded with the effusive rocks, and indicate that part of the volcanic activity in this area took place in the late middle Miocene. At some localities Mohnian strata overlie the volcanic rocks, suggesting that activity persisted at least until the beginning of the Mohnian.

The predominantly andesitic Glendora volcanic rocks grade southward in the subsurface into rocks of a more basaltic composition. Luisian sedimentary rocks overlie the buried lavas and breccias, and are interbedded with or underlie the exposed extrusive rocks, indicating that volcanic activity in this part of the basin took place during Luisian time.

DIKES IN THE PRE-TERTIARY BASEMENT COMPLEX POSSIBLY RELATED TO MIOCENE VOLCANIC ACTIVITY

The plutonic and metamorphic rocks of the San Gabriel, Verdugo, and eastern Santa Monica Mountains are cut by many dikes of pegmatite, aplite, and diabase, and by less abundant dikes of rhyolite, malchite, and dacite. The dikes of pegmatite and aplite probably are related to one or more cycles of pre-Tertiary plutonic igneous activity, as is the malchite described by Neuerburg (1953, p. 14). Little work has been done on any of these dikes, as they are scattered over a wide area and are volumetrically unimportant. According to the present state of knowledge, the malchite bodies are restricted to the eastern Santa Monica Mountains, and the dacite bodies to the San Gabriel Mountains near Glendora.

With the exception of the Glendora area, where dikes of diabase cut the middle Miocene Glendora volcanic series, none of these intrusive bodies traverses rocks younger than the "basement complex." Thus there is no way of determining an upper age limit for them or of establishing a firm correlation between the dikes and the volcanic rocks under discussion. Petrographically, the diabase of the dikes is not unlike the olivine basalts in the Los Angeles basin, and it may be genetically related to them. The dacite dikes near Glendora were discussed by Shelton (1955, p. 69), who considers them to be related possibly

to the pre-Glendora Mountain Meadows dacite.

Miller (1934) mapped abundant diabase dikes in the western San Gabriel Mountains. Many of these dikes are scattered randomly throughout the range, but some of them are clustered in a narrow belt parallel to the San Gabriel fault. Specimens of this diabase were collected from several of the dikes near the front of the range between San Gabriel Canyon (west of Glendora) and Sunland. They range from dark greenish gray, severely altered, porphyritic diabase to fresh, dark gray olivine basalt. The altered facies contain phenocrysts of plagioclase, replaced by albite (?), calcite, and clay, and an unidentified ferromagnesian mineral replaced by calcite and penninite, in a groundmass of plagioclase, ilmenite, penninite, and subordinate epidote. Unaltered facies consist of euhedral phenocrysts of olivine (8 percent), marginally altered to bowlingite (?) and biotite, in a groundmass comprising 40 to 45 percent of calcic labradorite, 20 to 25 percent of clinopyroxene, 10 percent of olivine, 5 percent of magnetite, and subordinate apatite, biotite, and chlorophaeite. Amygdules filled with natrolite (?), and veinlets filled with calcite and quartz occur locally. The trace-element composition of the freshest of these rocks is similar to that of the flows of olivine basalt at Sunland.

Northwest of Chilao Flats, in the western San Gabriel

Mountains, a swarm of crudely parallel dikes of porphyritic rhyolite is exposed. The rock is chalky white in color, and is texturally distinct from aplite exposed nearby. Phenocrysts, which are not abundant, consist of euhedral quartz, orthoclase, and albite-oligoclase. The groundmass is composed of a mixture of potash feldspar and quartz, accompanied by subordinate shreds of muscovite. Aside from rare clumps of tiny garnet crystals, no ferromagnesian minerals were noted in the rock. Reconnaissance mapping of the dikes failed to reveal a pattern of convergence that might indicate the presence of a volcanic center, and aside from their compositional similarity to the volcanic rocks at the northern tip of the Puente Hills, these dikes offer no evidence of a relationship with the Miocene volcanic rocks of the Los Angeles basin.

If cones or other volcanic peaks once dotted the crest of the San Gabriel Mountains, no trace of their former presence remains. Shelton (1955, p. 69) encountered apparent vent-like structures in the Glendora area, but they are close to the front of the range and to outcrops of the Glendora volcanic rocks. As a group, the dikes described above are far too small and too few in number to account for surface manifestations of volcanic activity, and it seems extremely improbable that they coalesced upward to form feeders of larger magnitude.

RHYOLITIC TUFFS

Beds of fine-grained vitric tuff abound in the Miocene stratigraphic section of southern California. They are common not only in the middle and upper Miocene Monterey shale and its stratigraphic equivalents, but also in Miocene continental beds on the north side of the San Gabriel Mountains (Tick Canyon and Mint Canyon formations). Their widespread geographic distribution and general stratigraphic persistence indicate the existence of continuously active volcanic sources. Their significance in this discussion is one of origin: what is their relationship to the Miocene flows and coarser pyroclastic rocks of the Los Angeles basin?

Detailed stratigraphic studies have revealed that although the tuffs are most abundant in middle and upper Miocene strata, they are by no means restricted to this part of the section. The oldest tuff studied during the course of the present investigation came from exposures of the Vaqueros formation (lower and lower middle Miocene) in the Santa Ana Mountains. The youngest occurs in the Pleistocene Saugus formation in Bear Canyon, west of Fillmore, California (northwest of the area under discussion). Between these extremes of Cenozoic age are other tuffaceous rocks, all of similar lithologic character. A selected group is described in Table 4.

Host Formation	Age	Locality	Lithology	Remarks
Vaqueros	Early to early middle Miocene	Peters Cyn.Rd., Santa Ana Mts.	Shards of clear, colorless glass< .10 mm. in diameter, aggregate R.I. = 1.486-1.490. Accompanied by grains of plagioclase, biotite, and pale green pyroxene. Color: light yellowish gray.	Collected by J. E. Schoellhamer.
Monterey (Altamira mem.) (Portuguese tuff)	Early middle Miocene (Relizian)	Klondike Cyn., Palos Verdes Hills	"Light colored" bentonitic ash; no data on petrography.	Thickness: 55 feet at type locality. Source of information: Woodring et al. (1946,p.18).
Monterey (Altamira mem.) (Miraleste tuff)	Late middle Miocene (Luisian)	Aqua Negra Cyn., Palos Verdes Hills	Dark brown pumice lapilli (R.I.=1.54_), max. diameter one inch, in matrix of light colored vitric shards (R.I.=1.50_). Partially bentonitized.	Maximum thickness eight feet. Source of information: Woodring et al. (1946, p.19).
Topanga	Middle Miocene (Relizian?)	South of Fascination Springs, San Gabriel Mountains (Sunland quadrangle)	Fragments of clear, colorless glass, .03 mm. in diameter, R.I. =1.498. No mineral fragments present. Color: white.	

TABLE 4. RELATIONS OF TERTIARY RHYOLITIC TUFFS IN COASTAL SOUTHERN CALIFORNIA

Host Formation	Age	Locality	Lithology	Remarks
Topanga	Middle Miocene undivided	East of El Modeno, Orange County	Shards of colorless glass, R.I.=1.504, accompanied by grains of biotite, plagioclase, magnetite (?) and rarely, quartz. Color: white.	Yerkes (195_) described this and other tuffs in the area in detail.
Modelo	Early late Miocene (Mohnian)	Road cut west of Hansen Dam, San Fernando Valley	Predominantly vitric ash, altered to "bentonite." Relic shards have R.I.=1.475 to 1.495. Very fine-grained. Color: white.	
Puente (Modelo)	Late late Miocene (Delmontian)	Court Street, immediately above Hill St. tunnel, city of Los Angeles	Clear, colorless fragments and rods of glass and pumice, .05 to .15 mm. in diameter, R.I.= 1.511. No mineral constituents present. Unconsolidated and friable. Color: yellowish gray.	Collected by W. H. Holman
Repetto	Lower Pliocene	Malaga Cove, Palos Verdes Hills	Light colored vitric ash, in beds 6 inches thick. No data on mineralogy or refractive index of glass.	Source of information: Woodring et al. (1946,p.41).

TABLE 4. Continued

Host Formation	Age	Locality	Lithology	Remarks
Saugus	Pleistocene	NW 1/4 sec. 28, T.4N.,R.20W., (Fillmore quadrangle)	Shards and fragments of glass and pumice, .15 mm. in diameter, R.I.=1.503. Accompanied by tiny, angular fragments of sodic plagioclase, quartz, magnetite, altered ferromagnesian mineral(s), and biotite (?). Fine-grained matrix of colorless or pale yellow glass, partially devitrified, R.I.=1.504 to 1.510. Color: yellowish gray.	Collected by W. H. Holman

TABLE 4. Continued

Refractive indices of the glass of the least altered tuffs range from approximately 1.511 to 1.488. According to the data of George (1924), this corresponds, approximately, to a range in silica content of 68 to 75 percent, indicating glass of rhyodacitic or rhyolitic composition. A review of the Miocene volcanic rocks in the Los Angeles basin reveals that the only ones of similar composition are the Elephant Hill breccia in the Puente Hills, a felsitic rhyolite in the San Jose Hills, and the altered soda rhyolite encountered in Standard Oil Company's Baldwin-Cienega No. 105 well. Together, these rocks constitute less than three percent of the total volume of lavas and pyroclastic rocks in the basin, indicating that rhyolitic differentiates played an insignificant role in the local volcanic activity.

In the central Coast Ranges of California rhyolitic rocks of Miocene age are associated with olivine basalt and other basic and intermediate rocks, but the relative percentage of rhyolite is considerably greater than it is in the Los Angeles basin. Taliaferro (1943a) described several thousand feet of rhyolitic tuff, augite andesite, and olivine basalt, accompanied by sills of diabase and plugs of rhyolite porphyry, in the San Luis Obispo-Huasna region (150 miles northwest of Los Angeles). He also mentioned a belt of large plugs of rhyolite porphyry at the crest of the Santa Lucia range. Thus the fact that

rhyolitic ash in the Los Angeles basin is associated with a group of predominantly intermediate and basic volcanic rocks does not exclude the possibility that the ash is genetically related to these flows and breccias, but the relative proportion of rhyolitic tuffs to local rhyolitic pipes and plugs suggests that some of the ash may have originated elsewhere.

The structure at Elephant Hill probably marks the site of a former volcanic vent (Shelton, 1955), yet beds of rhyolitic tuff are not notably abundant or unusually thick in the surrounding area.

Although the tuffs under discussion are compositionally unlike the bulk of the volcanic rocks in the area, they closely resemble one another. If they are the products of a single volcanic source, this source had a much longer life span than any of the vents in the vicinity of Los Angeles, for the tuffs range in age from lower Miocene or lower middle Miocene to Pleistocene, whereas volcanic activity in the basin had all but ceased by the end of late middle Miocene (Luisian) time.

Most of the samples of tuff that were studied are fine-grained, and except in the Miraleste bed, coarse pumiceous material was not found. There also appears to be a low percentage of admixed crystal or lithic debris in these tuffs, although the one near El Modeno is an exception. It is possible, therefore, that much of the ash may

have travelled a considerable distance before settling in the basin, for the denser rock and crystal fragments of composite ash generally attain higher terminal velocities of fall, and are selectively sorted out during windborne transportation.

On the basis of the evidence presented above, it is concluded that not all of the rhyolitic tuffs in late Tertiary and early Quaternary sedimentary rocks in coastal southern California are related to volcanoes that were active in the immediate vicinity of the Los Angeles basin. A few thin beds of middle Miocene ash may have had their source at these vents, but there is no way of distinguishing them from beds representing ash that was transported to the area by the wind. The provenance of this tuffaceous material is therefore problematical.

A review of the geology of regions surrounding the Los Angeles basin reveals that volcanic activity was more or less continuous during the latter half of the Tertiary period in two specific areas: the Mojave Desert, northeast of the basin (Figure 22), and the central Coast Ranges, northwest of the basin (Figure 23). Detailed studies of the effusive rocks of the Mojave region are far from complete, but the recent summaries of McCulloh (1954) and Hewett (1954) are adequate for the purposes of the present discussion.

As far as is known, the oldest Tertiary volcanic

rocks in the Mojave Desert are flows of andesite exposed in Antelope Valley (see Figure 22). They lie beneath continental sedimentary rocks that are supposedly correlative with Miocene marine beds farther west. Older flows and breccias of andesite and basalt of Oligocene (?) age are exposed in the Soledad basin nearby (Vasquez formation), but this area properly belongs to the Tranverse Range province rather than the Mojave Desert. The Calico Mountains, in the central part of the desert, contain crudely stratified beds of dacitic and andesitic tuff and tuff-breccia that are unconformably overlain by the middle and upper Miocene Barstow formation. This formation consists primarily of arkosic sedimentary rocks, but includes interbedded tuffs and lavas of an andesitic composition as well.

Records of lower Pliocene volcanic activity are preserved in the El Paso Mountains, where andesite breccia and olivine basalt flows are intercalated with sedimentary strata of the Ricardo formation, and in the Avawatz Mountains where the so-called "Avawatz beds" consist in part of pumice and other volcanic debris. Middle Pliocene andesite and dacite flows and tuffs are exposed in the Lava Mountains near Randsburg.

Olivine basalt of questionable Pleistocene age has been reported at Black Mountain, north of Hinkley. Recent eruptions are indicated by cinder cones and craters at

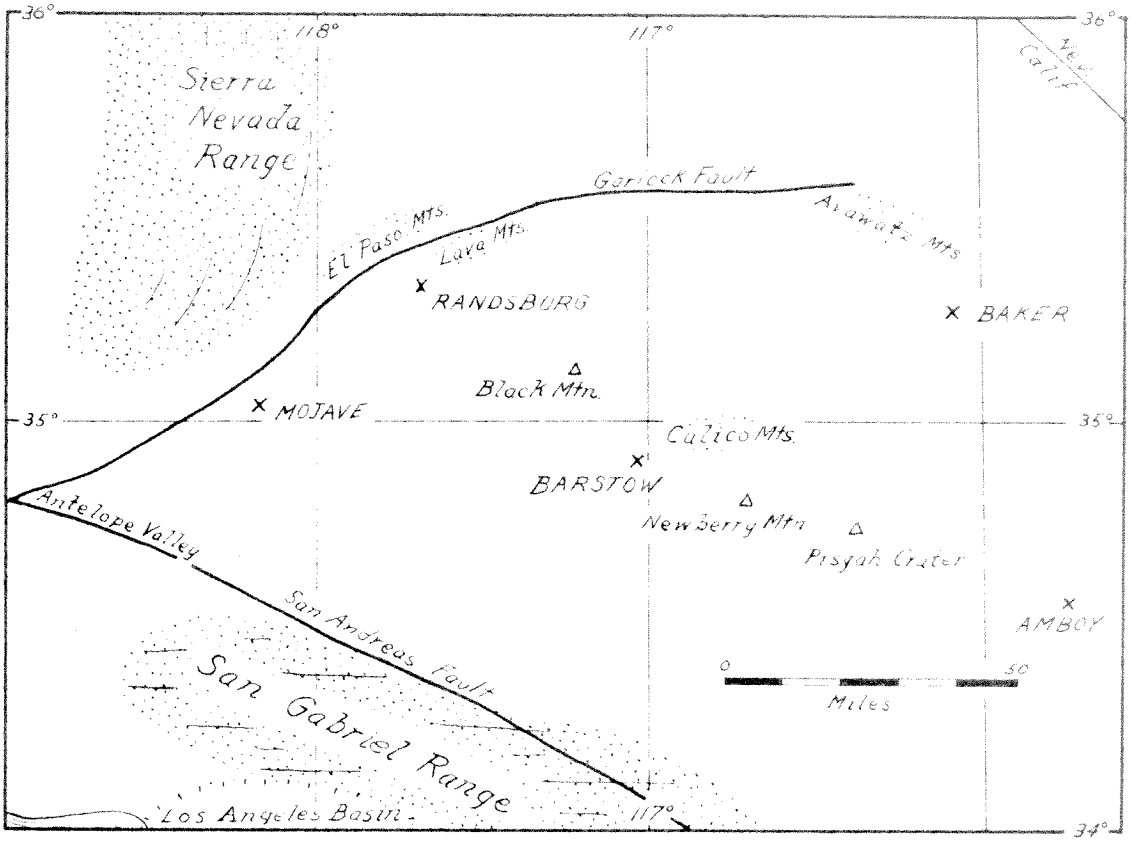


Figure 22. Index map of the Mojave Desert, showing localities referred to in text.

Pisgah Crater, Newberry Mountain, and east and southwest of Amboy. The cones are undeformed and have undergone little erosion.

In addition to these extrusive rocks, shallow-seated dikes, plugs, and sills occur both in the Calico Mountains and in the area near Randsburg. They consist variously of basalt, andesite, dacite, latite, and rhyolite. Some of the plugs are as much as 4,000 feet in diameter.

The Cenozoic volcanic record of the Mojave Desert thus indicates that local eruptive activity began shortly before middle Miocene time and continued intermittently to the Recent. The relative percentage of rhyolitic rocks in this area is small, but considerably more petrographic work needs to be done before the area can be dismissed from consideration as a possible source of the rhyolitic ash in the Los Angeles basin.

As mentioned earlier, the sequence of volcanism in the central Coast Ranges was summarized by Taliaferro (1943a). The oldest record of local effusive activity is found in the Eocene Domengine and Kreyenhagen formations near San Francisco Bay and along the west side of the San Joaquin Valley (see Figure 23). The volcanic rocks consist primarily of dacitic and rhyolitic ash, partially altered to bentonite.

In the Mount Diablo and San Francisco Bay regions, the Kirker formation of Oligocene age contains more than 100

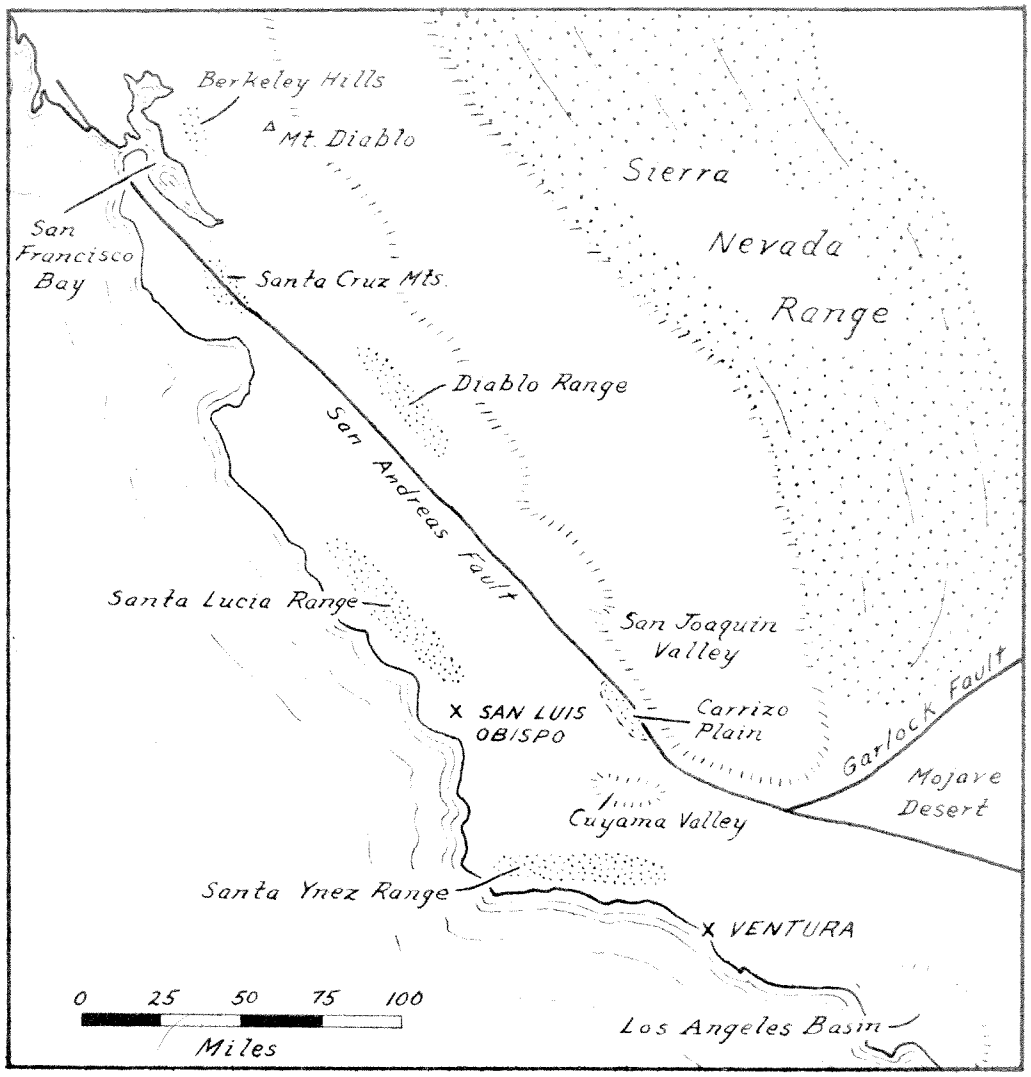


Figure 23. Index map of part of the California Coast Ranges, showing localities referred to in text.

feet of rhyolitic tuff, but elsewhere evidence of Oligocene volcanic activity is lacking. Evidently a period of near dormancy prevailed until the beginning of middle Miocene time, when violent eruptions of ash took place in the vicinity of San Luis Obispo. In this area, ash accumulated to a depth of several hundred feet. Bramlette

ispo tuff, and stated that it thins to the southeast and pinches out near Ventura. Dibblee (1950) correlated the Tranquillon volcanics of the western Santa Ynez Range with the Obispo tuff because the two lie in close proximity to each other, and are both of late Saucesian (late early Miocene) age. The Tranquillon rocks consist of rhyolite flows, agglomerates, and tuffs. Probable correlatives include basalt and basaltic agglomerate in the Santa Rita Hills.

According to Taliaferro (op. cit., p. 140), "over most of the Coast Ranges volcanic activity did not begin until after the beginning of middle Miocene sedimentation." Middle and upper Miocene volcanic rocks are too numerous to describe. Prominent areas include the Santa Lucia Range, Santa Cruz Mountains, Berkeley Hills, Cuyama Valley, San Luis Obispo Valley, and the Carrizo Plain. The rocks comprise tuffs, flows, and intrusive plugs of rhyolite, flows and breccias of olivine basalt, and sills of analcite diabase. Taliaferro (op. cit.) also stated that middle and upper Miocene strata throughout the region contain at

least a small percentage of volcanic ash, and that these beds are not confined to the vicinity of eruptive centers.

Evidence of Pliocene volcanism is lacking in places, but abundant flows and pyroclastic rocks of andesitic and basaltic composition, and brecciated necks of rhyolite are present in the San Francisco Bay region. Occurrences of Pleistocene lava are limited almost entirely to olivine basalt exposed in the Santa Lucia and Diablo ranges, and near the edge of the San Joaquin Valley south of Pacheco Pass.

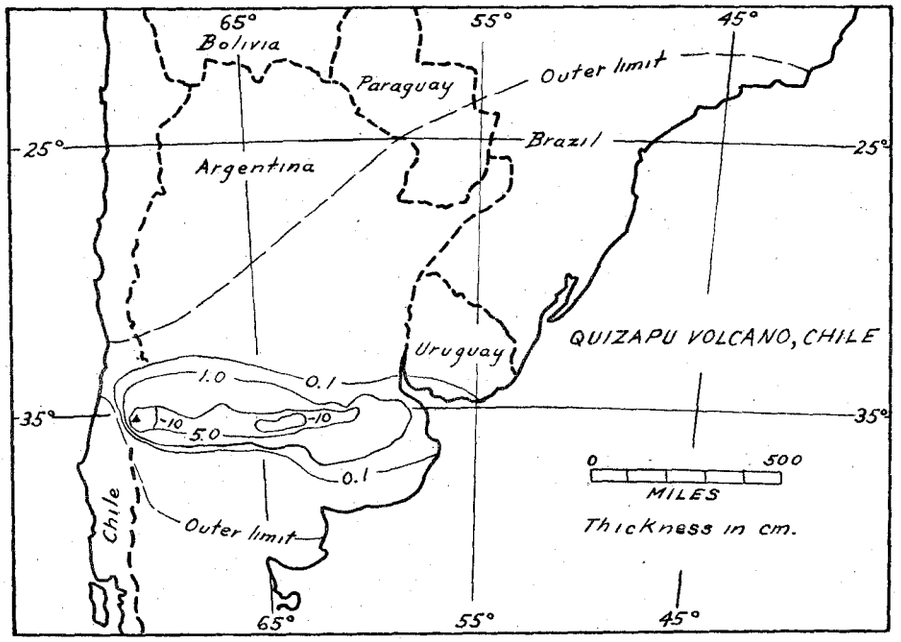
In the central Coast Ranges, as in the Mojave Desert, the time span of volcanism is more than adequate to account for the age range of the rhyolitic tuffs observed in the Los Angeles basin. If the material in the basin were derived from volcanoes in one of these two regions, however, it was dependent upon the wind as an agent of transportation.

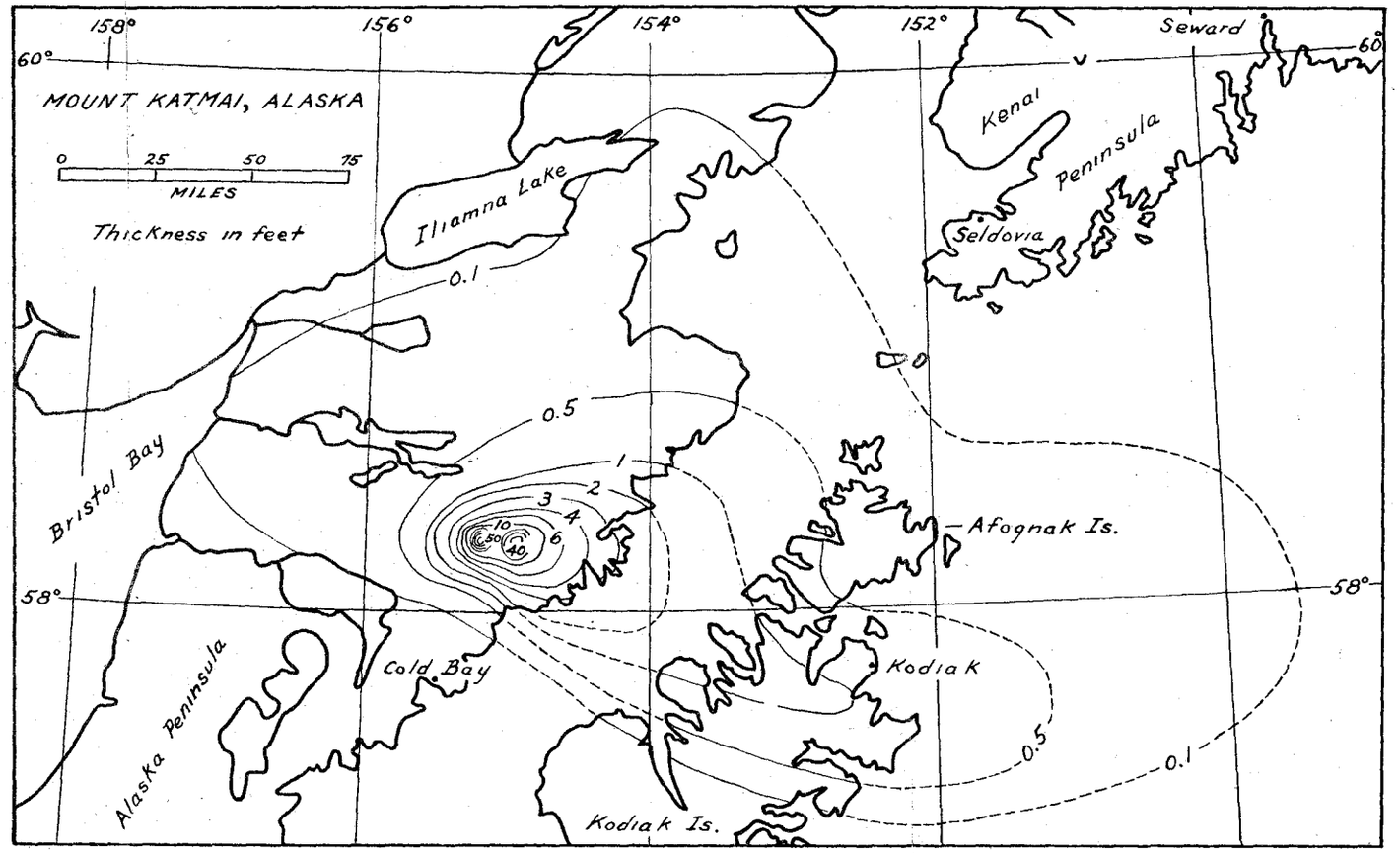
Observations of explosive eruptions of volcanoes in many parts of the world indicate that the direction of the wind at the time of eruption is highly important in the resulting geographic distribution of volcanic ash (see Frontispiece). Historic eruptions that have shown this particularly well include the following:

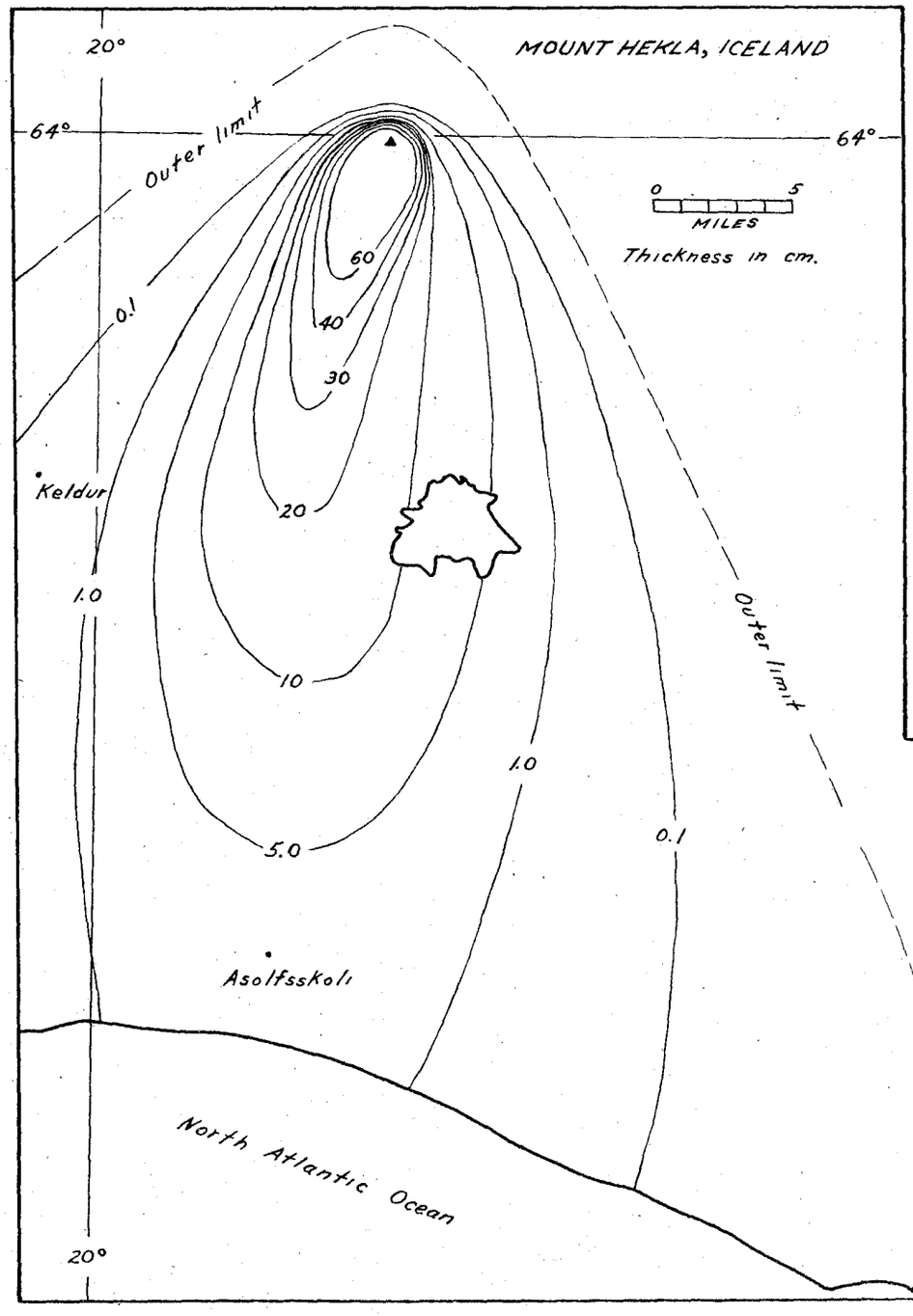
Volcano	Location	Year	Source
Mt. Hekla	Iceland	1947	Thorarinsson (1950)
Katmai	Alaska	1912	Martin (1913)
Komagatake	Japan	1929	Kozu (1934)
Quizapu	Chile	1932	Larsson (1935)
Mt. Ruapehu	New Zealand	1945	Beck (1950)
Mt. Spurr	Alaska	1953	Juhle and Coulter (1955)

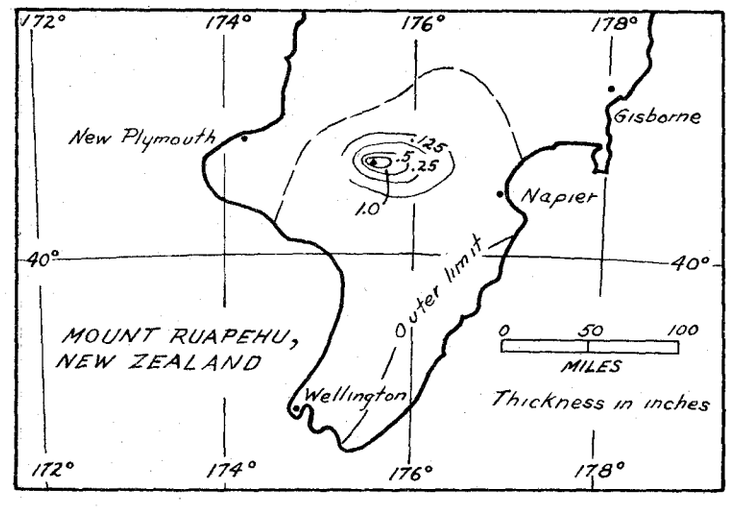
The distribution of ash from five of these volcanoes is shown in Figure 24, along with that from a volcano on the Alaska-Yukon Territory boundary (Capps, 1916). (Note that the map scales and units of thickness vary from figure to figure.) A considerable range in the magnitude of these eruptions is indicated, for the ash from Mt. Natazhat (?) accumulated to a thickness of one foot at a distance of 200 miles from the volcano, whereas that from Mt. Ruapehu accumulated to a thickness of only one-eighth of an inch at a distance of 45 miles. The descriptions of Martin (1913, p. 148) and Thorarinsson (1950, p. 161) portray the effect of the wind in transporting volcanic ash. Concerning the eruption of Katmai, Martin stated:

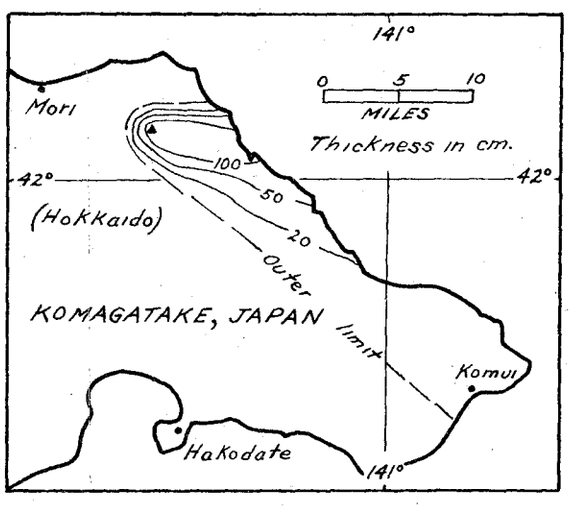
> The material hurled into the air by the explosions... ascended to great heights and travelled east under the influence of the prevailing wind in a succession of clouds. The coarser material began to fall at once, but so great was the total volume of material that the clouds travelled several hundred miles before very considerable amounts of dust had ceased to fall and before they ceased to spread absolute darkness over the land and sea.











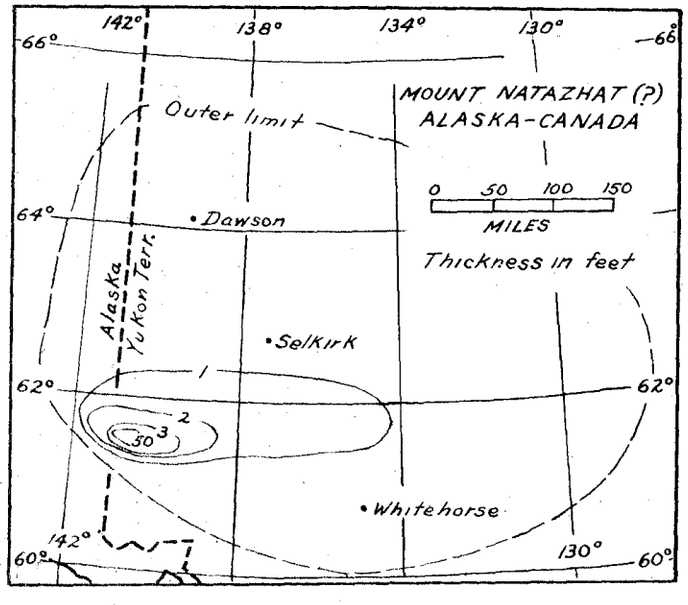


Figure 24. Isopach maps showing thickness and distribution of wind-borne volcanic ash from six historic eruptions. The predominance of ash east of the volcanoes reflects the importance of westerly winds at high altitudes in these areas. Note that map scales and units of thickness vary from figure to figure. Data from Beck (1950), Capps (1916), Griggs (1922), Kozu (1934), Larsson (1935), and Thorarinsson (1950).

Thorarinsson, who observed the eruption of Mt. Hekla, stated:

> As the wind was blowing from north, the erupted pumice and ash were carried southwards...During the two first hours of the eruption about 180 million cubic meters of ash, pumice, bombs and scoriae were whirled from the fissure...According to a report from the British trampship "Sacramento," which was located in the Atlantic 820 kms. south of Hekla, the ashfall there amounted to 30 tons per square km. Dust from Hekla was transported in the upper layers of the troposphere to Finland, where it began to fall about 40 hours after the eruption had begun.

Assuming that much of the rhyolitic ash in the Los Angeles basin was carried into the area by the wind, the first step in determining the source of this ash is to establish the direction of the "prevailing" winds of the region. Winds in most areas are capricious, in that they show short-period fluctuations in direction about the mean. Thus a determination of the "prevailing" or resultant wind of an area has a significance that is no greater than the constancy of the wind as measured statistically. This constancy is sometimes defined as the frequency (measured as percentage of time) with which the wind blows in a direction within 45 degrees of its modal direction. The data of Mintz and Dean (1952) indicate that at sea level, the constancy of the wind along coastal southern California is approximately 60 in July and 40 in January. At the 500 millibar level (3.1 miles above sea level) the constancy is 50 in July and 70 in January.

The direction of the wind is dependent upon three factors:

1) The direction of the maximum pressure gradient

2) A deflecting force (Coriolis) resulting from the rotation of the earth

3) Surface friction with the land and sea

At increasing altitudes above the earth, the influence of friction decreases and the winds tend to become geostrophic, that is, they tend to flow more nearly parallel to the isobars (lines of equal pressure). Likewise, the influence of the relative distribution of oceans and continents (which has a pronounced effect on the direction of the pressure gradient) also becomes less at higher altitudes, and hence there is a tendency for the development of directionally more steady winds. The well-known westerly "jet stream" reaches its maximum strength approximately 7.4 miles above the earth, at 27°N. in winter and 42°N. in summer (Mintz and Dean, 1952).

The importance of upper-level winds in the transportation of volcanic ash cannot be overemphasized. Table 5 gives figures for the maximum elevation of ash-laden clouds of 12 observed eruptions. A complete range of elevations from 3.5 to 18.0 miles is indicated. It should be stressed, however, that these figures represent the maximum elevation of the top of the cloud, and in most instances, the general elevation of the top of the cloud was less. For example, the cloud issuing from Mt. Hekla reached a relatively

Volcano	Locality	Date	Elevation* of top of cloud in miles
Mt. Pelée	Caribbean Sea (Is.of Martinique)	December 16,1929	3.7±
Sakurashima	Japan	January 12,1914	3.7
Paricutin	Mexico (Michoacan)	March 18-24,1943	3.7 - 5.0±
Komagadake	Japan (Honshu)	November 16-18,1942	5.0
Vulcano	Mediterranean (Is.of Vulcano)	January 6,1889	6.0+
Komagatake	Japan (Hokkaido)	June 17-19,1929	7.5±
Mt. Vesuvius	Italy	April 8,1906	8.1
Mt. Spurr	Alaska	July 9,1953	13.2+
Mt. Hekla	Iceland	March 29,1947	16.7+
Colima	Mexico (Jalisco)	March 7,1903	17.0±
Krakatao	Dutch East Indies	August 26,1883	17.0±
Santa Maria	Guatemala	October 24,1902	18.0±

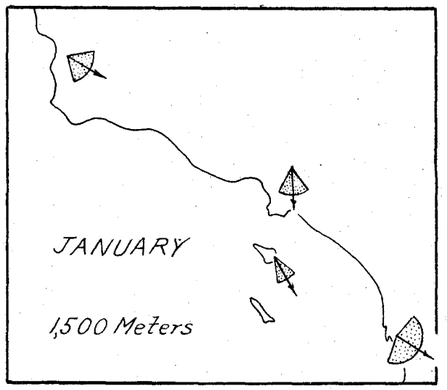
TABLE 5: MAXIMUM HEIGHT OF ASH-LADEN CLOUDS FROM OBSERVED VOLCANIC ERUPTIONS

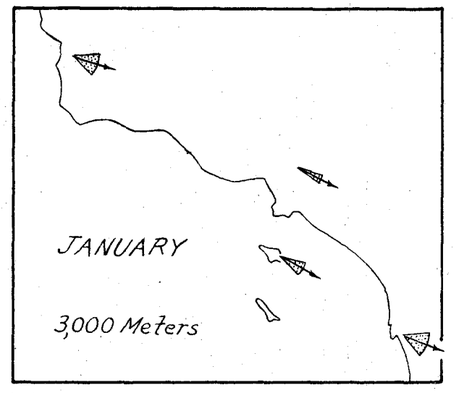
* Figures vary in reliability; obtained by triangulation, aerial observation, estimation, or measurements from photographs by various investigators.

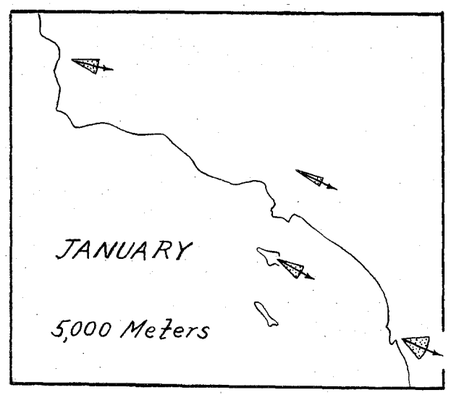
steady-state condition 6.2 miles above sea level after having attained a maximum elevation of 16.7 miles. Clouds reaching 6.0 miles in elevation in the middle latitudes are capable of feeding a considerable amount of ash into the jet stream, provided that they are nourished from below.

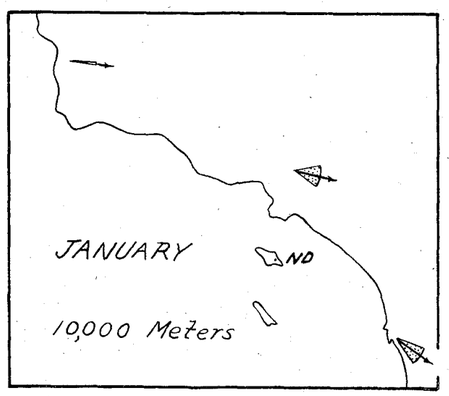
The resultant winds at four scattered weather stations in southern California are shown in Figure 25. The data on which the figures are based were taken from pilot balloon and rawin (radar) wind observations of the U. S. Weather Bureau. These data are published monthly by the Bureau as Climatological Data - National Summaries. Resultant wind directions are shown at four altitudes above each station, 1,500 meters (.93 miles), 3,000 meters (1.86 miles), 5,000 meters (3.1 miles), and 10,000 meters (6.2 miles). In general, the number of observations at the 10,000 meter level is meager. The arrow at each station represents a median resultant wind direction, and the width of the sector represents the directional range of extreme resultant winds. The months of January, April, July, and October were selected as being representative of the four seasons of the year.

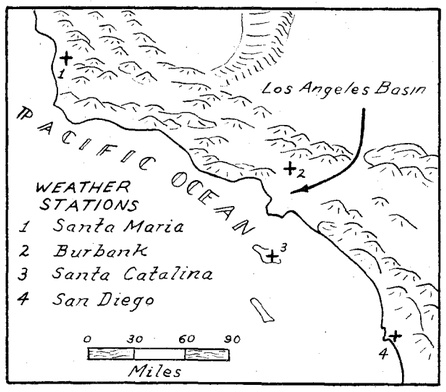
There is a well defined seasonal shift of the upper level winds from northwesterly in winter to southwesterly in summer. This shift is in direct response to the relative proximity of the so-called Pacific and Bermuda "highs,"



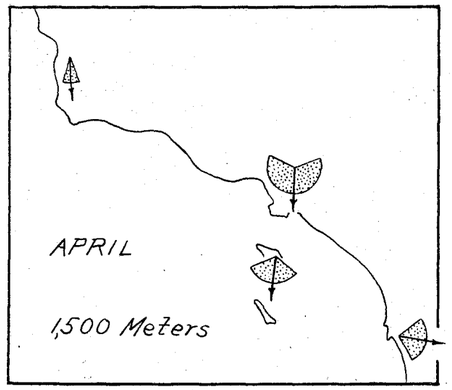


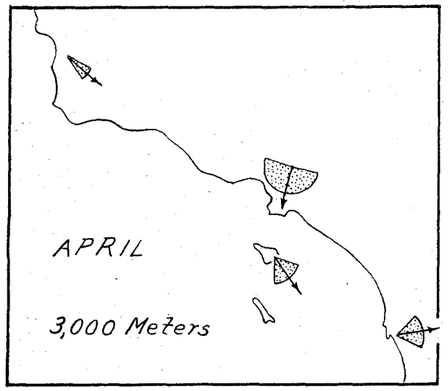


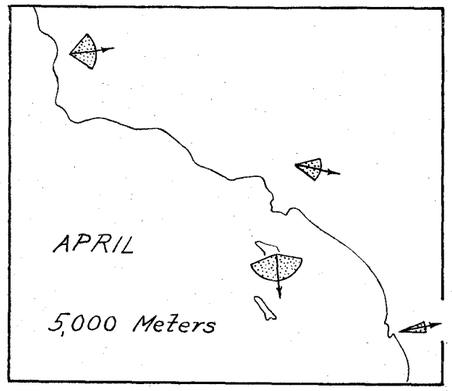


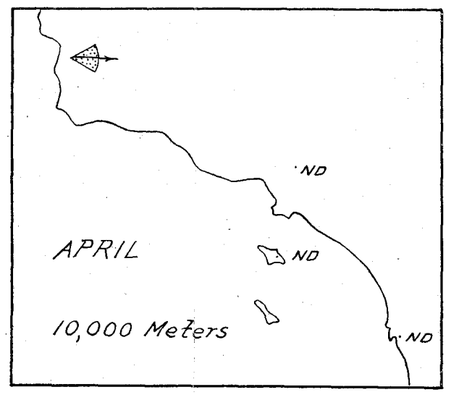


Index Map





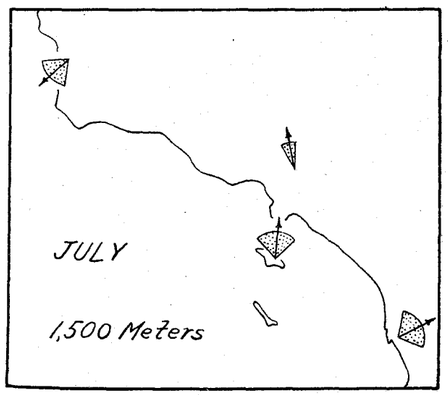


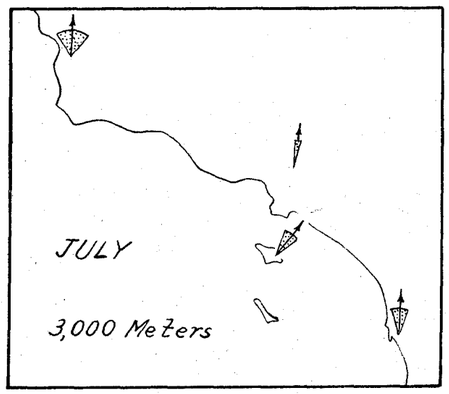


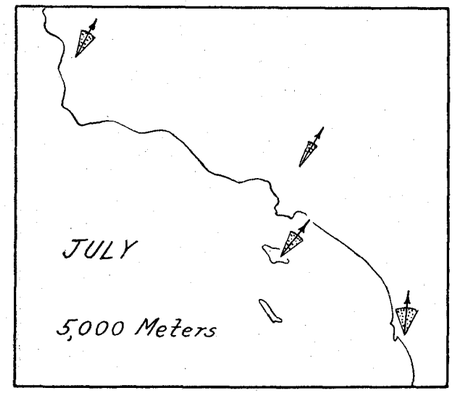
Wind directions over southern California based on pilot balloon observations and rawin data.

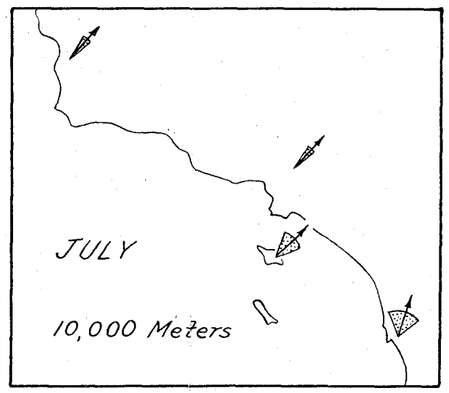
Resultant winds are shown at four altitudes. Width of sector indicates extreme variations of resultant winds during five year period 1950-1954, inclusive. Data largely from U. S. Weather Bureau's Climatological Data National Summary, Vols. 1-5. ND indicates no data.

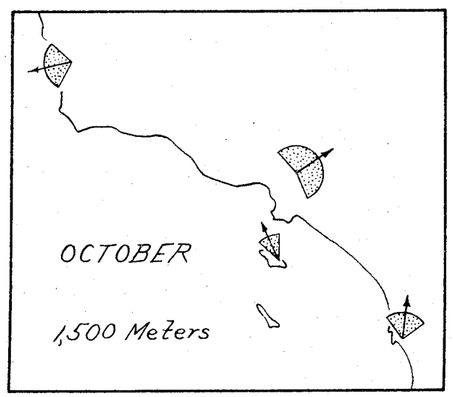
Figure 25

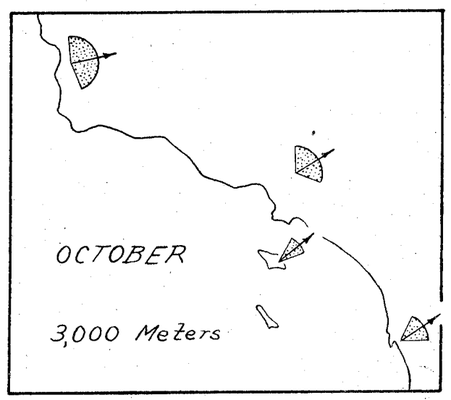


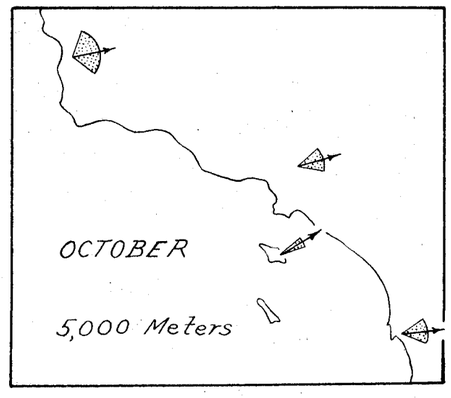


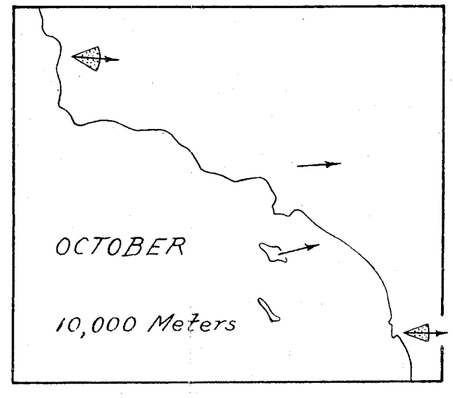










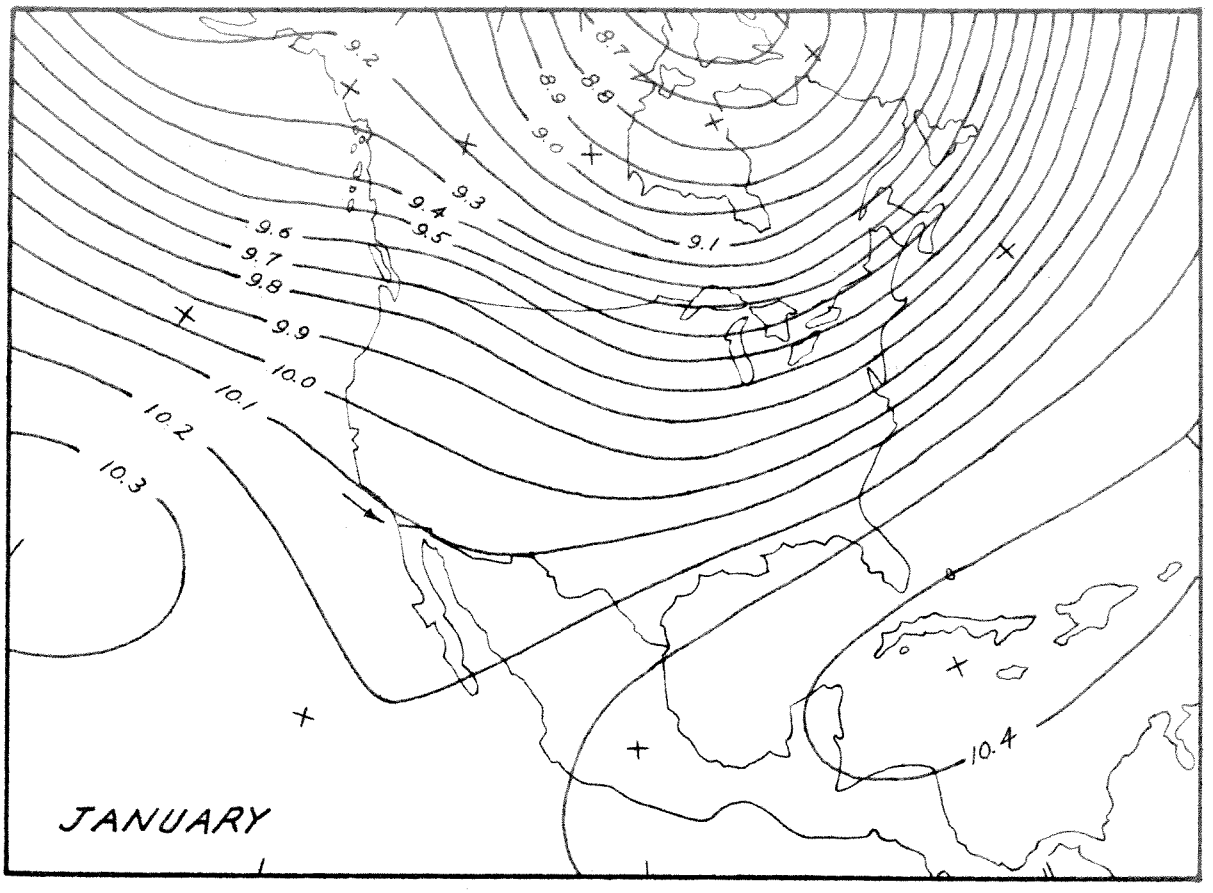


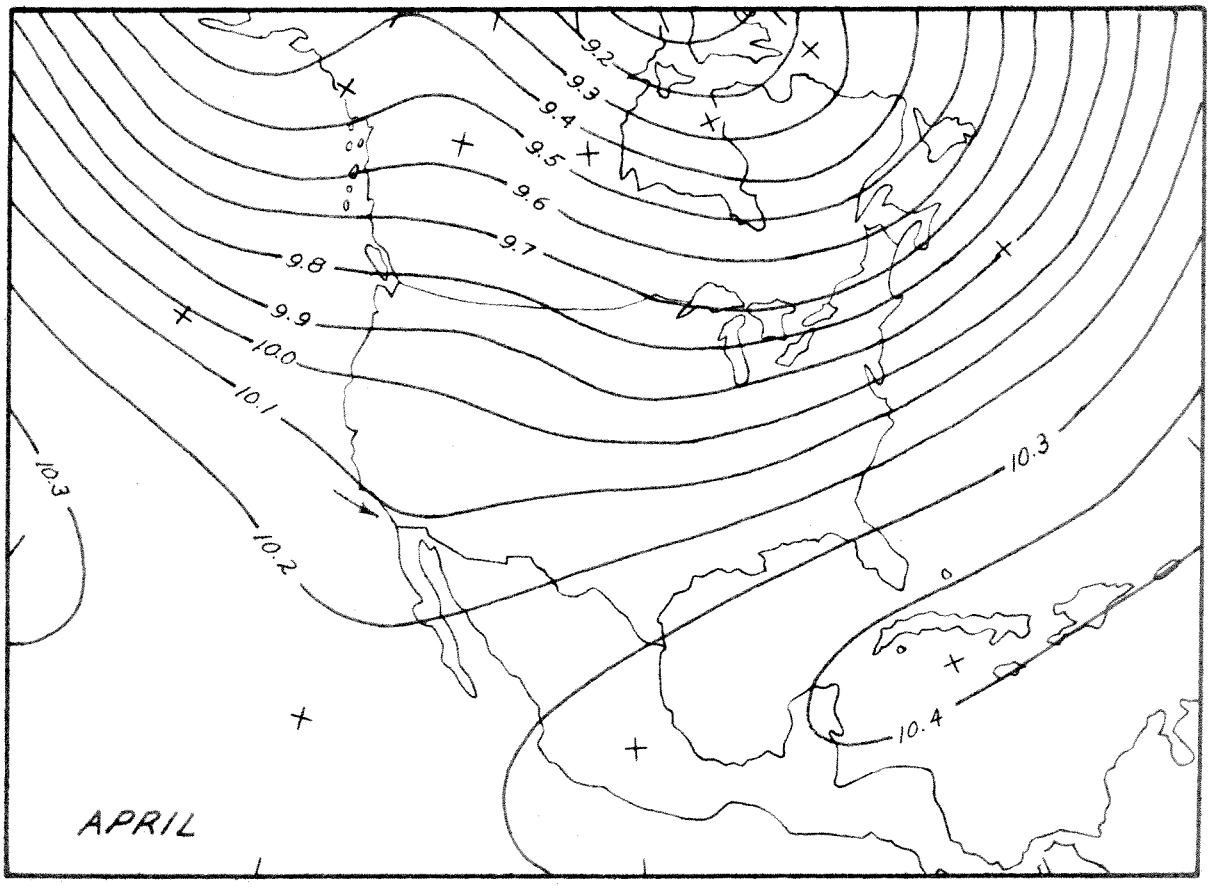
quasi-permanent subtropical anticyclones that exist over the eastern Pacific and central Atlantic Oceans, respectively (J. T. Williams, personal communication, 1955). Figures 26 and 27 show the location of these highs during the four seasons of the year by means of contours drawn on the 700-millibar pressure surface. The small arrows shown near Los Angeles indicate the approximate directions of the geostrophic wind. These directions agree reasonably well with those of the observed resultant winds shown in Figure 25.

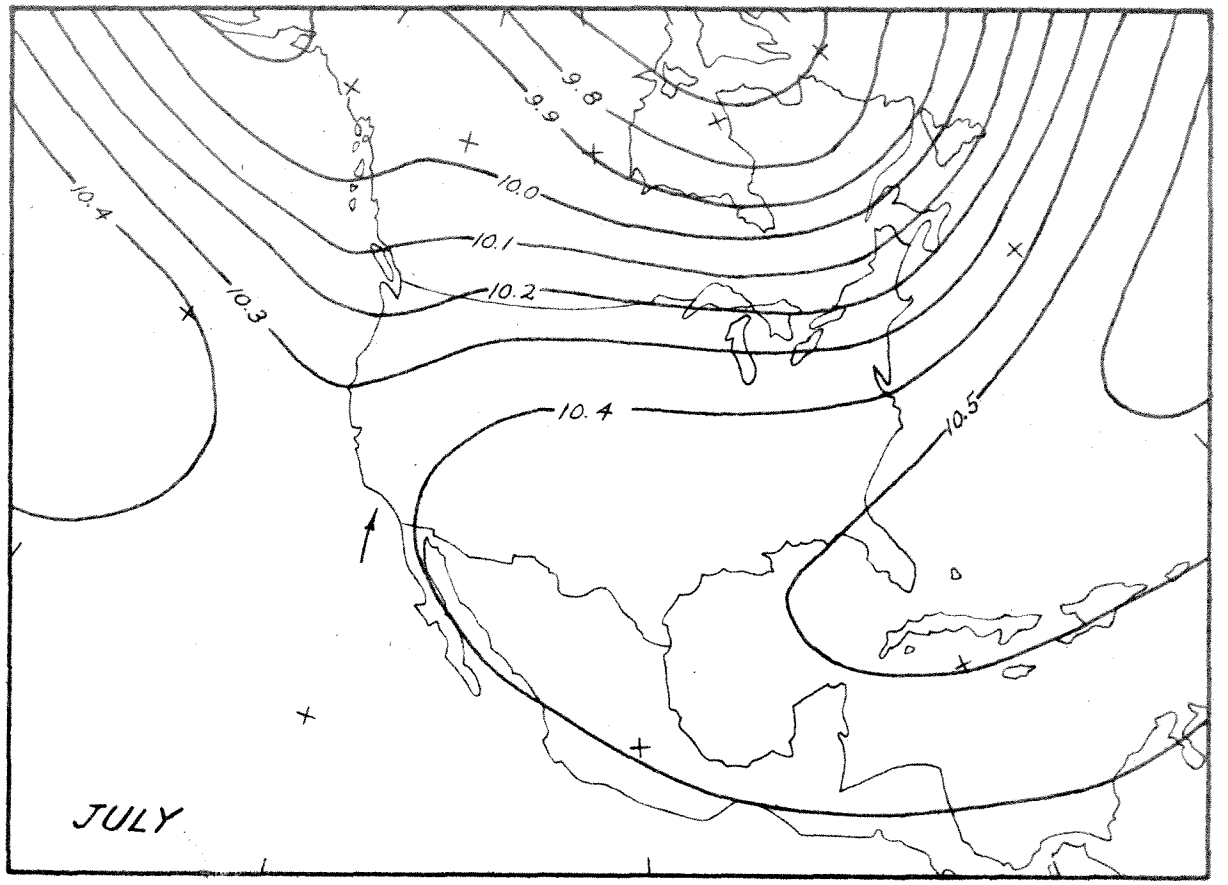
The winds along coastal southern California blow from the northeast (Mojave) quadrant only rarely. Airflow over the San Gabriel Mountains below 4,000 meters is occasionally from the north or north-northeast, but at the same time, the winds near Point Conception blow from the northwest. This means that at the present time volcanic ash from the Mojave Desert would have much less chance of reaching the Los Angeles basin than ash from the central Coast Ranges.

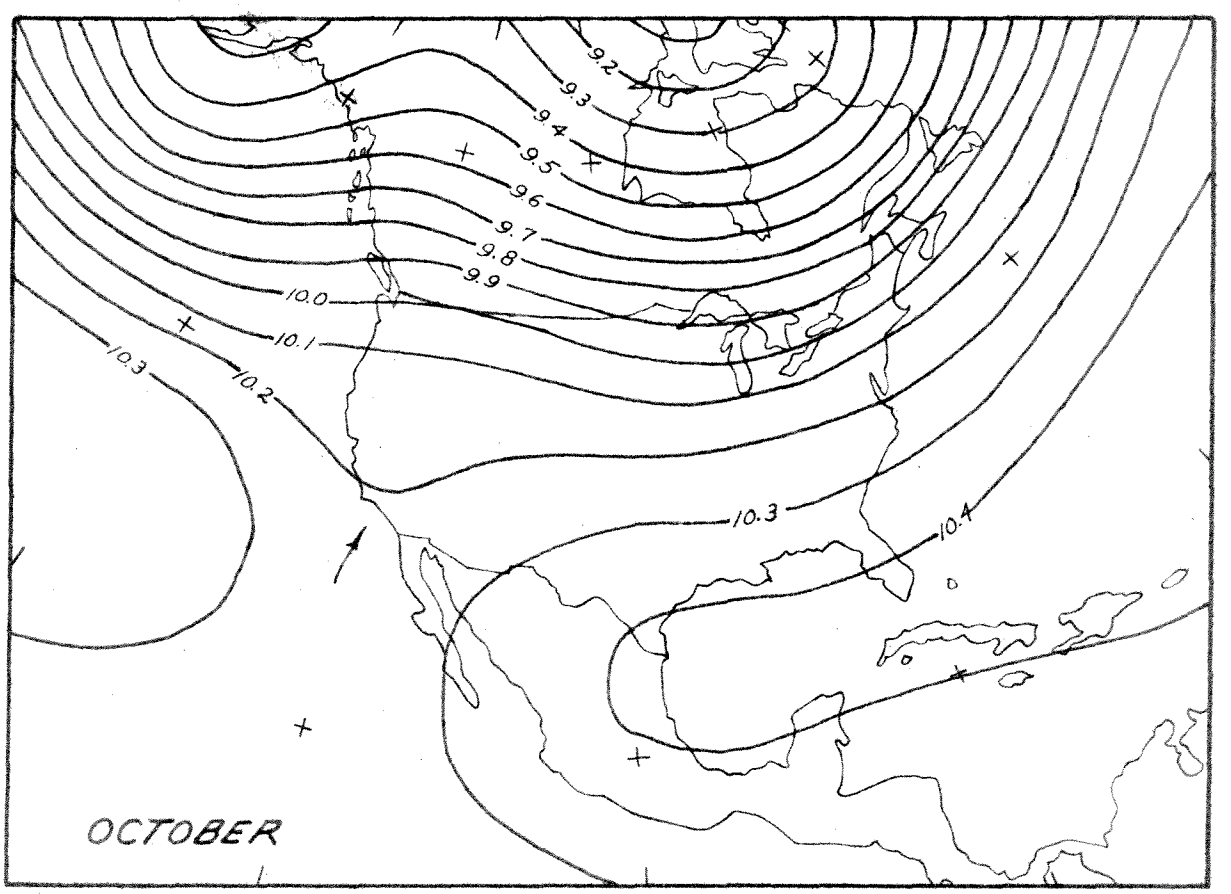
If the Tertiary climate of the world was different from that of today, it is probable that the wind pattern in most regions was different also. The factors that constitute the climate of a specific region are the mean values and periodic fluctuations of temperature, precipitation, and cloudiness. Variations in these factors are in part a function of the surface winds, but they are

Figures 26 and 27. Contours on the mean 700 mb. pressure surface during the four seasons; contours in thousands of feet, contour interval 100 feet. Note the relative position of the Pacific and Bermuda "highs" and how their location with respect to Los Angeles affects the approximate direction of the geostrophic winds (shown by arrows). Data from U. S. Weather Bureau.


9.2
8.7
8.9
8.8
9.0
9.3
9.4
9.5
9.1
9.6
9.7
9.8
9.9
10.0
10.1
10.2
10.3
10.4
JANUARY


9.2
9.3
9.4
9.5
9.6
9.7
9.8
9.9
10.0
10.1
10.3
10.2
10.3
10.4
APRIL


9.8
9.9
10.0
10.1
10.2
10.3
10.4
10.4
10.5
JULY


9.2
9.3
9.4
9.5
9.6
9.7
9.8
9.9
10.0
10.1
10.2
10.3
10.3
10.4
OCTOBER

primarily dependent upon the distribution of thermal energy over the globe, the size and arrangement of continents and oceans, and locally, the height and extent of mountain ranges. Variations in any one of the latter factors result in variations in the directions of the winds.

The data of Woodford et al. (1946) and Edwards (1934) indicate that former mountains stood on the site of the present-day San Gabriel and San Bernardino Mountains throughout most of Miocene and Pliocene times. The conspicuous lack of marine sedimentary rocks of late Tertiary age in the Mojave Desert is further evidence of the existence of these ancestral mountains. The influence of topography on the winds therefore could not have been much different from that of today. Similarly, the Cenozoic paleogeographic maps of Schuchert (1955) indicate that the size and shape of the North American continent has changed very little since Oligocene times.

Estimates of the amount of precipitation that fell during the Tertiary period have been determined from paleobotanical evidence. According to Axelrod (1939, 1950), the Miocene Tehachapi flora and the Pliocene Mount Eden and Piru Gorge floras (all in southern California) were supported by an annual precipitation that differed from that of today only in the fact that part of it fell during the summer as thunder-showers. Axelrod

also concluded that annual fluctuations in temperature were more moderate than those of today. Thus the climate and gross physiography of the region have changed only slightly since the latter part of the Tertiary epoch.

In general, the climate of the earth is thought to have been warm throughout most of geologic history, and present-day temperatures are believed to be intermediate between those of a typical warm period and a typical glacial period (Brooks, 1949). Evidence presented by Brooks indicates the early to middle Tertiary period was was warm, but the mean temperature of the earth fell steadily from Oligocene to Pleistocene times. According to Emiliani (1954) the temperature of Pacific bottom waters decreased 8° C. during this period, and Durham (1950) presented evidence that surface oceanic temperatures in the vicinity of Los Angeles fell approximately 12° C. Thus Miocene and Pliocene temperatures were warmer than those of the present. The mean temperature of the periods of glacial maxima (Pleistocene) must have been relatively cooler.

It is known from paleobotanical evidence that the latitudinal zonation of climates during the warm periods was far less intense than it is today (Barghoorn, 1953). This implies a lessened temperature gradient between the Equator and Poles. Inasmuch as the pressure gradient on which the planetary winds are dependent would be affected

by a reduced meridional thermal gradient, it is incorrect to assume that the winds near Los Angeles blew in the same directions during Miocene and Pliocene times as they do today. In order to make a qualitative determination of the wind directions during the latter half of the Tertiary period, it is necessary to consider the causal mechanics that give rise to the observed winds.

Until 1950, theories concerned with the general circulation of the atmosphere were patterned after a meridional cell model (see, for example, Rossby, 1941). According to this theory, the winds of the northern hemisphere behave as follows: air, warmed at the Equator, rises and flows northward, being deflected toward the east by the rotation of the earth. At approximately 30°N latitude, it loses heat by radiation and begins to settle toward the surface. Upon reaching the surface, part of it flows southward toward the Equator and is deflected toward the west, and part flows northward and is deflected toward the east. In the Polar regions a similar cell exists, and Polar air at the surface flows southward to a relatively warm, low-pressure zone at 60°N. There it rises and flows Poleward at high altitudes. These two cells were believed to "drive" a third, large cell in intermediate latitudes. Circulation in this middle-latitude cell is known to be toward the north and east at the surface (the "prevailing westerlies"), and was thought to be, rather logically,

toward the south and west in the upper troposphere. Meteorological observations during and after World War II established the presence of the westerly jet stream (flowing due east), however, and since then the older concept of the general circulation of the atmosphere has been seriously re-examined.

At the time of this writing, there is no universally accepted theory of the general circulation of the atmosphere. It is still agreed that a thermal contrast between the Equator and Poles is the prime driving force of atmospheric circulation, but the hydrodynamic effects of the earth's rotation are thought to play a highly significant role.

Recent theories of the general circulation were summed up by Bolin (1952). It has been shown by scale-model studies that simple differential heating between the center and rim of a circular pan of water leads to the formation of one or more meridional (vertical) cells like those described above, but with concomitant rotation of the pan, the meridional circulation gives way to quasi-horizontal circulation at a certain critical velocity of rotation. Thus the pattern of atmospheric circulation is dependent upon a balance between the meridional temperature gradient and the rate of rotation of the earth. Circulation in low latitudes, where rotation around a vertical is zero, leads to meridional movement, but in middle and high latitudes,

where rotation around a vertical is significant, there develops a quasi-horizontal flow. If the thermal contrast between the Equator and Poles was less during the Miocene and Pliocene epochs, and greater during the Pleistocene epoch than it is today, then the latitude at which meridional circulation gave way to horizontal circulation must have been different also.

Willett (1949) made a detailed study of long-period changes in the circulation of the atmosphere, and concluded that there is a basic factor underlying all such changes, namely, a contraction (warm period) or expansion (cool period) of the circum-Polar front. He considered the warm periods of the earth to be similar to the interglacial periods of the Pleistocene epoch, and stated in a later paper (1953, pp. 54-55):

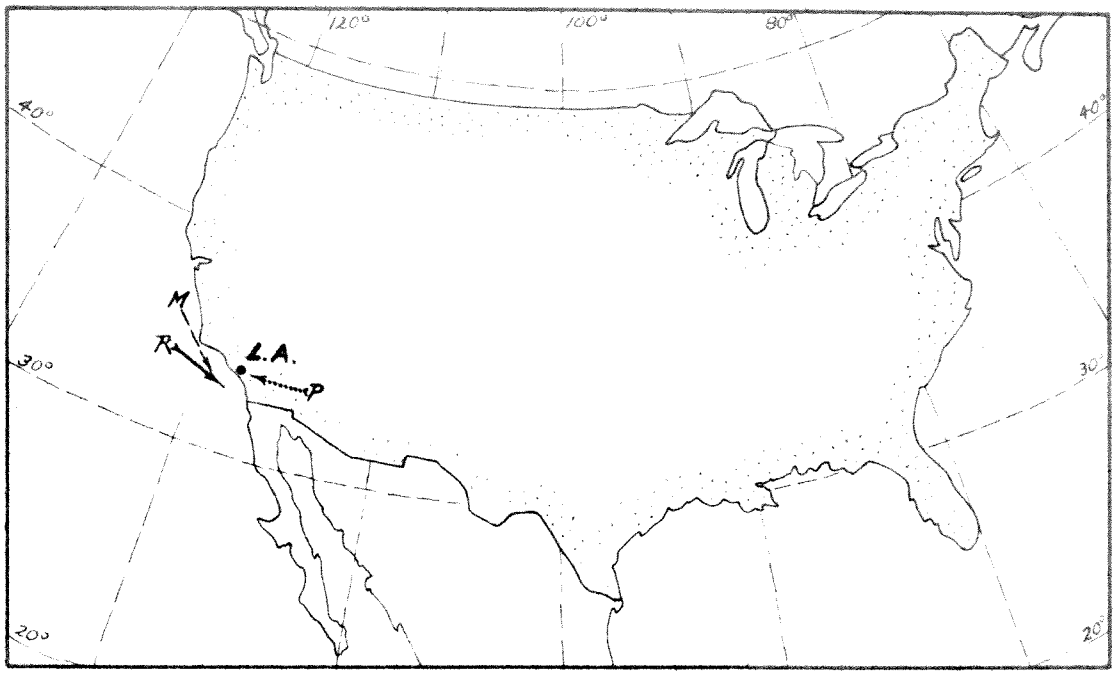
> The present pattern of terrestrial climate, and the corresponding pattern of atmospheric circulation, lie somewhere between the extreme of a maximum of glaciation and the extreme of an interglacial minimum, probably approximately two thirds of the way from the glacial to the interglacial extreme... The middle latitude belt of maximum cyclonic rainfall probably extends its influence 15 degrees farther Equatorward (during the glacial maximum) into the present subtropical high pressure belt of relatively dry and settled weather, which in turn is compressed toward the Equator... The interglacial pattern of climate and of atmospheric circulation, in comparison with that of today, departs in the opposite sense from the interglacial extreme.

Thus Willett pictures a broad diffusion and weakening of the climatic zones during a warm period, with a

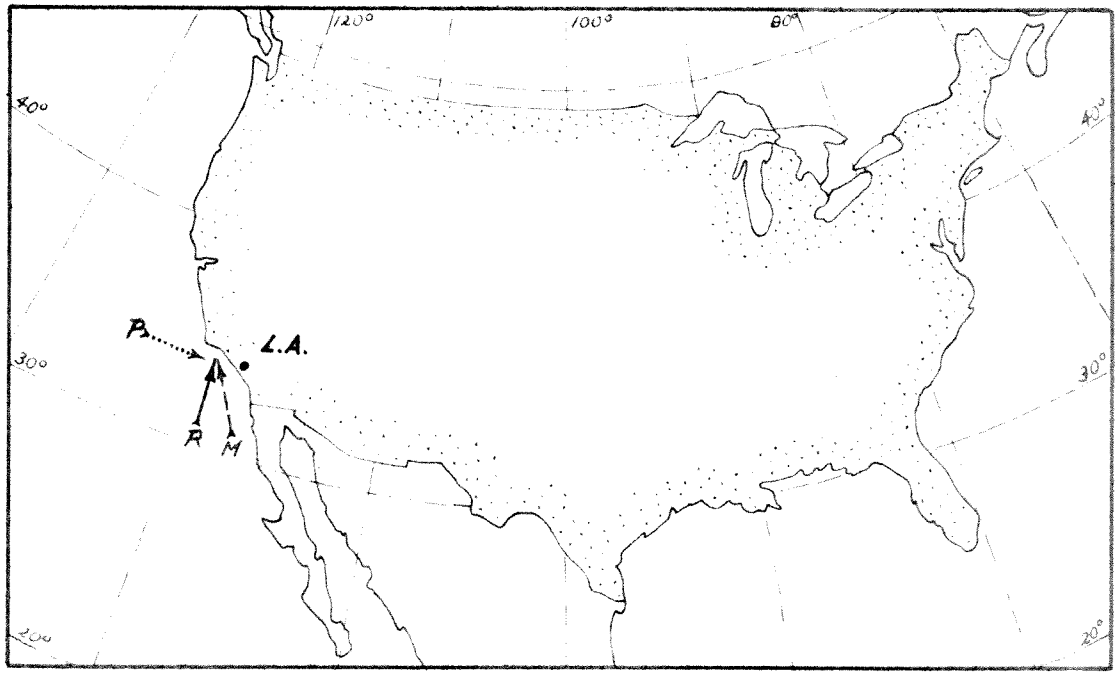
concomitant shift of these zones toward the Poles. It is probable that the shift of the Pacific and Bermuda "highs," on which the winds near Los Angeles are dependent (Figures 26 and 27), amounted to no more than 10° of latitude. Referring to Figures 26 and 27, a simple shift of the contoured pressure surface 10° north (probably a good approximation of the actual conditions) leads to a late Tertiary wind pattern near Los Angeles as follows: January, northwest winds; April, west winds; July, southeast winds; October, south-southeast winds. In other words, there is little difference between the late Tertiary wind pattern and that existing today (Figure 25).

The map presented by Willett (1950, Figure 1) indicates that during the last glacial maximum of the Pleistocene epoch, the region near Los Angeles lay within a pressure "saddle," with highs on the north and south and lows on the east and west. The geostrophic winds in such a region are difficult to determine, but if the highs and lows shifted slightly south of where Willett showed them (as in winter) the wind would probably blow from the east, and if they shifted toward the north (as in summer) the wind would blow from the west. These winds are shown in Figure 28.

From the foregoing, it seems likely that most of the rhyolitic volcanic ash in the Tertiary stratigraphic section of the Los Angeles basin originated in the central



Winter



M ——→ Miocene
P ·····→ Pleistocene
R ——→ Recent

Summer

Figure 28. Probable relations between seasonal winds near the Los Angeles basin during three Cenozoic epochs. Direction of Recent winds based on data of U.S.Weather Bureau, direction of Pleistocene winds inferred from data of Willett (1950), direction of Miocene winds inferred from paleoecological data (see text).

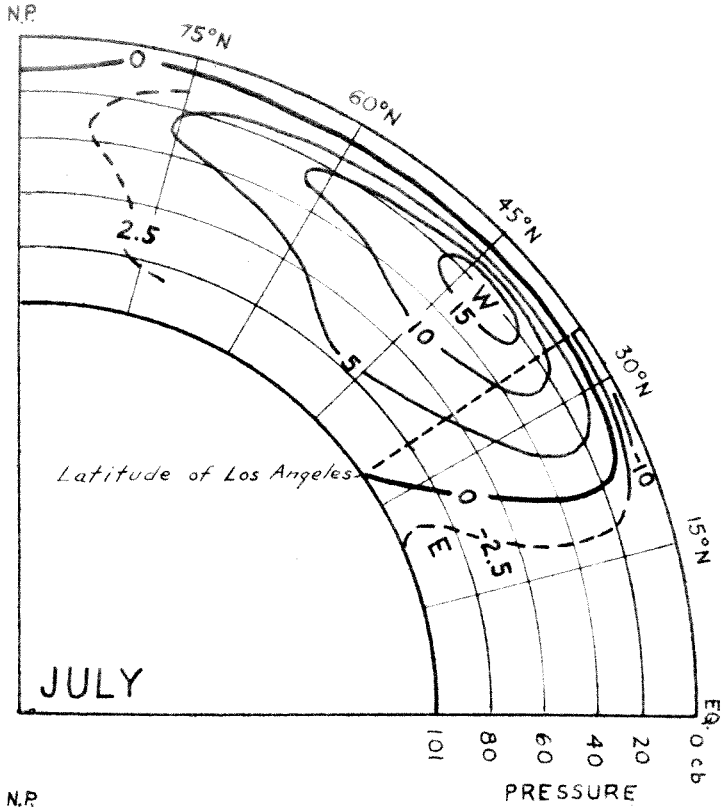
Coast Ranges or on the continental shelf, rather than in the Mojave Desert.

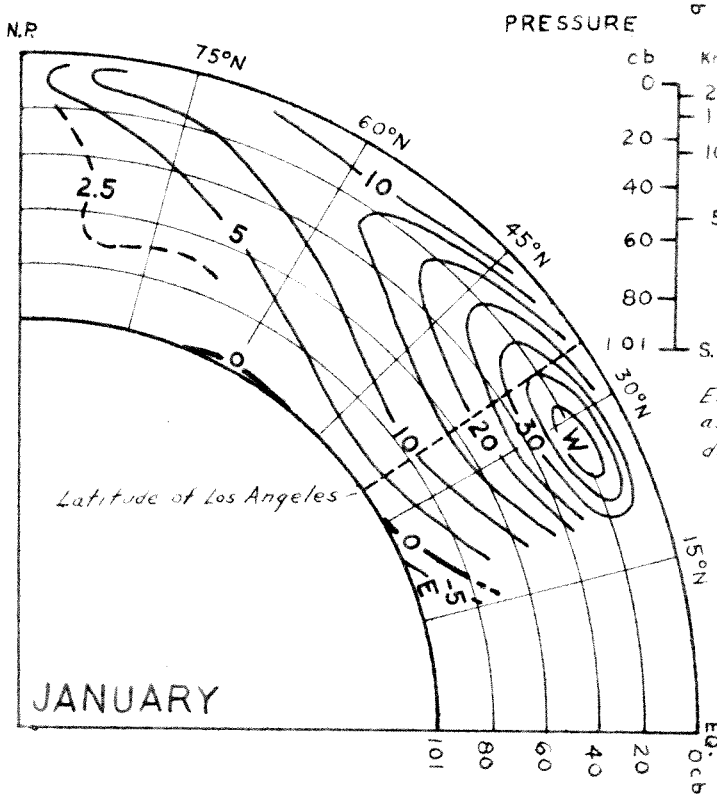
Two other aspects of the problem are worthy of discussion. The first is the fact that the latitudinal boundary between east and west winds, now at 35°N. at the surface, is farther south in the upper troposphere (Figure 29). This means that if the Poleward shift of climatic belts was greater than the 10° postulated earlier, and the Los Angeles area lay within the belt of the Trade Winds (easterlies), ash clouds rising to high altitudes would still encounter pronounced west winds, making the transportation of volcanic ash from the Mojave Desert to the Los Angeles basin difficult.

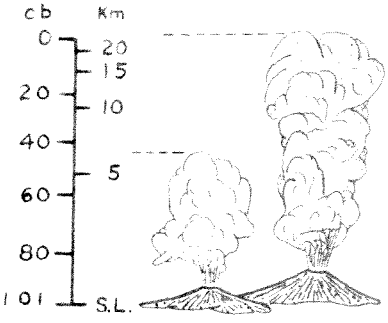
It should be noted that recent studies of the San Andreas fault zone (Hill, 1954) suggest that right-lateral movement on the fault since the Miocene epoch has amounted to at least as much as 20 miles, and possibly much more. This suggests that during the Miocene epoch the Mojave Desert region was 20 miles farther northwest, relative to the Los Angeles basin, than it is today. If post-Miocene movement was greater than 20 miles the relative positions of the two regions may have been such that ash from volcanoes in the Mojave Desert could have been swept southward into the Los Angeles basin.

Geomagnetic studies of rocks of various ages from different parts of the world indicate that there was

Figure 29. The mean geostrophic zonal wind (in meters per second), averaged over all longitudes. Note that west winds prevail at high altitudes over areas in which the surface winds are easterly. At the right is a sketch of two ash clouds showing the extremes in elevation of clouds described in Table 5 of this report. They indicate that if the Los Angeles area lay south of the belt of "prevailing westerlies" during the Miocene epoch, ascending ash clouds nevertheless would have encountered westerly winds aloft. Wind diagrams from Mintz and Dean (1952).







Extremes in elevation of ash-laden clouds described in Table 5.

considerable migration of the magnetic poles during the history of the earth. The previous magnetic poles are believed by most geophysicists to have corresponded to the geographic poles, and the migration is thought to have resulted from a slipping of the outer shell of the earth over the interior. According to the data of Creer et al. (1954), the Miocene pole was located at a point that is now at 80°N. latitude, 170°E. longitude. If this coincided with the Miocene geographic pole of the earth, the Los Angeles basin, presently centered at 34°N. latitude, must have been at approximately 36°30'N. latitude during the Miocene epoch. Thus if there was a northward migration of climatic zones during parts of the Tertiary period, the climatic effect in the Los Angeles area was compensated in part by the fact that the Los Angeles basin was also farther north. It is concluded, therefore, that the rhyolitic ash in the Los Angeles basin probably did not come from the Mojave Desert, but instead came from the central Coastal Ranges or the continental shelf. Independent geologic evidence, discussed in the following paragraphs, affords confirmation of this conclusion.

The Obispo tuff is several hundred feet thick at its type locality near the town of San Luis Obispo, but thins to the south and southeast in the direction of Los Angeles. Near Point Conception it is approximately 125 feet thick, near Gaviota 50 to 100 feet thick, near Naples

30 feet thick, and near Ventura only a few feet thick (Bramlette, 1946). This systematic variation in thickness is indicative of a source to the north or northwest. In addition, Bramlette (op. cit.) pointed out that the amount of tuffaceous material in the upper Miocene rocks of southern California is notably less than it is farther north, which suggests that explosive activity was more prevalent in the north than it was near Los Angeles.

Concerning a source on the continental shelf, flows of rhyolite accompanied by sheets of pumice as much as 20 feet thick are exposed on San Clemente Island south of the Los Angeles basin (Smith, 1898). In addition, the Portuguese tuff member of the Monterey shale, an impure tuff mixed with subordinate epiclastic material, has a maximum thickness of 60 feet in the Palos Verdes Hills (Woodring et al., 1946). As far as the writer is aware, no other tuff in the Los Angeles basin equals the Portuguese tuff in thickness. Fragments of pumice as large as one inch in diameter occur in the Miraleste tuff in the same area. Inasmuch as size sorting is known to take place during eolian transportation, these pumice lapilli suggest a relatively close source. The detailed stratigraphic sections presented by Woodring et al. (1946) reveal that there are more than 20 beds of tuff or tuffaceous sediments in the lower part of the Monterey formation. All of this evidence suggests that the Palos Verdes Hills

lay close to the site of an active volcano.

The distance from San Luis Obispo, at the southern end of the Coast Ranges, to the southeastern end of the Los Angeles basin is approximately 190 miles, and the distance from San Clemente Island, on the continental shelf, to the northwestern end of the basin is approximately 100 miles. These distances are less than those travelled by wind-borne ash from several well known volcanic outbursts of the Quaternary period. Figure 30 shows down-wind variations in the thickness of ash from four such eruptions. Note that in two of these eruptions, ash accumulated to a thickness of more than one foot at a distance of 200 miles from the source volcano.

Pumiceous ash ejected from a volcano at the northeastern end of Lake Taupo in New Zealand contains lumps of pumice three inches in diameter at a distance of 40 miles from the lake (Grange, 1931), and the 1815 eruption of Tambora, in the Dutch East Indies, threw rock fragments as large as six inches in diameter 25 miles from the volcano (van Padang, 1951). Thus the pumice lumps in the Miraleste tuff may have travelled a distance of 40 or 50 miles. Ash from the same eruption must have blanketed the Los Angeles basin, and must have become thinner to the northeast as less and less of it rained from the sky into the waters of the basin.

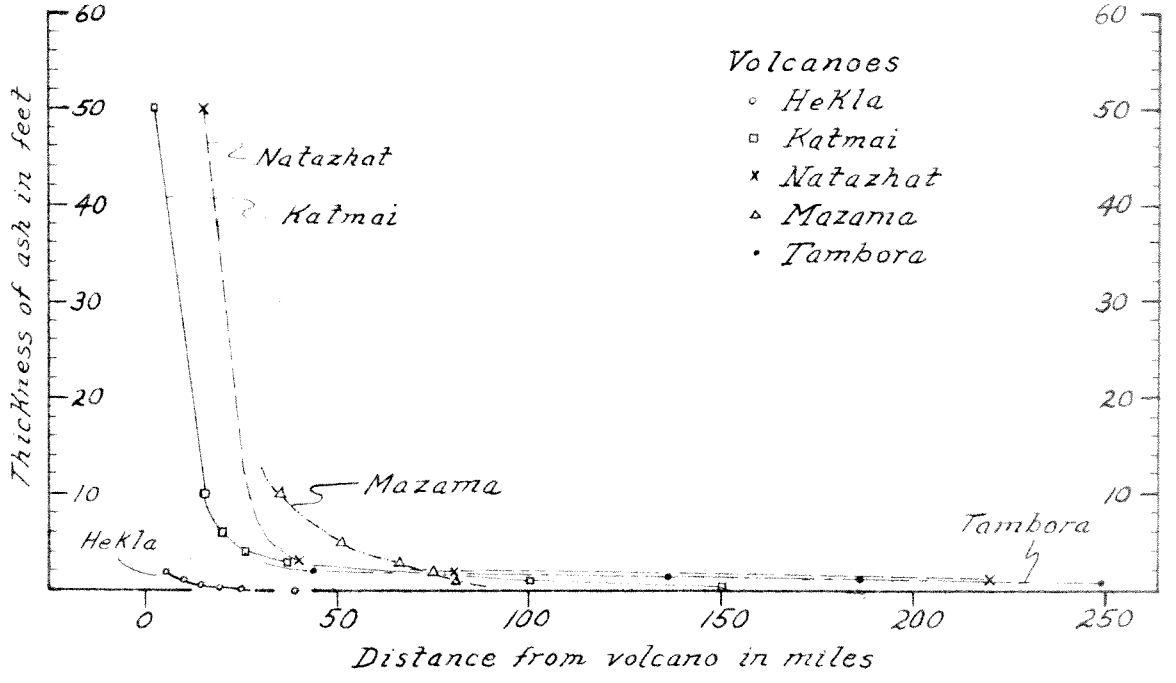


Figure 30. Downwind longitudinal profiles of volcanic ash deposits from five Cenozoic eruptions. Note that ash accumulated to a thickness of about one foot at a distance of more than 200 miles from two of the volcanoes.

ROLE OF VOLCANISM IN THE HISTORY OF THE LOS ANGELES BASIN

General Statement

The earliest legible record of volcanic activity near Los Angeles is provided by the Santiago Peak formation of Jurassic age in the Santa Ana Mountains. (The historical volcanic record prior to this time is entirely unknown.) The Santiago Peak rocks comprise slightly metamorphosed andesites, quartz latites, and subordinate trachytes. They have received so little detailed attention except locally (cf. Jahns and Lance, 1950), that not much is known of their lithologic sequence, variations in thickness, or probable source. Until they are more thoroughly studied, a complete tectonic-volcanic interpretation of the region cannot be readily made. On the other hand, detailed studies of Cenozoic sedimentation and tectonic activity in the Los Angeles basin are complete enough to make possible a synthesis of geologic events in the region that includes the Miocene volcanic activity described in the preceding pages. An earlier attempt at seeking a relationship between the tectonic and volcanic activity of the region was made by Reed and Hollister (1936).

The most striking feature of the Pacific margin of North and South America is the active orogenic belt with

which volcanic activity has been associated since early Tertiary times. Waters (1955) estimated that approximately 100,000 cubic miles of lava was extravasated in the Cascade Range of Oregon and Washington alone. The volume of lava and pyroclastic rocks in the Andean volcanic chain of South America is many times greater. In a previous section of this report, it was suggested that the volume of Miocene volcanic rocks in the Los Angeles basin may have approximated 85 cubic miles. If the western Santa Monica Mountains and the continental shelf are included as part of the same volcanic province, the volume may have been as great as 8,000 cubic miles. This area of volcanic activity in coastal southern California coincides with a tectonically active region in which the principal structural evolution has been the development of subsiding, graben-like basins bounded by major zones of fracture.

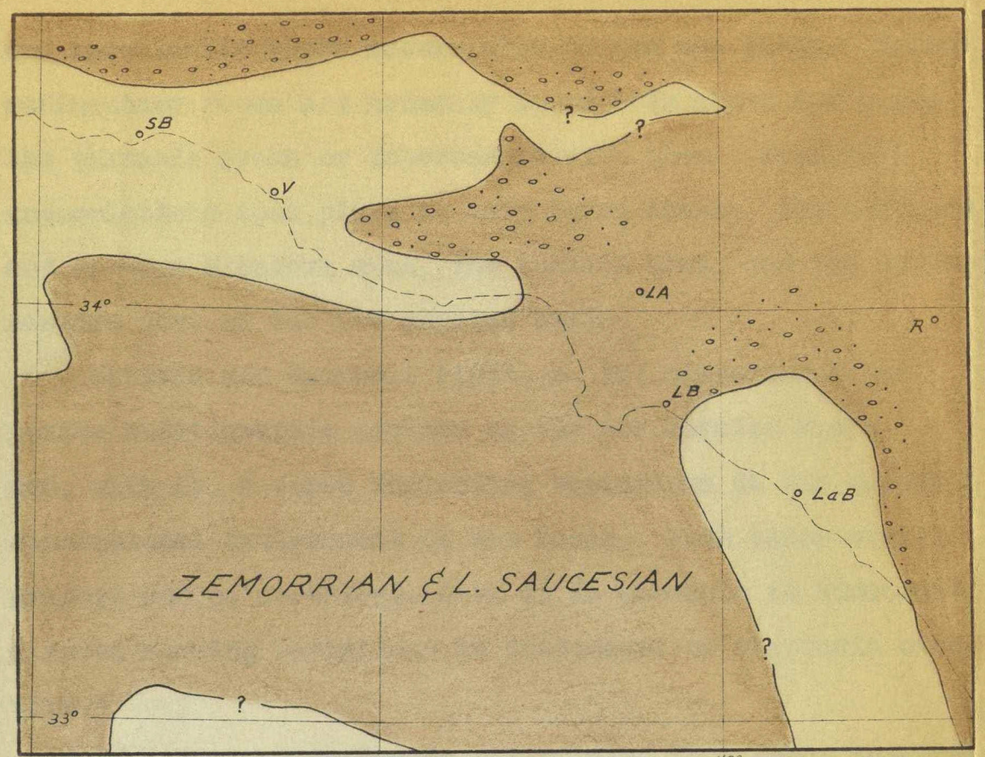
The Time of Volcanism

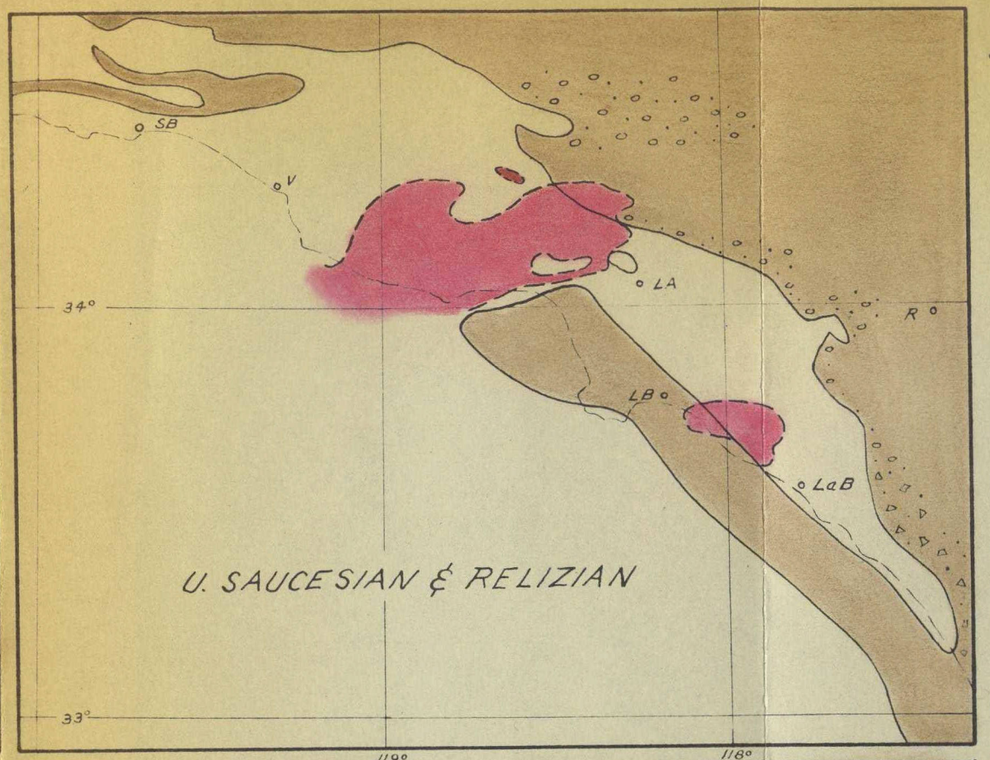
Volcanic activity in the Los Angeles basin was restricted in time to the middle Miocene and the early part of the upper Miocene epoch, but in the central Coast Ranges of California and the Mojave Desert, similar eruptive activity continued until Quaternary times. Either the supply of magma that nourished the conduits of the Los Angeles basin became exhausted during upper Miocene times,

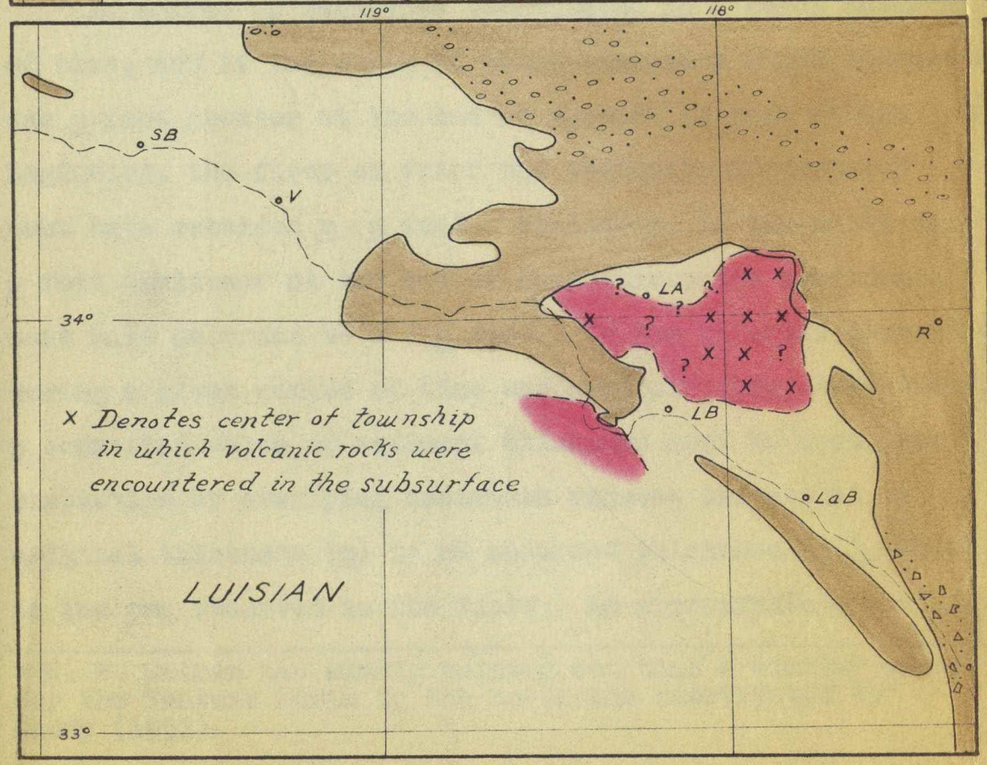
or the conduits were sealed by tectonic movement. Inasmuch as the volcanoes near Los Angeles coincided geographically with a subsiding sedimentary basin it is likely that there was a genetic relationship between the two.

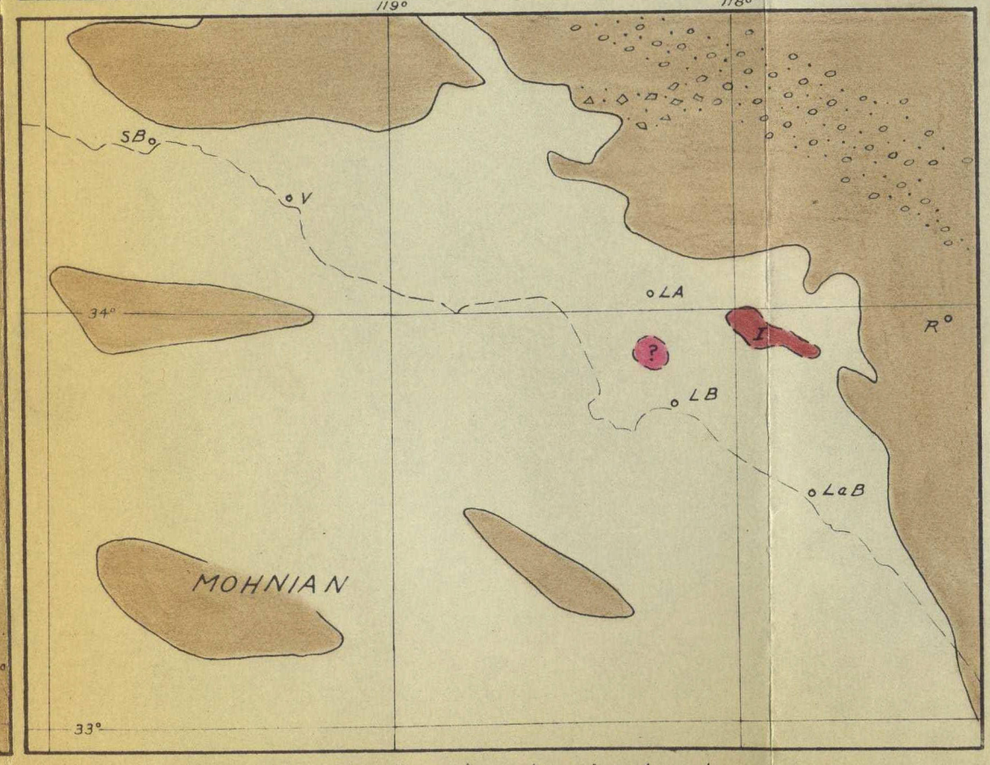
Figure 31 shows the paleogeographic distribution of volcanic rocks in the basin during three stages of the Miocene epoch. The base maps on which the volcanic rocks are plotted are those of Corey (1954). These maps indicate that the unconformity between Mohnian sedimentary rocks and the ridge of "basement" rocks along the southwestern edge of the present-day basin represents an emergent condition (of the ridge) that persisted until Mohnian times. An alternative interpretation is that middle Miocene strata, including volcanic rocks, were originally present along this ridge but were removed by erosion prior to the beginning of Mohnian sedimentation. For lack of conclusive evidence, the volcanic rocks are shown only on the northeast side of the ridge. Volcanic rocks in the Palos Verdes Hills are indicated as Luisian in age, and those near the San Joaquin Hills are indicated as Relizian. Actually, volcanic activity in the Palos Verdes Hills took place very early in Luisian times, and that in the San Joaquin Hills, very late in Relizian times, and thus the two may have overlapped in time. The sharp distinction indicated by the figures is therefore unreal.

It is evident from the maps that most of the flows









EXPLANATION

Cities

SB = Santa Barbara
V = Ventura
LA = Los Angeles
LB = Long Beach
LaB = Laguna Beach
R = Riverside

Present shoreline

Paleoshoreline*

Areas of continental deposition

Upland areas

Volcanic rocks, extrusive and intrusive undiff.

I Intrusive rocks only

SCALE
0 10 20 30 40 50
Miles

*Paleoshorelines from Corey (1954)

Figure 31. Paleogeographic distribution of the Miocene volcanic rocks in the Los Angeles basin, by stage.

and pyroclastic rocks accumulated on the sea floor. Marine sedimentary rocks are commonly found both above and below the volcanic rocks or interbedded with them. Subaerial accumulations took place in only three areas: the northern and eastern Glendora area, the Sunland area, and the southeastern part of the Los Angeles basin.

Natland and Rothwell (1954, p. 40) presented a composite stratigraphic section of the Los Angeles basin and, with it, a curve indicating variations in the probable depositional environment of the basin. From these stratigraphic and paleoecologic data it is possible to construct a curve showing variations in subsidence of the basin with time.*

If m feet of sediments accumulated in a given interval of time, and if the depth of water overlying these sediments was n feet greater at the end of deposition than at the beginning, the floor on which the sediments accumulated must have subsided $m + n$ feet. Similarly, if the water was n feet shallower at the end of deposition, the subsidence must have amounted to $m - n$ feet. If the material deposited during a given period of time was predominantly clay, then a corrected value of sediment thickness must be used, for compaction by overlying sediments reduces the actual original thickness (m) to an apparent thickness (m'), which is the one observed in the field. An approximate correction

* W. H. Holman has kindly pointed out that a similar curve for the Ventura basin to the north was constructed by Bandy (1953).

can be made by using the formula of Athy (1930) for the percentage of compaction as a function of depth of burial. Compaction leads to a further difficulty in calculating the subsidence rate, for part of the subsidence of a given stratigraphic unit overlying a clay shale is not the result of subsidence of the basin floor, but of compaction of the underlying shale. Most of this compaction takes place during accumulation of the first four thousand feet of overlying sediments, however, and can be corrected for algebraically.

The time scale (abscissa) of the curve shown in Figure 32 is based on data presented by J. P. Marble's report of the National Research Council Committee on the Measurement of Geologic Time, 1949-1950 (1950, p. 18). Inasmuch as these data include a breakdown by epoch only, a further subdivision based on the Foraminiferal stages of California stratigraphy was made as follows: 21 marine stratigraphic sections measured in different parts of the state and described in California Division of Mines Bulletins 118 (1943) and 170 (1954) were analyzed, and a mean percentage figure for the time duration of each stage was calculated on the assumption that within each section in which the entire sequence consists of rocks of the same lithology and texture, the rate of sedimentation has been more or less uniform. Sections of thick interbedded shales and sandstones or sandstones and conglomerates were not used.

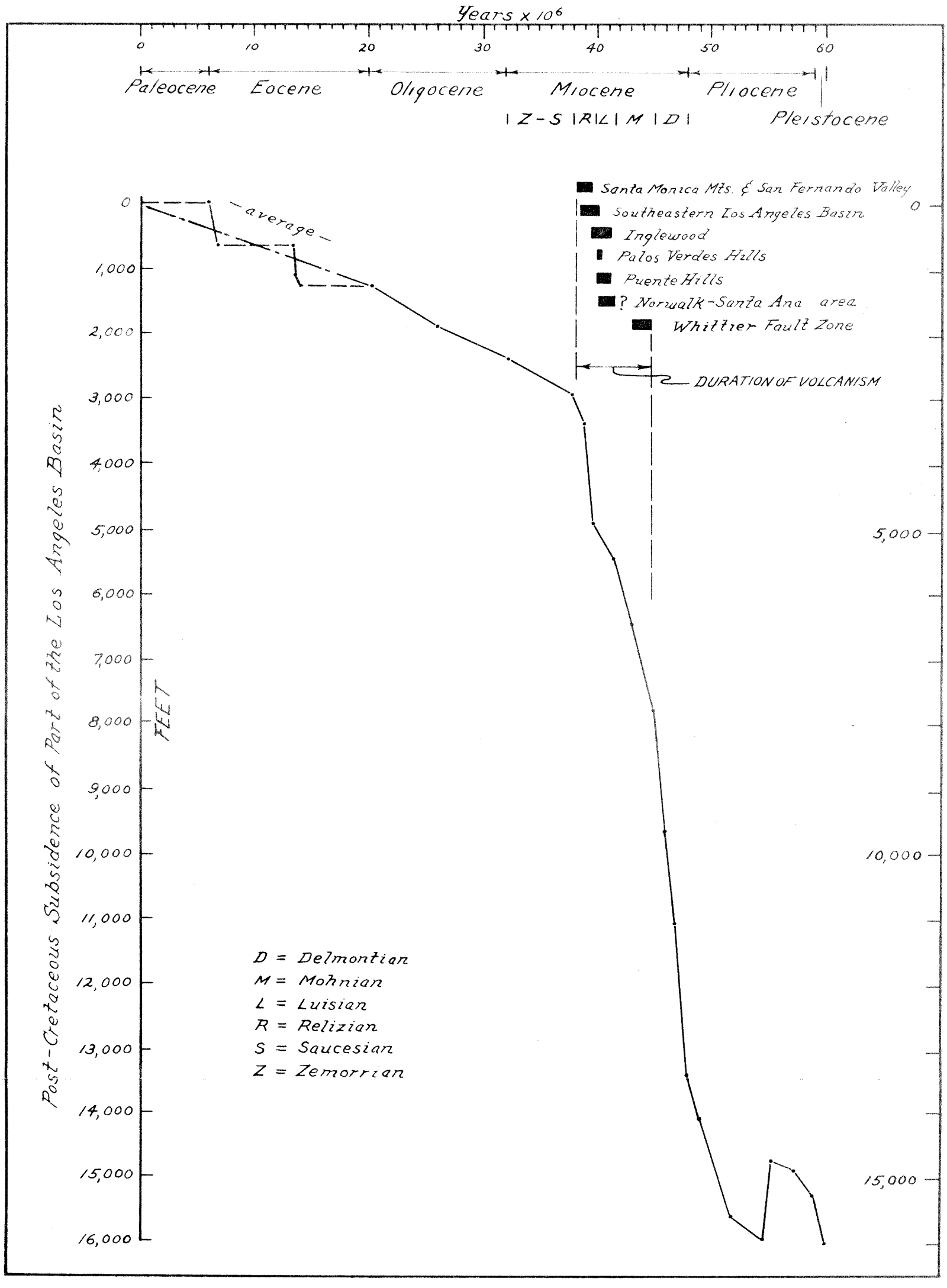


Figure 32. Post-Cretaceous subsidence and volcanism in the Los Angeles basin. The curve shows the variation in subsidence of the basin with time, and the short, solid bars indicate intervals of time within which episodes of volcanism occurred in different parts of the basin.

The results of these calculations are shown in Figure 32. Also shown are several heavy bars representing the approximate time and duration of volcanic activity in different parts of the basin. From the beginning of the Cenozoic era to the beginning of middle Miocene (Relizian) time the average rate of subsidence was approximately 76 feet per one million years, but from this time to the end of the Miocene epoch, the rate was 1050 feet per one million years. The acceleration was abrupt, and coincided in time with the outbreak of volcanism.

That the expulsion of lavas and resultant drainage of magma reservoirs beneath the basin floor was not responsible for the accelerated subsidence of the basin is apparent from the fact that subsidence continued at a fairly steady rate long after volcanic activity had ceased. In addition, the amount of subsidence was many times greater than the volume of lavas erupted.

The time of cessation of volcanic activity is more difficult to determine. In general, eruptions in most parts of the basin had ceased by the end of Luisian times. The Whittier diabase is demonstrably post-early Mohnian in age, but aside from it, other manifestations of post-Luisian volcanism, excepting the rhyolitic tuffs discussed previously, are few in number. Activity ceased either because the supply of magma gave out or because the deeper parts of the volcanic conduits were closed by tectonic

movement. Inasmuch as there was a compressive (?) deformational episode near the end of middle Miocene times, as evidenced by a pronounced angular discordance between the Topanga and Modelo formations in the eastern Santa Monica Mountains and by the late middle Miocene erosion of more than 3,000 feet of early middle Miocene sediments in the San Joaquin Hills (Woodford et al., 1954), the writer is inclined to believe that the conduits were closed by tectonic movement. It should be emphasized that if such movement did bring volcanism to a close, it must have been of a deep-seated type, for faulting of the crustal rocks recurred many times after local volcanic activity ceased. Surface expressions of faulting commonly reflect readjustments of material at depth, and owing to the time-dependent property of creep exhibited by rocks, this faulting may take place over a considerable period of time after the initial application or release of stress. It is possible therefore, that readjustments at depth cut off the supply of magma feeding the Miocene volcanoes of the Los Angeles region and at the same time gave rise to compressional strain at the surface that was followed by a nearly continuous episode of faulting lasting until the Quaternary period.

In the following section of this report it is demonstrated that most of the Miocene volcanoes of the region were located near major faults. This implies that the

lava rose to the surface along accessible fractures. It is proposed that the sequence of tectonic and volcanic events in the region was as follows:

1) Paleocene to early Miocene: slow subsidence of basin by gentle downwarping of the crust.

2) Early middle Miocene: strength of crust exceeded during downwarping, development of major fractures (faults).

3) Middle Miocene: lavas rise to surface along fractures, rapid subsidence by block-fault movement rather than warping.

4) Early late Miocene: conduits closed by episode of compressional (?) folding and faulting, basin continues to subside.

The Locus of Volcanism

Miocene volcanic activity in the Los Angeles and Ventura basins, the ancestral Santa Monica Mountains, and the adjacent continental shelf was greater than that in any neighboring area, with the possible exception of the Mojave Desert. In the region of the western Santa Monica Mountains and Conejo Hills volcanic rocks accumulated to a thickness of 14,000 feet, and the thickness of similar rocks underlying the continental shelf (Figure 21) may have been as great, although little is known about these rocks. The location of this volcanic province corresponds to the intersection of two major structural belts: the east-trending Transverse Ranges and the northwest-trending Coast Range-Peninsular Range province. The Coast Range-

Peninsular Range trend can be traced for a distance of 1,500 miles along the coast of California, and the Transverse Ranges extend from Point Conception on the coast for a distance of nearly 350 miles inland. In addition, the bathymetric studies of Menard (1955) indicate that the Transverse Range structural trend continues seaward for 1,900 miles as the "Murray fracture zone." The shoreward-projected northern edge of the Murray fracture zone corresponds to the Santa Ynez Mountains, northernmost of the Transverse Ranges and site of volcanic activity during late early Miocene (Saucesian) times (Tranquillon volcanics of Dibblee, 1950). The projected southern edge of the Murray fracture zone passes near San Clemente Island, southernmost point of exposed middle Miocene volcanic rocks near coastal southern California. Reportedly "a parallel line of ... submarine volcanoes" (Menard, op. cit., p. 1164) lies along the Murray fracture zone at sea.

There are three other east-trending fracture zones in the eastern Pacific ocean: the Mendocino fracture zone north of the Murray, and the Clarion and Clipperton fracture zones to the south. The Clarion fracture zone is coaxial with the transverse Volcanic Province of southern Mexico. This province extends from Cape Corrientes on the Pacific Ocean to a point 50 miles northwest of the city of Veracruz on the Gulf of Mexico. It is approximately 600 miles long in an east-west direction, and 45 to 60 miles wide. It has been referred to variously as

the Volcanic Province of Mexico (Thayer, 1916), the Neo-Volcanic Zone (Williams, 1950), and the Mexican Volcanic Axis (Foshag and Gonzalez, 1956). It is transverse to the eastern circum-Pacific volcanic belt (the Andes of South America, the volcanic lineament of Central America, and the Cascades Range of North America).

Volcanic activity in the Mexican province began during early or middle Tertiary times and has continued to the present. The earliest flows are andesitic in composition, but the later ones are basalts. The high volcanoes of Popocotapetl, Orizaba, and Colima belong to this province, as does the lesser, but well known Paricutin. Williams (1950) studied the rocks in the vicinity of Paricutin and reported olivine basalts, olivine-bearing basaltic andesites, pyroxene (hypersthene-augite) andesites, and hornblende andesites. There is thus a striking lithologic similarity between the rocks of the transverse Volcanic Province of Mexico and those of the Los Angeles basin.

Thayer (1916, p. 89) noted that the structure and "basement" rocks of the province are difficult to observe, owing to concealment by Quaternary lava flows and volcanic breccias. Where the "basement" is exposed, however, he found "...massive Cretaceous limestones and shales, folded along east-west axes, badly faulted, cut by granitic intrusives, and covered by a great cap of lava and tuff."

The westward-flowing Rio Grande de Santiago, near the northern margin of the province, is dotted with numerous volcanic cones that probably mark "...an important fracture, corresponding to a place of dislocation in the general elevation of the (volcanic) plateau..." (Thayer, op. cit., p. 89). From studies at the southern margin of the province, Foshag and Gonzalez (op. cit.) reported Jurassic (?) black slates and Cretaceous limestones cut by diorite, monzonite, granite and adamellite.

The province of Sierra del Sur (Thayer, op. cit.) lies south of the volcanic province, and also has an east-west orientation. Tertiary volcanic rocks that at one time covered the area have been stripped away, and the dissected "basement" rocks that are exposed comprise undated metasedimentary rocks unconformably overlain by Triassic and Jurassic sandstones, conglomerates, and shales, and subordinate Lower Cretaceous strata. The orientation of folds in this area, like that in the Volcanic Province, is east-west.

Thus the similarities between this region and that at the southern edge of the Transverse Ranges in southern California are more than lithological. The structure in both areas has an east-west alignment that is transverse to the more dominant northwest trends that parallel the margins of the continents. The pre-Tertiary rocks of both areas include Triassic, Jurassic, and Lower Cretaceous

sedimentary strata that have been cut by dioritic and monzonitic intrusive rocks.

The Clipperton fracture zone, south of the Clarion, has not been traced as far east as the coast of Central America, but an extrapolation of its trend intersects the coast in the vicinity of Nicaragua. Many active volcanoes are located along the coast of Central America; Kennedy and Richey (1947) list 27 of them. The alignment of these volcanoes is essentially parallel to the coast, and it was not until recently (1954) that a major structural trend transverse to the coastal trend was clearly defined. In a discussion of Cenozoic volcanic activity in El Salvador, Williams (1954, pp. 326-327) stated:

> Toward the close of Pliocene time, a long and gentle east-west geanticline developed in El Salvador. Its crest, which had been the site of a chain of Pliocene volcanoes, collapsed to form a through-going trough that continued beyond the Republic... to join the long depression now holding Lakes Managua and Nicaragua. This is one of the fundamental structural units of Central America. Subsequently, a new chain of volcanoes developed...within the trough... .

Thus in this region, as in southern Mexico, a major east-west structural lineament transverse to the circum-Pacific cordillera of Central and South America developed. In both areas, the intersection of the transverse structure with the circum-Pacific structure is characterized by pronounced volcanic activity. In El Salvador, the volcanicity of the east-west lineament is less apparent because of the

outpouring of lavas from vents aligned parallel to the principal structural grain (northwest-southeast) in adjacent areas.

Both of these areas resemble, in gross structure, the southern California volcanic region of Miocene times. All three belong to the circum-Pacific volcanic belt, but they are unusual among the sub-provinces of this belt (e.g., the Andes and the Cascade Range) in that they occupy positions of intersection with trans-eastern Pacific fracture zones of continental dimensions. It is thought that volcanism was a direct response to deep fracturing of the crust in these areas.

Menard (1955, p. 1189) compiled data on the seismicity of the east-trending fracture zones, and concluded that they are seismically more active than those parts of the ocean floor between the zones. The number of epicenters within the Clarion and Clipperton zones, however, is far greater than that within the Murray zone. It is interesting to note that there is a correspondence in the present degree of volcanicity in these zones. The continental parts of the Clarion and Clipperton zones are currently active volcanically, whereas the Murray fracture zone is not.

Menard (op. cit., p. 1191) stated that Miocene (?) Foraminifera were found atop Erben Guyot in the Murray fracture zone, and concluded that the first activity in

the Murray zone antedated the Miocene epoch by an unknown length of time. From the data on the subsidence of the Los Angeles basin (Figure 32), the present writer suggests that tectonic activity in the zone started during the Paleocene and increased in intensity to the Pliocene epoch.

The principal Cenozoic orogeny of the eastern circum-Pacific region is known as the "Cascadian revolution." One of the striking contrasts between it and other orogenic episodes of the North American continent is the lack of large-scale overthrusts and overturned folds. In the Los Angeles area most of the deformation was by block-faulting, with vertical movements dominant. The blocks are apparently bounded by zones of fracture, one oriented northwest-southeast, the other, east-west.

In all, 13 basins with average depths of more than 2,000 feet occupy the continental shelf off the southern California coast (Emery and Shepard, 1946). These basins are believed to have evolved in the same manner as the Los Angeles and Ventura basins. Volcanic rocks are found within or near all of them. With the subsidence of each block, the base of the crust must have moved into geothermally warmer subcrustal regions, and partial fusion of the crustal rocks may have taken place.

Benioff (1954, pp. 399-400) concluded, from a study of seismic after-shock sequences, that part of the strain that accumulates prior to an earthquake is time-dependent,

and therefore is not released during the primary shock. A small part of this elastic-creep energy is converted into seismic waves as after-shock sequences, but the remainder is converted into heat. This heat is dissipated very slowly because the "thermal time constant" of the rocks at depth is very long. If repeated strain accumulations take place at a rate greater than the rate of heat dissipation, the heat will accumulate.

With the possible combined accumulation of seismically-generated heat and the rise of temperatures in the region surrounding the crust beneath each basin (as a result of subsidence), melting of the rocks probably took place beneath coastal southern California. When fractures developed, narrow zones of reduced pressure resulted and the magma was forced into them and ascended to the surface.

Figure 33 shows the inferred locations of eruptive centers in the Los Angeles basin. Criteria used in identifying these centers included exposures of pipe-like intrusive masses, existence of radial dike swarms, increases in thickness of the volcanic pile toward a common center, concentrations of time-related intrusive rocks in areas underlain principally by flows, and restricted areas of outcrop of individual rock types otherwise not broadly distributed. The Los Angeles basin has undergone post-eruptive deformation of such intensity that the scattered remnants of the Miocene volcanic field do not allow a more accurate means of locating former vents.

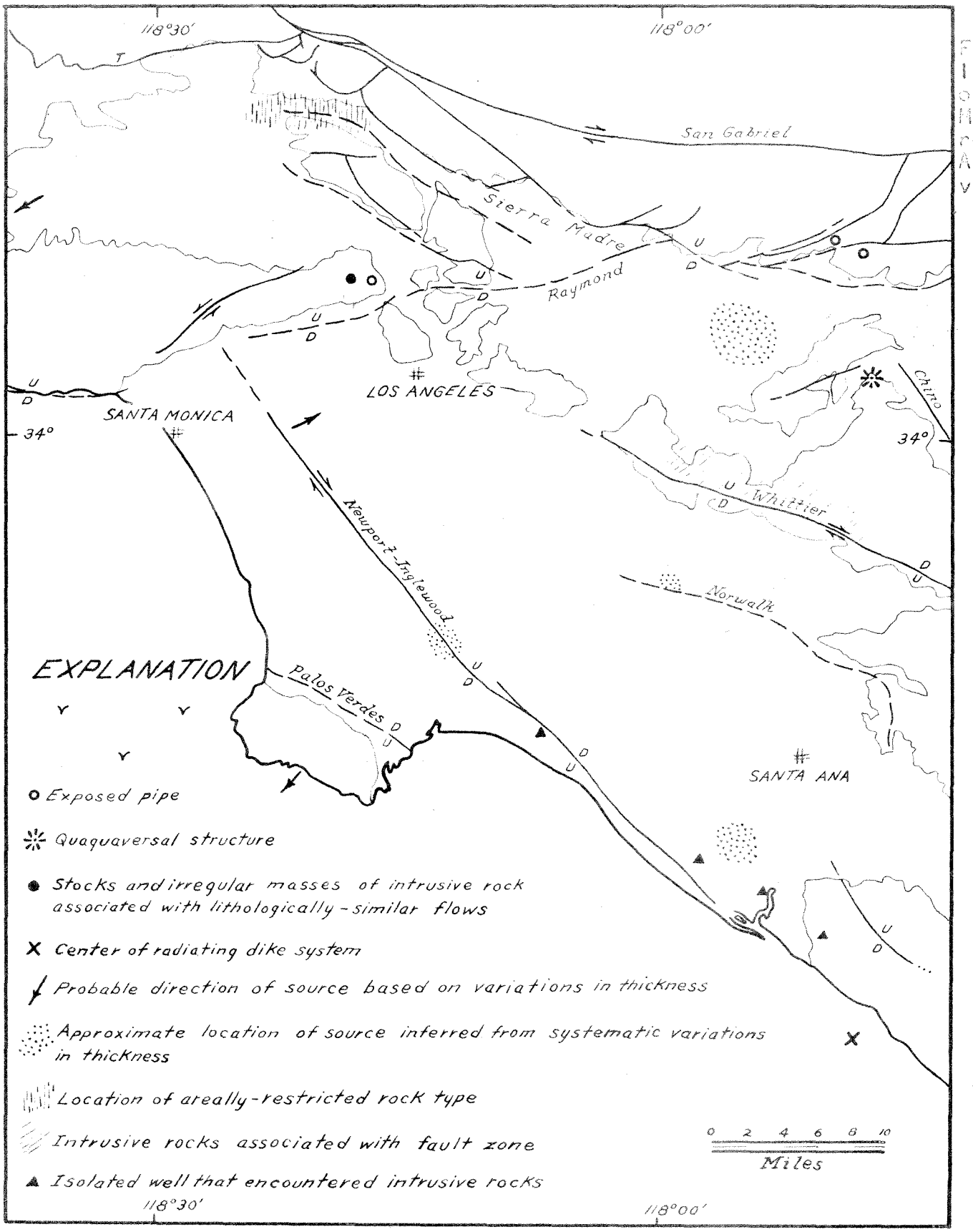


Figure 33. Inferred centers of eruption of Miocene volcanic rocks in the Los Angeles basin and vicinity.

The close proximity of inferred volcanic centers to the principal faults of the region is striking. This relationship is significant, however, only for those faults that pre-date the volcanic activity. The Sierra Madre fault zone, near which the Glendora and Sunland volcanic rocks were erupted, is probably pre-Miocene or early Miocene in age, for the San Gabriel Range, which it bounds, is known to have been an elevated block in middle Miocene times. Crowell (1954, p. 52) postulated a late Oligocene or early Miocene age for the ancestral San Gabriel fault. The Whittier fault is believed by Woodford et al. (1954, p. 75) to be of post-middle Miocene age, and results of the present investigation reveal that the Whittier diabase is intrusive into rocks of late Miocene age. Movement in the Newport-Inglewood zone is characterized as "old" by Woodford et al. (op. cit.), and cross-sections indicate that the amount of vertical displacement has been less and less in successively younger beds, beginning with middle Miocene strata. One of the principal faults in the San Joaquin Hills disappears beneath Luisian strata of the Monterey formation. This fault and others in the hills, as well as some of those in the Santa Monica Mountains, were invaded by magma belonging to the eruptive episode under discussion. Thus most of the major faults in the area were in existence prior to the volcanic activity, and therefore could have served as channel-ways for

ascending magma. Many of these faults experienced more than one period of movement, and as a result the lavas locally were cut by them.

Two principal types of faults predominate in the region. The Sierra Madre, Whittier, Cherry Hill, Santa Susana, and others are characterized by reverse dip-slip movement, whereas the San Gabriel fault shows evidence of pronounced lateral (strike-slip) movement. Evidence discussed above indicates that many of these faults were active prior to the period of volcanism. Thus it cannot be said, as it has been of many volcanic regions, that the area is one that primarily underwent extension. It is probable, as Menard (op. cit.) suggested, that these faults are relatively superficial fractures that are incidental to local variations in plastic deformation near the base of the crust. The thrusting that took place in the Santa Ynez Range, and, to a limited extent, at the front of the San Gabriel Range, was probably the result of horizontal components of stress arising from differential subsidence and marginal crowding at the sides of down-settling crustal blocks.

PETROLOGY

Mineralogy of the Rocks

Detailed petrographic descriptions of the Miocene volcanic rocks in the Los Angeles basin have been given on previous pages. Modal analyses of a selected number of these rocks are presented in Table 6. The rocks are characteristic of the basalt-andesite-rhyolite association of the circum-Pacific orogenic belt. They range in composition from olivine basalt to rhyolite, but lavas and pyroclastic rocks of andesitic composition predominate. The latter comprise olivine-bearing basaltic andesite, hypersthene-augite andesite, and subordinate hornblende andesite. Dacites are conspicuously few in number.

With the exception of the mineral oligoclase, which was noted by Shelton (1955) in rhyolites and acid andesites from the Glendora area, the rocks of the region are typified by plagioclase feldspars that range from calcic andesine to calcic labradorite. In general, the phenocrysts and microphenocrysts are more calcic than the groundmass individuals. Here and there, rocks containing phenocrysts of bytownite can be found but they are not abundant. Zoning is common, and is predominantly normal in character. These feldspars are accompanied by one or more of the following mafic minerals: olivine, augite

TABLE 6. MICROMETRIC ANALYSES OF SELECTED MIOCENE VOLCANIC ROCKS FROM THE LOS ANGELES BASIN, CALIFORNIA. (Data in part from Shelton, 1955.)

KEY TO ABBREVIATIONS USED IN TABLE 6.

ROCK TYPES

alt bas = altered basalt

and = andesite

aug and = augite andesite

bas = basalt

cal and = "calcic andesite" of Shelton (1955)

fel rhy = felsitic rhyolite

f-g and = "fine-grained andesite" of Shelton (1955)

h-a and = hypersthene-augite andesite

h-b band = hypersthene-bearing basic andesite

hbl and = hornblende andesite

hyp and = hypersthene andesite

hyp bas = hypersthene basalt

o-b bas and = olivine-bearing basaltic andesite

olv bas = olivine basalt

olv dia = olivine diabase

rhy = rhyolite

sdm tbx = sideromelane tuff-breccia

TEXTURE

f-g = fine grained

hlh = holohyaline

hlx = holocrystalline

hyh = hypohyaline

hyo = hyaloophitic

hyx = hypocrystalline

ing = intergranular

ins = intersertal

mpk = micropoikilitic

oph = ophitic

pil = pilotaxitic

ser = seriate

s-o = subophitic

trc = trachytic

vph = vitrophyric

OCCURRENCE

ext = extrusive

int = intrusive

Und = undetermined

SPECIMEN: See end of table for location of specimen.

Abbreviations (cont.)

MINERALS

Plagioclase

- s = sodic
- m = median
- c = calcic
- A = andesine
- Alb = albite
- B = bytownite
- L = labradorite
- O = oligoclase

Alt = altered

Anl = analcite

Apa = apatite

Aug = augite

Bio = biotite

Cal = calcite

Cel = celadonite

Cha = chalcedony

Chp = chlorophaeite

Dol = dolomite

En_{55} = % enstatite in hypersthene

Gls = glass

Hbl = hornblende

Hyp = hypersthene

Ilm = ilmenite

Mag = magnetite

Nat = natrolite

Olv = olivine

Opl = opal

Ore = ore

Pal = palagonite

Pyr = pyrite

Qtz = quartz

Sid = sideromelane

Tia = titanaugite

tr. = trace amount

Und = undetermined

% SiO_2

All figures are recast on an H_2O-free, CO_2-free basis.

"a" indicates a determination by chemical analysis

"b" indicates a determination by the Mathews' bead test

SPECIMEN	BVD-3b	BVD-5	BVS-7I	BVP-6	BVF-I	BVN-4
ROCK TYPE	o-b bas and	olv bas	o-b bas and	olv dia	olv dia	bas
% SiO_2	56a	50a	58b	50b	5Ib	Und
PHENOCRYSTS						
Plagioclase	c-L 12.2	m-B 20.3	B+L 17.5			L-B 15.0
Olivine	I.9	5.8	0.3			alt 2.4
Clinopyroxene	Aug 0.9		Aug I.3			Aug 2.6
Orthopyroxene						
Other						
GROUNDMASS	85.I		80.0			
Plagioclase	c-A	s-L 29.6	A-L	c-L 53.4	c-L 59.7	m-L 40.8
Olivine		alt 5.7		I3.8	21.0	alt 2.4
Clinopyroxene	Und	Aug 26.6	Und	Aug 23.7	Aug I4.9	Und 24.8
Orthopyroxene						
Hornblende						
Biotite						
Ores	Mag	Ilm 7.0	Mag	Ilm 4.9	Ilm 4.8	Und 4.0
Other	Blo tr.	Apa				
Alteration products		Unk. 4.3		Non? 4.0		ChP 7.7
TEXTURE	hyx pil	hlx s-o amy	hlx f-g ing	hlx ing	hlx s-o	hlx ing
OCCURRENCE	int	ext	ext	int	int	Und

SPECIMEN	BVN-30	BVN-36	BVN-57	BVN-63	BVV-5b	BVV-14b
ROCK TYPE	hyp bas	olv dia	sdm tbx	olv bas	alt bas	h-a and
$\%SiO_2$	53a	48b	Und	49a	Und	57a
PHENOCRYSTS						
Plagioclase	L 8.7		m-L ~3		s-B 5.9	s-B 14.1
Olivine	2.1	3.0	~7			
Clinopyroxene	Aug 4.2					Aug 0.4
Orthopyroxene						En_{59} 3.0
Other						
GROUNDMASS						
Plagioclase	m-L 51.0	c-L 42.3		m-L 47.3	m-L 35.6	m-L 21.4
Olivine		alt		20.7		
Clinopyroxene	Aug 17.0	Aug 19.1		Aug 22.7	Aug 3.0+	Und 8.6
Orthopyroxene	En_{55} 6.6					Hyp 2.0
Hornblende						
Biotite						
Ores	Mag 5.1	Ilm 3.3		Ilm 4.0	Ilm 3.0	Ilm 0.7
Other	Apa		sdm ~37		Gls 4.0+	Gls 34.5
Alteration products	Und 4.2	Cel? Chp 31.9	Pal ~49	Und 5.1	Chp Cal Pyr 48.3	Dol Chp Pyr 14.0
TEXTURE	hlx ing ser	hlx oph	pyx	hlx s-o	hyx hyo	hyx hyo
OCCURRENCE	ext	int	ext	ext	int	int

SPECIMEN	BVV-21	BVJ-7	BVJ-2	BVJ-9a	BVE-1	No. 5
ROCK TYPE	olv dia	h-a and	h-b band	aug and	o-b bas and	olv bas
%SiO_2	50b	60a	57a	57a	54b	Und
PHENOCRYSTS						
Plagioclase		m-L 33.3	m-L 24.6		c-L 0.7	m-L 20
Olivine					alt	alt 24
Clinopyroxene		Aug 5.1+				
Orthopyroxene		En_{57} 11.2	En_{68} 13.5			
Other						
GROUNDMASS						54
Plagioclase	c-L 47.0		s-L 34.5	m-L 60.3	m-L 45.6	m-L
Olivine	18.4					
Clinopyroxene	Tia 20.4		Aug 20.2	Aug 18.1	Und 28.2	
Orthopyroxene						
Hornblende						
Biotite						
Ores	Ilm 3.1		Und 4.3	Mag 4.6	Und 7.8	Mag
Other	Nat 10.2	Gls 51.1		Gls 16.2		
Alteration products	Hbl Bio? Pyr tr.		Chp 2.9		Und 16.6	Chp
TEXTURE	hlx oph	hyh vph	hlx lng	hlx lng trc	hlx ing ser	hlx s-o
OCCURRENCE	?	ext	int	int	ext	ext

SPECIMEN	S-422	S-347	S-615	S-333$_2$	S-339	S-519	
ROCK TYPE	olv bas	olv bas	olv bas	cal and	f-g and	hbl and	
%SiO_2	49a	49a	54a	60a	61a	66a	
PHENOCRYSTS							
Plagioclase				m-L 28.0		s-L 18.6	
Olivine			4.6				
Clinopyroxene							
Orthopyroxene				Hyp 8.0			
Other						Hbl 9.3	
GROUNDMASS							
Plagioclase	c-L 46.2	m-L 67.0	m-L 45.3	c-A 43.0	c-A 71.0	Und ~25	
Olivine	14.0	1.0					
Clinopyroxene	Und 19.4	Aug 11.0	Aug 23.0	Aug 4.0	Aug 6.0		
Orthopyroxene		Hyp 5.0					
Hornblende							
Biotite							
Ores	Mag 1.5	Mag 8.0	Mag 6.5	Und 6.0	Und 5.0	Mag ~2	
Other	Und 4.6	Cha 8.0	Gls 12.8	Gls 11.0	Gls 15.0	Gls ~15	Und ~30
Alteration products	Und 14.0	Chl	Und 7.8		Chl 3.0		
TEXTURE	hlx oph	hlx ing	hyx ins	hyx	hyx pil	hyx	
OCCURRENCE	Und	ext	ext	ext	ext	ext	

SPECIMEN	S-468	S-673	S-496
ROCK TYPE	hyp and	rhy	fel rhy
$\%SiO_2$	67a	76a	77a
PHENOCRYSTS			
Plagioclase	m-L 32.3	Al-Olg 20-25	Olg 5-10
Olivine			
Clinopyroxene	Aug 4.7		
Orthopyroxene	Hyp 4.7		
Other		Qtz 1-2	Bio 1-2
GROUNDMASS	61.3		
Plagioclase	Und		
Olivine			
Clinopyroxene			
Orthopyroxene			
Hornblende			
Biotite			
Ores	Mag		
Other	Gls Qtz	Gls 75	Gls 90-95
Alteration products			
TEXTURE	hyh mpk	hlh	hlh
OCCURRENCE	ext	ext	ext

LOCATION OF SPECIMENS

SUNLAND AREA

BVD-3b : Akens Canyon, San Gabriel Mountains

BVD-5 : Akens Canyon, San Gabriel Mountains

BVS-71 : Southwest edge of Sunland, Verdugo Mountains

BVP-6 : Central Pacoima Hills

SANTA SUSANA MOUNTAINS

BVF-1 : West edge of Aliso Canyon oil field

EASTERN SANTA MONICA MOUNTAINS

BVN-4 : Main Brush Canyon quarry, Griffith Park

BVN-30 : Vista del Valle Drive, Griffith Park

BVN-36 : Mt. Hollywood Drive, Griffith Park

BVN-57 : Mulholland Drive near Outpost Drive

BVN-63 : Mulholland Drive and Woodrow Wilson Drive

PALOS VERDES HILLS

BVV-5b : Bluff Cove

BVV-14b: Sea cliff north of Point Vincente

BVV-21 : Southern slope of hills, east of Point Vincente

SAN JOAQUIN HILLS

BVJ-7 : Bonita Reservoir

BVJ-2 : West of Signal Peak

BVJ-9a : U.S. Hwy 101, Laguna Beach

EL MODENO AREA

BVE-1 : Irvine Park Drive, El Modeno Hills

No. 5 : See Yerkes (195_)

GLENDORA AREA

See Shelton, 1955

(and rarely pigeonite), hypersthene, hornblende, and the "ores," chiefly magnetite and ilmenite.

In a general way, the variety of mafic minerals present in a given rock is characteristic of its gross composition. It can be seen from Figure 34 that each mafic mineral is restricted to a certain range in composition, and, although the ranges of the different minerals overlap somewhat, combinations of two or more of them define the composition of the rock rather closely. Olivine, in amounts ranging from 1 to 21 percent, characterizes the basalts with 45 to 54 percent of silica,* and in lesser amounts (0 to 2 percent), the basaltic andesites with 54 to 58 percent of silica. Augite is also present in these rocks, but its range extends beyond that of olivine to andesites containing as much as 67 percent of silica. In olivine basalts with 47 to 51 percent of silica, a titaniferous variety of augite (pinkish brown in color) is common. In olivine-free basalt, olivine-bearing basaltic andesites, and basic hypersthene-augite andesites, the augite is diopsidic, and is colorless, very pale yellow, or pale yellow-green. In the acid hypersthene-augite andesites and hornblende-augite andesites it is generally pale green.

Measurements of the optic angles of clinopyroxenes

---

* In the discussion that follows, all references to the silica content of the rocks refer to silica percentages of recast analyses from which water and carbon dioxide have been deleted.

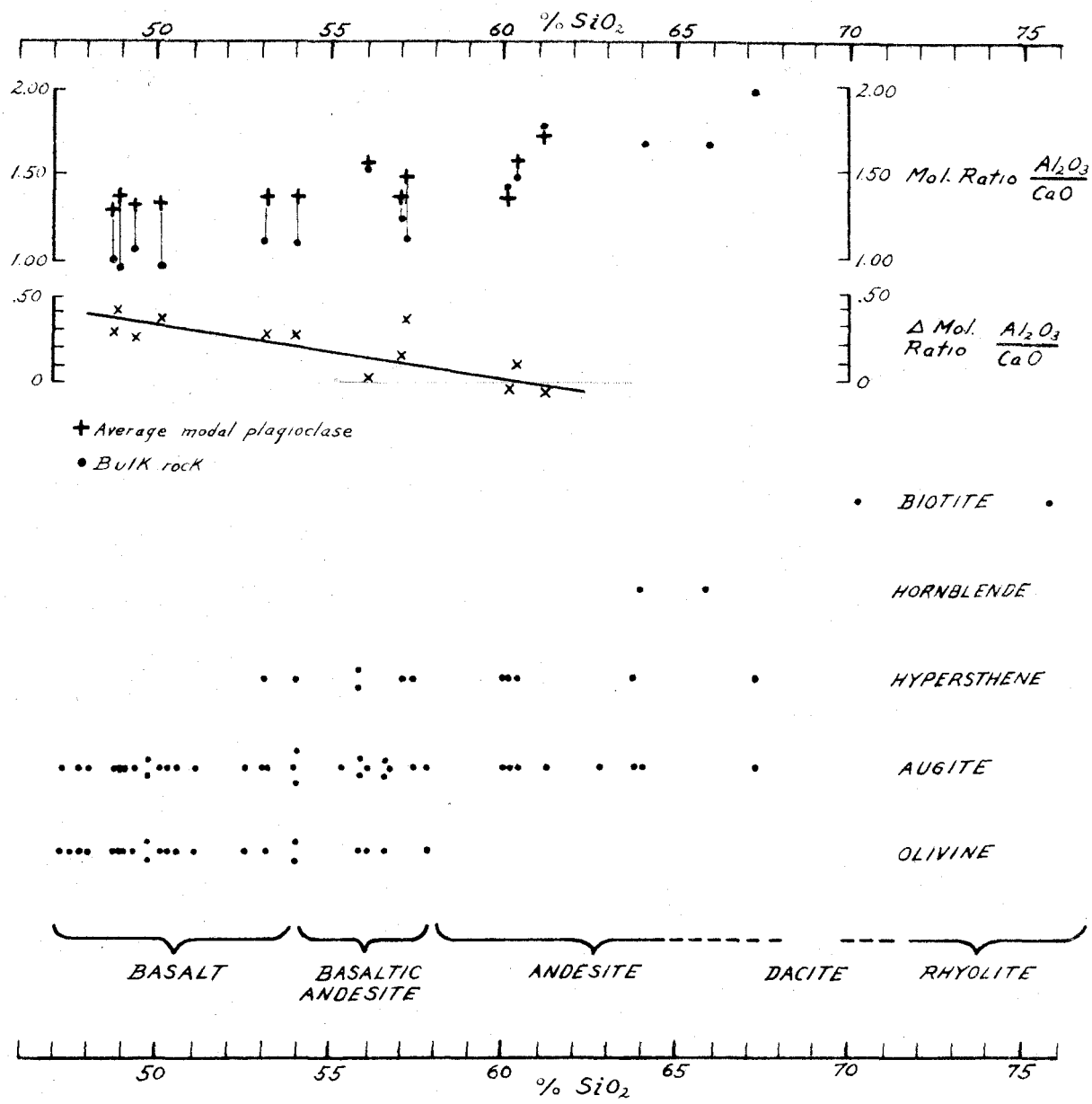


Figure 34. Diagram showing the ranges in rock composition (measured in terms of % SiO_2) over which specific mafic minerals were noted to have crystallized. Each point represents an analyzed specimen in which the mineral under consideration was observed. Values for % SiO_2 were determined by chemical analysis and artificial fusion of rock powders. The upper part of the diagram shows the contrast between the molecular ratio Al_2O_3 : CaO of the chemically analyzed bulk rocks and that of the average modal plagioclase of the rocks. The difference in this ratio determines, in part, the type of pyroxene that will crystallize.

indicate that pigeonite ($2V = 0^{\circ}$ to 18°) is an uncommon mineral in this region. The only specimens in which it was found came from dikes and other hypabyssal intrusive bodies in the San Joaquin Hills. In a few of these rocks it is accompanied by calcium-poor augite ($2V = 30^{\circ}$ to 42°).

Hypersthene is present in rocks ranging in composition from basalt to acid andesite, but its greatest abundance is in the andesites. Its range overlaps that of olivine, but the number of specimens in which it was found in coexistence with olivine is far fewer than the number in which each occurred only with augite. Shelton (1955, p. 68) described a basalt in which he found hematite "pseudomorphous after hypersthene." In Figure 34 the point representing this rock would lie well within the basalt range, at approximately 49.4 percent silica. It is not included on the diagram.

In most specimens, the hypersthene is a colorless or nearly colorless variety, ranging in composition from En_{53} to En_{75}. It commonly displays prismatic jackets of clinopyroxene or irregular mantles of finely granular clinopyroxene. Many of the volcanic rocks from the circum-Pacific volcanic-orogenic region contain hypersthene, and although it is present in a few basalts, it occurs most commonly in what different investigators have called "two-pyroxene andesites," "hypersthene andesites," or "hypersthene-augite andesites."

A characteristic feature of volcanic rocks from this region is their relatively high content of alumina. It is this alumina and its relationship to the amount of lime in the rocks that accounts for the abundance of hypersthene. In rocks with a lesser amount of alumina, some of the lime is free to participate in the formation of diopsidic pyroxene, but in the more aluminous rocks calcium is taken up by calcic plagioclase (in the so-called "anorthite molecule"). This relationship can be expressed schematically as follows:

plagioclase 1 augite

$$(xCaAl_2Si_2O_8, NaAlSi_3O_8) + (Ca \cdot Mg, Fe)Si_2O_6 + Al_2O_3 \rightarrow$$

plagioclase 2 hypersthene

$$(yCaAl_2Si_2O_8, NaAlSi_3O_8) + (Mg, Fe)SiO_3 \qquad (\text{where } x < y)$$

The same relationship accounts for the fact that hypersthene crystallizes in greater abundance in the andesites than in the basalts of the Los Angeles basin. Plotted at the top of Figure 34 are two sets of points. One represents the molecular ratio of alumina to lime in the analyzed bulk rocks, and the other represents the same ratio for the plagioclase feldspars of these rocks. Compositions of the plagioclase were determined from weighted averages of the modal plagioclase. In the rocks that are partially glassy, however, the modal plagioclase may not represent the plagioclase that would have been formed ultimately

if crystallization had been complete. Points representing the plagioclase composition and the bulk composition of a given rock are joined by a straight line.

The curve shown below these points is based on the algebraic difference between the molecular ratio of alumina to lime in the plagioclase and bulk rock. Ideally, as this curve approaches zero, that is, as the ratio of alumina to lime in the rock and in the plagioclase approach equality, hypersthene should begin to crystallize. This can be explained in the following manner. The proportion of total alumina to total lime in a rock is a function of the composition of the magma from which the rock has crystallized, but the relative proportion of these components in a given mineral phase of the rock is in part a function of their distribution in all of the coexisting mineral phases. If the plagioclase crystallizing from a melt of given composition has a relatively higher ratio of alumina to lime than the melt, and if all of the alumina is taken up in the feldspar structure only, then the relatively lower ratio of alumina to lime in the rock must be a function of an "excess" of lime. In most of the holocrystalline basic and intermediate rocks of the basin, plagioclase, olivine, pyroxene(s), apatite and ilmenite or magnetite are the only minerals present. The alumina can enter, in significant amounts, only the plagioclase structure, and thus if the alumina of the plagioclase that is crystallizing

does not "saturate" all of the lime that is present in the melt, then the latter can enter diopside.

In general, hypersthene is not the only mafic silicate mineral present in the Los Angeles volcanic rocks. In most of the rocks, the "alumina-saturation" of lime has not been so complete that augite is prevented from crystallizing. This in part represents a departure from the idealized conditions described in the previous paragraph. The departure is a function not only of the relative amounts of alumina and lime present in the rocks, but also of the amounts of ferrous iron and magnesia, both of which can enter clinopyroxene, and orthopyroxene as well. If lime is "available" for the formation of diopside, and there is an excess of ferrous iron and magnesia, these constituents commonly will form hypersthene. The reader will recognize that this forms part of the basis for the computation of the C.I. P.W. "norm."

The compositional range of rocks in which hornblende occurs is restricted primarily to the acid andesites. Oxyhornblende is the predominant variety, but green hornblende was found in a few specimens. The range of both augite and hypersthene overlap that of hornblende.

Biotite is represented by only two specimens in Figure 34. One of these (at 70 percent silica) is the Mountain Meadows dacite, which Shelton (1955, p. 54) considered to be pre-middle Miocene in age. He also described

a breccia of biotite andesite (op. cit., p. 59) and a dike of "augite-biotite basalt (or calcic andesite)," (op. cit., p. 69). If these two rocks represent normal differentiates of the Los Angeles basin parent magma, then it must be assumed that the crystallization range of biotite covers a variety of rocks from basic andesite (or even basalt) to rhyolite.

In recapitulation, rocks containing modal augite and olivine are basalts or basaltic andesites (47 to 58 percent of silica), those with hypersthene, augite, and olivine are chiefly basaltic andesites (53 to 58 percent of silica), those with hypersthene and augite only are basaltic andesites or acid andesites (53 to 67 percent of silica), those with hornblende (and commonly augite) are intermediate or acid andesites (available specimens are too few in number for determining the range quantitatively), and those with biotite are commonly rhyolitic or andesitic in composition. Any geographic or time variation in the mineralogy of a group of lavas, therefore, is at least in part a measure of the extent of local differentiation.

In reviewing the order of eruptions in the basin for the purpose of defining possible time variations, one finds that during Relizian time olivine basalt was erupted in the eastern Santa Monica Mountains area, olivine basalt and olivine-bearing basaltic andesite were erupted near Sunland, and hypersthene-augite andesite was erupted in

the vicinity of the San Joaquin Hills. During the Relizian-Luisian transition interval, volcanic activity near Inglewood produced rocks of basaltic and rhyolitic composition. A short time later (early Luisian) peperites and other bodies of hypersthene-augite andesite and olivine diabase were emplaced in the Palos Verdes Hills, and a compositionally-varied suite of rocks ranging from olivine basalt to rhyolite was extruded near Glendora. Late in the Luisian, olivine basalt and breccias, and flows of olivine-bearing basaltic andesite were extravasated near Norwalk and Orange. This activity continued until the end of the Luisian stage, and possibly even longer. During Mohnian time, olivine diabase was intruded along the Whittier fault zone, and breccias of basalt may have been erupted near Dominguez. There seems to have been little similarity of composition, therefore, between the lavas extruded concomitantly in different parts of the basin. For this reason, it is impossible to determine the relative age of a given rock specimen on the basis of its mineralogical composition alone.

Although lavas of a given type did not predominate at any one time during the course of volcanic activity, there was a tendency toward a geographic restriction of lava compositions. Olivine basalt and olivine-bearing basaltic andesite characterize the northwestern part of the region (San Fernando Valley, Sunland, and eastern

Santa Monica Mountains), and hypersthene-bearing andesites characterized the southwestern, southern, and northeastern parts of the region (Palos Verdes Hills, Santa Catalina and San Clemente Islands, San Joaquin Hills and adjacent areas, and San Jose Hills and San Gabriel Mountains). In the eastern half of the area, acid and intermediate rocks are found to the north (Glendora volcanic series), but only those of intermediate composition are found to the south. Shelton (1954, p. 33) reported that andesites containing hornblende and hypersthene are present in the Conejo Hills (western Santa Monica Mountains), and thus the area of predominantly basic rock in San Fernando Valley and the eastern Santa Monica Mountains is flanked on either side by areas of intermediate volcanic rocks. Evidently the course of magmatic differentiation in the eastern Santa Monica Mountains area differed from that in other parts of the region.

Petrographic Data Bearing on the Mechanism of Magmatic Differentiation

One of the fundamental problems underlying any attempt to understand the mechanism of magmatic differentiation is that of determining the composition of the parent magma. Unless this is known, it is difficult to determine uniquely the process of evolution of each of the rocks in the group. Olivine basalt or diabase occurs in almost

every part of the Los Angeles basin, and during the course of the present investigation specimens were collected from every area but the San Joaquin Hills. On the basis of its widespread occurrence, it is conceivable that this rock represents the parent magma of the region. On the other hand, olivine basalts in certain volcanic sub-provinces to the north were considered by Nockolds and Allen (1953) to represent "accumulative rocks"(i.e., rocks that had formed or been contaminated through the accumulation of early-formed crystals). The rocks which these investigators considered to be representative of the parent magmas of the northern areas are more closely related to rocks in the Los Angeles basin that are intermediate in composition between basaltic andesite and basalt. It is noteworthy that the proportion of andesites to other volcanic rocks in the basin is large. If a magma of andesitic composition were not the parent magma, any proposed hypothesis of differentiation must be capable of explaining the great preponderance of this rock.

If it be assumed, for the sake of argument, that the parent magma of the Los Angeles basin had the composition of basaltic andesite, then the more basic rocks such as olivine basalt must have resulted from the accumulation of early-formed crystals of olivine and possibly calcic plagioclase. Inasmuch as these two minerals are higher in the Bowen reaction series than any of the minerals

crystallizing from the basaltic andesite magma, the magma would have been supersaturated with respect to them, and therefore would have been incapable of converting (melting) them to the liquid state unless superheated (Bowen, 1928). Even though the magma would be incapable of melting these crystals, equilibrium would be maintained by a process of reaction, whereby the "foreign" crystals would be partly converted through ionic transposition to pyroxene, and to another, less calcic, plagioclase. If samples of this magma could be drawn off and quenched at various stages of the process, from the moment that olivine and plagioclase crystals came into contact with the magma of basaltic andesite to the moment of complete crystallization, a detectable amount of at least two solid phases would be found in all specimens. In the early ones, there would be phenocrysts of olivine and plagioclase, and in the later ones, phenocrysts of olivine and possibly pyroxene, and perhaps, a more sodic plagioclase. Thus the process of accumulation would yield rocks of vitrophyric or porphyritic texture in which the "accumulated" crystals would occur as phenocrysts. Bowen (op. cit., pp. 159-165) described many examples of this phenomenon.

West of Cahuenga Pass, in the eastern Santa Monica Mountains, is a glassy tuff-breccia of olivine basalt that was rapidly quenched as a result of submarine deposition. A study of thin sections of this rock revealed

that it was erupted in a molten state. The blocks and bombs that are present are partially crystalline and vitrophyric, but the smaller, more rapidly quenched lapilli are composed almost entirely of glass. The latter indicate that the crystals of olivine and calcic plagioclase in the holocrystalline equivalents of the lapilli are not the result of an accumulation process. These crystals nucleated and grew directly from a melt that had the composition of olivine basalt. On the basis of this kind of evidence, the parent magma of the Los Angeles volcanic rocks is thought to have had the composition of olivine basalt.

With an initial magma of this composition, all of the other rocks in the area must have evolved via some mechanism of magmatic differentiation. Bowen's (op. cit.) thesis of fractional crystallization is particularly appealing, in view of the fact that the relative volume of rhyolite in the basin is approximately what might be expected from the extended fractional crystallization of basalt. On the other hand, the large amount of andesite relative to that of basalt suggests that other factors also may have been involved in the differentiation of these rocks.

The basaltic tuff-breccia of the eastern Santa Monica Mountains sheds light on the process of differentiation by fractional crystallization. Clasts of all sizes occur

in this unit, and each has undergone a degree of crystallization that is roughly proportional to its size. The smallest ones consist almost entirely of glass with scattered crystallites of olivine, whereas the largest ones are holocrystalline and consist of plagioclase, olivine, augite, and magnetite. A series of these clasts was collected, and micrometric analyses were made of them. The results of these analyses are shown in Figure 35. During the earliest stages of crystallization, olivine was present in an amount exceeding that of plagioclase. When the rock had reached a stage of 15 percent crystallinity, however, the amount of plagioclase began to increase rapidly, a trend that remained active until the rock was almost two-thirds crystalline. During the same period of time olivine crystallized in very small amounts. It reached its maximum development when the rock was 70 percent crystalline, and at this time augite began to appear. The significance of these findings lies in the fact that they place definite boundary conditions on any hypothetical mechanism of differentiation that might be proposed. Inasmuch as augite did not begin to crystallize until the rock was 70 percent crystalline, it would have been impossible for this mineral to have taken an active part in differentiation by crystal fractionation. On the other hand, nearly half of all the olivine was crystalline when the rock was still 90 percent molten, and thus it could

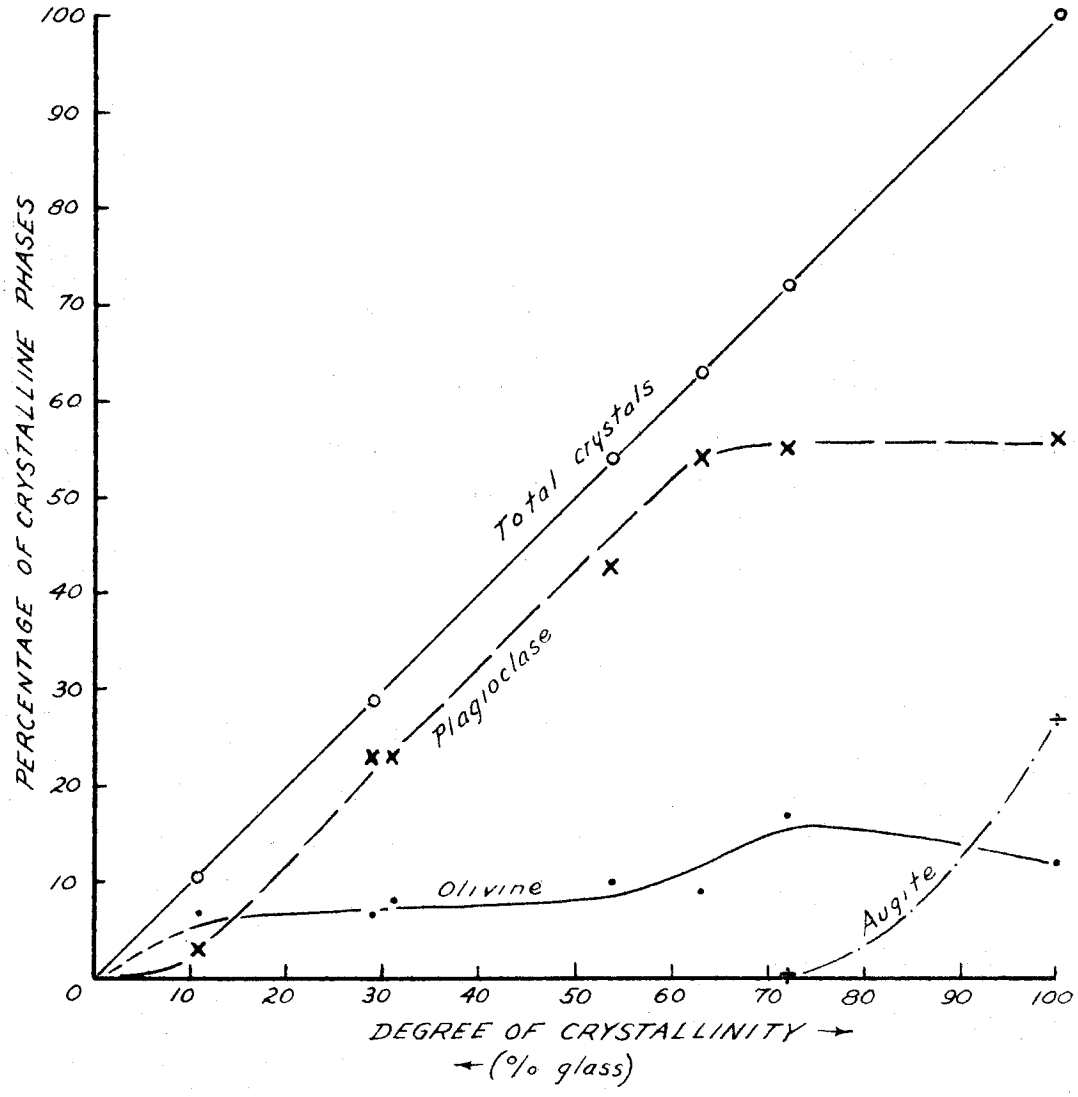


Figure 35. Diagram showing the relative proportions of various mineral phases at different stages in the crystallization of an olivine basalt in the eastern Santa Monica Mountains. Based on micrometric analyses of lapilli and blocks of a sideromelane tuff-breccia.

have played a very active part.

Another process of differentiation worthy of consideration is that of contamination of the lavas by assimilation of country rock. Several inclusions of plutonic rock, apparently of quartz dioritic composition, were found in one of the flows of basaltic andesite exposed south of Sunland. These inclusions are less than three inches in diameter, and consist primarily of anhedral crystals of andesine, quartz, subordinate potash feldspar (?), and biotite. These crystals have been rounded by corrosion, and are partly detached at the edges of each inclusion. Wholly detached crystals are rounded and deeply embayed.

Partially digested xenoliths of gabbro (?) were encountered in flows of hypersthene-augite andesite in the northwestern part of the San Joaquin Hills. R. F. Yerkes, who made a careful study of these xenoliths, reported (personal communication, 1956) that in places they constitute as much as five percent of the flows by volume. They are composed principally of labradorite and augite, in a ratio of approximately four to one. Like the quartz diorite inclusions at Sunland, these show evidence of corrosion and partial disintegration.

Shelton (1955, p. 55) noted euhedral crystals of garnet in flows of felsophyre in the northern part of the Puente Hills. He attributed them to contamination of the lava by garnetiferous pegmatite dikes which cut the quartz

diorite "basement" rocks nearby. All of these inclusions indicate that foreign debris was contributed to the magma by the country rocks through which the magma passed. The corrosion of the individual mineral constituents of these inclusions suggests that some of this debris may have been melted or dissolved.

Inasmuch as the major mineral constituents of quartz diorite and granitic pegmatite are lower in the Bowen reaction series than the minerals that normally crystallize from a basaltic magma, such a magma would be able to incorporate the foreign material in the liquid phase by melting it. This melting, however, would be accompanied by concomitant crystallization of minerals with which the magma was saturated.

Chemical Data Bearing on the Mechanism of Magmatic Differentiation

The results of eight new chemical analyses of volcanic rocks in the Los Angeles basin are presented in Table 7. Fourteen previously published analyses are given in Table 8 for the sake of reference. Three of the latter are from Smith (1897, 1898); the remainder are from Shelton (1955).

The relatively high percentages of water in the analyzed rocks are noteworthy. Sample BVJ-7 represents a fresh glassy flow with only minute amounts of hydroxyl-bearing minerals lining its vesicles. Inasmuch as the

TABLE 7: NEW CHEMICAL ANALYSES OF MIOCENE VOLCANIC ROCKS FROM THE LOS ANGELES BASIN, CALIFORNIA

(All figures in percents)

ROCK	OLIVINE-BEARING BASALTIC ANDESITE (BVD-3b)	OLIVINE BASALT (BVD-5)	HYPERSTHENE BASALT (BVN-30)
SiO_2	55.48	48.20	51.72
Al_2O_3	18.03	18.53	18.58
Fe_2O_3	7.56	3.54	3.18
FeO	1.74	4.72	3.92
MgO	2.06	5.48	5.86
CaO	6.57	10.46	9.20
Na_2O	4.44	3.02	3.05
K_2O	1.18	.38	.66
H_2O+	.40	2.31*	1.56
H_2O-	.73	1.39*	1.28
CO_2	-----	Tr.	-----
TiO_2	1.54	1.58	1.01
P_2O_5	.30	.14	.15
S	-----	-----	-----
MnO	.10	.14	.07
OTHER	-----	-----	-----
OTHER	-----	-----	-----
TOTAL	100.13	99.89	100.24
LOCATION	Akens Cn. San Gabriel Mts.	Akens Cn. San Gabriel Mts.	Griffith Park Santa Monica Mts.
ANALYST	W.H.Herdsman Glasgow	W.H.Herdsman Glasgow	W.H.Herdsman Glasgow

*Thought to be in error.

ROCK	OLIVINE BASALT (BVN-63)	HYPERSTHENE-AUGITE ANDESITE (BVV-14b)**
SiO_2	48.03	52.42
Al_2O_3	16.37	15.64
Fe_2O_3	1.88	3.42
FeO	9.61	2.97
MgO	8.64	3.72
CaO	9.33	8.06
Na_2O	2.69	2.88
K_2O	.31	1.03
H_2O+	1.18	2.47
H_2O-	.80	.69
CO_2	-----	2.70
TiO_2	1.12	1.15
P_2O_5	.08	.07
S	-----	3.49
MnO	.16	.03
OTHER	-----	C 1.20
OTHER	-----	-O for S 1.74
TOTAL	100.20	100.20
LOCATION	Mulholland Dr. near Woodrow Wilson Dr. Eastern Santa Monica Mts.	Immediately north of Pt. Vincente Palos Verdes Hills
ANALYST	W.H.Herdsman Glasgow	W.H.Herdsman Glasgow

**Contaminated rock.

ROCK	HYPERSTHENE-AUGITE ANDESITE (BVJ-7)	AUGITE ANDESITE (BVJ-9a)	HYPERSTHENE-BEARING BASALTIC ANDESITE (BVJ-2)
SiO_2	58.24	55.32	55.6
Al_2O_3	15.97	17.04	13.5
Fe_2O_3	1.39	2.28	2.3
FeO	5.25	3.84	6.8
MgO	4.33	5.72	6.0
CaO	6.19	7.63	6.7
Na_2O	3.02	3.58	3.8
K_2O	.99	.52	.60
H_2O+	2.28	1.46	} 2.0
H_2O-	.80	1.57	
CO_2	-----	-----	Tr
TiO_2	1.28	.86	1.7
P_2O_5	.08	.15	.24
S	-----	-----	-----
MnO	.06	.06	.13
OTHER	-----	-----	-----
OTHER	-----	-----	-----
TOTAL	99.88	100.03	99.4
LOCATION	Bonita Res. San Joaquin Hills	Laguna Beach San Joaquin Hills	Signal Pk. San Joaquin Hills
ANALYST	W.H.Herdsman Glasgow	W.H.Herdsman Glasgow	U.S.G.S. Laboratory (Unpublished analysis, courtesy of R.F.Yerkes)

TABLE 8: PREVIOUSLY PUBLISHED CHEMICAL ANALYSES OF MIOCENE VOLCANIC ROCKS FROM THE LOS ANGELES BASIN, CALIFORNIA

(All figures in percents)

ROCK	RHYOLITE	DACITE	HYPERSTHENE AUGITE ANDESITE
SiO_2	70.39	66.85	61.05
Al_2O_3	14.09	14.08	18.30
Fe_2O_3	.53	3.08	3.49
FeO	2.12		1.11
MgO	.62	.91	2.59
CaO	3.08	4.69	7.75
Na_2O	3.70	3.80	4.06
K_2O	3.51	2.57	1.36
H_2O+	2.50	2.07	.71
H_2O-			
CO_2			-----
TiO_2	-----	-----	.09
P_2O_5	-----	-----	-----
S	-----	-----	-----
MnO	-----	-----	-----
BaO	-----	-----	-----
OTHER	-----	-----	-----
TOTAL	100.54	98.05	100.51
LOCATION	San Clemente Island	San Clemente Island	Santa Catalina Island
ANALYST	W.S.T.Smith	W.O.Smith	W.S.T.Smith
SOURCE	Smith, 1898	Smith, 1898	Smith, 1897

ROCK	OLIVINE BASALT (S-422)	OLIVINE BASALT (S-347)	OLIVINE BASALT (S-615)
SiO_2	47.23	48.20	51.06
Al_2O_3	16.65	16.89	15.36
Fe_2O_3	1.43	2.60	2.38
FeO	7.66	6.86	5.85
MgO	8.15	6.93	5.88
CaO	9.08	8.58	9.59
Na_2O	4.17	3.32	3.08
K_2O	.37	1.16	.78
H_2O+	2.77	1.35	1.02
H_2O-	.39	.80	.73
CO_2	.01	.09	1.49
TiO_2	1.59	2.33	1.60
P_2O_5	.35	.49	.72
S	.03	.02	.01
MnO	.16	.14	.12
BaO	.02	.03	.06
OTHER	-----	-----	-----
TOTAL	100.06	99.79	99.73
LOCATION	1 mi. east of San Gabriel Cn. San Gabriel Mts.	E. fork of Sycamore Cn. San Gabriel Mts.	N.W. of Puddingstone Dam San Jose Hills
ANALYST	J. Kerr	J. Kerr	J. Kerr
SOURCE	Shelton, 1955	Shelton, 1955	Shelton, 1955

ROCK	CALCIC ANDESITE ($S-333_2$)	FINE-GRAINED ANDESITE (S-339)	HYPERSTHENE ANDESITE (S-345)
SiO_2	59.53	59.90	63.19
Al_2O_3	18.30	17.89	18.18
Fe_2O_3	2.71	1.27	2.02
FeO	2.09	4.07	1.47
MgO	2.85	2.33	2.05
CaO	6.90	5.51	6.00
Na_2O	3.96	4.44	4.14
K_2O	.98	.90	.71
H_2O+	.47	1.56	.50
H_2O-	.88	.30	.90
CO_2	.00	.01	.00
TiO_2	.93	1.09	.56
P_2O_5	.28	.42	.16
S	.04	.01	.03
MnO	.06	.11	.04
BaO	.03	.01	.03
OTHER	-----	-----	-----
TOTAL	100.01	99.82	99.98
LOCATION	Glendora Foothills of San Gabriel Mts.	Mull Canyon San Gabriel Mts.	North of San Dimas Foothill Park
ANALYST	J. Kerr	J. Kerr	J. Kerr
SOURCE	Shelton, 1955	Shelton, 1955	Shelton, 1955

ROCK	HORNBLENDE ANDESITE (S-519)	HYPERSTHENE ANDESITE (S-468)	PERLITE (S-597)
SiO_2	64.93	66.16	72.16
Al_2O_3	17.20	16.65	13.73
Fe_2O_3	2.80	2.38	.32
FeO	.92	1.08	.88
MgO	1.30	1.00	.10
CaO	5.55	4.68	1.04
Na_2O	4.20	4.40	3.69
K_2O	.73	1.01	3.95
H_2O+	.73	.63	3.52
H_2O-	.78	.66	.14
CO_2	.00	.00	.01
TiO_2	.53	.75	.04
P_2O_5	.28	.20	.03
S	.03	.03	.02
MnO	.03	.03	.04
BaO	.14	.03	.07
OTHER	-----	-----	-----
TOTAL	100.15	99.69	99.74
LOCATION	Harwood Hills (San Dimas Area)	West of Pomona	West of Pudding-stone Dam (San Jose Hills)
ANALYST	J. Kerr	J. Kerr	J. Kerr
SOURCE	Shelton, 1955	Shelton, 1955	Shelton, 1955

ROCK	BANDED RHYOLITE (S-673)	FELSITE (S-496)
SiO_2	73.10	75.50
Al_2O_3	13.74	13.45
Fe_2O_3	.71	.63
FeO	.35	.17
MgO	.14	.10
CaO	.69	.85
Na_2O	3.94	3.85
K_2O	3.87	3.88
H_2O+	2.71	.62
H_2O-	.36	.43
CO_2	.03	.01
TiO_2	.03	.03
P_2O_5	.02	.04
S	.03	.13
MnO	.02	.01
BaO	.06	.14
OTHER	----	----
TOTAL	99.80	99.84
LOCATION	Near Spadra	Harwood Hills (San Dimas Area)
ANALYST	J.J.Engel	J. Kerr
SOURCE	Shelton, 1955	Shelton, 1955

microphenocrysts of this rock are fresh and unaltered, the only possible site for the water is the glassy mesostasis. In the other rocks, at least two-thirds of the water is present in secondary alteration products. These products comprise chlorophaeite, iddingsite, and bowlingite, the respective water contents of which are 22 percent, 15 percent, and 18 percent. Only a few volume percent of each of these minerals is required to account for a moderate weight percentage of water (one or two percent). In most of the rocks, these alteration products are secondary after olivine or glass. Wispy halos of iddingsite or chlorophaeite on olivine are typical, but in none of the analyzed rocks is the alteration extensive. In many instances, the alteration (particularly hydration) of the rocks resulted from their submarine accumulation.

The figure for the water content of sample BVD-5 is believed to be in error by nearly one percent. Three re-determinations of the percentage of total water in this rock (by W. J. Blake, W. Otto, and the writer) gave an average value of 2.74 percent. The source of this discrepancy is not known.

Figure 36 is a silica-variation diagram of the rocks represented by the analyses in Tables 7 and 8. The analyses were recast on a carbon dioxide-free and water-free basis, with all iron recalculated as FeO before the data were plotted. Visual comparison of the variation curves

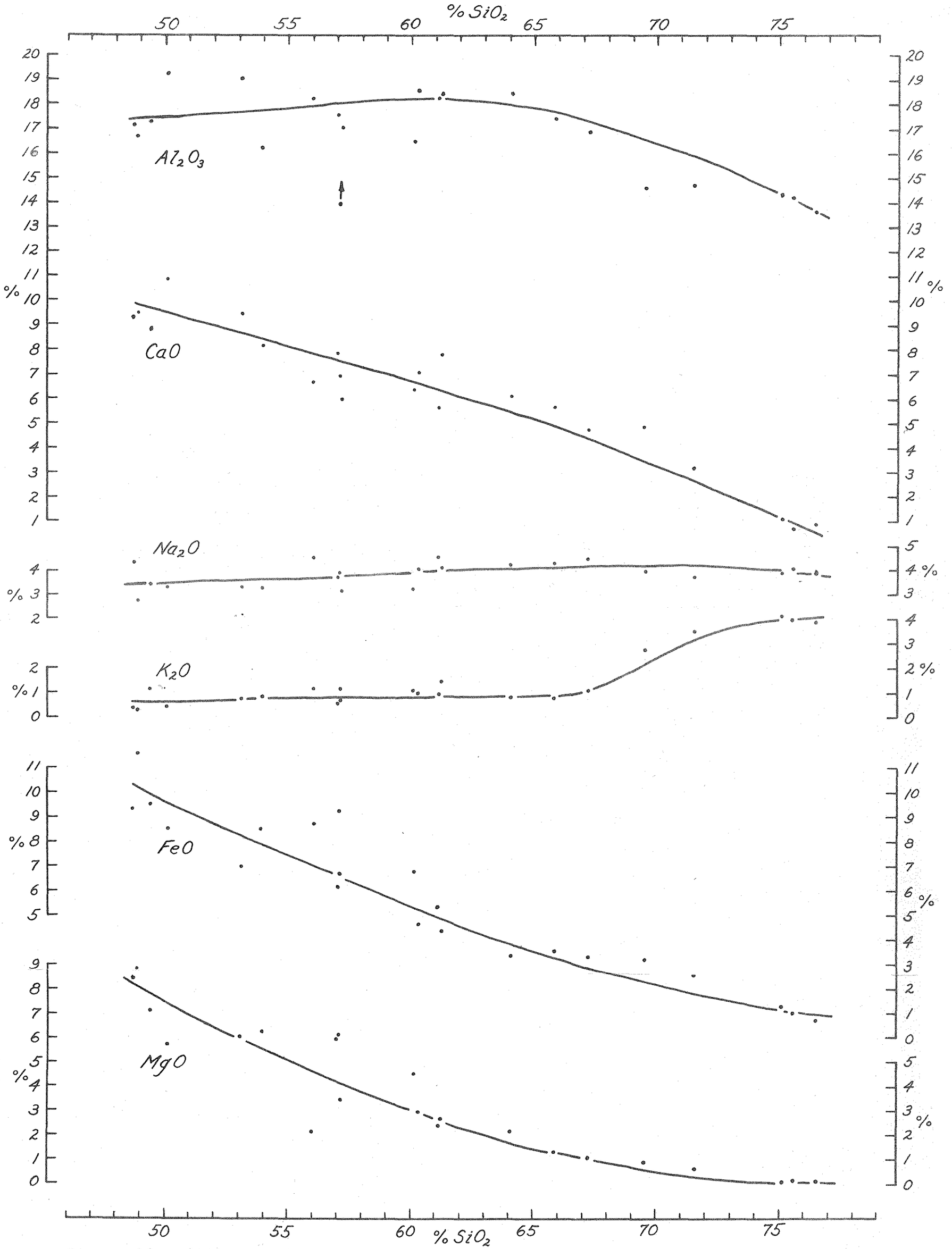


Figure 36. Silica-variation curves of the major oxides in the Miocene volcanic rocks of the Los Angeles basin; (compare Figure 37).

with those of other late Tertiary lavas of the eastern circum-Pacific province (e.g., Markleeville, California (Curtis, 1951), and Steens Mountain, Oregon (Fuller, 1931)), indicates that the differentiation trends in the rocks of all three areas were approximately the same. The Markleeville basalts (Mio-Pliocene) show a higher content of magnesia than the Los Angeles basalts, and the Steens Mountain basalts (Mio-Pliocene) a lower content of magnesia, but in the andesites and more silicic lavas the magnesia level in all three suites is the same. In addition, the Markleeville rocks show a more conspicuous enrichment of alumina in the andesite range than do the rocks from the Los Angeles basin and Steens Mountain area.

Williams (1935, pp. 293-300) compared the lavas of several volcanic sub-provinces in northern California and southern Oregon, and concluded that there are recognizable differences between the lavas of the High Cascade volcanoes (e.g., Mount Mazama, Mount Shasta, Lassen Peak) and those from volcanoes of the so-called "Interior Platform" (e.g., Medicine Lake Highlands, Newberry Volcano, and Steens Mountain). As compared with the rocks of the "Interior Platform," the High Cascade lavas are richer in alumina, lime, and magnesia, and poorer in iron and potash. By contrast, the Miocene volcanic rocks of the Los Angeles basin are like those of the "Interior Platform" in alumina and magnesia, like those of the High Cascades in potash,

and intermediate between those of the two areas in iron and lime.

For purposes of comparison, the alkali-lime indices (Peacock, 1931) of these rocks and of others in the eastern circum-Pacific province are presented in Table 9. The high index of the Los Angeles basin volcanic rocks is striking. It exceeds the indices of the rocks of the other areas, both to the north (northern California, Oregon, and Washington) and to the south (Mexico and El Salvador). The principal reason for its high value is the low potash content and the lack of enrichment in this component in rocks ranging in composition from 49 to 67 percent of silica. The rhyolites in the Los Angeles basin are similar in composition to those of the other areas, but the rise of potash to the rhyolitic level is abrupt, increasing nearly three percent in the range from 67 to 75 percent of silica. A second, though quantitatively less important reason for the high value of the index is the percentage of lime in these rocks. It is slightly greater than the average for the rest of the eastern circum-Pacific volcanic belt. Inasmuch as the alkali-lime index is defined in terms of the silica percentage at which total alkalies and lime are equal, a lower total alkali curve (as a result of lower potash), or a higher lime curve, will shift the index in the calcic direction. This is primarily why the indices of the High Cascade

Volcanic Sub-province	Alkali-lime Index
Calc-alkalic rocks	
Newberry Volcano, Oregon	58.0
Steens Mountain, Oregon	58.0
Markleeville, California	59.8
Transverse Volcanic Province of Mexico	60.0
Medicine Lake Highlands, California	60.5
Calcic Rocks	
Paricutin region, Michoacan, Mexico	61.5
Paricutin Volcano, Mexico	62.0
Mount Mazama (Crater Lake), Oregon	62.0
Volcanoes of El Salvador	62.0
Mount St. Helens, Washington	63.2
Mount Shasta, California	63.7
Lassen Peak, California	63.9
Los Angeles basin, California	65.2

TABLE 9: ALKALI-LIME INDICES OF ROCKS FROM THE EASTERN CIRCUM-PACIFIC VOLCANIC PROVINCE

(Data from Anderson, 1941; Curtis, 1951; Wilcox, 1954; and Williams, 1935, 1942, 1950, 1955)

volcanoes are higher than those of the volcanoes of the "Interior Platform" (Table 9).

The points representing alumina in Figure 36 show a high degree of scatter relative to the alumina curve. To a lesser extent this scatter is also present in the data for magnesia and total iron. It represents a deviation from the averaged trend of differentiation, and reflects a lack of consistency in the differentiation mechanism. The same data are shown in Figure 37, but in this diagram a distinction has been made between rocks from different parts of the basin. In drawing the solid line curves, only the points representing the Glendora lavas were considered. The scatter of points for rocks from this geographically isolated area is negligible. With but one exception, the points for alumina show a close conformance to the alumina curve, and the same is true of the points for magnesia and total iron. This implies that the Glendora volcanic rocks had a common heritage, and that they evolved from an isolated chamber of differentiating magma.

Points representing rocks from the Palos Verdes Hills, San Joaquin Hills, Santa Catalina Island, and San Clemente Island also show a common group behavior. They are consistently poorer in alumina than the Glendora rocks, and consistently richer in magnesia and iron. As indicated in an earlier section of this report, specimens from these areas are strikingly similar to one another in mineralogical composition and texture. The criteria of chemical

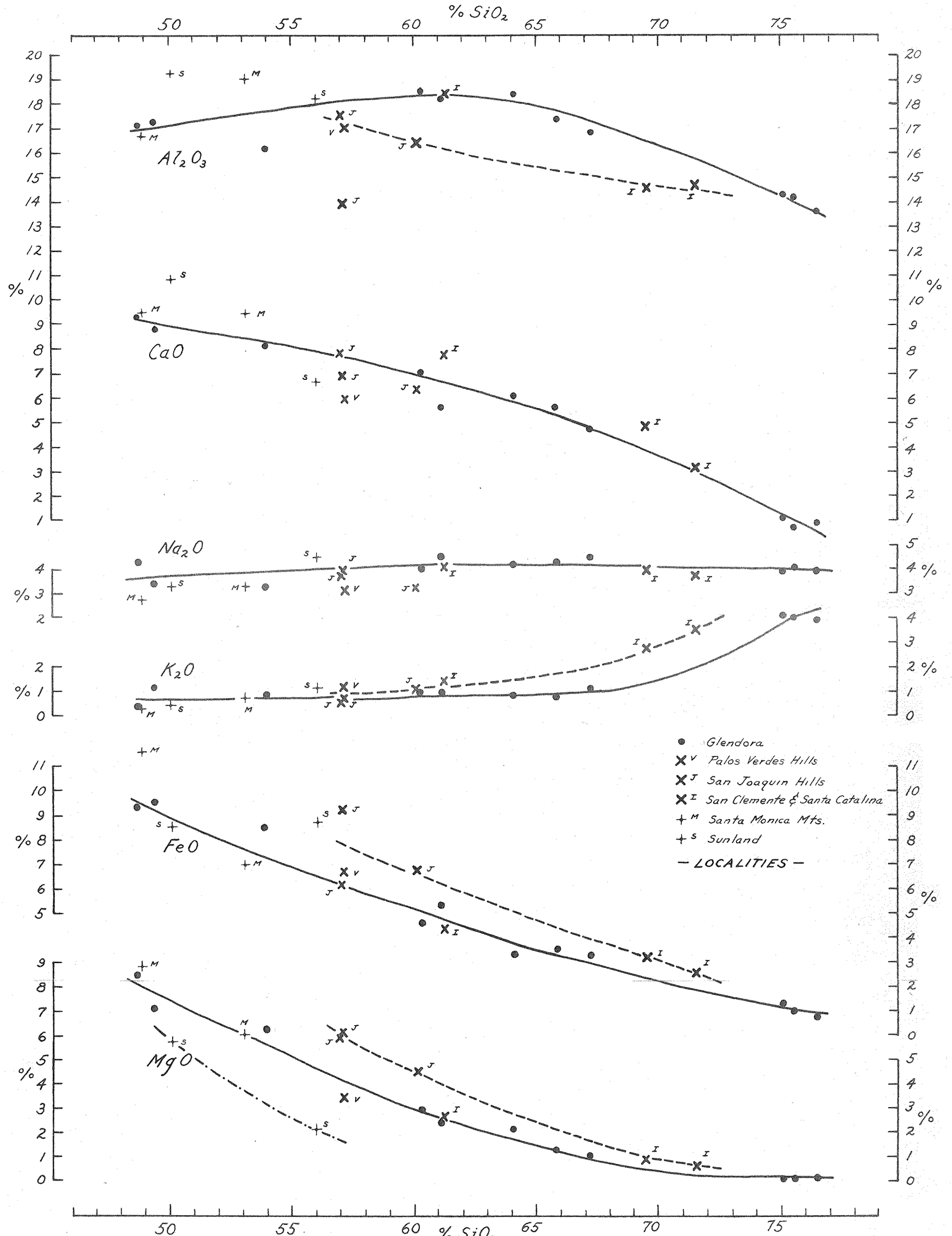


Figure 37. Silica-variation curves of the major oxides in the Miocene volcanic rocks of the Los Angeles basin, plotted by area. Note the contrasting group behavior of the Glendora lava suite (solid circles and lines) and the coastal lava suite (x's and dashed lines).

and mineralogical group similarity, as well as the compositional difference between this group and others in the basin, form a reasonable basis for the assumption that the lavas of these four areas also had a common heritage (as a group), and that they, too, evolved from a single magma chamber.

The number of analyzed specimens from Sunland and the Santa Monica Mountains is too small to provide an adequate determination of their trend of differentiation. The analyzed lavas from Sunland are relatively poor in magnesia and rich in alumina (Figure 37), and hence differ from the lavas exposed near the coast in approximately the same manner as do the Glendora volcanic rocks.

It has been known for some time that the pre-Tertiary "basement" rocks underlying the sedimentary strata on the southwest side of the Los Angeles basin and in the Palos Verdes Hills consist chiefly of chlorite-bearing schist, with subordinate amounts of saussuritic gabbro and serpentine. These rocks belong to the Catalina metamorphic facies of Woodford (1924), and are well exposed in their type locality on Santa Catalina Island, southwest of the Los Angeles basin. In contrast, the "basement" rocks of the Santa Monica and Santa Ana Mountains consist largely of slate, quartzite, and graywacke intruded by quartz diorite or granodiorite. In addition, the pre-Tertiary rocks of the Santa Ana Mountains include metamorphosed

andesite. Northeast of the southern edge of the Puente and Repetto Hills, the "basement" comprises gneisses and plutonic rocks of granodioritic or quartz dioritic composition, anorthosite and related gabbroic rocks, and subordinate phyllite, quartzite, and marble. Woodford et al. (1954, p. 74) expressed the belief that the two major fault zones of the region, the Newport-Inglewood and Whittier, form the boundaries between these different "basement" rocks.

As a group, the lavas of the Palos Verdes Hills, San Joaquin Hills, Santa Catalina Island, and San Clemente Island were all extruded within, or at the margin of, a terrane consisting wholly of rocks of the Catalina metamorphic facies. The San Onofre breccia of middle Miocene age is exposed in the same areas as these lavas. It is composed largely of fragments of Catalina schist. Its texture and other lithologic features led Woodford (1925) to postulate the presence of a steep-fronted mountain mass of Catalina schist southwest of the present-day coast. Its period of emergence must have overlapped that of the local volcanic activity.

In contrast, the Glendora volcanic rocks were extruded from vents within a terrane primarily consisting of biotite-bearing quartz diorite and granodiorite. The composition of Miocene conglomerates associated with the Glendora volcanic rocks indicates that the San Gabriel Mountains were high at this time also.

Inasmuch as the lavas in these two areas are of approximately equivalent age (late Relizian and early Luisian coastal lavas, Luisian Glendora lavas), and as they were erupted within 40 miles of each other, on the opposite flanks of a subsiding basin, there is little reason to doubt that they originated from the same primary magma. The composition of this magma must have been modified in the separate cupolas, conduits, or secondary chambers from which the respective lavas issued.

The higher alumina and lower magnesia and iron content of the Glendora lavas, the composition of the "basement" rocks through which they must have passed, and the presence of inclusions (e.g., quartz diorite at Sunland, where lavas of approximate compositional equivalence occur; garnet from granitic pegmatite (?) near Pomona) all point to the possibility of assimilation at depth. The higher content of magnesia and iron in the coastal volcanic rocks, the more mafic composition of the "basement" there, and the presence in the lavas of partially digested xenoliths of gabbroic rocks suggest that modification by assimilation also took place in this area. Schoellhamer and Woodford (1951) stressed the magnesian composition of the "basement" rocks near the coast by stating that "the Catalina rocks... (include)...considerable amounts of high magnesia, low silica rocks..."

Magma ascending from sources beneath the floor of the

Los Angeles basin evidently became separated into two (and possibly more) bodies that rose to the surface through rocks of different chemical composition. The influence of these country rocks is apparent in the variations of composition and differentiation trends of the lavas from different parts of the basin. Because this influence did not vary with the passage of time, attempts to determine the relative age of the lavas on the basis of their compositions are severely limited. A geographic, rather than a temporal distinction is apparent.

The number of reliable chemical analyses of the Glendora volcanic rocks far exceeds the number of analyses of the hypersthenic lavas near the coast, and for this reason the Glendora rocks were selected for studying the differentiation trends shown in Figure 37. Specimen S-422 (Shelton, 1955, p. 72) was chosen as a representative sample of the parent magma, on the grounds of its compositional similarity to the aphyric basaltic glass in the Santa Monica Mountains. As mentioned in a preceding section of this report, the latter is considered to be an uncontaminated sample of the parent magma of the region.

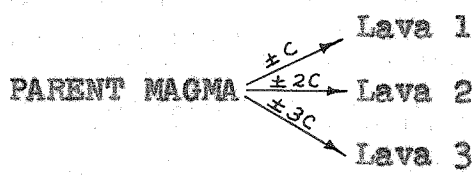
Four restrictions can be placed on any scheme designed to simulate observed compositional trends of differentiation of the Los Angeles volcanic rocks. First is the petrographic evidence discussed earlier, indicating that the crystallization of augite occurs at a stage so late

in the solidification of olivine basalt that this pyroxene cannot participate in any differentiation involving the selective removal of crystals. Second, it is possible to determine petrographically those minerals that crystallize early, and further, to determine their specific composition, thereby obviating speculation as to the nature of minerals taking part in crystal fractionation. Third, if assimilation played a role in the differentiation, attempts should be made to determine as closely as possible the composition of the materials that were assimilated. Last, once an hypothesis of differentiation has been selected, calculations should be made to determine the amounts of materials added to or subtracted from the parent magma during the production of a particular derivative lava. These amounts then should be considered from a standpoint of the thermal energy involved.

Only two processes, crystal fractionation and assimilation, were considered during the course of the present study. They were tested graphically, as separately acting processes and as concomitant processes. The methods that Wilcox (1954) applied to the lavas of Paricutin volcano were used in handling the variations of two or more substances.

Two systems of petrogenic descendency are possible:

1) Direct descendency from a common parent magma:



(Where C represents a material of given composition)

2) Serial descendency:

PARENT MAGMA $\xrightarrow{\pm C_1}$ Lava 1 $\xrightarrow{\pm C_2}$ Lava 2 $\xrightarrow{\pm C_3}$ Lava 3

(Where C_1 differs in composition from C_2 etc.)

In the first system, all lavas are derived from a common parent by the same process (e.g., crystal fractionation of mineral A). The difference in composition between derivative lavas results from tapping the source at different stages of the process (e.g., after five percent of mineral A has separated, after 10 percent has separated, etc.). In the second system, lava No. 1 is derived from the parent magma by process No. 1 (e.g., separation of mineral B), lava No. 2 is derived from lava No. 1 by process No. 2 (e.g., separation of mineral C), etc.

The composition of sample S-422 was used as that of the parent magma in testing both systems. Mineralogically, this rock is composed of calcic labradorite ($An_{65\pm}$), olivine ($Fo_{80\pm10}$), clinopyroxene, and magnetite. Studies of direct descendency included the graphical subtraction of material having the composition of Fo_{80} or An_{65} or both, and/or the graphical addition of material having a

composition thought to be like that of the local country rock. The selection of a composition representative of the average country rock was based on estimates of the relative volumes of different plutonic "basement" rocks exposed in the area. In the vicinity of the Glendora volcanic rocks, the average composition of the "basement" is approximately that of a granodiorite. Miller (1946, p. 522) presented an analysis of a rock of this type (Lowe granodiorite), which crops out in the San Gabriel Mountains to the north, but because his sampling is not believed to be as representative as that of Larsen (1948), the average composition of another granodiorite (Woodson Mountain granodiorite, Larsen, op. cit., p. 80) was selected for that of the country rock of the Glendora area (see Table 10). Larsen (op. cit., p. 138) estimated this granodiorite makes up 25.5 percent of the batholith of southern California.

Considering the region as a whole, a study of the literature indicates that quartz diorite (tonalite) and granodiorite predominate. Descriptions have been given by Larsen (op. cit., Bonsall tonalite and Woodson Mountain granodiorite), Miller (op. cit., Wilson quartz diorite and Lowe granodiorite in the San Gabriel Mountains), and Neuerburg (1953, Vermont quartz diorite, Lar quartz diorite, and Feliz granodiorite in the eastern Santa Monica Mountains). Larsen's figures for the volume percentage of the

various rocks in the southern California batholith (op. cit., p. 138) indicate that the ratio of quartz diorite to granodiorite is approximately five to three. For this reason, an average composition of the "basement" rocks northeast of the Norwalk fault was calculated as an alternative country rock. The data of Larsen for the Bonsall tonalite and Woodson Mountain granodiorite were combined with the data of Miller (op. cit.) for the Wilson quartz diorite and Lowe granodiorite. A ratio of five to three was taken as the relative proportion of quartz diorite to granodiorite, and greater weight was assigned to the figures of Larsen, because they are believed to represent a more accurate sampling of the crystalline plutonic rocks. The compositions of the two "country" rocks are given in Table 10. The seven major components were recast to 100 percent, with all iron as FeO.

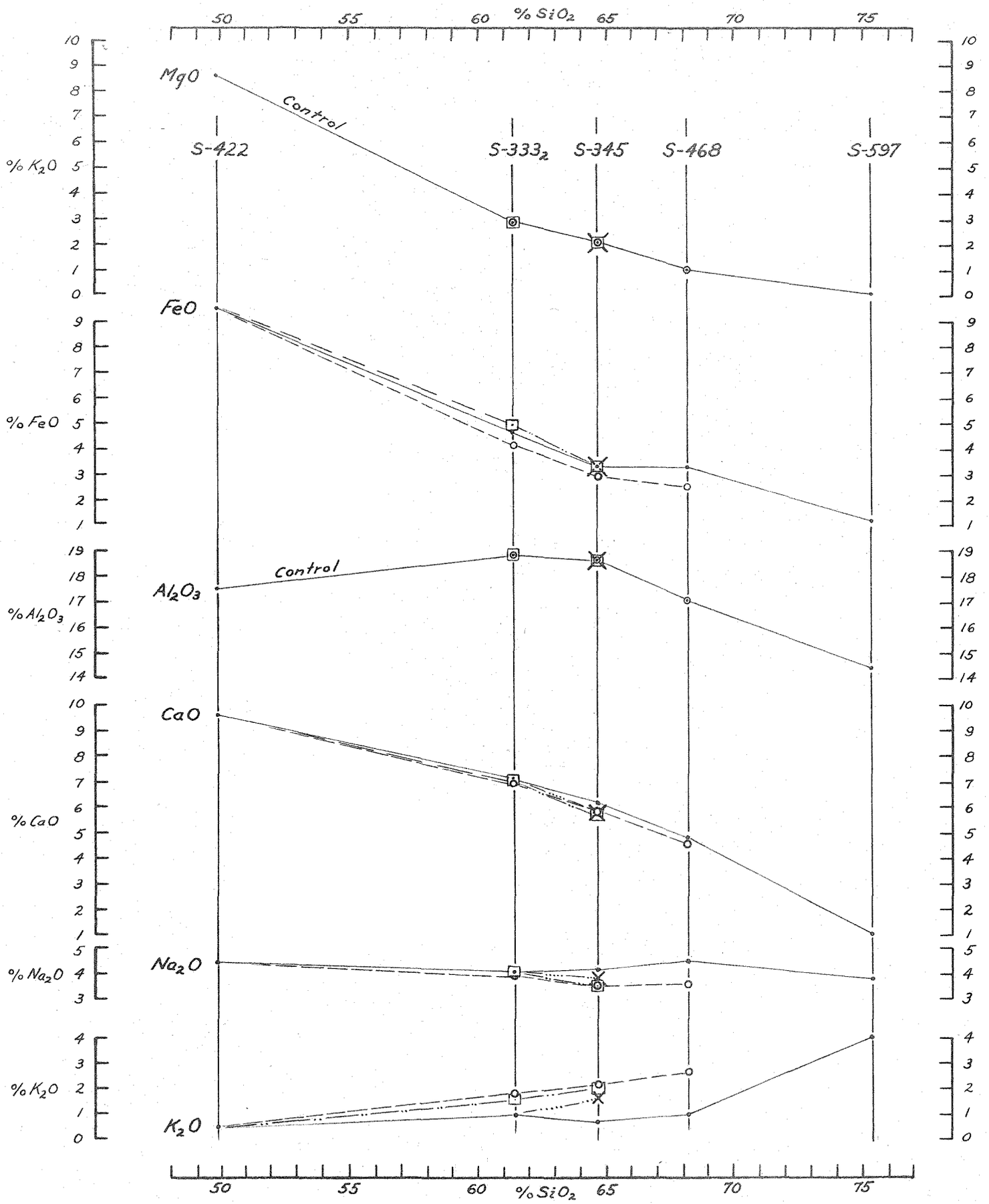
A total of 15 calculations was made to check the hypothesis of direct descendency of the lavas from a common parent magma (S-422). Theoretical subtraction of olivine ($Fo_{80 \pm 10}$) alone, or in combination with plagioclase ($An_{65\pm}$), failed to yield material similar in composition to lavas lower in the differentiation series (andesites or rhyolites), as did the simple theoretical addition of either one of the country rocks. Combined theoretical subtraction of olivine or plagioclase with addition of one of the country rocks also gave unsatisfactory results,

	Granodiorite (Woodson Mountain)	Average Regional "Basement" Rock
SiO_2	73.9	67.0
Al_2O_3	14.2	16.2
FeO	2.3	4.3
MgO	0.4	1.8
CaO	2.1	4.5
Na_2O	3.4	3.6
K_2O	3.5	2.5

TABLE 10. INFERRED COMPOSITION OF TWO COUNTRY ROCKS AT THE NORTHEASTERN MARGIN OF THE LOS ANGELES BASIN (Recast from analyses of Larsen (1948) and Miller (1946)).

but subtraction of both olivine and plagioclase with the concomitant addition of country rock yielded hypothetical lavas fairly close to the observed ones in composition. The calculated and observed compositions are shown in Figure 38.

The graphical procedure outlined by Wilcox (1954, pp. 326-339) was used in the determination of the composition of the hypothetical lavas. Silica, alumina, and magnesia were used for controlling the amounts of material theoretically added to, or subtracted from, the differentiating magmas. In studying the variations of one constituent only, silica was used as a control, and in studying the variations of two constituents, silica and alumina or magnesia were used. Lavas that lie compositionally between those shown in Figure 38 also were tested, but are not



EXPLANATION

- Actual composition of bulk rock as determined by chemical analysis
- Hypothetical lava derived by "addition" of Woodson Mt. granodiorite and "subtraction" of Fo_{80} & An_{65} from S-422.
- Hypothetical lava derived by "addition" of average regional "basement" rock and "subtraction" of Fo_{80} & An_{65} from S-422.
- Hypothetical lava derived by "addition" of Woodson Mt. granodiorite and "subtraction" of En_{75} & An_{58} from $S-333_2$.

FIGURE 38.

WILCOX DIAGRAM COMPARING ACTUAL LAVA COMPOSITIONS WITH THOSE OF HYPOTHETICAL LAVAS, CALCULATED AS INDICATED ABOVE. ALL SAMPLES FROM GLENDORA AREA, SEE SHELTON (1955)

shown on the diagram.

The difference between the observed and calculated compositions of pyroxene andesite S-333_2 is greater than Wilcox (op. cit., p. 336) considered reasonable, but the difference in overall composition between this rock and that of its parent (S-422), as measured in terms of silica content, is more than twice as great as the difference between the compositions of the parent and final derivative magma studied by Wilcox. Lavas closer to S-422 in composition show much less divergence. On the other hand, lavas with a composition more silicic than that of S-333_2 (e.g., S-345 and S-468) show a much greater divergence, and the differences between the observed and calculated compositions of these rocks are so great that the procedure, in effect, breaks down.

The writer feels that the mechanism of olivine and plagioclase fractionation, combined with the assimilation of country rock, accounts reasonably well for the derivation of lavas up to, and including, the andesite represented by sample S-333_2, but that the more silicic lavas were probably derived in some other way. The divergence for S-333_2 may be the result of a lack of compositional correspondence between the actual country rock and the inferred country rocks of Table 10.

The most perplexing aspect of the calculations is the increasingly great divergence exhibited by potash in

the rocks of silicic composition. Evidently the potash content of the assimilated rocks was lower than that of the average country rock used in the calculations, or an unusually large percentage of potash was removed through the fractionation of plagioclase, or both.

A total of 14 calculations was made for the purpose of checking the hypothesis of serial descendency. Rocks ranging in composition from S-422 (olivine basalt) to $S\text{-}333_2$ (pyroxene andesite) could have been derived equally as well by serial descendency as by direct descendency, for if the same constituents (Fo_{80}, An_{65}, and country rock) are subtracted and/or added to each successive lava, the procedure is identical to that used in checking direct descendency. Attempts were made to derive more silicic lavas by the subtraction of hypersthene, hornblende, or biotite and a more sodic plagioclase, as well as by assimilation of wall rock. Graphical subtraction of early-formed crystals does not yield hypothetical lavas closely approximating the observed rocks, nor does the simple addition of country rock. A product resembling sample S-345 was derived from $S\text{-}333_2$, however, by theoretical subtraction of hypersthene (En_{75}) and plagioclase (An_{58}) with simultaneous addition of granodiorite. The composition of this lava is shown by crosses in Figure 38. From sample S-519 (a hornblende andesite not shown in Figure 38), rocks with the composition of S-468 (micropoikilitic dacite)

were derived theoretically by subtraction of hornblende and sodic labradorite.

Any assimilation of "basement" material by derivative magmas of this composition (65 to 70 percent silica) is improbable from the standpoint of thermodynamics. In fact, the average regional "basement" rock of Table 10 has approximately this silica composition itself. Consideration of the thermal requirements of assimilation in even the first stages of the proposed differentiation scheme indicate the necessity of obtaining heat from sources other than the latent heats of crystallization of the minerals with which the magma is saturated and/or the heats of mixing. Wilcox (op. cit., pp. 341-343), who studied the problem in detail, suggested that convective transfer of heat from below might satisfy the requirements of the differentiating magma. In order to derive the compositional equivalent of S-333_2 from S-422, approximately 50 to 60 grams of Woodson Mountain granodiorite must be added to 100 grams of uncontaminated magma. A comparable figure for the assimilation of the "average basement rock" listed in Table 10 indicates that equal parts of magma (S-422) and country rock must be mixed in order to obtain a rock resembling S-333_2. The amount of heat required to accomplish this assimilation is wholly beyond reason.

In summary, the writer believes that the first stages of differentiation of the Glendora rocks were effected

through direct descendency of the lavas by crystal fractionation of olivine and calcic labradorite, and by simultaneous assimilation of rock with the composition of granodiorite. The later stages were effected through serial descendency by fractionation of hypersthene or hornblende and plagioclase, and possibly by subordinate assimilation. Schematically, this differentiation can be outlined as shown in Figure 39.

Trace-Element Composition of the Lavas

General statement

Spectrochemical analysis of the Los Angeles volcanic rocks was undertaken in the hope that it might offer a precise way in which to "fingerprint" rocks from different parts of the basin in terms of their relative age. If a single deep reservoir beneath the basin furnished magma to all of the volcanic conduits, the rocks should bear some evidence of their common heritage. If subsequent chemical changes were then effected within this reservoir, successive fractions drawn from it might be expected to exhibit characteristics that would vary with time. Relizian lavas, erupted simultaneously at a number of different places in the basin, might disclose unique interareal similarities, and at the same time might show marked contrasts with respect to the succeeding Luisian lavas. As

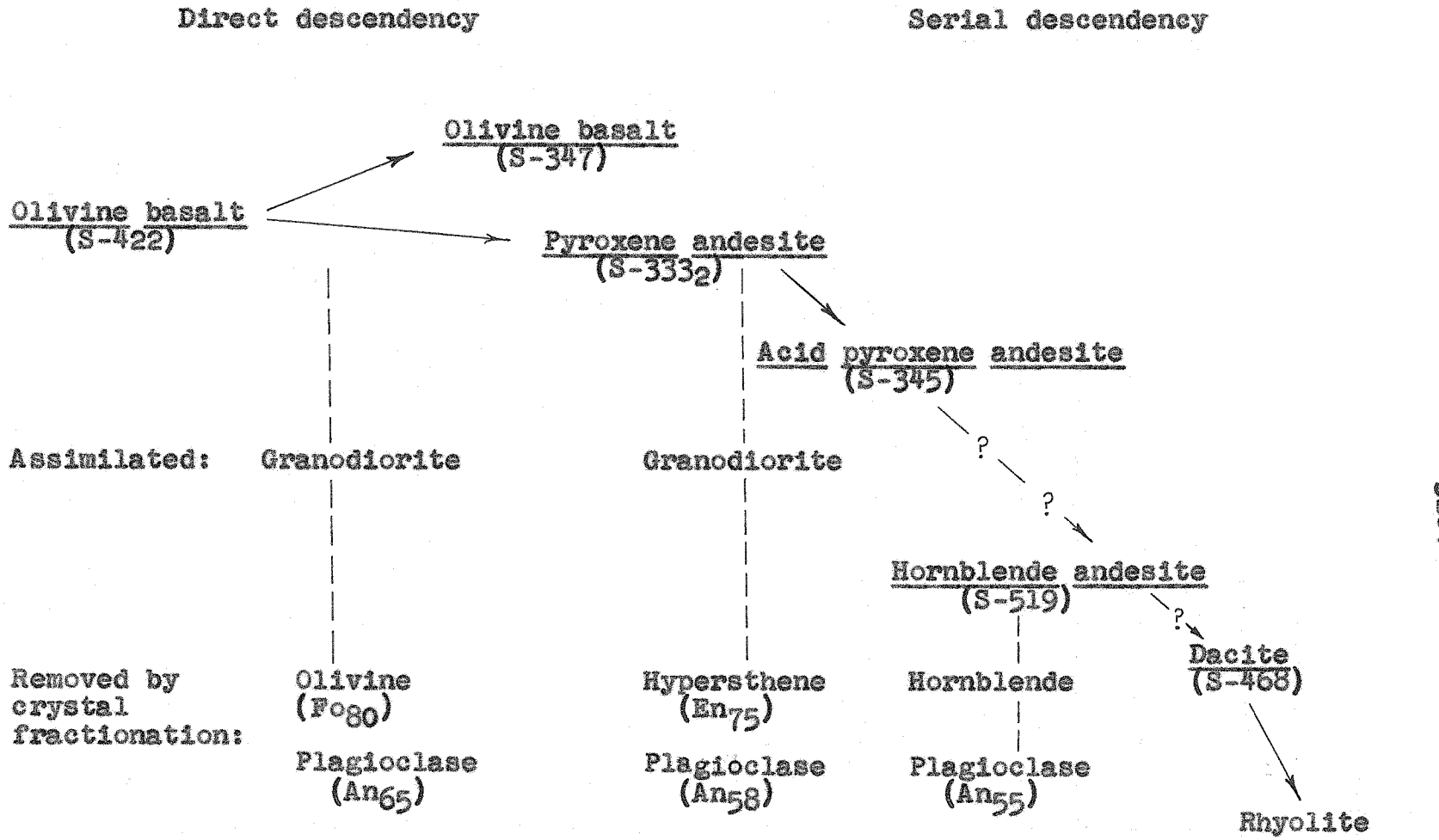


Figure 39. Possible mode of magmatic differentiation of the Glendora volcanic rocks

already noted, however, at least two separate conduits served the middle Miocene volcanic vents in the basin, and the differences in composition displayed by the lavas from these conduits is pronounced.

Methods of analysis

A sample of the rock to be analyzed, weighing approximately 200 grams, was reduced to fragments by means of a stainless steel chisel and plate. These fragments, measuring one-half inch in diameter, were further reduced in a steel percussion mortar to pieces roughly one-tenth inch in maximum diameter. These were passed through an aluminum microsplitter, and a fraction weighing approximately 25 grams was retained. This was re-crushed by percussion until it passed a cheesecloth sieve of approximately 40 mesh. After sieving, further splitting was done to obtain a fraction weighing two grams. This fraction was reduced to minus 200 mesh in an automatic agate mortar. The only possible contaminants with which the samples came in contact were iron, aluminum, and silicon, all major elements in the rocks.

The spectrochemical technique employed was that described by Fleischer et al. (1952). The samples were diluted with an equal weight of "soda quartz," a ten-percent mixture of sodium carbonate in pure quartz. Samples weighing 25 milligrams were then burned in pure graphite

electrodes, with the sample electrode serving as the anode. The electrode shape was patterned after that of Myers (1951). Instrumentation was as follows:

1) Jarrell-Ash 21 foot difraction grating spectrograph; dispersion in the first order: 5.2 Å/mm.

2) Wave length range: 2300-4800 Å, first order.

3) 15 ampere D.C. arc.

4) 4 mm. analytical gap magnified 5 times and focussed on the slit. Central 2 mm. used with 25 micron slit width.

5) Applied Research Laboratory densitometer, model No. 2250.

The plates were calibrated by measuring iron lines of known intensity in four pegmatite standards. All samples were run in duplicate, and the figures listed in Table 11 are average values.

Elements that were looked for during the analysis include: Ag, As, Au, B, Ba, Be, Bi, Cd, Co, Cr, Cu, Ga, Ge, In, La, Mn, Mo, Nb, Ni, Pb, Pt, Sb, Sc, Sn, Sr, Ta, Th, Ti, Tl, U, V, W, Y, Yb, Zn and Zr. Of these, Ag, As, Au, Bi, Cd, Ge, In, La, Pt, Sb, Sn, Ta, Th, Tl, U, W, and Zn were not found.

Many factors give rise to differences or modifications in the trace-element composition of a suite of rocks. In order to study possible <u>time</u> variations, other variations must be recognized and their effects evaluated. Those considered during the present study include the following:

1) Variations accompanying differences in the gross chemical composition of a group of rocks, i.e., those arising from magmatic differentiation or from the existence of two or more parent magmas.

2) Differences in trace-element composition between two or more flows of similar rock type within a given area, as a result of short-term variations in the composition of the magma.

3) Variations within a given rock unit, i.e., from one part of a flow to another.

4) Differences between mineralogically similar lavas, contemporaneously extruded at widely separated geographic localities.

5) Variations arising from alteration of the rock, or from the development of secondary minerals.

6) Contamination of well samples resulting from contact with drilling equipment and from the permeation of drilling fluids.

7) Variations dependent on the degree of precision or reproducibility of the analyses.

TABLE II: SPECTROCHEMICAL ANALYSES
OF SELECTED VOLCANIC ROCKS
FROM LOS ANGELES BASIN, CALIFORNIA (IN PPM)

AREA	SUNLAND			
Lab.#	G-1	G-27	AV.	G-2
Spec.	BVD-3b	BVD-3b	BVD-3b	BVD-5
B	7	20	15	8
Ba	300	250	275	150
Be	---	---	---	---
Co	55	55	55	55
Cr	70	95	85	150
Cu	25	25	25	60
Ga	7	8	7.5	3
Mn	450	350	400	650
Mo	---	---	---	---
Nb	---	---	---	---
Ni	30	30	30	55
Rb	---	poss. tr.	---	---
Sc	30	30	30	30
Sr	950	750	850	1000
Ti	7000	8000	7500	5000
V	150	150	150	200
Y	60	50	55	20
Yb	3	2.5	2.75	1
Zr	250	300	275	75
$\%SiO_2$ (dry)	56.04	56.04	56.04	50.11
Rock	Olivine-bearing basaltic andesite	Olivine-bearing basaltic andesite	Av. of two on left	Olivine basalt

AREA	SUNLAND			
Lab.#	G-3	G-4	G-9	AV.
Spec.	BVD-5a	BVD-24	BVD-24	BVD-24
B	20	20	8	15
Ba	150	150	150	150
Be	---	---	---	---
Co	40	50	60	55
Cr	150	300	300	300
Cu	80	85	75	80
Ga	5	5.5	3	4.25
Mn	550	750	550	650
Mo	---	---	---	---
Nb	---	---	---	---
Ni	50	100	100	100
Rb	---	---	---	---
Sc	35	30	20	25
Sr	1000	800	800	800
Ti	6500	5500	4500	5000
V	200	150	150	150
Y	30	20	15	17.5
Yb	2	1	1	1
Zr	100	100	75	90
$\%SiO_2$ (dry)	badly altered	*52	*52	*52
Rock	Altered olivine basalt	Olivine basalt	Olivine basalt	Av. of two on left

AREA	SUNLAND			
Lab.#	G-19	G-5	G-8	G-7
Spec.	BVS-55	BVS-71	BVP-4	BVP-6
B	15	6	10	8
Ba	250	250	200	200
Be	---	---	---	---
Co	35	30	30	55
Cr	35	35	20	250
Cu	15	15	15	80
Ga	6	4.5	7	3
Mn	450	300	500	500
Mo	---	---	---	---
Nb	---	---	---	---
Ni	15	10	7	100
Rb	---	---	---	---
Sc	25	25	30	30
Sr	650	850	500	550
Ti	5500	5500	7000	4500
V	200	200	200	150
Y	35	35	35	15
Yb	2	1	1	1
Zr	150	150	150	65
$\%SiO_2$ (dry)	*58	*58.0	*57	*50
Rock	Porphyritic olivine-bearing basaltic andesite	Porphyritic olivine-bearing basaltic andesite	Porphyritic olivine-bearing basaltic andesite	Olivine diabase

AREA	SUNLAND	SANTA SUSANA MTS.	SANTA MONICA MTS.	
Lab.#	G-10	G-11	G-34	G-41
Spec.	BVP-12	BVF-1	BVN-30	BVN-30
B	10	10	8	15
Ba	250	200	300	300
Be	---	---	---	---
Co	45	55	30	35
Cr	400	150	200	200
Cu	70	60	25	35
Ga	4	2.5	3	4
Mn	400	450	500	550
Mo	---	---	---	---
Nb	---	---	---	---
Ni	200	100	65	65
Rb	---	---	---	---
Sc	30	25	25	30
Sr	1000	800	800	1000
Ti	5500	5500	4500	6000
V	200	150	150	200
Y	25	20	10	15
Yb	1.5	1	< 1	< 1
Zr	100	100	75	100
$\%SiO_2$ (dry)	*50	*51	53.10	53.10
Rock	Altered olivine basalt	Olivine diabase	Hypersthene basalt	Hypersthene basalt

AREA	SANTA MONICA MTS.			
Lab.#	AV.	G-12	G-35	G-14
Spec.	BVN-30	BVN-36	BVN-40	BVN-63
B	10	10	10	10
Ba	300	65	350	100
Be	---	---	---	---
Co	35	40	30	65
Cr	200	200	300	200
Cu	30	20	35	85
Ga	3.5	2.5	3	3
Mn	525	550	550	850
Mo	---	---	---	---
Nb	---	---	---	---
Ni	65	100	100	100
Rb	---	---	---	---
Sc	30	35	20	35
Sr	900	400	1000	400
Ti	5250	3000	6000	3500
V	175	150	150	150
Y	15	15	20	15
Yb	< 1	1	1	1
Zr	90	35	150	35
$\%SiO_2$ (dry)	53.10	*48	*55	48.90
Rock	Av. of two preceding	Olivine diabase	Altered quartz-bearing basalt	Olivine basalt

AREA	SANTA MONICA MTS.		PALOS VERDES HILLS	
Lab.#	G-13	G-16	G-17	G-18
Spec.	BVN-69	BVV-14b	BVV-15	BVV-21
B	10	7	15	10
Ba	45	550	250	50
Be	---	---	---	---
Co	45	50	55	65
Cr	150	150	150	300
Cu	80	25	60	80
Ga	2.5	3	3	4.5
Mn	700	500	250	600
Mo	---	---	---	---
Nb	---	---	---	---
Ni	100	30	55	85
Rb	---	---	---	---
Sc	30	20	20	40
Sr	350	400	250	350
Ti	3000	4000	4000	4500
V	150	100	100	200
Y	15	25	75	30
Yb	1	1	4	1.5
Zr	25	150	150	80
$\%SiO_2$ (dry)	*48	57.03	*63	*50
Rock	Olivine basalt	Hypersthene-augite andesite	Glassy pyroxene andesite	Olivine diabase

AREA	PALOS VERDES HILLS		SAN JOAQUIN HILLS	
Lab.#	G-32	G-15	G-38	G-31
Spec.	BVV-27	BVV-28	BVJ-6	BVJ-7
B	20	7	20	30
Ba	200	450	350	1000
Be	---	---	---	---
Co	60	35	30	45
Cr	200	150	150	150
Cu	75	80	30	25
Ga	4.5	3	6	7
Mn	650	750	650	550
Mo	---	---	---	---
Nb	---	---	---	---
Ni	100	100	35	50
Rb	---	---	---	poss.tr.
Sc	45	35	20	20
Sr	350	200	550	750
Ti	5000	3500	6500	6000
V	200	150	150	150
Y	35	25	20	35
Yb	2	1	2	2
Zr	100	85	150	150
$\%SiO_2$ (dry)	altered	*51	*59	60.17
Rock	Highly altered olivine diabase	Partly altered olivine diabase	Hypersthene-augite andesite	Hypersthene-augite andesite

AREA	SAN JOAQUIN HILLS			EL MODENO
Lab.#	G-39	G-33	AV	G-36
Spec.	BVJ-9a	BVJ-9a	BVJ-9a	BVE-1
B	15	15	15	15
Ba	500	400	450	300
Be	---	---	---	---
Co	20	30	25	40
Cr	150	150	150	250
Cu	25	25	25	25
Ga	4	7	5.5	3
Mn	650	550	600	500
Mo	---	---	---	---
Nb	---	---	---	---
Ni	100	200	150	15
Rb	---	---	---	---
Sc	20	20	20	30
Sr	2000	1500	1750	1500
Ti	3500	4000	3750	6000
V	150	150	150	200
Y	15	15	15	20
Yb	1	1	1	1
Zr	70	100	85	150
$\%SiO_2$ (dry)	57.02	57.02	57.02	*54
Rock	Augite andesite	Augite andesite	Av. of two preceding	Olivine-bearing basaltic andesite

AREA	EL MODENO DIKE IN BASEMENT		DRILLING MUDS	
Lab.#	G-37	G-40	G-29	G-30
Spec.	BVE-3	BVB-2	S.O.Co.Baldwin-Cienega No.105	S.O.Co.Emery No. 87
B	15	10	35	35
Ba	450	250	1.5%	2.0%
Be	---	---	---	---
Co	40	55	15	40
Cr	150	400	80	350
Cu	20	35	60	100
Ga	5	3	4	2
Mn	550	800	550	650
Mo	---	---	8	6
Nb	---	---	---	---
Ni	15	200	40	200
Rb	---	---	65	200
Sc	25	30	15	20
Sr	1000	1500	650	2500
Ti	5000	6000	3500	3000
V	150	200	100	100
Y	10	10	30	20
Yb	1	< 1	2.5	1.5
Zr	100	100	100	100
$\%SiO_2$ (dry)	*56	*47		
Rock	Basaltic andesite	Olivine diabase	Misc. Ag:1	Misc. Ag:1 Zn:500

AREA	GLENDORA			
Lab.#	G-20	G-21	G-22	G-23
Spec.	S-422	S-615	S-333$_2$	S-345
B	20	20	15	20
Ba	75	600	300	600
Be	---	---	---	---
Co	100	85	35	65
Cr	200	300	90	70
Cu	100	70	10	8
Ga	4	4	5	6
Mn	800	500	200	350
Mo	---	---	---	---
Nb	---	---	---	---
Ni	100	150	40	20
Rb	---	---	---	poss.tr.
Sc	35	25	15	15
Sr	850	1500	800	1000
Ti	5000	6500	4500	3500
V	200	200	150	100
Y	25	25	15	15
Yb	1.5	1.5	tr.	1
Zr	85	150	150	150
%SiO_2 (dry)	48.76	53.98	60.35	64.11
Rock	Olivine basalt	Olivine basalt	"Calcic andesite"	Hypersthene andesite

AREA	GLENDORA			
Lab.#	G-24	G-28	AV.	G-25
Spec.	S-468	S-468	S-468	S-597
B	20	25	25	35
Ba	350	300	325	850
Be	---	---	---	1
Co	55	40	50	10
Cr	60	45	55	3.5
Cu	20	15	20	20
Ga	5	5	5	7.5
Mn	150	150	150	200
Mo	---	---	---	1
Nb	---	---	---	tr.~10
Ni	15	15	15	tr.
Rb	poss.tr.	poss.tr.	poss.tr.	~10
Sc	10	10	10	---
Sr	600	450	525	100
Ti	3500	4000	3750	15
V	100	85	100	20
Y	90	85	90	25
Yb	5	5	5	tr.
Zr	150	150	150	90
$\%SiO_2$ (dry)	67.25	67.25	67.25	75.12
Rock	Hypersthene andesite	Hypersthene andesite	Av. of two preceding	Perlite

AREA	GLENDORA	WELL CORES (SEE NOTE)		
Lab.#	G-26	G-49	G-42	G-43
Spec.	S-496	BW-3	BW-10	BW-14
B	35	20	20	25
Ba	1500	500	300	250
Be	2	---	---	---
Co	100	30	80	25
Cr	50	150	650	80
Cu	7	90	200	25
Ga	10	6	~1	5
Mn	50	850	1000	450
Mo	1	7**	---	---
Nb	20	---	---	---
Ni	tr.~1	95	400	40
Rb	15	---	---	---
Sc	---	35	25	10
Sr	150	800	600	550
Ti	15	7500	2000	3500
V	30	200	100	90
Y	35	45	15	9
Yb	1	3	1	< 1
Zr	100	200	20	150
$\%SiO_2$ (dry)	76.49	*53	*< 45	*64
Rock	Rhyolite	Basalt	Olivine basalt	Hypersthene-augite andesite

AREA	WELL CORES (SEE NOTE)			
Lab.#	G-44	G-45	G-46	G-47
Spec.	BW-38	BW-48	BW-62	BW-87
B	10	70	15	35
Ba	150	650	150	700
Be	---	---	---	---
Co	30	40	35	25
Cr	250	25	500	45
Cu	80	150	80	15
Ga	6	2	4	6
Mn	600	100	600	650
Mo	---	80**	---	---
Nb	---	---	---	---
Ni	100	55	200	25
Rb	---	---	---	---
Sc	40	25	40	20
Sr	700	300	800	800
Ti	4500	6500	4000	6000
V	200	80	200	150
Y	20	70	15	15
Yb	1.5	3	1.5	1.5
Zr	50	100	65	150
$\%SiO_2$ (dry)	*48	No data	*49	*59
Rock	Olivine basalt	Basalt (W: 1000** Zn: 200**)	Olivine basalt	Hornblende andesite

AREA	WELL CORES (SEE NOTE)	MEAN ERROR	σ ERROR
Lab.#	G-48		
Spec.	BW-100		
B	15	26%	20.6
Ba	450	6%	5.2
Be	---		
Co	30	11%	7.7
Cr	150	6%	7.9
Cu	20	7%	7.9
Ga	5	16%	12.8
Mn	550	8%	6.1
Mo	---		
Nb	---		
Ni	15	7%	14.8
Rb	---		
Sc	30	6%	8.8
Sr	1500	10%	5.9
Ti	5500	9%	3.1
V	200	4%	6.4
Y	15	9%	8.1
Yb	1	2%	4.3
Zr	150	11%	6.9
$\%SiO_2$ (dry)	*56		
Rock	Olivine-bearing basaltic andesite		

* Fused bead values to nearest percent
** Contamination from laboratory drill

Note:

Specimen	Well
BW-3	S. O. Co. Baldwin-Cienega No. 105 (Inglewood), core interval 8,136'-8,146'
BW-10	S. O. Co. Emery No. 87 (Leffingwell area), core interval 9,998'-10,001'
BW-14	S. O. Co. Irvine No. 1 (near Newport Lagoon), core interval 2,199'
BW-38	S. O. Co. Shell Puente C. H. 4 (Northern Puente Hills), core interval 1,837'-1,845'
BW-48	Union Hellman No. 56 (Dominguez), core interval 10,920'-10,938'
BW-62	General Petroleum Corp. Heath No. 1 (S.W. of Leffingwell), core interval 11,276'
BW-87	Texas Garnier (San Jose Hills), core interval 3,165'
BW-100	S. O. Co. Taft (Santa Ana area), core interval 3,006'-3,011'

In order to determine analytical precision, two samples of powder from each of several specimens were submitted for analysis under different identifying numbers. A sample analyzed during a given run also was included in a later run under a new designation. Under the circumstances, the analysis of these pairs was carried out without bias. The results are shown in Table 12, along with the calculated mean errors and standard deviations for each of the elements. The data are meager, but the duplication of analyzed samples represents one out of every nine, and is thought to be representative of the reproducibility. With the exception of boron, the figures for all of the elements are precise to within plus or minus 20 percent.

Special attention should be given to the data for certain elements. Boron is present as an impurity in the spectrograph electrodes, and analytical data for this element are therefore not reliable. Titanium and zirconium are refractory elements, and the analyses for these elements frequently show poor reproducibility. In the method used for copper, determinations were made from one of two different spectral lines, depending upon the concentration of this element in the sample. On a few plates, both of these lines were present, indicating two distinct and conflicting levels of abundance. Because of this, there exists an artificial hiatus in the analyses from about 35 to 60 ppm. This difficulty conceivably could

Specimen	Elements															Rock Name	Locality
	B	Ba	Co	Cr	Cu	Ga	Mn	Ni	Sc	Sr	Ti	V	Y	Yb	Zr		
BVD-3b	7	300	55	70	25	7	450	30	30	950	7000	150	60	3	250	Olivine-bearing basaltic andesite	Sunland
BVD-3b	20	250	55	95	25	8	350	30	30	750	8000	150	50	2.5	300		
BVD-24	20	150	50	300	85	5.5	750	100	30	800	5500	150	20	1	100	Olivine basalt	Sunland
BVD-24	8	150	60	300	75	3	550	100	20	800	4500	150	15	1	75		
BVN-30	8	300	30	200	25	3	500	65	25	800	4500	150	10	<1	75	Hypersthene-bearing basalt	Eastern Santa Monica Mts.
BVN-30	15	300	35	200	35	4	550	65	30	1000	6000	200	15	<1	100		
BVJ-9a	15	500	20	150	25	4	650	100	20	2000	3500	150	15	1	70	Augite andesite	San Joaquin Hills
BVJ-9a	15	400	30	150	25	7	550	200	20	1500	4000	150	15	1	100		
S-468	20	350	55	60	20	5	150	15	10	450	4000	85	85	5	150	Hypersthene andesite	Glendora
S-468	25	300	40	45	15	5	150	15	10	525	3750	100	90	5	150		
σerror	20.6	5.2	7.7	7.9	7.9	12.8	6.1	14.8	8.8	5.9	3.1	6.4	8.1	4.3	6.9		
Mean error	26%	6%	11%	6%	7%	16%	8%	7%	6%	10%	9%	4%	9%	2%	11%		

TABLE 12. REPRODUCIBILITY OF SPECTROCHEMICAL ANALYSES OF SELECTED VOLCANIC ROCKS FROM LOS ANGELES BASIN, CALIFORNIA

be overcome by scanning a number of plates in which both of the sensitive lines are present and determining their specific relationship.

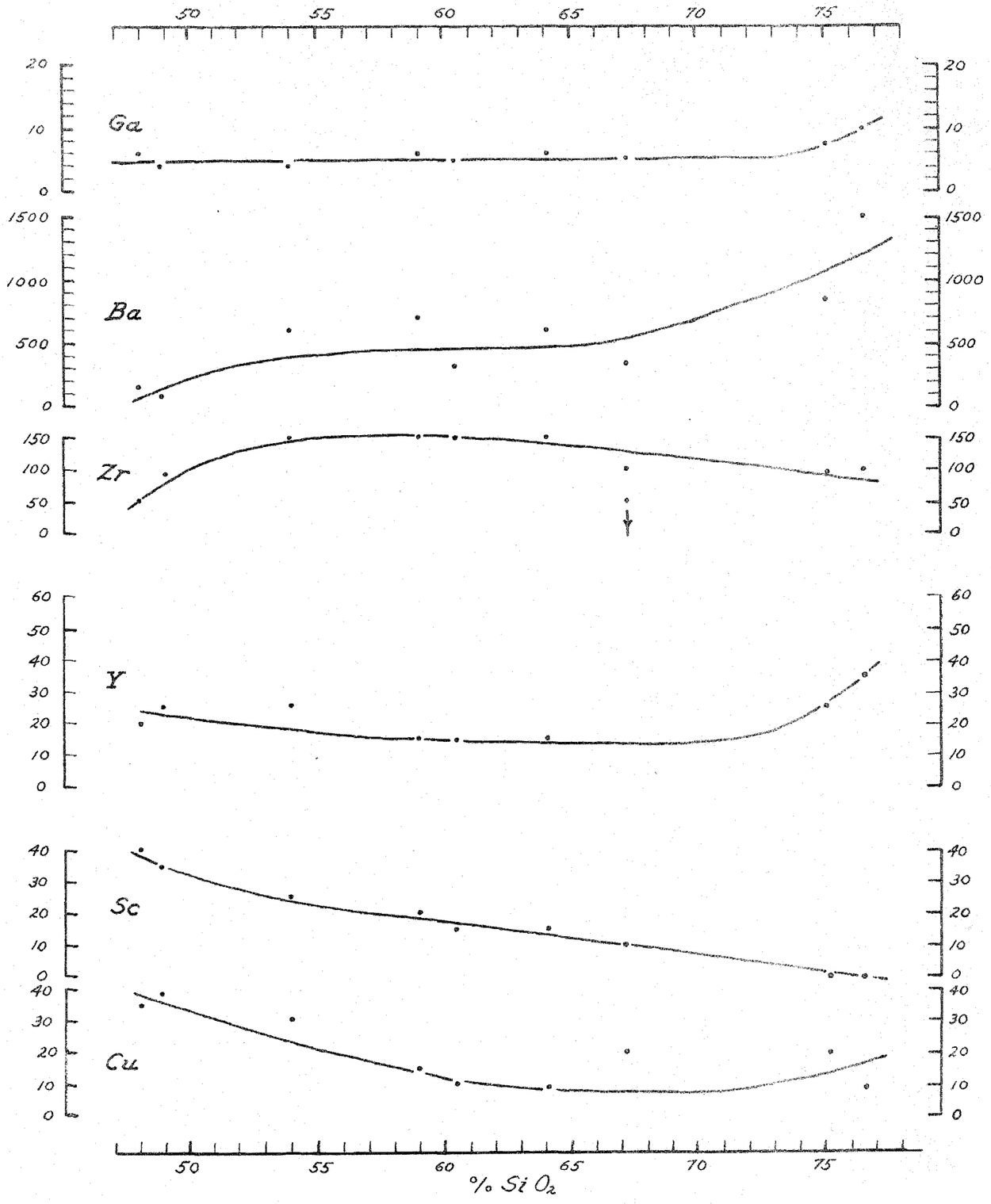
The samples were prepared by the writer, and the spectrographic analyses were made by Mr. Arthur Chodos of the Spectrochemical Laboratory of the Division of Geological Sciences, California Institute of Technology.

Variations in the trace elements of the lavas

The work of Wager and Mitchell (1951) and Nockolds and Allen (1953) indicates that during the process of differentiation, marked trends of relative enrichment or impoverishment of certain trace elements occur. Inasmuch as the data for the rocks of the Glendora area exhibit smooth variation curves for the major oxides (Figure 37), and as they are amenable to calculations from which a mechanism of differentiation has been adduced (Figure 38), these rocks were selected for checking the variations in trace-element composition of a group of temporally and areally restricted lavas. As far as is known, all these rocks are of Luisian age, and being closely related in a geographic sense, they should show no effects other than those of differentiation. Figure 40 shows the variation curves of eleven elements in the rocks from this area. The analyses are listed in Table 11.

Of the rocks included, seven were collected by Shelton (1955; this report Table 8), and the other two were taken from Shell Oil Company's Puente C. H. 4 and the Texas Company's Garnier wells. The reader will note, in studying Table 11, that there are 15 elements for which the abundance levels were measured, but that only 11 of them are included in Figure 40. The reason for this is that the other four elements show a high degree of scatter when plotted on a diagram of this kind. These four include boron, which is present as an electrode impurity, ytterbium, which is present in amounts close to the threshold level of measurement, and cobalt and titanium, which behave in an inexplicable manner. The other 11 elements follow trends that are consistent with theory. A discussion of these trends follows. It is included for the sake of further comparing the lavas of the Los Angeles basin with those of northern California and southern Oregon, and for comparing the relative behavior of certain major and minor elements during the course of differentiation.

Gallium ranges from 4 to 10 ppm, showing an increase toward the silicic end of the series. As illustrated in Figure 40, this increase is negligible from olivine basalt to acid hypersthene andesite, but it is pronounced at the rhyolitic end of the curve. In contrast, rocks from elsewhere in the circum-Pacific volcanic province (Crater Lake, Medicine Lake Highlands, East Central Sierra Nevada



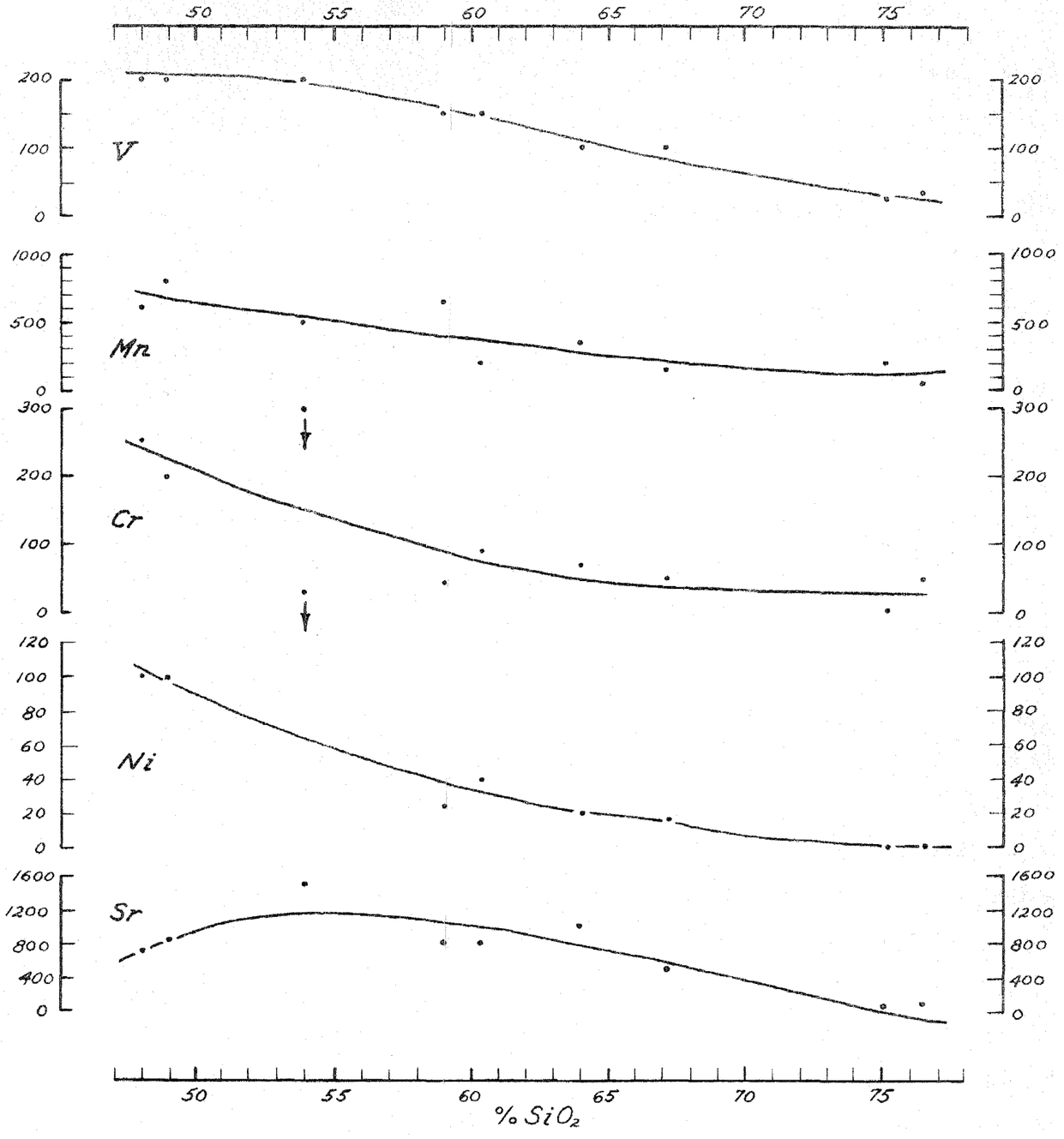


Figure 40. Silica-variation curves of eleven minor elements in the Miocene (Luisian) volcanic rocks of the Glendora area, Los Angeles basin, California.

(Markleeville, California), and Lassen Peak; Nockolds and Allen, 1953) exhibit an average abundance of gallium that ranges from three to five times that of the Los Angeles rocks. With the exception of Lassen Peak, the rocks in these areas show a decrease of gallium toward the silicic end of the variation curves. Relative to aluminum, gallium in rocks from the Los Angeles basin shows a steady enrichment from olivine basalt to rhyolite.

	Olivine basalt					Rhyolite	
Rock	S-422	S-615	S-333$_2$	S-345	S-468	S-597	S-496
Ga x 10^4/Al	.44	.47	.51	.62	.56	.99	1.40

The ionic size of trivalent gallium is nearly identical with that of aluminum, but the absolute concentration of the former element is much lower. Because it is less strongly bonded, it tends to concentrate in the later mineral phases, being relatively enriched in the magma through the subtraction of calcic plagioclase. Its behavior is therefore compatible with what one would predict on the basis of the mechanism of differentiation proposed in an earlier section of this report.

Barium shows sporadic variations, but in general appears to be concentrated in the more silicic rocks. The average value for basalt is 100 ppm, for andesite 500 ppm, and for rhyolite 1150 ppm. This trend of enrichment is

similar to that exhibited by other volcanic suites in the western United States (Nockolds and Allen, op. cit.), but the points representing individual rocks from the Glendora area do not fall as close to the mean curve as do those of the other suites. The trend of enrichment is compatible with theory, for barium is characteristically captured by the potassium-bearing minerals, which are concentrated in the later rocks.

The abundance of zirconium ranges from 50 to 150 ppm, and is highest in the intermediate rocks. In this respect, the Los Angeles volcanic rocks are like those of Lassen Peak, Crater Lake, Medicine Lake Highlands, and the east central Sierra Nevada (Nockolds and Allen, op. cit.). This behavior is puzzling, for according to Rankama and Sahama (1950), zirconium theoretically should show an increase toward rocks of granitic (rhyolitic) composition. In the Skaergaard intrusion (Wager and Mitchell, 1951), zirconium was found to be present in the clinopyroxenes of early-formed rocks, and in the apatite of the intermediate rocks. Neither of these minerals is more abundant in the intermediate rocks than in the basic or acid rocks of the Glendora area. Inasmuch as individual mineral phases were not analyzed separately during the present investigation, it is difficult to account for the behavior of zirconium.

Yttrium behaves in a manner opposite to that of

zirconium, being least abundant in the intermediate rocks. It ranges from 15 to 35 ppm, with the exception of one andesite in which the concentration is 90 ppm. Data from Nockolds and Allen (op. cit.) indicate little variation of this element in the rocks they examined, although subordinate increases are evident in the rocks of intermediate composition. According to Rankama and Sahama (op. cit.), yttrium is present in many early-formed calcium minerals, but it does not occur in anorthite, and thus the control of its behavior by plagioclase is unlikely. Inasmuch as the calcium-bearing mineral augite did not take an active part in the differentiation of the Los Angeles lavas, it is improbable that pyroxene control of yttrium accounts for the element's behavior either.

Scandium shows a well defined trend of impoverishment from olivine basalt to rhyolite. Deviations from the mean curve are small, and in this respect scandium exhibits the most consistent behavior of any of the elements studied. The total range in variation is 40 to 0 ppm. This is in distinct contrast to the volcanic rocks in northern California and Oregon. Those rocks exhibit unvarying concentrations of 0 to 10 ppm or variation ranges of 50 to 15 ppm. Scandium characteristically proxies for magnesium or divalent iron, and thus probably was removed during the course of differentiation because of its entry into early-formed crystals of olivine and hypersthene.

Copper, as mentioned previously, caused difficulty during the analytical work because of its tendency to produce two spectral lines, the photometric densities of which indicated conflicting values of concentration. The curve shown in Figure 40 has been "adjusted" by determining, to a first approximation, the proportionality between the concentrations indicated by these lines, and transposing the values to a single reference level. The resulting data show a relative trend of impoverishment of copper from olivine basalt to andesite, and a less well defined enrichment from andesite to rhyolite. Goldschmidt (1954) doubted "...whether any appreciable amount of copper in a truly ionic state enters the usual silicates of magmatic rocks such as olivine, pyroxene, ...", but sulfide minerals do not appear to be relatively more abundant in basalts than in other rocks of the Los Angeles basin, and it seems likely that copper substituted for ferrous iron in either olivine or augite, for its ionic radius and valence are the same as those of ferrous iron.

Vanadium shows a persistent decrease from olivine basalt to rhyolite (200 to 20 ppm). Its trend is thus in close agreement with that of the northern California lavas analyzed by Nockolds and Allen (op. cit.). Theoretically, vanadium proxies for ferric iron. This appears to be confirmed by the data under discussion, for the variation curve of vanadium shown in Figure 40 is similar to that of

total iron (Figure 37). In all probability, the vanadium of the Glendora volcanic rocks is concentrated in magnetite.

Manganese ranges from 800 to 50 ppm, decreasing erratically from olivine basalt to rhyolite. It logically proxies for divalent iron, and its impoverishment is almost certainly due to the removal of olivine and hypersthene from the differentiating magma. Comparison with values obtained from wet chemical analysis indicates that the two methods yield results of the same order of magnitude. The spectrochemical results, however, show a much smaller range of variation. The agreement between the two methods is poorest for the mafic rocks.

Chromium, like scandium, vanadium, and nickel, shows a steady decrease toward the silicic end of the variation diagram. Its total range is from 250 to 0 ppm. The rock with a silica content of 54 percent is exceptional, having a value of 300 ppm. This rock (Shelton's S-615, 1955) also shows a strong deviation from the variation curve for nickel, and in the variation diagram of the major oxides (Figure 37) a deviation from the curves for alumina, soda, and total iron. It thus is not characteristic of the rest of the rocks in the suite, and may be indicative of local assimilation of material of mafic composition.

The general trend of the chromium curve is like that presented by Nockolds and Allen (op. cit.) for the suites from Crater Lake, Lassen Peak, and the Medicine Lake Highlands.

This element characteristically participates in early-crystallizing iron- and magnesium-bearing minerals such as olivine and pyroxenes. Goldschmidt (op. cit.) has suggested that the pleochroism of hypersthene is due to the presence of minute amounts of chromium. The serial subtraction of both olivine and hypersthene from the parent magmas readily accounts for the impoverishment of this element.

The ionic radius and charge of nickel are similar to those of divalent magnesium and iron, and because of this, nickel tends to accumulate in olivine and pyroxene. Attention was first called to this fact by Vogt (1923) and later by Wager and Mitchell (1950). In the pyroxene family nickel shows a preference for hypersthene over augite. The removal of the former (preceded by that of olivine) is entirely adequate to account for the behavior of nickel in the Glendora rocks. They exhibit a steady impoverishment of nickel from olivine basalt to rhyolite. The lavas from northern California and southern Oregon show similar tendencies. The variation in the Glendora rocks is 100 to 0 ppm, with an anomalous value of 150 ppm in sample S-615.

The behavior of strontium in the Glendora volcanic rocks is identical with that in lavas of the east central Sierra Nevada (Nockolds and Allen, op. cit.). It rises in abundance from the mafic to the intermediate rocks and

then falls toward the rhyolites. The ionic charge and size of strontium are similar to those of calcium, which makes it possible for strontium to substitute for the latter in the structure of plagioclase. Owing to its larger radius, however, it is less strongly bonded, and therefore is enriched only in the later crystallizing plagioclases. This behavior accounts for its relative enrichment in andesitic rocks, the control being effected through the separation of plagioclases of varying composition. The total range of variation of strontium is 1,500 to 100 ppm.

The principal significance of the variations described above is the fact that there are pronounced modifications in the trace-element composition of lavas in the Los Angeles basin resulting from magmatic differentiation. If age correlations are to be made on the basis of certain differences in the trace-element content of these lavas, the effects arising from differentiation (i.e., differences in gross composition) must be sorted out first. In other words, for the purpose of correlation, the trace-element composition of a given rock cannot be contrasted meaningfully with that of another rock of grossly different composition. The refractive index of artificially fused beads was found useful for determining the bulk compositions of the rocks, thereby enabling the writer to select rocks of similar composition for comparison.

Even if the gross composition of a given flow or series of flows has been carefully determined, the selection of a single specimen for correlation cannot be made without first assuming that there are no compositional variations from one part of the flow to another, or that all flows of like composition in a given area are identical in their trace-element content or show similar contrasts among various elements. As a check on the validity of these assumptions, specimens were collected from several pairs of neighboring bodies of rock of like gross composition, and one of the andesite flows near Sunland was sampled at several points approximately one quarter of a mile apart.

Table 13 indicates the differences that exist between neighboring flows of like composition in four different areas. Comparison of these differences with those arising from errors in reproducibility (Table 12) indicates that there are significant inter-flow variations in the elements Ba, Co, and Cr.

Table 14 illustrates the maximum variation in the trace-element composition of a single flow. The elements Mn, Ni, and Sr show differences greater than the mean error of reproducibility. This means that in order for possible time variations to be recognized, they must exceed the differences exhibited by the elements of a single flow or series of neighboring flows as indicated in Tables 13 and 14.

Spec.	B	Ba	Co	Cr	Cu	Ga	Mn	Ni	Rock Type and Locality
BVN-63	10	100	65	200	85	3.0	850	100	Olivine basalts, Santa Monica Mts.
BVN-69	10	45	45	150	80	2.5	700	100	
BVD-5	8	150	55	150	60	3.0	650	55	Olivine basalts, Sunland
BVD-24	15	150	55	300	80	4.0	650	100	
BVJ-6	20	350	30	150	30	6.0	650	35	Hypersthene-augite andesites, San Joaquin Hills
BVJ-7	30	1000	45	150	25	7.0	550	50	
S-422	20	75	100	200	100	4.0	800	100	Olivine basalts, Glendora
BW-38	10	150	30	250	80	6.0	600	100	
Mean Var.	21%	30%	23%	15%	9%	13%	8%	12%	----------
σvar.	14.9	20.8	22.6	13.7	4.7	5.5	5.9	14.3	----------

TABLE 13. EXAMPLES OF THE DIFFERENCES IN TRACE ELEMENT COMPOSITION BETWEEN NEIGHBORING FLOWS OF LIKE GROSS COMPOSITION

Spec.	Sc	Sr	Ti	V	Y	Yb	Zr	Rock Type and Locality
BVN-63	35	400	3500	150	15	1	35	Olivine basalts, Santa Monica Mts.
BVN-69	30	350	3000	150	15	1	25	
BVD-5	30	1000	5000	200	20	1	75	Olivine basalts, Sunland
BVD-24	25	800	5000	150	18	1	90	
BVJ-6	20	550	6500	150	20	2	150	Hypersthene-augite andesites, San Joaquin Hills
BVJ-7	20	750	6000	150	35	2	150	
S-422	35	850	5000	200	25	1.5	85	Olivine basalts, Glendora
BW-38	40	700	4500	200	20	1.5	50	
Mean Var.	6%	11%	4%	4%	11%	0	13%	---------
σvar.	4.1	3.3	3.3	7.0	11.7	0	8.2	---------

TABLE 13. Continued

Spec.	B	Ba	Co	Cr	Cu	Ga	Mn	Ni
BVS-55	15	250	35	35	15	6.0	450	15
BVS-71	6	250	30	35	15	4.5	300	10

	Sc	Sr	Ti	V	Y	Yb	Zr
BVS-55	25	650	5500	200	35	2	150
BVS-71	25	850	5500	200	35	1	150

TABLE 14. MAXIMUM INTRA-FLOW VARIATIONS (IN PPM) IN A FLOW OF OLIVINE-BEARING BASALTIC ANDESITE. (Specimens from northern edge of Verdugo Mountains)

Another source of variation investigated during the present study is that resulting from the alteration of the rocks. Table 15 shows the nature and extent of variations in the trace-element content due to deuteric alteration. The elements B, Ga, Sc, Ti, Y, Yb, and Zr appear to have been relatively enriched during alteration.

Comparison of the values of enrichment of these elements with those of the errors in reproducibility indicates that the variations shown by B, Ti, Y, and Yb are significant, but that those for Ga, Sc, and Zr probably are not. Boron is characteristically enriched in the acid rocks. It is a volatile element and has been detected in the gases of many volcanoes, which accounts for its presence in the fluids causing deuteric alteration. The elements Y and Yb are known to increase in concentration in the residual liquors of differentiating magmas, and the Y rare earths,

Mineral Variations	Mineral Variations
1) Olivine altered to iddingsite and hematite	1) Partial replacement of plagioclase by Fe-rich "montmorillonite" clay
2) Magnetite altered to other iron oxides	2) Replacement of augite by celadonite and re-aggregated chlorophaeite
3) Vesicles lined with fibrous yellow and brown secondary minerals	3) Interstitial development of re-aggregated chlorophaeite

Ele.	Fresh	Altered	Partly altered	Severely altered
B	8	20	7	20
Ba	150	150	450	200
Co	55	40	35	60
Cr	150	150	150	200
Cu	60	80	80	75
Ga	3	5	3	4.5
Mn	650	550	750	650
Ni	55	50	100	100
Sc	30	35	35	45
Sr	1000	1000	200	350
Ti	5000	6500	3500	5000
V	200	200	150	200
Y	20	30	25	35
Yb	1	2	1	2
Zr	75	100	85	100
	BVD-5 olivine basalt	BVD-5a altered olivine basalt	BVV-28 partly altered olivine diabase	BVV-27 highly altered olivine diabase

TABLE 15. TRACE ELEMENT VARIATIONS RESULTING FROM DEUTERIC ROCK ALTERATION
(Specimens BVD-5 and BVD-5a: western San Gabriel Mts.; specimens BVV-28 and BVV-27: southern Palos Verdes Hills)

in particular, have been observed in late mineral veins (Goldschmidt, 1954). The apparent enrichment of Ti is problematical. In general, this element participates in the structures of early-formed minerals such as ilmenite, and as a result shows an impoverishment in the more silicic rocks. Under the circumstances, its behavior during alteration is puzzling. With the exception of the elements noted, deuteric alteration has resulted in little or no change in the trace-element composition of the lavas.

Core samples commonly become contaminated by the injection of drilling muds into minute fractures in the rock, or by streaks of metal resulting from contact with the drilling equipment. For the purpose of spectrochemical analysis, the outer part of each core was removed with a chisel, and only the inner part was analyzed. Inasmuch as small amounts of drilling mud can penetrate to the centers of cores, however, two analyses of caked muds were run for control purposes. These muds were scraped from cores of Standard Oil Company of California's Baldwin-Cienega No. 105 and Emery No. 87 wells. The analyses appear in Table 16 below. Noteworthy are the concentrations of B and Sr, the very high concentration of Ba, and the presence of Mo, Pb, Ag, and Zn. The amount of mud contaminating any one sample probably does not exceed one or two percent of the sample by volume, however, and it is unlikely that any of these elements except Ba would be detected in the course of analysis.

B	Ba	Co	Cr	Cu	Ga	Mn	Mo	Ni	Pb	Mud
35	>.15%	15	80	60	4	550	8	40	65	B.C.#105
35	>.20%	40	350	100	2	650	6	200	200	Emery #87

Sc	Sr	Ti	V	Y	Yb	Zr	Ag	Zn	Mud
15	650	3500	100	30	2.5	100	--	--	B.C.#105
20	2500	3000	100	20	1.5	100	1	500	Emery #87

TABLE 16. PARTIAL SPECTROCHEMICAL ANALYSES OF DRILLING MUDS FROM TWO STANDARD OIL COMPANY OF CALIFORNIA WELLS (IN PPM)

To summarize the preceding paragraphs, it was found that B, Ba, Co, Cr, Sr, Ti, Y, and Yb show variations that are significantly greater than the errors of reproducibility. None of these variations is strictly time-dependent, however. Differences in the trace-element composition of rocks of different ages must be larger than these in order to be recognizable.

It was shown earlier that there are pronounced differences in the major-element composition of rocks in certain geographically restricted parts of the basin. These differences are thought to have resulted from the process of assimilation. Similar differences are evident at the trace-element level of abundance. In Table 17, olivine basalts of approximately equivalent age from three different localities are compared. There are significant

contrasts in the abundance of Ba, Mn, Sr, Ti, and Zr. Intra-regional compositional contrasts such as these make the establishment of time-dependent variations difficult.

Correlational methods of statistical analysis were applied to the data of Table 11 in a search for such time-dependent variations in the trace elements, but none were discovered. Instead, additional variations dependent on the geographic location of the lavas were found. It is concluded, therefore, that spectrochemical analysis does not offer a fruitful solution for the correlation of these volcanic rocks.

B	Ba	Co	Cr	Cu	Ga	Mn	Ni	Sample
8	250	50	250	80	4.0	700	95	1
10	75	100	200	85	3.0	800	100	2
10	200	50	300	70	3.5	550	100	3

Sc	Sr	Ti	V	Y	Yb	Zr	Sample
40	300	4000	200	30	1.5	85	1
35	400	3500	150	15	1.0	30	2
30	950	5000	200	20	1.0	90	3

TABLE 17. DIFFERENCES IN THE TRACE-ELEMENT COMPOSITION OF COEVAL OLIVINE BASALTS FROM DIFFERENT AREAS (Sample 1: Average of two analyses, early Luisian rocks, Palos Verdes Hills; Sample 2: average of two analyses, Relizian rocks, Santa Monica Mountains; Sample 3; average of three analyses, Sunland area)

Significance of Geographic Differences in the Trace-Element Composition of the Lavas

In the preceding section of this report, small, geographically-dependent differences in the trace-element composition of the Miocene lavas in the Los Angeles basin were reported. Independent evidence suggests that, although the primary magma serving the volcanoes of the basin was originally homogeneous, in the process of rising from a depth of 30 or 40 kilometers it split into two or more fractions that experienced contrasted changes in composition as a result of contact with wall rocks of different lithology. These changes are thought to have been responsible for the intra-regional differences in the trace-element composition of the lavas also.

Compositional differences between rocks of geographically restricted regions define what have been called "petrographic provinces." The differences between the rocks of such provinces result from contrasted parent magmas or from different modes of magmatic evolution from similar parents. Inasmuch as the trace elements in a magma commonly behave in accordance with major elements to which they are related (in terms of size and valence), factors causing variations in the abundance of the major elements also cause variations in the abundance of the minor elements. On the other hand, original differences in the

trace-element content of several similar parent magmas may give rise to trace differences in rocks that evolve from these magmas, even though the modes of magmatic evolution are the same for each (i.e., even though the end products are lithologically similar). As a result, trace elements assist in defining the boundaries of petrographic provinces that are not otherwise apparent on the basis of lithology. Caution must be exercised in applying this technique to a search for such provinces, however, for most of the so-called quantitative methods of spectrochemical analysis actually are only semi-quantitative in character, and owing to the use of different analytical methods in different laboratories, the data of the laboratories are not always directly comparable. Comparisons can be most safely made between rocks analyzed with the same technique or in the same laboratory.

As an example, variation diagrams of selected trace elements in the Miocene volcanic rocks of the Los Angeles basin are shown in Figure 41, along with others for the Pliocene volcanic rocks of the Lava Mountains (north central Mojave Desert; data from Smith, 1956). In this figure, points for all of the rocks analyzed during the present investigation are shown. The total number of points differs from the number of analyses listed in Table 11 because all duplicate analyses were averaged, and the drilling muds and severely altered rocks were

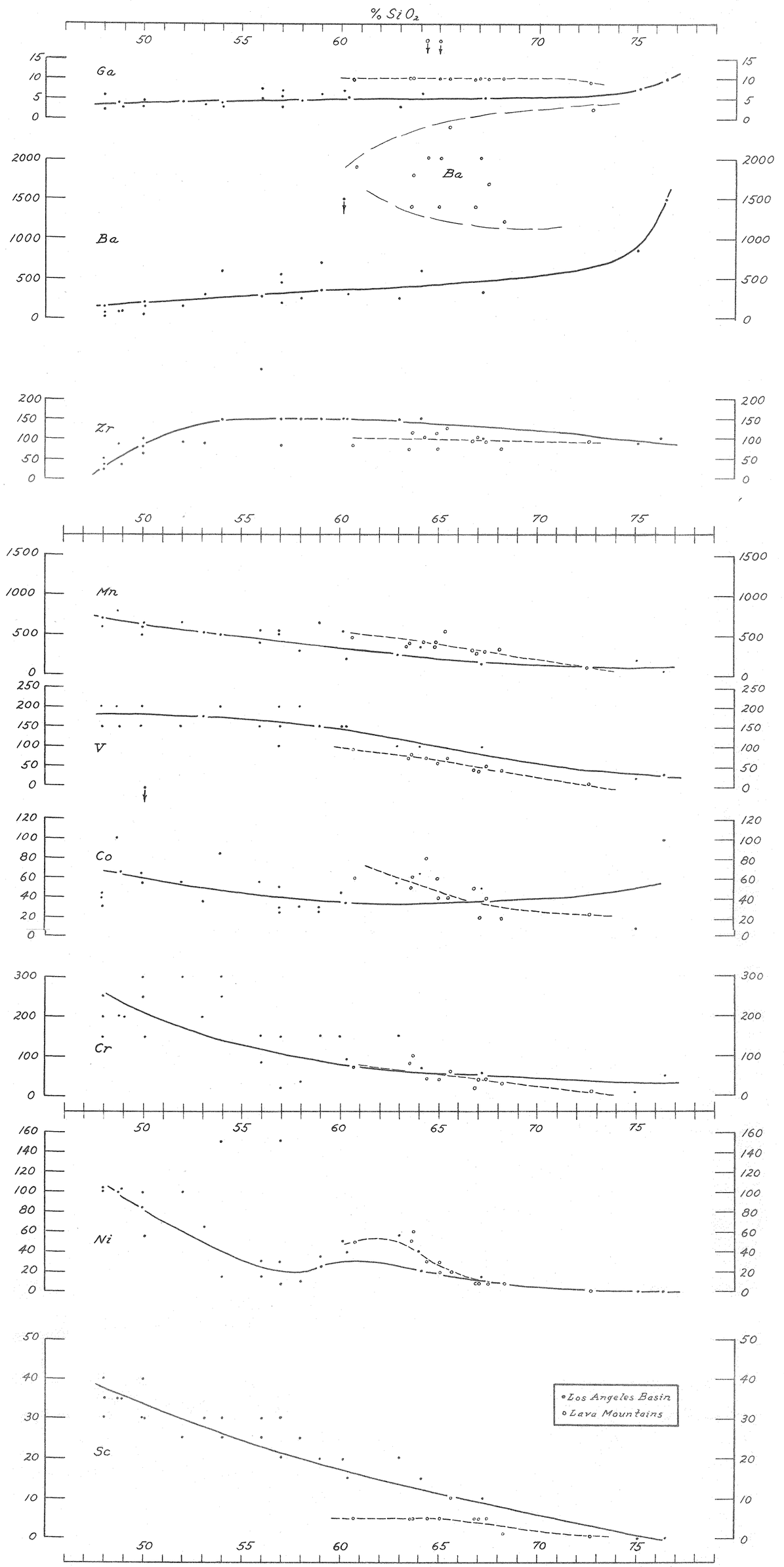


Figure 41. Silica-variation curves of nine minor elements in the Miocene volcanic rocks of the Los Angeles basin, and a comparison with curves for a similar suite of Pliocene volcanic rocks of the Lava Mountains, near Randsburg, California. The whole of the Los Angeles basin suite is represented. Data on the Lava Mountain rocks are from Smith (1956).

omitted from consideration. Altered rocks from the Lava Mountains (selected on the basis of a moderate or high total water content) were also omitted. The silica content of the rocks (abscissa) was recalculated on a water-free basis.

Lithologic variations in the volcanic rocks of the Lava Mountains are not as great as those in the rocks of the Los Angeles basin, but the compositional ranges of the two overlap. Hypersthene and hornblende-bearing andesites and dacites are common to both.

Trace-element contrasts between the rocks differ from one element to another. There are only minute differences in the abundance of Cr and Ni. Small absolute differences are evident for Mn (average Δ = 100 ppm), Zr (Δ = 35 ppm), V (Δ = 30 ppm), Sc (Δ = 5 ppm), and Ga (Δ = 5 ppm), and large differences are evident for Ba. Points for Ba in the rocks of the Lava Mountains show considerable scatter, but the average difference between the rocks of the two regions is 1400 ppm. In terms of percentage differences (considered here to be more significant), Ba and Ga show pronounced contrasts, and V and Zr less contrast. Not shown on the diagram, but nevertheless significant, is the element Pb. It does not occur in the volcanic rocks of the Los Angeles basin, but is present in the rocks of the Lava Mountains in amounts varying from 10 to 20 ppm.

Summary and Conclusions

1) Miocene and volcanic rocks of the Los Angeles basin range in composition from olivine basalt to rhyolite, but rocks of andesitic composition predominate. Flows, pyroclastic tuff-breccias, and hypabyssal intrusive bodies are common.

2) An approximate distinction between basic, intermediate, and acid rocks can be made on the basis of the mafic minerals present. Olivine is characteristic of the basalts and basaltic andesites, hypersthene of the basic, intermediate, and acid andesites, hornblende of the acid andesites and dacites, and biotite of the dacites and rhyolites. Augite occurs in all rocks except rhyolite.

3) The predominance of hypersthene-augite andesite among the intermediate varieties is thought to be due to the relatively high alumina content of the rocks.

4) Both mineralogically and chemically, the rocks of the area are typical of the basalt-andesite-rhyolite association of the circum-Pacific volcanic belt. The alkali-lime index is 65.2, calcic.

5) A variation diagram of the major oxides shows well defined contrasts between rocks in different parts of the basin. The strongest contrast is that between rocks of the Glendora area and those along the coast. The latter are relatively rich in FeO and MgO, and relatively poor in Al_2O_3.

6) On the basis of these compositional contrasts and additional field and petrographic evidence bearing on inclusions of "basement" rocks in the lavas, it is concluded that the difference between the Glendora lavas and the coastal lavas is largely the result of assimilation. The coastal lavas represent assimilation of rocks of the Catalina metamorphic facies, the Glendora lavas, assimilation of granodioritic plutonic rocks. If more data were available from rocks in other parts of the basin it is possible that they would show these provincial contrasts also.

7) The postulated assimilation indicates that magma ascending beneath the floor of the basin split into two or more fractions that came to occupy isolated cupolas or conduits.

8) Graphical calculations for the Glendora volcanic rocks indicate that magmatic differentiation took place by fractional crystallization and assimilation.

9) None of the lava types is restricted to a specific part of the stratigraphic section. Hence, attempts to make intra-basinal stratigraphic correlations on this basis were unproductive. The only apparent distinction of lava types is an areal one. Basalts predominate in the northwestern part of the basin, and andesites in the eastern and southern parts.

10) The abundances of specific trace elements in the rocks show that variations arise from magmatic differentiation, interflow compositional differences, and contamination of core samples. Variations arising from deuteric alteration are small. As is true of the major elements, contrasts exist between similar rocks of identical age in different parts of the basin.

11) Statistical analysis of the analytical spectrochemical data failed to reveal time-dependent differences in the trace-element composition of the rocks. For this reason, it is thought that further attempts to establish correlations on the basis of petrographical or chemical analytical data would be unprofitable.

BIBLIOGRAPHY

Anderson, C. A., 1941, Volcanoes of the Medicine Lake highland, California: California Univ., Dept. Geol. Sci., Bull., vol. 25, no. 7, pp. 347-422.

Athy, L. F., 1930, Density, porosity, and compaction of sedimentary rocks: Am. Assoc. Petroleum Geologists Bull., vol. 14, pp. 1-24.

Axelrod, D. I., 1939, A Miocene flora from the western border of the Mohave Desert: Carnegie Inst. Washington Pub. No. 516, pp. 1-143.

_____, 1950, Studies in late Tertiary paleobotany: Carnegie Inst. Washington Pub. No. 590, pp. 1-323.

Bailey, E. H., 1941, Mineralogy, petrology, and geology of Santa Catalina Island, California: Unpub. Ph.D. thesis, Stanford University.

Bandy, O. L., 1953, Ecology and paleoecology of some California Foraminifera. Part II. Foraminiferal evidence of subsidence rates in the Ventura basin: Jour. Paleontology, vol. 27, pp. 200-203.

Barghoorn, E. S., 1953, Evidence of climatic change in the geologic record of plant life: in Climatic change (Shapley, H., 1953), Harvard Univ. Press, Cambridge, pp. 235-248.

Beck, A. C., 1950, Volcanic activity at Mt. Ruapehu from August to December, 1945: New Zealand Jour. Sci. and Tech., vol. 31, sec. B, pp. 1-13.

Benioff, H., 1954, Orogenesis and deep crustal structure - additional evidence from seismology: Geol. Soc. America Bull., vol. 65, pp. 385-400.

Bishop, W. C., 1950, Geology of southern flank Santa Susana Mountains, Los Angeles County, California: Unpub. M. A. thesis, University of California at Los Angeles.

Bolin, B., 1952, Studies of the general circulation of the atmosphere: Advances in Geophysics, Academic Press, New York, 349 pages.

Bowen, N. L., 1928, The evolution of the igneous rocks: Princeton University Press, 322 pages.

Bowen, O. E., 1954, Geology and mineral deposits of Barstow quadrangle, San Bernardino County, California: California Div. Mines, Bull. 165.

Bramlette, M. N., 1946, The Monterey formation of California and the origin of its siliceous rocks: U. S. Geol. Survey,Prof. Paper 212.

Brooks, C. E. P., 1949, Climate through the ages: McGraw-Hill Book Company, New York, 395 pages.

Callaghan, E., 1933, Some features of the volcanic sequence in the Cascade Range in Oregon: Am. Geophys. Union Trans., pp. 243-249.

Capps, S. R., 1916, An ancient volcanic eruption in the upper Yukon Basin: U. S. Geol. Survey, Prof. Paper 95-D, pp. 59-64.

Corey, W. H., 1954, Tertiary basins of southern California: California Div. Mines, Bull. 170, Ch. III, pp. 73-83.

Creer, K. M., Irving, E., and Runcorn, S. K., 1954, The direction of the geomagnetic field in remote epochs in Great Britain: Jour. Geomag. and Geoelect., vol. 6, pp. 163-168.

Crowell, J. C., 1954, Strike-slip displacement of the San Gabriel fault, southern California: California Div. Mines, Bull. 170, Ch. IV, pp. 49-52.

Crump, R. M. and Ketner, K. B., 1953, Feldspar optics: Geol. Soc. America Memoir 52, 139 pages.

Curtis, G. H., 1951, Geology of the Topaz Lake and the eastern half of the Ebbets Pass quadrangles, California: Unpub. Ph.D. thesis, University of California.

_____, 1954, Mode of origin of pyroclastic debris in the Mehrten formation of the Sierra Nevada: California Univ., Dept. Geol. Sci., Bull., vol. 29, pp. 453-502.

Daviess, S. N. and Woodford, A. O., 1949, Geology of northwestern Puente Hills, Los Angeles County, California: U. S. Geol. Survey Oil and Gas Inv. Prelim. Map 83.

Dibblee, T. W., Jr., 1950, Geology of southwestern Santa Barbara County, California: California Div. Mines, Bull. 150.

Diller, J. S. and Patton, H. B., 1902, The geology and petrography of Crater Lake National Park: U. S. Geol. Survey, Prof. Paper 3.

Driver, H. L., 1948, Genesis and evolution of Los Angeles basin: Am. Assoc. Petroleum Geologists Bull., vol. 32, pp. 109-125.

Durham, J. W., 1950, Cenozoic marine climates of the Pacific coast: Geol. Soc. America Bull., vol. 61, pp. 1243-1264.

Durrell, Cordell, 1953, Tertiary igneous rocks of the Santa Monica Mountains: Abstract in Pac. Petrol. Geol., vol. 7, no. 12.

_____, 1954, Geology of the Santa Monica Mountains, Los Angeles and Ventura Counties, California, Map Sheet No. 8: California Div. Mines, Bull. 170.

Edwards, E. C., 1934, Pliocene conglomerates of Los Angeles basin and their paleogeographic significance: Am. Assoc. Petroleum Geologists Bull., vol. 18, pp. 786-812.

Elam, J. G., 1948, Geology of Seminole quadrangle, Los Angeles County, California: Unpub. M. A. thesis, University of California at Los Angeles.

Eldridge, G. H. and Arnold, R., 1907, The Santa Clara Valley, Puente Hills, and Los Angeles oil districts, southern California: U. S. Geol. Survey Bull. 309.

Emery, K. O. and Shepard, F. P., 1945, Lithology of the sea floor off southern California: Geol. Soc. America Bull., vol. 56, pp. 431-478.

Emiliani, C., 1955, Temperatures of Pacific bottom waters and polar superficial waters during the Tertiary: Science, new ser., vol. 119, pp. 853-855.

_____, 1956, Oligocene and Miocene temperatures of the equatorial and subtropical Atlantic Ocean: Jour. Geology, vol. 64, pp. 281-288.

English, W. A., 1926, Geology and oil resources of the Puente Hills region, southern California: U. S. Geol. Survey Bull. 768.

Fleischer, M., Murata, K. J., Fletcher, J. D., and Narten, P. R., 1952, Geochemical association of niobium (columbium) and titanium and its geological and economic significance: U. S. Geol. Survey Circular 225, 13 pages.

Foshag, W. F. and Gonzalez, J., 1956, Birth and development of Paricutin Volcano, Mexico: U. S. Geol. Survey Bull. 965-D, pp. 355-486.

Frye, J. C., Swineford, A., and Leonard, A. B., 1948, Correlation of Pleistocene deposits of the central Great Plains with the glacial section: Jour. Geology, vol. 56, pp. 501-525.

Fuller, R. E., 1931, The geomorphology and volcanic sequence of Steens Mountain in southeastern Oregon: Washington Univ. Pub. in Geology, vol. 3, pp. 1-130.

Gale, H. S. and Gale, H. R., 1932, Miocene volcanism (abstract): Geol. Soc. America Bull., vol. 43, Part 1, pp. 234-235.

George, W. O., 1924, The relation of the physical properties of natural glasses to their chemical composition: Jour. Geology, vol. 32, pp. 353-372.

Goldschmidt, V. M., 1954, Geochemistry: Clarendon Press, Oxford, 730 pages.

Grange, L. I., 1931, Volcanic-ash showers: New Zealand Jour. Sci. and Tech., vol. 12, pp. 228-240.

Griggs, R. F., 1922, The Valley of Ten Thousand Smokes: The National Geographic Society, Washington, 340 pages.

Hanna, M. A., 1926, Geology of the La Jolla quadrangle, California: California Univ., Dept. Geol. Sci., Bull., vol. 16, pp. 187-246.

Hess, H. H., 1949, Chemical composition and optical properties of common clinopyroxenes: Part I: Am. Mineralogist, vol. 34, pp. 621-666.

Hewett, D. F., 1954, General geology of the Mojave Desert region, California: California Div. Mines, Bull. 170, Ch. II, pp. 137-170.

Hill, M. L., 1930, Structure of San Gabriel Mountains, north of Los Angeles: California Univ., Dept. Geol. Sci., Bull., vol. 19, pp. 137-170.

_____, 1954, Tectonics of faulting in southern California: California Div. Mines, Bull. 170, Ch. IV, pp. 5-14.

Hoots, H. W., 1931, Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, California: U. S. Geol. Survey, Prof. Paper 165-C.

Jahns, R. H. and Lance, J. F., 1950, Geology of the San Dieguito pyrophyllite area, San Diego County, California: California Div. Mines, Special Report 4.

Juhle, W. and Coulter, H., 1955, The Mount Spurr eruption, July 9, 1953: Am Geophys. Uion Trans., vol. 36, pp. 199-202.

Kennedy, W. Q. and Richey, J.E., 1947, Catalogue of the active volcanoes of the world: Bull. Volc., Supplement to Series 2, vol. 7, 11 pages.

Kew, W. S. W., 1924, Geology and oil resources of a part of Los Angeles and Ventura Counties: U.S. Geol. Survey Bull. 753.

Kleinpell, R. M., 1938, Miocene stratigraphy of California: Am. Assoc. Petroleum Geologists, Tulsa, 450 pages.

Köhler, A., 1949, Recent results of investigation on the feldspars: Jour. Geology, vol. 57, pp. 592-599.

Kozu, S., 1934, The great activity of Komagatake in 1929: Min. pet. Mitt., vol. 45, pp. 133-174.

Krauskopf, K. B., 1948, Lava movement at Paricutin Volcano, Mexico: Geol. Soc. America Bull., vol. 59, pp. 1267-1284.

Ladd, H. S., 1951, Brackish-water and marine assemblages of the Texas coast, with special reference to mollusks: Pub. of the Inst. of Marine Sci., vol. 46, pp. 125-164.

Larsen, E. S., Jr., 1938, Some new variation diagrams for groups of igneous rocks: Jour. Geology, vol. 46, pp. 505-520.

_____, 1948, Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, California: Geol. Soc. America Memoir 29, 182 pages.

Larsson, W., 1935, Vulkanische Asche von Ausbruch des chilenischen Vulkans Quizapu (1932) in Argentine gesammelt: Upsala Univ., Geol. Inst., Bull., vol. 26, pp. 27-52.

Macdonald, G. A., 1939, An intrusive peperite at San Pedro Hills, California: California Univ., Dept. Geol. Sci., Bull., vol. 24, pp. 329-337.

_____, 1953, Pahoehoe, aa, and block lava: Am Jour. Sci., vol. 251, pp. 169-191.

Martin, G., 1913, The recent eruption of Katmai Volcano in Alaska: Nat. Geog. Mag., vol. 24, pp. 131-181.

Mathews, W. H., 1951, A useful method for determining approximate composition of fine grained igneous rocks: Am. Mineralogist, vol. 36, pp. 92-101.

McCulloh, T. H., 1954, Problems of the metamorphic and igneous rocks of the Mohave Desert: California Div. Mines, Bull. 170, Ch. VII, pp. 13-24.

Menard, H. W., 1955, Deformation of the northeastern Pacific basin and the west coast of North America: Geol. Soc. America Bull., vol. 66, pp. 1149-1198.

Miller, W. J., 1934, Geology of the western San Gabriel Mountains: Univ. California at Los Angeles Pub. in Math. and Physical Sci., vol. 1, no. 1, pp. 1-114.

Minakami, T., Ishikawa, T., and Yagi, K., 1951, The 1944 eruption of Volcano Usu in Hokkaldo, Japan: Bull. Volc., Ser. II, Tome X, pp. 157-168.

Mintz, Y. and Dean, G., 1952, The observed mean field of motion of the atmosphere, Geophysics Research Directorate, Air Force Cambridge Research Center: Geophys. Res. Papers No. 17, 65 pages.

Myers, A. T., 1951, Improved cutting tool for spectroscopic electrodes: Anal. Chem., vol. 23, pp. 209-210.

National Research Council, 1950, Report of the committee on the measurement of geologic time, 1949-1950: Nat. Research Council, 118 pages.

Natland, M. L. and Rothwell, W. T., Jr., 1954, Fossil Foraminifera of the Los Angeles and Ventura regions, California: California Div. Mines, Bull. 170, Ch. III, pp. 33-42.

Neuerburg, G. J., 1953, Geology of the Griffith Park area, Los Angeles County, California: California Div. Mines, Special Report 33, 29 pages.

Noble, L. F., 1954, Geology of the Valyermo quadrangle and vicinity, California: U. S. Geol. Survey Quadrangle Series, G. Q. 50.

Nockolds, S. R. and Allen, R., 1953, The geochemistry of some igneous rock series, Part I: Geochim. Cosmochim. Acta, vol. 4, pp. 105-142.

Padang, M. N. van, 1951, Catalogue of the active volcanoes of Indonesia: International Volcanological Association, Naples, 271 pages.

Peacock, M. A., 1931, Classification of igneous rock series: Jour. Geology, vol. 39, pp. 54-67.

_____ and Fuller, R. E., 1928, Chlorophaeite, sideromelane and palagonite from the Columbia River Plateau: Am. Mineralogist, vol. 13, pp. 360-383.

Popenoe, W. P., 1941, Trabuco and Baker conglomerates of the Santa Ana Mountains: Jour. Geology, vol. 49, pp. 738-752.

_____, 1942, Cretaceous formations and faunas of southern California: Am Assoc. Petroleum Geologists Bull., vol. 26, pp. 162-187.

Rankama, K. and Sahama, Th. G., 1949, Geochemistry: Univ. Chicago Press, 912 pages.

Raw, R., 1943, Some altered palagonite tuffs from Jamaica and the origin and history of their chlorites: Jour. Geology, vol. 51, pp. 215-243.

Reed, R. D. and Hollister, J.S., 1936, Structural evolution of southern California: Am Assoc. Petroleum Geologists, Tulsa, 146 pages.

Rossby, C. G., 1941, The scientific basis of modern meteorology: Yearbook of Agriculture, U. S. Gov't. Printing Office, pp. 599-655.

Schoellhamer, J. E., Kinney, D. M., Yerkes, R. F., and Vedder, J. G., 1954a, Geologic map of the northern Santa Ana Mountains, Orange and Riverside Counties, California: U. S. Geol. Survey Oil and Gas Inv., Map 154.

_____, Vedder, J. G., and Yerkes, R. F., 1954b, Geology of the Los Angeles basin: California Div. Mines, Bull. 170, Part II, Plate 1.

_____ and Woodford, A. O., 1951, The floor of the Los Angeles basin, Los Angeles, Orange, and San Bernardino Counties, California: U. S. Geol. Survey Oil and Gas Inv., Map OM 117.

Schuchert, C., 1955, Atlas of paleogeographic maps of North America: John Wiley and Sons, New York, 177 pages.

Shapley, H., 1953, Climatic change: Harvard University Press, 318 pages.

Shelton, J. S., 1946, Geologic map of northeastern margin of San Gabriel basin, Los Angeles County: U. S. Geol. Survey Oil and Gas Inv., Prelim. Map 63.

Shelton, J. S., 1954, Miocene volcanism in coastal southern California: California Div. Mines, Bull. 170, Ch. III, pp. 31-36.

_____, 1955, Glendora volcanic rocks, Los Angeles basin, California: Geol. Soc. America Bull., vol. 66, pp. 45-90.

Smith, G. I., 1956, Geology and petrology of the Lava Mountains, San Bernardino, California: Unpub. Ph.D. thesis, California Institute of Technology.

Smith, W. S. T., 1897, Geology of Santa Catalina Island: California Acad. Sci. Proc., 3rd series; vol. I, pp. 1-72.

_____, 1898, A geological sketch of San Clemente Island: 18th Annual Report of U. S. Geol. Survey, Part II, pp. 465-496.

Smithsonian Institution, 1951, Smithsonian meteorological tables, 6th rev. ed.: Smithsonian Misc. Coll., vol. 114, 527 pages.

Soper, E. K., 1938, Geology of the central Santa Monica Mountains, Los Angeles County: California Jour. Mines and Geology, vol. 34, pp. 131-180.

Stenzel, H. B., 1945, Paleoecology of some oysters: Nat. Research Council, Report of the committee on marine ecology as related to paleontology, pp. 37-46.

Swineford, A., 1949, Source area of Great Plains Pleistocene volcanic ash: Jour. Geology, vol. 57, pp. 307-311.

Taliaferro, N. L., 1943a, Geologic history and structure of the central Coast Ranges of California: California Div. Mines, Bull. 118, pp. 119-163.

_____, 1943b, Franciscan-Knoxville problem: Am. Assoc. Petroleum Geologists Bull., vol. 27, pp. 109-219.

Terpening, J. N., 1951, Geology of part of the eastern Santa Monica Mountains: Unpub. M. A. thesis, University of California at Los Angeles.

Thayer, T. P., 1937, Petrology of later Tertiary and Quaternary rocks of the north-central Cascade Mountains in Oregon, with modes on similar rocks in western Nevada: Geol. Soc. America Bull., vol. 48, pp. 1611-1652.

Thayer, W. N., 1916, The physiography of Mexico: Jour. Geology, vol. 24, pp. 61-94.

Thorarinsson, Sigurdur, 1950, The eruption of Mt. Hekla, 1947-1948: Bull. Volc. Ser. II, Tome X, pp. 157-168.

Truex, J. N., 1950, Geology of the northern part of the Santa Monica Mountains between Beverly Glen and Laurel Canyon Boulevard: Unpub. M. A. thesis, University of California at Los Angeles.

U. S. Dept. Commerce, Weather Bureau, 1951-1954, Climatological data, national summary, vols. 2-5.

Vogt, J. H. L., 1923, Nickel in igneous rocks: Econ. Geology, vol. 18, p. 307.

Wager, L. R. and Mitchell, R. L., 1951, The distribution of trace elements during strong fractionation of basic magma - a further study of the Skaergaard intrusion, East Greenland: Geochim. Cosmochim. Acta, vol. 1, pp. 129-208.

Waters, A. C., 1955, Volcanic rocks and the tectonic cycle: Geol. Soc. America, Special Paper 62, pp. 703-722.

Wentworth, C. K. and Williams, H., 1932, The classification and terminology of the pyroclastic rocks: Nat. Research Council Bull. 89, pp. 19-53.

Wexler, H., 1951, Spread of the Krakatoa volcanic dust cloud as related to the high-level circulation: Bull. American Meteorological Soc., vol. 32, pp. 48-51.

Wilcox, R. E., 1954, Petrology of Paricutin Volcano, Mexico: U. S. Geol. Survey Bull. 965-C, pp. 281-353.

Willett, H. C., 1949, Long-period fluctuations of the general circulation of the atmosphere: Jour. of Meteorology, vol. 6, pp. 34-50.

_____, 1950, The general circulation at the last (Würm) glacial maximum: Geografiska Annales, häfte 3-4, pp. 179-187.

Williams, H., 1932, Geology of the Lassen Volcanic National Park, California: California Univ. Dept. Geol. Sci. Bull., vol. 21, pp. 195-386.

_____, 1935, Newberry volcano of central Oregon: Geol. Soc. America Bull., vol. 46, pp. 253-304.

Williams, H., 1942, The geology of Crater Lake National Park, Oregon: Carnegie Inst. Washington Pub. 540, 159 pages.

_____, 1950, Volcanoes of the Paricutin region: U. S. Geol. Survey Bull. 965-B, pp. 165-279.

_____, 1954, Problems and progress in volcanology: Quart. Jour. Geol. Soc. London, vol. CIX, pp. 311-332.

_____ and Meyer-Abich, H., 1955, Volcanism in the southern part of El Salvador: California Univ. Geol. Sci. Bull., vol. 32, pp. 1-54.

_____, Turner, F. J., and Gilbert, C. M., 1954, Petrography: W. H. Freeman, San Francisco, 406 pages.

Winchell, A. N., 1951, Elements of optical mineralogy: Part II, 4th ed., New York, 551 pages.

Wissler, S. G., 1943, Stratigraphic relations of the producing zones of the Los Angeles basin oil fields: California Div. Mines, Bull. 118, pp. 209-234.

Woodford, A. O., 1924, The Catalina metamorphic facies of the Franciscan series: California Univ. Geol. Sci. Bull., vol. 15, pp. 49-68.

_____, 1925, The San Onofre breccia: its nature and origin: California Univ. Dept. Geol. Sci. Bull., vol. 15, pp. 159-280.

_____, Moran, T. G., and Shelton, J. S., 1946, Miocene conglomerates of Puente and San Jose Hills, California: Am. Assoc. Petroleum Geologists Bull., vol. 30, pp. 514-560.

_____, Schoellhamer, J. E., Vedder, J. G., and Yerkes, R. F., 1954, Geology of the Los Angeles basin: California Div. Mines, Bull. 170, Ch. II, pp. 65-82.

_____, Shelton, J. S., and Moran, T. G., 1944, Stratigraphy and oil possibilities of Puente Hills and San Jose Hills, California: U. S. Geol. Survey Oil and Gas Inv., Prelim. Map 23.

Woodring, W. P., Bramlette, M. N., and Kew, W. S. W., 1946, Geology and paleontology of Palos Verdes Hills, California: U. S. Geol. Survey, Prof. Paper 207, 145 pages.

Yerkes, R. F., 195_, in press, Volcanic rocks of the El Modeno area, Orange County, California: U. S. Geol. Survey, Prof. Paper 274-G.

APPENDIX I. FAUNAL LIST OF MEGAFOSSIL SUITES COLLECTED FROM INTRUDED ARKOSIC SANDSTONE ON THE SOUTH FLANK OF THE SAN GABRIEL MOUNTAINS, NORTH-NORTHWEST OF SUNLAND, CALIFORNIA.

(Identifications by L. G. Hertlein. Suite GE-1 collected by G. P. Eaton, Suite S-XXVI by W. H. Holman)

PELECYPODA	Suite GE-1	Suite S-XXVI
Cardium sp.	x	x
Chione cf. C. temblorensis Anderson	x	
Chione sp.		x
Diplodonta cf. D. harfordi	x	
Dosinia cf. D. merriami Clark	x	x
Macoma cf. M. ocoyana Conrad	x	
Nuculana cf. N. ochsneri Anderson and Martin	x	
Nuculana sp.		x
Ostrea sp. (thick shell)	x	x
Panope estrellana Conrad	x	x
Pecten (Aequipecten) discus Conrad		x
? Pitar sp.	x	
Solen cf. S. gravidus Clark	x	
Spisula albaria Conrad		x

GASTROPODA	Suite GE-1	Suite S-XXVI
Calyptraea filosa Gabb	x	
Calyptraea cf. C. inornata Gabb	x	x
Crepidula cf. C. princeps Conrad	x	x
? Epitonium sp.	x	
Oliva californica Anderson	x	
Phos cf. P. dumbleana Anderson in Hanna	x	
Polinices cf. P. ocoyana Conrad	x	
Polinices sp. (large)	x	
Trophon kernensis Anderson	x	x
Trophosycon cf. T. ocoyana Conrad (T. kernianum Cooper)	x	x
? Vermetus sp.		x

AGE: MIDDLE MIOCENE. FORMATION: TOPANGA

APPENDIX II. SUPPLEMENTARY WELL DATA PERTAINING TO PLATE VIII

(Asterisk indicates data from Schoellhamer and Woodford, 1951.)

No.	Operator	Well	Location (Section-T-R)	Remarks
S-1	Ajax Petroleum Co.	Maney	(21-6-10)	Passed through 1,326′ of Relizian strata with 40° dips (1,020′ stratigraphic thickness). T.D. 7,250′
S-2	Amerada Petroleum Co.	Irvine No.63-1	(27-5-9)	Upper Mohnian rocks in "ditch" at 2,860′-2,880′, poorly preserved arenaceous Foraminifera suggest upper Cretaceous rocks in core at 3, 729′-3,741′.
S-3*	British American Oil Producing Co.	Bodger No.5	(22-3-14)	Entered schist from upper Miocene strata at 9,120′.
S-4*	British American Oil Producing Co.; The Texas Co.; Seaboard Oil Co. of Delaware	Alandra Park No.1	(22-3-14)	Entered schist from upper Miocene strata at 9,336′.
S-5	Continental Oil Co.	Anaheim 4-1	(5-4-10)	Mohnian (?) strata rest on Vaqueros-Sespe formations undivided between 8,700′ and 8,750′; volcanic rocks missing.
S-6*	Dominguez Estate Co.	Fee No.1	(2-4-14)	Entered schist from upper Miocene strata at 7,125′.

No.	Operator	Well	Location (Section-T-R)	Remarks
S-7	General Petroleum Corp.	Terminal No.1	(4-5-13)	Upper Miocene strata 2,968′-6,620′; Luisian strata 6,620′-6,787′ (no volcanic rocks). Schist 6,787′-6,814′.
S-8	Honolulu Oil Co.	Santa Ana Valley Irrigation Co. No.1	(29-3-8)	Passed through 1046′ of Luisian and Relizian strata with 40° dips and bottomed at 2,220′. No volcanic rocks.
S-9*	A.T. Jergins Trust Co.	Palos Verdes No.1	(34-4-14)	Penetrated mostly brown shale, presumably Miocene; altered igneous rock 2,037′-2,050′. Entered schist at 2,195′; in same to 2,782′. Data from Woodring (1946).
S-10*	J. I. Listle	Shell-McKenna No.1	(33-3-14)	Entered schist from upper Miocene strata at 7,221′.
S-11	McCaslin Oil Co.	Transport No.17	(10-6-11)	Passed through 1,500′± Relizian strata with no volcanic rocks. T.D. 8,365′.
S-12*	Ohio Oil Co.	Gardena Community No.6-1	(24-3-14)	Entered schist (?) from upper Miocene beds at 10,530′.
S-13*	Ohio Oil Co.	G. D. Howland No.1	(21-2-15)	Entered schist from upper Miocene strata at 6,810′.
S-14*	Ohio Oil Co.	Gough No.8	(7-3-14)	Entered schist (?) from upper Miocene strata at 7,513′.
S-15*	Reconstruction Finance Corp.	Del Rey No.5	(27-2-15)	Entered schist from upper Miocene strata at 5,839′; no volcanic rocks.

No.	Operator	Well	Location (Section-T-R)	Remarks
S-16	Richfield Oil Corp.	Pertusati	(20-2N-16)	Entered Paleocene at 2,220′; no volcanic rocks encountered.
S-17	Seaboard Oil Co. of Delaware	Corehole No. 5	(14-1-13)	Entered Santa Monica slate from upper Miocene strata at 2,704′.
S-18	Seaboard Oil Co. of Delaware	Park No. 1	(9-1-13)	Upper Miocene strata 0-1,323′; middle Miocene (?) strata 1,323′-1,338′; "basement" 1,338′-2,300′.
S-19*	Seaboard Oil Co. of Delaware	Pauley-Seaboard No.61-20	(20-3-14)	Entered schist from upper Miocene strata at 8,049′.
S-20	Shell Oil Co., Inc.	Alamitos 48-A	(29-4-12)	Entered schist at 14,700′± from Division E Mohnian strata
S-21	Shell Oil Co., Inc.	Dolley No. 2	(29-4-12)	Entered schist at 10,509′± from Division E Mohnian strata
S-22*	Shell Oil Co., Inc.	Lloyd Dabney No. 1	(33-3-14)	Entered schist at 6,220′± from upper Miocene strata
S-23	Southwest Exploration Co.	Southern Belle Rex No. 12	(2-6-11)	Lower Mohnian beds cored in interval 6,082′-6,092′ (La Vida equivalent). Top of middle Miocene section at 6,246′. No volcanic rocks. T. D. 6, 692′.
S-24	Southwest Exploration Co.	State No.65	(4-6-11)	Top of middle Miocene section at 6,100′. Passed through 3,000′± of middle Miocene strata with no volcanic rocks. T.D. 9,626′.

No.	Operator	Well	Location (Section-T-R)	Remarks
S-25	Shoreline Petroleum Co.	Pinkerton No.1	(5-5-9)	Went from Pliocene rocks into Vaqueros formation at 1,750'. Elevation of well 180'.
S-26	Standard Oil Co.	Del Amo No.1	(8-4-13)	Entered schist (?) from upper Miocene strata at 10,187'.
S-27	Standard Oil Co.	Houghton No.1	(36-2-12)	Bottomed without reaching middle Miocene. T.D. 14,444'.
S-28	Standard Oil Co.	Irvine Co. No.1	(26-6-10)	Top of Relizian section at 518'. Went to 5,627' without encountering volcanic rocks. T.D. 5,627'.
S-29*	Standard Oil Co.	Refinery No.8	(13-3-15)	Entered schist (?) from upper Miocene strata at 7,152'.
S-30*	Standard Oil Co.	Six Companies No.2	(2-3-15)	Entered schist from upper Miocene strata at 6,918'.
S-31	Superior Oil Co.	Eberle No.1	(10-6-11)	Passed through 1,500' of Relizian strata and bottomed therein; no volcanic rocks encountered. T.D. 9,048'.
S-32*	Superior Oil Co.	Inglewood Ext. No.1	(25-2-15)	Entered schist (?) at 9,467'. No volcanic rocks encountered.
S-33*	Superior Oil Co.	Torrance No.66	(24-4-14)	Entered schist (?) from upper Miocene strata at 5,723'.

No.	Operator	Well	Location (Section-T-R)	Remarks
S-34	The Texas Co.	Dinkler No.1	(7-4-9)	Entered upper Miocene section at 6,200′. In Relizian strata at 6,970′. Entered possible lower Miocene or older beds at 7,350′. T.D. 7,392′.
S-35	The Texas Co.	Stern	(1-4-11)	Passed through unconformity at base of Repetto formation into Topanga strata at 10,140′. In Topanga to 10,430′. No volcanic rocks encountered.
S-36*	Union Oil Co. of California	El Segundo No.1	(8-3-14)	Entered schist (?) from upper Miocene strata at 7,681′.
S-37*	Union Pacific Railroad Co.	Union Pac. No.E-10	(3-5-13)	Entered schist at 5,620′; no volcanic rocks encountered.
S-38*	Zephyr Oil Co.	Banning No.8-1	(29-4-13)	Entered schist (?) from upper Miocene strata at 6,755′.