Frontispiece. Section of "ribbon rock" tactite, magnified 9.5 diameters.

TACTITE ROCKS OF THE IRON MOUNTAIN DISTRICT, SIERRA AND SOCORRO COUNTIES, NEW MEXICO

Thesis

by

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ABSTRACT

The pyrometasomatic deposits at Iron Mountain, near the northern end of the Sierra Cuchillo in Sierra and Socorro Counties, New Mexico, have been formed through replacement of calcareous beds of Paleozoic age, generally at or near contacts with intrusive masses of rhyolite, rhyolite porphyry, aplite, and fine-grained granite. The metamorphism is probably mid-Tertiary in age. Its two chief products are (a) light-colored, dense, fine-grained granulites rich in diopside, clinozoisite, bytownite, and other iron-poor silicate minerals, and (b) coarser-grained, dark-colored, iron-rich rocks, called tactites. The spatial and temporal relations of these iron-poor and iron-rich contact rocks, not only to each other but to adjacent igneous bodies and to relatively unmetamorphosed beds, appear to have been determined in a regular and definite manner; this is discussed and illustrated in detail by several examples.

The iron-rich pyrometasomatic deposits contain a large number of unusual minerals. Most remarkable are helvite and

at least three other beryllium-bearing silicate minerals, which are known to occur in noteworthy concentrations in only one type of rock, a peculiar rhythmically layered variety of tactite to which the name "ribbon rock" has been given. The structure of such tactite is very conspicuous, and appears in section as thin, finely crenulated bands of magnetite alternating with similar bands of silicate minerals and finely crystalline fluorite. Concentric banding about fluorite-rich pods is common. Bodies of "ribbon rock" vary in size from inch-thick lenses to large masses amounting to thousands of tons; most appear to have formed along contacts between recrystallized limestone and massive magnetite-andradite tactite, chiefly by replacing fluids penetrating the limestone from fractures. The layered structure is interpreted as a diffusion effect.

The formation of massive and "ribbon rock" tactites can be traced through a range of falling temperatures from a stage characterized by deposition from iron-rich vapors to a stage in which hydrothermal solutions were dominant. Both vapors and liquids appear to have been acid, and reducing conditions undoubtedly existed during the latter part of the hydrothermal stage. The occurrence of beryllium in "ribbon rock", but not in typical massive tactite may signify that its compounds in pyrometasomatic deposits are confined to rocks of hydrothermal origin. The occurrence of "ribbon rock" itself is suggested as a potentially useful clue for recognition of beryllium-bearing contact deposits elsewhere; at least two other occurrences of what apparently is "ribbon rock" have been described in the literature.

INTRODUCTION

Location and physical features

Deposits of contact metamorphic origin are known to occur throughout much of the Iron Mountain district, an area that embraces about 15 square miles in northwestern Sierra County and southwestern Socorro County, New Mexico. Much of the mineralization appears to be confined to Iron Mountain itself, a narrow, elongated fault-block ridge that forms the north end of the Sierra Cuchillo (fig. 1), and most of the deposits can be reached by trail or tractor road from a semi-permanent camp at the base of this mountain. A 2-mile side road, which extends westward down a pediment slope, connects this camp, known as Brown City, with State Highway 52, a poorly conditioned dirt and gravel road that leads 10 miles south to Winston, the nearest town. Hot Springs, on the Rio Grande 30 miles southeast of Iron Mountain, is reached from Winston over 31 miles of fair gravel road and 9 miles of the paved U. S. Route 60 for the remainder of the distance. Branch lines of the Atchison, Topeka, and Santa Fe railway serve Magdalena and Hatch, the latter 40 miles south of Hot Springs by paved highway. Engle, a small station on the Albuquerque-El Paso line of the same railroad, lies 19 miles east of Hot Springs, but much of the intervening road is in poor condition.

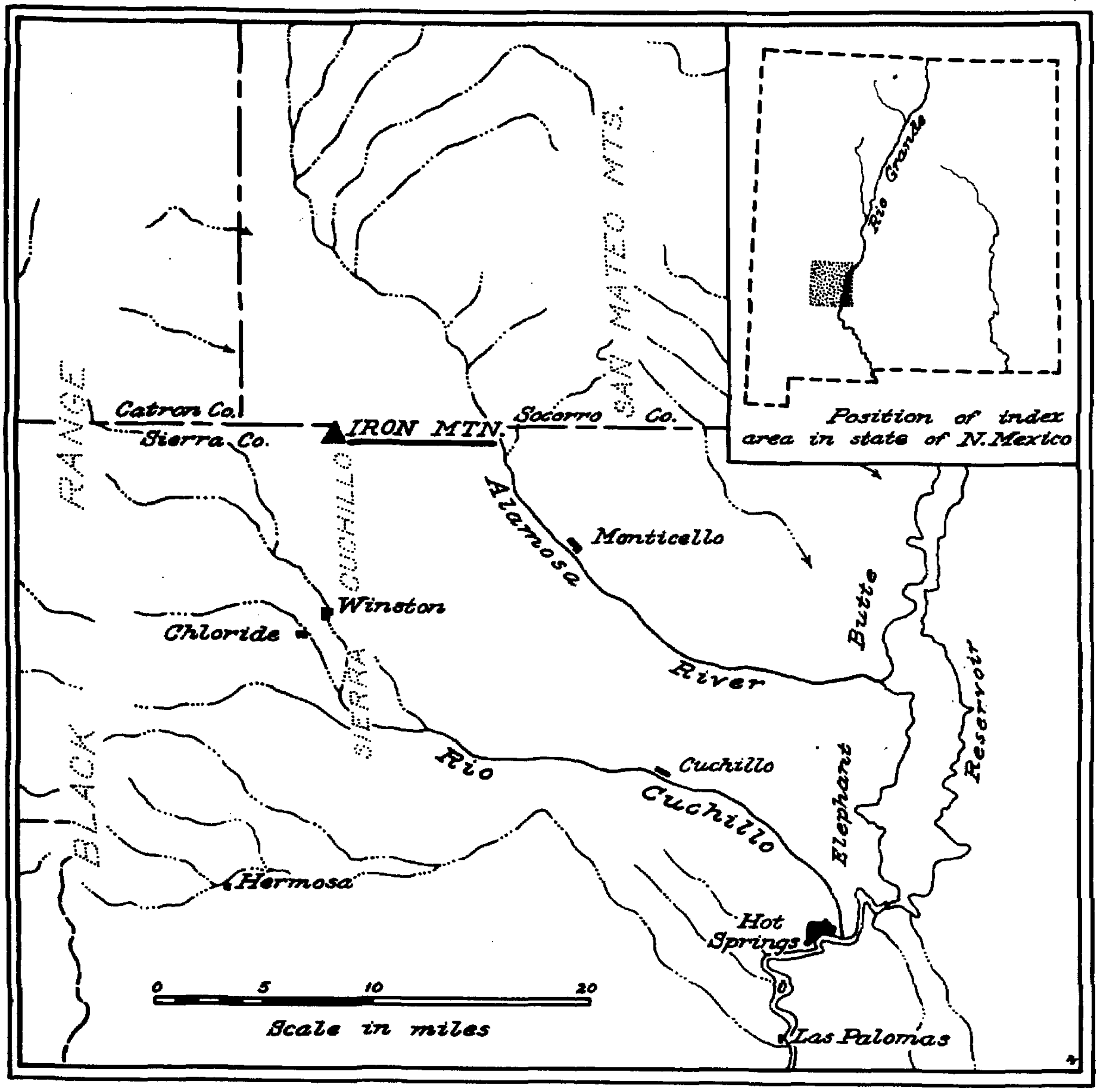


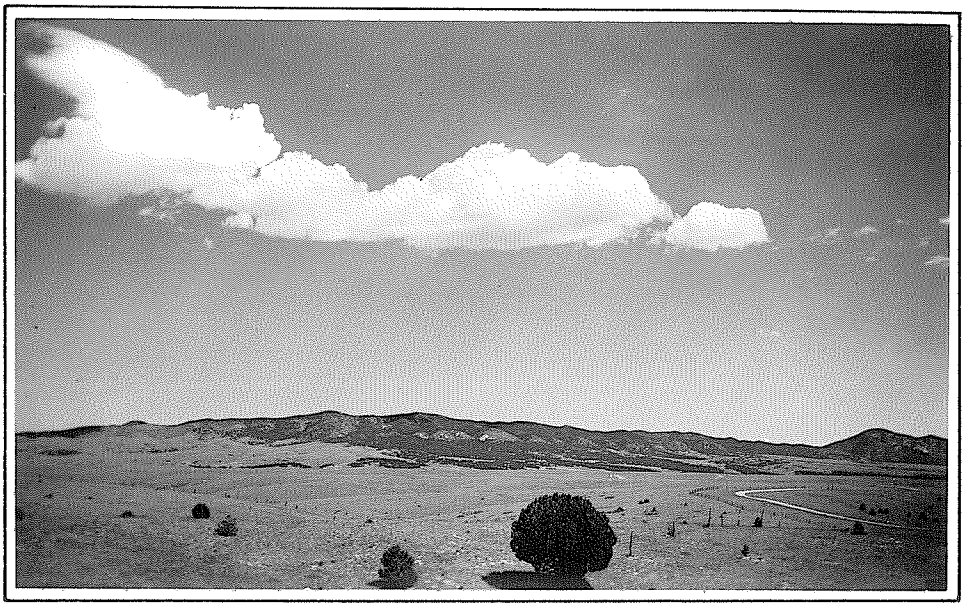
Figure 1. Index map, showing location of Iron Mountain in southwestern New Mexico.

The northern Sierra Cuchillo is separated from the Black Range to the west by a long, pedimented valley 3 to 8 miles in width (pl. 2). It rises to heights of 300 to 700 feet above the pediment surfaces, and the altitude along the crest of the ridge-like Iron Mountain is about 8000 feet. The slopes are steep but tend to be smoothly contoured, and most of the canyons are deep and narrow (pl. 3).

Much of the range is covered with piñon pine, juniper, and scrub cedar, with open stands of yellow pine on protected north and east slopes. The pediment surfaces are dominantly grass land. Most of the precipitation, which ordinarily is about 15 inches a year, occurs as heavy downpours during the late summer and fall months, but all permanent water must be obtained from relatively deep wells. Despite its altitude, the district rarely has winter weather severe enough to interfere with transportation or mining activity, although some roads are impassable immediately following unusually heavy cloudbursts.

Development of the district

The magnetite deposits of the northern Sierra Cuchillo have attracted the attention of prospectors for almost a century, and the late T. K. Scales of Winston spent many years in repeated attempts to exploit the area for its iron, gold, and base metals. A few tons of oxidized lead-copper ore, said to have been shipped by Scales and his associates



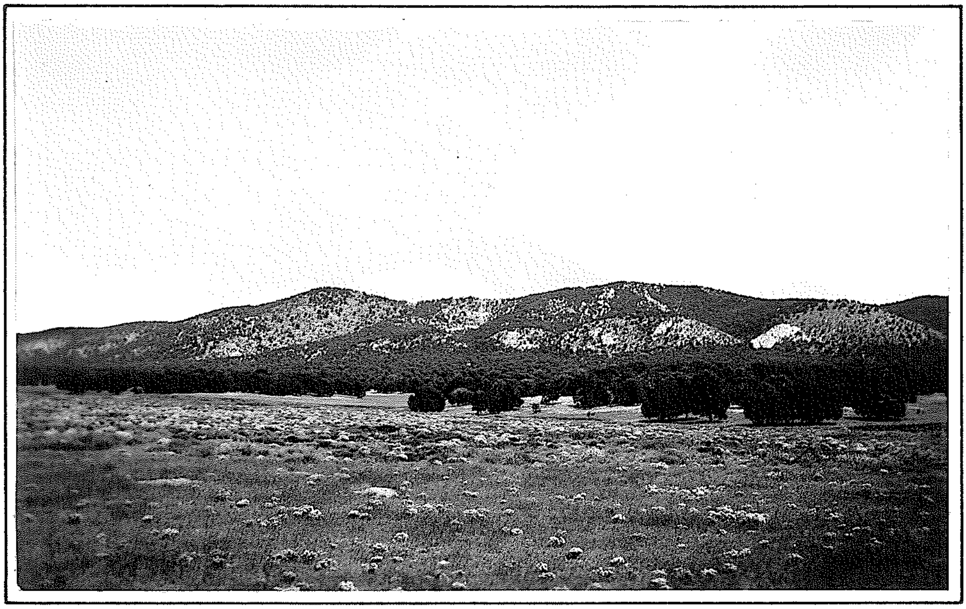


Plate 2. General views of the northern Sierra Cuchillo.

Top ----- View looking east-southeast from edge of the Black Range. Iron Mountain is in middle distance, Reilly Peak at extreme right. Note the faceted spurs along the base of the range.

Bottom -- Nearer view of the Iron Mountain block, looking east-northeast. North Peak is at left, South Peak to the right. The bold, cliff-like mass near the canyon mouth at right is part of a large intrusive body of fine-grained granite.

from small deposits in the southern part of the district during the period 1880-1925, constitutes the only record of production. About 20 years ago T. C. Parker relocated several of the old claims that had been permitted to lapse, and during his search there for workable quantities of zinc, gold, and fluorspar he noted with interest a peculiar garnet-like mineral that he was unable to identify. It was not until November, 1941, when L. W. Strock[1/] determined the mineral as

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1/ Strock, L. W., A new helvite locality -- a possible beryllium deposit: Econ. Geol., vol. 36, pp. 748-751, 1941.

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helvite, a complex silicate-sulfide species that contains beryllium, manganese, iron, and zinc, that the potentialities of the deposits as a source of beryllium were first suspected. Strock's recognition of this element and subsequent identification of the principal beryllium-bearing mineral as helvite were made with the aid of the spectrograph during a preliminary examination of ores. Interest in the district was further quickened in June, 1942, when Parker discovered promising occurrences of tungsten ore.

The Federal Geological Survey was engaged in detailed examination and mapping of the deposits from May 5, 1942 to April 10, 1943, and thus has been able to follow closely the development of the area and to actually participate in the discovery of several ore bodies. The Federal Bureau of Mines effectively explored and sampled the deposits during the period June, 1942 to May, 1943.

Field and office work

As representative for the Geological Survey, the writer was assigned to the study of the Iron Mountain deposits from May 5, 1942, to February 10, 1943, during which period the data discussed in this paper were obtained. A topographic and geologic map of the district was made on a scale of 1 inch = 1000 feet with use of a barometer, hand level, and a corrected aerial mosaic obtained from the Soil Conservation Service; this map is reproduced on a smaller scale in plate 1. A detailed map of Iron Mountain itself was made on a scale of 1 inch = 200 feet with plane table and alidade (pl. 3), and several larger-scale maps of small mineralized areas were made by the same method (pls. 3, 4, 6-10).

Forty-one systematic samples and more than 150 specimens of tactite and other rock types have been examined petrographically in the field and in the laboratories of the New Mexico School of Mines and the California Institute of Technology in Socorro, New Mexico, and Pasadena, California, respectively. Jewell J. Glass has studied the detailed properties of the beryllium-bearing minerals and many associated species in the laboratories of the Geological Survey, and her work is acknowledged wherever its results appear in the text. Most of the illustrations were prepared by the writer in Pasadena during the period February 15 - April 15, 1943.

Acknowledgments

It is a pleasure to acknowledge the uniformly cordial hospitality of the several claim owners and their representatives, notably Messrs. T. C. Parker, Blanchard Hanson, A. H. Gunnell, and L. A. Wilkie and L. A. Wilke of Continental Machines, Inc. Mr. Parker was particularly helpful during the early stages of the investigation, when he accompanied the writer on frequent exploratory examinations of the property. Many courtesies were received from Mr. and Mrs. H. R. Johnson of Winston and from other local residents too numerous to mention. Profs. S. B. Talmadge and A. C. Walters of the New Mexico School of Mines and Ian Campbell and J. P. Buwalda of the California Institute of Technology kindly made available needed facilities for laboratory and library work.

The consistently friendly cooperation of Mr. F. A. Rutledge, engineer in charge of exploration by the Federal Bureau of Mines, greatly increased the effectiveness of geologic work in the vicinity of the ore bodies, and the many courtesies received from all members of the Bureau of Mines are greatly appreciated. W. Porter Irwin served ably as field assistant during the summer of 1942, and Frances H. Jahns gave valuable assistance in the final preparation of the manuscript. The writer is further indebted to Drs. Ian Campbell of the California Institute of Technology and S. G. Lasky of the Geological Survey for their many helpful suggestions and stimulating discussions in the field, and to Dr. Campbell and Drs. H. M. Bannerman, J. J. Glass, G. R. Mansfield and C. S. Ross of the Geological Survey for their critical examination of the manuscript.

GENERAL GEOLOGY

Introduction

Iron Mountain and its immediate extensions form a ridge-like mass 3½ miles long, 1000 to 3000 feet wide, and 300 to 700 feet high (pl. 1). This mass is a narrow, north-trending block of the basin and range type, and has been briefly described by Smythe[2/], Lasky[3/], and Harley[4/]. It is bounded

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2/ Smythe, D. D., A contact metamorphic iron-ore deposit near Fairview, New Mexico: Econ. Geol., vol. 16, pp. 410-418, 1921.

3/ Lasky, S. G., The ore deposits of Socorro County, New Mexico: New Mexico School of Mines, State Bur. of Mines and Min. Res., Bull. 8, pp. 138-139, 1932.

4/ Harley, G. T., The geology and ore deposits of Sierra County, New Mexico: New Mexico School of Mines, State Bur. of Mines and Min. Res., Bull. 10, p. 118, 1934.

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from the pedimented valley on the west and north by a conspicuous fault zone and from a rugged region to the east and south by a more irregular group of faults. These zones along which the Iron Mountain block has been uplifted converge to the north near the end of the range and to the south near Goat Canyon (pl. 1); they effectively delimit the mineralized area of chief interest.

Although the northern part of the Sierra Cuchillo is shown on published maps as a great mass of volcanic rocks, the Iron Mountain block and the area immediately adjacent on the east present a rather complete section of eastward-dipping upper Paleozoic sedimentary beds, as well as local Mesozoic (?) strata. The oldest rocks in the district are limestones, quartzites, and shaly beds of the Pennsylvanian Magdalena group; these are overlain in succession by red beds and limestones of Permian age and by sandstone, conglomerate, and shale of probable Cretaceous age. Unconformably above the sedimentary rocks is a thick Tertiary volcanic series, consisting in ascending order of andesitic breccia, andesite and latite with tuffs of corresponding composition, latite, and rhyolite with associated pyroclastics. Sills, dikes, and plug-like bodies of Tertiary monzonite, felsite, rhyolite, rhyolite porphyry, aplite, and fine-grained granite cut all the sedimentary units and at least the lower members of the volcanic series. The valley area west and north of the range is underlain by coarse, poorly consolidated sediments of late Tertiary and Quaternary age. The distribution of all rock types in the district is shown in plate 1, and a general section in the following table.

Table 1

General section of rocks in the
Iron Mountain district

		Thickness (feet)
	Sedimentary rocks	
Quaternary	Alluvium---unconsolidated sand and gravel	0-20
	-Unconformity-	
	Pediment gravels	0-15
	-Unconformity-	
Tertiary	Santa Fe (?) formation---poorly consolidated conglomerate, breccia, sandstone, fanglomerate, and siltstone	400+
	-Unconformity-	
Cretaceous (?)	Reddish to dark gray shale (very local)	0-200
	Dakota (?) sandstone---coarse, friable sandstone with quartz and limestone conglomerates	0-220
	-Unconformity-	
Permian	Yeso and San Andres formation--limestone and red beds, with very little gypsum	1200+
	Abo sandstone---buff to red sandstone with subordinate maroon shale .	1250
	-Unconformity-	
Pennsylvanian	Magdalena limestone--limestone with subordinate quartzite and shaly beds; quartzite and quartz conglomerate at base	1420
	Igneous rocks	
Tertiary	Lamprophyre, andesite, and basalt Red felsite Aplite and fine-grained granite Rhyolite and rhyolite porphyry Monzonite	Intrusive
	Rhyolite and associated tuffs White felsite Latite and associated pyroclastics Andesite and associated pyroclastics	Extrusive (several 1000's of feet)

Sedimentary rocks

Magdalena group

Beds of the Pennsylvanian Magdalena group are exposed in the western part of the range along a belt half a mile wide, and dip rather uniformly at moderate angles to the east and east-northeast (pl. 1). Thus the edges of these beds appear on the bold western face of the Iron Mountain block, whose eastern face is essentially a dip slope. This sedimentary series, which is about 1400 feet thick, consists predominantly of slabby to thick-bedded non-magnesian marine limestone, much of which is cherty. It is best exposed where least affected by metamorphism, as in the southern part of the district. Rather continuous sections appear in Campsite and Goat Canyons (pl. 1).

Although it is fossiliferous, the Magdalena in the Iron Mountain district is not readily divisible into a large number of formations[5/] that are mappable or consistently recognizable units. A rather persistent group of white to brownish vitreous feldspathic quartzite beds does appear at the base of the series, and in a small canyon 1300 feet south-southeast of Brown City (pl. 3) it is underlain by at least 20 feet of quartz-rich pebble conglomerate. These clastic strata, which

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5/ See, for example, Thompson, M. L., Pennsylvanian system in New Mexico: New Mexico School of Mines, State Bur. of Mines and Min. Res., Bull. 17, p. 25 et. seq., 1942.

are 120 feet thick, are overlain by a comparable thickness of tan to dark brown calcareous shales. Six-inch to ten-foot beds of quartzite and thinner beds of shale and shaly limestone occur locally higher in the section, but are rarely traceable for more than 1500 feet along their strike.

Younger pre-Tertiary rocks

The Magdalena group is overlain with slight unconformity by the Abo sandstone, which in turn is overlain conformably by limestones and red beds of the Yeso and San Andres formations. All these rocks, which are Permian in age, are well exposed east and southeast of the Iron Mountain block, especially in Campsite, Goat, and Reilly Canyons (pl. 1). Like the Magdalena beds, they dip in general to the east and east-northeast. Their total thickness is at least 2400 feet. Tan to maroon sandstone and shaly sandstone are most characteristic of the Abo, and fine-grained, dark gray limestone and reddish sandstone are most common in the younger formations. Resting with distinct unconformity on these rocks is a thin series of sandstone, conglomerate, and shale beds, most of which are tentatively correlated with the Dakota sandstone of Cretaceous age.

Tertiary and Quaternary deposits

The coarse-grained, poorly-consolidated sedimentary beds that underlie the valley area west and north of Iron

Mountain are probably the equivalent of the Pliocene Santa Fe formation in the Rio Grande valley to the east. They are generally in fault contact with the older rocks, a feature well shown immediately east of Iron Mountain, where they are preserved in the down-faulted Havill Canyon block, or graben (pl. 1). Fault relations are also shown at the mouths of Campsite and Goat Canyons.

These Pliocene (?) beds have been strongly pedimented and veneered with coarse, loose gravel of Quaternary age. Narrow strips of Recent alluvium lie along the bottoms of arroyos and washes that have been cut into the pediment surfaces.

Igneous rocks

Volcanic rocks

A great eastward dipping series of Tertiary volcanic rocks several thousand feet in thickness flanks the sedimentary belt on the east; parts of it also appear in fault slices along the west base of the range. The series consists in the areas shown in plate 1 of andesitic breccia, andesite, latite, and tuffaceous beds of andesitic and latitic composition. These volcanics are cut by dikes of intrusive rocks with which the mineralization in the Iron Mountain block to the west is genetically associated, and hence are older than the mineralization.

Intrusive rocks

Monzonite. -- The oldest intrusive rock in the district is an extremely fine-grained, white to pearl gray monzonite, which resembles a felsite in that its component mineral grains are not readily discernable without the aid of a microscope. It consists chiefly of lath-like plagioclase that ranges in composition from andesine to labradorite, more stubby masses of orthoclase, and much accessory diopside; its composition over large areas clearly reflects the digestion of considerable quantities of limestone, with attendant increase in content of calcium.

This homogeneous rock is resistant to weathering and forms Reilly Peak, one of the highest mountains in the district. The Reilly Peak mass is a large, irregular laccolithic intrusion that has split apart and removed several hundred feet of Magdalena strata, and is traceable northward into a thick sill (pl. 1). Elsewhere the monzonite appears as much thinner sills and dikes, many of which are too small to be shown on the map.

Rhyolite and rhyolite porphyry. -- Rhyolite and rhyolite porphyry occur throughout the district as plugs and dikes that consistently transect the structure of the enclosing rocks. Most of the dikes dip steeply west or southwest. The rock is dark gray to greenish gray where fresh, but weathers to a striking pink or reddish brown. It commonly forms ridges and irregular crags that stand distinctly above the surrounding areas, as on the west slope of the mountain immediately adjacent to Brown City (pl. 3).

The larger bodies consist chiefly of very coarse rhyolite porphyry, in which numerous half-inch phenocrysts of orthoclase and smaller, rounded quartz masses occur in a fine-grained groundmass (plate 11). In most of the smaller bodies and throughout much of the large, plug-like intrusion a mile south of Brown City the rock is very fine grained and homogeneous; the few phenocrysts are generally quartz. Several dikes, notably the one that crosses Iron Mountain near South Peak (pls. 1, 3), are clearly composite; they consist of several rhyolite intrusions of recognizably differing age and texture.

Most of the dikes and elongate plugs occupy fracture or fault zones, but are themselves little sheared. Their characteristically sharp borders generally are marked by an extremely fine-grained chilled zone 1/8 inch to 4 inches thick. Primary flow structures, marked by layers of differing texture or color or by a crude orientation of feldspar phenocrysts, are common in the dikes, but are faint to unrecognizable in the larger bodies. Since the rhyolite cuts monzonite along the east slope of Reilly Peak and on the ridge between Goat and Campsite Canyons, it evidently represents a later stage in the intrusive sequence, involving much more silicic material.

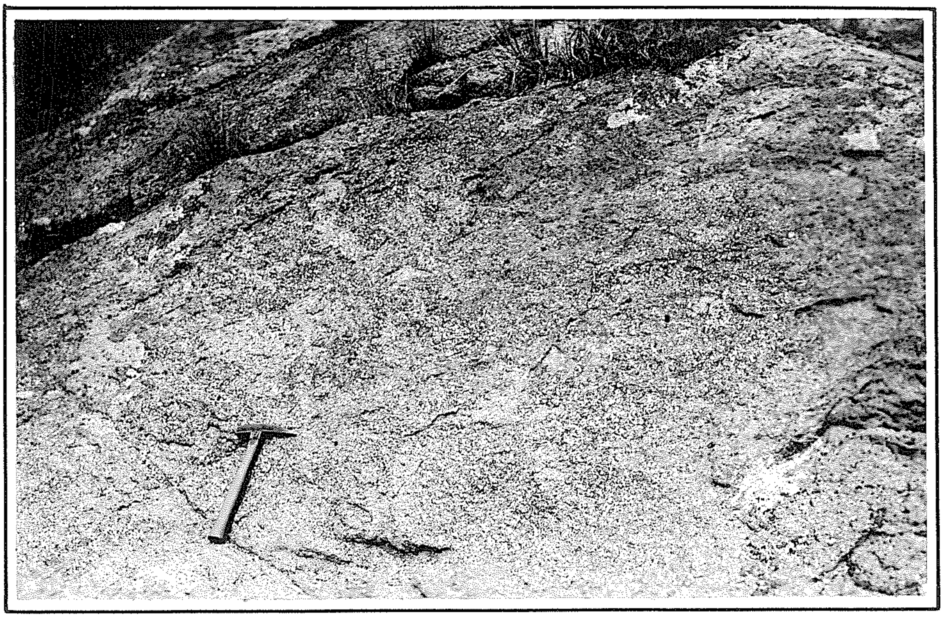

Plate 11. Intrusive rocks, Iron Mountain and vicinity.

Above -- Typical exposure of coarse rhyolite porphyry, dike 0.7 mile southeast of Rouse Ranch.

Right -- Sharp contact between rhyolite (dark) and fine-grained granite (light), canyon mouth 1.0 mile south of Brown City. Note angular fragments of rhyolite in the granite, as well as thin dikelet of granite in the rhyolite near end of hammer handle.

Aplite and fine-grained granite. -- Large, irregular sill-like masses of light gray to flesh-colored, fine-grained granite and thin sills and dikes of aplite are common in the Iron Mountain block, but appear nowhere else in the area. They occur along the west face and at the extreme north end of the range (pl. 3), where the granite forms many small cliffs (pl. 2). This alaskitic rock, which is almost wholly an even-grained intergrowth of quartz and orthoclase with minor biotite, is coarsest in the North End area, where its average grain size is a millimeter or more. It is cut by numerous irregular dikes of bluish to milky white quartz, especially on the ridge 2500 feet north of North Peak, but no pegmatite masses have been observed. All gradations can be seen between vein quartz masses and anhedral quartz in the granite itself, through transitional zones in which irregular masses of granite 0.1 to 6 inches in size are enclosed by quartz. Both granite and aplite appear to have crystallized from a very "dry" melt.

Flow structures are faint, but can be recognized from orientation of biotite flakes and feldspar crystals; those near the borders of the intrusions tend to conform to the adjacent contacts. Both aplite and granite appear as dikes in the rhyolite and rhyolite porphyry, and locally contain inclusions of these earlier rocks. Such relations are particularly well shown on the north side of Discovery Gulch

700 feet east of Brown City and throughout a broad contact zone a mile south of Brown City (pl. 11).

Other intrusive rocks. -- Local zones of fracturing and brecciation in the monzonite, rhyolite, granite, aplite, and in the Paleozoic rocks are cemented with a reddish brown felsite that is mineralogically similar to the groundmass of the rhyolite. Several of these zones are shown in plate 3. The youngest intrusives are numerous thin dikes of dark green to black lamprophyre, andesite, and basalt; none of these is sufficiently large to be shown on the maps.

Structure

The pre-Tertiary sedimentary rocks in and near the Iron Mountain block dip eastward at moderate angles, and appear to represent the west flank of a syncline that pitches gently to the south and south-southeast. The nose of this syncline, partially covered by younger volcanic rocks and much disturbed by faulting, is shown near the northeast corner of the geologic map (pl. 1). Conspicuous cross-faults of slight displacement are common. Many are filled with dikes of rhyolite or monzonite and have experienced little post-intrusion movement; on the other hand, considerable post-rhyolite movement has occurred along the steeply-dipping fault zone that bounds the range on the west. Total vertical displacement along this zone amounts to several thousands of feet, as shown, for example, by the juxtaposition of Magdalena limestone and

Tertiary volcanic rocks near the mouth of Goat Canyon and west of Reilly Peak (pl. 1).

A strikingly consistent pattern of fractures that appear in igneous and sedimentary rocks alike is present throughout the area. Two prominent sets of joints trend northwest and east-northeast, with steep dips; that they conform to the orientations of many faults and dike-filled fault planes is evident from an inspection of plate 1. A third set of fractures trends north-northwest and dips steeply westward; it is most strongly developed along the western edge of the range, where it makes an acute angle with the trace of the range-border fault zone. Fracturing appears to have begun prior to the intrusion of monzonite and to have continued intermittently and with little reorientation throughout the ensuing period of igneous activity, metamorphism, and mineralization. Many of the relations of igneous rocks to structural features are evident on the maps.

Age and geologic history

The Paleozoic formations have been correlated with known sections in other parts of the country[6/] on the basis of

6/ Harley, G. T., The geology and ore deposits of Sierra County, New Mexico: New Mexico School of Mines, State Bur. of Mines and Min. Res., Bull. 10, pp. 27-29, 1934.

their distinctive lithology, and their age assignments have been confirmed by L. G. Henbest[7/], who examined several fos-

7/ Henbest, L. G., letter dated October 16, 1942.

sil collections submitted by the writer to the laboratories of the Geological Survey. The volcanic series, as correlated on the basis of sequence and detailed petrography with eruptive rocks in the Black Range[8/] and Mogollon district[9/] to

8/ Hill, J. M., The Taylor Creek tin deposits, New Mexico: U. S. Geol. Survey, Bull. 725-G, p. 349, 1922.

Fries, Carl, Jr., Tin deposits of the Black Range, Catron and Sierra Counties, New Mexico: U. S. Geol. Survey, Bull. 922-M, p. 360, 1940.

9/ Ferguson, H. G., Geology and ore deposits of the Mogollon district, New Mexico: U. S.Geol. Survey, Bull. 787, pp. 5-6, 1927.

the west and the Magdalena district[10/] to the north, is most

10/ Loughlin, G. F., and Koschmann, A. H., Geology and ore deposits of the Magdalena district, New Mexico: U. S. Geol. Survey, Prof. Paper 200, in press.

probably mid-Tertiary in age. That it is pre-Pliocene is suggested by the occurrence of portions of its members as clastic fragments in coarse sediments lithologically similar to and areally continuous with the Santa Fe formation of the Rio Grande Valley. These sediments also contain fragments of the intrusive and contact metamorphic rocks found on the Iron Mountain block.

The following generalized sequence of events during Tertiary time is suggested for the district:

1. Broad folding of the pre-Tertiary rocks, probably in early Eocene time.

2. Faulting and long-continued volcanic activity during early and middle Tertiary time, involving a gradual change from intermediate to silicic rocks.

3. Strong faulting and fracturing, accompanied by eastward tilting.

4. Intrusion of monzonite, chiefly as sills and laccolithic masses.

5. Fracturing and minor faulting.

6. Intrusion of rhyolite as dikes and plugs.

7. Fracturing and renewed movement along a few major faults.

8. Intrusion of granite and aplite, chiefly in concordant bodies.

9. Fracturing and local faulting, especially along the western range-border fault, with deposition of coarse sediments in structural basins during Pliocene (?) time.

Contact metamorphism of the nearby Paleozoic beds accompanied the periods of intrusion (stages 4, 6, and 8).

Despite the overlap that must have existed between adjacent stages in the above sequence, it is plain that the irruption of monzonite and younger igneous rocks post-dated most of the large-scale structural adjustments in the area. Since the metamorphism and mineralization were genetically related to the intrusives, such processes must have effected the sedimentary rocks as they lay in essentially their present tilted positions.

CONTACT METAMORPHISM

General relations

Many of the beds in the Magdalena group, as well as certain strata near the base of the Abo sandstone have been altered in appearance and composition at and near contacts with masses of intrusive rock. The most widespread and profound effects are shown in the northern half of the Iron Mountain block, where large areas are underlain by fine-grained granite and rhyolite porphyry. The mineralogic and textural properties of these igneous masses are suggestive of a shallow-seated origin, and their shapes and distribution further suggest confluence at no great depth beneath the present surface. Thus many of the intervening belts of altered sedimentary rocks can best be viewed as pendants or septa within igneous bodies, or as the downward-projecting remnants of a relatively thin sedimentary cover that has been eroded away. The amount of exposed igneous rock decreases in a southerly direction, and the exposed altered zones in the sedimentary terrane become correspondingly smaller and more scattered.

As in many areas of contact metamorphism, the metamorphosed rocks in the Iron Mountain district can be readily assigned to one of two zones. In the zone of recrystallization or simple metamorphism the original rock constituents have been rearranged to form new minerals and fresh crystals of certain pre-existing minerals without appreciable addition of material from outside sources. In the zone of recrystallization and reconstitution, or metasomatism, the newly-formed minerals in the altered rock plainly reflect the introduction of material from outside sources, and rocks of this zone tend to occur near or immediately adjacent to igneous bodies. The reconstituted rocks are characteristically rich in silicate minerals, and are themselves clearly differentiable into two types on the basis of their iron content; these correspond to the zones of light- and dark-colored silicates as defined by Hess and Larson[11]. Only the

11/ Hess, F. L., and Larsen, E. S., Contact-metamorphic tungsten deposits of the United States: U. S. Geol. Survey, Bull. 725-D, pp. 252-253, 1921.

dark-colored silicate rocks have been appreciably metallized.

Recrystallized rocks

The chief product of recrystallization is coarse-grained, white to bluish gray marble in which individual calcite crystals half an inch across are common. Much of it is interbedded with finer-grained, relatively little-affected carbonate rock, and appears to have formed preferentially from thick beds of rather pure crinoidal limestone. In many places stratification is marked by layers of different composition, color, or grain size. Calcite is the only constituent of note, although scattered masses of tremolite, pale yellow garnet, and iron-poor epidote appear as irregular, brownish gray crusts on weathered surfaces. Since most beds containing these silicate minerals are traceable along their strike into unmetamorphosed beds of impure limestone, the minerals were probably formed from the impurities originally present in the rock. The contact zones between recrystallized carbonate rocks and the unmetamorphosed beds from which they were derived are measurable in hundreds of feet; many such zones are well exposed along the west front of the range north of Campsite Canyon.

Recrystallization in the quartzites has resulted in a visible increase in grain size, but the appearance of the rock is otherwise unchanged. The shaly strata, on the other hand, have been converted to a platy, dense, brittle hornfels of tan to dark reddish brown color. Quartz and mica are its chief constituents, with widespread minor amounts of epidote, diopside, andalusite, ottrelite, clinozoisite, and bytownite. No great change in the over-all composition of the rock appears to have resulted from the formation of these minerals, most of which clearly reflect its aluminous character.

The recrystallized rocks occupy large areas and commonly extend from igneous contacts for distances of many tens of feet across the bedding and 1000 feet or more along the strike. Although they generally grade imperceptibly into beds not recognizably affected by the metamorphism, they tend to be much more sharply defined from the more strongly metamorphosed rocks.

Iron-poor silicate rocks

The earliest-formed rocks in the zone of reconstitution, or metasomatism, are extremely fine-grained, homogeneous granulites that are composed predominantly of iron-poor silicate minerals. They are hard, compact, and brittle in marked contrast to the calcareous beds from which they were formed, but in most places are so severely broken into small polygonal blocks that they are not prominently exposed. Their color is typically pale green, but buff to pure white beds are not rare. The latter, which superficially resemble chert, are exceedingly difficult to distinguish megascopically from the fine-grained monzonite.

Quartz, diopside, clinozoisite, epidote, and lime-soda feldspars in the bytownite-anorthite range are the common minerals, and occur in various combinations and proportions (table 2). Tremolite, wollastonite, hedenbergite, grossularite, chlorite, calcite, sericite, and thulite are minor constituents, some of which have developed along fractures as aggregates of coarse crystals. On the other hand, the minerals in the main mass of the rock are generally 0.01 to 0.1 mm. in diameter and lie in a subequigranular mosaic; hence they rarely are megascopically distinct.

Most of the granulites appear to have been formed through silication of the more sandy and shaly limestone beds, and their composition bespeaks the addition of large quantities of silicon and minor quantities of magnesium and aluminum; with a great loss of carbon dioxide. Such iron-poor silicate rocks can be traced along the strike into un-replaced beds through transition zones measurable in hundreds of feet, but contacts paralleling the strike tend to be rather abrupt (fig. 2). That the silication operated with much selectivity in beds of favorable composition and physical properties is clearly shown by the distribution of granulite in the area of dominantly calcareous rock west and northwest of South Peak (pl. 3). Contacts between granulite and the more severely metamorphosed iron-rich silicate rocks are marked by transition zones half an inch or less in width (fig. 2); many such zones are exposed along the ridge immediately south of North Peak.

A persistent zone of dense, pale green granulite in 1- to 4-foot beds appears stratigraphically above the basal Magdalena quartzite along the west face of the mountain between Brown City and Campsite Canyon (pl. 1). It represents the almost wholesale silication of a 120-foot thickness of argillaceous limestone and calcaroues shale with local ferruginous layers. A somewhat similar though smaller and less continuous series of granulite beds appears high on the west slope west and northwest of North Peak (pl. 3). The granulites west of South Peak, on the other hand, are more thinly bedded and lighter in color, and were formed at the expense of distinctly purer limestones; in them diopside and other iron-bearing silicates are subordinate to clinozoisite, tremolite, and wollastonite.

Table 2

Modal composition of iron-poor silicate rocks from Iron Mountain, New Mexico*

	1	2	3	4	5	6
Quartz	31	42	50	9	10	14
Plagioclase	11	7	2	Tr	3	Tr
Diopside	54	4	41	--	30	--
Clinozoisite	Tr	32	Tr	81	4	66
Epidote	Tr	4	Tr	4	10	--
Calcite	--	--	--	Tr	34	11
Tremolite	--	3	--	--	3	2
Wollastonite	--	4	--	2	Tr	Tr
Grossularite	1	Tr	2	--	2	Tr
Chlorite	1	--	Tr	--	Tr	--
Sericite	1	2	Tr	--	2	5
Thulite	--	--	--	3	Tr	--
Hedenbergite	--	--	4	--	--	--
Alteration products	1	2	1	1	2	2

1. Pale green, massively-bedded granulite, 1750 feet south-southeast of Brown City.

2. White to buff, platy granulite, west slope of South Peak.

3. Pale green, massively-bedded granulite, west slope of North Peak.

4. Heavily fractured buff-colored granulite, small knob 1170 feet east-southeast of Brown City.

5. Buff to very pale green granulite, contact zone with recrystallized limestone, 3800 feet south of South Peak.

6. Pure white, platy granulite, north side of Campsite Canyon 1520 feet east-northeast of mouth.

*Specimens 2 and 4 determined microscopically by the counting of 1000 grains of representative crushed material; others determined from thin sections.

Iron-rich silicate rocks: tactites

Massive tactite

General description. -- Much of the iron-rich silicate rock, or tactite[12/], is a massively bedded, dark greenish to black rock that consists typically of coarsely crystalline magnetite and yellowish green to coffee-brown andradite garnet with locally abundant hedenbergite and specular hematite. Minor constituents, most of which represent a sensibly later mineralization, are fluorite, apatite, diopside, iron-rich amphibole, quartz, feldspar, spinels, idocrase, biotite, chlorite, helvite, scheelite, powellite, willemite, pyrite, pyrrhotite, sphalerite, and galena (table 3). The rock is found in the zones of most intense metamorphism, and has been formed by large-scale replacement of recrystallized limestone and to a lesser degree at the expense of iron-poor silicate rocks. This process must have involved the addition of large quantities of iron and silicon, together with minor amounts of magnesium, sulfur, tungsten, molybdenum, and base metals. Great quantities of calcium and carbon dioxide must have been driven off.

12/ Hess, F. L., Tactite, the product of contact metamorphism: Am. Jour. Sci., 4th ser., vol. 48, pp. 377-378, 1919.

Distribution and structure. -- The bodies of massive tactite vary in size from inch-thick lenses to great masses

Table 3

Modal composition of massive tactite
from Iron Mountain, New Mexico*

	1	2	3	4	5
Magnetite	91	73	19	28	16
Hematite	Tr	1	6	7	9
Andradite	8	16	4	54	4
Hedenbergite	-	Tr	45	-	-
Diopside	-	3	-	-	-
Amphibole	-	-	3	-	-
Feldspar	Tr	1	13	Tr	-
Fluorite	Tr	2	2	4	52
Quartz	-	1	1	Tr	1
Apatite	-	-	Tr	-	Tr
Spinels	-	-	Tr	-	1
Idocrase	-	-	-	-	6
Biotite	-	Tr	-	-	Tr
Chlorite	-	-	Tr	-	4
Scheelite and powellite	-	-	1	2	3
Willemite	-	-	Tr	1	1
Pyrrhotite	Tr	1	Tr	-	-
Alteration products, chiefly limonite	Tr	1	5	3	2

1. Specimen of simple massive tactite, summit of North Peak.

2. Composite chip sample, Old Adit body, Discovery Gulch.

3. Composite chip sample, northeast slope of North Peak.

4. Systematic five-foot channel sample, Upper Star body, North End area.

5. Specimen of highly mineralized tactite, west slope of North Peak.

Nos. 1 and 2 are most nearly representative of the massive tactite as a whole.

*Each mode determined microscopically by the counting of 1000 grains of representative crushed material.

amounting to millions of tons; the largest of these crop out boldly along the summit and high on the east and west slopes of Iron Mountain (pls. 1 and 3). The size and distribution of each appear to have been governed by several factors, notably the position and attitude of the nearby igneous contact, the size of the igneous mass, and the chemical composition and physical susceptibility of the sedimentary beds. Thus, where other factors have been equal, tactite has formed immediately adjacent to igneous bodies rather than at a distance from them; it has formed most extensively adjacent to the largest bodies; it has formed in impure limestones rather than in pure limestone, quartzite, or shale; and it has formed preferentially in the more permeable, highly fractured parts of the contact zones.

Although many stratigraphic details have been obscured by pre-metamorphism faulting and by the metamorphism itself, it is clear that most of the tactite bodies do not lie at consistent horizons, but are instead distributed as irregular patches over the exposed calcareous terrane. Despite many complexities of detail, they are generally tabular and conform very crudely to the bedding of the enclosing rock. They vary in thickness from an inch to more than 100 feet and are traceable along the strike for distances as great as two miles (pl. 1). They do not everywhere lie immediately adjacent to the igneous intrusions, but may be separated from them by a few feet or tens of feet of relatively less metamorphosed sedimentary rocks. Masses of tactite that flank concordant igneous bodies are much more continuous than those adjacent to cross-cutting contacts; the latter tend to feather out along favorable beds and hence are extremely irregular in pattern.

Contacts between massive tactite and other rocks are sharp (fig. 2B, C). That the tactite postdates recrystallized limestone and much of the granulite is demonstrated by its occurrence as cross-cutting and invading masses in these rocks, and by their presence in the tactite as inclusions and residual masses (fig. 2B, C). Such relations can be seen wherever contacts or irregular contact zones are exposed.

Evidently the brittle tactite was repeatedly broken and sheared during the later stages of its formation, each fracture or other opening being promptly "healed" by magnetite, andradite, or other minerals. The resultant rock consists of garnet and magnetite with many thin laminae and lenses of later minerals, chiefly magnetite, andradite, scheelite, and powellite (fig. 2D). It is stout and solid where no post-mineral shearing has occurred. A still later period of mineralization is represented by fluorite-rich shear and breccia zones in which beryllium, manganese, and zinc minerals are locally abundant.

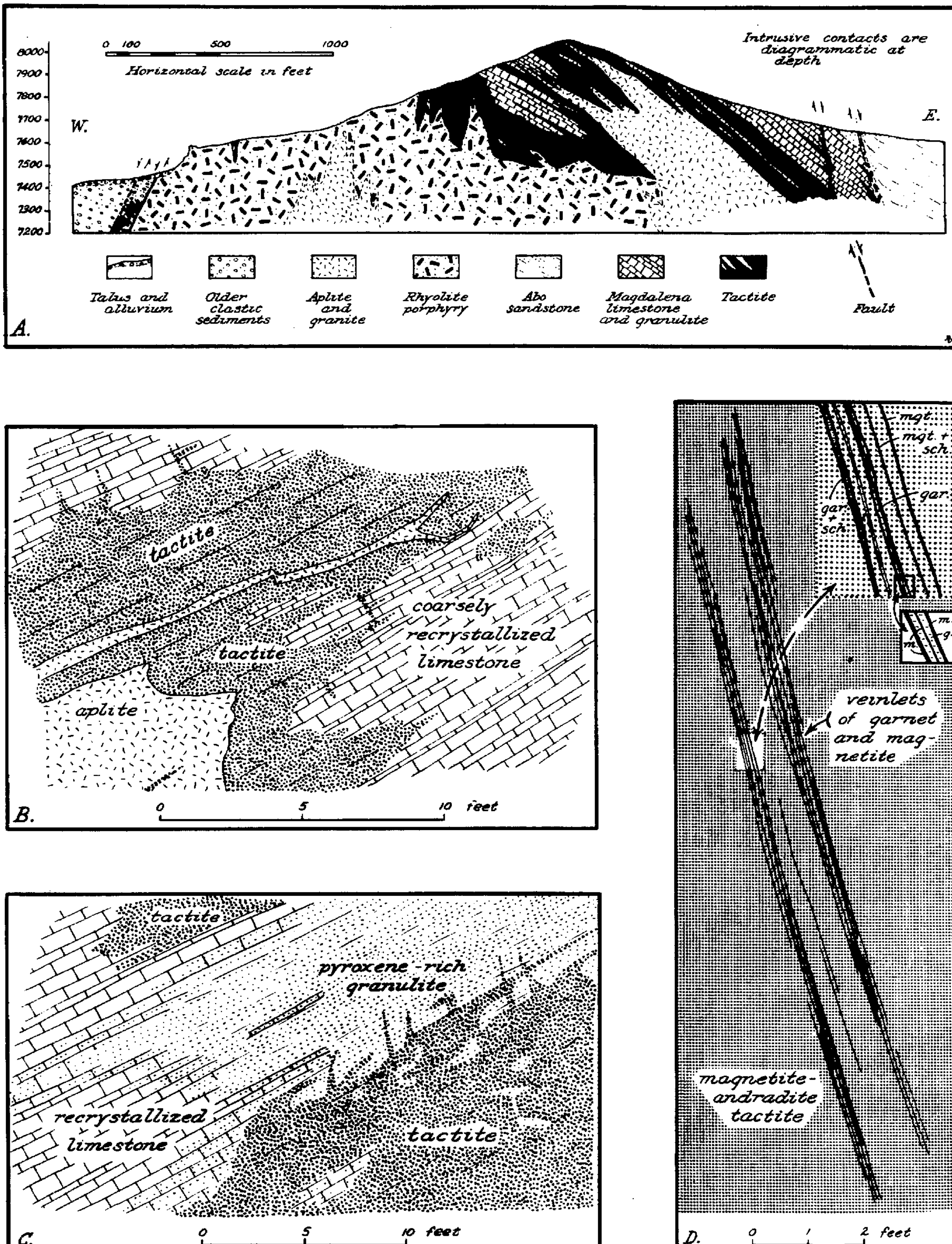

Figure 2. Section of Iron Mountain through North Peak and sketches of tactite-granulite-limestone relations in the North Peak area.

"Ribbon rock" tactite

General description. -- The "ribbon rock" variety of Iron Mountain tactite is named for the layered structure that at once distinguishes it from the massive tactite described in the preceding paragraphs. It consists typically of thin, continuous, minutely crenulated layers or shells, each contrasting mineralogically with the layers immediately above and below (pl. 12). In section the layers appear as wavy ribbons 0.05 mm. to 3 mm. wide, with a probable average of about 0.2 mm.; seemingly broader ribbons are found upon close inspection to be themselves finely banded. Many of the layers are arranged concentrically about spherical or irregularly ellipsoidal crystalline pods, and are progressively thicker toward the pods. Other layers appear to be nearly flat sheets or gently curving shells, and can be traced for distances as great as six inches before becoming involved in zones of intricate convolutions that surround groups of pods and their associated concentric shells. Typical sections through "ribbon rock" masses are shown in plates 13 and 14 and in figure 5.

A strikingly similar ribboned tactite from the Seward Peninsula, Alaska, has been termed "orbicular contact

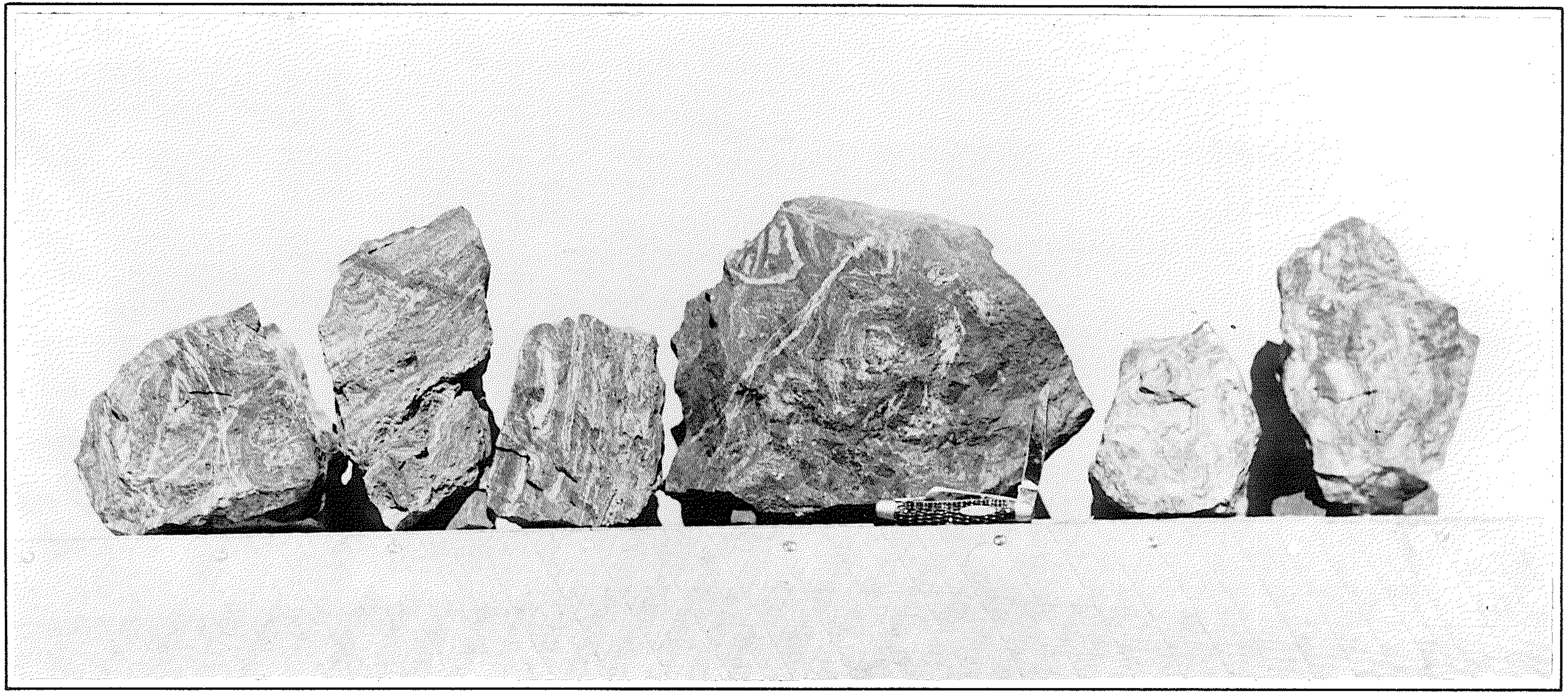

Plate 12. Typical specimens of "ribbon rock" tactite from North End area.

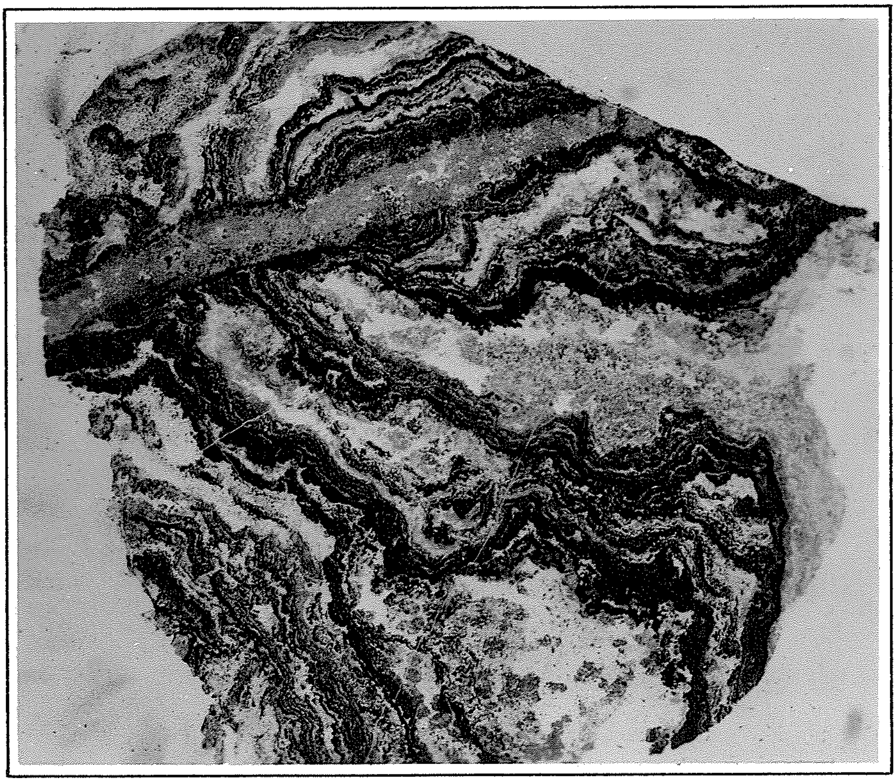

Plate 13. Sections of fluorite-rich "ribbon rock" tactite, magnified 7.5 diameters.

Top ----- Orbicular, biotite-rich phase, Old Adit body, Discovery Gulch.

Bottom -- "Ribbon rock" with late-stage fluorite-idocrase veinlet, North End area. White to light gray minerals are chiefly fluorite, grossularite, and idocrase.

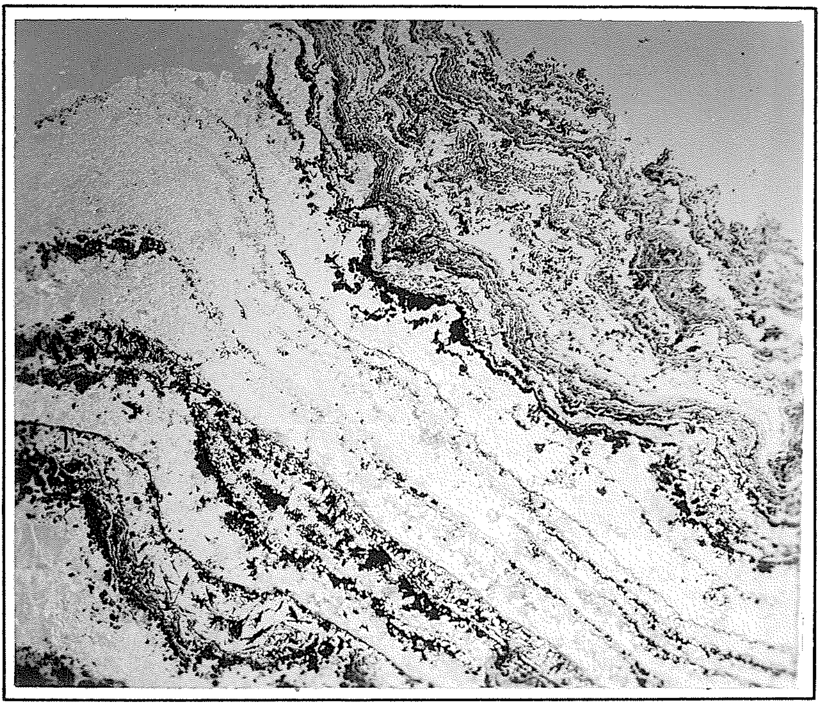

Plate 14. Sections of "ribbon rock" tactite from North End area, magnified 5 diameters.

Top ---- Thinly ribboned, fluorite-rich phase. Light gray to white bands are fluorite, darker gray masses are silicate minerals, and needle-like opaque grains at lower left are specularite. Opaque bands are chiefly magnetite.

Bottom -- Concentrically ribboned phase with fluorite-rich pods.

metamorphosed rock" by Knopf[13/], who describes it as follows:

13/ Knopf, Adolph, Geology of the Seward Peninsula tin deposits: U. S. Geol. Survey, Bull. 358, pp. 45-46, pl. IV, 1908.

See also Steidtmann, Edward, and Cathcart, S. H., Geology of the York tin deposits, Alaska: U. S. Geol. Survey, Bull. 733, pp. 73-76, pl. IX, 1922.

> "The orbules are composed of an alternating succession of concentric black and white bands, commonly a millimeter or so in breadth..........
> .....Many of the sections through the orbules are perfect circles, a maximum diameter of 8 inches being noted, but elliptical forms, due to the interference of contiguous orbules, are common ....Where several small independent orbules have formed around closely spaced centers highly intricate structure resembling that of contorted gneiss has been evolved."

Another occurrence of what is probably typical "ribbon rock" tactite has been described from Pitkäranta, Finland, by Trustedt[14/].

14/ Trüstedt, O., Die erzlagerstätten von Pitkäranta am Ladoga-See: Bull. Comm. Geol. de Finlande, No. 19, p. 226, 1907.

Mineralogy. -- The Iron Mountain "ribbon rock" is essentially a garnet-poor magnetite-fluorite tactite. Layers of magnetite and local intimately associated hematite generally alternate with somewhat thinner layers composed of crystalline fluorite, silicate minerals, or fluorite-silicate mineral aggregates. Two distinctive varieties of "ribbon rock" occur in the district; they differ chiefly in the mineralogy of their magnetite-free layers.

A dark, beryllium-rich variety forms small bodies in Discovery Gulch, the narrow canyon immediately east of Brown City, and in the West Slope area about 1400 feet northeast of Brown City. Its wavy magnetite laminae are 0.2 mm. to 8 mm. thick, with much thinner intervening layer-aggregates of fluorite, helvite, and local quartz. Irregular masses of adularia occur in the less strongly layered parts of the rock. Limonite, kaolin, manganese oxides, and other alteration products are locally abundant; an appreciable part of the limonite and manganese oxides has been formed from near-surface oxidation of the helvite, a complex silicate-sulfide mineral that contains beryllium, iron, manganese, and zinc. It occurs as rutile red to amber colored crystals and crystalline aggregates, and has been overlooked in times past because of its exceedingly close resemblance to garnet[15/]. The detailed and distin-

15/ See, for example, Smythe, D. D., A contact metamorphic iron-ore deposit near Fairview, New Mexico: Econ. Geol., vol. 16, p. 414, 1921.

guishing properties of this interesting mineral species have been described[16/] as follows:

16/ Jahns, R. H., and Glass, J. J., Beryllium occurrence near Winston, New Mexico: U. S. Geol. Survey, Memorandum for the Press, Nov. 7, 1942.

> ".........the helvite ranges from dark reddish brown to pale, creamy yellow. Shades between mahogany red and amber brown (Ridgway's color standards) are most characteristic, although the

> color varies within a hand specimen or even within a single crystal. The helvite crystals are isometric, generally tetrahedral in habit.......... ....and commonly deeply striated. The helvite crystals are rather brittle; their hardness is about that of feldspar (6), but less than that of garnet (6.5-7.5). Their specific gravity, which is slightly more than 3.3, is less than that of garnet. The luster is resinous to vitreous. Finely powdered helvite is brownish yellow, whereas powdered garnet from the Iron Mountain area is brownish gray. Fragments from coarse crystals of the helvite are completely isotropic under the microscope and have an index of refraction of 1.747. The garnet at Iron Mountain has an index of refraction ranging from 1.865 to 1.885. Helvite may also be distinguished from garnet by chemical tests, as the helvite dissolves slowly in boiling hydrochloric acid, releasing the odor of hydrogen sulfide and forming a silica gel, whereas garnet is very difficultly soluble, does not yield hydrogen sulfide, and does not gelatinize."

So far as can be determined, garnet is absent from the magnetite-rich variety of "ribbon rock". The mineral compositions of several samples and typical specimens are given in Table 4.

The predominance of dark-colored constituents causes most of the layered structure to be indistinct on freshly broken faces, though it is readily recognizable on most weathered surfaces. The layers are unusually thick in this type of "ribbon rock", but crystalline pods are not common; where they do occur, they consist chiefly of helvite and fluorite, and may reach thicknesses of an inch or more. Small vugs lined with drusy fluorite, helvite, and low-temperature quartz have also been observed.

The other, more typical variety of "ribbon rock"

Table 4

Modal composition of magnetite-rich "ribbon rock" from Iron Mountain, New Mexico*

	1	2	3	4	5
Magnetite	68	39	42	28	47
Fluorite	16	41	25	30	37
Helvite	11	5	14	24	2
Adularia	-	-	9	5	3
Quartz	3	-	2	4	-
Biotite and chlorite	-	4	-	-	3
Alteration products (limonite, kaolin, etc.)	2	11	8	9	8

1 - Systematic grid sample from area of 11 square feet, Hot Spot body, Discovery Gulch.

2 - Systematic grid sample from area of 14 square feet, Hot Spot Extension body, Discovery Gulch.

3 - Systematic two-foot channel sample from Jackpot No. 2 body, 1500 feet northeast of Brown City.

4 - Specimen of high-grade beryllium ore, Hot Spot body.

5 - Specimen of low-grade beryllium ore, Jackpot No. 2 body.

*Each mode determined microscopically by the counting of 1000 grains of representative crushed material.

contains less magnetite and consequently is lighter in color; ordinarily it occurs as much larger masses of somewhat wider distribution. Many of its thin magnetite layers include intimately associated hematite, and in some places near crystalline lenses and pods they give way entirely to layers of specularite (pl. 14). The light-colored minerals, which combine with the iron oxides to give the rock a greenish tan to rusty brown appearance, are chiefly colorless to greenish fluorite, green biotite and chlorite, and a pale, yellowish green prismatic mineral near idocrase. Minor constituents are honey-yellow grossularite, a somewhat similar species first recognized by J. J. Glass as an unusual variety of helvite, and diopside, clinozoisite, spinels, quartz, adularia, graphite, opal, and finely-divided alteration products. The results of modal determinations made on several samples and specimens appear in Table 5.

The idocrase, garnet, helvite, and some of the chlorite are known to contain small quantities of beryllium, and combine to make the rock a potential large-tonnage, low-grade source of that metal. The idocrase also contains an appreciable amount of boron, and much of the "ribbon rock" biotite gives a positive test for fluorine in the open tube. All these minerals are being studied in detail by J. J. Glass and other members of the Geological Survey.

The crystalline pods and druses, as well as the

Table 5

Modal composition of typical "ribbon rock" tactite from Iron Mountain, New Mexico

	1[1/]	2[1/]	3[1/]	4[2/]	5[2/]	6[2/]	7[2/]	8[2/]	9[2/]	10[3/]	11[3/]	12[3/]
Magnetite	32	30	23	41	82	32	80	62	57	66.67[4/]	57.30[4/]	72.73[4/]
Helvite	1	1	Tr	Tr	-	1	1	3	Tr	0.08	0.43	0.22
Garnet	2	Tr	4	6	-	7	1	1	4	--	5.12	0.82
Fluorite	33	22	13	25	5	34	7	14	12	12.33	8.54	6.81
Idocrase	2	11	37	2	Tr	3	-	Tr	5	--	1.70	--
Biotite	14	13	7	2	3	6	1	-	3			
Sericite & chlorite	5	15	3	4	4	2	3	10	2			
Hematite	3	Tr	5	Tr	1	7	4	3	7			
Diopside	Tr	-	-	Tr	-	-	-	1	-			
Clinozoisite	1	-	2	Tr	-	-	Tr	-	Tr			
Spinels	-	Tr	-	-	-	Tr	-	-	-			
Quartz	3	Tr	1	2	-	4	-	Tr	1	20.92	26.91	19.42
Adularia	-	2	Tr	-	Tr	Tr	-	-	Tr			
Graphite	-	Tr	2	-	-	-	-	-	-			
Sulfides	Tr	Tr	-	-	-	-	-	Tr	-			
Opal and zeolites	-	-	1	-	-	1	-	-	1			
Extremely fine-gr. alteration products, etc.	4	6	2	17	4	2	3	5	7			

(Values in columns 10, 11 and 12 opposite Quartz are bracketed totals for Biotite through Extremely fine-gr. alteration products, etc.)

1 -- Specimen from old adit, lower Discovery Gulch.
2 -- Specimen from Hot Spot Extension body, Discovery Gulch.
3 -- Specimen from west slope of North Peak.
4 -- Composite chip sample, Jackpot No. 1 body, 2300 feet north-northeast of Brown City.
5 -- Ribboned veinlets in recrystallized limestone, Jackpot Extension body, 2300 feet north-northeast of Brown City.
6 -- Coarsely crystalline specimen, Beryllium Queen body, North End area.
7 -- Beryllium Reef body
8 -- Beryllium Reef body
9 -- Reef Extension body
10 -- Beryllium Chief body
11 -- Upper and Lower Star bodies
12 -- Beryllium King and Queen bodies

(7–12: 75- to 150-pound composite samples, North End area)

1/ Determined from thin sections.
2/ Determined microscopically by counting of 1000 grains of representative crushed material.
3/ Determined microscopically by J. J. Glass and R. W. Lemke by the counting of 8000 or more grains of representative crushed material.
4/ Percent by weight; other constituents by volume.

coarser of the surrounding layers consist chiefly of fluorite with minor grossularite, helvite, quartz, and feldspar. Films of bluish white opal coat the minerals lining some of the vugs. Carbonate-zeolite veinlets that cut layers and crystalline pods alike represent a sensibly later stage of mineralization, and commonly contain graphite, carbonate and oxides of manganese, sulfides, and chalcedony.

Distribution and structural relations. -- The magnetite-rich "ribbon rock" occurs in terranes of recrystallized limestone as thick pods, pipe-like masses, and thin, tabular masses measurable in feet or tens of feet. Where appreciable elongation or finger-like projections are present, they tend to conform to the bedding of the surrounding sediments. In many places this rock grades insensibly into typical lighter-colored, silicate-rich "ribbon rock", but in the lower part of Discovery Gulch it passes abruptly into massive andradite-magnetite tactite.

The more widely distributed silicate-rich "ribbon rock" appears northeast of Brown City on the west slope of the mountain, as well as on the ridge summit and eastern slopes a mile north-northeast of Brown City. In the latter area are exposed the largest bodies, several of which are shown on the geologic map (fig. 3). They are rudely lenticular, trend parallel with the strike

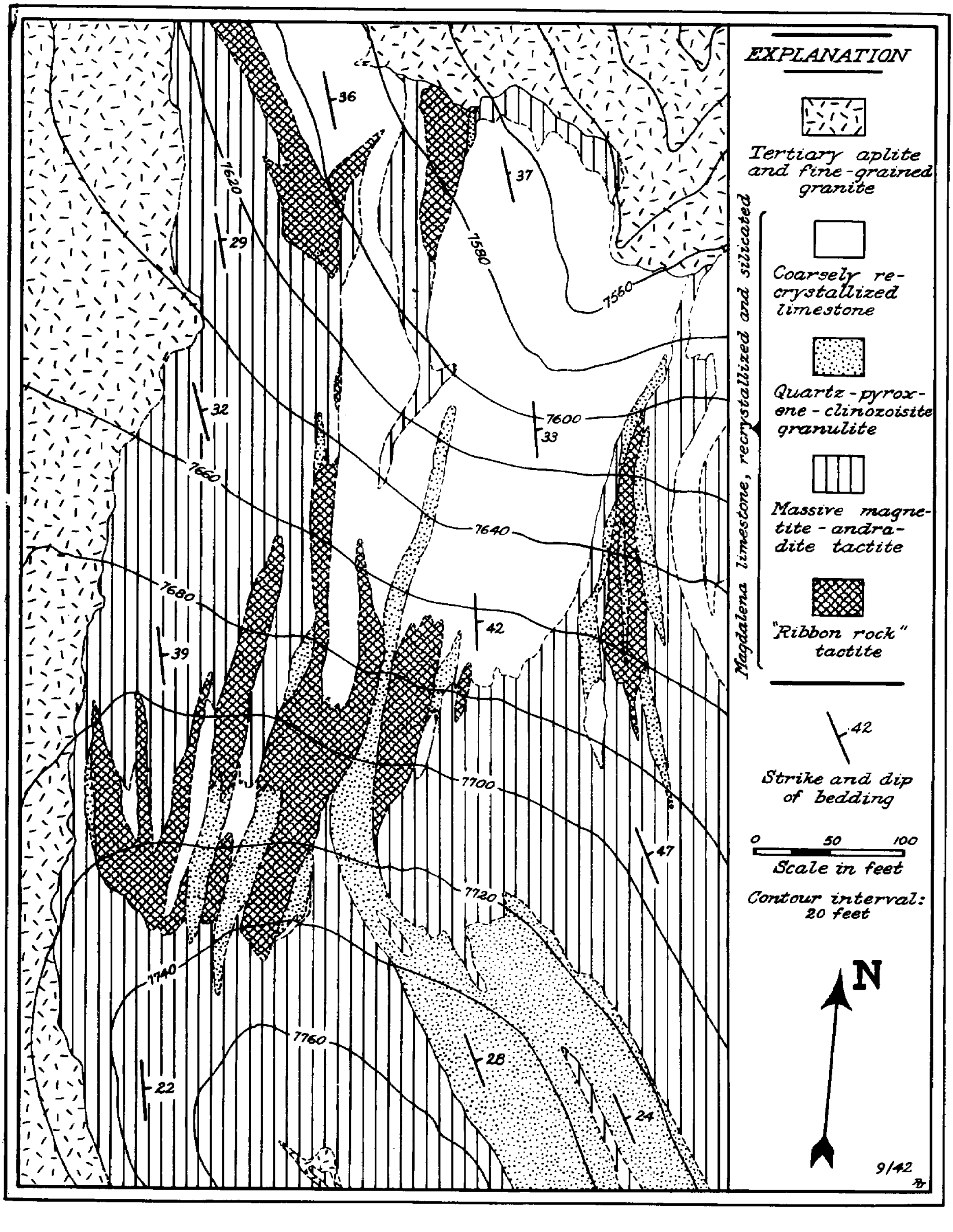

Figure 3. Geologic map of a part of the North End area, Iron Mountain.

of the adjacent beds, and appear to dip eastward in approximate conformity with the beds. Representative dimensions are shown in fig. 3. Such "ribbon rock" is sharply bounded from the massive tactite, granulite, and hornfels, but generally grades into recrystallized limestone through transition zones several inches to several feet wide.

Wherever "ribbon rock" and massive garnet-magnetite tactite are both present, the massive tactite tends to occur between the "ribbon rock" and the nearest intrusive contact, as shown on the map and in the idealized sections (fig. 4). Thus the "ribbon rock" ordinarily lies between massive tactite on one hand and recrystallized limestone or iron-poor silicate rocks on the other. Such a spatial arrangement is similar to that of most pyrometasomatic ores, which according to Umpelby[17/], tend to occur in that

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17/ Umpelby, J. B., The occurrence of ore on the limestone side of contact zones: Univ. Calif. Dept. Geol. Bull., vol. 10, pp. 25-37, 1916.

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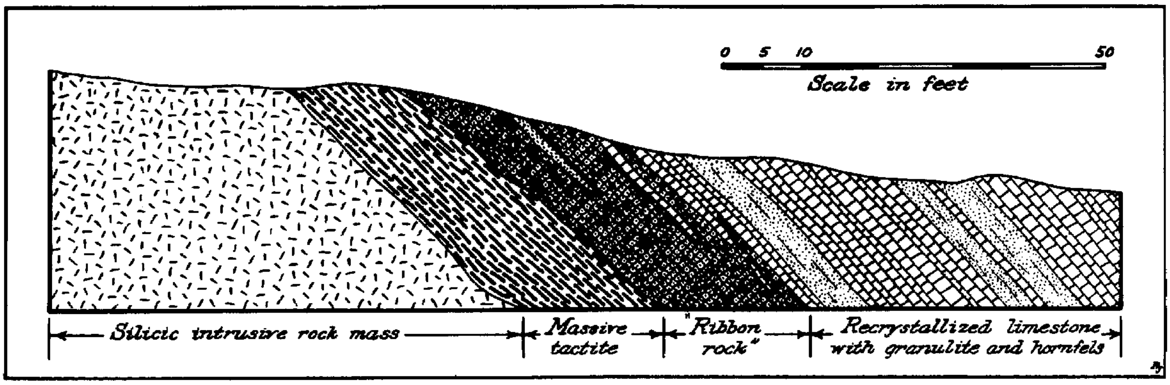
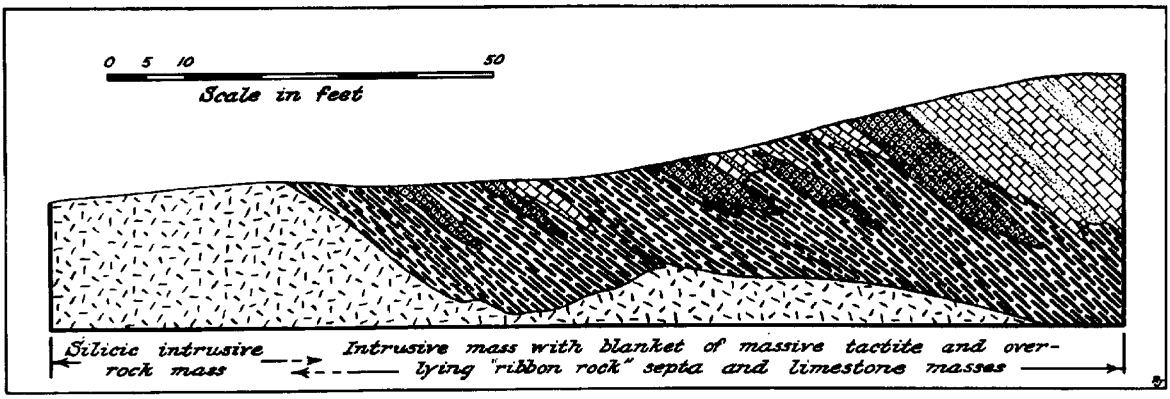
part of the contact zone nearest the unreplaced limestone. Since the "ribbon rock" tactite and most contact ores are known to be late-stage products in the pyrometasomatic sequence, neither the similarity of their position nor the position itself is particularly surprising.

The contact zones between limestone and "ribbon rock", though of great geologic interest, are rarely exposed. One particularly instructive outcrop, however, was found on the



a. Concordant igneous mass.



b. Discordant igneous mass.

Figure 4. Idealized cross sections showing typical relations between "ribbon rock" tactite and other rocks in the contact zones.

west edge of a small tactite body in the Jackpot Extension area, 2350 feet north-northeast of Brown City, and demonstrates clearly the formation of "ribbon rock" at the expense of the recrystallized limestone. Five typical stages in this process are shown in fig. 5 by sketches of specimens collected from this locality. Iron-rich solutions plainly entered the limestone along fractures (fig. 5A), and penetrated outward from each fracture with replacement of the calcite (fig. 5B, C). The rhythmic banding in the replacing material conforms in general to the original fractures and to the retreating faces of the calcite aggregates. Irregular, isolated carbonate masses (fig. 5C, D), which represent the cores of original fracture blocks, are completely analogous in position to many of the fluorite-rich crystalline pods and druses in the end product (fig. 5E), the calcite-free "ribbon rock".

A somewhat similar series of exposures appears near the west base of the range about 6400 feet south of Brown City, where a rather continuous 2- to 12-foot bed of massive tactite dips gently eastward beneath coarsely recrystallized limestone. Small lenses of typical "ribbon rock" appear from place to place at the top of the massive tactite, and send finger-like projections upward along fractures in the limestone. Where the solutions penetrated far enough to delimit small fracture blocks, the ribboned veinlets stand out boldly from the present sur-

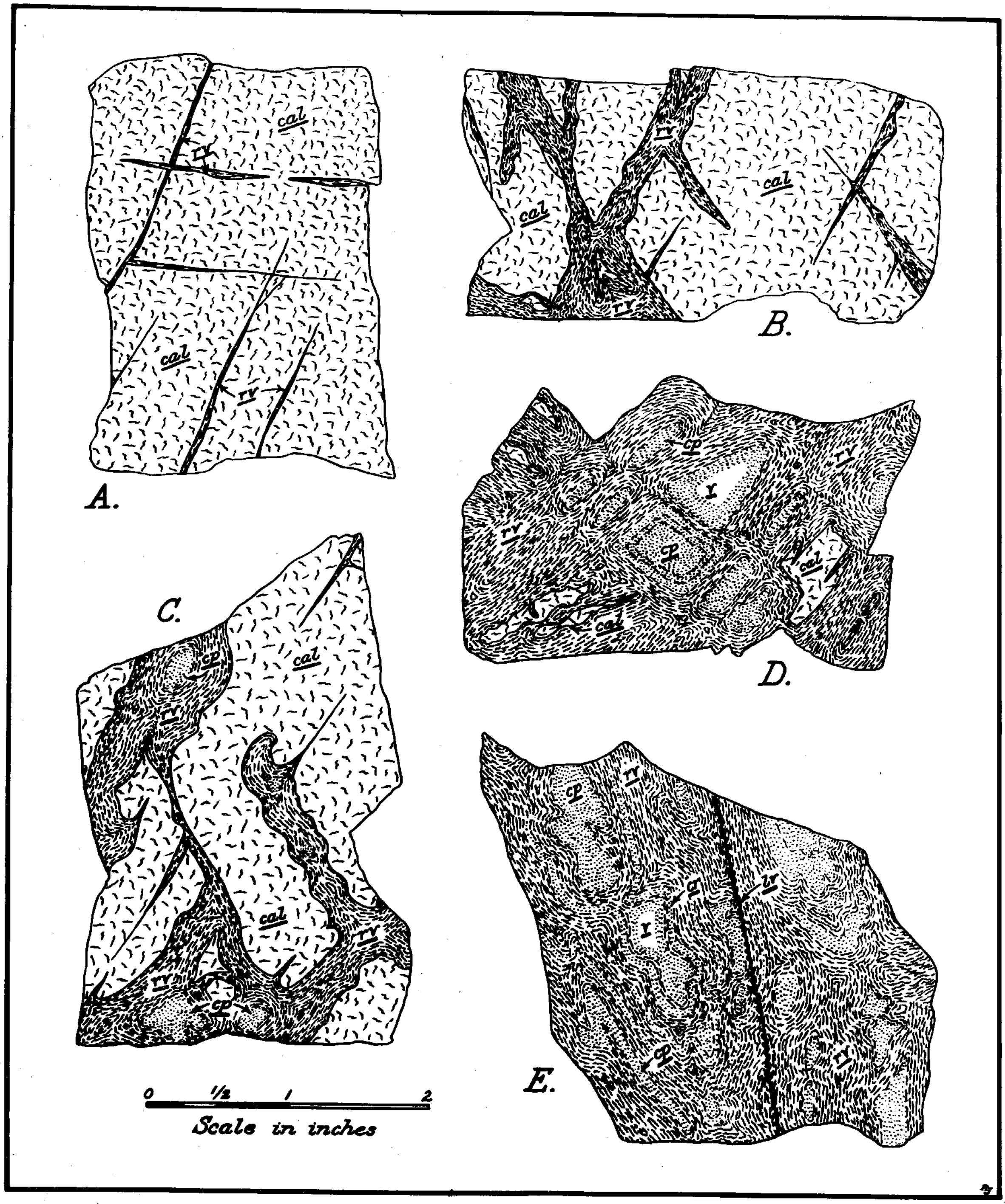


Figure 5. Sketches of actual specimens, showing typical stages in the development of "ribbon rock" tactite from recrystallized limestone. cal -- calcite; rv -- ribboned veinlet or mass; cp -- crystalline pod; v -- vug (rare); cr -- crystalline ribbon or layer; lv -- late-stage veinlet.

face of the weathered limestone as an intricate boxwork. A few small veinlets fill fractures in the massive tactite, but are not markedly ribboned.

Endomorphosed rocks

The igneous rocks in the Iron Mountain district are strikingly free from endomorphic effects. The sill-like body of granite immediately east of the North Peak is altered to a quartz-augite-epidote rock near its borders, but the alteration is confined to fracture-controlled zones rarely more than an inch wide. Somewhat similar zones of pyroxene-rich rhyolite and granite occur on the north side of Discovery Gulch, but are too poorly exposed to permit detailed study. Although a few smears of scheelite have been noted along fracture surfaces in the rhyolite dike west of South Peak, no significant amounts of tungsten- or beryllium-bearing minerals are known to occur in any of the exposed igneous rocks.

DESCRIPTION OF SELECTED AREAS

Lower Discovery Gulch

Several small bodies of beryllium-bearing tactite in lower Discovery Gulch appear to have been formed through replacement of susceptible beds or groups of beds in an eastward-dipping limestone series that is exposed on the south side of the gulch (1, pl. 2, and pl. 4). To one ascending the gulch, therefore, the tactite appears as a series of irregular pods encountered in successively higher strata. Several of these masses are in contact with coarse rhyolite porphyry that crops out to the north.

The Old Adit body, largest and most heterogeneous of the tactite pods, contains thick-bedded massive tactite, "ribbon rock" tactite, and strongly shattered and sheared tactite with minor granulite. It is bounded on the north and northeast by rhyolite porphyry, on the south by recrystallized limestone, and on the west by pale green bytownite-diopside granulite and fine-grained aplitic granite. Where recognizable, the bedding dips very gently eastward, but the cross-cutting rhyolite contact dips to the south-southwest, as shown in the fence diagram (pl. 5). The subsurface distribution of the tactite was determined by exploratory workings of the Federal Bureau of Mines.

The contacts between tactite and the adjacent rocks are everywhere sharp, but the distribution of the different varieties of tactite within the body is so complex that its beryllium-bearing portions cannot be outlined with assurance. The rock richest in beryllium is a medium to fine, even-grained, dark greenish tactite that consists chiefly of magnetite, fluorite, biotite, chlorite, and diopside. Idocrase commonly occurs as prismatic crystals in radiating groups a quarter of an inch or more in diameter. Ribboned structure is apparent throughout much of the rock and is locally very orbicular (pl. 13, top).

The Hot Spot, Little Hot Spot, and Hot Spot Extension bodies, which lie farther up the gulch (pl. 4), consist chiefly of the dark-colored, helvite-rich "ribbon rock" tactite, although the lighter-colored, silicate-rich variety forms the long projection of the Hot Spot Extension body. The Hot Spot body, from which the material first identified by Strock as helvite was collected, appears to be surrounded by thin, poorly exposed rhyolite dikes. The attitudes of faint primary flow-layering in these igneous bodies suggest that the one on the south is actually a thin, steeply dipping dike, but that the other may well be the partially exposed roof of a much larger stock- or plug-like mass. That at least the eastern part of the Hot Spot Extension body is bottomed in igneous rock is demonstrated by a shallow test pit (pl. 4), in which rhyolite porphyry and aplite were encountered at a depth of only 5 feet.

West Slope area

Four small bodies of tactite that crop out on the west slope of the mountain about 1400 feet north-northeast of Brown City (2, pl. 3, and pl. 6) have been well exposed by exploratory trenching. The tactite lenses form an irregular, discontinuous fringe around a large septum of coarsely recrystallized limestone that is bounded on three sides by fine-grained granite. Faint primary flow structure in the granite, which is best shown by aligned small flakes of biotite, suggests that the igneous rock dips eastward beneath the western part of the septum and northeastward beneath its southern part. Two of the tactite masses are separated from the granite by narrow belts of recrystallized limestone, but the others rest directly against it (pl. 6).

The Jackpot No. 2 body is an irregular lens 200 feet long and 5 to 25 feet in outcrop width. It appears to dip eastward in rough conformity with the adjacent limestone beds, and is probably less than 10 feet thick throughout most of its length. It consists of strongly banded, dark-colored, helvite-rich "ribbon rock" that differs from the tactite of the Hot Spot body only in the presence of abundant chlorite. The somewhat smaller Little Jackpot and Lower Talus bodies contain intimately admixed helvite-rich "ribbon rock" tactite and beryllium-free massive tactite, and the much larger Upper Talus body consists chiefly of massive tactite, with two poorly-defined zones of silicate-rich "ribbon rock" in its northern, broader half. This "ribbon rock" probably covers a total area of about 700 square feet, but its attitude and distribution beneath the surface are not known.

Brown area

The Brown area lies 1100 feet east-northeast of Brown City at an altitude of about 7800 feet (3, pl. 3), and in it tactite forms the thick western border of a limestone septum that extends northward into fine-grained granite (pl. 7). At least three thin aplitic sills cut the coarsely recrystallized limestone and extend into the tactite; they may be younger than some of the enclosing tactite, since locally they appear to cut off individual magnetite crystals. One small mass of silicate-rich "ribbon rock", 18 feet long and 4 feet thick, occurs near the north end of the body, and the remainder of the tactite is massively bedded, with local ribboned zones.

Jackpot No. 1 and Jackpot Extension areas

Several small bodies of tactite are exposed on the west slope of the mountain 2200 feet north-northeast of Brown City (4, pl. 2). The Jackpot No. 1 body, which lies near the mouth of a narrow gulch, is a thick, curved, pod-like tactite mass 180 feet long and about 70 feet in maximum width (pl. 8). On its northeast side it is separated from a tongue of fine-grained granite by 15 to 20 feet of massive, magnetite-rich tactite; elsewhere it rests sharply against recrystallized limestone that has been altered along favorable zones to a dense, buff-colored granulite. Except for a narrow belt of typical silicate-rich "ribbon rock" along its southeastern edge, the body is composed of massive tactite with many small lenses and irregular, poorly-defined masses of "ribbon rock". A 20-foot test pit near the southwest end of the "ribbon rock" belt passes through 2 feet of "ribbon rock", 17 feet of partially silicated limestone, and is bottomed in massive tactite, thus demonstrating the eastward dips of the altered rocks exposed west of the pit. The "ribbon rock" probably dips eastward also. The 30-foot adit in the north part of the body follows the contact between massive tactite and a 4-foot aplite dike for several feet, then bends slightly and extends eastward through massive tactite with minor ribboned zones for the remainder of the distance. Similar material was encountered in a short crosscut, but the "ribbon rock" zone was struck in the top 2 feet of a 24-foot raise to the surface.

West of the Jackpot No. 1 body and separated from it by a small, poorly-exposed complex of aplite, rhyolite, tactite, and vein quartz is another lens of beryllium-bearing tactite. Similar material, associated with coarsely recrystallized limestone, massive tactite, and large masses of manganiferous pyroxene, occurs in the Jackpot Extension body 350 feet up the slope to the east (4a, pl. 3). These rocks lie near the north end of a large inclusion in fine-grained granite. Exposed in a deep exploratory cut is the very instructive 2-foot contact zone between "ribbon rock" and limestone that plainly shows the mode of formation of this peculiar tactite at the expense of the carbonate rock, as previously described.

North End area

The largest known bodies of "ribbon rock" tactite in the district are exposed in the North End area, about a mile north-northeast of Brown City (pl. 1). Figure 3 shows the distribution of these masses throughout much of the area. Both "ribbon rock" and massive tactite occur with quartz-diopside-clinozoisite granulite in a large septum of altered limestone that is underlain and flanked by quasi-concordant bodies of fine-grained granite. Exploratory drilling by the Federal Bureau of Mines has established the presence of this igneous rock beneath the "ribbon rock" lenses at depths nowhere in excess of 100 feet. At least two post-tactite faults with vertical displacements of 50 feet or more are also known from drill records, but exposures are too poor to permit their exact location at the surface.

The exposed bodies of "ribbon rock" appear to be the remnants of large lenses whose upper portions have been removed by erosion. They are almost everywhere separated from the igneous rock by earlier-formed massive tactite, both laterally and at depth, and hence probably represent replaced limestone bodies that extended into or alongside massive tactite as pendants or septa at the close of an earlier stage of metamorphism. Much of the "ribbon rock" may thus be treated as a "secondary tactite zone" whose spatial and temporal relations to massive tactite are not unlike the relations of the massive tactite to the igneous rocks. At the time the "ribbon rock" was being formed from carbonate rocks by iron- and fluorine-rich solutions, the same solutions deposited fluorite, magnetite, specularite, and beryllium-bearing minerals in shear and breccia zones in the massive tactite. Such mineralized zones, in which little or no ribboned structure occurs, are exposed near the "ribbon rock" lens east of the large limestone mass shown in figure 3.

Scheelemite area

The Scheelemite area lies high on the west slope of the mountain, approximately 600 feet west-southwest of North Peak (5, pl. 3). A large, irregular body of massive, magnetite-rich tactite lies in contact with rhyolite and rhyolite porphyry on the west (pl. 9) and with diopside-rich granulite on the east. A southward-projecting septum of recrystallized limestone splits the tactite mass to the north. Small, poorly exposed sills and dikes of aplite and fine-grained granite and an irregular body of rhyolite lie within the tactite area.

Two stages of mineralization are readily distinguish-able in the tactite. The first was characterized by deposition of scheelite and powellite as coarse disseminations and as smears along fractures, particularly in the narrow belt of tactite between the two rhyolite intrusions (pl. 9). This was followed by a period of fracturing, during which a strongly sheared and brecciated zone was developed astride the rhyolite contact in the southern part of the area; as traced from an old open cut to a large, recent cut near the center of the area, the zone is at least 20 feet wide, with a N. 10-20 W. strike and a very steep westerly dip. In the open spaces resulting from such structural adjustments were deposited coarsely crystalline fluorite and specularite, idocrase, grossularite, carbonate and silicates of manganese, willemite, and chalcedony. The distribution of this later mineralization is shown in part in plate 9.

Parker Strike area

The Parker Strike area, which lies on the ridge midway between North and South Peaks (6, pl. 3), is traversed by a thick dike of rhyolite porphyry that trends north-northwest and dips to the west at moderate angles (pl. 10). The more susceptible beds and groups of beds in the eastward-dipping calcareous series on both sides of the dike have been strongly silicated, with development of much granulite and massive tactite. The latter rock occurs in irregular pods and thin lenses that are generally measurable in many tens of feet (pl. 10).

At least two pre-rhyolite faults that trend east-northeast and dip vertically or nearly so are readily recognizable by their truncation of thin but prominent beds of vitreous quartzite. A strong set of joints and shear planes lies parallel to these faults, and a second set conforms to the dike in trend, but dips more steeply west (pl. 10). At the intersections of particularly strong zones in these two sets the brittle contact rocks are severely shattered, and two such shatter zones have been hosts for tungsten mineralization. The scheelite and powellite occur as unusually coarse disseminations in fracture blocks and as smears and thicker, but more discontinuous fillings of the fractures themselves; the distribution and relative intensity of the mineralization are shown in plate 10.

ORIGIN OF THE TACTITES

General statement

The detailed mapping and study of about 18 square miles south and east of Iron Mountain proper have established within narrow limits the sequence of geologic events preceding and contemporaneous with the contact metamorphism. These are presented here with a minimum of comment.

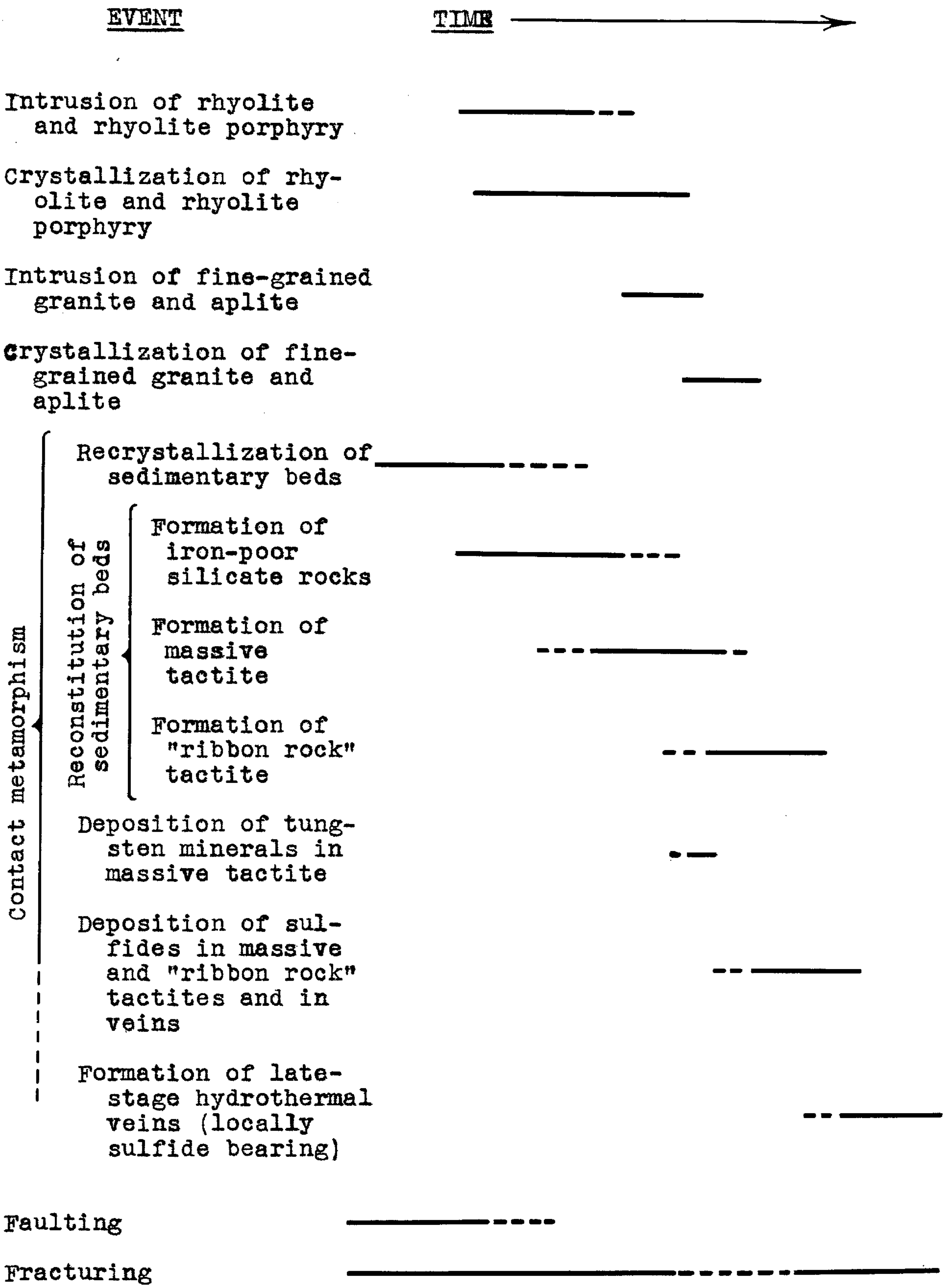


Figure 6. Sequence of mid-Tertiary events at any one place in the Iron Mountain block.

The silicic intrusive rocks with which the contact deposits are genetically associated are late-stage members of a great Tertiary igneous series. The rhyolite masses exposed on Iron Mountain doubtless represent in part the truncated feeders of a flow-series now eroded away; extensive remnants of these flows are preserved several miles to the east. The mineralogic and textural properties of the Iron Mountain rhyolites are characteristic of a rock intermediate between an extrusive and a plutonic type, and the shape and distribution of the masses suggest convergence at no great depth beneath the present surface. These masses were intruded during and immediately following a well-defined period of fracturing and faulting; much of the metamorphism appears to be similarly related to these structural readjustments.

The sequence of events at any one place on Iron Mountain proper is shown in detail in fig. 6. Lengths of the lines do not correspond rigorously to the duration of the respective events, but are merely intended to give a general sequential picture. It will be noted that the "ribbon rock" is intermediate in time between the massive tactite and the late hydrothermal vein stages, as demonstrated in many places by the reliable criterion of one rock type occurring as fracture fillings in another. The "ribbon rock" was formed immediately following a period of fracturing that had repeatedly affected the earlier-formed contact rocks, but was itself fractured to some extent prior to the late hydrothermal vein stage.

Many of the metamorphic effects appear to have preceded the final consolidation of the rhyolite, aplite, and fine-grained granite; others, however, were clearly post-consolidation, as shown by endomorphic effects that are localized along fracture zones. The rhyolite masses represent rather shallow-seated intrusions, as indicated by their texture and their role as feeders for flows that could not have lain many thousands of feet above the present surfaces. The thickness of the pre-rhyolite sedimentary and volcanic sections in areas to the east, as well as the known pre-rhyolite uplift of the Iron Mountain mass as a fault block (with concomitant erosion) suggest a cover whose maximum thickness probably was less than 5000 feet at the time of contact metamorphism and rhyolite intrusion. The thickness of the cover had of course increased somewhat by the time the aplite and fine-grained granite were irrupted, but the hypabyssal nature of such igneous masses is none the less plain.

Temperature of formation

The occurrence of pyramidal high-temperature quartz in the rhyolite and locally in the iron-poor silicated zones signifies temperatures of formation of those rock types in excess of 573° C. The wollastonite present in some of the hornfels and granulite beds suggests temperatures between 500° and 800° C.,[18] and temperatures above

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18/ Eckermann, H. von, The rocks and contact minerals of Tennberg: Geol. Fören. Forh., vol. 45, pp. 466-537, 1923.

Lindgren, Waldemar, Mineral deposits, p. 799, New York, 1933.

Knopf, Adolph, Pyrometasomatic deposits: Ore deposits of the Western States, p. 539, Am. Inst. Min. and Met. Eng., New York, 1933.

573° C. are further suggested by the presence of diopside[19].

19/ Eskola, P., On contact phenomena between gneiss and limestone in western Massachusetts: Jour. Geol., vol. 30, p. 285, 1922.

That the temperatures prevailing during the late stages of "ribbon rock" formation were distinctly lower is shown by the occurrence of typical prismatic low-temperature quartz in the druses. Anisotropic garnet, which is common in the tactite zones, may denote temperatures below 800° C., if an analogy can be drawn from experiments made by Merwin[20] on

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20/ Quoted by Wright, C. W., Geology and ore deposits of Kasaan Peninsula, Alaska: U. S. Geol. Survey, Prof. Paper 87, p. 108, 1915.

Alaskan garnets. The very low optic angle of the andularia occurring in the early-formed parts of the "ribbon rock" and locally in massive tactite would suggest heating to between 600° and 800° C.[21/], although this correlation be-

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21/ Glass, J. J., personal communication, July, 1942.

Winchell, A. N., Elements of optical mineralogy, Part II, p. 361, New York, 1933.

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tween optical properties and physical conditions may well be open to serious question[22/].

22/ Ross, C. S., personal communication, April, 1943.

It seems probable that the intrusive masses of rhyolite, porphyritic rhyolite, and aplitic granite must have solidified at temperatures in excess of 500° C.[23/]. The contact

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23/ Larsen, E. S., The temperatures of magmas: Am. Mineral., vol. 14, pp. 81-91, 1929.

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deposits on Iron Mountain are genetically associated with all three of these closely related rock types with no observable descrimination. At least a part of the massive tactite appears to have formed prior to the consolidation of nearby late-stage igneous masses, as shown, for example, by small dikes of aplite and rhyolite that break across structures and individual mineral crystals that were developed during metamorphism in large bodies of massive tactite. Thus the massive tactite seems to have been formed in part at relatively high temperatures during the period when magmatic material was still actively invading the enclosing rock. These data, together with specific information from geologically similar occurrences suggest that the massive tactite began to form at temperatures between 500° and 800° C., or distinctly above the critical temperature of pure water, and that the later "ribbon rock" tactite was formed at sensibly lower, gradually dwindling temperatures.

Mineral paragenesis

The common "primary" minerals of the massive tactite are magnetite and the iron-bearing silicates andradite and hedenbergite. The pyroxene was formed after the garnet and magnetite, as recorded by Smythe[24]. Spinels, apatite, and some feldspar are minor, relatively early-formed constituents, but the sulfides are consistently later, as are the scheelite, powellite, and willemite, which clearly fill fractures in the host rock. The massive tactite also contains mineralized zones rich in fluorite, idocrase, biotite, and specularite; these are regarded as time equivalents of the "ribbon rock" bodies, which in contrast were formed directly at the expense of limestone.

24/ Smythe, D. D., A contact metamorphic iron-ore deposit near Fairview, New Mexico: Econ. Geol., vol. 16, pp. 415-417, 1921.

Mineral paragenesis in the more complex "ribbon rock" is best interpreted on the basis of its known mode of formation. Thus the minerals in the thin, closely spaced laminae that lie at or near the positions of fractures in the pre-existing recrystallized limestone must be relatively early, whereas those in the crystalline pods and druses are late. The arrangement of banding on most faces of "ribbon rock" is generally a reliable clue to the distribution of fractures from which the silication began (see fig. 5).

The mineral paragenesis in "ribbon rock" tactite is shown in fig. 7. Since neither the absolute nor the relative durations of the various stages are known within satisfactory limits, intercepts at different horizontal positions are not necessarily to the same scale. The heights of the black areas along a given vertical line represent in a general way the relative amounts of the constituents being formed at a given time. Magnetite, biotite, idocrase, and some specularite are relatively early minerals, whereas fluorite and much of the specularite are sensibly later. The grossularite, helvite, and quartz are relatively later, and occur almost wholly in the crystalline layers, pods, and druses.

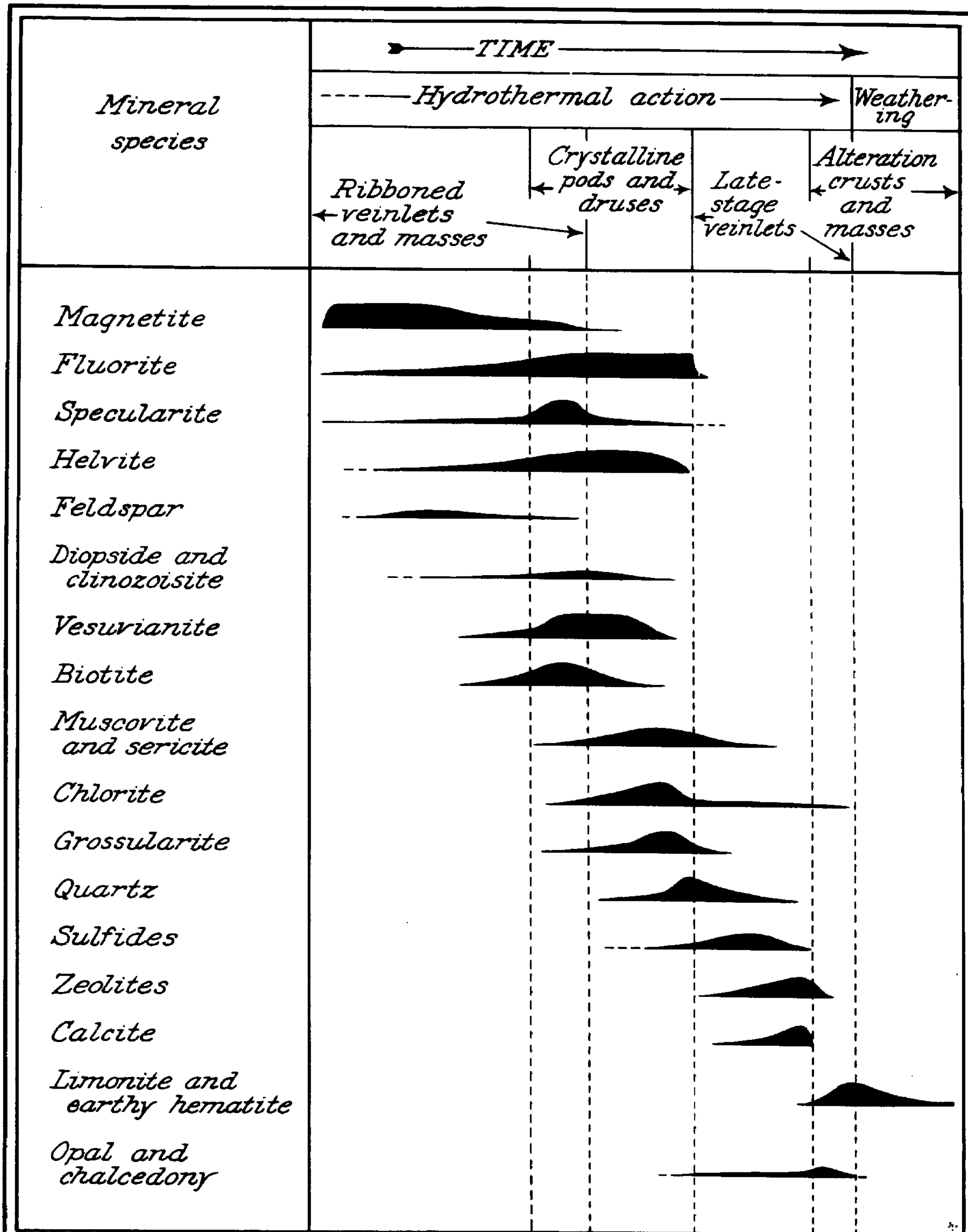

Figure 7. Mineral paragenesis in "ribbon rock" tactite.

Transfer of material

General relations

The structural simplicity of the Iron Mountain block, which permits the tracing of unaltered sedimentary beds into areas of increasing metamorphic intensity, greatly facilitates the study of compositional changes in the various zones of alteration. Moreover, it has been possible to determine the sequence of formation of certain contact rocks, and therefore something of the chronology involved in the transfer of material to and from the respective original sedimentary beds. A chronologic summary of mineral formation is presented in figure 8, and the implied additions and subtractions of certain elements are also indicated; the heights of the solid black areas above the base line or their depths below it along any vertical line are intended to indicate in a relative way the amounts of material brought in or removed at a given time and at any single place in the contact zone. Although preliminary investigation has demonstrated the feasibility of determining quantitatively the more important bulk changes in composition, as was done in the Hanover district by Schmitt[25/], such treatment of the material

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25/ Schmitt, Harrison, The Pewabic Mine: Bull. Geol. Soc. America, vol. 50, pp. 799-802, 1939.

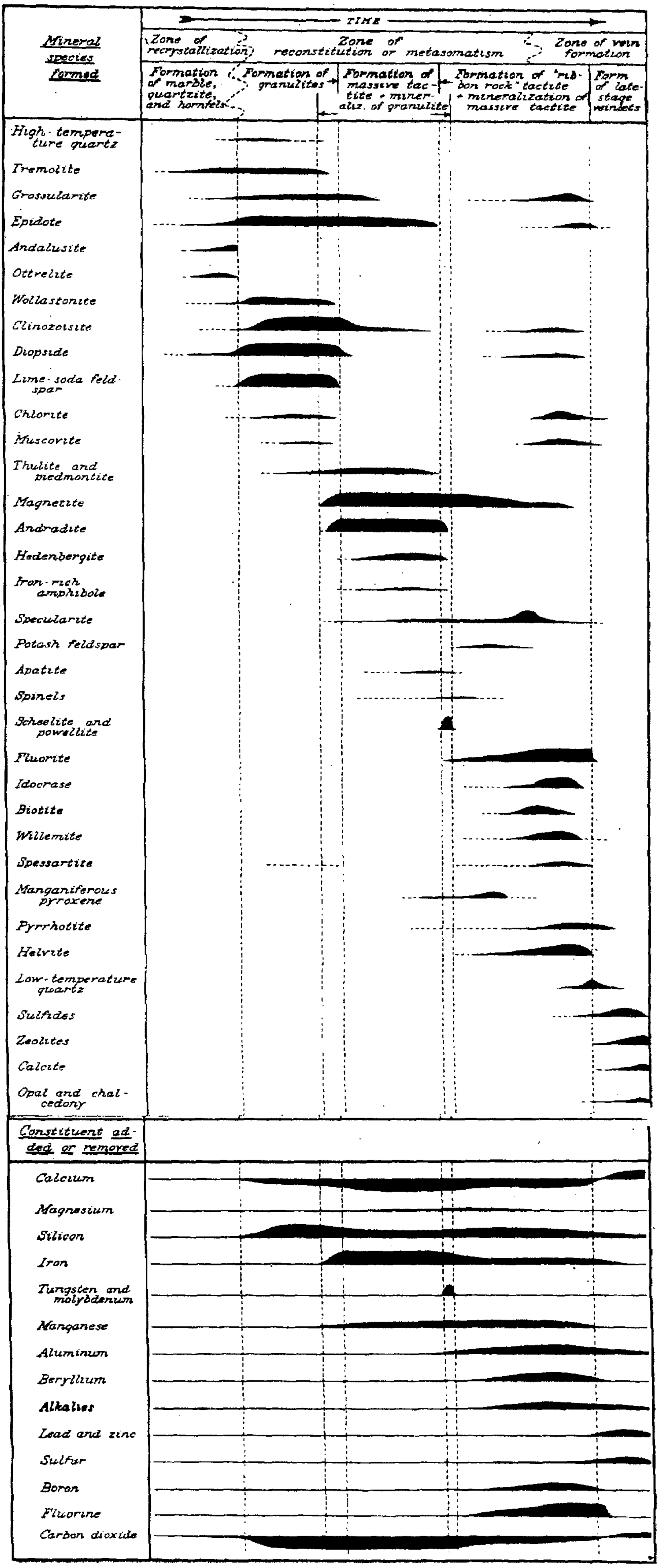

Figure 8. Paragenesis of representative minerals in the contact zones on Iron Mountain, with the implied additions and subtractions of certain elements.

transfer problem is beyond the scope of the present paper.

As shown in figure 8, little material other than silicon appears to have been added to form the iron-poor silicate rocks, and the addition of silicon and iron all but suffices to account for the "primary" constituents of massive tactite. During the later stages of metamorphism, however, large amounts of iron and silicon, as well as more moderate amounts of aluminum and magnesium, the alkalies, manganese (pyroxenes, helvite, spessartite, thulite, manganomagnetite), tungsten and molybdenum (scheelite, powellite, molybdenite), beryllium (helvite, idocrase, chlorite, grossularite), boron (idocrase, axinite), fluorine (fluorite, fluor-apatite, biotite, etc.), zinc, lead, and sulfur were introduced. Losses in lime and carbon dioxide occurred throughout the silication.

The physical and chemical nature of the solutions active in the formation of pyrometasomatic deposits can be determined with reasonable assurance in few places. In recent years the physical chemistry of magmatic differentiation and mineralization has been discussed at length by many investigators, among whom Bowen[26/], Fenner[27/],

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26/ Bowen, N. L., Crystallization-differentiation in silicate liquids: Am. Jour. Sci., 4th ser., vol. 39, pp. 175-191, 1915; The later stages of the evolution of igneous rocks: Jour. Geol., vol. 23, supplement to no. 8, pp. 1-91, 1915;

The behavior of inclusions in igneous magmas: Jour. Geol., vol. 30, supplement to no. 6, pp. 513-570, 1922; The evolution of the igneous rocks, Princeton University Press, 1928; The broader story of magmatic differentiation, briefly told: Ore deposits of the Western States, pp. 106-128, Am. Inst. Min. and Met. Eng., New York, 1933.

27/ Fenner, C. N., The Katmai magmatic province: Jour. Geol., vol. 34, no. 7, pt. 2, 1926; Pneumatolytic processes in the formation of minerals and ores: Ore deposits of the Western States, pp. 58-106, Am. Inst. Min. and Met. Eng., New York, 1933; Review and discussion of Prof. Paper 179 (U. S. Geol. Survey) by Clarence S. Ross on "Origin of the copper deposits of the Ducktown type in the southern Appalachian region": Econ. Geol., vol. 30, pp. 928-936, 1935.

Ross[28/], Schaller[29/], and Zies[30/] have been particularly

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28/ Ross, C. S., Physico-chemical factors controlling magmatic differentiation and vein formation: Econ. Geol., vol. 23, pp. 864-886, 1928; Differentiation as a source of vein and ore-forming materials: Ore deposits of the Western States, pp. 128-144, Am. Inst. Min. and Met. Eng., New York, 1933; Origin of the copper deposits of the Ducktown type in the southern Appalachian region: U. S. Geol. Survey, Prof. Paper 179, 1935.

29/ Schaller, W. T., The genesis of lithium pegmatites: Am. Jour. Sci., 5th ser., vol. 10, pp. 269-279, 1925; Mineral replacements in pegmatites: Am. Mineral., vol. 12, pp. 59-63, 1927; Pegmatites: Ore deposits of the Western States, pp. 144-151, Am. Inst. Min. and Met. Eng., New York, 1933.

30/ Zies, E. G., The Valley of Ten Thousand Smokes; I The fumarolic incrustations and their bearing on ore deposition, II The acid gases contributed to the sea during volcanic activity: Nat. Geog. Soc., Contributed Technical Papers, Katmai ser., vol. 1, no. 4, 1929.

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active in several closely allied fields. Complete agreement concerning results of the application of physico-chemical principles, experimental work, and field observations to the problem of ore deposition and associated mineralization is not yet at hand, and for many parts of the problem definite answers are still lacking. It is plain, therefore, that the following conclusions concerning the origin of the Iron Mountain tactite rocks are necessarily tentative.

Formation of massive tactite

The massive tactite, with its extremely simple "primary" mineralogy (chiefly magnetite and andradite) and its occurrence immediately adjacent to essentially contemporaneous igneous bodies of volcanic and hypabyssal, rather than plutonic affinities, seems well explained as a product of deposition from iron-rich magmatic emantions that may have been incapable of transporting appreciable quantities of aluminum and the alkali earths. Their wholesale replacement of massive limestone and granulite beds suggests great penetrative power, and the high temperatures of these fluids are demonstrated by their ability to form andradite at the expense of calcium carbonate. It has already been noted that the cooling intrusive masses were overlain by a freshly fractured, relatively thin cover of sedimentary and volcanic rocks; this condition would favor the rapid escape from the magma of so-called volatile elements, which would pass directly into the gas phase and be subject to typical gas-phase reactions[31/]. Escape of the

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31/ See, for example:

Zies, E. G., The Valley of Ten Thousand Smokes; the fumarolic incrustations and their bearing on ore deposition: Nat. Geog. Soc., Contributed Technical Papers, Katmai ser., vol. 1, no. 4, 1929.

Fenner, C. N., Pneumatolytic processes in the formation of minerals and ores: Ore deposits of the Western States, pp. 58-106, Am. Inst. Min. and Met. Eng., New York, 1933.

Wells, F. G., The origin of the iron ore deposits in the Bull Valley and Iron Springs districts, Utah: Econ. Geol., vol. 33, pp. 498-507, 1938.

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gases could be prevented at any time by constriction or complete closure of the fracture passageways, and pressure in the underlying solutions could then be built up to the point where liquid-phase reactions would become dominant.[32/]

32/ See, for example:

Morey, G. W., The development of pressures in magmas as a result of crystallization: Jour. Wash. Acad. Sci., vol. 12, pp. 219-230, 1922.

Ross, C. S., Physico-chemical factors controlling magmatic differentiation and vein formation: Econ. Geol., vol. 23, pp. 876-881, 1928.

Formation of the massive tactite, at least a part of which might be viewed as the product of gaseous transfer, has involved the deposition of large amounts of iron and the removal of carbon dioxide. Some silica also must have been introduced. How could such transfer be effected? Halogens have been regarded as the chief carriers of iron and other metals in magmatic gases because of their volatility and their proven role in fumarolic deposition, and the presence of considerable amounts of at least one of these elements in the Iron Mountain deposits is shown by extremely abundant fluorite, fluor-apatite, and other fluorine-bearing minerals. Chlorine may have been present also, but the absence of scapolite and the solubility of most other chlorine compounds in aqueous solutions makes its total effect difficult to evaluate. A second mode of transfer, involving the solvent action of volatiles on non-volatile compounds at supercritical temperatures, has been pointed out by several investigators[33/], but its applications to geologic processes are imperfectly known at the present time.

33/ See, for example:

Ingerson, Earl, Relation of critical and supercritical phenomena of solutions to geologic processes: Econ. Geol., vol. 29, pp. 454-470, 1934.

Geijer, Per, Processes in contact metamorphism: Econ. Geol., vol. 20, pp. 688-689, 1925.

Greig, J. W., Merwin, H. E., and Shepherd, E. S., Notes on the volatile transport of silica: Am. Jour. Sci., 5th ser., vol. 25, pp. 71-73, 1933.

That the magmatic exhalations were acid is suggested by the known acid character of volcanic gases[34], and the

34/ Day, A. L., and Allen, E. T., The volcanic activity and hot springs of Lassen Peak: Carnegie Inst. Wash., Pub. 360, p. 125, 1925.

contained halogen compounds and other substances of relatively low critical temperatures would minimize the tendency of any extremely low-volatile solutes to greatly raise the critical temperature of such escaping gases. Maier[35] has shown that the vapor pressures of the chlo-

35/ Maier, C. G., Vapor pressure of the common metallic chlorides and a static method for high temperature: U. S. Bur. Mines, Tech. Paper 360, pp. 1-54, 1925.

rides of Al, Fe, Zn, Pb, Ni, and some of the other common metals are high, whereas those of calcium and magnesium chlorides are very low. Beryllium chloride may well belong in the latter group, though no data on its vapor pressure appear to be available. Vapor pressures of the fluorides of these metals may be analogous to those of the chlorides. The tendency of $AlCl_3$ (and perhaps AlF_3) to hydrolyze in the presence of excess water vapor[36] probably inhibits

36/ Fenner, C. N., op. cit., p. 84, 1933.

its transportation for great distances in the gaseous phase.

On the other hand, Zies[37/] cites experimental evidence to

37/ Zies, E. G., op. cit., pp. 7-10, 1929.

show that iron can be transferred as chlorides in the gaseous state, and that magnetite will form when steam reacts with the two chlorides at temperatures near 550° C. A part of the Iron Mountain magnetite might well be accounted for according to the following analogous fluoride reactions:

$$Fe_2O_3 + 6\ HF = 2\ FeF_3 + 3\ H_2O$$

$$FeO + 2\ HF = FeF_2 + H_2O$$

$$2\ FeF_3 + FeF_2 + 4\ H_2O = Fe_3O_4 + 8\ HF$$

Since a given amount of HF will have far greater effect in driving the first two equations to the right than the addition of an equal amount of water in driving them to the left, the iron should remain as volatile halides so long as markedly acid conditions are maintained. This assuredly would be the case near the source magma, as well as in those channels where jacketing of carbonates by iron oxides would prevent further removal of acids from the vapors. Wherever acid could be removed through reactions with carbonates, however, formation of magnetite should proceed according to the third equation. Since all three equations are qualitative, they are merely suggested to show a reasonable mechanism for the transfer of iron and formation of magnetite that is compatible with field observations and experimental data.

Silica might be transported as the volatile fluoride, according to the equation:

$$SiO_2 + 4\ HF = SiF_4 + 2\ H_2O$$

The HF concentration, however, would have to be high to prevent hydrolysis of the silicon tetrafluoride. Silica can also be transported with water vapor at high temperature and pressure[38/], particularly in the presence of

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38/ Greig, J. S., Merwin, H. E., and Shepherd, E. S., op. cit., pp. 71-73, 1933.

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other volatiles. Quartzite beds and chert lenses in the limestone, as well as the silicic magma itself are the most likely sources of the SiO_2.

The hot, acid gases, with their metallic halides, water, and silica or silicon halides, presumably escaped from the magma chamber into a freshly fractured, relatively thin cover of sedimentary and volcanic rocks. Thus their pressure need not have been great. Upon reaching beds of favorable composition and structural situation, they reacted strongly with calcite and deposited magnetite and small amounts of hematite, possibly through much the same mechanism as that involved in the formation of fumarolic incrustations[39/]. If an analogy can be drawn from calcium

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39/ See, for example:

Zambonini, F., Mineralogia Vesuviana, p. 70, Napoli, 1910.

Zies, E. G., op. cit., pp. 5-10, 116, 1929.

chloride, a substance of very low vapor pressure, calcium fluoride would be difficult to remove from such a system as a gas. Some calcium may have been used on the spot to form andradite, according to the hypothetical equations:

$$CaCO_3 + 2HF = CaF_2 + CO_2 + H_2O$$

$$2FeF_3 + 3CaF_2 + 3SiF_4 + 12H_2O = Ca_3Fe_2(SiO_4)_3 + 24HF$$

It is clear, however, that a considerable amount of calcium must be removed in other ways. Gaseous transfer of this element may be accomplished in a system rich in water vapor according to Fenner[40/], who lists experimental evidence and

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40/ Fenner, C. N., Pneumetolytic processes in the formation of minerals and ores: Ore deposits of the Western States, pp. 84-87, Am. Inst. of Min. and Met. Eng., New York, 1933.

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known occurrences of calcim-rich fumarolic deposits in support of such a view. Ingerson[41/] also has suggested that

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41/ Ingerson, Earl, Relation of critical and supercritical phenomena of solutions to geologic processes: Econ. Geol., vol. 29, pp. 454-470, 1934.

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such a non-volatile substance might be transferable in gaseous solution with volatile solvents. It seems likely, however, that the presence of appreciable quantities of a liquid phase may best account for removal of large amounts of calcium. Thus the solutions passed outward and upward following their reaction with the country rock, their temperature and acidity considerably reduced; they appear to have carried with them such constituents as lead, zinc, and manganese for deposition in cooler parts of the terrane, and probably were accompanied by condensation products rich in calcium and the halogens.

Following the escape of the gaseous emanations, their subsequent deposition of magnetite and andradite, and their partial condensation, additional iron-rich vapors and subordinate accompanying liquids appear to have arisen from the underlying masses of cooling and solidifying rock. These may well have participated heavily in the formation of the massive tactite, and they appear to have deposited magnetite, andradite, hedenbergite, iron-rich amphibole, feldspar, scheelite, powellite, hematite, and minor amounts of other minerals. Evidently they were able to transport a variety of substances in quantity, to pervade and attack limestone on a large scale, and to carry away both calcium and carbon dioxide.

The derivation and behavior of residual magmatic solutions have been discussed clearly and at length by Bowen[42/] and Ross[43/]. Critical phenomena appear to have

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42/ Bowen, N. L., The broader story of magmatic differentiation, briefly told: Ore deposits of the Western States, pp. 106-128, Am. Inst. of Min. and Met. Eng., New York, 1933.

43/ Ross, C. S., Physico-chemical factors controlling magmatic differentiation and vein formation: Econ. Geol., vol. 23, pp. 864-886, 1928.

no bearing on such solutions because of the large proportion of dissolved compounds[44], hence the persistence

44/ Morey, G. W., Relation of crystallization to water content and vapor pressure of water in a cooling magma: Jour. Geol., vol. 32, pp. 291-295, 1924.

Ross, C. S., op. cit., pp. 878-879, 1928.

of a liquid phase is to be expected. This would account for the transfer of alkalies, aluminum, and much silica, in addition to the iron and other elements carried in the vapor phase. Bowen[45] has shown that this vapor phase is

45/ Bowen, N. L., op. cit., pp. 119-125, 1933.

acid, and that its ability to attack and remove minerals is greatest after it has condensed to a liquid.

The massive tactite at Iron Mountain therefore appears to have been formed under vapor-phase conditions, at first from material that left the magma as gases and later condensed, and subsequently from material forced from the magma as vapor-rich residual solutions. The durations of these stages, as well as the intensity of action during any period within them were presumably controlled by the physical condition of the relatively thin, fractured cover that overlay the igneous masses. The partial or complete sealing of escape channels, alternating with periods of fracturing and fissuring would make for intermittent rising of the mineralizing solutions[46/]; abundant evidence for such

46/ See Burbank, W. S., A source of heat-energy in crystallization of granodiorite magma, and some related problems of volcanism: Am. Geophys. Union, Trans., 17th Ann. Meeting, pp. 236-255, National Research Council, Washington, D. C., 1936.

spasmodic action is found in the tactite masses, where each of several groups of fractures plainly was "healed" by newly-deposited tactite minerals before the succeeding group of fractures was formed. This appears to have been most common during the latest stages of massive tactite formation.

Formation of "ribbon rock" tactite

The earliest-formed constituents of the "ribbon rock" tactite differ but slightly from those of the older massive tactite, and transitional varieties of tactite actually have been observed. The relative proportions of later minerals in the "ribbon rock", however, denote certain orderly and progressive changes. Although magnetite remained dominant at first, fluorite and minerals containing aluminum, beryllium, alkalies, fluorine, and boron became more and more abundant. Biotite, helvite, and idocrase crystallized in preference to garnet, and specular hematite gradually supplanted magnetite. During the latest stages helvite, grossularite, and low-temperature quartz were formed, especially in the magnetite-poor varieties of "ribbon rock".

The great variety of elements in the "ribbon rock" tactite strongly suggests introduction of material transported chiefly in hot liquids of steadily decreasing temperature. Such hydrothermal solutions may be viewed in part as condensations of the vapors treated in the preceding section; the transition between the vapor-rich and hydrothermal periods appears to have been gradual, as shown by the gradual mineralogic changes during the early stages of "ribbon rock" formation. The hydrothermal solutions must have been reducing rather than oxidizing in character during the later stages, when some helvite and sulfides of iron, lead, zinc, and copper were deposited at the expense of calcite and earlier formed iron oxides.

The strikingly layered structure of the "ribbon rock" seems best interpreted as a product of diffusion and rhythmic precipitation of replacing material. Trüstedt[47/]

47/ Trüstedt, O., Die Erglagerstätten von Pitkäranta am Ladoga-See: Bull. Comm. Geol. de Finlande, No. 19, p. 226, 1907.

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ascribed the origin of similar rock from Pitkäranta, Finland, to crustification produced by magmatic waters of rapidly changing temperature and composition. This explanation is plainly unsatisfactory for the Iron Mountain occurrences, since the layers were formed in a succession progressing away from fractures into masses of relatively unfractured carbonate rock. The arrangement of layers corresponds closely to that of iron-stained weathering rings seen in blocks of even-grained granite and silicic volcanic rocks. Laminated diffusion structures analogous to those in the Iron Mountain tactite, as well as those in the "ore arteries" from Pitkäranta[48/], Finland, and the

48/ Trüstedt, O., idem, 1907.

"orbicular contact metamorphosed rock" described by Knopf[49/]

49/ Knopf, Adolph, Geology of the Seward Peninsula tin deposits: U. S. Geol. Survey, Bull. 358, pp. 45-49, 1908.

from Alaska have been reproducted in the laboratory. The original experiments of Liesegang[50/] are particularly well

50/ Liesegang, R. E., Geologische diffusionen, Dresden and Leipzig, 1913.

known.

The important role of diffusion in replacement processes has been upheld by many students of ore deposits[51/]

51/ See, for example:

Knopf, Adolph, idem., 1908.

Watanabe, M., Some problems of diffusion in the special reference to the study of ore deposits: Sci. Rept., Tohoku Imp. Univ., sec. III, vol. 2, Sendai, 1924.

Whitmann, A. R., Diffusion in ore genesis: Econ. Geol., vol. 23, pp. 473-488, 1928.

Lindgren, Waldemar, Mineral deposits, pp. 176-177, New York, 1933.

and needs no further comment here. The individual "ribbon rock" layers obviously could not have been controlled directly by a structure in the limestone, such as bedding, cross-lamination, or closely-spaced curving fractures, but their distribution does appear to be satisfactorily explainable as a diffusion effect. This is the conclusion reached by Knopf[52/] in his study of the markedly similar

52/ Knopf, Adolph, idem., 1908.

Alaskan occurrences.

Summary and conclusions

The development of iron-rich contact rocks at Iron Mountain can be traced through a period characterized by deposition from vapors to a period during which hydrothermal solutions were dominant. The vapor stage probably was supplanted by the hydrothermal stage gradationally and with no recognizable breaks. Both vapors and liquids appear to have been acid, and reducing conditions undoubtedly existed during late stages of the hydrothermal sequence. A somwhat similar sequence appears to have obtained during pyrometasomatism in the nearby Hanover district of southwestern New Mexico[53/] .

53/ Schmitt, Harrison, The Pewabic Mine: Bull. Geol. Soc. America, vol. 50, p. 812, 1939.

The magmatic vapors, apparently well above the critical temperature of pure water, were highly pervasive and thus were able to replace great masses of carbonate rock with minor regard for fractures and other avenues of immediate access. The hydrothermal mineralization, on the other hand, possessed much less penetrative power, as demonstrated by its obvious dependence upon fractures for access to the recrystallized limestone and early silicate rocks. Magnetite was deposited from both vapors and liquids, but was itself attacked during the latest stages of hydrothermal activity, during which calcite, quartz, sulfides, and zeolites were deposited. Fluorite, aluminum-bearing silicate minerals, specularite, helvite, graphite, and pyrrhotite were laid down somewhat earlier in the hydrothermal period, and might be characterized with equal justification as hypothermal or as late-stage pyrometasomatic products. Thus the Iron Mountain deposits present a rather complete gradation from an early stage of gaseous, or vapor phase reaction to a later, typically hydrothermal stage; no typical pegmatitic stage appears to have existed, and the amount of pegmatite observed in the area is negligible.

The occurrence of beryllium in "ribbon rock", but not in noteworthy quantities in massive tactite may well indicate that little of that element could be transferred in the gaseous state. Beryllium thus would be somewhat analogous to the related elements calcium and magnesium. If this conclusion can be extrapolated to other pyrometasomatic deposits, we should not expect to find beryllium minerals as primary constituents of those rocks formed from magmatic gases or vapors, such as the "contact" iron ores in southwestern Utah[54/]. Tactites of this type are

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54/ Wells, F. G., The origin of the iron ore deposits in the Bull Valley and Iron Springs districts, Utah: Econ. Geol., vol. 33, pp. 498-507, 1938.

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mineralogically simple, and generally consist chiefly of iron oxides and iron-rich silicates. If the beryllium were present in the magmatic fluids in quantities sufficient to form appreciable amounts of its compounds in the contact zones of a given deposit, such compounds should be sought for in the rocks or mineralized zones of hydrothermal origin. The occurrence of "ribbon rock" should be a useful clue, even though its consistent association with beryllium-bearing minerals is well established in but one deposit; on the other hand, there is no obvious reason why such minerals should not occur in hydrothermal bodies from which ribboned structures are absent.

For

MINOR THESIS

by

RICHARD H. JAHNS

Presented in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy,

"STRATIGRAPHY OF THE EASTERNMOST VENTURA BASIN, CALIFORNIA, WITH A DESCRIPTION OF A NEW LOWER MIOCENE MAMMALIAN FAUNA FROM THE TICK CANYON FORMATION,"

See

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CONTRIBUTIONS TO PALEONTOLOGY

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With three plates and nine text figures

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Balch Graduate School of the Geological Sciences
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Contribution No. 300

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CONTENTS

STRATIGRAPHY OF THE EASTERNMOST VENTURA BASIN, CALIFORNIA, WITH A DESCRIPTION OF A NEW LOWER MIOCENE MAMMALIAN FAUNA FROM THE TICK CANYON FORMATION

INTRODUCTION

The great thickness of dominantly nonmarine Tertiary strata in the eastern part of the Ventura Basin has impressed geologists since the time of the earliest surveys of the region. The younger of these strata, comprising the so-called Mint Canyon formation, have been eroded to form a great basinlike area in which numerous badland exposures occur (see fig. 1). Erosion has been due principally to the poor consolidation of the sediments and in part also to the rather scant cover of typical Sonoran vegetation. Although several earlier investigators examined these badlands, the first recorded discovery of vertebrate remains came as a result of reconnaissance mapping by Kew in 1919. In the publication that followed, a provisional list of the forms found here was furnished by Stock,[1] although no detailed study of the fauna was made.

After obtaining additional materials from the Mint Canyon beds, Maxson [2] in 1930 published a detailed discussion of the fauna, and agreed with Stock on an upper Miocene age for the series. He further recognized that this vertebrate assemblage not only furnishes valuable data from which an age determination of the deposits might be made, but likewise sheds light on the age of the overlying marine strata and on their correlation with continental equivalents in the Great Basin and Great Plains provinces to the east. In a subsequent critical review of the fauna, Stirton [3] reached conclusions not in accord with those of Maxson, and advocated a lower Pliocene age for the strata. Since that time, several papers [4] of a mildly controversial nature have dealt directly or indirectly with the age of the Mint Canyon and with the stratigraphic relations of the fossils involved. The non-uniform character of the fauna, in which primitive and advanced types of mammals appear to be in association, has presented an additional

[1] W. S. W. Kew, U. S. Geol. Surv. Bull. 753, p. 54, 1924.

[2] J. H. Maxson, Carnegie Inst. Wash. Pub. No. 404, paper VII, pp. 77–112, 1930.

[3] R. A. Stirton, Amer. Jour. Sci., 5th ser., vol. 26, pp. 569–570, 1933.

[4] P. Teilhard de Chardin and R. A. Stirton, Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 23, pp. 277–290, 1934. R. A. Stirton, Amer. Jour. Sci., 5th ser., vol. 32, pp. 174, 188, 1936; Jour. Paleontol., vol. 13, pp. 135–136, 1939. P. O. McGrew and G. E. Meade, Amer. Jour. Sci., 5th ser., vol. 36, pp. 197–207, 1938. G. E. Lewis, Amer. Jour. Sci., 5th ser., vol. 36, pp. 208–211, 1938. J. H. Maxson, "Miocene-Pliocene boundary" (abstract), Bull. Amer. Assoc. Petrol. Geol., vol. 22, pt. 2, pp. 1716–1717, 1938. J. H. Maxson, Bull. Geol. Soc. Amer., vol. 49, no. 12, pt. 2, pp. 1916–1917, 1938. J. E. Eaton, Bull. Amer. Assoc. Petrol. Geol., vol. 23, pp. 533–534, 1939.

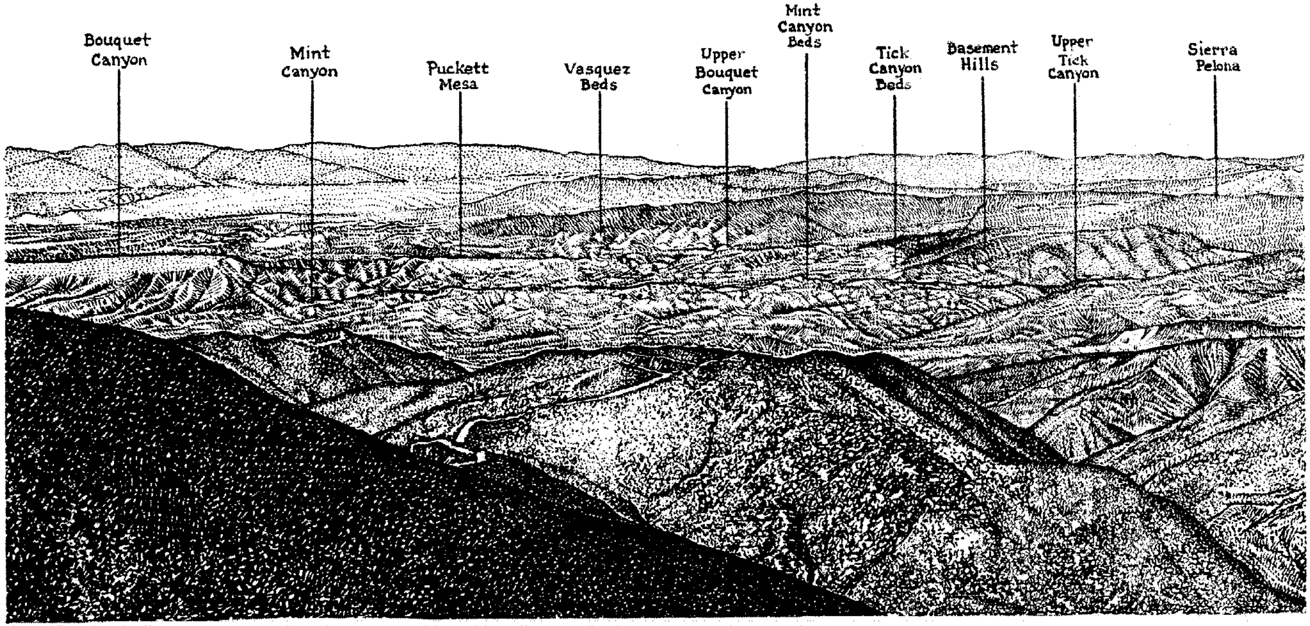


FIG. 1. The Mint Canyon area as viewed from Santa Clara Ridge in the San Gabriel Mountains to the southeast. The higher regions are composed of crystalline rocks; the basinlike lowlands have been eroded out of softer sedimentary rocks. Note the Vasquez and Tick Canyon beds lapping against the darker-colored granitic basement in the middle distance.

complication. Both Maxson and Stirton have commented [5] on this peculiar feature, although no stratigraphic break has been noted in the section.

That disagreement continues to exist in regard to the stratigraphy of the Mint Canyon area is not surprising, chiefly for three reasons, as follows:

1. Not only are the vertebrate remains fragmentary and poorly preserved, but there is a paucity of forms comparable to those of other known vertebrate horizons.

2. The orogenic disturbances active in this region during Tertiary time have created structural complexities, the true nature and extent of which become apparent only after detailed geologic study. Although in regions of flat-lying strata the plotting of fossil localities on a topographic map suffices to create a clear picture of the actual field relations, such a procedure in the highly folded and faulted Mint Canyon area has been of little value. Further, the irregular lateral lithologic gradations characteristic of the fossiliferous strata greatly reduce the number of available marker beds and key horizons. As a consequence, there has been a lack of definite data on the stratigraphic position of each form.

3. The generalized character of the geologic mapping previously done, as well as some confusion in the literature, has thrown doubt on the position and relations of the Mint Canyon beds and adjacent formations, particularly the overlying marine strata. That a fuller understanding of these relations is essential to a successful marine-nonmarine correlation naturally follows.

NATURE AND SCOPE OF PRESENT INVESTIGATION

In an attempt to obtain a clearer concept of Mint Canyon stratigraphy and to determine definitely the field relations between marine and nonmarine beds, the writer devoted some forty-five field days to reconnaissance observations and to detailed mapping of a "critical area" in the basin. This area is approximately 15 square miles in extent; it includes nearly all the important known vertebrate localities, many of the badland exposures most promising as potential sources of additional material, and a significant part of the contact between the Mint Canyon and overlying marine strata. The detail of the mapping has permitted a determination of the relative stratigraphic position of each fossil occurrence within narrow limits.

The collection by H. D. Curry, Dr. J. H. Maxson, and R. W. Wilson of oreodont, equid, and rodent remains from the lowermost beds of the Mint Canyon furnished the best basis for analyzing the problem of the "mixed fauna." The fossil types were kindly turned over to the writer for study by Dr. Maxson, and the results obtained are presented in this paper with newly acquired stratigraphic data. No further review of forms previously obtained from beds higher in the section is attempted, inasmuch as pertinent detailed discussions are available in the existing literature.[6]

[5] J. H. Maxson, Carnegie Inst. Wash. Pub. No. 404, paper VII, pp. 81, 85, 1930. R. A. Stirton, Amer. Jour. Sci., 5th ser., vol. 26, p. 575, 1933; vol. 32, p. 188, 1936.

[6] J. H. Maxson, *op. cit.*, 1930. R. A. Stirton, *op. cit.*, 1933.

ACKNOWLEDGMENTS

The present investigations were made under the direction of Dr. Chester Stock, to whom the writer is greatly indebted, not only for his invaluable advice and suggestions and his critical examination of the manuscript, but for his continued interest in all phases of the problem. Dr. J. H. Maxson made available the new fossil material from the lower Mint Canyon beds and furnished valuable information on the invertebrate fauna collected by him from the overlying marine strata. Sincere appreciation is also expressed for the advice and criticism given by E. L. Furlong and J. F. Dougherty, and by Dr. R. W. Wilson, who studied the rodents of the new fauna. L. W. Davenport, R. E. Wallace, and W. T. Potter, Jr., gave generously of their time in helpful field assistance. The illustrations have been prepared or supervised by D. P. Willoughby.

LOCATION

The easternmost portion of the Ventura Basin, discussed in this paper, is located in the northwestern part of Los Angeles County, California, and is drained by the upper Santa Clara River and its tributaries (see fig. 2). Most important of the latter are Bouquet, Mint, and Tick Canyons, which join the Santa Clara Valley on its north side. Although hilly and rough

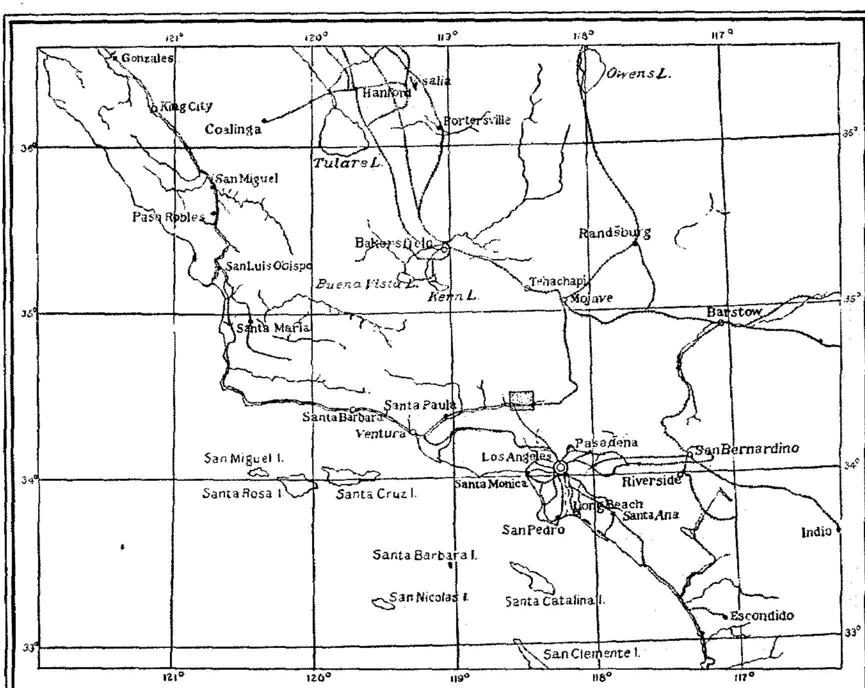


Fig. 2. Index map of a part of southern California, showing location of the eastern part of the Ventura Basin. The stippled rectangle represents the area shown in figure 3.

in detail, the topography is rather subdued when compared with that of the San Gabriel Mountains immediately to the south. Lying within this part of the basin, in the main between Mint and Bouquet Canyons (Humphreys Quadrangle, U. S. Geol. Surv.), is the smaller area which was mapped in detail (see hachured area in fig. 3). C.I.T. Vert. Pale. Loc. 201, the quarry from which most of the new fossil material was obtained, is situated near the narrows of Vasquez Canyon, a tributary of Bouquet Canyon, at a distance of approximately 10 miles by road from Saugus, a small town on the Southern Pacific Railroad.

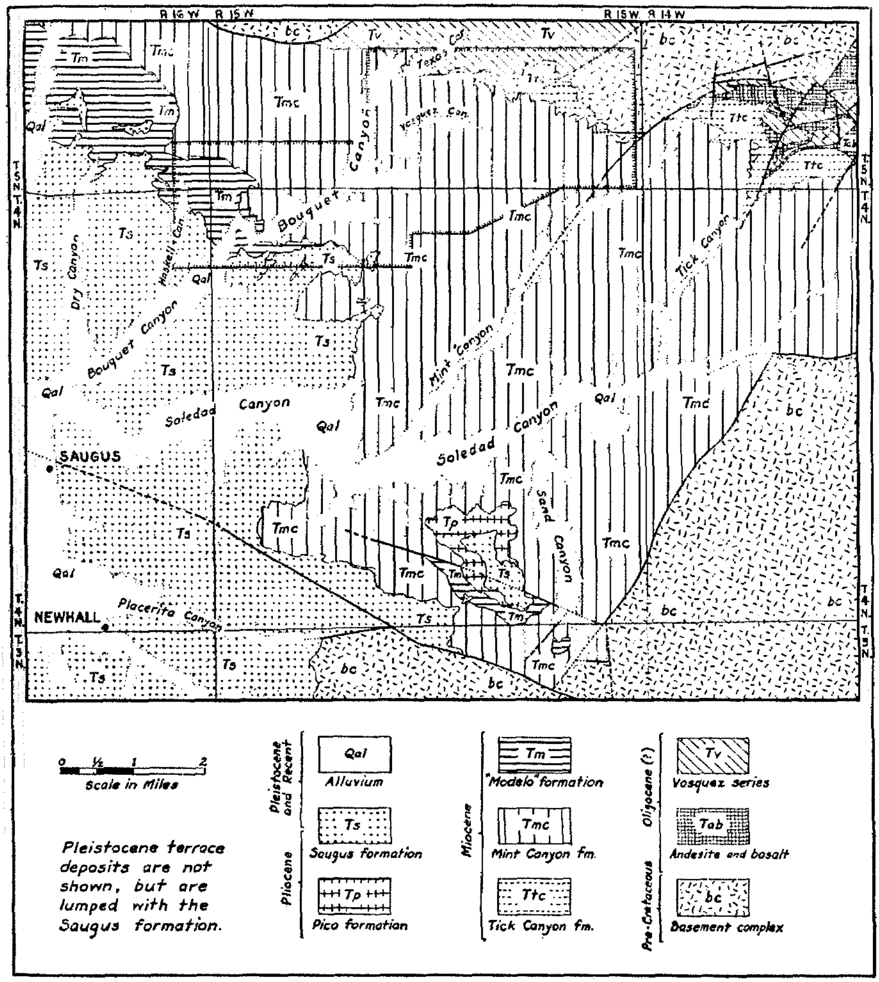


FIG. 3. Geologic map of a part of the Mint Canyon area, easternmost Ventura Basin; after Kew, with modifications by C. T. Smith and R. H. Jahns. The area with irregular outline in the northern part of the map and traversed by Bouquet Canyon is that shown in the large geologic map (fig. 4).

STRATIGRAPHY

General Statement

The easternmost Ventura Basin consists of a pre-Cretaceous crystalline basement complex, over part of which lies a thick section of predominantly nonmarine Tertiary sedimentary rocks. The basinlike distribution of these rocks north of the Santa Clara River makes for a general decrease in age of exposed units from the north and east to the south and west. A steadily progressive decrease in degree of consolidation of the sediments is also evident as one passes upward through the Tertiary section. Although large-scale faulting is very common in the region, a sufficient number of depositional contacts are available to prove an unconformity between each formation and the succeeding one in the accompanying chart.

Age	Unit
Pleistocene and Recent	Alluvial sands and gravels Terrace gravels
Pliocene	Saugus formation
Miocene	"Modelo" formation
	Mint Canyon formation
	Tick Canyon formation
Oligocene ?	Vasquez series
Pre-Cretaceous	Crystalline basement complex

The mammalian species collected in the lowermost Mint Canyon beds demonstrate the presence of a distinctly older horizon than has been hitherto ascribed to the series. There is necessarily implied not only a greater age range, but the presence of at least two formations within that part of the section heretofore mapped as Mint Canyon. This is corroborated by stratigraphic evidence obtained during the course of the detailed mapping. It has been suggested,[7] therefore, that the older, lowermost beds be termed the Tick Canyon formation,[8] and that for the remaining land-laid beds, which constitute the bulk of the section, the name Mint Canyon formation be retained. For the section as a whole, Mint Canyon series appears to be a suitable term, and should apply to all areas previously mapped as Mint Canyon formation but in which there is reason to suspect the presence of strata of Tick Canyon age.

[7] R. H. Jahns, Amer. Jour. Sci., 5th ser., vol. 37, p. 819, 1939.

[8] The name Tick Canyon is assigned because of excellent exposures about ½ mile down the canyon from an abandoned borax mine at the head of Tick Canyon, as well as in the vicinity of the Tick Canyon–Mint Canyon divide (Lang Quadrangle, U. S. Geol. Surv.). The type section, however, is located between Mint and Vasquez Canyons in the Humphreys Quadrangle (see figs. 3, 4).

Crystalline Basement Complex

The extreme complexity of the so-called basement complex is typical of most ancient terranes in which metamorphic rocks have become intimately associated with later igneous intrusives. One large exposure of these rocks, a westward prong of the Sierra Pelona (see fig. 1), appears in the Mint-Bouquet Canyon area. The dominant type is the fine-grained, bluish-gray rock known as the Pelona schist; with it are associated minor amounts of quartzite, hornblende-rich schist, and phyllite. Into the metamorphics has been injected much granitic material, giving rise to many masses of migmatitic rocks. Chief among these are "spotted diorites" and porphyroblastic gneisses. A few small bodies of syenite and granodiorite are also present. Little can be said concerning the age of these rocks except that they are considered as pre-Cretaceous, a view based on their injection by supposedly Sierran plutonics.

Vasquez Series

Cropping out in a large area between Bouquet and Vasquez Canyons are the coarse, light-colored sandstones and conglomerates doubtfully referred by Kew [9] to the Sespe, but called the Escondido series by Hershey [10] and Simpson.[11] More recently, Sharp [12] has suggested the name Vasquez in place of Escondido, which is preoccupied; his usage is followed in this discussion. These coarse, massive sediments are faulted against the basement complex in Vasquez Canyon, but lie with depositional contact upon the crystallines in the type area to the east (Ravenna Quadrangle, U. S. Geol. Surv.). South and east of Mint Canyon these deposits increase in coarseness and degree of consolidation, and appearing with them are interbedded flows and sills of andesite and basalt. A distinct reddish color becomes characteristic.

Available data indicate a localized fault-block basin of deposition for the 9000 feet of Vasquez beds, with transportation of material subaerially for short distances from rather steep source slopes. The general trend of deposition was westward, with a gradual decrease in detrital coarseness in that direction. Intermittent periods of volcanic activity produced an additional 4000 feet of basic flows and shallow concordant intrusions. The exact age of the series is shrouded in doubt. Because all attempts to find fossils in the more promising strata have proved unsuccessful, the various postulated ages of Eocene, Oligocene, and middle Miocene have been based on nonpaleontological evidence. A doubtful Oligocene assignment is here made; a detailed discussion follows in the section dealing with the age of the Mint Canyon.

[9] W. S. W. Kew, U. S. Geol. Surv. Bull. 753, pp. 38–39, 1924.
[10] O. H. Hershey, Amer. Geologist, vol. 29, pp. 349–372, 1902.
[11] E. C. Simpson, Calif. Jour. Mines and Geol., vol. 30, pp. 391–395, 1934.
[12] R. P. Sharp, Pan Amer. Geologist, vol. 63, p. 314, 1935.

Tick Canyon Formation

The basal beds of Hershey's Mellenia series [13] and Kew's Mint Canyon formation [14] are traceable in a narrow, irregular band extending from the Tick Canyon area northwesterly to a point between Vasquez and Texas Canyons, where lack of exposures prevents their demarcation from the overlying Mint Canyon strata. At the type section near locality 201 (locality *Bt* on geologic map, fig. 4) the formation consists of 593 feet of reddish-brown clay, siltstone, and sandstone, with a thick, irregular zone of poorly lithified boulder to cobble conglomerate at the base (see measured section on page 163). Nearly everywhere else, it is much thinner, with an average thickness of approximately 350 feet; in at least one locality, it appears to wedge out entirely between the Mint Canyon and the basement complex. The fine-grained, evenly laminated character of certain beds, as well as the local worm borings which the sediments contain, suggests a lacustrine origin; the bulk of the section, however, is fluviatile.

For a distance of more than a mile between Mint and Vasquez Canyons, the very coarse basal beds of the Tick Canyon formation lap against the basement complex on a steeply dipping depositional contact. The attitude and coarseness of these beds, as well as the angularity and lack of sorting of their contained fragments, indicate deposition at the base of a very steep slope, with transportation of sediment for only a limited distance. Similar relations exist between the Tick Canyon and the Vasquez series, although the contact is not so clearly exposed. That at least a part of the Vasquez formed highlands during Tick Canyon time is shown by the presence in the latter of fragments of a peculiar volcanic breccia characteristic only of the upper Vasquez.

Mint Canyon Formation

Inasmuch as the Mint Canyon beds have an aggregate thickness of about 4000 feet, and have generally less steep attitudes than either of the above-noted formations, it is scarcely surprising that the exposures of this formation have a considerable areal extent (see fig. 3). Its general lithologic characters have been discussed by Kew [15] and Maxson,[16] who indicated a division of the section into two main parts. For purposes of structural interpretation and stratigraphic location, the writer has made a 27-fold subdivision of the Mint Canyon formation. Each member represents a time, rather than lithologic, unit, and its distribution has been traced, so far as possible, by marker beds or exposures sufficiently clear for recognition as time boundaries within areas of changing lithology. The following measured section illustrates the typical distribution of rock types throughout the 27 members; their areal pattern appears on the geologic map (fig. 4).

[13] O. H. Hershey, *op. cit.*, pp. 356–358, 1902.
[14] W. S. W. Kew, *op. cit.*, p. 52, 1924.
[15] *Ibid.*, pp. 52–53, 1924.
[16] J. H. Maxson, Carnegie Inst. Wash. Pub. No. 404, paper VII, p. 81, 1930.

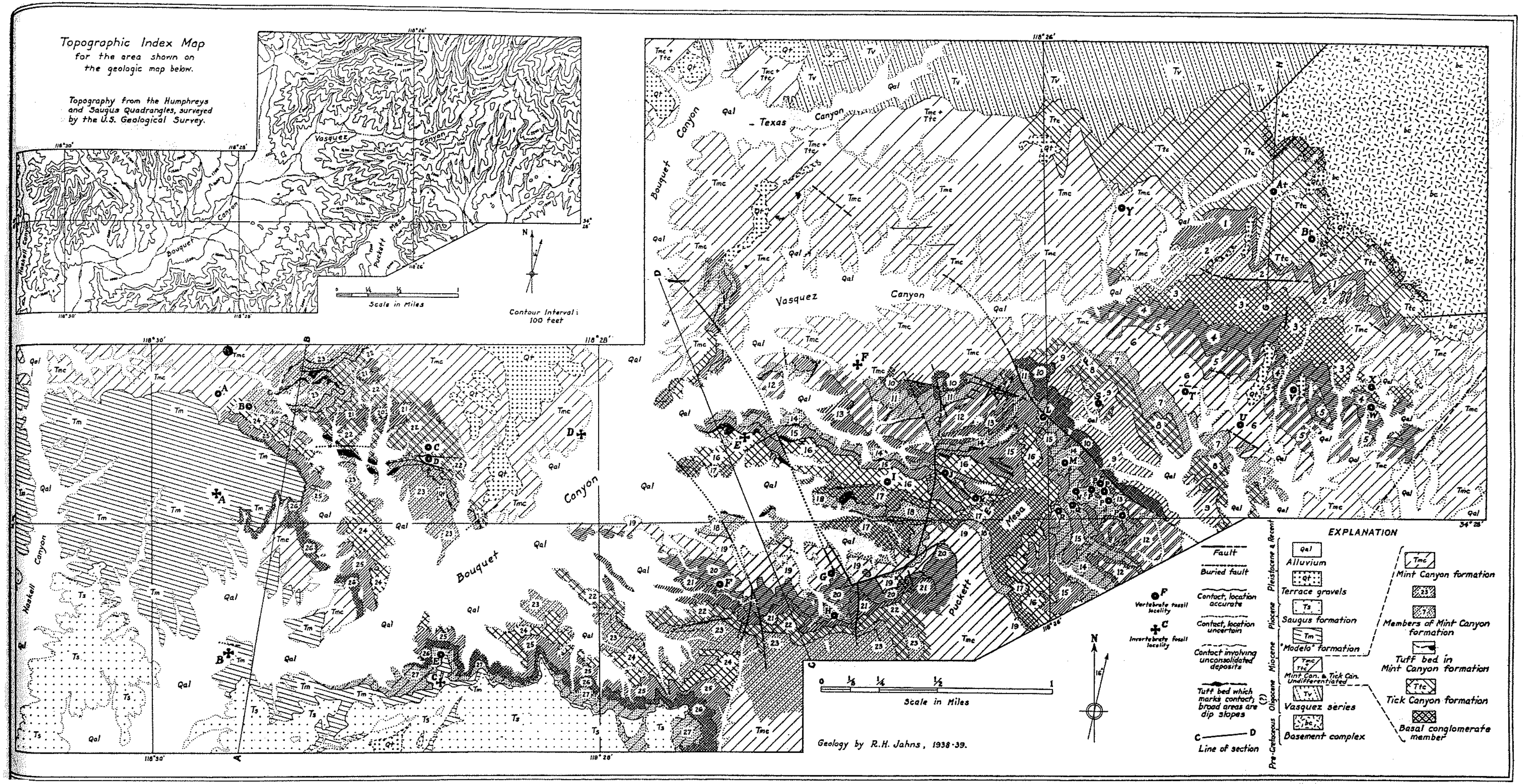


Fig. 4. Detailed geologic map of a part of the Mint Canyon area

MEASURED SECTION OF TERTIARY FORMATIONS FROM BOUQUET CANYON NEAR THE NEW ERA SCHOOL TO UPPER VASQUEZ CANYON, VIA PUCKETT MESA, CALIFORNIA

(Section is composite, with all matched parts from areas no more than ¼ mile apart in the field.)

	Thickness (feet)	
SAUGUS FORMATION		
Sandstone and silt, rusty brown and pinkish, poorly consolidated, irregularly bedded, with local lenses of very coarse gravel	30+	
Conglomerate, light gray, sandy, cross-bedded, poorly cemented	4	
Sandstone, as above, with brownish schist-rich zones and beds of pink and red clay; poorly exposed	120	
Total thickness, Saugus formation		154+
Unconformity		
"MODELO" FORMATION		
Shale, sandy, buff to brown, thin-bedded, with reddish-brown concretionary structures	14	
Sandstone, buff and tan, arkosic, very friable, locally gypsiferous, with small reddish-brown clastic dikelets	45	
Shale, gray to brown, sandy, with minor sandstone beds	11	
Pebble conglomerate, gray to tan, well bedded, gypsiferous	13	
Sandstone, as above, with intercalated shale and conglomerate lenses	22	
Sandstone, light gray, massive, very friable	17	
Shale, greenish gray to reddish brown, sandy, gypsiferous, locally rich in concretions, clastic dikelets, and charcoal; breaks into small blocks	56	
Sandstone, gray to brown, arkosic, friable, poorly exposed	159	
Sandstone, light gray, massive, with minor shale	134	
Cobble conglomerate, light brown, evenly bedded, very gypsiferous, with fragments of quartz, granitic and schistose rock types, silicic and intermediate volcanics, and Mint Canyon sandstone in an arkosic matrix; forms cliffs and is a good marker horizon	16	
Total thickness, "Modelo" formation		487
Unconformity		
MINT CANYON FORMATION		
Member 27		
Sandstone, buff to gray, well sorted but with local pebble lenses, and siltstone, greenish gray, blocky, alternating in thin layers; the whole weathers to sandy or gravelly slopes	115+	
Conglomeratic sandstone, creamy to light gray, cross-bedded, massive, broadly lenticular, with minor intercalated blocky pinkish siltstone; locally cliff-making	32	

		Thickness (feet)
MINT CANYON FORMATION—*Continued*		
Conglomerate, heavy and massive, rich in pebbles and cobbles of andesite and andesite breccias; forms distinct cliff	7	
Total thickness, member 27		154+
Member 26		
Conglomeratic sandstone, light gray, and siltstone, greenish gray to buff, blocky, not massive, alternating in thick layers with the latter subordinate; locally resistant	28	
Siltstone and clay, dominantly buff, pinkish, and greenish, sandy, well bedded; scattered vertebrate fossils	38	
Pebble conglomerate, continuous, moderately well sorted, rich in subrounded andesite and schist fragments	5	
Total thickness, member 26		71
Member 25		
Sandstone, silty and locally pebbly, creamy gray, with intercalated thin, hard, persistent, flaggy brown arkosic sandstone; forms smooth-faced cliffs	71	
Vitric tuff, friable, pearly gray with bluish cast, medium-grained, granular but not gritty; associated with tuffaceous sandy beds; exposed only locally	4	
Total thickness, member 25		75
Member 24		
Conglomerate, very sandy, creamy gray, blocky, with sandy lenses; forms cliffs	5	
Siltstone and clay, brown, tan, and pinkish, with flaggy interbeds of hard brown sandstone; scattered vertebrate remains (C.I.T. Loc. 101)	17	
Cobble conglomerate, brown to gray, well bedded, rich in fragments of basement complex; forms vertical, smooth-surfaced cliffs	23	
Siltstone and clay, as above	34	
Cobble conglomerate, white to gray, otherwise as above	13	
Total thickness, member 24		92
Member 23		
Siltstone, locally sandy and pebbly, tan, gray, pink, and brown, with subordinate conglomerate, coarse-grained, creamy gray to white, rich in andesite and granite fragments; the whole poorly exposed	240±	
Vitric tuff, granular, fine- to medium-grained, bluish gray, in part friable; highly lenticular and poorly exposed	3	
Sandstone, hard, brown, irregularly jointed, arkosic, and with local mafic-rich lenses	2	

		Thickness (feet)
Conglomerate, poorly cemented, coarse-grained, rich in andesite, volcanic breccia, and schist fragments, with sandstone and sandy siltstone, white to buff, weathering into soily slopes; upper part poorly exposed	82	
Vitric tuff, as above	4	
Sandstone, hard, brown, as above	2	
Total thickness, member 23		333±
Member 22		
Boulder conglomerate, gray, massive, poorly sorted, resistant	14	
Sandstone, gray, coarse, and conglomeratic, regularly bedded, with local lenses of light gray cobble conglomerate; cliff-making horizon	35	
Siltstone, tan to gray, sandy, blocky; blocks exfoliate, then crumble to soily masses; irregularly fossiliferous (C.I.T. Loc. 99)	42	
Cobble and pebble conglomerate, cross-bedded, light gray to white, with associated channel sandstones, gray, friable, lenticular	28	
Total thickness, member 22		119
Member 21		
Siltstone, pinkish, tan, and greenish gray, with sandy lenses rich in clay nodules; scattered beds of conglomeratic sandstone, well sorted, vertically jointed, resistant	33	
Sandstone, arkosic, coarse, well sorted, with subordinate siltstone, tan and greenish; forms cliff	24	
Sandstone, creamy gray, massive, resistant, with silty partings	11	
Total thickness, member 21		68
Member 20		
Siltstone, buff, bluish gray, and pinkish, sandy, evenly bedded, and sandstone, conglomeratic, massive, cliff-making, alternating in thick layers; forms local badlands with scattered vertebrate fossils	91	
Vitric tuff, bluish gray, friable to blocky, lenticular, poorly exposed	3	
Sandstone, brown, hard, ripple-marked, flaggy	3	
Total thickness, member 20		97
Member 19		
Siltstone, light gray to tan, evenly bedded, with thin sandy and pebbly layers; forms smooth-faced vertical cliffs	58	
Sandstone, pebbly, light gray, cross-bedded, well sorted, massive	8	

		Thickness (feet)
MINT CANYON FORMATION—*Continued*		
Siltstone, light gray to pinkish brown, regularly bedded, with few resistant layers; forms badlands, sparsely fossiliferous (C.I.T. Loc. 102)	51	
Total thickness, member 19		117
Member 18		
Conglomerate, heavy, massive, coarse, locally sandy	12	
Sandstone, poorly consolidated, with siltstone, light gray, thinly bedded; much less resistant than conglomerate above	34	
Total thickness, member 18		46
Member 17		
Crystal tuff, medium-grained, white to buff, delicately bedded, with associated tuffaceous sandstone; whole weathers into angular blocks	3	
Sandstone, arkosic, hard, coarse, brown, flaggy	2	
Conglomerate, light gray, heavy, resistant, with rounded pebbles and cobbles of andesite, schist, and granitic rocks; minor interbeds of sandy siltstone	38	
Crystal tuff, as above; lenticular and poorly exposed	2	
Sandstone, gray and tan, well sorted, evenly bedded, and siltstone, brown to gray, blocky, weathering into gritty soil; alternate in 1- to 6-foot layers and form steep, corrugated cliffs	55	
Conglomerate, as above	15	
Siltstone, very gritty, light gray, locally rich in clay nodules	14	
Total thickness, member 17		129
Member 16		
Pebble conglomerate, white to gray, evenly but massively bedded; weathers to gravelly slopes but forms local cliffs	23	
Siltstone, sandy to pebbly, gray; forms fluted cliffs and badlands with scanty vertebrate remains (C.I.T. Loc. 100)	58	
Conglomerate, bouldery, poorly cemented, associated with channel sandstones	12	
Total thickness, member 16		93
Member 15		
Crystal tuff, snow white to buff, ripple-marked, delicately bedded, weathering into angular blocks; local tuffaceous sandstone, bearing plant fossils	4	
Sandstone, brown, hard, flaggy	3	
Sandstone, light gray, friable, rich in clay nodules, and local brown, flaggy arkose; subordinate siltstone, pearl gray, weathering blocky	89	

		Thickness (feet)
Boulder conglomerate, crudely bedded, cross-bedded, poorly sorted; shows cut-and-fill channel structure	6	
Total thickness, member 15		102
Member 14		
Crystal tuff, as in member 15	3	
Sandstone, brown, hard, flaggy	2	
Siltstone, very sandy, greenish to tan, and pebbly sandstone, alternating in thick layers; local vertebrate fossil accumulations (C.I.T. Loc. 103, Los Angeles Museum Loc. 1006)	15	
Sandstone, massive, friable, vertically jointed	3	
Siltstone, as above	19	
Conglomerate, typical stream-channel type	7	
Siltstone, fine-grained, yellowish to greenish gray, locally rich in vertebrate fossils (Univ. of Calif. Loc. 3564)	58	
Sandstone, bluish gray, friable, persistent	1	
Total thickness, member 14		108
Member 13		
Sandstone and siltstone, light gray, alternating regularly in 1- to 4-foot layers; form cliffs of corrugated appearance	27	
Cobble conglomerate, cross-bedded, poorly sorted, with channel-filling structures	4	
Sandstone, silty, buff to gray, friable, poorly exposed	17	
Sandstone, tan, massive, vertically jointed	5	
Total thickness, member 13		53
Member 12		
Siltstone, tan, buff, and gray, locally very sandy, with scattered interbeds of hard, flaggy brown sandstone; very poorly exposed, weathering to sandy slopes	113	
Crystal tuff, with much tuffaceous sandstone, white to light gray, hard to crumbly	2	
Total thickness, member 12		115
Member 11		
Siltstone and clay, light green, tan, pinkish, buff, and purplish, evenly and thinly bedded, highly gypsiferous, with a few flaggy interbeds of hard, brown arkosic sandstone	88	
Sandstone, buff to light gray, well sorted, very resistant	5	
Total thickness, member 11		93
Member 10		
Clay, highly colored in greens, buffs, and pinks, gypsiferous, with flaggy beds of hard brown sandstones	27	

		Thickness (feet)
MINT CANYON FORMATION—*Continued*		
Siltstone and clay, dominantly gray and brownish, with interbeds of papery brown sandstone	68	
Clay, as above	24	
Sandstone, brown, friable, tending to massive	4	
Crystal tuff, white to gray, lenticular, with much tuffaceous sandstone	1	
Total thickness, member 10		124
Member 9		
Clay, dark gray to black, crumbly	3	
Siltstone, gray to buff	11	
Siltstone, brown to maroon, with flaggy interbeds of hard brown sandstone	15	
Sandstone, light gray, blocky, impure	4	
Siltstone, maroon, gypsiferous, clayey	30	
Sandstone, as above	30+	
Sandstone, white to tan, and clayey siltstone, buff to maroon, alternating in thin beds; lower part poorly exposed, sparsely fossiliferous (Univ. of Calif. Loc. 3571)	142+	
Total thickness, member 9		235+
Member 8		
Siltstone, gray, clayey	15	
Siltstone, pearl gray, brown, and greenish, gritty	14	
Sandstone, tan, blocky, with conglomerate zone at base	5	
Conglomerate, light gray, well bedded, with silty matrix	17	
Sandstone, gray, coarse, arkosic, with minor pebble conglomerate, rich in fragments of granitic crystallines, andesites, and volcanic breccias; whole weathers to sandy and gravel-strewn slopes	87	
Total thickness, member 8		138
Member 7		
Siltstone, light tan to pinkish, thinly bedded, weathering into soily slopes	43	
Sandstone, arkosic, brown, blocky to flaggy	3	
Siltstone and sandstone, tan and gray, fine to coarse, the whole very heterogeneous	46	
Sandstone, as above	3	
Siltstone, sandy, white to pinkish, seriate but generally fine-grained	41	
Conglomerate, white, poorly cemented, well stratified, with cobbles of the usual igneous rocks	5	
Siltstone, sandy, as above	46	
Siltstone, sandy to clayey, dominantly pinkish, fine-bedded; forms local badlands	10	
Total thickness, member 7		197

		Thickness (feet)
Member 6		
Siltstone, pinkish, and sandstone, whitish, interbedded intimately; rich in clay nodules and vivianite smears; the whole nonresistant and poorly exposed, with local badlands carrying scattered vertebrate remains (Univ. of Calif. Loc. 3555)	138	
Sandstone, tan to gray, friable, arkosic; weathers to soily slopes	104	
Conglomerate, chalky red, massive with sandy lenses, locally cross-bedded; prominent marker bed but not persistent	9	
Sandstone, as above	49	
Conglomerate, white, poorly cemented, with rounded cobbles of granitic rocks	4	
Siltstone and clay, pearl gray, smoky gray, tan, pink, purple, and brown, heavily gypsiferous, fine-grained, thin-bedded, rich in white clay nodules; locally forms badlands	152	
Total thickness, member 6		456
Member 5		
Sandstone, light gray to tan, very impure, poorly cemented, with many resistant flaggy beds, arkosic, brown, very evenly spaced in section	145	
Clay, greenish, tan, purple, pinkish, buff, and brown, gypsiferous, and conglomerate, light brown, alternating fairly regularly; whole becomes very red locally	26	
Total thickness, member 5		171
Member 4		
Sandstone, white, coarse, friable	4	
Clay and siltstone, greenish, pinkish, tan, brown, and dark gray, gypsiferous; forms slumped slopes and isolated badlands	56	
Siltstone, pinkish to brownish, blocky, with thin, resistant, flaggy sandstone lenses; bears scanty vertebrate fossil remains	83	
Sandstone, brownish, impure, friable, poorly exposed	75	
Cobble conglomerate, brown, well cemented, well stratified, cross-bedded; forms cliffs	8	
Total thickness, member 4		226
Member 3		
Sandstone, reddish brown, massive, impure, and pebble conglomerate, thinly bedded, well cemented, alternating in thick layers	52	
Siltstone, gray to tan, blocky, with flaggy sandstone, thin, brown, arkosic	51	
Sandstone, as above	145	

	Thickness (feet)		
MINT CANYON FORMATION—*Continued*			
Pebble conglomerate, chalky reddish brown, massive, well cemented, locally sandy, rich in schist fragments; forms cliff	15		
Sandstone, reddish brown to ocherous, arkosic, with minor pebble conglomerate and siltstone	112		
Pebble conglomerate, chalky reddish brown, well sorted, evenly stratified, locally cross-bedded, moderately well cemented, with local lentils of arkosic sand; forms ridges and cliffs	27		
Total thickness, member 3		402	
Member 2			
Siltstone, brown and reddish brown, sandy, poorly exposed	34		
Conglomerate, light gray, poorly cemented, well bedded	11		
Sandstone, reddish brown, conglomeratic, arkosic, friable, poorly exposed	87		
Conglomerate, gray to brownish, thinly but irregularly bedded, persistent, resistant, rich in schist fragments	4		
Total thickness, member 2		136	
Member 1			
Conglomerate, chalky brown, heavily bedded, rich in flaggy schist fragments, and conglomeratic sandstone, friable, arkosic, alternating in 6- to 10-foot layers; whole forms local cliffs	94		
Total thickness, member 1		94	
Total thickness, Mint Canyon formation			4044±

Unconformity

TICK CANYON FORMATION	
Sandstone, uniformly reddish brown, friable, with minor silty and soily beds; poorly exposed, but forms badlands locally	158
Conglomerate, tan to reddish brown, cross-bedded, poorly cemented	6
Sandstone, as above; siltstone, ocherous to reddish brown, thinly laminated, gypsiferous; and scattered thin beds of sandy shale, compact, reddish to greenish brown, with casts of worm borings	110
Conglomerate, light gray, poorly consolidated, pebbles and cobbles subrounded, white arkosic cement	12
Sandstone, as above, but with more pebbly and flaggy beds	68
Siltstone, reddish brown, compact, evenly and thinly bedded, with minor flaggy sandstone and greenish clay; locally fossiliferous (C.I.T. Loc. 201)	55
Clay and siltstone, red, tan, olive green, yellow, and brown, fine-grained, highly gypsiferous, poorly exposed	75
Sandstone and arkose, reddish brown, crumbly, poorly sorted	15

	Thickness (feet)	
Cobble to boulder conglomerate, tan to gray, poorly bedded, sorted, and lithified, with large fragments of underlying basement rocks	94	
Total thickness, Tick Canyon formation		593

Unconformity

BASEMENT COMPLEX

Mica schist, syenite, granodiorite, quartzite, and miscellaneous migmatitic rock types

TOTAL THICKNESS OF SEDIMENTARY SECTION		5278±

It will be noted that the beds in the lower half of the section (members 1 to 11) are characteristically fine-grained, thin-bedded, and of variegated colors, whereas those higher up are more irregular, coarser, and subdued in color. Vertebrate remains seem to occur in horizons having a rather even vertical distribution, although the upper horizons yield a greater abundance of material. Another gradation of unusual interest is that between the coarse fluviatile sandstones and conglomerates adjacent to Puckett Mesa on the southeast and their fine-grained, evenly bedded lacustrine counterparts to the northwest. This is particularly well shown at the base of member 15, where within a distance of a half-mile a heavy channel conglomerate passes laterally without break through a littoral sandstone zone into thinly bedded lacustrine silts and clays. That such a relation actually exists is demonstrated by a prominent light-colored marker bed of water-laid tuff, which lenses out immediately beneath the conglomerate. The relative distribution of fluviatile and lacustrine strata in the vicinity of Bouquet Canyon is shown in figure 5; section *CD* in figure 6 illustrates the gradational phenomenon mentioned above.

Greenish to gray silty beds in the lacustrine section contain numerous fresh-water gastropod remains, chief among which is the species *Paludestrina imitator* Pilsbry.[17] Localities where these mollusks are conspicuous are recorded in figures 4 and 5. The occasional vertebrate fragments found with them are confined to the margins of the large lacustrine basin (see fig. 5). Detailed mapping of the silty deposits, especially their tracing across the broadly alluviated Bouquet Canyon, was made possible by the presence in the section of several marker beds of white to gray tuff and tuffaceous sandstone. These beds, because they are confined in their extent to the regions of soft lake deposits, stand out clearly and form the ridges in the present topography.

The Mint Canyon formation overlies the older Tick Canyon in all places where the latter is exposed. In the vicinity of locality 201 an angular unconformity is suggested between the two; two small folds and associated

[17] W. S. W. Kew, U. S. Geol. Surv. Bull. 753, p. 54, 1924.

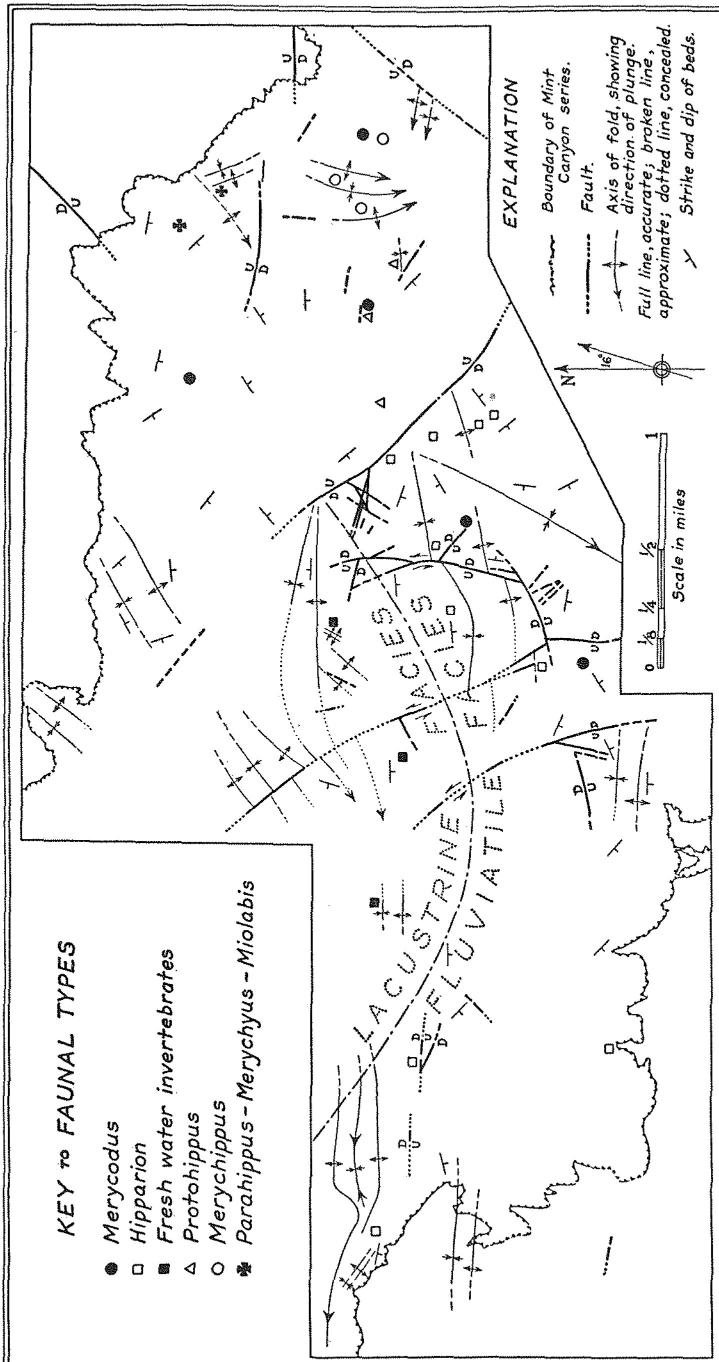


Fig. 5. Outline of that portion of the Mint Canyon region mapped in detail (see fig. 4), showing structural axes and distribution of faunal types.

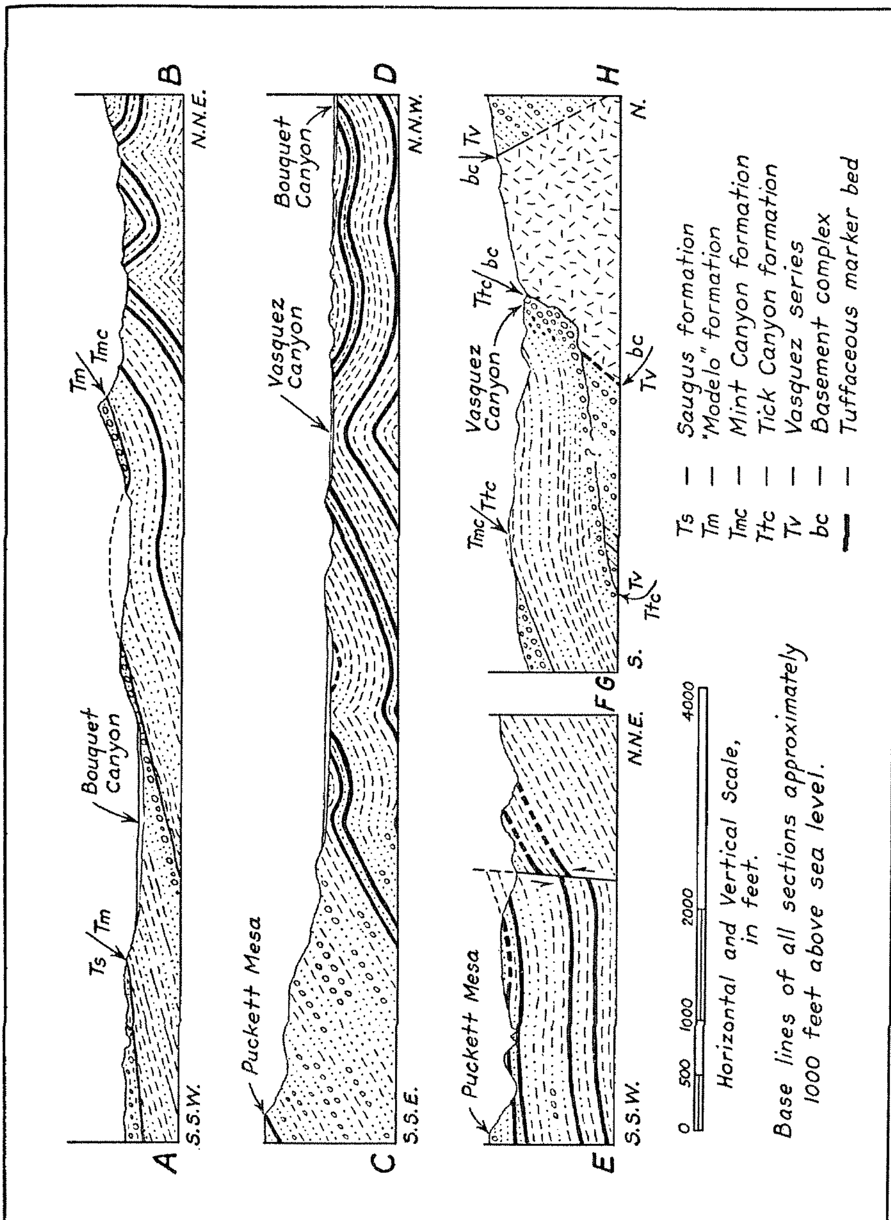


FIG. 6. Structure sections across parts of the Mint Canyon area (see fig. 4 for exact locations).

minor plications in the fine-grained older beds do not appear in the superjacent conglomeratic strata of the Mint Canyon formation. This feature, however, might be merely the result of differences in competence of the two rock types. That a sedimentary break indicated by the faunal differences does appear, probably as a disconformity, is shown by the location of the contact at the base of a thick conglomerate zone, a location fixed with certainty by fossil occurrences. Its unconformable nature is further shown by a general change in lithology (see measured section or section *GH*, figure 6) and by the irregular distribution of the Tick Canyon beds. Where these strata are not exposed, the Mint Canyon nonconformably overlies the Vasquez series, or is faulted against older rocks.

"Modelo" Formation

Above the Mint Canyon lie the fossiliferous brownish sandstones and shales tentatively correlated with the Modelo by Kew.[18] Although they are equivalent to the upper part of the Modelo group, these beds are herein termed "Modelo" because they do not correspond in age to the Modelo, *stricto sensu*, of Hudson and Craig.[19] They were deposited under brackish-water and marine conditions, and are the only marine beds in the easternmost Ventura Basin north of the Santa Clara Valley. The "Modelo" is exposed over a broad area in the higher hills between Haskell and Bouquet Canyons, but pinches out between Mint Canyon strata and the overlying Saugus formation on the south side of the latter canyon.

Although Kew recorded a pronounced nonconformity between the marine and the underlying nonmarine strata, it has since been suggested [20] that the relation is one of interfingering or lateral and upward intergrading, due presumably to marine transgressive overlap. The resulting confusion has thrown serious doubt on the exact stratigraphic relations between the "Modelo" invertebrates and the Mint Canyon vertebrate horizons. That the features of the Bouquet-Haskell Canyon contact area are in no way attributable to interfingering or gradation of the type suggested, but are on the other hand characteristic of a true unconformity is denoted by the following cogent facts:

1. The base of the "Modelo" is marked by a persistent, evenly bedded cobble conglomerate member which contains fragments of Mint Canyon material. Throughout the area this conglomerate remains of surprisingly uniform thickness and is quite distinct from the underlying siltstones of the Mint Canyon formation. Its bedding is everywhere parallel with its trend.

2. Although the post-"Modelo" age of much of the folding in the Mint Canyon has resulted in essentially concordant relations between the two

[18] W. S. W. Kew, U. S. Geol. Surv. Bull. 753, pp. 67–69, 1924.

[19] F. J. Hudson and E. K. Craig, Bull. Amer. Assoc. Petrol. Geol., vol. 13, pp. 509–518, 1929.

[20] T. Clements, Bull. Amer. Assoc. Petrol. Geol., vol. 21, p. 215, 1937. R. A. Stirton, Jour. Paleontol., vol. 13, chart on p. 135, 1939.

formations, there are local discrepancies of attitude. Non-conformability is especially well shown on the west side of Haskell Canyon.

3. The detailed mapping has revealed a north-northeastward convergence between the two formations amounting to about 200 feet in a half-mile. In the absence of interfingering in the area, this feature is suggestive of a post-Mint Canyon pre-"Modelo" southwestward tilting and a subsequent erosion interval.

4. As pointed out by Clements,[21] the Mint Canyon formation does thin to the northwest. This thinning, however, is accomplished by the loss of *basal* members, probably because of an approach to a landward margin of the Mint Canyon basin of deposition. It appears likely that any marine interfingering in which the Mint Canyon has a part is to be found toward the *west* and *southwest*, not toward the northwest.

On the basis of invertebrates determined by Clark [22] and Woodring [23] as *Amphyssa* sp., *Ostrea titan*, *Pecten crassicardo*, *Pecten raymondi*, and *Astrodapsis* cf. *tumidus*, an upper Miocene age was assigned to the "Modelo." An invertebrate collection subsequently made by Maxson and identified by U. S. Grant IV [24] substantiates this age determination and justifies a more specific correlation with the uppermost Miocene Neroly. In addition to the forms given above, those determined by Grant include:

Terebratalia occidentalis
Terebratalia occidentalis obsoleta
Anadara osmonti
Anadara obispoana
Aequipecten discus
Lyropecten crassicardo
Lyropecten cf. estrellanus
Astrea aff. ? brangulata
Polinices sp.
Tegula sp.

Rather meager foraminiferal evidence reported by Hughes [25] further strengthens a Neroly age assignment. Thus, the Mint Canyon vertebrate horizons are older than the uppermost Miocene of the Pacific coast marine sequence.

Saugus Formation

The Saugus formation rests unconformably on the "Modelo" and Mint Canyon strata, and represents extensive deposition on a broad, westward-dipping floodplain or alluvial-fan series. Its beds are light gray to reddish

[21] T. Clements, *loc. cit.*, 1937.

[22] W. S. W. Kew, *op. cit.*, pp. 68–69, 1924.

[23] W. P. Woodring, "Age of the Modelo formation of the Santa Monica Mountains, California" (abstract), 28th Ann. Meeting, Cordilleran Section, Geol. Soc. Amer., Stanford University, California, 1929.

[24] J. H. Maxson, from paper entitled "Miocene-Pliocene boundary," 15th Ann. Meeting, Pacific Section, Amer. Assoc. Petrol. Geol., Los Angeles, California, November 3, 1938.

[25] R. M. Kleinpell, Miocene stratigraphy of California, p. 71. Amer. Assoc. Petrol. Geol., 1938.

brown, crudely stratified, and poorly consolidated. Mainly unsorted sands and conglomerates, they reflect the nature of the terranes from which they were derived. Fragments of the basement complex are most common, but silicic and intermediate volcanics are far from rare. Occasionally a mass of "Modelo" or Mint Canyon sandstone appears. Although these continental beds are generally nonfossiliferous, their marine analogues to the west yield invertebrates of late Pliocene and early Pleistocene affinities.

Quaternary Deposits

Terrace deposits of Pleistocene age are not uncommon, especially on the north side of Bouquet Canyon and in an ill-defined zone peripheral to the exposed basement complex between Vasquez and Mint Canyons. These rather flat-lying deposits consist of angular, unsorted gravelly material, commonly rich in fragments of schist, granitic rocks, and other types characteristic of the basement complex. Derivation from the latter under flood-plain conditions seems certain in this part of the basin. Although their typical form is locally obscured by later stream dissection, the terrace deposits are easily recognized by their predominant reddish-brown color, rather flat-lying attitude, and limited thickness. Although individual terraces (as they now occur) may have been formed at slightly different times, they all are Pleistocene in age.

More recently deposited alluvium forms broad flats in all the larger canyons and extends up the smaller ones as narrow tongues. It is generally made up of flat-lying sands and gravels of light gray color and varying degrees of coarseness, and is dissected to a limited extent by the present streams.

GEOLOGIC STRUCTURE

Evidences of crustal movements in the Mint Canyon area are widespread and well defined. No attempt has been made to interpret the intricate structural features found in the basement complex, but of post-Cretaceous orogeny a fairly clear picture can be obtained. In addition to the post-"Modelo" and post-Saugus periods of deformation characteristic of southern California, there is evidence of extensive faulting in the early Tertiary (late Eocene?), folding and faulting in post-Vasquez, pre-Mint Canyon time, and folding following deposition of the Mint Canyon formation. The early Tertiary structures seem to reflect tensional forces, and those of later age compression and shear; exceptions, however, are not uncommon.

In spite of the intense compressional forces indicated by certain of the faults, nearly all the folds are broad and open. The very competent Vasquez strata are little folded except in upper Tick Canyon, where the finer, softer beds which appear in the uppermost part of the section attain dips of 80° or more. Those of the Mint Canyon series, on the other hand, have been thrown into a great number of subdued flexures of prevailing east-west trend and shallow westward plunge (see fig. 5). North of Bouquet Canyon is an area of more acute folding, the convolutions of two tuffaceous beds serving admirably as structural guides. Maximum dips are about 65°. Immediately to the southwest the "Modelo" is broadly folded with the usual east-west trend. Post-Modelo strata retain their original attitudes in the area mapped, but the Saugus is warped and folded a few miles to the south and west.

Faulting presents a more complex problem. Little is known of the early Tertiary faults, except that they presented sufficient vertical movement before and probably during at least a part of Vasquez deposition to demarcate a local basin deep enough to receive some 9000 feet of coarse sediments. In the region to the east, there is some evidence that these early faults were of the tensional block type, with dips of 65° or more. The close of Vasquez deposition ushered in a period of profound crustal movement, during which the older faults became active once more and new steeper fractures developed. Both normal and reverse movements occurred. The Vasquez-basement fault in Vasquez Canyon was a product of this orogenic period. Following the inception of Mint Canyon deposition, these faults experienced relatively little movement. The third period of faulting may be considered post-Mint Canyon, pre-Saugus, and resulted in fractures of northwest trend, steep dip, and dominantly strike-slip movement. In all cases, their northeast sides have moved north; they appear to have a gash fracture relation to the San Andreas rift, which lies several miles to the north. It is of interest that they cut and offset folds in the Mint Canyon formation wherever the two features occur in juxtaposition. That Pleistocene or even younger movements have occurred is evidenced by local offsets in the terrace deposits; such movements, however, have been of very slight extent.

AGE OF DEPOSITS

Tick Canyon Formation

The mammalian assemblage obtained from the Tick Canyon beds furnishes an independent means of reaching an age assignment. Inasmuch as a detailed discussion of the faunal relations appears elsewhere in this paper, it suffices at this point to note a similarity in stage of evolution between the species from the Tick Canyon and those from the lower Hawthorn formation of Florida and from the upper Harrison and upper Rosebud formations of Nebraska and South Dakota. A comparison with these faunas, as well as with others, presents evidence strongly favoring a late lower Miocene or earliest middle Miocene age. The Tick Canyon formation is thus placed in a position stratigraphically below that of the Merychippus zone at Coalinga and slightly below that of the Phillips Ranch horizon. Its marine time equivalent is probably the lower part of the Temblor as that term is broadly used, and upper-middle Temblor of the type section (see fig. 7).

VASQUEZ SERIES

The presence of a lower Miocene horizon unconformably above the Vasquez series introduces a feature not in accord with certain age assignments made for the latter series in the past. Although Kew [26] proposed an Oligocene (?) age, middle Miocene has been advocated by other investigators, notably W. J. Miller [27] and Simpson.[28] The arguments advanced to support this contention are:

1. The lavas interbedded with the Vasquez strata are typical of those extruded over broad areas in the western United States during the middle Miocene.
2. A strong resemblance exists between the Vasquez and the middle Miocene Topanga formation, not only in the associated volcanics, but in thickness and lithology.
3. The Vasquez seems to be a correlative of the middle Miocene Rosamond formation of the Mojave region.

The relation of the Vasquez to the lower Miocene Tick Canyon formation should constitute compelling enough evidence against a middle Miocene age determination for the former. Moreover, the writer feels that none of the above arguments furnishes evidence sufficiently strong to stand in the face of paleontologic data, indirectly applied though they may be. Granting a preponderance of volcanic activity during the middle Miocene, a possibility of earlier activity is not thereby precluded, particularly since such instances have been recorded.[29] Furthermore, the lavas of the Vasquez are mineralogically different from all others known from Los Angeles County,[30] a feature which is particularly noticeable in a comparison with the Rosamond formation. Finally, any correlation with the Topanga, no matter how tentative, is subject to serious error. The Topanga is marine and the Vasquez continental, so that a correspondence in total thickness or lithology is probably coincidental. The origin of the Vasquez as a fluviatile accumulation in a highly localized basin invalidates most correlations based on lithologic character, thickness, or probable prevailing climatic conditions.

The Vasquez is unconformably underlain by the lower Eocene Martinez formation in the Tejon Quadrangle to the west. The age possibilities are thus restricted to lower Miocene, Oligocene, and upper Eocene, essentially the age range of the Sespe. Although the Vasquez beds may never have been directly connected with the whole or any part of the Sespe, they probably were laid down in a somewhat similar topographic environment during a period corresponding to at least a part of the Sespe. An Oligocene age is tentatively assigned to the series, pending the discovery of fossil remains,

[26] W. S. W. Kew, U. S. Geol. Surv. Bull. 753, pp. 38–39, 1924.
[27] W. J. Miller, Univ. Calif. at Los Angeles Publ., vol. 1, 1934.
[28] E. C. Simpson, Calif. Jour. Mines and Geol., vol. 30, pp. 391–395, 1934.
[29] R. D. Reed, Bull. Amer. Assoc. Petrol. Geol., vol. 21, pp. 549–559, 1937.
[30] Y. Bonillas, personal communication.

although the associated flows suggest a time range extending into the lower Miocene.

Mint Canyon Formation

Because of previous discussions by Maxson,[31] Stirton,[32] and others, the fauna of the Mint Canyon formation need not be examined in detail at this time. Aside from disagreements on the exact nature of certain forms, the principal contentions appear to relate to the presence of *Hipparion,* Maxson favoring the theory of the appearance of the genus in the Miocene and Stirton holding the view that it is confined to the Pliocene. The question of utilization of *Hipparion* as a criterion of Pliocene age for the beds in which it occurs is one of world-wide application, and has brought forth discussion in Europe and Asia as well as in America. This genus has served as a basis for transoceanic correlation because of its wide and rapid dispersal from a probable American source. In this respect, its presence should be accepted as furnishing a more conclusive criterion than that of any late Tertiary invertebrate genus.

Because of the incompleteness of the original European section of the Tertiary as defined by Lyell and Deshayes, the critical Pontian and Sarmatian stages and their faunas were not included in the succession. Disagreement has subsequently arisen among European paleontologists with regard to the exact position of the Miocene-Pliocene boundary, as well as with regard to the relations of the invertebrate and vertebrate fossils employed in determining this boundary.[33] At present there is no unity of opinion as to the exact age of the type *Hipparion*-yielding strata. Nor are the stratigraphic relations of the beds containing *Hipparion* always clear. For Europe, then, the question is still unsettled.

Although at least the upper part of the Mint Canyon formation admittedly yields a fauna of undeniably lower Pliocene affinities (based on standards established by some vertebrate paleontologists), the bulk of the available evidence seems to favor a sensibly older assignment. The concept of a strict *Hipparion*-Pliocene affinity, together with the clear-cut unconformity between the Mint Canyon and overlying uppermost Miocene marine "Modelo," furnishes a striking example of the peculiar situation recognized by Reed and Hollister,[34] in which "the Lower Pliocene of most vertebrate paleontologists is at least in part the equivalent of the Upper Miocene of the invertebrate paleontologists." The confusion resulting from such conflict of views can be eliminated only by a change in age standards of either

[31] J. H. Maxson, Carnegie Inst. Wash. Pub. No. 404, paper VII, 1930.

[32] R. A. Stirton, Amer. Jour. Sci., 5th ser., vol. 26, pp. 569–576, 1933.

[33] G. H. R. von Koenigswald, Zentralbl. f. Mineral., pt. B, pp. 42–48, 1931. E. Stolley, Zentralbl. f. Mineral., pt. B, pp. 191–207, 1938. E. Stromer, Bayer. Akad. d. Wiss., Math.-naturwiss. Abt., vol. 32, pp. 1–20, 1938. H. Tobien, Deut. geol. Gesellsch. Ztschr., vol. 90, pp. 177–192, 1938.

[34] R. D. Reed and J. S. Hollister, Structural evolution of southern California, pp. 1586–1588. Amer. Assoc. Petrol. Geol., 1936.

vertebrate or invertebrate paleontologists, at least in that part of the geologic column near the Miocene-Pliocene boundary.

Because of the present state of disagreement with regard to the European section, disagreement in vertebrate correlations based on the genus *Hipparion*, and the clearly recognizable marine-nonmarine stratigraphic relations in the Mint Canyon area, the age determination of the Mint Canyon formation is here based on the invertebrate time scale of California, and the formation is therefore considered to be upper Miocene. This places the beds in a Tertiary marine succession whose record is essentially complete (as opposed to the fragmentary continental record and to the incomplete European marine record) and whose period boundaries commonly correspond to epeirogenic boundaries in the Pacific coast province. *Hipparion* remains thus occur stratigraphically below a Neroly marine fauna, with an appreciable sedimentary break between the two.

An apparent faunal gradation appears within the Mint Canyon formation, as shown by detailed mapping. *Hipparion* is found in the upper two-thirds of the section, and seems to give way to a merychippine fauna in the lowermost strata (see fig. 5). An intermediate protohippine fauna may exist, but disagreement exists concerning the forms. There is an indication, however, that a considerable time range is represented by the deposition, although even the lowermost beds may be post-Barstow in age.

The marine equivalent of the Mint Canyon formation is not found in the Ventura Basin east of the San Gabriel fault, in which area only Neroly marine strata are exposed. West of the fault, in the type section of the Modelo, the Modelo formation (restricted) of Hudson and Craig[35] is probably in part the equivalent of the Mint Canyon (see fig. 7). The unconformity noted by these investigators between the restricted Modelo and deposits which they call Santa Margarita may correspond to the Mint Canyon–"Modelo" unconformity of the Bouquet Canyon–Haskell Canyon area.

GEOLOGIC HISTORY

The geologic history of the Mint Canyon region has been touched upon in the discussion of various aspects of the present study. A brief review, therefore, should suffice to bring all the structural and lithologic data into a coherent sequence. The following events, in chronological order, are postulated for Tertiary and Quaternary time:

1. Early Tertiary (perhaps late Eocene) faulting, with attendant formation of an elongated topographic basin bordered for the most part by igneous terranes.
2. Oligocene and possibly early Miocene deposition of poorly sorted, coarse fanglomerates, sandstones, and silty beds in the basin, which was gradually subsiding.

[35] F. S. Hudson and E. K. Craig, Bull. Amer. Assoc. Petrol. Geol., vol. 13, pp. 509–518, 1929.

3. Extravasation of many flows and shallow intrusions of andesite and basalt during most of the period of accumulation of the thick Vasquez series.
4. Strong early Miocene faulting and subsidiary folding, in many cases along earlier zones of movement, elevating the Vasquez beds to a topographic position sufficiently high to induce active erosion.
5. Late lower Miocene deposition of the Tick Canyon strata, apparently in alluvial fans (fronting the steeper slopes), floodplains, and local lakes, with concomitant volcanism as evidenced by the presence of tuffaceous beds.
6. Early middle Miocene cessation of deposition, accompanied perhaps by uplift and minor folding.
7. Deposition of the Mint Canyon strata, both as coarse fluviatile and as fine lacustrine sediment; volcanism in adjacent areas is demonstrated by several lacustrine tuffaceous beds.
8. Late Miocene uplift and moderate erosion, concurrent with small-scale orogenic movements.
9. Invasion by marine waters from the west and deposition in them of the uppermost Miocene "Modelo" sandstones and shales.
10. Recession of the marine waters, post-"Modelo" folding, and at a slightly later time strike-slip faulting.
11. Pliocene and early Pleistocene development of broad, open plains receiving coarse sediment from adjacent dominantly granitic highlands.
12. Minor folding and warping.
13. Pleistocene terrace formation in much the same manner as in 11 above.
14. Uplift and dissection of terrace deposits.
15. Recent alluviation and minor uplifts.

FAUNA OF THE TICK CANYON FORMATION

Occurrence and Preservation of Material

Fossils are very sparsely distributed in the Tick Canyon strata. Only four localities yielding more than splinters of bone have been reported since collecting first began. Previously described material was obtained from thin fault slices of the Tick Canyon formation near the Mint Canyon narrows, but the material described in the following pages was collected from a large exposure near the head of Vasquez Canyon (*Bt* on the geologic map, fig. 4). The fossiliferous beds are reddish-brown sandy siltstones, occurring about 360 feet stratigraphically below the base of the Mint Canyon formation. Though chalky and very fragile, the remains themselves are well preserved. The occurrence, in which fairly complete skulls, dental series, and limb bones are found, is in striking contrast to that in the younger Mint Canyon strata, where remains are very fragmentary. None of the bones seems to have suffered from abrasion. Apparently the conditions of burial were favorable to the preservation of several individuals within a small area, for many skeletal parts were found in close association. These features suggest a death from some catastrophe with immediate and rapid burial.

List of Species

The following faunal list comprises the forms definitely recorded from the Tick Canyon formation:

- Rodentia:
  - Heteromyid, prob. n. gen. and sp.
  - Archaeolagus (?) sp.
- Perissodactyla:
  - Parahippus maxsoni, n. sp.
- Artiodactyla:
  - Merychyus calaminthus, n. sp.
  - Miolabis californicus Maxson

Faunal Environment

Geologic observations furnish evidence of the existence of an adjacent mountain mass to the northwest during Tick Canyon time. The rather rapid progression from conglomeratic strata to fine-grained siltstones and clays further suggests a fairly flat-lying area of deposition at the base of this mountain mass. Certain strata noted in the section signify the presence of lakes; these were not of the playa type, but probably attained considerable depths. It is not surprising that these postulated conditions, which favor not inconsiderable local variations in environment, are in agreement with the evidence presented by the mammalian forms.

The pocket mouse is not particularly diagnostic so far as environment is concerned, in view of the present wide distribution of related forms under varying climatic conditions. The lagomorph, on the other hand, is suggestive, though not necessarily indicative, of a plains environment. *Parahippus*, with its short-crowned grinding teeth, was probably a browsing type, favoring wooded areas rather than an open, grassy terrane. *Merychyus* and *Miolabis* may have been plains-dwellers, although wooded areas near bodies of water probably attracted them. An analysis of the fauna as a whole, when combined with available geologic data, lends support to the view that the environment was that of a broad grassy plain, moderately and perhaps irregularly wooded, with a higher mountain mass lying immediately to the northeast. The climate was probably mild, with a rainfall greater than that which characterizes the region today.

Evolutionary Stage of Fauna

The various mammals of the Tick Canyon fauna present a homogeneous picture so far as stage of advance, as indicated by the phylogenetic development of individual types, is concerned. On the basis of recognized age determinations of North American Tertiary mammal horizons occupying an equivalent position in the evolutionary sequence, the Tick Canyon forms may be regarded as late lower Miocene or possibly earliest middle Miocene in age. In spite of the prevalence of new species, the fossil material is well enough preserved to afford an evaluation of those characters most necessary for determination of the stage of evolution represented. The rodents indicate a stage presumably rather low in the Miocene. The equid material exhibits characters most commonly found in forms known from the lower Miocene. The well-preserved merycoidodonts resemble most closely Great Plains species from the upper Harrison and upper Rosebud, and the camelid is typically more primitive than allied forms from the middle Miocene.

Faunal Relationships

Comparative lists of mammalian species from the Tick Canyon, lower Hawthorn of Florida, and upper Harrison of Nebraska appear below. The latter two horizons are chosen because they most closely approximate the position of the Tick Canyon fauna in the Tertiary vertebrate sequence (see fig. 7). No direct comparison of the Rodentia is possible, but the Equidae and Merycoidodontidae are closely related. Although the camelid forms listed from horizons occurring beyond the Californian area are of the giraffe-camel line, they nevertheless show evolutionary characters corresponding to those of *Miolabis californicus.*

Comparative faunal lists

Tick Canyon	Lower Hawthorn	Upper Harrison
Rodentia:	Rodentia	Rodentia:
Heteromyid, prob. n. gen. and sp.		Indet. sp.
Archaeolagus (?) sp.		
Perissodactyla:	Perissodactyla:	Perissodactyla:
Parahippus maxsoni, n. sp.	Archeohippus nanus	Parahippus coloradensis praecurrens
	Parahippus leonensis	Parahippus nebrascensis
		Parahippus n. primus
		Parahippus wyomingensis
		Parahippus pawniensis atavus
Artiodactyla:	Artiodactyla:	Artiodactyla:
Merychyus calaminthus, n. sp.		Merycochoerus magnus
		Merychyus arenarum minimus
		Merychyus a. leptorhynchus
Miolabis californicus	Oxydactylus floridanus	Oxydactylus longipes
		Oxydactylus brachyceps
		Procamelus (?) sp.

Pacific coast. The Tick Canyon is the only horizon of the Pacific coast province in which *Parahippus* appears to be the characteristic type of horse. The Merychippus zone at Coalinga [36] and the Caliente horizon,[37] in which *Parahippus* is found, are characterized by several merychippine types. Even the Phillips Ranch horizon,[38] occupying a position in the stratigraphic

[36] F. D. Bode, Carnegie Inst. Wash. Pub. No. 453, paper VI, p. 70, 1935.
[37] J. F. Dougherty, Carnegie Inst. Wash. Pub. No. 514, paper VIII, p. 115, 1940.
[38] J. P. Buwalda, Univ. Calif. Publ., Bull. Dept. Geol., vol. 10, pp. 75–85, 1916.

column slightly in advance of the Tick Canyon, yields a primitive *Merychippus*. The species of *Parahippus* occurring in the Caliente fauna appears to be a much more advanced form than *P. maxsoni*. The Coalinga anchitheriine, *P. brevidens*, exhibits a similar relation. Among the oreodonts, *Merychyus calimontanus* from the Caliente is a larger and more advanced form than *M. calaminthus*.

A large gap appears in the column below the Tick Canyon, the horizons nearest in age being the lower Miocene upper Sespe [39] and the lower Miocene or upper Oligocene Tecuya.[40] The only comparable forms from these horizons are oreodonts of much more primitive character than *M. calaminthus*.

Great Basin. The Tertiary vertebrate horizons of the Great Basin most nearly related to the Tick Canyon are the Virgin Valley,[41] Skull Spring,[42] and Mascall.[43] *Parahippus brevidens* and *P. avus* from the latter are advanced forms, as is *P.* near *coloradensis* from the Skull Spring horizon. This indication of later age is further borne out by the presence of merychippine forms in the Nevada and Oregon faunas. The merycoidodonts in these assemblages are generically distinct and thus preclude direct comparison, but they exhibit characters generally considered to be more advanced than those of the Tick Canyon form. The only camelid comparable to *Miolabis californicus* is *M. transmontanus* from the Mascall, a species whose characters are distinctly more advanced than those of the former. When comparisons are made with the upper John Day, the great faunal disparity is demonstrated by the presence in that formation of *Mesohippus*, *Eporeodon*, and *Paratylopus*, types that are much more primitive than comparable forms known from the California horizon.

Great Plains. The similarity of the upper Harrison faunas [44] to that from Tick Canyon, as based on the comparisons of *Parahippus*, *Merychyus*, and the long-limbed camels, has been noted. *Merychyus delicatus* from the upper Rosebud [45] most closely approaches *M. calaminthus* from the Tick Canyon; the equid and camelid forms from these two horizons likewise show similarities. The Sheep Creek horizon [46] presents a fauna slightly more advanced, but forms comparable to those from Tick Canyon are present. *Parahippus cognatus*, *Merychyus* sp., and *Miolabis tenuis* are larger and more advanced than *P. maxsoni*, *M. calaminthus*, and *M. californicus*, respectively. Presence in the fauna of *Merychippus insignis primus* is also indicative of a later stage. The lower Rosebud horizon is earlier in the

[39] C. Stock, Carnegie Inst. Wash. Pub. No. 404, paper III, pp. 31–36, 1930.

[40] C. Stock, Univ. Calif. Publ., Bull. Dept. Geol., vol. 12, pp. 267–276, 1920; Carnegie Inst. Wash. Pub. No. 418, paper IV, p. 89, 1932.

[41] J. C. Merriam, Univ. Calif. Publ., Bull. Dept. Geol., vol. 6, pp. 204–209, 1911.

[42] C. L. Gazin, Carnegie Inst. Wash. Pub. No. 418, paper III, pp. 42–48, 1932.

[43] J. C. Merriam and W. J. Sinclair, Univ. Calif. Publ., Bull. Dept. Geol., vol. 5, pp. 195–197, 1907.

[44] O. A. Peterson, Ann. Carnegie Mus., vol. 4, pp. 56–72, 1906.

[45] F. B. Loomis, Bull. Amer. Mus. Nat. Hist., vol. 51, pp. 31, 33–34, 1924.

[46] W. D. Matthew, Bull. Amer. Mus. Nat. Hist., vol. 50, pp. 65–73, 1924.

Suggested Correlations of Middle Tertiary Invertebrate and Vertebrate Horizons

California Stratal Units: Series	Stage		Formations at Type Locality		Formations in Eastern part of Ventura Basin: Undivided Marine	Divided Marine	Mint Canyon Area	Vertebrate Horizons: Pacific Coast Province	Great Basin Province	Great Plains Province	Atlantic-Gulf Coast Province	Series
Upper Miocene	Delmontian	Upper	Monterey	Salinas	"Modelo"	Santa Margarita (Stricto sensu)	"Modelo"	Mint Canyon				Upper Miocene
		Lower					? Mint Canyon ?					
	Mohnian	Upper				Modelo (Stricto sensu)			Barstow		Calvert	
		Lower				?						
Middle Miocene	Luisian	Upper				Topanga				Lower Snake Creek		Middle Miocene
		Lower										
	Relizian	Upper	Gould					Coalinga; Caliente	Virgin Valley; Skull Spring; Mascall	Sheep Creek		
		Lower	Temblor				? Tick Canyon ?	Phillips Ranch			Upper Hawthorn	
Lower Miocene	Saucesian	Upper						Tick Canyon		Upper Harrison; Upper Rosebud	Lower Hawthorn	Lower Miocene
		Lower		? — Vaqueros						Lower Harrison; Lower Rosebud		
	Zemorrian	Upper					Vasquez ?	Tecuya; Upper Sespe				
		Lower							Upper John Day			
Oligocene	Refugian		Gaviota					Sespe				Oligocene

FIG. 7. Correlation chart showing time relations of middle Tertiary invertebrate and vertebrate horizons. Note position of the Mint Canyon and Tick Canyon faunas.

Miocene, so much so that it has been correlated with the upper Sespe.[47] The lower Harrison is also earlier, but apparently does not range quite so far down in the lower Miocene as does the lower Rosebud.

Atlantic-Gulf coast. The only mammal-bearing horizons in this province comparable to the Tick Canyon are the upper and lower Hawthorn of Florida.[48] That the lower Hawthorn is closely related to the California horizon, in spite of a paucity of comparable forms, has been pointed out. The upper Hawthorn differs from the Tick Canyon in yielding a primitive *Merychippus*, but lacks the presence of other forms on which a correlation might be established; it may be considered as approximately of same age as the Phillips Ranch horizon of the Pacific coast province.

Correlation. The upper lower Miocene position of the Tick Canyon formation, approximately equivalent to that of the upper Rosebud, upper Harrison, and lower Hawthorn, as well as its suggested marine analogues, is indicated in figure 7. Certain revisions in the section dealing with vertebrate horizons suggested by recent work in the Caliente Mountains have been the result of discussions with J. F. Dougherty. The section on California stratal units is taken from Kleinpell [49] and the division of the Modelo formation is the work of Hudson and Craig.[50] The following lists of certain Tertiary perissodactyls and artiodactyls are furnished for purposes of comparison not only with the Tick Canyon, but with the overlying Mint Canyon, thus demonstrating the faunal gap between the two.

DESCRIPTION OF SPECIES

Rodentia

Dr. Robert W. Wilson, who contemplates a detailed study of the Tick Canyon rodents and lagomorphs, has kindly supplied the following preliminary statement concerning the several forms involved:

The small mammal specimens obtained from quarry 201 comprise two incomplete skulls and five rami of a heteromyid rodent possibly representing a new genus, and two maxillae and three rami of a lagomorph, *Archaeolagus* (?).

The heteromyid genus has a premolar pattern typical of the perognathine division of the family, and except for the absence of grooves in the upper incisors is comparable superficially to the genus *Perognathus*. Characters in addition to the smooth incisors which may be noted are: (1) $P\underline{4}$ with single-cusped protoloph; union with metaloph delayed but median or slightly lingual; (2) palate between premolars slightly ridged; (3) $P\overline{4}$ relatively small, four-cusped; metalophid and protolophid well separated but uniting to form X pattern (protolophid joins metalophid via anteroexternal cusp); (4) weak H pattern in lower molars; some development of Y-shaped anterior crest but stylid not anterior in position; (5) cusps of cheek teeth apparently

[47] C. Stock, Carnegie Inst. Wash. Pub. No. 404, paper III, pp. 31–34, 1930.

[48] G. G. Simpson, Florida Geol. Surv., Bull. 10, pp. 11–16, 1932.

[49] R. M. Kleinpell, Miocene stratigraphy of California, fig. 14. Amer. Assoc. Petrol. Geol., 1938.

[50] F. J. Hudson and E. K. Craig, Bull. Amer. Assoc. Petrol. Geol., vol. 13, pp. 509–578, 1929.

Comparative perissodactyl-artiodactyl faunal lists of certain North American Tertiary horizons

1. Ricardo
2. Mint Canyon
3. Barstow
4. Lower Snake Creek
5. Coalinga
6. Skull Spring
7. Mascall
8. Caliente
9. Sheep Creek
10. Upper Hawthorn
11. Lower Hawthorn
12. Tick Canyon
13. Upper Rosebud
14. Upper Harrison
15. Upper John Day

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Perissodactyla:															
Pliohippus-Hipparion forms	×	×	...	...	...	...	...	...	...	...	...	...	...	...	...
Protohippus-Merychippus forms	...	×	×	...	...	...	...	...	...	...	...	...	...	...	...
Archeohippus mourningi	...	...	×	...	×	...	...	...	...	...	...	...	...	...	...
Archeohippus ultimus	...	...	...	...	...	...	×	...	...	...	...	...	...	...	...
Archeohippus penultimus	...	...	...	...	...	...	...	...	×	...	...	...	...	...	...
Archeohippus cf. nanus	...	...	...	...	...	...	...	...	...	×	...	...	...	...	...
Archeohippus nanus	...	...	...	...	...	...	...	...	...	...	×	...	...	...	...
Merychippus (Protohippus) intermontanus	...	×?	×	...	...	...	...	...	...	...	...	...	...	...	...
Merychippus calamarius stylodontus	...	...	×	...	...	...	...	...	...	...	...	...	...	...	...
Merychippus sumani	...	×?	×	...	...	...	...	...	...	...	...	...	...	...	...
Merychippus paniensis	...	...	...	×	...	...	...	...	...	...	...	...	...	...	...
Merychippus proparvulus	...	...	...	×	...	...	...	...	...	...	...	...	...	...	...
Merychippus campestris	...	...	...	×	...	...	...	...	...	...	...	...	...	...	...
Merychippus eohipparion	...	...	...	×	...	...	...	...	...	...	...	...	...	...	...
Merychippus sejunctus	...	...	...	×	...	...	...	...	...	...	...	...	...	...	...
Merychippus brevidontus	...	...	...	...	×	...	...	...	...	...	...	...	...	...	...
Merychippus californicus	...	...	...	...	×	...	...	...	...	...	...	...	...	...	...
Merychippus isonesus	...	...	...	...	...	×	×	...	...	...	...	...	...	...	...
Merychippus stevensi	...	...	...	...	...	...	...	×	...	...	...	...	...	...	...
Merychippus seversus	...	...	...	...	...	...	×	...	...	...	...	...	...	...	...
Merychippus relictus	...	...	...	...	...	...	×	...	...	...	...	...	...	...	...
Merychippus insignis	...	...	...	...	...	...	×	...	...	...	...	...	...	...	...
Merychippus carrizoensis	...	...	...	...	...	...	...	×	...	...	...	...	...	...	...
Merychippus insignis primus	...	...	...	...	...	...	...	...	×	...	...	...	...	...	...
Merychippus gunteri	...	...	...	...	...	...	...	...	...	×	...	...	...	...	...

(*Continued on following page*)

Comparative perissodactyl-artiodactyl faunal lists of certain North American Tertiary horizons—Continued

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Perissodactyla—*continued*															
Parahippus integer				×											
Parahippus brevidens					×		×								
Parahippus near coloradensis						×									
Parahippus avus							×								
Parahippus sp.								×?							
Parahippus cognatus									×						
Parahippus leonensis											×				
Parahippus maxsoni, n. sp.												×			
Parahippus coloradensis *praecurrens*													×	×	
Parahippus nebrascensis														×	
Parahippus nebrascensis primus														×	
Parahippus wyomingensis														×	
Parahippus pawniensis atavus														×	
Mesohippus equiceps															×
Mesohippus acutidens															×
Mesohippus praestans															×
Artiodactyla:															
Metoreodon californicus	×														
Metoreodon relictus				×											
Merycochoerus *buwaldi*			×												
Merycochoerus sp.							×								
Merycochoerus magnus														×	
Merycochoerus matthewi													×		
Merycoidodont sp.							×	×		×					
Ticholeptus sp.						×		×?							
Pronomotherium siouense				×					×						
Merychyus sp.				×					×						
Merychyus calimontanus								×							
Merychyus calaminthus, n. sp.												×			
Merychyus delicatus													×		
Merychyus arenarum minimus														×	
Merychyus arenarum leptorhynchus														×	

Comparative perissodactyl-artiodactyl faunal lists of certain North American Tertiary horizons—Continued

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Artiodactyla—*continued*															
Eporeodon sp.															X
Eporeodon major longifrons															X
Promerycochoerus, several sp.															X
Alticamelus sp.		X	X		X?										
Alticamelus leptocolon				X											
Alticamelus procerus				X											
Alticamelus altus							X								
Alticamelus priscus									X						
Oxydactylus sp.					X?										
Oxydactylus floridanus											X				
Oxydactylus longipes													X	X	
Oxydactylus brachyceps														X	
Pliauchenia sp.			X												
Procamelus sp.			X		X								X?		
Protolabis angustidens				X					X						
Protolabis pusillus									X						
Protolabis saxeus									X						
Miolabis sp.					X?					X?			X		
Miolabis fissidens				X											
Miolabis transmontanus							X								
Miolabis tenuis									X						
Miolabis californicus												X			
Paratylopus cameloides															X

remain prominent for some time; (6) traces of posterior cingula in lower cheek teeth, anterior cingula in upper cheek teeth in some, at least, of the specimens; (7) $M\frac{3}{3}$ not noticeably reduced; (8) height of crowns moderate. The Mint Canyon heteromyid possesses an assemblage of characters which makes it difficult to allocate to any of the established genera. Structurally, it might be ancestral to either *Perognathoides* or *Cupidinimus*. Perhaps it is closer to the latter. No definite age determination can be made on the basis of the material at present, but a Miocene rather than Pliocene age is indicated.

The lagomorph remains apparently represent an advanced *Archaeolagus* or a very primitive *Hypolagus*. The Mint Canyon genus has a P$\underline{2}$ with only one anterior inflection. P$\overline{3}$ is very close to the comparable tooth in *Archaeolagus*. The upper molars have simple, short inflections without crenulations. These teeth lack the enamel crescents present, though not invariably, in the John Day *Archaeolagus*. Anterior and posterior columns of M$\overline{3}$ are united by an isthmus of dentine of varying width, and none of the three specimens available exhibits the complete separation of the columns typical of *Hypolagus*. Cited characters indicate a form close to *Archaeolagus*, which in turn suggests a rather early Miocene age, but probably post-John Day, for the specimens. However, notes by L. R. Dice [51] on *Panolax* Cope indicate that forms of *Archaeolagus* type may have existed as late as the Santa Fe.

PERISSODACTYLA

Parahippus maxsoni, n. sp.

(Plate 1, figure 1)

Holotype. C.I.T. No. 1385, palate of immature individual with well-preserved deciduous grinding teeth, a cervical vertebra, part of a humerus, shaft of fibula and tibia, incomplete manus and right pes.

Type locality. C.I.T. Vert. Pale. Loc. 201; west side of small canyon in the SW. corner of section 25, T. 5 N., R. 15 W., San Bernardino Base and Meridian, Humphreys Quadrangle, U. S. Geological Survey.

Geologic horizon. Tick Canyon formation, upper part of lower Miocene or lowermost middle Miocene.

Specific characters. Comparisons based on individual deciduous tooth measurements, as well as on the length of the deciduous premolar series, indicate a size greater than that of *Parahippus pristinus*,[52] but less than that of *P. cognatus* Leidy,[53] the genotype, and *Merychippus isonesus* (Cope).[54] The teeth are short-crowned, with a rather primitive pattern involving simple, straight, connected lophs, strongly developed cingulum below protoloph, and short, well-developed triangular hypostyle. A tiny crochet appears on the metaloph of Dp$\underline{3}$ and Dp$\underline{4}$. Cement is lacking, or present in negligible amount. The dentition resembles that of *P. pristinus*, but differs specifically in greater size, and in development of crochet, greater prominence of parastyle and mesostyle, and greater elongation of Dp$\underline{2}$. The

[51] L. R. Dice, Jour. Mammal., vol. 4, no. 3, 1923.

[52] H. F. Osborn, Mem. Amer. Mus. Nat. Hist., vol. 2, pt. 1, pp. 76-77, pl. 25.1, 1918.

[53] Joseph Leidy, Proc. Acad. Nat. Sci. Phila., vol. 10, p. 26, 1858; Jour. Acad. Nat. Sci. Phila., vol. 7, p. 314, 1869.

[54] F. D. Bode, Carnegie Inst. Wash. Pub. No. 453, paper V, pl. 2, 1934.

metapodials and phalanges suggest an animal of rather light build. The pes is anisotridactylous.

The writer takes pleasure in naming this species for Dr. John H. Maxson.

Description

Dentition. The teeth are represented by a well-preserved set of deciduous cheek teeth. The narrowness of the space separating the right and left series may be due to a considerable crushing of the palate. The milk teeth are short-crowned, little worn, and very closely spaced. The length of the series, 61.6 mm., is compared with that of other forms in the table of measurements. The peglike first premolar is relatively large, elongated anteroposteriorly. Its crown is divided into two distinct basins, the posterior of which is much the smaller, roughly ovoid in shape, and shallow when compared with the crown height of the tooth. The large anterior basin is bounded externally by a strong, crescentic ridge, interiorly by a very low, narrow ridge. This tooth seems to have functioned, at least in part. The second premolar is the longest tooth present; it is markedly narrower than in *P. pristinus*, broader than in *M. isonesus*, but of nearly the same proportions as in *P. cognatus*. Although the transverse dimension of the remaining teeth increases to a maximum in $Dp\underline{4}$, these teeth are relatively less broad than in most other species of the genus. The enamel surfaces are smooth, but local areas of slight rugosity do occur, chiefly on the interior faces of the lophs, on which appear tiny, irregular vertical striations. Local patches of a very thin calcareous scale, confined in general to the outer face of the ectoloph and to the inner surfaces of protocone and hypocone, may represent cement. The total amount present is very small. When the tooth row is viewed from the side, it presents a gently downward convex profile.

The protoloph, though sharply constricted and slightly bent between protocone and protoconule, is simple, continuous, and fairly straight. The bulbous, subconical protocone is larger than the protoconule, which is developed as a ridge-shaped swelling on the loph. The metaloph crest drops to a low saddle and follows a single tiny plication before joining the ectoloph. This union becomes progressively stronger from $Dp\underline{2}$ to $Dp\underline{4}$. The hypocone is symmetrically formed; from a point near its apex the metaloph slopes away in a nearly straight, continuous ridge, on which a metaconule is faintly indicated. An extremely small, thin, and bladelike crochet projects from the anterior side of the metaloph in $Dp\underline{3}$ and $Dp\underline{4}$, perhaps also in $Dp\underline{2}$. This feature appears in the occlusal pattern only after much wear. Ptychoid crenulations and additional crochets are absent. The short hypostyle is strongly developed and triangular in cross section. It nearly encloses a small fossette, but opens externally in a sharp, V-shaped groove. By means of a low, narrow ridge it connects with the ectoloph, the most elevated part of the tooth. No pli-hypostyle is present.

A strong cingulum lies at the base of the protoloph; additional cingula are represented internally by the merest traces at the anterointernal base of the hypocone, externally by a slightly better defined bench at the base of the ectoloph. The external walls of the paracone and metacone are smooth, broken only by a low, narrow, rounded median rib. The para- and mesostyles are prominent, though rounded and narrow. A bladelike metastyle is distinct on $Dp\underline{3}$ and $Dp\underline{4}$, whereas on $Dp\underline{2}$ the protostyle reaches prominence.

In its broad aspects the deciduous tooth pattern of the Tick Canyon specimen agrees with that of *Miohippus gemmarosae* Osborn,[55] an advanced form of the genus from the lower Rosebud formation, but differs in the union of metaloph and ectoloph, in the presence of a crochet, and in the shape of the individual teeth. Although the same differences in pattern persist, there is closer agreement in tooth shape and size with a species described by Douglass [56] as *Altippus taxus* and by Osborn [57] as *Parahippus taxus*, but later referred to the genus *Miohippus* by Schlaikjer.[58] From the dentition of *P. pristinus*, *P. maxsoni* differs in its larger size, presence of two basins in Dp1, superior development of the crochet, greater prominence of para- and mesostyles, and greater elongation of Dp2. Comparisons with the occlusal pattern of permanent dentitions furnish little of specific value, but lengths of premolar series are included in the table of measurements. In this respect, *P. maxsoni* is larger than *P. pristinus*, roughly comparable to *P. coloradensis praecurrens*, *P. pawniensis*, and *P. avus*, and distinctly smaller than *P. nebrascensis*, *P. nebrascensis primus*, *P. crenidens*, *P. tyleri*, and *P. wyomingensis*.

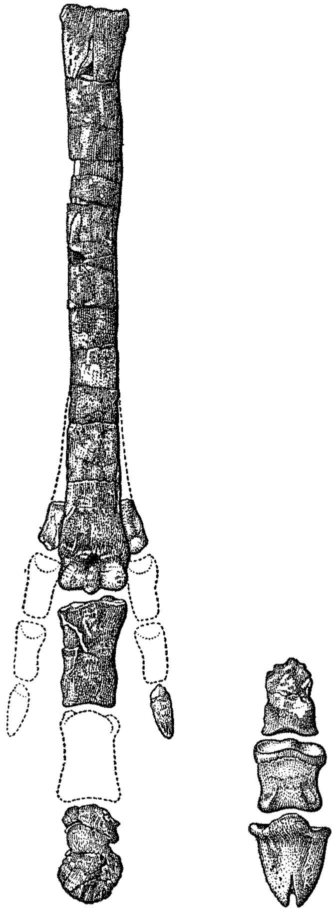


FIG. 8. *Parahippus maxsoni*, n. sp. Skeletal parts of feet, C.I.T. No. 1385, front view; ×½. Lower Miocene, Tick Canyon Formation, California.

Skeleton. The vertebral column is represented by one partially preserved third or fourth cervical. Although the neural spine is broken off, the specimen seems to have been of rather small size. The transverse process is wide and stubby. The zygapophyses are large, the prezygapophyses having a marked forward extent. The ventral keel is sharp and prominent. The neural canal is ovoid in section, with a moderate amount of flattening. The vertebrarterial canal is large and round.

The fore-limb bones are very fragmentary. The distal portion of a humerus bears a deep, elongated olecranon fossa, strongly developed epicondyle, and lateral condyloid crest. The only carpal bone present is a magnum, typically more flattened than in *Miohippus*. On the ventral surface are a strong, flat face and a small oblique facet for articulation with the third and second metacarpals, respectively. Articulating faces for scaphoid and lunar are represented by slight concavities on the dorsal surface,

[55] H. F. Osborn, *op. cit.*, pp. 66–68, 1918.
[56] E. Douglass, Ann. Carnegie Mus., vol. 4, pp. 271–273, 1908.
[57] H. F. Osborn, *op. cit.*, pp. 85–86, 1918.
[58] E. M. Schlaikjer, Bull. Mus. Comp. Zool., Harvard, vol. 80, p. 272, 1937.

from the rear of which rises a strong projection. The phalanges are in general like those of the hind foot, but are shorter and broader.

Portions of shafts of fibula and tibia denote a slender build; both are nearly circular in section throughout their middle extent, with a diametral ratio of approximately 1 : 4.5. A gently curving cnemial crest becomes very strong near the proximal end of the tibia. The only bone of the tarsus preserved is a cuboid. This element is large and extended anteroposteriorly. Although its proximal surface is transversely convex, it differs from that in *P. wyomingensis* in lacking an anteroposterior concavity on the rear portion. Additional articulating surfaces located on the distal side are an ovoid facet for metatarsal IV and a small oblique facet for metatarsal III; on the internal side, a faintly concave ovoid facet for the navicular. A large, bulbous tuberosity is present on the posterointernal corner of the distal surface. Remains of feet are shown in figure 8. Metapodial III is long and slender, with an expanded distal portion. A shallow, transversely elongated fossa lies on the dorsal surface of the distal portion, midway between the lateral tubercles. Both the rounded articulating surface and its keel are canted backward. The distal ends of metapodials II and IV show similar relations, but are much smaller and compressed transversely. The ungual phalanx is strongly notched at its distal end.

Discussion

Although the skeletal characters, so far as they are known, serve only to indicate an appreciable advance over *Miohippus*, the dentition of *P. maxsoni* is far more diagnostic. Comparisons with other deciduous dentitions seem to fix within reasonably small limits the stage of evolution of this species in the genus. That the Tick Canyon species represents a more advanced stage than does the lower Miocene *P. pristinus* and a slightly earlier stage than does the middle Miocene *P. cognatus* has been pointed out. The negligible amount of cement, very simple loph structure, and shape and size of the teeth denote rather primitive characters, even for a deciduous dentition. Inasmuch as both milk and permanent dentitions are known for *P. pristinus*, if we accept Schlaikjer's suggestion [59] that *P. cognatus* and *P. coloradensis praecurrens* (the latter represented by permanent teeth) are specifically identical, the opportunity presents itself to compare *P. maxsoni* with other members of the genus, at least so far as relative evolutionary development is concerned. It appears that the Californian species occupies a position in the evolutionary sequence of the Equidae corresponding to that of forms from the upper Harrison and upper Rosebud formations of the Great Plains province, or to that of the Merycochoerus-Parahippus zone of Osborn.[60] Further, it seems reasonable to refer to *P. maxsoni* the equid material previously collected from the same beds. This specimen was described by Maxson [61] as *Parahippus ?* (*Archeohippus*) near *mourningi* and later referred by Bode [62] and Stirton [63] to *Parahippus* sp. Bode notes at least one character which suggests that this fossil species belonged to an earlier stage than that to which it has been assigned (upper Miocene).

[59] *Ibid.*, pp. 275–276, 1937.
[60] H. F. Osborn, *op. cit.*, p. 79, 1918.
[61] J. H. Maxson, Carnegie Inst. Wash. Pub. No. 404, paper VII, pp. 91–92, 1930.
[62] F. D. Bode, Carnegie Inst. Wash. Pub. No. 440, paper V, pp. 55–56, 1933.
[63] R. A. Stirton, Amer. Jour. Sci., 5th ser., vol. 26, pp. 570–571, 1933.

*Comparative measurements (in millimeters) of deciduous dentitions**

1. *Parahippus maxsoni*, n. sp., C.I.T. No. 1385.
2. *Parahippus pristinus* Osborn, A.M. No. 12915.†
3. *Parahippus cognatus* Leidy, U.S.N.M. No. 567.‡
4. *Parahippus taxus* Douglass, Car. Mus. No. 836.† §
5. *Merychippus isonesus* (Cope), C.I.T. No. 544.‖

	1	2	3	4	5
Superior series, Dp$\underline{1}$ to Dp$\underline{4}$, length	61.6	54	..	59¶	..
Superior series, Dp$\underline{2}$ to Dp$\underline{4}$, length	55.5	46	67¶	50¶	65
Dp$\underline{1}$, anteroposterior diameter	9.2	11	..	11	..
Dp$\underline{1}$, transverse diameter	6.5	6	..	7	..
Dp$\underline{1}$, crown height	8.1	**	..	**	..
Dp$\underline{2}$, anteroposterior diameter	21.2	17	25	20¶	27
Dp$\underline{2}$, transverse diameter	15.0	14	18	15	18
Dp$\underline{2}$, crown height	11.1	**	..	**	11
Dp$\underline{3}$, anteroposterior diameter	17.0	14	19	15	20
Dp$\underline{3}$, transverse diameter	16.8	15	20	16	19
Dp$\underline{3}$, crown height	12.5	**	..	**	13
Dp$\underline{4}$, anteroposterior diameter	18.5	15	20	15	20
Dp$\underline{4}$, transverse diameter	17.8	15	20	17	19
Dp$\underline{4}$, crown height	13.6	**	..	**	12

* Anteroposterior diameter of Dp$\underline{1}$ and Dp$\underline{2}$ is the maximum diameter at the base of crown; otherwise the system of measurements is that of Bode (*op. cit.*, p. 46, 1933).
† H. F. Osborn, *op. cit.*, pp. 76–77, 85–86, 1918.
‡ Joseph Leidy, *op. cit.*, p. 314, pl. 21, 1869.
§ Referred to genus *Miohippus* by Schlaikjer.
‖ F. D. Bode, *op. cit.*, pl. 2, 1934.
¶ Approximate.
** Measurements not taken because of worn character of tooth.

*Comparison of permanent dentition of Parahippus maxsoni with those of other forms (measurements in millimeters)**

Species	Superior premolar series, P$\underline{1}$ to P$\underline{4}$	Superior premolar series, P$\underline{2}$ to P$\underline{4}$
Parahippus maxsoni (C.I.T. No. 1385)	61.6†	55.5†
Parahippus pristinus Osborn (A.M. No. 12918)	50	42
Parahippus tyleri Loomis (Amer. Coll. No. 1079)	65‡	59
Parahippus nebrascensis Peterson (Car. Mus. No. 1440)	72	66
Parahippus n. primus Osborn (A.M. No. 13770)	77	71
Parahippus coloradensis praecurrens Osborn (A.M. No. 13018)	..	54
Parahippus avus Marsh (Yale Mus. No. 11281)	61‡	57
Parahippus crenidens Scott (Prin. Mus. No. 10430)	68	58
Parahippus pawniensis Gidley (A.M. No. 9085)	59	51
Miohippus gemmarosae Osborn (A.M. No. 13808)	61	52
Parahippus wyomingensis Schlaikjer (M.C.Z. No. 6309)	65	59

* Measurements taken in part from Osborn.
† Deciduous dentition.
‡ Approximate.

Limb measurements (in millimeters)

	Parahippus maxsoni	*Parahippus wyomingensis* Schlaikjer*
Metatarsal III, maximum length	154.6	223.4
Metatarsal III, maximum width at proximal end	20.0†	30.2
Metatarsal III, maximum width at distal end	20.4	30.0
First phalanx of middle digit, pes, maximum length	30.4	42.8
Second phalanx of middle digit, manus, maximum length	20.7	28.1
Second phalanx of middle digit, pes, maximum length	25.0	29.7
Ungual phalanx, manus, middle digit, maximum length	23.1	34.8
Ungual phalanx, manus, middle digit, maximum width	21.3	....
Ungual phalanx, pes, middle digit, maximum length	24.6	40.7
Ungual phalanx, pes, middle digit, maximum width	20.0†	35.5

* E. M. Schlaikjer, *op. cit.*, pp. 270–271, 1937.
† Approximate.

*Measurements (in millimeters) and indices of the ungual phalanx, middle digit, of the pes**

Species	Length	Width	Index
Parahippus pristinus	26.0	19.0	0.730
Parahippus pawniensis atavus	33.0	26.0	.790
Parahippus maxsoni	24.6	20.0†	.81†
Parahippus avus	35.5	30.0	.845
Parahippus leonensis	28.0	24.0	.856
Parahippus tyleri	39.0	33.5	.859
Parahippus wyomingensis	40.7	35.5	.872
Parahippus coloradensis praecurrens	35.0	31.0	0.886

* Data on all species other than *P. maxsoni* taken from Schlaikjer.
† Approximate.

ARTIODACTYLA

Merychyus calaminthus, n. sp.

(Plate 1, figures 2–3*a*; plates 2, 3)

Cotypes. C.I.T. No. 1383, incomplete skull of an adult animal with nearly perfect cheek-tooth series; C.I.T. No. 1342, poorly preserved adult mandible; C.I.T. No. 1382, middle and posterior part of skull with nearly complete molar series and well-preserved basicranial region; C.I.T. No. 1829, skull of an immature animal, complete anterior to cranium, lower jaws present, one in articulation with skull and one separated.

Paratypes. C.I.T. No. 1384, imperfect skull and lower jaws of a young individual; C.I.T. No. 2684, miscellaneous teeth; C.I.T. No. 2681, parts of left hind foot and tibia.

Type locality. C.I.T. Loc. 201; west side of small canyon in SW. corner of section 25, T. 5 N., R. 15 W., San Bernardino Base and Meridian, Humphreys Quadrangle, U. S. Geological Survey.

Geologic horizon. Tick Canyon formation, upper part of lower Miocene or lowermost middle Miocene.

Specific characters. The most mature specimens are slightly smaller than *Merychyus delicatus*, heretofore the smallest recorded species of the genus,[64] and notably smaller than *M. arenarum minimus*[65] and *M. curtus*.[66] The slender build is further indicated by the small eye socket, slender zygomata, and smallness of cranial region of the skull. The most diagnostic single character, however, is a pronounced ovoid antorbital fossa, at the anterior edge of which is a tiny facial vacuity. The dentition closely resembles that of *M. delicatus*, with uncrowded premolars and characteristic premolar pattern; the only notable character is a distinct spur projecting outward from the inner crescent of $P\underline{4}$.

Description

Skull. Although no complete skull is available, accurate composite measurements indicate a mesocephalic index of about 0.54. The dorsal surface, as shown in No. 1382, is low and flattened, with its highest point at the postorbital constriction. The brain case has a nearly circular horizontal cross section, and its upper surface is marked by two broad, very low temporal ridges. These ridges unite just in back of the glenoid fossae to form a short, narrow sagittal crest that is clearly defined but not prominent. The occipital crests are sharp and well developed.

[64] F. B. Loomis, Bull. Amer. Mus. Nat. Hist., vol. 51, art. 1, pp. 31, 33–34, fig. 22, 1924.
[65] O. A. Peterson, Ann. Carnegie Mus., vol. 4, pp. 56, 67–68, fig. 16, 1906.
[66] F. B. Loomis, *op. cit.*, pp. 31–33, figs. 19, 20, 1924.

The malar is of medium build, but the zygomatic arches are light. The elevated orbits are rather small and only slightly elongated anteroposteriorly. From the orbits, the lachrymals project forward to occupy a rather extensive area on the face; they are concave outward, forming pronounced, anteroposteriorly elongated antorbital fossae. At the front edges of these ovoid depressions are very small facial vacuities, bounded mainly by the maxillaries, in part by the lachrymals, and apparently to a small extent by the frontals. The short nasals are widest at their anterior ends. These elements appear to be slightly constricted at the middle, and are rounded posteriorly. The frontals, flat to gently convex, rise to a low ridge at the orbital rim. Although the relations are obscured to some extent by dorsoventral crushing, the palate appears to be gently vaulted and wide.

Both basioccipital and basisphenoid are narrow and strongly convex downward. The tympanic bullae are not preserved. Projection of the occiput over the foramen magnum is not great. The pterygoids are not fully preserved, but appear to have been thin; the vomer, on the other hand, is thick. The rather open glenoid fossae lie in a line normal to the basicranial axis, and are bounded posteriorly by sharply defined, downward-directed postglenoid processes. Although the paroccipital processes are broken off, they seem to have been sensibly smaller than the postglenoid processes.

Mandible. The inclination of the symphyseal border of the jaw makes an angle of 43° with the tooth row in the young individual, No. 1384; this angle is apparently increased in more mature animals. The symphysis is short and vertically slightly convex. The inferior edge of the mandible is straight, sloping gently backward and terminating in a poorly defined angle; the depth of the jaw at this point is considerably less than in other representatives of the genus. The coronoid process is short, thin, and rounded at its end. A broad and shallow sigmoid notch is bounded posteriorly by a slender condyle with very straight transverse surface. At its horizontal, clearly marked lower edge, the masseteric fossa is deep, but becomes shallower toward the coronoid process.

Foramina. In spite of local crushing, several foramina are clearly visible in the basicranial region. A large foramen ovale is situated internally with respect to the glenoid fossa, and a small, round foramen lacerum anterius is completely concealed in ventral view by a marked overhang of the pterygoid. There is no trace of a foramen rotundum, and an alisphenoid canal is not present; instead, the carotid artery appears to have been carried in a short, moderately narrow, but very deep groove. This groove is bounded exteriorly by a stubby pyramidal process situated on the posterior outer edge of the alisphenoid, and interiorly by one of the ventrally diverging pterygoids.

A portion of the rim of the foramen lacerum medium is preserved postero-internally to the foramen ovale, and there is a suggestion of an edge of a foramen lacerum posterius in back of the space occupied by the tympanic bulla.

The infraorbital foramina lie above the middle part of $P\underline{3}$, and the posterior palatine foramina occupy positions opposite $P\underline{4}$. The supraorbital foramina are only 5 mm. apart, and are situated immediately adjacent to the frontonasal suture. They open into shallow grooves which apparently extend directly forward. The mental foramen, the only one observable in the mandible, lies below the anterior end of $P\overline{3}$.

Dentition. The superior teeth are sub-hypsodont to hypsodont, and are closely spaced but not crowded. The incisors are small, with ovoid cross sections; the canines are pyramidal and moderately large. The molar-premolar rows are nearly straight both horizontally and vertically, although a tendency toward downward convexity is displayed in immature individuals. Except for a backward tilt in P1 and P2 and an oblique position for P1, the individual cheek teeth stand straight in the jaw. The molars, which overlap slightly, increase in length rapidly from M1 to M3. M2 resembles M1 more closely in size than it does M3. M1 is essentially square in outline, in which character this tooth differs from the posterior molars. This difference is due in part to differential wear. Shortening of the tooth row has taken place with reduction in size of the anterior parts of P1, P2, and P3 and with complete loss of the anterior end of P4.

The cheek teeth follow the typical *Merychyus* pattern, with the addition of certain minor characters. A small but distinct spur projects outward from the inner crescent of P4, but lies too far posterior to be a vestige of the median crest. The tiny pit (a remnant of the anterior basin) present at the anterior outer corner of P4 in *M. curtus* and *M. delicatus* is absent in *M. calaminthus*. Below the corners of the crescent are short cinguli; the anterior one is very sharp and trough-like. No distinct cingulum is present elsewhere in teeth of the upper dentition. In P3, which is shorter transversely than in *M. delicatus*, the posterior basin is obliquely elongated. The anteriorly convex anterior intermediate crest is sharper and more prominent than either of the adjacent crests or the anterior crescents. This crest has a greater extent in P2, and in the latter tooth that portion of the basin in front of the intermediate crest is vestigial or absent. Parastyle and mesostyle are inconspicuous in M1, but become increasingly prominent in M2 and M3. Moreover, M3 possesses a distinct metastyle.

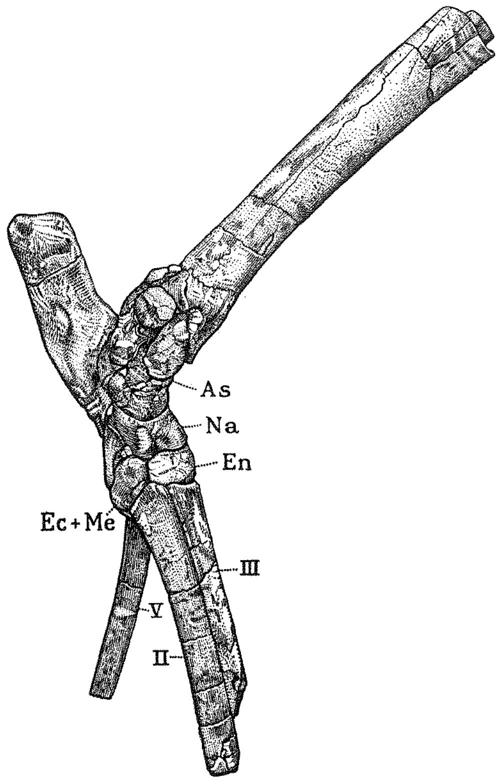


FIG. 9. *Merychyus calaminthus*, n. sp. Left pes with tibia, inner view; ×1. *As*, astragalus; *Na*, navicular; *En*, entocuneiform; *Ec* & *Me*, ecto- and mesocuneiform; II, III, V, metatarsals. Lower Miocene, Tick Canyon Formation, California.

The superior milk dentition is represented by poorly preserved premolars. The molariform Dp4 seems crowded into a nearly square outline; it contains two basins and bears a well-developed parastyle, mesostyle, and metastyle.

Dp$\underline{2}$ and Dp$\underline{3}$ are too imperfectly preserved to permit a clear picture of their occlusal patterns.

Because of the worn grinding surfaces of the inferior teeth, little of their pattern can be discerned. The premolars are crowded and partially overlapping, P$\bar{1}$ and P$\bar{2}$ lying transversely in the jaw. The strongly caniniform P$\bar{1}$, though short-rooted, is larger than the canine, which is also transverse. As in the superior dentition, M$\bar{3}$ is much larger than M$\bar{1}$ or M$\bar{2}$. Styles are strongly developed, especially on the molars. Straight, narrow internal cinguli appear on P$\bar{3}$ and P$\bar{4}$, which are further characterized by a very deep *indentation of the external wall just forward of the posterior crest*, with an attendant anterior narrowing of each tooth. The deciduous lower teeth show much the same characters as the corresponding permanent units, except for the molariform, three-basined Dp$\bar{4}$, whose well-defined crescents are separated by deep, narrow valleys extending only part way down the crown. Styles typical of the molars are also present on this tooth.

Skeleton. Among the best preserved of the skeletal remains is a left pes, with the distal parts of the tibia and a thin, slender fibula; all bones are in articulation (fig. 9). The phalanges are missing, and of the metatarsals only the second is reasonably complete. The estimated length from the end of metatarsal II to the posterior end of the calcaneum is 81 mm. The cuboid is rather elongated; the navicular shows a slender anterior projection on the under side of the foot; and the middle and external cuneiform bones are not fused. That the animal was of light build is indicated by the relative slenderness of all the foot bones, especially the metatarsals (for comparisons with *M. arenarum minimus*, see table of measurements). Other, more fragmentary and poorly preserved hind-limb elements have similar characteristics.

Discussion

Although the brain case is slightly wider than in *M. delicatus*, the smaller features of *M. calaminthus* are reflected by lighter zygomata, more restricted skull width between orbits, and smaller diameter of orbit. The skull in the Californian species is of nearly the same shape as in *M. arenarum minimus*, as is shown by comparison of cephalic indices, 0.54 and 0.55 respectively; that of *M. delicatus* is 0.62 (approximately). *Differences in the dentition* are seen in the molar-premolar ratios, 0.80 for *M. calaminthus* as compared with 0.83 for *Merycoidodon*, 0.84 for *Merychyus delicatus*, and 0.74 for *M. arenarum minimus*. In addition to the differences in occlusal pattern of the premolars that have been pointed out, it should be noted that complete internal cinguli, present in P$\underline{4}$ and M$\underline{3}$ of *M. delicatus*, are absent in the comparable teeth of the species from southern California.

Merychyus calaminthus is more primitive than most species of the genus, as is demonstrated by its cephalic index, small size, restricted facial vacuities, presence of an open groove which appears to represent a vestigial alisphenoid canal, lack of extensive shortening in P$\underline{2}$ and P$\underline{3}$, lack of strong backward cant to upper premolars, and the heavy styles in M$\underline{3}$. On the other hand, this form may represent a slight advance beyond *M. delicatus*, as is indicated perhaps by presence of a facial vacuity, slightly broader brain case, lower molar-premolar index (reflecting greater premolar shortening), and more complex premolar pattern. Additional comparisons can be made from the table of measurements.

Comparative measurements (in millimeters)

1. *Merychyus calaminthus*, n. sp., C.I.T. No. 1383.
2. *Merychyus calaminthus*, n. sp., C.I.T. No. 1342.
3. *Merychyus calaminthus*, n. sp., C.I.T. No. 1382.
4. *Merychyus calaminthus*, n. sp., C.I.T. No. 1829.
5. *Merychyus calaminthus*, n. sp., C.I.T. No. 1384.
6. *Merychyus delicatus* Loomis.*
7. *Merychyus arenarum minimus* Peterson.*
8. *Merychyus curtus* Loomis.*

Skull	1	3	4	5	6	7	8
Maximum length			126.0†	96.0‡	140‡	160.0	156
Basal length					130‡	148.0	148
Bizygomatic diameter	75.0‡	67.9	68.0		88‡	88.5‡	98
Postorbital constriction, diameter		36.0	35.0	33.0‡	34	34.5	32
Brain case, diameter		42.3	42.0‡	36.0‡	40‡	44.0	42
Width between middle of orbits	58.0	50.0	48.5	42.0‡	56	58.0	50
Orbits, anteroposterior diameter	21.5	20.0	18.8		24	22.0	25
Orbits, vertical diameter	20.0	16.2	14.7		20	24.0	24
Molar, depth below orbit	13.0	10.8	8.0		12	16.0	18
Bulla, anteroposterior diameter					16	19.6	22
Bulla, transverse diameter						14.0	18
Palate, width between P$\underline{1}$	20.5‡		16.5	12.8‡		19.6	21
Palate, width between M$\underline{3}$	25.0‡	23.0	22.0	16.5‡		24.6	28
Facial vacuity, maximum diameter			3.0‡			19.0	14
Facial vacuity, minimum diameter						10.0	3
Ramus, maximum length			82.0‡	91.0‡	110	129.0	122
Symphyseal length				20.0	27	32.0	25
Depth, coronoid to angle			50.0‡		71	73.0	76
Depth below M$\overline{3}$			20.0		28	28.0	27
Cephalic index			0.54		0.62‡	0.55	0.62

* Measurements taken in part from M. R. Thorpe, Mem. Peabody Mus. Nat. Hist., vol. 3, 1937.
† Composite value; measurements made on two specimens.
‡ Approximate.

Superior dentition	1	3	4	5	6	7	8
Superior dental series, C to M$\underline{3}$					74.0	77.0	70.0
Superior molar series	36.2	31.0	28.6	30.0‡	36.0	40.5	38.0
Superior premolar series	29.0				30.2	30.0	28.0
$\underline{C}$, anteroposterior diameter			5.4	3.4	4.0	7.3	4.0
$\underline{C}$, transverse diameter			4.4	2.5	4.0	6.7	6.0
P$\underline{1}$, anteroposterior diameter	6.9		6.0	6.5	7.3	7.1	6.3
P$\underline{1}$, transverse diameter	4.5		4.4	3.7	5.6	4.3	4.5
P$\underline{2}$, anteroposterior diameter	7.7				9.0	9.4	7.5
P$\underline{2}$, transverse diameter	6.5				7.5	7.0	5.8
P$\underline{3}$, anteroposterior diameter	8.1				8.0	9.2	7.5
P$\underline{3}$, transverse diameter	7.8				9.0	8.6	7.2
P$\underline{4}$, anteroposterior diameter	7.3				7.7	8.6	7.0
P$\underline{4}$, transverse diameter	9.2				10.9	10.4	9.0
M$\underline{1}$, anteroposterior diameter	10.7	8.6	10.2	8.7	9.7	12.3	12.0
M$\underline{1}$, transverse diameter	10.8	8.7	9.3	7.3	12.6	12.5	11.5
M$\underline{2}$, anteroposterior diameter	13.5	11.7	13.5	9.5	12.5	15.2	14.0
M$\underline{2}$, transverse diameter	11.9	11.5	10.8	8.7	14.1	14.1	13.0
M$\underline{3}$, anteroposterior diameter	15.7	14.2	13.9‡	12.0‡	16.4	18.6	15.0
M$\underline{3}$, transverse diameter	13.0	10.5	10.6	8.5‡	15.1	14.7	12.0
Molar-premolar index	0.80		0.80		0.84	0.74	0.74

‡ Approximate.

(Continued on following page)

Comparative measurements (in millimeters)—continued

Inferior dentition	2	4	5	6	7	8
Inferior molar series	36.0‡	...	...	39.0	43.0	42.0
Inferior premolar series	...	...	...	29.0	30.0	33.0
$\overline{C}$, anteroposterior diameter	...	...	4.0	...	4.5	2.0
$\overline{C}$, transverse diameter	...	...	3.1	...	6.5	...
P$\overline{1}$, anteroposterior diameter	4.3	6.6	4.7	...	8.0	5.0
P$\overline{1}$, transverse diameter	4.7	5.2	2.5	...	6.3	4.0
P$\overline{2}$, anteroposterior diameter	...	...	6.2	8.0	8.3	6.0
P$\overline{2}$, transverse diameter	...	...	3.0	4.0	5.3	3.0
P$\overline{3}$, anteroposterior diameter	7.2	...	8.1	9.0	9.5	9.8
P$\overline{3}$, transverse diameter	5.3	...	4.1	6.6	5.3	4.0
P$\overline{4}$, anteroposterior diameter	9.0	...	...	10.2	11.6	10.5
P$\overline{4}$, transverse diameter	6.0	...	...	8.0	7.0	5.2
M$\overline{1}$, anteroposterior diameter	8.4	9.5	10.4	10.1	10.7	9.7
M$\overline{1}$, transverse diameter	7.1	6.7	6.0	8.9	8.9	6.2
M$\overline{2}$, anteroposterior diameter	10.3	13.0	12.7‡	12.0	14.2	11.5
M$\overline{2}$, transverse diameter	7.3	7.5	7.5	10.2	9.5	6.5
M$\overline{3}$, anteroposterior diameter	17.4	12.0‡	...	20.0	21.7	19.0
M$\overline{3}$, transverse diameter	8.2	7.0‡	...	10.3	10.7	7.5

‡ Approximate.

Deciduous dentition	4	5
Superior deciduous series, length	23.0	....
Dp$\underline{2}$, anteroposterior diameter	6.2	....
Dp$\underline{2}$, transverse diameter	4.9	....
Dp$\underline{3}$, anteroposterior diameter	7.4	....
Dp$\underline{3}$, transverse diameter	7.1	....
Dp$\underline{4}$, anteroposterior diameter	7.8	....
Dp$\underline{4}$, transverse diameter	8.2	6.1
Inferior deciduous series, length	24.0	26.5
Dp$\overline{2}$, anteroposterior diameter	5.0	....
Dp$\overline{2}$, transverse diameter	3.6	....
Dp$\overline{3}$, anteroposterior diameter	6.9	....
Dp$\overline{3}$, transverse diameter	4.1	....
Dp$\overline{4}$, anteroposterior diameter	11.6	12.5
Dp$\overline{4}$, transverse diameter	5.8	5.4

Skeleton	C.I.T. No. 2681	*M. a. minimus*§
Length of left pes, calcaneum to distal end of metatarsal II	81.0 ‡	83.0
Calcaneum, length	34.8	35
Calcaneum, average depth	10	....
Calcaneum, average transverse diameter	7	....
Navicular, maximum depth	12.7	....
Astragalus, transverse diameter at distal pulley	11.6	12.2‡
Metatarsal II, length	41.0‡	42.0‡
Metatarsal II, dorsoventral diameter of shaft	3.8	....
Metatarsal II, transverse diameter of shaft	4.6	3.0
Metatarsal III, dorsoventral diameter of shaft	5.5‡	....
Metatarsal III, transverse diameter of shaft	6.5	7.0
Metatarsal IV, dorsoventral diameter of shaft	5.0‡	....
Metatarsal IV, transverse diameter of shaft	6.0‡	7.0
Metatarsal V, dorsoventral diameter of shaft	3.9	....
Metatarsal V, transverse diameter of shaft	3.7	4.0

‡ Approximate.
§ O. A. Peterson, Ann. Carnegie Mus., vol. 15, pp. 299–304, 1923.

Camelidae

(?) **Miolabis californicus** Maxson

Two lower teeth, C.I.T. Nos. 2682 and 2683, were obtained at C.I.T. Loc. 201. They represent a moderately worn fourth premolar and an unworn deciduous premolar of like position. Although the absence of a lower dentition in the type specimen precludes the possibility of direct comparison, these teeth are provisionally referred to *Miolabis californicus* Maxson.[67]

The size of the specimens presumably agrees with that of *M. californicus* as inferred from the upper dentition of the latter. $\overline{P4}$ is larger than in *Miolabis tenuis* Matthew[68] and roughly comparable to the corresponding tooth in *Oxydactylus floridanus* Simpson,[69] *O. longipes* Peterson,[70] and *Paratylopus cameloides* (Wortman).[71] Lack of mandibular material prevents comparison with *Miolabis transmontanus* (Cope), the genotype. Though typically compressed laterally, the tooth is broader, longer-crowned, and more robust than in *Paratylopus cameloides*. It has two roots, the posterior of which is strongly developed on the inner side. In spite of its fore-and-aft straightness, an asymmetrical appearance is caused by a marked constriction throughout the whole of the anterior portion.

The curvature of the posterior crescent is concentrated at the tooth corner, resulting in a straight posterior edge and a broad, slightly convex inner wall. The posterior valley appears only near the base of the crown. The most unusual character is the anterior narrowing of the tooth. This causes a compression of the crescent and creates a broadly concave inner wall, thus thrusting the anterior pit backward against the median crest. The external valley so well developed in *P. cameloides* and in *O. floridanus* is absent in the Tick Canyon specimen, its place being taken by the internal constriction noted above. The posterior pit is large and pear-shaped, and is situated centrally within the basin, as contrasted with its extreme posterior position in *P. cameloides*.

The narrow, sharp mesostylid is exceeded in prominence by a strong parastylid, hooklike in section. A corresponding prong on the interior corner is slightly less developed than the parastylid. Broad, low median ribs, extending downward from the posterior and anterior crests, mark the outer surface. No cinguli are present.

The deciduous tooth is a typical three-lobed fourth premolar, with very strong constrictions between the lobes. In shape it is not unlike the corresponding tooth in *Procamelus coartatus* Stirton,[72] although it is smaller in size.

Discussion

The teeth are referred to *M. californicus* not only because they were collected in the same stratigraphic horizon as the type, but because they have characters suggesting a comparable stage of evolution among the Camelidae. Although no mandibular material is available in the type specimen, the size, shape, and robust build of the permanent fourth premolar indicate rather primitive features characteristic of the skull described by Maxson.

[67] J. H. Maxson, Carnegie Inst. Wash. Pub. No. 404, paper VII, pp. 106–109, 1930.
[68] W. D. Matthew, Bull. Amer. Mus. Nat. Hist., vol. 50, pp. 191–193, 1924.
[69] G. G. Simpson, Florida Geol. Surv. Bull. 10, pp. 35–37, 1932.
[70] O. A. Peterson, Ann. Carnegie Mus., vol. 2, p. 446, 1904.
[71] J. L. Wortman, Bull. Amer. Mus. Nat. Hist., vol. 10, pp. 117–120, 1898.
[72] P. C. Henshaw, Carnegie Inst. Wash. Pub. No. 514, paper I, pp. 21–22, 1939.

It seems worthy of note that certain questions pertaining to the ancestry of *M. californicus* are clarified by the new information on the age of the strata in which it occurs. An age determination as upper lower Miocene rather than upper Miocene, as based on diagnostic equid and oreodont material, furnishes the explanation for the anomalous situation noted by Maxson,[73] wherein the Tick Canyon camel appeared to be more closely related to John Day and White River types than to *M. tenuis* and *M. longiceps* from the Sheep Creek beds of Nebraska. Moreover, *M. californicus*, which seems to have more primitive features than *M. transmontanus*, occurs in beds now known to be older than Mascall, from which the genotype is recorded. A late lower Miocene age thus satisfies fully all the conflicting stratigraphic and biologic evidence.

Comparative measurements (in millimeters)

1. (?) *Miolabis californicus* Maxson, C.I.T. No. 2682.
2. *Miolabis tenuis* Matthew, A.M. No. 18965.*
3. *Paratylopus cameloides* (Wortman), C.I.T. No. 128.
4. *Oxydactylus floridanus* Simpson, F.S.G.S. No. V-5238.†
5. *Oxydactylus longipes* Peterson, Car. Mus. No. 918.‡
6. *Procamelus coartatus* Stirton, C.I.T. No. 2316.§

	1	2	3	4	5	6
P$\overline{4}$, anteroposterior diameter	13.0	9‖	11.4	13.5	12	11.2
P$\overline{4}$, transverse diameter	6.7	6‖	5.3	7.5	7	5.5

	M. californicus (C.I.T. No. 2683)	*P. coartatus* (C.I.T. No. 2319)
Dp$\overline{4}$, anteroposterior diameter	19.2	25.5
Dp$\overline{4}$, transverse diameter, anterior lobe	5.1	5.7
Dp$\overline{4}$, transverse diameter, middle lobe	5.8	7.2
Dp$\overline{4}$, transverse diameter, posterior lobe	6.1	6.8

* W. D. Matthew, *op. cit.*, pp. 191–193, 1924.
† G. G. Simpson, *op. cit.*, p. 37, 1932.
‡ O. A. Peterson, *op. cit.*, p. 446, 1904.
§ P. C. Henshaw, *op. cit.*, p. 22, 1939.
‖ Approximate.

[73] J. H. Maxson, *op. cit.*, p. 108, 1930.

Plate 1

Parahippus maxsoni, n. sp.

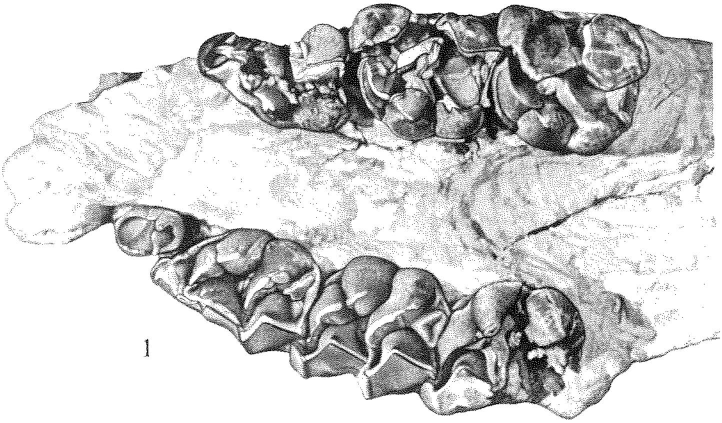
Fig. 1. Type specimen, No. 1385, palate, with deciduous dentition, Dp$\underline{1}$–Dp$\underline{4}$, occlusal view. × 1.

Merychyus calaminthus, n. sp.

Figs. 2, 2*a*. Imperfect mandible with lower dentition, No. 1384. Fig. 2, lateral view; fig. 2*a*, occlusal view. × 1.

Figs. 3, 3*a*. Mandible and lower dentition, No. 1829. Fig. 3, lateral view; fig. 3*a*, occlusal view. × 1.

Calif. Inst. Tech. Vert. Pale. Coll.
Lower Miocene, Tick Canyon, California.



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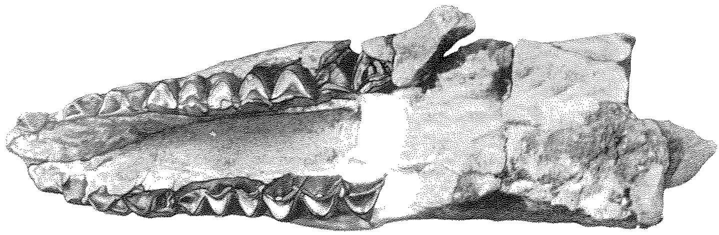

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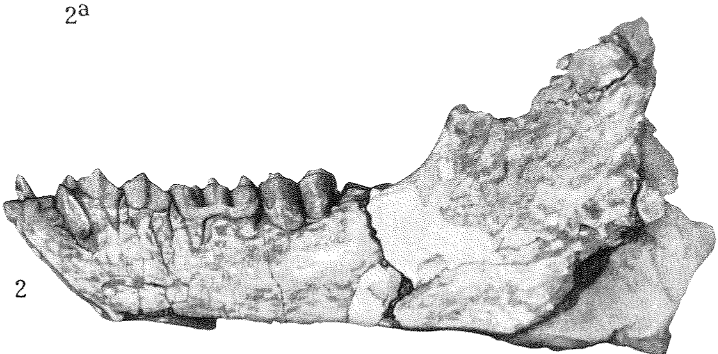

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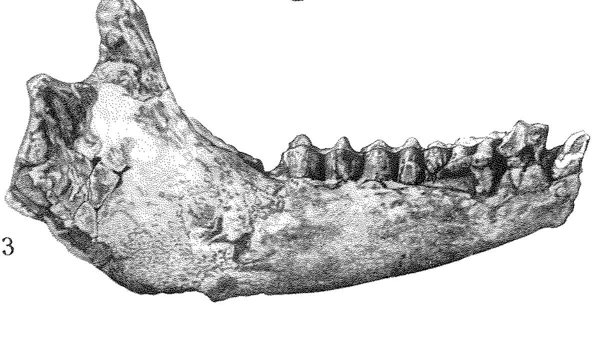
3a



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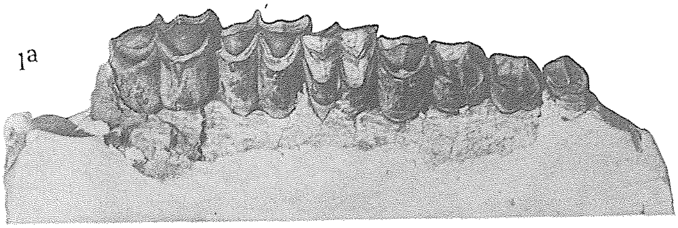

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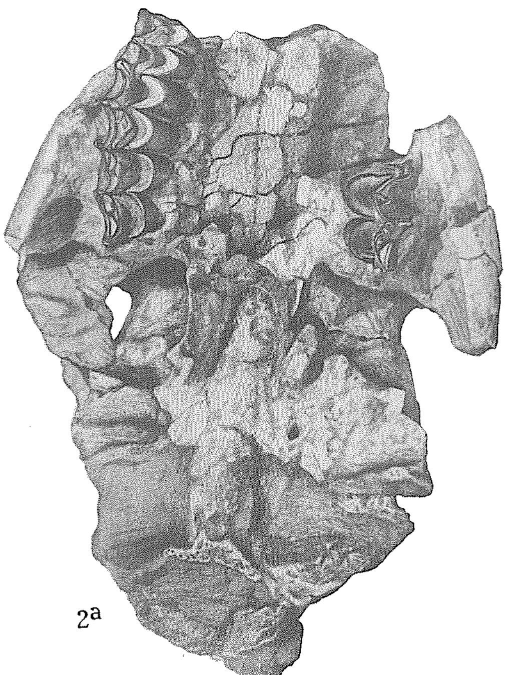
2



2a

Plate 2

Merychyus calaminthus, n. sp.

Figs. 1, 1*a*. Cotype, incomplete skull and upper dentition, No. 1382. Fig. 1, lateral view; fig. 1*a*, occlusal view. × 1.

Figs. 2, 2*a*. Cotype, middle and posterior part of skull, No. 1382. Fig. 2, dorsal view; fig. 2*a*, ventral view. × 1.

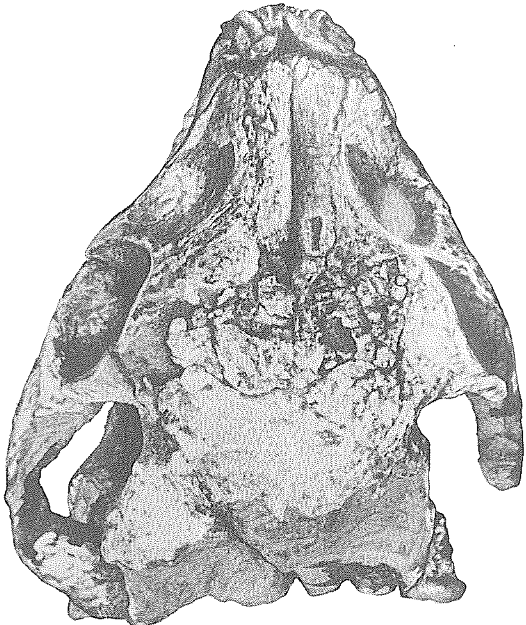
Calif. Inst. Tech. Vert. Pale. Coll.
Lower Miocene, Tick Canyon, California.

Plate 3

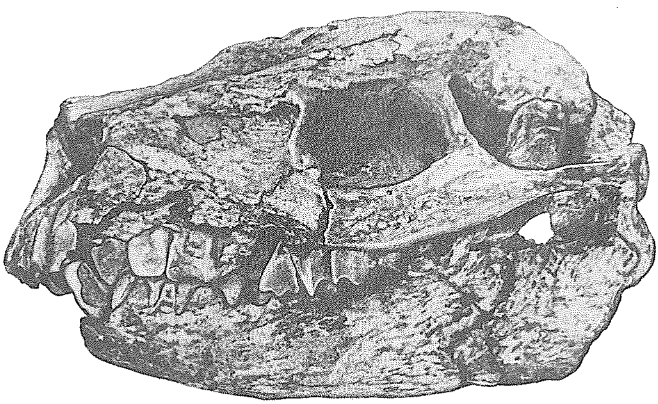
Merychyus calaminthus, n. sp.

Figs. 1, 1*a*. Cotype, skull and lower jaw, No. 1829. Fig. 1, anteroexternal view; fig. 1*a*, dorsal view. × 1.

Calif. Inst. Tech. Vert. Pale. Coll.
Lower Miocene, Tick Canyon, California.



1a



1