THE ORIGIN OF SOME CHROMITE DEPOSITS IN THE PACIFIC COAST REGION

A thesis

by

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In partial fulfillment of the requirements

for the degree of Doctor of Philosophy

California Institute of Technology

Pasadena, California

1943


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ONE CENT
UNITED STATES OF AMERICA

Orbicular and nodular chromite from McGuffey Cree
Siskiyou County, California.

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THE ORIGIN OF SOME CHROMITE DEPOSITS IN THE PACIFIC COAST REGION

ABSTRACT

Chromite deposits have long been regarded as products of magmatic segregation. As additional data have become available, other processes have been invoked to account for the observed facts. The writer, in the employ of the U. S. Geological Survey, has visited many of the known chromite localities in the western part of the United States and has collected much field evidence bearing on the problem of the origin of chromite.

Laboratory data furnishes much information which is not compatible with some of the field data. The temperatures of intrusion of ultramafic magmas, the time-sequence of crystallization of the various constituents, and the degree of liquid immiscibility are a few of the features indicated by field relations which are difficult to reconcile with laboratory data.

Spectrochemical investigations made in connection with this research suggest that the minor elements contained in the chromite molecule, namely, nickel, manganese, silver, vanadium, sodium and cobalt, show regular variations in amount when arranged in the time-crystallization sequence proposed in this paper; such differences are

thought to represent variations in the conditions of crystallization and deposition.

Each chromite deposit is regarded as having been formed under the influence of several forces. Under ideal conditions the resultant of these forces is thought to approach equilibrium, presumably consisting of a layer of olivine and small amounts of chromite in the base of the magma chamber, succeeded by a layer of chromite and topped by a large mass of olivine with small amounts of chromite; a thin layer of pyroxene may cap the mass if any is present. This ideal condition is seldom attained in nature, except in the stratiform deposits, and the degree of aberration from equilibrium conditions determines the characteristics of the ore deposit formed.

The origin of the various chromite deposits may be likened to quenching practice used to determine the constituents of a high temperature melt or liquid at various stages during its cooling cycle. Each chromite deposit is examined for evidence indicating at what stage in the process of cooling or crystallization of the ultramafic magma its development was arrested by relatively rapid cooling or quenching. Following physico-chemical principles, beginning with the ultramafic magma in a fully liquid state, many of the difficulties in understanding the formation of various types of deposits are partially explained.

THE ORIGIN OF SOME CHROMITE DEPOSITS IN THE PACIFIC COAST REGION

INTRODUCTION

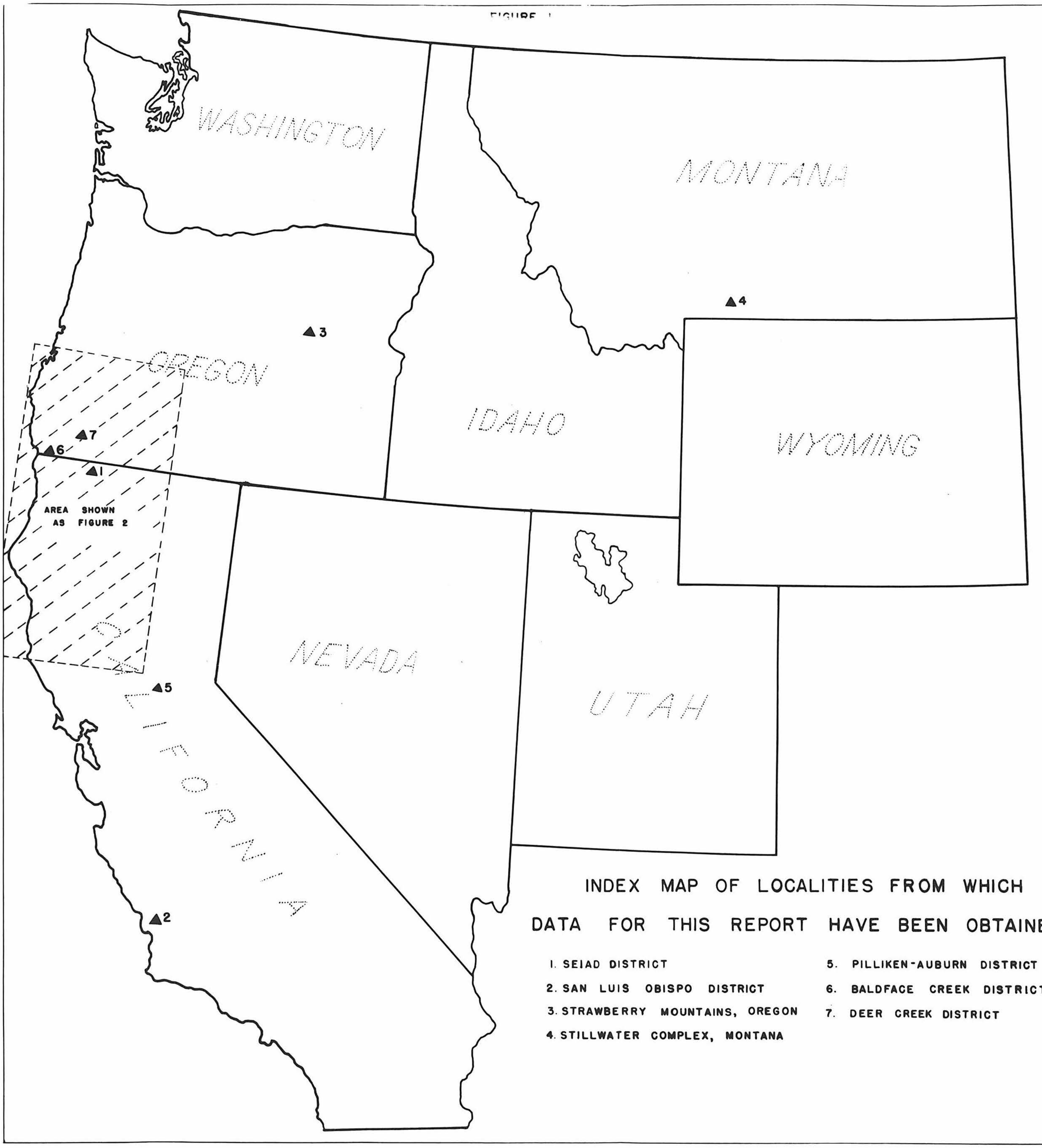
Chromite deposits have long been regarded as products of magmatic segregation. As additional data have become available, considerable doubt has been cast upon the segregation origin of all chromite deposits, and various other processes have been invoked to account for the observed facts. Many of the theories so far promulgated have resulted from one or another of two types of investigation: (1) an intensive laboratory study of specimens collected by individuals other than the investigators with little or no attention given to field occurrences; or (2), a detailed field investigation of a single deposit or district with no opportunity for comparison with other deposits or districts by the same individual. Obviously, this condition has led to a multiplicity of ideas regarding the conditions governing the deposition and concentration of chromite.

The recent search for domestic sources of strategic and critical materials conducted by the U. S. Geological Survey and U. S. Bureau of Mines, has afforded the writer an unique opportunity to visit and make detailed investigations of many localities and districts where chromite was formerly produced or where chromite is now being mined. The areas which have furnished most of the data for this paper may be listed in order of their relative importance as, (1) Seiad Creek mine and adjacent deposits in the Klamath Mountains, northern California; (2) San Luis Obispo district in the Santa Lucia Range of the Coast Ranges a few miles northwest of San Luis Obispo, California; (3) chromite deposits in the Strawberry Mountains, Grant County, Oregon; (4) Stillwater Complex, Montana; (5) El Dorado and Placer counties, California; and (6) scattered deposits in the Klamath Mountains of southwest Oregon, (see figure 1).

The districts visited are thought to represent an adequate cross section of ore types as determined from published mine descriptions. The areas listed are either marginal or sub-marginal producers during peacetime. However, since these deposits seem to show the same characteristics as higher grade ores it is hoped that the discussion and conclusions presented herein may assist in successful exploration in areas containing greater concentrations of chromite.

Acknowledgements: The writer is indebted to Dr. W. D. Johnston, Jr. of the U. S. Geological Survey for making possible work on so many different areas, and for constructive criticism in the early stages of the investigation. From colleagues and co-workers in the U. S. Geological Survey invaluable information, theoretical as well as

FIGURE 1



INDEX MAP OF LOCALITIES FROM WHICH DATA FOR THIS REPORT HAVE BEEN OBTAINED

1. SEIAD DISTRICT
2. SAN LUIS OBISPO DISTRICT
3. STRAWBERRY MOUNTAINS, OREGON
4. STILLWATER COMPLEX, MONTANA
5. PILLIKEN-AUBURN DISTRICT
6. BALDFACE CREEK DISTRICT
7. DEER CREEK DISTRICT

factual, has been gained. The writer is particularly indebted to Mr. G. A. Rynearson who collaborated in the early portions of this investigation, as well as to Dr. D. F. Hewett, Dr. J. W. Peoples, Dr. F. G. Wells, and Dr. T. P. Thayer, all of the U. S. Geological Survey. Dr. H. J. Fraser supervised the research and critically read several preliminary papers and short reports on individual districts. Dr. Peoples, Dr. Wells, Dr. Thayer, Dr. Fraser, and Dr. Ian Campbell have critically read this manuscript and offered suggestions which have materially aided in its preparation.

Previous work: Early workers considered that weathering of chromiferous silicate minerals released chromium which oxidized to form chromite deposits. Vogt[1/] in 1894,

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1/ J. H. L. Vogt, Zeitschr. prakt. Geol., pp. 384-393, 1894.

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suggested a magmatic origin for chromite deposits and by 1910 had developed the magmatic segregation hypothesis in essentially its present form. The magmatic segregation theory for the origin of chromite deposits postulated that chromite was the first mineral to crystallize, the source magma being ultramafic in composition. The early formed chromite crystals agglomerated or concentrated to form larger masses of chromite-rich material. The agglomeration or concentration was due to several phenomena, among them, gravity settling, convection currents, mutual attraction, and filter pressing.

Chromite investigations in this country received a great impetus when the reduction of imports during the first world war focussed attention on our domestic deposits. The genesis of most of these chromite deposits was interpreted according to the magmatic segregation theory.

In 1929 Sampson[2] and Ross[3] first questioned the

2/ E. Sampson, Econ. Geol., pp. 632-641, vol. 24, 1929.

3/ C. S. Ross, Econ. Geol., vol. 24, pp. 641-645, 1929.

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validity of this hypothesis as applying universally to all chromite deposits and L. W. Fisher[4] published the results

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4/ L. W. Fisher, Econ. Geol., vol. 24, pp. 691-721, 1929.

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of a detailed microscopic study of a variety of ores. Fisher divided chromite occurrences into three groups depending upon whether the chromite crystallized in the "early magmatic" period, in the "late magmatic" period, or in an hydrothermal state. Fisher's conclusion was that the major proportion of chromite deposits consist of "late magmatic" rather than "early magmatic" chromite as demanded by the magmatic segregation theory.

We are now in the midst of another world conflict and again the search for strategic metals has stimulated investigations of domestic chromite deposits. Nearly all recent papers have been published by the U. S. Geological

Survey as chapters in Bulletins 922, 931, or 935. These recent publications favor a relatively early crystallization period for chromite with a subsequent differentiation into typical magmatic segregation deposits, or, injection of already crystallized chromite into the higher and cooler portions of the magmatic chamber yielding a "late magmatic" type of deposit. Not all authors are in agreement and the present hypotheses are undergoing constant revision.

Method of investigation: From 1938 to 1941, inclusive, the author spent two to six months each year for the U. S. Geological Survey in field work on chromite deposits in California, Oregon and Montana. Some of the projects to which the writer was assigned were cooperative investigations by the Geological Survey and the U. S. Bureau of Mines. The exploration work of the Bureau of Mines gave unusual opportunity to study deposits in three dimensions.

Since the completion of the work with the Geological Survey, a year has been spent in office work and laboratory research on the various chromite ores investigated, the work culminating in the preparation of this manuscript.

The field mapping ranged from detailed plane table sheets of individual deposits on a scale of one inch to 40 feet to areal maps of districts on a scale of one inch to the mile. Where possible, underground workings were mapped on a scale of an inch to 40 feet or less. As much of the detailed work as possible was carried out with either transit or alidade since magnetic anomalies are usually strong in ultrabasic rocks, and compass or magnetic needles are correspondingly affected.

In the laboratory investigations nearly 300 thin sections of rocks from various localities have been examined. Samples made up of pure chromite from various localities were analysed spectro-chemically.

GEOLOGY

Chromite deposits in different localities have many features in common, perhaps more so than most other types of mineral deposit. The universal association of chromite with ultramafic rocks is almost unique in ore geology, and yet, continued investigations in this apparently simple and restricted field have resulted, not in a clear and concise picture, but only in controversy and complexity. However, before a description of chromite deposits is understandable some sort of a classification of occurrences is necessary.

Classification of chromite deposits

Sampson[5/] has suggested a classification of chromite

5/ E. Sampson, Symposium on ore deposits as related to structural features. Princeton University Press, pp. 110-125, 1942.

deposits primarily intended to focus attention on the structural features of chromite occurrences. The division is five fold: Evenly scattered, schlieren banded, stratiform, sackform, and fissureform. Although this classification undoubtedly has genetic significance, it serves a strictly structural or descriptional purpose; Sampson[6/]

6/ E. Sampson, op. cit., p. 111, 1942.

for example, observes that the sackform division may include chromite of such diverse origin as magmatic segregation and hydrothermal replacement. But in the interests of uniformity and simplification, Sampson's classification will be followed in this paper.

Sackform chromite deposits: Sampson states, "No English term of which the writer knows is satisfactory to describe this class of ore body, though the German term schauch, used by Lepez and meaning goatskin bag is expressive." Sackform is taken by the writer to include such terms as pod and lens, as well as more irregular shapes. Most of the world's production of chromite has come from sackform deposits. The outline is generally rounded although protuberances are common and some reentrants may be deep and narrow. Boundaries with the enclosing rocks are commonly sharply defined but may be vague and gradational. The sackform bodies are commonly found in highly altered or serpentinized rocks, although occurrences in only slightly altered rocks have been reported.

Stratiform chromite deposits: Stratiform deposits occur in igneous complexes produced by extreme differentiation. The rocks exhibit well-developed layering on both a large and small scale, and usually indicate that the layers were formed while in a nearly horizontal position. Compositionally they are distinctive, generally having large amounts of pyroxene and olivine with some feldspar in direct association with the ore mineral. These deposits are remarkable for their great stratigraphic regularity, continuous outcrops of individual zones often being traceable for a mile or more.

Schlieren banded chromite deposits: Schlieren banded chromite deposits consist of streaks of chromite scattered through olivine and serpentine. In the western states, those chromite deposits found in fresh rocks commonly occur as schlieren banded deposits. All gradations are found from vaguely defined accumulations of chromite grains to sharply defined layers traceable for many tens of feet. The majority of the deposits show a linear structure with only vaguely defined planar structures. Schlieren banded structures, where found in fresh rocks, are often difficult to distinguish from fissureform deposits.

Fissureform chromite deposits: Fissureform chromite deposits comprise the most controversial types. They are vein-like deposits localized along fissures and fractures, which in turn, usually parallel regional fracture patterns. The major interpretive problem is the question of whether the chromite localized the fractures or the fractures localized the chromite. It is noteworthy that the only two well-established localities for this type of deposit, the Thetford asbestos area in Quebec and the Selukwe chromite district in Rhodesia, occur in areas of completely altered and fractured rocks. This may or may not have genetic significance.

Evenly scattered chromite deposits: Evenly scattered chromite is well known as an accessory constituent in most ultramafic rocks. In some areas the amount of chromite may increase until it becomes advantageous to concentrate it to a marketable grade ore. All gradations exist between this type of chromite accumulation and other types of deposit, although individual deposits may or may not show such gradation. It has been the writer's experience that where chromite ore bodies occur in relatively fresh rocks they are often surrounded by a halo of evenly scattered chromite which decreases in abundance as the distance from the ore body increases; where deposits occur in serpentinized or highly altered rocks, the boundaries of the ore bodies are sometimes sharp, often slickensided, and disseminated chromite may be sparsely distributed.

Definition of terms

Ultramafic rocks are a group characterized by a high proportion of magnesium and iron. The chief original constituent minerals are olivine and pyroxene; varying proportions of these two minerals determine the broad class into which a given ultramafic rock may fall.

In this paper the ultramafic rocks are divided into four types. Those rocks containing 95 percent or more of olivine and 5 percent or less of pyroxene are called dunite; those rocks containing from 5 percent or more to 95 percent or less of pyroxene, the other essential constituent being olivine, are called peridotite; those rocks containing 95 percent or more of pyroxene and less than 5 percent olivine are called pyroxenite. Where the alteration of the constituent minerals has been complete or nearly so, the rock is termed serpentine.

Peridotites are further differentiated by means of the pyroxene they contain. This distinction yields a multiplicity of rock names such as saxonite, harzburgite, lherzolite, wehrlite, cortlandite, etc. Saxonite is the most common type containing essential amounts of ortho-pyroxene and olivine. In this paper rock descriptions are restricted to the general term peridotite.

Klamath Mountains, California and Oregon

The general geology of the Klamath Mountain region of northern California and southwestern Oregon is fairly well-known, but detailed mapping of parts of the area is incomplete. Published reports include work by Diller[7/], Hinds[8/],

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7/ J. S. Diller, U. S. Geol. Surv. Bull. 725, pp. 1-84, 1921; A. I. M. E. Bull. 153, p. 2018, 1919.

8/ N. E. A. Hinds, Univ. Calif. Bull. Dept. Geol., vol. 20, pp. 375-410, 1932.

Shenon[9/], Maxson[10/], Averill[11/], Rynearson and Smith[12/],

9/ P. J. Shenon, U. S. Geol. Surv. Bull. 846, 1933.

10/ J. H. Maxson, Calif. Jour. Mines and Geol., vol. 29, pp. 123-160, 1933.

11/ C. V. Averill, Calif. Jour. Mines and Geol., vol. 31, pp. 255-338, 1935.

12/ G. A. Rynearson and C. T. Smith, U. S. Geol. Surv. Bull. 922-J, pp. 281-306, 1940.

and Wells[13/].

13/ F. G. Wells, Preliminary geologic map of the Medford quadrangle, Oregon. Oregon Dept. of Geol. and Mineral Industries, 1939; Preliminary geologic map of the Grants Pass quadrangle, Oregon. Oregon Dept. of Geol. and Mineral Industries, 1940.

The Klamath Mountains are composed of schists, meta-volcanics, meta-sediments, and unmetamorphosed Jurassic sediments and volcanic rocks, complexly intruded by a group of peridotites, granodiorites and other igneous rocks. Several geologic periods are represented by the rock sequence, but paleontological or other evidence indicating specific age is extremely meagre.

The oldest rocks in the region are hornblende, chlorite and mica schists which are tentatively identified as pre-Cambrian in age. These are overlain by a complicated series of metamorphosed volcanic and sedimentary rocks which have yielded both Paleozoic and Mesozoic fossils. The so-called Jurassic rocks are sandstones and shales with interbedded volcanic flows and tuffs. Taliaferro[14]

14/ N. L. Taliaferro, Bull. Amer. Assoc. Petrol. Geol., vol. 27, pp. 109-219, 1943.

correlates these rocks with the Franciscan series of the California coast ranges, but mapping is incomplete.

A complex group of plutonic rocks intrudes the Paleozoic and Mesozoic rocks. This group may be divided into two parts; (1) a metamorphosed quartz-diorite, associated with the Paleozoic formations, and (2) peridotite and granodiorite, probably associated with the late Jurassic (?) intrusives which form the core of the Siskiyou Mountains.

On the flanks of the mountains, coarse clastic Cretaceous and Tertiary rocks are exposed. They resemble shore line or beach deposits laid down around an island formed by the older rocks of the mountains. Considerable exposures of volcanic rocks occur to the north and east.

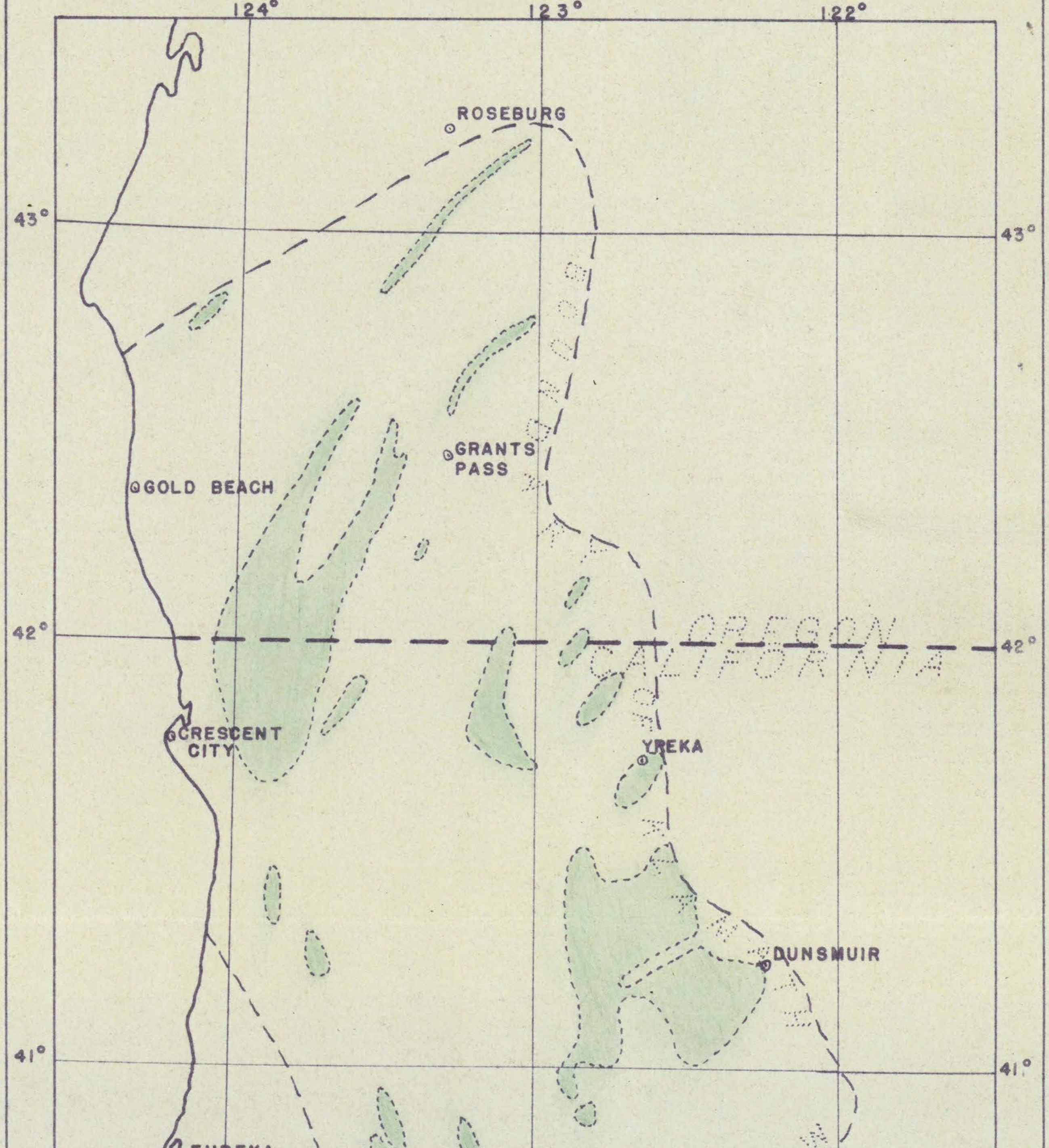
Recent gravels and alluvium partially fill the larger canyons; along the major streams remnants of old terrace deposits, some possibly Pleistocene in age, some auriferous, are found at various points high above the level of present river beds.

Detailed descriptions of other than ultramafic rocks will be omitted as bearing no relation to the chromite deposits.

<u>Peridotite and serpentine</u>: The principal exposures of peridotite and serpentine are found in the more northerly and westerly parts of the Klamath Mountains. The largest area lies in Curry County, Oregon, where several hundred square miles of ultramafic rocks are exposed. A tongue of this same mass extends southward into Del Norte County, California and is well exposed along the middle fork of the Smith River. Other sizable areas of ultramafic rocks are found in Shasta County, west of Dunsmuir, California, in Trinity County, west of Weaverville, California, and in the Seiad quadrangle, Siskiyou County, California; small scattered patches outcrop randomly throughout the mountains. (see figure 2).

The large mass of ultramafic rocks in Curry County, Oregon, contains few known chromite deposits, although several moderately sized sackform bodies are found in its southward extension in Del Norte County, California. Other chromite deposits are found in the northern part of the Seiad quadrangle where schlieren banded and injection type ore bodies occur in a northwest-striking discontinuous sill-like mass of peridotite (see plate I). Small scattered pods and lens-like bodies of chromite are sparsely distributed throughout the ultramafic rocks in Trinity, Shasta, Glenn, and Tehama Counties, and in the smaller serpentine masses in many parts of the mountains. Detailed discussion will be confined to the Seiad area where the rocks are generally fresher and more detailed work has been done.

FIGURE 2



SKETCH MAP OF THE KLAMATH MOUNTAINS SHOWING GENERALIZED AREAS OF ULTRAMAFIC ROCK OUTCROPS

ULTRAMAFIC ROCKS (INCLUDES DUNITE, PERIDOTITE, PYROXENITE, AND SERPENTINE)

The greater part of the Seiad ultramafic masses is dunite. Locally, due to an increase in the percentage of the rhombic pyroxene, enstatite, the dunite grades into saxonite peridotite. The dunite is relatively fresh; alteration to serpentine is most pronounced along joint planes and shear zones. Small bodies of completely serpentinized rock occur in several places, commonly not associated with the larger fresher rocks, but these may represent a different phase of the intrusion. The dunite is yellowish-green to greenish-black on fresh surfaces and weathers to a brownish to brick-red color. The accessory minerals tend to be more resistant to weathering and stand out in relief on the otherwise smooth surface of the rock. The more highly serpentinized rocks weather to a light green or greenish-brown color and are characterized by slick, curved surfaces with a waxy luster. As a rule, areas of dunite and serpentine may be recognized in the field by their associated reddish colored surface and soil and by the sparse vegetation they support.

The mineral composition of the dunite varies only slightly. Olivine is the chief constituent. Chromite and magnetite occur as accessory minerals, usually as sparsely disseminated grains, but sometimes in concentrations large enough to be of economic importance. Tremolite, talc, anthophyllite, chlorite, magnetite, and serpentine occur as products of regional metamorphism and hydrothermal alterations.

The age of the dunite and serpentine in the Klamath Mountains is not accurately known. They intrude so-called Jurassic rocks and are overlain by Cretaceous rocks thought to be Horsetown or Chico in age; probably they were intruded at the time of the widespread period of batholithic intrusion that occurred in the Pacific Coast region during late Jurassic or early Cretaceous time. The order of intrusion in the Seiad region appears to have been peridotite and dunite followed by granodiorite and pegmatite.

San Luis Obispo County, California

The geology of the San Luis Obispo quadrangle and adjacent areas has been adequately described by Fairbanks[15],

15/ H. W. Fairbanks, U. S. Geol. Surv. Geol. Atlas, San Luis Folio (No. 101), 1904.

Harder[16], Logan[17], Laizure[18], Franke[19], Allen[20], and

16/ E. C. Harder, U. S. Geol. Surv. Bull. 430, pp. 167-183, 1910.

17/ C. A. Logan, Calif. State Mining Bur. Bull. 76, pp. 103-104, 167-178, 1918; Calif. State Mining Bur. State Mineralogist's Report 21, pp. 507-510, 1925.

18/ C. McK. Laizure, California State Mining Bur. State Mineralogist's Report 21, pp. 507-510, 1925.

19/ H. A. Franke, Calif. Jour. of Mines and Geol., vol. 31, no. 4, pp. 406-409, 1935.

20/ J. E. Allen, Calif. Jour. of Mines and Geol., vol. 37, no. 1, pp. 139-144, 159-164, 1941.

Taliaferro[21]. The detailed geology of several chromite

21/ N. L. Taliaferro, California State Division of Mines Bull. 118, pt. 2, pp. 119-163, 1941.

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deposits has been worked out by the writer and Allan B. Griggs, of the U. S. Geological Survey[22].

22/ Clay T. Smith and Allan B. Griggs, U. S. Geological Surv. Bull. in preparation.

The oldest rocks in the region are sandstones, shales, chert, basic intrusives, and basaltic lava flows. These are known collectively as the Franciscan series and are of probable Jurassic age. Although Fairbanks[23], has stated

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23/ H. W. Fairbanks, op. cit., p. 3, 1904.

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that thin-bedded sandstones and shales of the Knoxville group overly Franciscan rocks with marked unconformity, Taliaferro[24] has recently held them to be conformable and

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24/ N. L. Taliaferro, op. cit., p. 126, 1941; op. cit., p. 109 et seq., 1943.

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states that the Knoxville is merely the upper portion of the Franciscan. The chromite deposits occur in serpentinized dunite and peridotite masses that intrude Franciscan and Knoxville rocks. Serpentinized rocks outcrop in discontinuous belts having a general northwest trend, and are found on the eastern slopes of the San Luis Range, in San Luis Valley, and in the western portion of the Santa Lucia Range (see plate II).

Tertiary sediments, predominately shales and sandstones, cap many of the higher ridges and form the bulk of the Santa Luica range farther north. Minor amounts of both dikes and lava flows ranging from rhyolite to basalt are found associated with these younger sediments.

No large alluviated areas are found within the Santa Lucia range, although the valleys on either side are well-filled with recent deposits.

Peridotite and dunite: Serpentinized ultramafic intrusives are widely distributed in the coast ranges of California. In the San Luis Obispo area these masses occur in discontinuous belts generally having a northwest trend. They are usually 2 to 3 miles in length and less than 1 mile in width. A large mass containing the better chromite deposits outcrops continuously for over 10 miles and attains a maximum width of 2.5 miles (see plate II). The chromite deposits are always associated with serpentinized dunite which occurs as irregular bodies in serpentinized peridotite, although accessory chromite occurs in both. Although the rocks are completely altered to serpentine, they are described as the original rock types to emphasize the chromite distribution.

No olivine remains in serpentinized peridotite and pyroxene crystals are represented by pseudomorphs of bastite. The peridotite contains about 40 percent pyroxene (bastite). On fresh surfaces the rock is dark green or brown with dark spots formed by pyroxene (bastite) crystals. With weathering the rock becomes a light tan or buff color and dark brown altered pyroxene crystals sometimes stand out in relief. However, the texture of the original rock is well-preserved, and unless it is badly sheared, peridotite is easily identified.

The dunite varies from dark green to black in color on fresh surfaces, and has a granular texture in hand specimen. It weathers to a smooth reddish brown to buff colored surface which local miners have called "buckskin". Olivine in dunite has been completely altered to serpentine minerals.

Dunite is found in fairly small irregular bodies grading outward into peridotite. Sharply differentiated bands of the two types, which are common in many ultramafic rocks, were not found, and nearly all exposures seen exhibited little structural relation to one another. The dunite bodies are commonly restricted in any direction to a few hundred feet. Generally, these bodies trend northwesterly within the peridotite parallelling the outlines of the larger bodies of ultramafic rocks, although locally, wide variations may be observed.

Fairbanks[25] states that peridotite intrudes both

25/ H. W. Fairbanks, op. cit., p. 6, 1904.

the Franciscan and Knoxville formation, but that at no place has it been observed to intrude younger rocks. Accordingly, the ultramafic rocks of the Santa Luica range are regarded as late Jurassic or early Cretaceous in age.

Diabasic and schistose rock masses are common in the ultramafic rocks. Some of the masses have a random orientation within the dunite and peridotite while others are found in definite alinement, such as might be expected with dikes. All the foreign rock material contains hornblende, chlorite, and plagioclase feldspar in varying amounts, and shows the effects of considerable metamorphism. Although some of the rocks are blocks of material which have been broken from earlier formations, others are dikes which cut the ultramafic bodies and are either contemporaneous with them or later. Field relations indicate that much of the material has been intruded as disconnected diabase dikes, although part of the discontinuity of the dikes may have been produced by later deformation of the serpentinized peridotite.

Strawberry Mountains, Grant County, Oregon

The geology of the Strawberry Mountains has been comprehensively treated by Lindgren[26/], and notes on the occurrences of chromite have been published by Lindgren[27/], Westgate[28/], Furness[29/], Allen[30/], and Thayer[31/].

26/ W. Lindgren, U. S. Geol. Surv., 22nd Ann. Rept., pt. 2, pp. 712-717, 1901.

27/ W. Lindgren, op. cit., p. 713, 1901.

28/ L. G. Westgate, U. S. Geol. Surv. Bull. 725, pp. 37-60, 1921.

29/ J. W. Furness, U. S. Bur. Mines, Mineral Resources U. S., 1925, pt. 1, p. 141, 1928.

30/ J. E. Allen, Oregon Dept. Geol. and Min. Ind. Bull. 9, pp. 53-69, 1938.

31/ T. P. Thayer, U. S. Geol. Surv. Bull. 922-D, pp. 75-113, 1940.

Thayer[32/] summarizes the general geologic features as follows: "The oldest rocks of the district are schists and layered diorite ....of Paleozoic age or older. The Mesozoic rocks, which consist mainly of sandstone, shale, chert, and limestone, contain some pebbly beds whose composition indicates that they were formed, at least in part,

32/ T. P. Thayer, op. cit., p. 78, 1940.

by erosion of the older rocks. Peridotite and dunite, partly altered to serpentine, are intrusive into both the Paleozoic and Mesozoic rocks. The ultramafics occur in two main belts (see figure 3), one of them near Canyon City and the other from 15 to 20 miles southwest of it. The chromite occurs in the peridotite and dunite. Tertiary lavas, tuffs, and conglomerates are widely distributed in the region surrounding the Strawberry Range. The area between the north base of the range and the John Day River is occupied by coalescing alluvial fans, which contain placer gold in the vicinity of Canyon City. Some fairly extensive areas of alluvium and some glacial deposits lie within the range."

Thayer[33/] has subdivided peridotite as described in

33/ T. P. Thayer, op. cit., p. 80, 1940.

this paper into two types, according to the amount of pyroxene originally present. Olivinite contains from 5 to 50 percent of pyroxene with the remainder olivine; peridotite contains from 50 to 95 percent of pyroxene together with olivine. In mapping the distinction between olivinite and peridotite can seldom be made and, as stated on page 11, the writer prefers to describe all rocks consisting of olivine with from 5 to 95 percent of pyroxene as peridotite. However, east of Canyon City the rocks are only about 50 percent serpentinized, and the various types are fairly readily distinguished. (See plate III.)

Dunite: The dunite is a dense uniform rock which weathers to a smooth reddish brown surface, and commonly has a well-developed platy jointing. Because of the weathering and jointing characteristics, outcrops are not often developed.

Peridotite: Peridotite weathers to a reddish brown or buff colored rock in which the pyroxene crystals stand out in relief from the olivine matrix. On fresh surfaces it is difficult to distinguish between dunite and olivine-rich peridotite without the aid of a hand lens.

Pyroxenite: Pyroxenite is coarse grained and crops out usually in the form of lenses yielding large reef-like masses. The pyroxenite is very resistant to weathering, but may show considerable alteration to serpentine.

Pyroxenite is found in the area east of Canyon City where it makes up portions of the banded and layered rock masses. The pyroxenite is generally confined to the borders of the ultramafic area, commonly as lenses in peridotite paralleling and within a few feet of the contacts.

Serpentine: In the Mt. Vernon serpentine belt, in the Field's Creek region and west of Canyon City, the rocks are completely altered to green serpentine and no traces of the original minerals remain. Distinction between different rock types has not been possible and these areas are mapped as serpentine. Although the transition from fresh material to green serpentine is gradational in some places, in others the contacts are quite sharp.

The rocks are much fractured and slickensided and weather to a dark green or reddish brown soil. In the serpentine the chromite occurs only as lenses or sackform deposits, whereas in the fresher rocks several of the occurrences are schlieren banded or show fissureform outlines. Large blocks of the Paleozoic and Mesozoic rocks are found as massive inclusions in the serpentine, some of them more than one hundred feet long. A noteworthy feature of these masses, which are usually siliceous, is the lack of reaction or metamorphic change between serpentine and inclusions.

In the Mt. Vernon serpentine area chrysotile asbestos is found in fibers nearly an inch long. The veins are small and discontinuous, but some mining has been attempted in one locality.

<u>Gabbroic rocks and pegmatites:</u> Banded gabbroic rocks occur interlayered with the ultramafic rocks in a layered part of the complex east of Canyon City, and also are found as small dikes and plugs cutting the ultramafic masses. At the Chambers mine the chromite ore bodies are cut by coarse basic pegmatite and medium to fine-grained gabbro dikes. Gradations between the pegmatite and gabbro

are found and both rocks seem to be related to the ultramafic rocks. Thayer[34/] considers the gabbro and pegmatite

34/ T. P. Thayer, op. cit., p. 85, 1940.

to be contemporaneous with the ultramafic rocks, although obviously representing the latest stages of the intrusion.

Structure: Much of the ultramafic rock mass is massive and apparently structureless, but in some of the region east of Canyon City banding is very prominent. The banding is of two types, either: (1) a layered structure consisting of alternating layers of dunite and peridotite or with increasing pyroxene, peridotite and pyroxenite, or (2) a linear arrangement of pyroxene crystals producing a banded pattern on certain surfaces. In the layered structures boundaries are gradational, although, if particularly contrasting rock types are involved, as dunite and pyroxenite, the structure is quite distinct and readily mappable. The linear elements are more obscure and not easily detected, although where found with the planar banding, the lineation lies in the plane of the layering. Linear arrangement of chromite crystals was noted in the chromite deposits at several localities.

The attitude of the layering varies greatly over the mass, and bears no relation to the chromite deposits as far as could be determined.

MINERALOGY

Chromite deposits are mineralogically simple; chromite is the only ore mineral, and in most cases, olivine is the predominant gangue mineral with small amounts of pyroxene. The gangue may be in all stages of transition to serpentine, a feature which oftentimes obscures the genetic characters of individual occurrences. Details of the mineralogy are perhaps best discussed in three groups: hand specimen mineralogy, thin section mineralogy, and minor elements determined by means of the spectrograph.

Hand specimen mineralogy

Olivine, pyroxene, chromite, and magnetite are the most abundant minerals associated with chromite deposits. Commonly the first two may be altered in part to serpentine, and iron oxide.

The olivine of chromite deposits is widely variant in texture. In the unaltered deposits it forms an equigranular mass of anhedral crystals, often showing considerable fracturing. It is readily altered to antigorite and chrysotile yielding slickensided surfaces along joint planes and other zones of dislocation; as alteration becomes more complete, the granular character of the rock disappears, and is replaced by a green, shiny, slick, aphanitic character.

Enstatite or bronzite is the common pyroxene associated with chromite deposits; hypersthene and augite are less common. Enstatite occurs as scattered crystals usually 5 mm. or more in length and sometimes including olivine and chromite. The pyroxene commonly alters to bastite preserving the outline of the original pyroxene crystal. In hand specimen it is difficult to determine the degree to which the pyroxene has been altered.

Chromite in hand specimen is dark brown to black and gives a brown streak; if crystals are present they are small octahedra commonly less than 2 mm. across. Some chromite is slightly magnetic and then is difficult to distinguish from magnetite. Chromite ore sometimes is dense, sometimes granular, and sometimes occurs as sparse disseminations through the gangue.

Magnetite always gives a black streak, is very magnetic and, if crystalline, has lustrous black crystal faces. It is distinguished from chromite by its much more intense magnetism and black streak. In chromite deposits there is commonly one percent of magnetite present.

Thin section mineralogy

Olivine in thin section shows random orientations, subhedral to anhedral crystal forms, and a characteristic pattern of irregular fractures. Olivine from some localities has a peculiar bladed intergrowth resembling twinning, and elsewhere shows long strings of similarly oriented crystals which have been described as ribbon structure by some observers.[35] Granulation is rare, although thin sections of olivine kindly furnished by T. P. Thayer of the U. S. Geological Survey from the Twin Sisters Range east of Bellingham, Washington, show mylonitization in a few limited areas. Crushing and granulation of olivine is usually obscured by later serpentinization.

35/ T. P. Thayer, personal communication.

Pyroxene in thin section rarely shows twinning and is often the first mineral to yield to alteration. Pyroxene is commonly the last mineral to crystallize and either poikilitically includes olivine and chromite, is molded on the olivine and chromite grains, or, fills interstices.

Chromite in thin section may be opaque or translucent in shades of reddish brown, deep red, or yellow. Little relation between color of chromite and percentage of Cr_2O_3 in the chromite molecule has been found, although the deep red chromite usually contains a greater percentage of Cr_2O_3 than does the yellow mineral. Chromite occurs in euhedral crystals, in irregular rounded masses and as massive aggregations of crystals. Much of the evenly-scattered chromite in the Pacific Coast deposits is fine-grained, and few deposits have been found where average grain diameters exceed 1 mm. Some chromite grains show serrate edges suggesting reaction after solidification. Relations between olivine, pyroxene and chromite indicate that chromite may be early, intermediate, or late in the crystallization sequence, while olivine is commonly early and pyroxene usually late.

Minor elements

Theoretically, pure chromite contains 68 percent of chromic oxide and 32 percent of ferrous oxide, but in nature this ideal composition is seldom attained owing to the presence of aluminum, ferric iron, and magnesium in the chromite molecule. Because of the presence of these other elements the formula for chromite is more accurately written as $(Fe,Mg)O\cdot(Cr,Al,Fe)_2O_3$. In addition to these major constituents, manganese, titanium, calcium, and silica are usually reported in amounts up to a few tenths of a percent. However, the spectrograph reveals other minor constituents which seem to be persistently associated with chromite regardless of the locality from which it is obtained, although present in amounts less than 0.01 percent. These are tellurium, vanadium, sodium, silver, potassium, cobalt, and nickel. Noteworthy is the lack of platinum group metals, even in specimens from the Stillwater complex, where platinum is known in other horizons in the complex.

semi-quantitative measurements of variations in the proportions of these minor elements are shown graphically in figures 4 through 12.

Figures 4 through 12 have as their ordinates the intensity ratios of each element investigated spectrographically. The intensity ratios were determined by the method described by Wilson[36]. They represent the relative amount

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36/ H. D. B. Wilson, Unpublished doctorate thesis, Calif. Inst. of Tech., 1942.

---

of a given element referred to a known standard, in this case, a standard lithium line. Since the intensities are based on the transmission values of the lines as photographed on the film in the spectrograph, they are proportional to the amounts of the elements present in the samples. However, the proportionality is not direct, and because only variation between samples was being investigated, the necessary working curves and standard samples for determining absolute quantitative percentages of the different elements were not included in this investigation. The numerical values of intensity ratios have no significance as far as actual percentage of different elements is concerned; however, an intensity ratio of 0.1200 represents twice as much of the element present as an intensity ratio of 0.0600. Thus, in the nickel diagram, figure 12, the sample from the Sweetwater mine with an intensity ratio for nickel of 0.2841 contains twice as much nickel as the sample from the Seiad Creek mine with an intensity ratio for nickel of 0.1449.

The abscissas of figures 4 through 12 are 21 localities grouped according to the hypothesis proposed in this paper. That is, each locality is assigned a position in the time-crystallization sequence and then its minor element intensity ratios are plotted accordingly. The time sequence ranges from a deposit which shows little or no concentration of chromite and no structural control to one in which field evidence suggests vein structure in the chromite ore bodies. The intermediate positions are determined by field evidence and approximately are divided into three groups: The typical sackform type of deposit with concentration of chromite dominant and little structural control; the schlieren banded type of deposit with concentration of chromite modified by structural control principally by flowage; and finally, approximating the fissureform type of deposit with concentration of chromite modified by fracturing, fissuring, and injection with possibly some replacement. It is significant that the main points of this sequence were worked out before the results of the spectrographic study were known; thus, the somewhat orderly arrangement of the minor elements partially substantiates the hypothesis presented in this paper.

Column one represents two rather widely separated samples from the Stillwater complex, Montana for comparison with the Pacific Coast types. Column 2 represents a sample of typical evenly-scattered chromite from the Seeley claims, San Luis Obispo County, California.[37] Column

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37/ C. T. Smith and A. B. Griggs, op. cit.

---

3 represents samples from the sackform bodies of the Chambers and Silver Lease deposits, Grant County, Oregon[38],

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38/ T. P. Thayer, op. cit., pp. 96-98, p. 110, 1940.

---

and from the evenly scattered and sackform bodies found at the Castro, Froom Ranch, Middlemast Ranch, and Pick and Shovel deposits, San Luis Obispo County, California.[39]

39/ C. T. Smith and A. B. Griggs, op. cit.

Column 4 represents samples from the Iron King and an unnamed prospect, Grant County, Oregon,[40] and from an un-

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40/ T. P. Thayer, op. cit., pp. 98-100, 1940.

---

named prospect near Callahan, California, all typical sackform masses. Column 5 represents samples from the schlieren-banded bodies of the Veta Grande, Veta Chica (Jumbo), Cerro Colorado, and Neptune claims, McGuffey Creek, Siskiyou County, California.[41] Column 6 represents sam-

[41] G. A. Rynearson and C. T. Smith, op. cit., pp. 304-305, 1940.

ples of orbicular and nodular chromite from the Mary Lou and Black Spot claims, McGuffey Creek, Siskiyou County, California.[42] Column 7 represents a schlieren-banded or

[42] G. A. Rynearson and C. T. Smith, op. cit., pp. 304-305, 1940.

fissureform sample from the Seiad Creek mine, Siskiyou County, California.[43] Column 8 represents a sample from

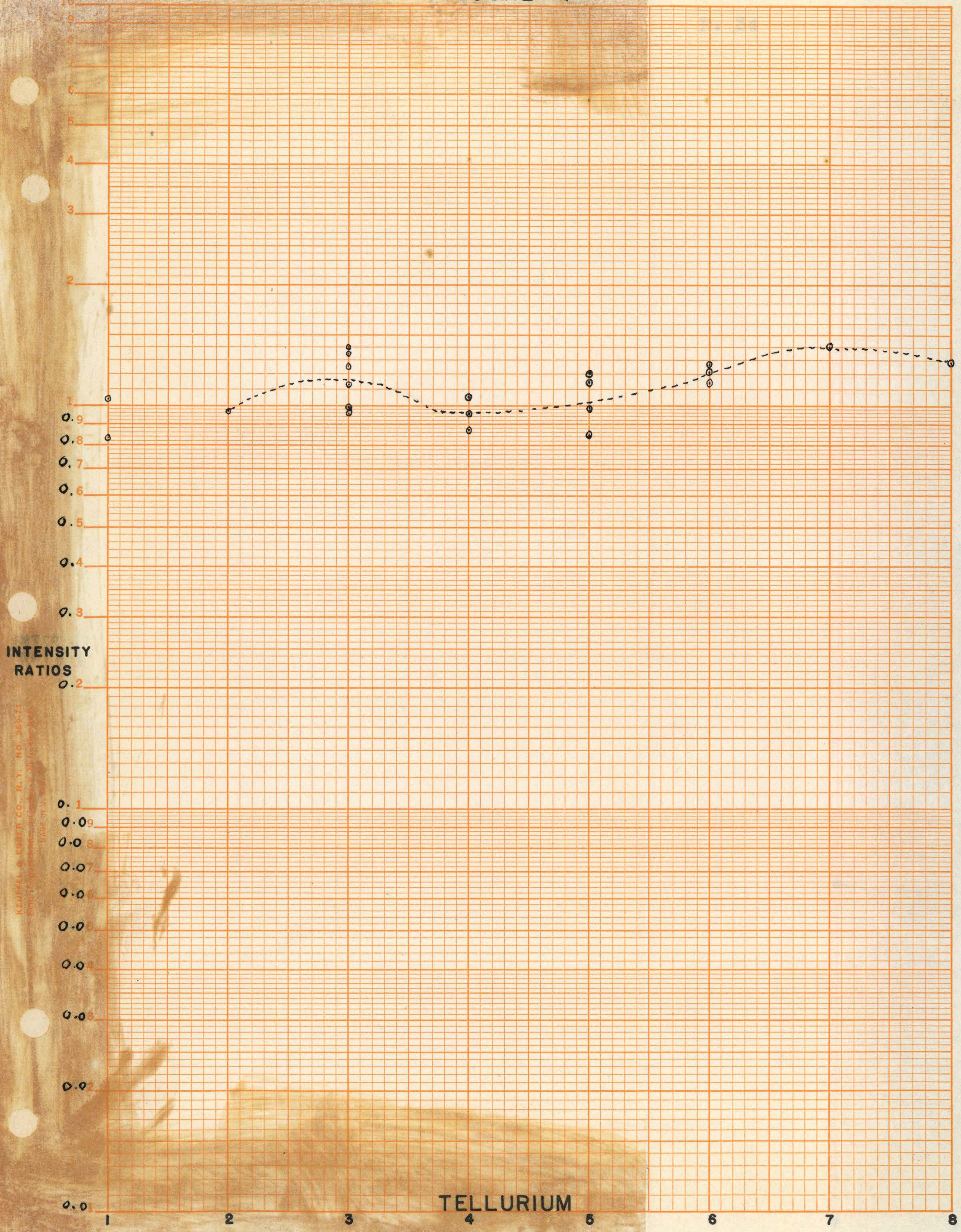
[43] G. A. Rynearson and C. T. Smith, op. cit., pp. 298-301, 1940.

fissureform (?) bodies at the Sweetwater mine, San Luis Obispo County, California.[44]

[44] C. T. Smith and A. B. Griggs, op. cit.

Manganese increases in amount appreciably from deposits believed to have formed early in the sequence to deposits which are so late in the sequence as to suggest injections and perhaps replacement of dunite by chromium-rich residual material. Although the manganese content of chromite from individual localities shows considerable spread, and makes impossible direct correlations between localities, the trend of increasing manganese content is

FIGURE 4



INTENSITY RATIOS
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.01
1
2
3
4
5
6
7
8
TELLURIUM

FIGURE 5

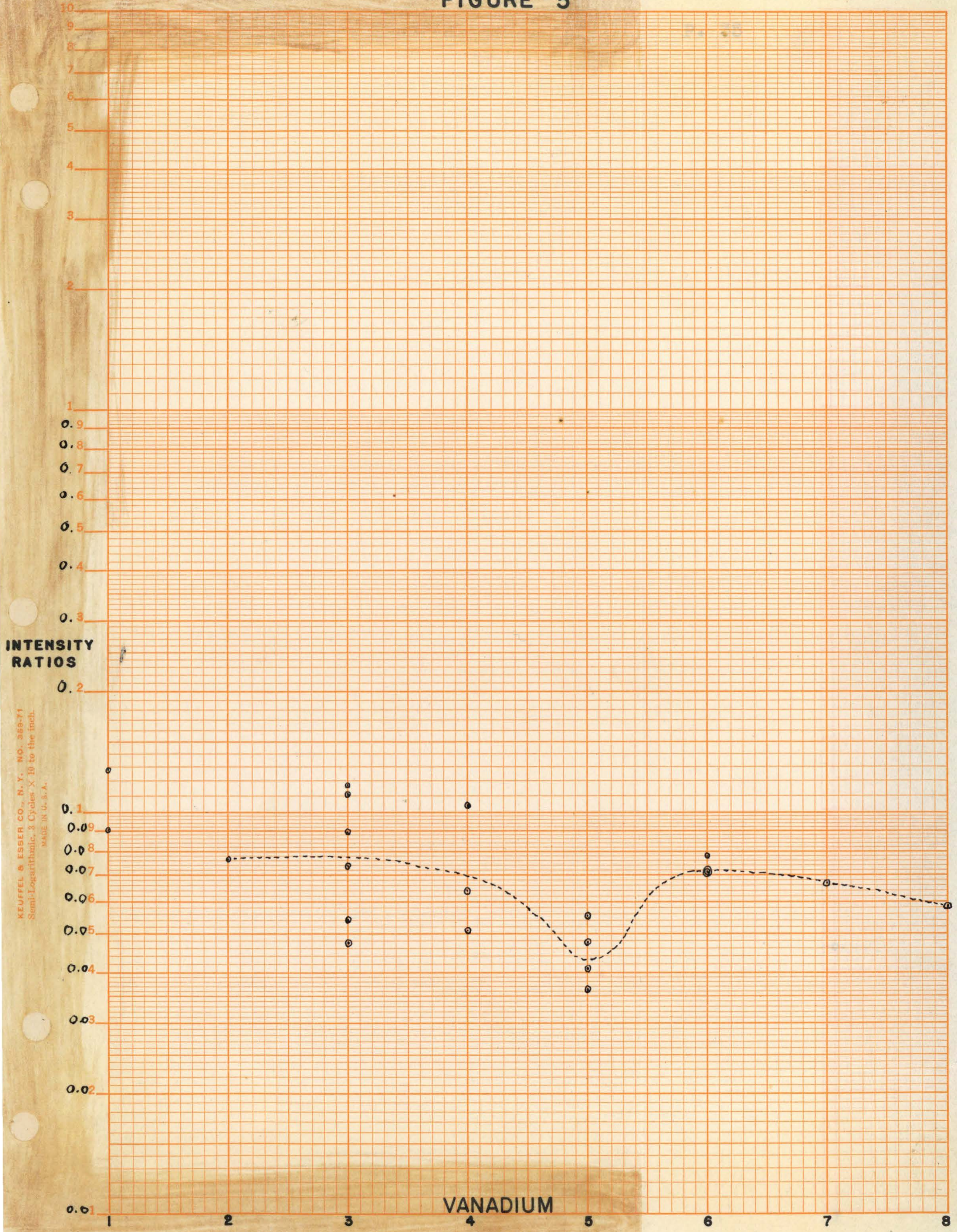
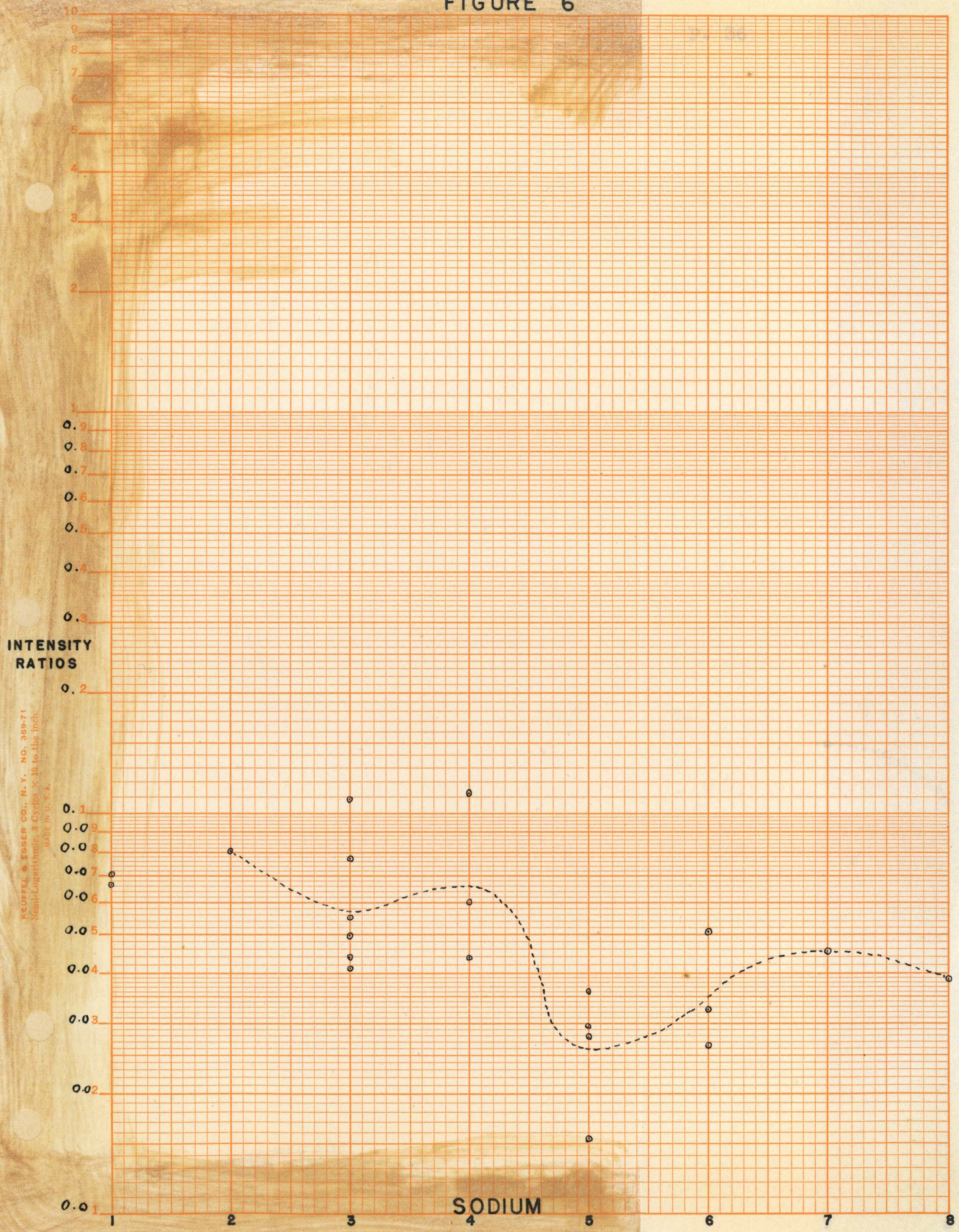
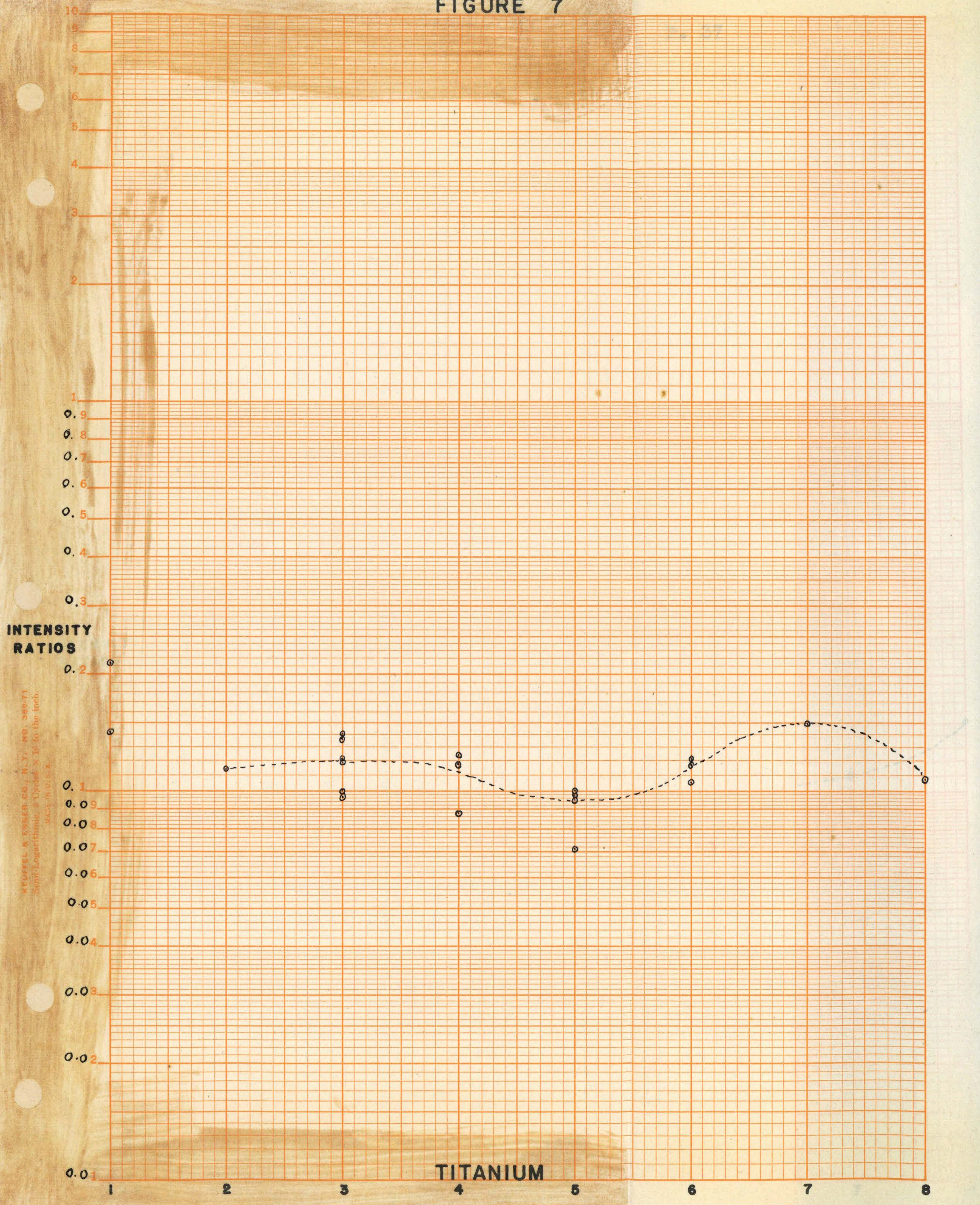

INTENSITY RATIOS
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
1
2
3
4
5
6
7
8
VANADIUM
KEUFFEL & ESSER CO., N. Y. NO. 359-71
Semi-Logarithmic, 3 Cycles X 10 to the inch.
MADE IN U. S. A.

FIGURE 6



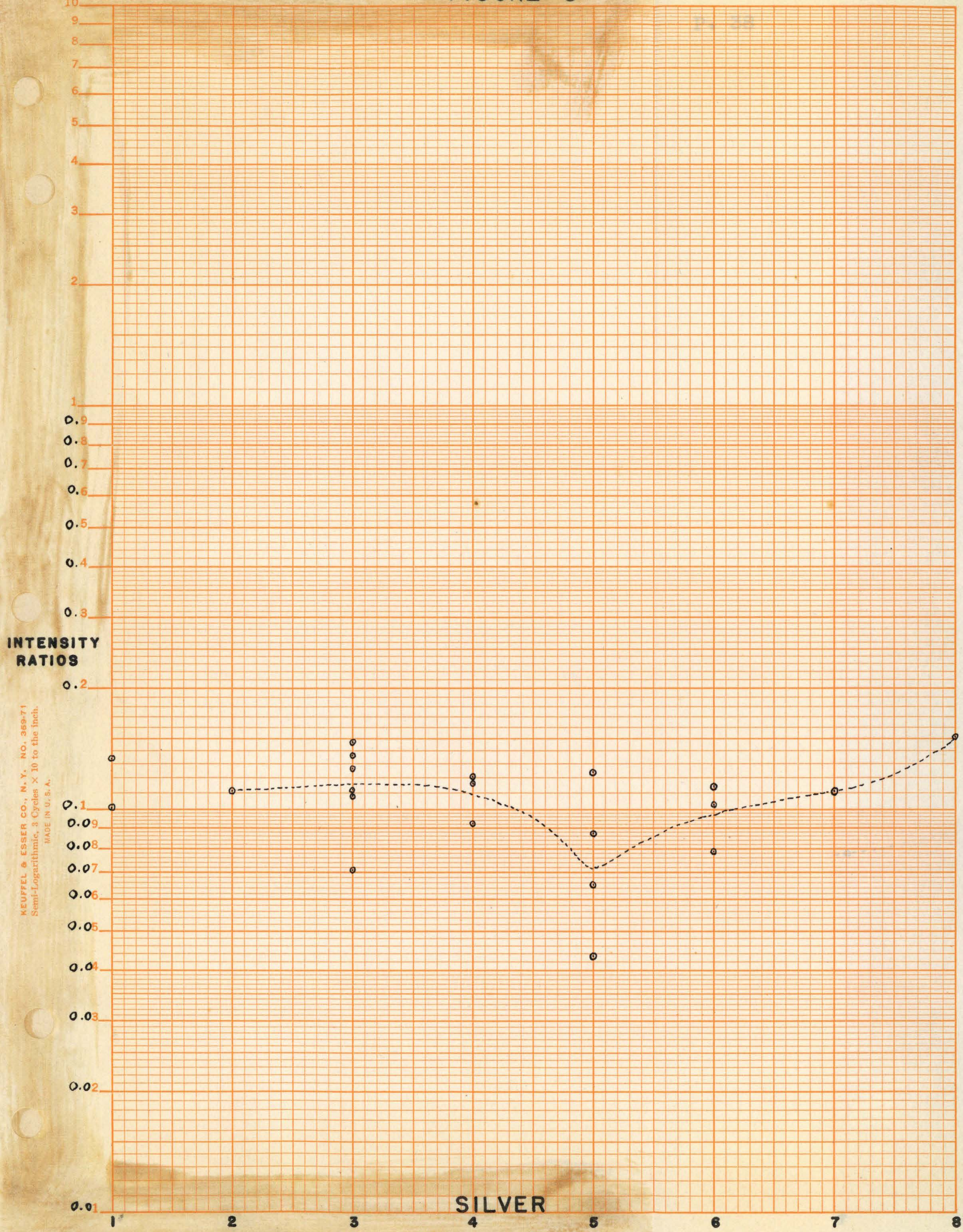
INTENSITY RATIOS
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
1
2
3
4
5
6
7
8
SODIUM
KEUFFEL & ESSER CO., N. Y. NO. 359-71
Semi-Logarithmic, 3 Cycles X 10 to the inch
MADE IN U. S. A.

FIGURE 7



INTENSITY RATIOS
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
KEUFFEL & ESSER CO., N.Y. NO. 359-71
Semi-Logarithmic, 3 Cycles X 10 to the inch.
MADE IN U.S.A.
TITANIUM
1
2
3
4
5
6
7
8

FIGURE 8



INTENSITY RATIOS
SILVER
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
1
2
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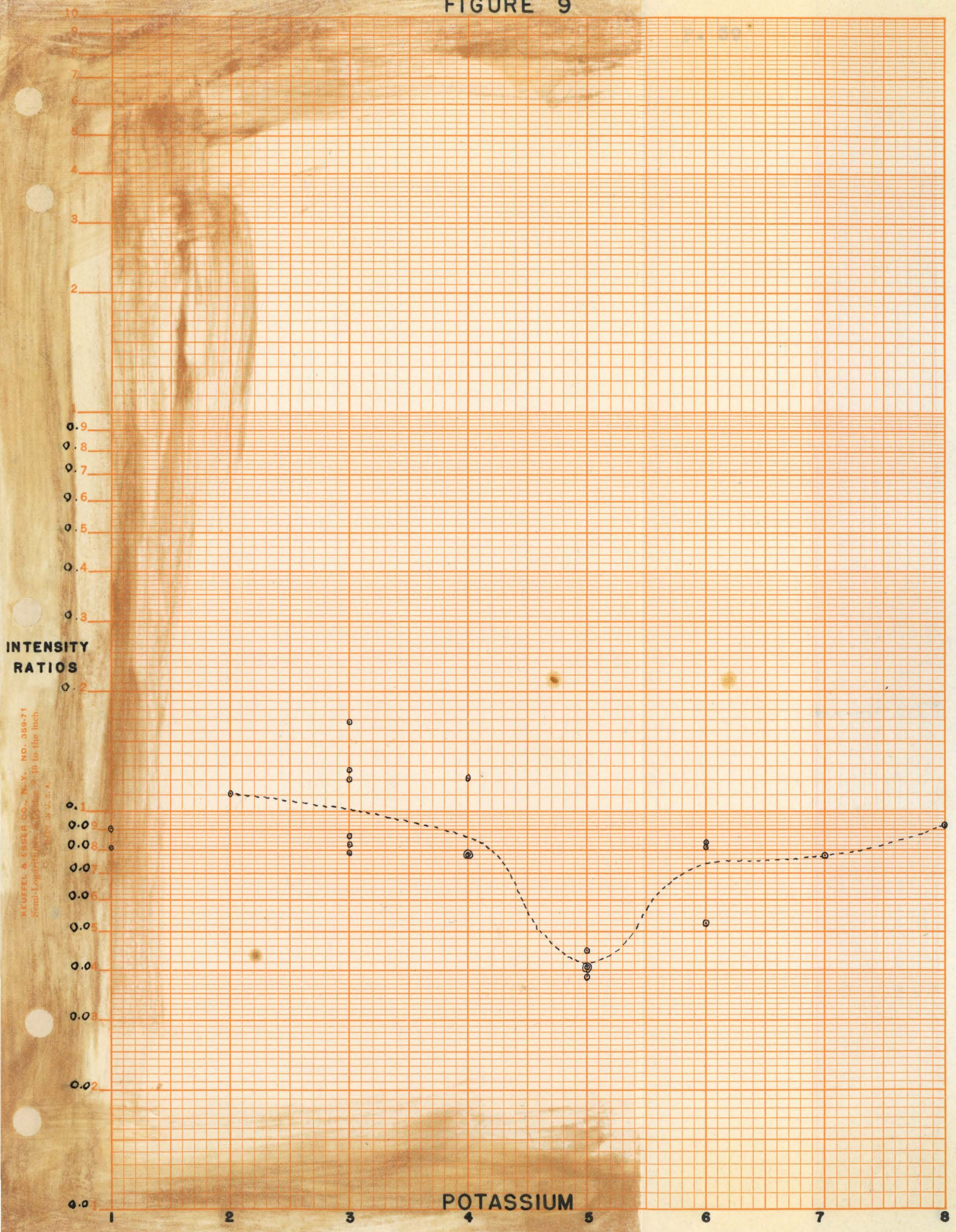
5
6
7
8
KEUFFEL & ESSER CO., N.Y. NO. 359-71
Semi-Logarithmic, 3 Cycles × 10 to the inch.
MADE IN U.S.A.

FIGURE 9



INTENSITY
RATIOS
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
1
2
3
4
5
6
7
8
POTASSIUM
KEUFFEL & ESSER CO., N. Y. NO. 359-71

FIGURE 10

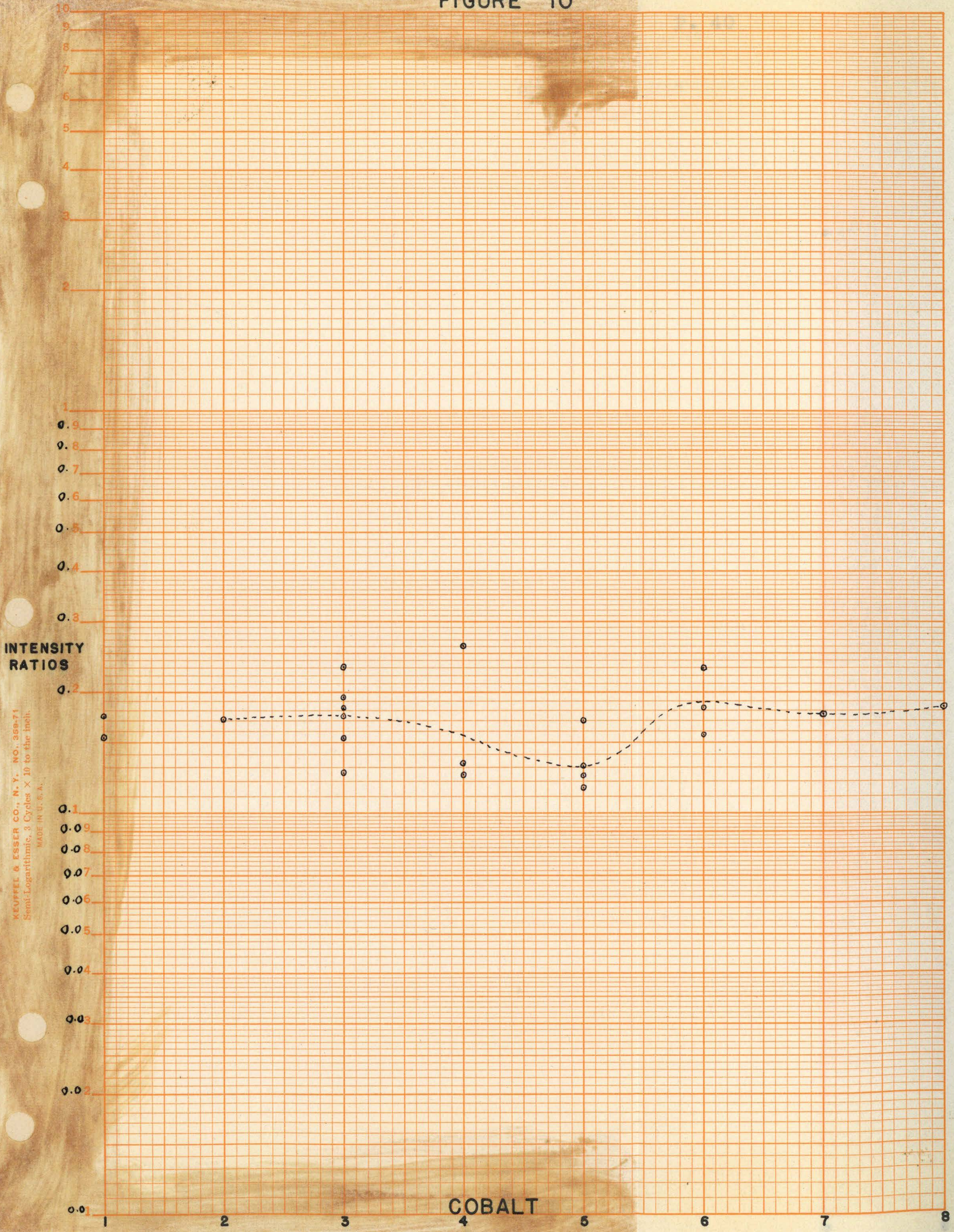
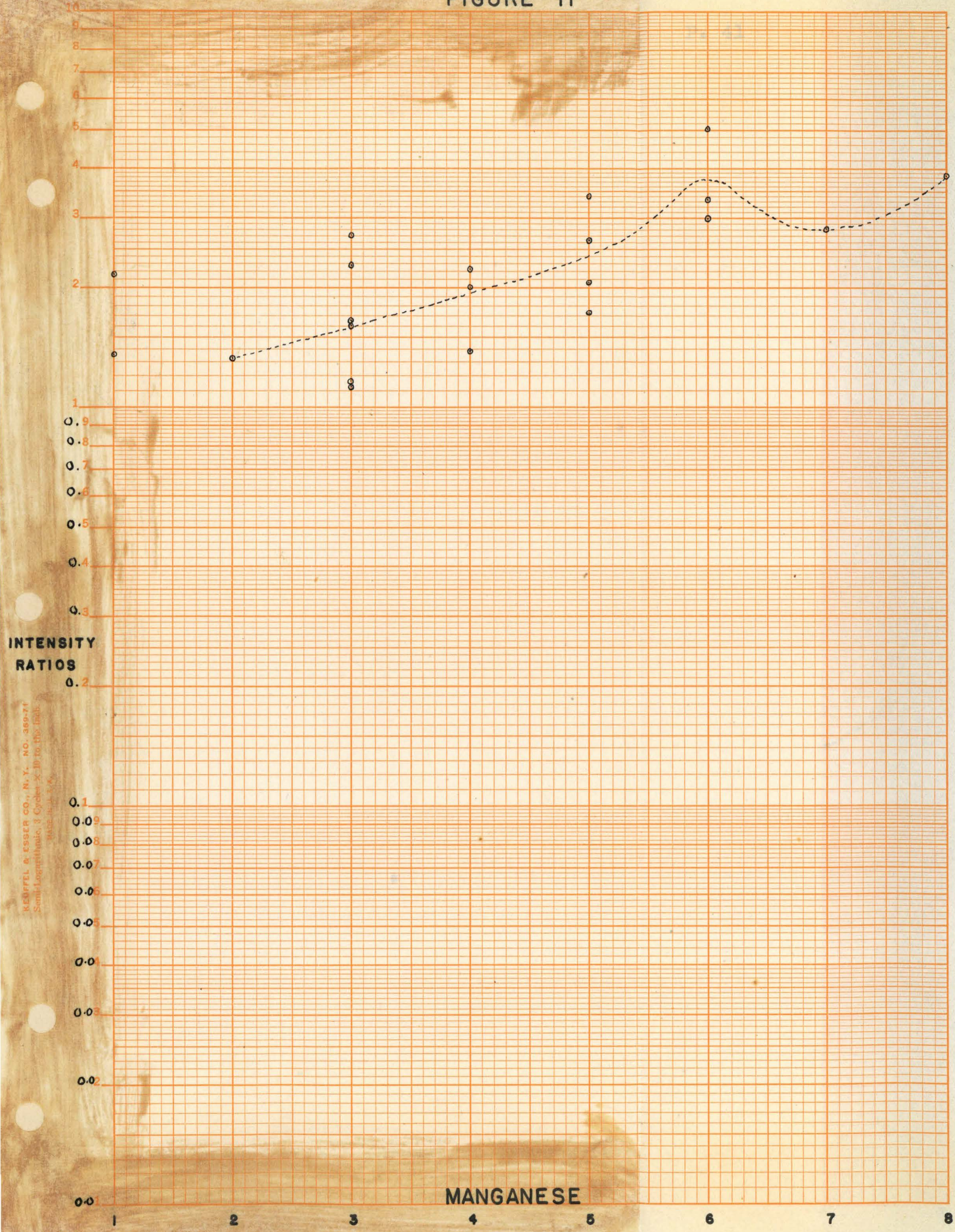
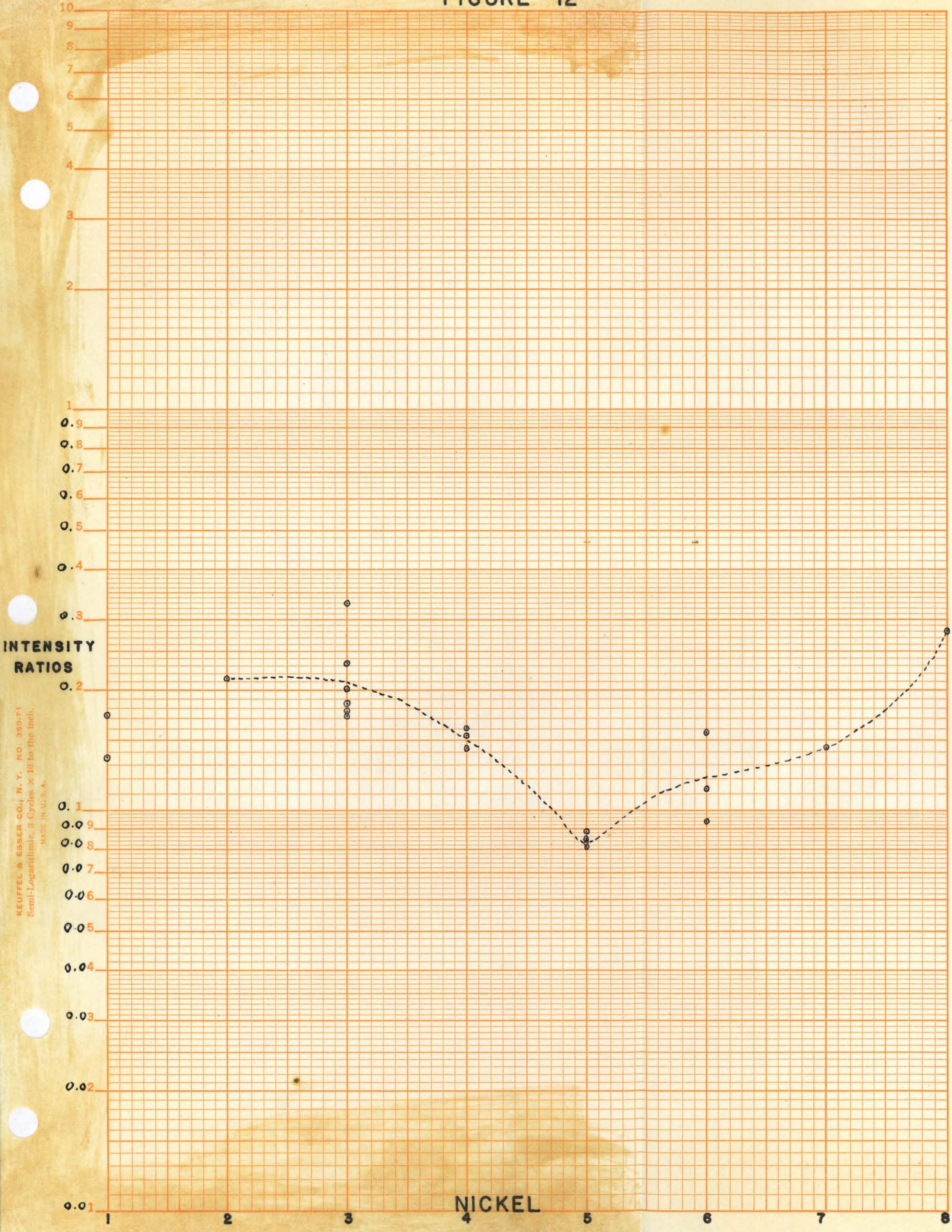

INTENSITY RATIOS
COBALT
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
1
2
3
4
5
6
7
8
KEUFFEL & ESSER CO., N. Y. NO. 359-71
Semi-Logarithmic, 3 Cycles X 10 to the inch.
MADE IN U. S. A.

FIGURE II



INTENSITY RATIOS
MANGANESE
KEUFFEL & ESSER CO., N.Y. NO. 359-71
Semi-Logarithmic, 3 Cycles × 10 to the Inch

FIGURE 12


INTENSITY RATIOS
NICKEL
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
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8
KEUFFEL & ESSER CO., N. Y. NO. 359-71
Semi-Logarithmic, 3 Cycles × 10 to the inch.
MADE IN U. S. A.

unmistakable. This is the only element which suggests a constant increase throughout the time interval considered.

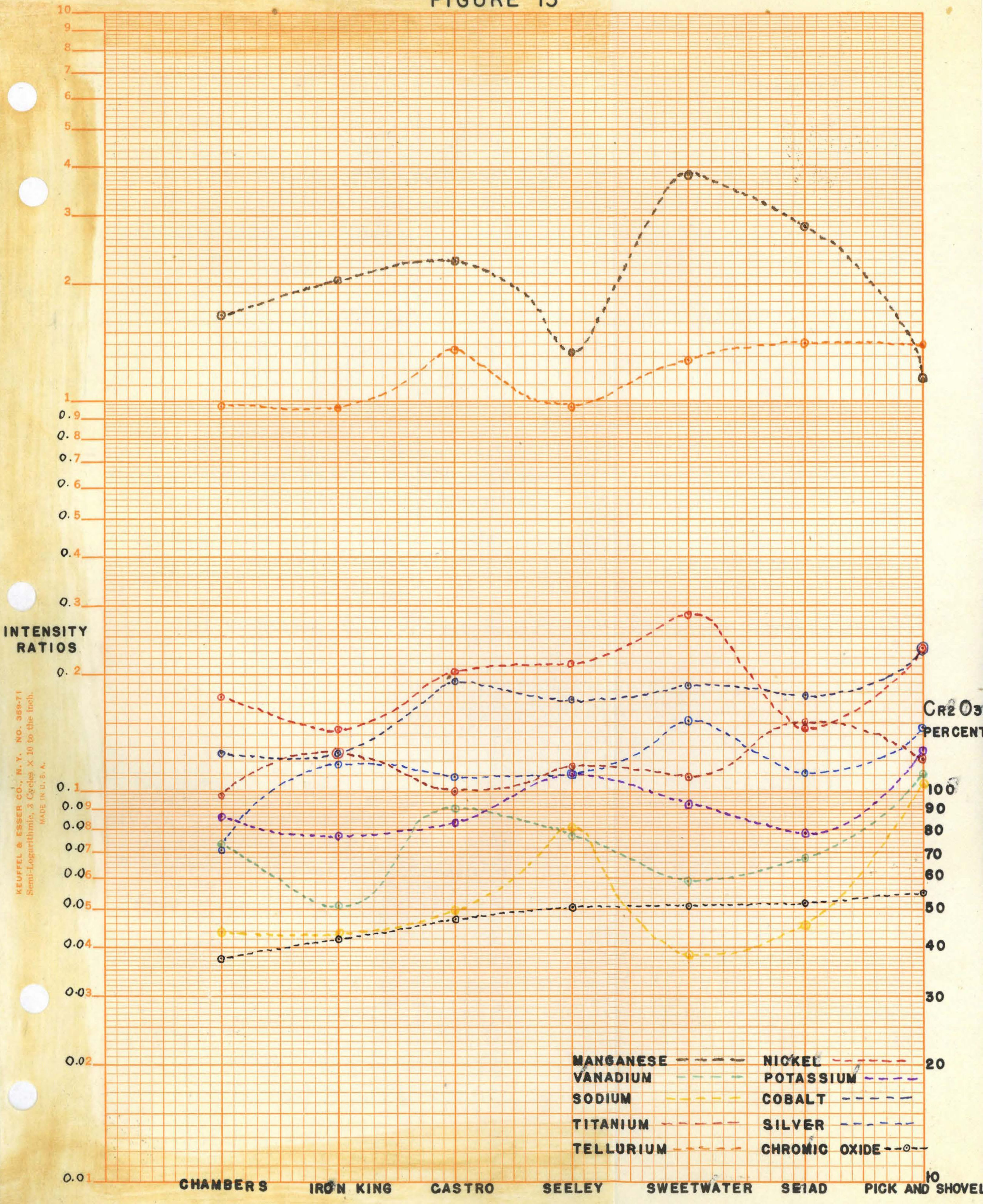
Nickel exhibits a u or v-shaped curve that, exclusive of manganese, is characteristic of nearly all the other elements investigated. The nickel content of the chromite molecule gradually decreases from the earliest crystallizing chromite to a minimum in the central part of the sequence and then rises to a content somewhat higher than the start of the sequence. Insufficient samples were investigated to determine to what factors this behaviour might be due.

The remainder of the curves are less significant. Each curve shows a minimum corresponding to the minimum shown by nickel and at nearly the same position in the time sequence. However, cobalt, silver, sodium and vanadium show less total variation in their curves than do the intensity ratios obtained from certain groups of localities. In the case of sodium and vanadium this is expectable because under the conditions prevailing in the determination of intensity ratios, the sensitive lines for these elements were so faint that accurate determination of their intensity values was not possible. It is significant that although the values may be in error by a considerable amount, the trend toward minimum values in the central portions of the curves is present. Titanium and tellurium show little variation and no particular pattern in their curves, and their content is but slightly affected by the time of chromite crystallization.

Figure 13 is a composite diagram in which intensity ratios of the elements investigated are plotted against Cr_2O_3 content of seven samples for which this latter information was available. The samples are plotted in order of increasing Cr_2O_3 content, ranging from 37.8 percent to 54.85 percent. The random variations are obvious when compared with figures 4 through 12.

Obviously, before conclusions can be drawn, many additional samples should be investigated. Depending on the size of a deposit, between 5 and 50 samples would be required to substantiate the trends suggested by the samples determined in this investigation. However, the curves for each element, although based on meager data, do suggest in the minor element content of the chromite molecule a regular variation when arranged in the time-crystallization sequence proposed in this paper; the variation is thought to reflect differences in the conditions of deposition and crystallization.

FIGURE 13



INTENSITY RATIOS
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
Cr_2O_3 PERCENT
100
90
80
70
60
50
40
30
20
10
CHAMBERS
IRON KING
CASTRO
SEELEY
SWEETWATER
SEIAD
PICK AND SHOVEL
MANGANESE
NICKEL
VANADIUM
POTASSIUM
SODIUM
COBALT
TITANIUM
SILVER
TELLURIUM
CHROMIC OXIDE
KEUFFEL & ESSER CO., N.Y. NO. 359-71
Semi-Logarithmic, 3 Cycles X 10 to the inch.
MADE IN U.S.A.

ALTERATION

The gangue minerals of chromite deposits are commonly altered to the groups of minerals generally classed as serpentine. In addition, tremolite or hornblende, talc, uvarovite, and kaemmererite or kotschubeite are sometimes present.

Early stage alteration products: Early alteration products are usually destroyed by some subsequent change in the rock mass. Possibly etched or rounded or resorbed crystals of early formed chromite may be preserved as early stage alterations, although alteration of this type is not usually apparent in hand specimen.

The principal alteration of ultramafic rocks visible in hand specimen is serpentinization. The serpentine may be green, yellow, brown, black or red and may or may not preserve the texture and structure of the original rock. Commonly two stages of serpentinization are visible, the more abundant being the early stage alteration product. Late veinlets of hydrothermal serpentine fill fractures and form cross-cutting stringers; quantitatively these are minor.

Two types of serpentine are known. The first and more common type is colored green to black, has slickensided joint surfaces and waxy luster, and yields no clues as to its original composition or structure. The second type often preserves the structures and textures of the original rock, is granular, and commonly colored brown to yellow or red. In some cases rocks that are completely altered to serpentine minerals are difficult to distinguish from fresh or partially altered rocks of similar original composition and estimation of the degree of alteration in hand specimen is largely a matter of experience.

In thin section serpentine derived from olivine is commonly the antigorite variety with occasional veinlets of chrysotile. All stages of conversion of olivine to antigorite may be observed in the various deposits, from the fresh olivine of the Twin Sisters Range, east of Bellingham, Washington, to the ultramafic rocks of the Santa Lucia Range northwest of San Luis Obispo, California, in which textures are well-preserved, but no shred of original olivine remains. Where serpentization is widespread and has not been localized by structural controls, chromite mineralization appears to be independent of the alteration. Structural controls which localize chromite deposition may tend to localize later serpentinization. Little alteration is observed on chromite grains, serrate edges suggestive of resorption or re-solution are found in a few localities, but most chromite grains in these localities are little affected. Platy pseudomorphs of bastite after enstatite are found, but often pyroxene is altered to antigorite, with no trace of original pyroxene remaining.

Late stage alteration products: Talc, tremolite, uvarovite, anthophyllite, and kaemmererite are secondary products found associated with chromite deposits; when present, they are commonly confined to minor cross-cutting fractures or post-ore shear zones. Tremolite and anthophyllite are usually developed during regional metamorphism of chromite bearing zones. Uvarovite seldom occurs in amounts sufficient to determine accurately its relation to associated minerals; kaemmererite is always associated with chromite and never with olivine or pyroxene and is derived from alteration of chromite. Kaemmererite usually occurs as fine-grained smears along tiny fractures and cracks in chromite, although crystals nearly an inch in diameter have been recovered from one locality in the Klamath Mountains. In some areas large masses of magnesite or other carbonates develop, although few localities contain appreciable quantities of magnesite associated with chromite.

In thin section late stage serpentine forms cross-cutting veinlets, the veinlets often containing minute amounts of chromite and magnetite. Some chrysotile also occurs as small veinlets.

STRUCTURE

Chromite deposits are structurally complex. As Sampson[45] has indicated in the classification referred to earlier in this paper, similar structures do not necessarily preclude dissimilar origins. Stratiform deposits are not known in the Pacific Coast region and these structures are ommitted from the discussion.

45/ E. Sampson, op. cit., p. 111, 1942.

Structures of chromite bodies may be discussed under three headings: first, structural relations of ore and gangue; second, size, shape, distribution, and structure of ore bodies; and third, deformation of chromite deposits.

Structural relations of ore and gangue

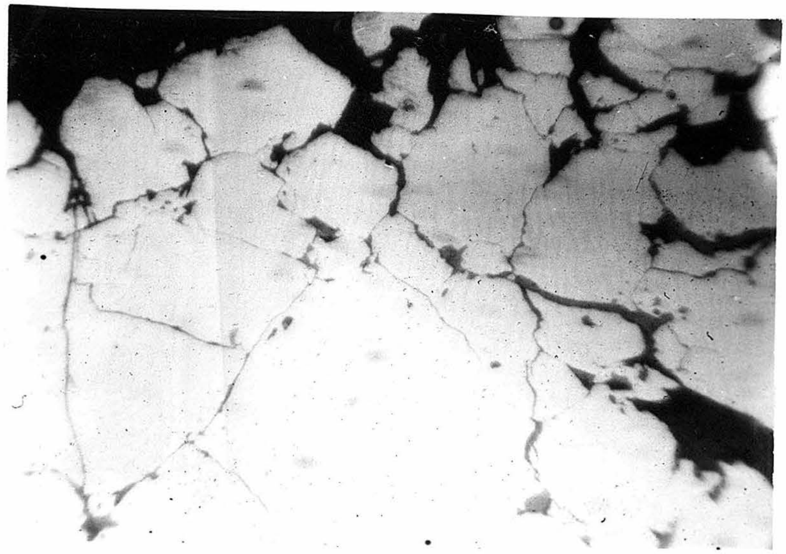
Structures confined to ore bodies are of necessity limited. The simple mineralogy of chromite deposits restricts variation even further, limiting structural considerations to features shown by olivine and chromite grains. Several peculiar textures are exhibited by nearly all chromite deposits, namely, linear and planar banding, nodular patterns, and orbicular structure. Some of these structures may have genetic significance, while others apparently occur regardless of the origin of the deposit in which they exist.

Massive chromite: Chromite in a single deposit may range from accessory grains scattered through dunite to massive aggregations of nearly pure chromite. (See figure 14). The aggregations are composed of anhedral grains of chromite, many of the grains comprising several crystal units; a few individual crystals of chromite are always found in massive ore.

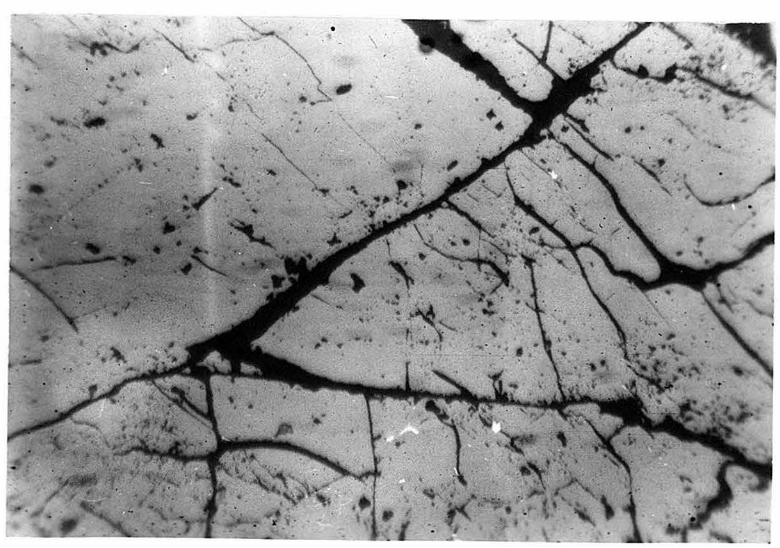
Evenly scattered chromite: Evenly scattered chromite occurs sparsely distributed throughout most ultramafic rocks. Where it is sufficiently abundant to warrant beneficiation as an ore of chromium, the grains may be euhedral or anhedral, and may be included in, molded around or replace olivine grains. Where evenly scattered chromite is a minor accessory, it commonly shows euhedral outlines.

Banded chromite: Banding is of common occurrence in chromite deposits; both linear and planar parallelism of chromite grains occurs, as well as, linear and planar parallelism of pyroxene or amphibole crystals in dunite or peridotite. The banding occurring on certain surfaces due to the exposure of traces of these linear and planar structures is hereinafter referred to as linear or

Figure 14



Photomicrograph of polished section of massive chromite from the schlieren banded and injection type deposit on Seiad Creek, Siskiyou County, Calif. Magnification approximately 50 X.



Photomicrograph of polished section of massive chromite from a sackform deposit near Auburn, Placer County, Calif. Magnification approximately 50 X.

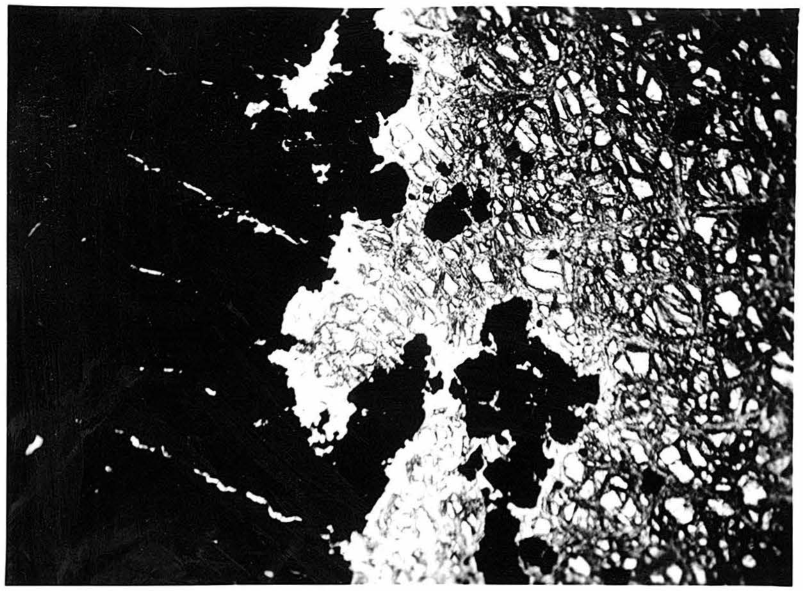
planar banding.

The chromite layers or streaks consist of alternating zones containing varying amounts of banded chromite and olivine. Where planar banding occurs the edges of the bands are sharply delimited, although, along the boundaries of the bands chromite grains are seen to cross cut the olivine grains, and sometimes olivine grains project into the chromite bands (see fig. 15a). The chromite bands are usually not more than a quarter of an inch wide but occasional zones are found with alternating layers of chromite and olivine as much as several inches to one foot in width. Single streaks or layers are not continuous for more than fifteen or twenty feet, but pinch out as another layer a few inches to one side or the other reaches a maximum width. In some cases banded ore may grade into massive ore, which may show a vague lineation or planar banding. Elsewhere, banded ore may grade outward into evenly scattered ore with linear structure, or directly into barren dunite.

Where pyroxene or amphibole banding occurs, it is very similar to chromite banding although the bands generally are larger; sharp boundaries are common due to elongation of pyroxene and amphibole crystals parallel to the planar or linear structure of the layer.

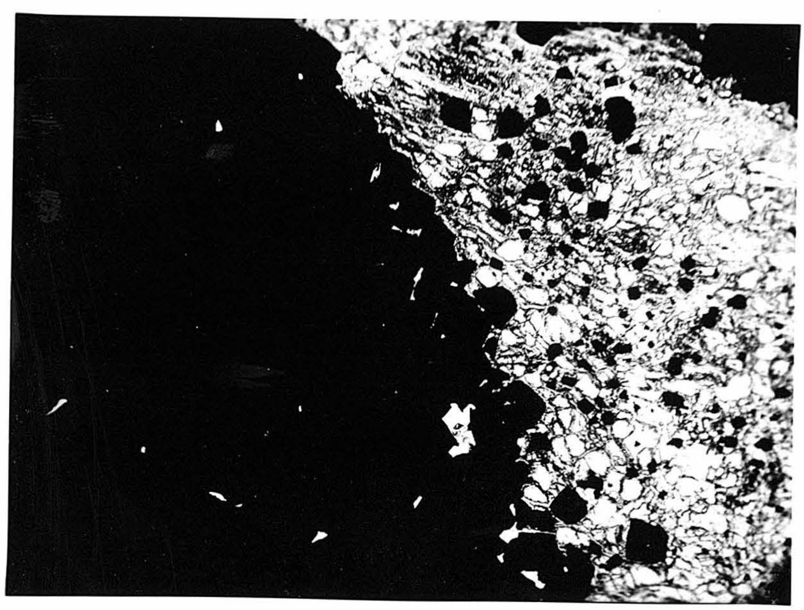
Nodular chromite: Chromite often occurs as rounded spherical aggregates to which the term nodular ore has

Figure 15



a

Photomicrograph of thin section of chromite band in dunite. Note interlocking grains at edge of band. Magnification approximately 25 X.



b

Photomicrograph of thin section of chromite nodule in dunite. Note euhedral grains at edge of nodule. Magnification approximately 25 X.

been given. The nodules may be perfect spheres but more commonly are ellipsoidal, occasionally distributed in an orientation paralleling the long axes of the ellipsoids. They vary from about 5 mm. up to 20 mm. in diameter. The nodules are embedded in a matrix of serpentinized olivine similar to other ore types. The nodules have a rough surface formed by the projecting edges of crystals and crystal faces, although the variation between points on the surface of the nodule is small compared to the size of the nodule. (See figure 15b). Pyroxene crystals are sometimes found occurring with nodules of chromite, and pyroxene may also show nodular form when occurring in this manner. The origin of the nodular structure is obscure; the nodules may result from crystallization of liquid globules produced by liquid immiscibility, or they may be the result of replacement of earlier formed structures now obliterated.

Orbicular chromite: Orbicular chromite consists of a center composed of chromite crystals surrounded by a shell of olivine, imbedded in a matrix of serpentine, chromite, and olivine. One or more alternating shells of chromite and olivine are sometimes found between the center and outside of the orbicule. In some specimens chromite interstitial to the orbicules is more abundant than chromite in the centers and in such cases orbicular rock is good ore. More often interstitial chromite is mixed with olivine and serpentine and is less abundant than the chromite in the center of the orbicule, and the rock is low grade.

The orbicules are sometimes spherical but more often are ellipsoidal or cylindrical; they are commonly about 20 mm. long and from 5-10 mm. in diameter. Flattening and elongation of the orbicules is parallel to the dip and strike of the banding in the chromite with which the orbicules are associated. Occurrence of orbicular and nodular chromite together suggests genetic similarity as also does their appearance in hand specimen (see frontispiece).

The origin of the orbicular ore is even more obscure than the nodular ore. Many recent workers[46/] have

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46/ H. Backlund, Jour. Geol., vol. 46, pp. 339-396, 1938.
P. Eskola, Jour. Geol., vol. 46, pp. 448-485, 1938.
Balyankin and Petrov, Min. Abstr., vol. 6, p. 304, 1935-37.
G. E. Goodspeed, Amer. Miner., vol. 27, pp. 37-47, 1942.

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felt that orbicular structures are the result of replacement rather than a special type of crystallization as was previously supposed. The writer is inclined to consider orbicular chromite the result of replacement, but the original structure which has been replaced is unknown. Some olivine in refractory bricks crystallizes in bladed rosettelike forms, but later inverts to the common granular crystalline mosaic; it is possible that such rosettes may serve as original structures for replacement by chromite, giving rise to orbicular structures.

Size, shape, distribution and structure of ore bodies

Evenly scattered deposits: Deposits of evenly scattered chromite comprise the simplest types. Chromite grains, euhedral to anhedral, are disseminated throughout a matrix of fresh or serpentinized olivine. The chromite may be earlier than the olivine or may replace the olivine or may be crystallized contemporaneously. Sackform deposits comprising masses of varying size are formed as the chromite grains become more abundant. Gradations between evenly scattered deposits and all other types are fairly common and in some cases distinct boundaries are difficult to determine. The outstanding characteristic of this type of deposit is its lack of significant structural features. Such an occurrence is illustrated by the Seeley claims in the San Luis Obispo region.

The Seeley claims contain ore consisting of fine-grained chromite disseminated through serpentinized dunite which grades outward into peridotite. Gradational boundaries characterize the edges of the ore at points where the contacts are not faulted; faulting is post-ore and post-dunite. Ore widths vary from 50 feet to 1 foot, and little relation exists between width and grade.

Two productive zones are known and they are vaguely delimited. The western ore body is a broad zone trending N. 60° W. as much as 50 feet wide, and carrying about 10 percent of chromite disseminated in dunite. Tunnelling beneath parts of the best surface outcrop failed to disclose any ore. The eastern ore body comprises two narrow zones of evenly scattered chromite in serpentinized dunite separated by a band of peridotite. The exposures are limited and the boundaries of the ore body are unknown.

Schlieren banded deposits: Schlieren banding has been invoked by many authors to explain the layered, linear, streaked structures observed in many chromite deposits. The streaks, and layering of chromite in dunite, are supposed to have resulted from flowage in still plastic magma after crystallization of a large part of the constituents. Although such flow structures are generally well-developed only near the margins of intrusive masses, many chromite deposits occurring in the centers of intrusions exhibit similar features.

Drag folds, and other minor flexures, indicate that movement probably takes place in a relatively viscous medium; dimensions of the folds are commonly measurable in inches rather than feet and seldom exceed two feet from limb to limb. These primary flexures may sometimes be confused with later deformation which usually results in larger scale effects. The schlieren banded deposits are characterized by a lack of continuity of streaks and layers in all directions, with their length being from ten to one hundred times greater than any other dimension; an average streak might be 10 feet long, 3 inches wide and less than a foot thick at its maximum thickness. Schlieren banded chromite layers are often connected by evenly scattered chromite ore; ore bodies formed by this process are often low grade and extremely variable. En echelon patterns are known, but this structure is more often developed in other types of deposits.

Sackform deposits: Sackform deposits together with the stratiform types furnish the bulk of the world's chromite production. The rounded, irregular masses are usually found in random orientations, much as raisins in a pudding. Occasionally they are grouped in clusters in ill-defined zones such as at San Luis Obispo, California; sackform masses occur less frequently irregularly distributed along easily recognized fracture patterns. In the Pacific Coast region the sackform deposits comprise two types: deposits found in completely serpentinized dunite, and deposits found in fresh or only partially altered rocks.

The sackform deposits found in serpentine usually have slickensided surfaces, are small, commonly containing less than 100 tons of massive chromite, and have apparently formed without recognizable structural controls. The size of the ore body bears little relation to the extent of the serpentine mass in which it is contained, although the very large deposits are confined to the larger intrusive masses. It seems probable that, in some cases at least, the structures that controlled the emplacement of the sackform deposit have been obliterated by serpentinization.

The sackform deposits found in the fresher rocks are often bounded by shear zones or faults, but it is questionable whether the shear zone localized the ore body or the ore body localized the shear zone. In nearly every case, linear or planar banding is also present resulting in gradations from this type into deposits of the schlieren banded type.

Deformation of chromite deposits

Evenly scattered deposits: Deformation is recognizable in evenly scattered deposits only where sufficient concentration of chromite has taken place to permit distinction of one part of the mass from another. Folded, crushed, and sheared chromite and dunite are found; oftentimes, localization of the chromite and localization of the effects of stresses causing deformation have coincided in space if not in time. The Castro mine near

San Luis Obispo, California, is a deposit of evenly scattered chromite which has been deformed by landsliding, faulting and shearing.

The ore bodies at the Castro mine are exposed by four large open cuts, several bulldozer trenches, and four levels of underground workings (see Plate IV). The upper cut, operated as a glory hole, has produced most of the tonnage shipped. The underground workings and bulldozer trenches were made during the exploration program conducted by the U. S. Bureau of Mines in 1941.

The chromite occurs as rounded to angular grains disseminated in a serpentinized matrix. The chromite is very uniformly disseminated and clots of massive chromite or patches of barren serpentine within the lenses are rare.

The boundaries between ore and gangue are sharp; barren serpentine at the contact usually forms an intensely sheared shell. The rock within the ore bodies is not sheared but is fractured, at some places highly so. Fractures are usually filled with opaline or clay-like material resembling fault gouge, but no measurable displacements were noted.

There are six separate ore bodies exposed at the Castro mine. They are tabular to lenticular in shape, nearly flat in attitude, and elongated in an east-west direction. A landslide has apparently displaced the two westernmost bodies, dropping them about 50 feet and moving them about 150 feet to the west. Serpentinized dunite envelops the bodies except in a few isolated places where ore is in contact with serpentinized peridotite or diabasic inclusions.

The lower ore body is by far the larger and has more of a tabular form than any of the others. It is cut near its northern boundary by a steeply dipping serpentinized dunite dike, 2 to 5 feet thick, striking N. 65° W. That portion of the ore body on the southwest side of the dike is dropped 3 feet.

Schlieren banded deposits: Deformation in schlieren banded deposits is commonly characterized by faulting or shearing. Individual faults may show small displacements, but net displacement of a single unit may be large due to additive effect of parallel or en echelon fractures. Detailed studies of faulting in chromite deposits are complicated by the presence of well-developed joint systems in the country rocks, and the fact that any fracture in dunite is commonly altered to serpentine; as a result surface traces of faults are almost impossible to differentiate from minor joints or secondary fractures.

Sackform deposits: Deformation of the sackform deposits yields very complex structures. The simplest of these are vein-like shear zones containing crushed and transported chromite which extend outward from the main ore bodies along the shear zones. As faulting and shearing increases in intensity, original structures may be completely obliterated, and former rounded equidimensional bodies may be elongated and narrowed until they appear veinlike. A typical example of this type of deposit is the Pick and Shovel Mine near San Luis Obispo, California.

The Pick and Shovel mine is developed on four levels of underground workings. The most important ore bodies have been worked from the 2nd and 4th levels, with the largest extending from nearly 30 feet above the 4th level down to the 3rd level, a distance of about 40 feet. The accompanying plan of the workings indicates clearly the haphazard distribution of the ore bodies. (See fig. 16).

Most of the ore consists of lenticular high grade bodies of chromite scattered through completely serpentinized dunite and peridotite, although all gradations occur between chromite grains disseminated in serpentine and massive high grade pods which contain little or no serpentine.

Post-ore shearing has developed long narrow stringers of chromite which have formed at the expense of high grade pods. On level No. 2 a high grade lens containing nearly 1000 tons of massive ore has been mined out, and extending in either direction along shear zones which pass through the lens, smaller pods and crushed ore have been mined for a distance of more than 100 feet beyond the main ore body.

Faulting may also deform sackform deposits although commonly, they tend to act as buttresses for stresses, forcing fault lines around their edges rather than yielding easily.

Interpretation of deformation in sackform deposits is particularly difficult since reference beds or zones are limited. The monomineralic character of the dunite makes recognition of structural features, by means other than the ore bodies themselves, uncertain.

Fissureform deposits: Fissureform deposits are among the most controversial types recognized at the present time. They nearly always occupy a faulted zone, oftentimes being faulted or sheared after the emplacement of the ore. The only deposit in the writer's experience which approaches the conditions required of this type is the Sweetwater Mine in the Santa Lucia Range northwest of the San Luis Obispo, California.

The mine workings at the Sweetwater Mine comprise five open pits alined in a N. 60° W. direction over a distance of 325 feet, five tunnel levels below and to the north of the pits, and a tunnel connecting the two easternmost pits with a cross-cutting adit from this tunnel to the surface. The overall length of chromite outcrops in the workings is 600 feet over a vertical range of 150 feet. There are 1400 feet of tunnelling and five small stopes from which chromite has been extracted. (See pl. V).

The chromite ore occurs as irregular masses, streaks (some due to post-mineral movement), small clots, and discrete grains. The mineable ore bodies are connected by grains and small clots of evenly scattered chromite. Ore bodies are elongated narrow bodies containing from less than one hundred up to several hundred tons of massive ore. Remnants of the extracted masses grade abruptly into barren rock or disseminated ore.

The ore bearing areas are contained within a mass of serpentinized dunite which is surrounded by peridotite; the dunite occurs as an elongated, irregular body which has a northwest trend. The ore bearing areas are further restricted to vaguely defined shoots within the dunite. The long axes of these shoots strike N. 25° W. and pitch from 20 to 25 degrees to the northeast, and lie in an en echelon pattern. Two of the shoots are exposed in the underground workings with their upper ends cropping out at the surface. Possibly two more are exposed in the middle pits. The ore shoots found in the underground workings can be traced almost continuously over a 200 foot range, and there is no indication that they do not continue in depth.

The ore shoots are irregular and there is a wide variation in their chromite content. They are widest adjacent to high grade ore bodies, attaining thicknesses of 30 feet; they narrow rapidly to widths of a few feet between stopes, in some places almost pinching out. The dunite enclosing these shoots may contain small amounts of chromite, but it is generally barren.

Many diabasic inclusions are found in the ore and surrounding rocks. They have no genetic relation to ore bodies, but they are cut by ore stringers or may occupy areas which might otherwise be solid ore. (See fig. 17).

Shearing of both chromite and dunite is evident throughout the deposit; the trend generally parallels the ore zones. This direction is also the trend of the larger structural features of the Santa Lucia Range.

Figure 17

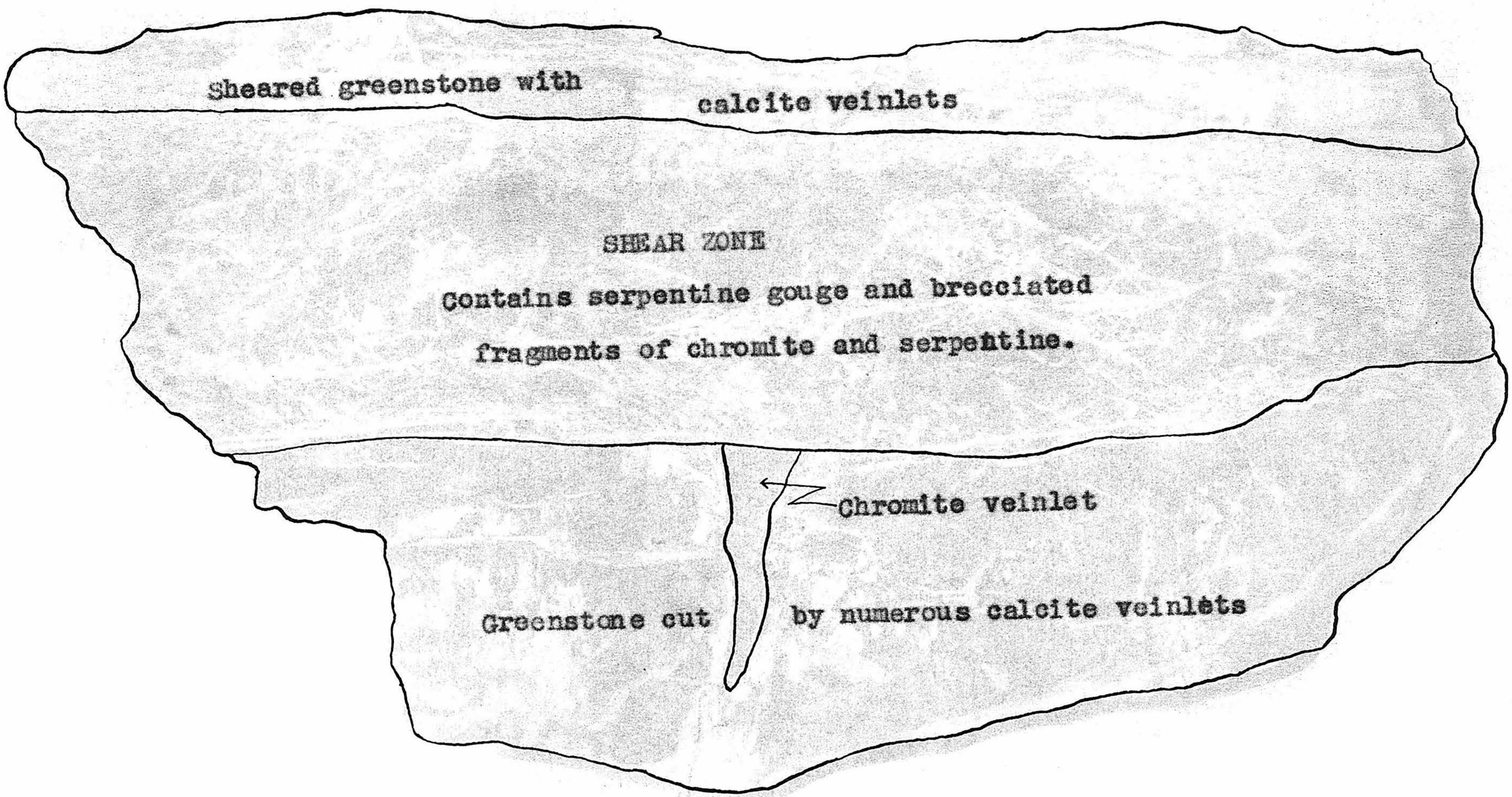
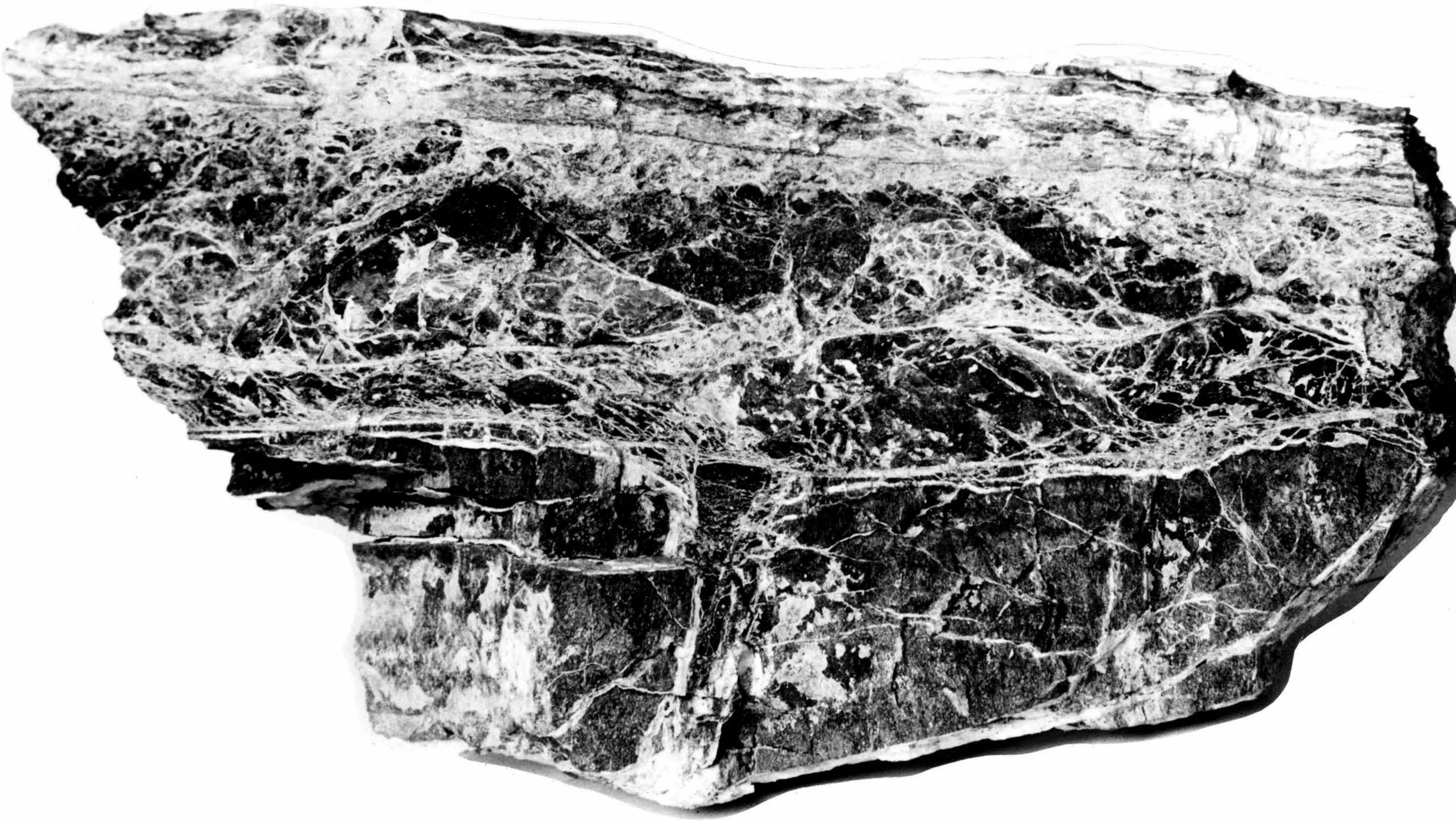


Figure 17: Chromite veinlet in greenstone inclusion from Sweetwater Mine, San Luis Obispo County, California.



ORIGIN

Hypotheses concerning the origin of chromite deposits have long presumed that chromite originated early in the magmatic stage, and that further concentration took place by essentially mechanical movement rather than chemical reaction. The classical magmatic segregation theory proposed by Vogt[47], assumed that chromite crystallized early in an ultramafic magma and that the deposits accumulated by crystal settling, agglomeration, and gravitative differentiation. Sampson[48], and Ross[49] pointed out certain features which seem to be opposed to this view: Sampson showed that chromite from stratiform type deposits crystallized after olivine and in many cases was later than bronzite. He also pointed out the occurrences of chromite in conglomerate in the Selukwe district of Southern Rhodesia. He interpreted the common association of more intense serpentinization accompanying chromite veinlets to mean that the chromite was introduced with the serpentine. Ross, from chromium-bearing ultramafic rocks near Webster, North Carolina, illustrates by chemical

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47/ J. H. L. Vogt, op. cit., pp. 384-393, 1894.

48/ E. Sampson, op. cit., pp. 632-641, 1929.

49/ C. S. Ross, op. cit., pp. 641-645, 1929.

analyses that chromium is carried in large amounts in later pyroxenites, but that earlier dunite with which chromite deposits are associated contains little or no chromium. He interprets this relation as indication that the original dunite was not chromium-bearing and that the chromite was introduced into the dunite from the later pyroxenite. In 1929 Fisher[50], published a paper on the

50/ L. W. Fisher, op. cit., pp. 691-721, 1929.

origin of chromite deposits, dividing them into three groups, early magmatic, late magmatic, and hydrothermal based upon the period of formation of the chromite. Bowen[51] develops a process combining successive frac-

51/ N. L. Bowen, The evolution of the igneous rocks, 1928.

tional crystallization with continuous removal of crystalline products, and reaction with liquid of constantly changing composition to obtain local accumulations of chromium-rich spinel crystals.

Nearly every idea presented has presumed to subdivide the magmatic process into a series of more or less disconnected stages, with little regard for the manner in which the magma attains the various conditions postulated. Although Bowen's hypothesis is as rigorous as possible with the laboratory data available, the field relations of many of the chromite deposits present evidence not

not compatible with the laboratory results. An attempt to indicate such evidence is embodied in the following section.

Field relations of chromite deposits: More than 95 percent of the chromite deposits visited by the writer were found in dunite or serpentinized equivalents and even where enclosed in peridotite they usually were surrounded by a shell of dunite. According to a survey of published literature, the constant association of olivine and chromite is almost universal, with the possible exception of the stratiform deposits. A few deposits show structural localization within the dunite mass which is interpreted as evidence of injection of the chromite into the dunite.

Much of the chromite of many ore deposits is clearly later than the olivine, either including olivine grains, molding itself around them, or replacing them. This feature is in accord with Bowen's hypothesis for the formation of spinel in igneous rocks[52/]. This hypothesis

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52/ N. L. Bowen, op. cit., pp. 277-281, 1928.

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postulates that the first crystalline phase to appear is either basic plagioclase or olivine (assuming a parent basaltic magma) which settling to hotter portions of the chamber reacts to produce spinel.

The presence of hydrous, secondary minerals such as talc, kaemmererite, and less common chromium bearing alterations demonstrates that chromium is mobile and can be carried in small amounts in hydrothermal solutions. Lack of baking, recrystallization, metamorphism, etc., along contacts of ultramfic rocks and adjacent formations, is interpreted to mean that temperatures of the masses when intruded are no greater, and apparently have less effect than those accompanying the intrusion of, for example, a thick basalt sill.

In the Seiad quadrangle portions of the peridotite mass are intruded as rather flat lying sills along planes of schistosity or along gneissic structures in an older diorite. Where the contacts are flat or dip less than 50 degrees, the contact between peridotite and diorite consists of alternating layers of the two rocks, ranging in width from a few inches to more than one hundred feet. The lack of recrystallization, except in the smaller diroite bands, and the wide diversity in composition of the two rocks suggests simple intrusion by a fluid olivine liquid or melt. Similar structures may be seen in many of the other ultramafic areas of the Pacific Coast region, and all the field evidence seen by the writer indicates that the ultramafic masses were intruded as liquid magmas and not as pasty accumulations of crystals.

The various relations outlined are most easily interpreted by assuming the existence of a parent peridotite magma which contains olivine-rich portions;

the field occurrences seem to indicate that chromium from the parent peridotite magma is concentrated in the olivine-rich fraction.

The ensuing section is devoted to a consideration of the laboratory data bearing on the existence and behaviour of an olivine-rich fraction of a peridotite magma.

<u>Experimental data on olivine-rich liquids</u>: Experimental data indicates that anhydrous melts containing olivine, a little pyroxene, and traces of oxides, must have completely crystallized above a minimum temperature of 1200 to 1300 degrees centigrade[53]. Recent work by

53/ N. L. Bowen and J. F. Schairer, Amer. Jour. Sci., vol. 29, (5), pp. 151-217, 1935.

Goranson[54] has indicated that small amounts of water

54/ R. W. Goranson, Amer. Jour. Sci., vol. 35-A, pp. 71-91, 1938.

(less than 5 percent by weight) can cause a decrease in the freezing point of albite by as much as 200 degrees, with a considerable increase in pressure in the system. In an olivine liquid this amount of water in the system would result in probably less than 20 percent serpentine.

Considerations of relations in the quaternary system, $FeO-MgO-Al_2O_3-SiO_2$, are limited to inferences drawn from the analogous system involving CaO instead of MgO[55],

55/ J. F. Schairer, Jour. Amer. Cer. Society, vol. 25, pp. 241-274, 1942.

and estimates made from the ternary systems comprising the faces of the tetrahedron of the quaternary system. Comparing the $MgO-Al_2O_3-SiO_2$ and the $CaO-Al_2O_3-SiO_2$ systems[56/],

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56/ R. B. Sosman and Olaf Andersen, Composition-Temperature Phase Equilibrium Diagrams of the Refractory Oxides, Research Lab, U. S. Steel Corp., Oct., 1933.

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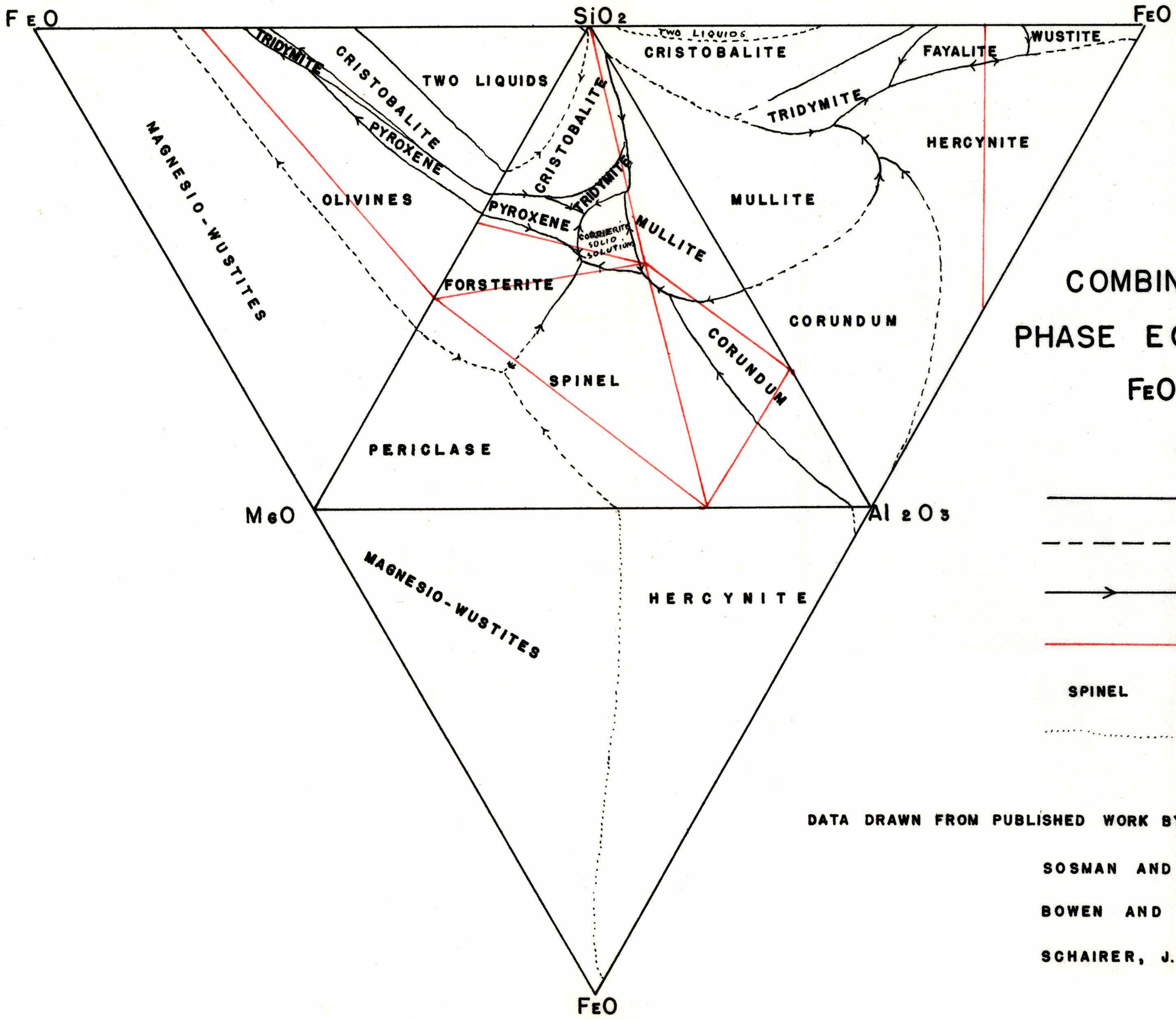
it may be observed that MgO does not form the numerous solid solution series and intermediate compounds exhibited by CaO; thus the spinellid field which is so large on the $FeO-Al_2O_3-SiO_2$ side of the tetrahedron, might be expected to extend over a large portion of the tetrahedron and fall very close to the $FeO-MgO-SiO_2$ face. (See figure 18). In nature this feature is substantiated by the occurrence of spinel group minerals in peridotites when the bulk composition of the peridotite cannot exceed at most 2 percent of Al_2O_3.

Inferences of the crystallization relations within the quaternary system, $FeO-MgO-Al_2O_3-SiO_2$, indicate that from a liquid containing approximately 25 percent of pyroxene, 75 percent of olivine, and accessory amounts of oxides, an olivine-rich mass cannot be obtained without some fractionation. The first mineral to crystallize is olivine followed by spinel and finally at an eutectic point pyroxene separates. If equilibrium conditions are maintained to the end point other phases may occur,

FIGURE 18



COMBINED TERNARY DIAGRAMS OF PHASE EQUILIBRIA IN THE SYSTEM $FeO - MgO - Al_2O_3 - SiO_2$

PROJECTED BOUNDARY CURVE, KNOWN

PROJECTED BOUNDARY CURVE, INFERRED

DIRECTION OF FALLING TEMPERATURE

BOUNDARY OF TERNARY CRYSTALLIZATION FIELD

SPINEL — PRIMARY PHASE

BOUNDARY CURVE, INFERRED

DATA DRAWN FROM PUBLISHED WORK BY: (SEE TEXT FOR REFERENCES)

SOSMAN AND ANDERSEN

BOWEN AND SCHAIRER

SCHAIRER, J. F.

but seldom is equilibrium attained in nature. Consequently, fractionation of the crystallizing liquid will lead in one portion of the magma to concentrations of pyroxene in the residual liquid in excess of the original 25 percent, and in other portions to concentrations rich in spinel. Greig[57] has shown that mixtures having a ferrous-ferric

57/ J. W. Greig, Amer. Jour. Sci., vol. 14, pp. 473-484, 1927.

iron ratio of about 1:1 are immiscible with silicate liquids over a range of compositions extending from over 90 percent of silica to less than 30 percent of silica. Although small amounts of alumina destroy this immiscibility, where the ferrous-ferric iron ratio is about 1:1 a minimum of at least 6 percent of Al_2O_3 is required. Anhydrous melts indicate limiting temperatures of about 1650° below which immiscibility does not occur. However, the temperature-boundary curve declines as the concentration of Fe_2O_3 increases over the range of compositions investigated. In this system, $FeO-Fe_2O_3-Al_2O_3-SiO_2$, compositions over 30 percent of Fe_2O_3 were not studied because of experimental restrictions.

It seems probable that concentrations of Cr_2O_3 in the amounts found in chromite might also result in immiscibility in liquids rich in the spinel. Thus, with fractionation, parts of the liquid rich in spinel would begin to break into two liquids one capable of precipitating large amounts of chromite with minor amounts of olivine, and the other performing the reverse function. Should fractionation proceed toward a pyroxene-rich liquid, no immiscibility would occur since the concentrations of Cr_2O_3 would always be small in these liquids.

In the foregoing statements fractionation is governed by a number of factors, among them, temperature, pressure, movement of liquid, settling of crystals, rate of cooling, etc. By variation in the above factors, the course of fractionation is determined. Thus we see that by fractionation parts of the mass will precipitate chromite far in excess of the bulk composition of the rock, and parts of the liquid adjacent and associated with this chromite-rich part will precipitate olivine in excess of the bulk composition of the rock. In other parts of the magma which are relatively chromium poor, pyroxene will be present in about normal bulk composition associated with olivine in slightly lesser amounts than its normal bulk composition.

<u>Hypothesis for the origin of chromite deposits:</u> As the olivine-rich, chromium-rich liquid crystallizes under perfect equilibrium conditions, it is subject to many variables which may promote a pseudo-stratification of the various components. The layers might be olivine with a little chromite at the bottom, followed by a chromite-rich portion of variable thickness; olivine

with a little chromite might comprise the overlying larger part of the mass, and, if present, a small amount of pyroxene might form an uppermost layer. The stratiform deposits approach rather closely these ideal conditions, although they form from a magma of quite different composition. It is to be emphasized that this type of crystallization would occur only if equilibrium is maintained until the mass is nearly solid, and if the forces acting on the magma are restricted to gravity and the action of slowly declining temperature and pressure.

Obviously, the position of the larger masses of ultramafic rocks within the cores and in the structurally active portions of mountain masses preclude the possibility that such ideal conditions will be maintained for any period of time. This paper attempts to evaluate the conditions continuously operating in the magmatic chamber, and in the light of some of the deposits described relate them to certain time intervals in a continuous magmatic cycle.

The components of the magma before crystallization begins may be inferred from the crystalline mass to be approximately 40 percent MgO, 15 to 20 percent FeO, and 40 percent SiO_2; less than 2 percent Cr_2O_3, and smaller amounts of Al_2O_3, MnO, TiO_2, and CaO, are also probably present. The amounts of the latter elements are so small that they rarely, if ever, form minerals, but are simply carried in solid solution in the major minerals, olivine, enstatite, and chromite. Water is certainly present, but in indeterminate amount.

Harker[58] has pointed out that for crystallization

[58] A. Harker, Nat. History of Igneous Rocks, pp. 209-227, 1909.

to begin in a liquid magma, some degree of supersaturation with respect to one of the constituents must take place. However, the degree of supersaturation determines the number of centers of crystallization which may form, and as Harker[59] points out, since olivine stands high on

[59] A. Harker, op. cit., p. 218, 1909.

the list of minerals in power of spontaneous crystallization, probably little supersaturation would occur; thus few centers of crystallization would form in a mass which was precipitating dominately olivine and continued crystallization might possibly give rise to larger liquid residua in a magma chamber than would occur with, for example, plagioclase. (See figures 19-24).

Figures 19 through 24 represent an attempt to illustrate the distribution of crystals and liquid in successive stages of crystallization in a dunite magma. Each figure represents an hypothetical section through a small portion of a magma chamber. The sections represent approximately one-half mile of length and a 1000 feet of depth. They do not illustrate any known occurrence, and must be regarded as purely diagrammatic.

The first crystalline phase to appear is olivine of high magnesia content; the crystals may be so mearly the same gravity as the magma that they probably remain suspended in the cooler portions of the magma or move but short distances from the area where they originally separated. If the magma were rapidly chilled at this point, by any means whatsoever, the resultant mass would be a peridotitic body with accessory chromite and pyroxene distributed relatively uniformly throughout the mass. Large areas in the Kerby quadrangle and in Curry County, southwestern Oregon, appear to have crystallized under these conditions.

If equilibrium conditions are maintained for a longer period, more olivine will continue to crystallize and the residual solutions will become slightly more enriched in chromite. (See figure 20). If chilling takes place during this interval, part of the mass will be slightly enriched. In local areas, if fractional crystallization has proceeded far enough, chromite might become immiscible in the silicate portion and small pods and concentrations of higher grade material might form. This type of deposit is common in the intrusives of the Coast Ranges of California. The deposits of the Twin Sisters range east of

Bellingham, Washington, may also belong in this type.

When an additional but indeterminate amount of the mass has crystallized as olivine, separation of chromite may begin; chromite and olivine probably crystallize simultaneously throughout most of the remainder of the cycle, at first, at least, in euhedral to subhedral forms; in those areas where local concentrations of oxides may build up high enough to give liquid immiscibility under the proper temperature and pressure conditions, crystallization of olivine might be inhibited. When the magma reaches approximately one-quarter solids tempera- ture differentials may begin to be appreciable through- out the mass; measurements[60] of the thermal conductiv- ity of a few rocks and minerals and a limited number of corresponding liquids indicate that the flow of heat in a crystalline mass exceeds the flow of heat through a liquid of similar composition. Thus, free or uniform exchange of heat may be inhibited by the coexistence of crystalline and liquid portions in the magmatic chamber. (See figure 21). Locally, small reaction systems, more or less insu- lated from one another, may arise and reaction or resorp- tion of earlier formed crystals and liquid may occur, because the crystals are no longer in equilibrium with the liquid. If chilling should occur in this interval, pods

60/ F. Birch, G. S. A. Special Paper 36, pp. 243-266, 1942.

and segregations of chromite would result in the areas where the residual liquids were concentrated. The ore bodies would not necessarily be composed of massive chromite, unless considerable immiscibility or marked fractionation had occurred, but might be disseminated, perhaps streaked or schlieren banded, should movement accompany the chilling. Chromite grains from the same zone could be euhedral, subhedral, and anhedral, depending on the time at which they crystallized and might show numerous anomalous relations with the accompanying olivine. Several deposits might be grouped in this classification; many of the sackform bodies near San Luis Obispo, California, such as the ore bodies of the Norcross, Castro, Trinidad, and New London deposits. The Chambers Mine near John Day, Grant County, Oregon, possibly also belongs in this group; ore from parts of the McGuffey Creek deposits, near Scott Bar, California, shows folding and flow banding which may have formed during this stage.

As crystallization proceeds to the point where more than 50 percent of the mass is crystalline, heterogeneity may be far advanced. (See figure 22). Some parts of the mass possibly consist of olivine crystals with little or no residual liquid; other parts may consist of olivine crystals with chromite more or less sparsely distributed through the olivine, and occasional areas where residual liquids little concentrated in chromite might remain;

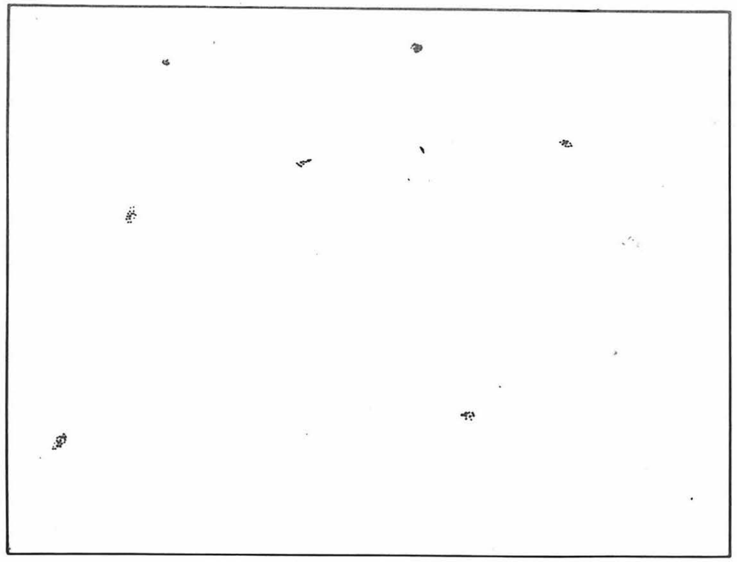


FIG. 19

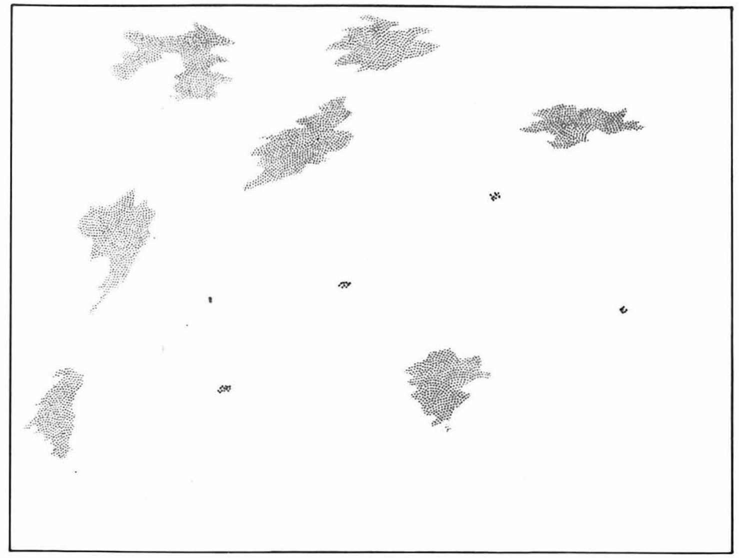


FIG. 20

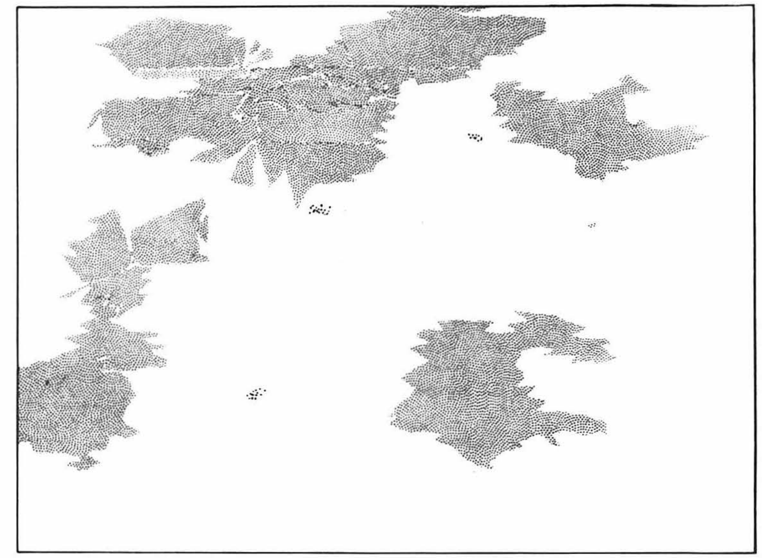


FIG. 21

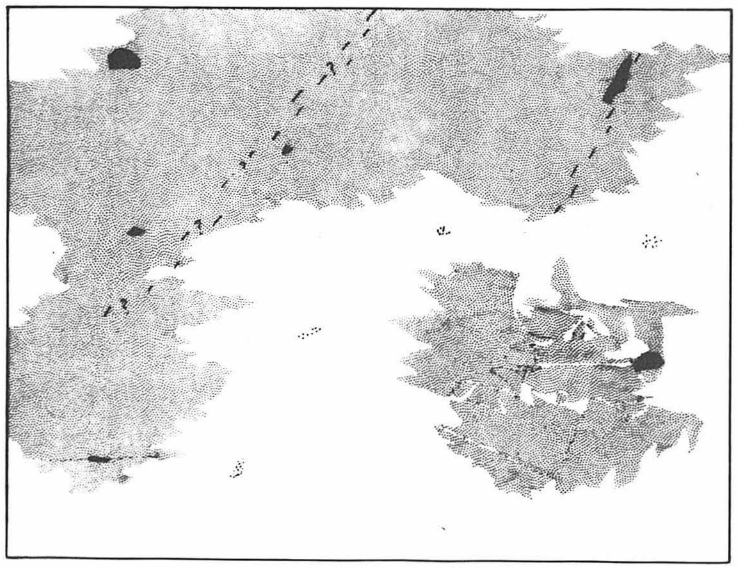


FIG. 22

FIG. 23

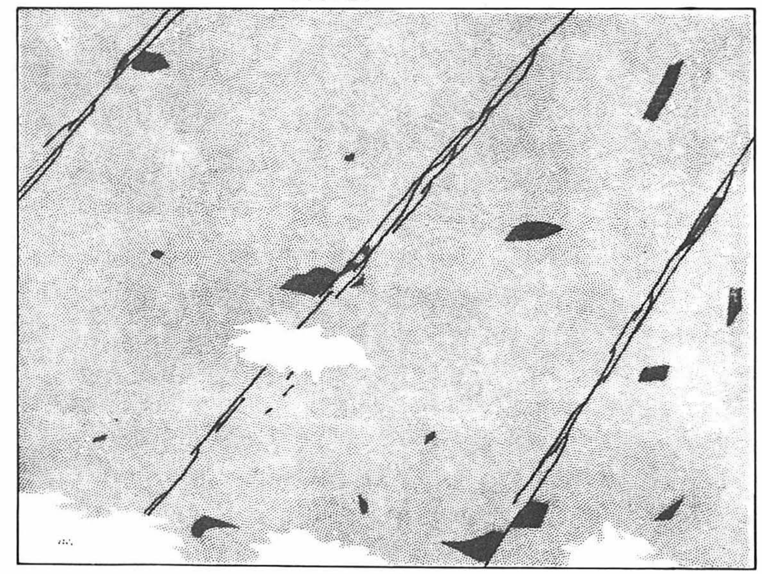


FIG. 24

FIGURES 19 - 24 DIAGRAMMATIC SKETCHES ILLUSTRATING THE SEQUENCE OF CRYSTALLIZATION IN AN OLIVINE - RICH LIQUID CONTAINING CHROMIUM

OLIVINE - RICH LIQUID

OLIVINE CRYSTALS. (IN FIGURES 21-24 INCLUDES ACCESSORY CHROMITE)

CHROMITE - RICH MASSES

FAULT OR FRACTURE ZONES

finally, some areas might contain large portions of the remaining liquids, which, had fractionation proceeded far enough, or conditions favorable for immiscibility been in existence long enough, might force the composition of the solution far over into the spinel field (see figure 18); in this case the liquid would be capable of precipitating only chromite and resorbing olivine, or perhaps might precipitate dominately chromite with olivine separating with the latest formed material in only negligible amounts. Should chilling occur in this interval, in chromium-rich residual portions massive pods might form; if the pods formed from residual solutions in which little or no liquid immiscibility had occured and the concentrations, pressure, and temperature were favorable, they would quite likely be bordered by evenly scattered chromite; however, if considerable immiscibility had occurred with the resulting differences in concentration, pressure, and temperature, the masses might be sharp walled and the surrounding dunite contain little or no evenly scattered chromite. The remainder of the mass would appear much the same as before except for additional concentrations of chromite in local areas with resultant scarcity elsewhere. It seems possible that some of the ore bodies of the Piliken Mine, near Auburn, California, as well as many of the chromite deposits of the entire Foothill belt of the Sierra Nevada, may belong in this group. The Pick and Shovel Mine, in the San Luis Obispo region, California, may also contain ore bodies of this type.

If crystallization proceeds from relatively few centers in the magma chamber as illustrated in figures 19 through 24, until the mass exceeds more than 50 percent of solids, external stresses other than those affecting pressure and temperature, probably have little effect on the conditions of deposition of the chromite. However, when the mass approaches 65 to 75 percent of crystallinity, at least portions of the rock may be sufficiently competent to fracture rather than to yield by flowage. The fractures may be discontinuous because some of them possibly still have liquid intersections. (See figure 23). After fracturing is possible in the magmatic chamber, any stresses which induce fracturing may also induce movement in the residual solutions since the rigidity of the mass possibly forces the liquid areas to act independently much like small intrusions; thus, as these movements take place parts of the mass may have the residual solutions injected into the fractures perhaps locally for considerable distances. Since much of the fracturing may possibly be induced by external stresses, the injected zones might be roughly parallel to regional features surrounding the intruded area; however, the structural heterogeneity of crystalline and liquid areas coupled with a lack of complete competence induced by such heterogeneity, might yield large local variations in the trend of fracture patterns.

Under the conditions postulated, many of the injected areas might show no feeder veinlets, and might have definite tops and bottoms, since the supply of available liquid is much restricted compared to the size of the mass into which it is injected; obviously, the presence of large liquid residuals will inhibit the development of fractured zones.

If chilling occurs during this period, the mass may exhibit areas of early crystallized dunite with little or no chromite, local areas containing small clots and schlieren of chromite with accessory amounts of disseminated ore, and more localized areas where a few larger liquid residuals possibly were injected into fracture zones and in some cases might have developed ore bodies. The Seiad Creek chromite deposit in the Klamath Mountains is thought to represent a deposit developed in this manner; the Sourdough Mine in Curry County, southwestern Oregon, may also be of this type.

As additional crystallization occurs, only the larger liquid residuals will remain, since they will be the only parts of the mass retaining enough heat to inhibit complete solidification. (See figure 24). Thus, the final stages of cooling in the magma might possibly yield a few large chambers (small in comparison to the mass of the entire intrusive containing liquid consisting of more chromite than olivine and probably considerable water. It is doubtful if liquid immiscibility could exist at the temperatures which might be present, since indications are that immiscibility ceases, even in the presence of water, possibly above 1000° C. or but slightly lower. Should conditions force the injection of this material into the crystalline cooler portions of the magma, the deposits formed would probably correspond to the fissureform type. Perhaps the Sweetwater Mine, near San Luis Obispo, California, might serve as an example of this type of deposit.

<u>Summary</u>: Each ore deposit is regarded as forming under the influence of several forces; some of the effects of these forces are predictable, such as the effect of falling temperature, and the effect of the force of gravity. Other forces are not predictable, such as variations in pressure, the results of stresses due to external or regional causes, stresses induced by the magma itself, and differences in composition. The resultant of the predictable forces is thought to approach an equilibrium condition consisting of a layer of olivine and small amounts of chromite in the base of the magma chamber, overlain by a layer of chromite and topped by

a large mass of olivine with small amounts of chromite; a thin layer of pyroxene may cap the mass if any is present. Chilled borders of olivine with accessory pyroxene and chromite might occur locally. This ideal condition is seldom attained in nature except, perhaps, in the stratiform deposits, and the degree of aberration from equilibrium conditions determines the characteristics of the ore deposit formed.

The origin of the various chromite deposits may be likened to quenching practice used to determine the constituents of a high temperature liquid or melt at various stages during its cooling cycle. A small sample of a melt is removed and quenched as rapidly as possible to more or less preserve it in the form in which it existed before being cooled. Each chromite deposit is examined for evidence indicating at what stage in the process of cooling or crystallization of the ultramafic magma its development was arrested by similar rapid cooling or quenching. By considering the formation of the ore deposits as a continuous process, beginning with ultramafic magma in a fully liquid state, many of the difficulties in understanding the formation of various types of deposits are partially elucidated.

UNITED STATES DEPARTMENT OF THE INTERIOR
Harold L. Ickes, Secretary
GEOLOGICAL SURVEY
W. C. Mendenhall, Director

Bulletin 922-D

CHROMITE DEPOSITS OF GRANT COUNTY, OREGON

A PRELIMINARY REPORT

BY

T. P. THAYER

Strategic Minerals Investigations, 1940
(Pages 75-113)

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1940

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - Price 45 cents

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CHROMITE DEPOSITS OF GRANT COUNTY, OREGON

A PRELIMINARY REPORT

By T. P. Thayer

ABSTRACT

The principal chromite deposits of Grant County, Oreg., occur in belts of peridotite and dunite, largely altered to serpentine, in the Strawberry Range. A few deposits have been found in the Greenhorn Mountains. The most productive mines are east of Canyon City in comparatively fresh unsheared ultramafic rocks in which the original mineralogic and textural characters are well-preserved. The borders of the mass are pyroxenitic, and the chrome deposits occur as irregular lenses in the less pyroxenitic and more dunitic central portion. The chromite appears to be genetically related to dunite and is probably of early magmatic origin. Most of the readily accessible deposits of high-grade chromite have been worked out, and future production will be predominantly from low-grade concentrating ore containing from 15 to 30 percent of chromic oxide (Cr_2O_3). The known reserve in the explored deposits is about 80,000 tons of ore averaging between 20 and 35 percent of chromic oxide. With sufficiently high prices, probably 200,000 tons of concentrating ore averaging between 20 and 25 percent of chromic oxide could be mined from the explored deposits in Grant County.

INTRODUCTION

The principal chromite deposits of this region occur in the Strawberry Range, in the south half of Grant County. Chromite has also been mined in the Greenhorn Mountains, which occupy the northeastern part of Grant County and the western edge of Baker County. The deposits in the Strawberry Range are described in this report.

The Strawberry Range extends eastward for about 50 miles, connecting the Ochoco Mountains on the west with the Blue Mountains on the east. The principal peaks of the range are between 7,000 and 9,100 feet in altitude. The chromite deposits and the topographic and geologic relations between the range and the John Day River Valley to the north are shown on plates 12 and 13. The distance from John Day, the commercial center of the district, to Baker, on the Union Pacific Railroad, is 96 miles via the John Day Highway. The distance to Portland is 300 miles by paved highway. The nearest shipping point is Seneca, 22 miles south of John Day, the terminus of the Oregon & Northwestern Railroad, which connects with the Oregon Short Line at Burns, Oreg. Ore shipped during 1917 and 1918 went from Prairie City, 13 miles east of John Day, to Baker, via the narrow gage Sumpter Valley Railroad, where it was transferred to the Union Pacific Railroad. The chromite deposits in the Greenhorn Mountains are served by mountain roads from Whitney and Sumpter, towns on the Sumpter Valley Railroad. In winter snow and mud render the roads impassable for heavy trucks.

History and production

Occurrence of chromite in the Strawberry Range was mentioned by Lindgren in 1901.[1/] Mining of chrome ore began in 1916 under the stimulus of high war-time prices, and shipments of 225 tons were made in January 1917. Total shipments of ore amounted to about 3,700 tons in 1917 and about 13,600 tons in 1918.[2/] Mining ceased when the war ended, and little ore was

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1/ Lindgren, Waldemar, The gold belt of the Blue Mountains of Oregon: U. S. Geol. Survey 22d Ann. Rept., pt. 2, p. 713, 1901.

2/ Westgate, L. G., Deposits of chromite in northeastern Oregon: U. S. Geol. Survey Bull. 725, p. 60, 1921.

shipped thereafter. The total production of Grant County to 1925 was estimated by Furness [3] at about 20,000 tons. During November and December 1939 about 100 tons of ore was shipped from the Dry Camp mine for concentration tests.

Previous work

The report on the gold belt of the Blue Mountains by Lindgren,[4] published in 1901, includes the most comprehensive account of the general geology of the Strawberry Range. Westgate [5] examined the chrome deposits in 1918, while mining was most active, and his report contains much information on workings that are now caved and inaccessible. Allen,[6] in a report published in 1938, described the principal chromite deposits of northeastern Oregon.

Field work and acknowledgments

This report is based on field work done by the writer between September 1 and December 10, 1939, with the assistance of P. W. Guild, Darwin Jepsen, and W. G. Lundstrum. The eastern part of the Canyon City chromite belt was mapped on a scale of 2,000 feet to the inch. The larger chromite deposits were mapped on a scale of 40 feet to the inch, with tape and plane table.

While the Geological Survey party was in the field, the United States Bureau of Mines explored and sampled the Chambers, Dry Camp, and Iron King deposits. Interpretation of the subsurface geology of these deposits is based largely on informa-

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3/ Furness, J. W., Chromite in 1925: U. S. Bur. Mines, Mineral Resources U. S., 1925, pt. 1, p. 141, 1928.
4/ Lindgren, Waldemar, op. cit., pp. 712-717.
5/ Westgate, L. G., op. cit.
6/ Allen, J. E., Chromite deposits in Oregon: Oregon Dept. Geology and Min. Ind. Bull. 9, pp. 53-69, 1938.

tion thus obtained, for which the writer is indebted to Mr. O. H. Metzger, of the Bureau of Mines. Thanks are due also to the many local residents who supplied much information and served as guides.

GEOLOGY

General features

The oldest rocks of the district are schists and layered diorite, which will be referred to collectively as the basement complex. They are of Paleozoic age or older. The Mesozoic rocks, which consist mainly of sandstone, shale, chert, and limestone, contain some pebbly beds whose composition indicates that they were formed, at least in part, by erosion of the basement complex. Peridotite and dunite, partly altered to serpentine, are intrusive into both the basement complex and the Mesozoic rocks. They occur in two main belts (see pl. 12), one of them near Canyon City and the other from 15 to 20 miles southwest of it. The chromite occurs in the peridotite and dunite. Tertiary lavas, tuffs, and conglomerates are widely distributed in the region surrounding the Strawberry Range. The area between the north base of the range and the John Day River is occupied by coalescing alluvial fans, which contain placer gold in the vicinity of Canyon City. Some fairly extensive areas of alluvium and some glacial deposits lie within the range (see pl. 13).

Basement complex

The basement complex consists mainly of hornblendic greenstone schist and of gneissic diorite or gabbro; it also includes some mica schist and quartzite. The rocks of the complex are the most resistant to erosion in the district. They occupy the higher part of the Strawberry Range, from Canyon Mountain to the foot of Strawberry Mountain, and small blocks of the complex in the ultramafic rocks commonly stand out in relief. The best exposure of the complex is in the bold cliffs forming the west face of Canyon Mountain. The greenstones and schists are readily distinguished from the ultramafic rocks by their schistose character. The dioritic rocks may be recognized by their abundant feldspar and also, in places, by the presence of pegmatite dikes containing a large proportion of black hornblende.

Mesozoic sedimentary rocks

Between Canyon Creek and Fields Creek, the Strawberry Range is made up almost wholly of highly deformed sedimentary strata. The sediments consist mainly of well-bedded dark-gray sandstones, shales, siliceous siltstones, and chert. Some altered lavas and tuffs alternate with the sediments. Limestone occurs sporadically in small lenses. Fossils obtained from limestone west of Fields Creek were identified by Mr. G. A. Cooper, of the U. S. National Museum, as certainly Triassic, and probably Upper Triassic, in age.[7] R. L. Lupher [8] has mapped Triassic and Jurassic rocks in the southern slopes of the Strawberry Range, and probably rocks of both ages are present in the area west of Canyon Creek. Unlike the crystalline rocks of the basement complex, the Mesozoic sediments are practically unmetamorphosed, except near the contacts of intrusive masses.

Ultramafic rocks

Character

The chromium ores of this district, and of nearly all other districts in the world, are all contained in intrusive igneous rocks that are collectively classed as ultramafic. The term

7/ Written communication from J. B. Reeside, Jr., Feb. 7, 1940.
8/ Personal communication, September 1939.

"ultramafic" was coined not many years ago as a substitute for "ultrabasic," which was regarded as inappropriate. Ultramafic implies, essentially, a high proportion of magnesium and iron. The chief original minerals that constitute ultramafic rocks are olivine and pyroxene, and the commonest accessory minerals are magnetite and chromite. The olivine, and to a less extent the pyroxene, are readily altered to minerals of the serpentine group. Rocks in which this alteration has been complete or nearly so are commonly called serpentine, and even where the alteration is only moderately advanced the resulting rock is often rather loosely called serpentine. In conformity with this popular usage, the ultramafic rocks are collectively designated serpentine on plate 12.

The ultramafic rocks of Grant County are divisible into four intergrading kinds, according to the proportions in which olivine and pyroxene were originally present. These are: (1) Dunite, consisting almost wholly of olivine, with not more than 5 percent of pyroxene; (2) olivinite, containing 5 to 50 percent of pyroxene; (3) peridotite, containing 50 to 95 percent of pyroxene; (4) pyroxenite, containing 95 percent or more of pyroxene.

It is impracticable to follow this classification strictly in mapping (see pl. 13). The dunite and olivinite that are not extremely altered are broadly distinguished from each other and from the more pyroxenic rocks, though the exact position of the boundary between intergrading rocks must obviously be uncertain in places. In many places, however, it is so difficult to distinguish peridotite from pyroxenite that these two rocks are mapped together. In large areas, moreover, the process of serpentinization has gone so far as to render uncertain the composition of the original rock; such areas are mapped as serpentine.

The average composition of the ultramafic body as a whole is probably about that of olivinite containing 25 percent of pyroxene. Although specks of chromite occur throughout all the ultramafic rocks, almost all the workable chromite deposits occur in dunite or olivinite.

The dunite is a dense uniform rock in which no minerals stand out. Weathered surfaces are smooth and reddish brown to buff, and it is from this characteristic that the miners' term "buckskin" originated. Platy jointing is very common in the dunite. As a result of this jointing and of low resistance to weathering, areas underlain by dunite are mostly covered with a mantle of loose chips, and bedrock is rarely exposed.

Olivinite and peridotite are red or brown to buff on weathered surfaces, are characterized by pyroxene grains that stand out in relief from the olivine matrix, and are readily identified by their conspicuous cleavage. Outcrops of these rocks are scarce on gentle timbered slopes but are almost continuously exposed on the precipitous walls of some of the canyons.

The pyroxenite is very tough and resistant to weathering. Weathered surfaces are light green to brown and are roughened by projecting pyroxene crystals ranging from a quarter of an inch to 1½ inches in length. In places the rock resembles a compact mass of wood chips. As pyroxenite occurs mainly in lenses rather than large homogeneous masses, its outcrops assume the form of reefs that commonly stand 10 to 20 feet high.

Nearly all of the ultramafic rocks are partly altered to serpentine, even though some of the pyroxenite appears fresh in hand specimen. The freshest-appearing dunite is now at least half serpentinized. In certain places alteration has gone so far that the original texture and composition are no longer recognizable in the field, and the rock can be mapped only as serpentine. That the serpentine is secondary is manifested by the complete gradations between serpentine and the least-altered rocks. The typical serpentine is medium to dark green or greenish black, soft, and broken by innumerable shear surfaces. This rock commonly forms smooth bare exposures that can be recognized from a considerable distance by their greenish colors and shiny slickensided surfaces.

Although possibly half of the ultramafic rocks are massive and apparently structureless, banding is prominent in a large part of them. The banding may express either: (1) a layered structure revealed by unequal proportions of pyroxene and olivine in alternating rock layers, or (2) a linear structure shown by alinement of pyroxene crystals in an otherwise uniform rock. The first type of banding is illustrated by alternation of layers of olivinite and pyroxenite, but it may involve almost any combination of ultramafic rock types. The contacts between layers are gradational, but the layers are more or less distinct, especially where contrasting rock types are involved. In a given exposure, the adjoining bands may range in width from about an inch to several feet; layering on a major scale gives rise to mappable bodies tens of feet wide and hundreds of feet long. The second type of banding is generally less prominent and even obscure, because the pyroxenes are arranged in discontinuous strings and there is no clear-cut alternation of different materials. Where the two types of banding occur together they are parallel. Linear structure, or arrangement of pyroxene and chromite grains in lines rather than planes, was noted in several places. This type of structure is well shown in several chromite deposits.

The attitude of the banding varies greatly from place to place, apparently without any system, over the district as a whole. In some areas, such as the upper drainage basin of Dog Creek, the dip and strike of banding varies only a few degrees over a square mile or more, but such consistency is rare.

Distribution

The ultramafic rocks are best preserved in the eastern half of the Canyon City belt, east of Canyon Creek. In the western half of the Canyon City belt and in the western or Murderers Creek belt the chromite-bearing rocks have been converted almost entirely to green serpentine. In the northeastern part of Grant County the chromite-bearing rocks are sheared green serpentine and talc-dolomite rocks that become yellow on weathering.

East of Canyon Creek the borders of the ultramafic belt are markedly pyroxenic. The general areal relations of pyroxenite and peridotite to olivinite and dunite are best exemplified in Byram Gulch, northwest of Canyon Mountain (pl. 13). There the border of peridotite and the central portion of dunite-olivinite are unusually well developed and distinct. The intrusive contact with the basement complex is exposed in many places, and the transition zone between dunite and peridotite is only a few feet wide. Farther east the peridotite does not form a solid border but consists of a great number of peridotite and pyroxenite lenses oriented parallel to the contact and enclosed in olivinite. The entire mapped portion of the southern border zone also contains numerous tabular blocks of basement complex. The relations along the northern margin of the ultramafic mass are partly concealed by overlapping Tertiary rocks, and even where exposed they are obscured by extensive serpentinization and faulting. Blocks of Mesozoic (?) sediments and basement complex, however, are abundant.

Age

The fossiliferous limestone west of Fields Creek lies in chert and argillite about 125 feet from the serpentine contact and is older than the serpentine. Lupher [9/] states that the serpentine in the Silvies River district south of Seneca is intruded into fossiliferous Upper Triassic limestone and is unconformably overlain by fossiliferous Lower Jurassic limestone. The serpentine and ultramafic rocks of the Strawberry Range are accordingly regarded as of Triassic age or younger.

Gabbroic banded rocks and pegmatites

Some chromite bodies, notably those at the Chambers mine, are cut by dikes of coarse pegmatite and medium to fine-grained gabbro. The known width of the dikes is between one-fourth inch and 1 foot, and diamond drill holes at the Chambers mine penetrated as much as 6 feet of gabbro between chromite walls. The feldspar in the pegmatite is calcic bytownite, and the pegmatite grades into the gabbro. Small exposures of banded gabbro are fairly common in the olivinite in the vicinity of the Chambers and Bald Eagle mines. These gabbroic bands are undoubtedly closely related to a banded complex of ultramafic rocks and gabbro that is exposed for a distance of about a mile along the ridge extending south from Bald Mountain. Some of the banded gabbro resembles parts of the basement complex.

The Celebration mine is in a dunite band included in the gabbro complex, and other chromite deposits may be present, although none have come to the writer's attention. The gabbro seems to have been affected by the same agencies that serpen-

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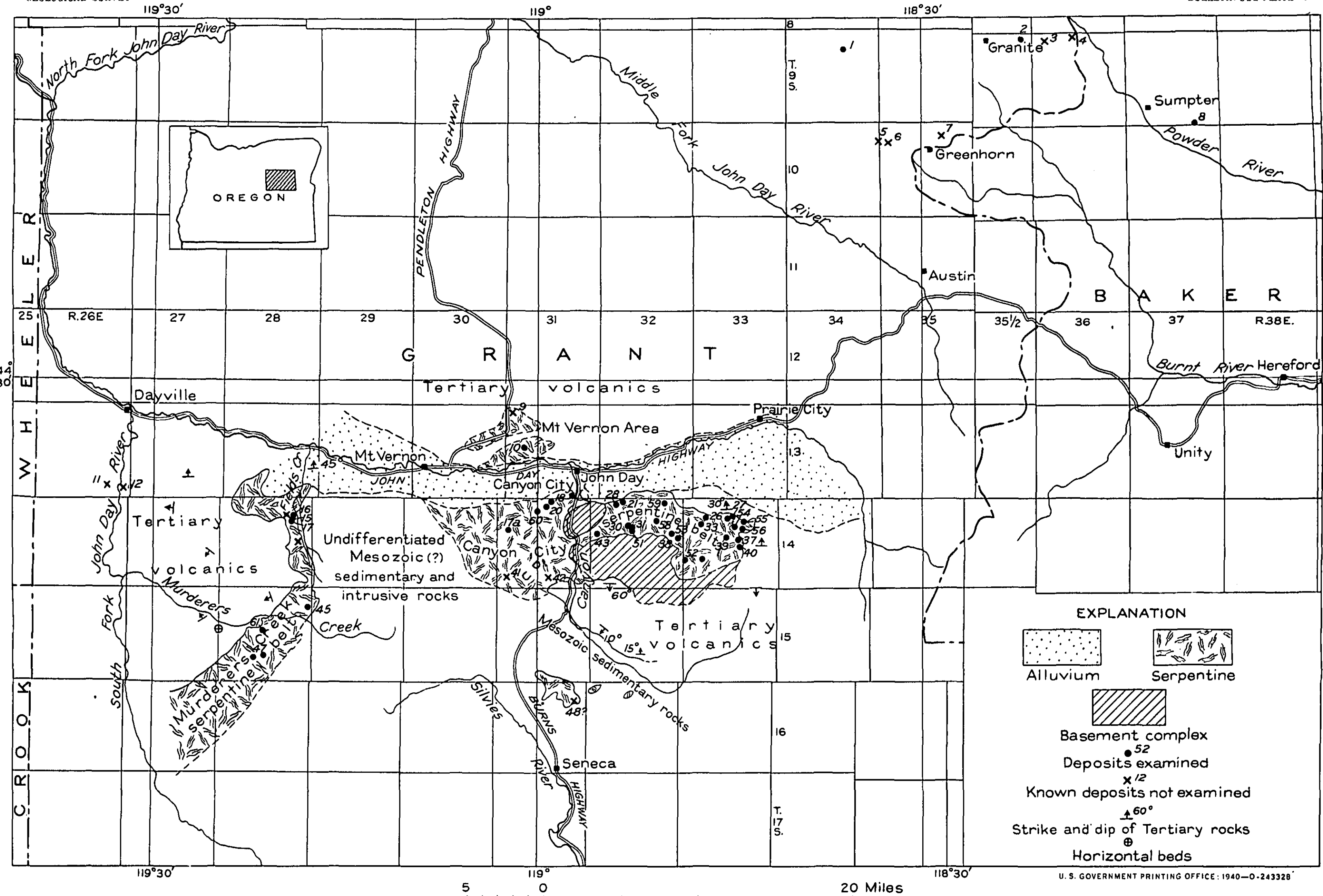
9/ Lupher, R. L., personal communication, September 1939.



MAP OF THE SERPENTINE BELTS OF THE STRAWBERRY RANGE AND THE CHROMITE DEPOSITS OF GRANT COUNTY, OREG.

The numbers refer to deposits described in the text or in earlier reports tinized the ultramafic rocks, and therefore probably antedates the serpentinization and is of about the same age as the ultramafic rocks--Triassic or younger.

Tertiary and Quaternary rocks

The oldest Tertiary deposits of the John Day district are conglomerates several hundred feet thick, which lie unconformably on the older rocks and were in part derived from them. The age of these conglomerates is not definitely known. The conglomerates are overlain by successive basalt flows several hundred feet thick, which are probably equivalent in age to the Columbia River basalt. In the vicinity of Mount Vernon, tuff of the Pliocene Rattlesnake formation is well-exposed and lies unconformably across the edges of the lower basalts. East of John Day and north of the John Day River, an upper series of basalt flows lies on pumiceous water-laid tuff that is probably part of the Rattlesnake formation. Volcanic rocks are well-exposed in Strawberry Mountain, in the valley of Berry Creek south of Canyon Mountain, and in the vicinity of Fields Creek.

East of Canyon Creek and south of the John Day River, the volcanics are buried under broad alluvial fans built out from the north base of the mountains. The largest fans were built by the creeks that drain the high parts of the range and whose headwaters bear unmistakable evidence of glaciation. The Little Pine Creek fan and the debris shed from Little Canyon Mountain contain placer gold that has been mined on a large scale. The present valley of the John Day River is cut along the outer edge of the old fans, and the alluvium of the valley floor is the latest deposit of the region. Down cutting by the John Day River and its tributaries left the old placer deposits perched 200 feet or more above the present stream beds.

Structure

The Strawberry Range is eroded from an east-west anticline between the John Day syncline on the north and the broad structural basin of Bear Valley on the south. The range is an easterly extension of the Ochoco Mountain uplift, although it is topographically separated from the Ochoco Mountains by the valley of the South Fork of the John Day River. East of Strawberry Mountain the anticline flattens and merges into the southeastern end of the Greenhorn Mountains. East of Canyon Creek the Strawberry Range anticline is symmetrical, and the dips in the Tertiary rocks on both flanks are between 30° and 60°. Between Canyon and Fields Creeks the anticline is markedly asymmetrical, the north limb dipping 30° to 45° and the south limb probably 5° to 10°. The transition zone between the symmetrical and asymmetrical parts of the anticline lies just west of Canyon Creek.

Although the structure of the pre-Triassic schists is very complex, and their contacts with the dioritic rocks are intricate, the structure of the dioritic rocks themselves is relatively simple. The deformation of these intrusive rocks is mainly shown by a persistent banding, the strike of which ranges from N. 65° W. to N. 85° E. and the dip from 65° N. to 65° S.

The contacts of the ultramafic intrusives with older rocks have been studied most thoroughly in the belt east of Canyon Creek, which is bounded on the south by the basement complex and on the north mainly by Mesozoic sediments. These contacts are everywhere nearly vertical. Their details are so complex as to be hard to decipher or to represent on even a large-scale map. The main mass has many offshoots extending into the older rocks, and it contains many inclusions of these rocks near the main contacts. In the valley of Canyon Creek the belt of ultramafic intrusives abruptly broadens and cuts off the basement complex, and at its western end it frays out into a series of lenses in the Mesozoic sedimentary rocks. The serpentine northeast of Mount Vernon was intruded into Mesozoic sedimentary rocks and may be a continuation of the Canyon City serpentine belt under the alluvium of the John Day Valley.

The Murderers Creek serpentine belt consists of several serpentine lenses trending north or northeast in the Mesozoic sedimentary rocks. It is overlapped on the west side by Tertiary lavas. The east limit of the belt is indefinite, and small serpentine lenses are known to occur in the area to the east where the Tertiary cover has been removed.

ORE BODIES

Workable chromite deposits occur as rather well defined irregular lenticular bodies scattered haphazardly in the olivinitic and dunitic parts of the ultramafic belt. The ore bodies range from deposits of a few pounds to those of several thousand tons, though relatively few of them contain more than 100 tons.

Mineralogy

The essential constituent of chrome deposits is the mineral chromite, which is easily scratched with a knife blade, forms a brown powder, and ordinarily is not attracted by a hand magnet. Theoretically pure chromite contains 68 percent of chromic oxide (Cr_2O_3) and 32 percent of ferrous oxide (FeO). In most chromite alumina (Al_2O_3) and ferric oxide (Fe_2O_3) replace part of the chromic oxide and magnesia (MgO) replaces part of the ferrous iron, so that the actual chrome content is far less

243328 O—40——3

than the theoretical maximum. The following analyses, made in the chemical laboratory of the United States Geological Survey, indicate that the chrome content for deposits in Grant County ranges from 34 to 52 percent.

Partial analyses of chromite from Grant County, Oreg.
[R. C. Wells, analyst]

Deposit	Type of ore sample	Concentrate in total sample (percent)	Analysis of concentrate		
			Cr_2O_3 (percent)	Fe (percent)	Cr/Fe
Dry Camp..	Massive...	82.8	51.6	12.7	2.77
Iron King.	Spotted...	60.6	42.0	13.9	2.06
Chambers..	Massive...	81.8	37.8	11.9	2.16
Ajax......	Nodular...	46.8	37.6	14.1	1.83
Bald Eagle	....do....	50.1	34.3	12.6	1.86
Delore 1/	Massive...	19.2	43.2	21.1	1.40
Do.2/...	....do....	78.1	41.1	21.0	1.33

1/ Moderately magnetic fraction. 2/ Weakly magnetic fraction.

Complete analyses have been made of only two specimens.

Complete analyses of chromite concentrates from Grant County, Oreg.
[R. C. Wells, analyst]

	1	2		1	2
SiO_2..........	1.9	2.8	TiO_2..........	0.3	0.2
Al_2O_3.........	27.0	13.3	Cr_2O_3.........	37.8	51.6
Fe_2O_3.........	.8	None	MnO...........	Trace	.3
FeO...........	14.6	16.4	H_2O...........	.3	1.3
MgO...........	15.2	13.4		97.9	99.4
CaO...........	.3	.1			

1. Massive ore from Chambers mine.
2. Massive ore from Dry Camp mine.

The analyses show that the chrome content of the chromite is variable and that it is not the same in any two deposits. This variation is of great economic importance, as the grade of any concentrate mechanically produced depends directly upon the purity of the ore-bearing mineral in the concentrate; for example, concentrates containing 50 percent of chromic oxide could probably be obtained commercially from the Dry Camp deposit, whereas concentrates from the Bald Eagle deposit might contain only 33 percent of chromic oxide. It is also obvious that bulk samples of spotted ore from the Dry Camp deposit and of massive ore from the Chambers deposit might give similar assays. Therefore assays of channel samples can give only partial information as to the real value of a deposit. Complete sampling procedure entails concentration of the channel samples with determination of the ratio of concentration of each and assays of enough of the concentrates to determine their average chromic oxide content.

The size of the chromite grains in spotted ore affects the degree of grinding necessary to free the ore from the gangue. Chromite crushes readily, and in fine grinding the loss caused by sliming is appreciable. The chromite grains in most of the deposits in Grant County are more than 1 mm. in diameter, and fine grinding is probably not necessary. In the Iron King deposit, however, the chromite grains average 0.2 to 0.5 mm. across, and loss due to sliming during the necessary fine grinding may be excessive.

In most deposits the matrix of the ore is serpentinized dunite, and the difference in gravity between chromite and gangue is great enough to permit concentration by gravity methods. All the ore contains some gangue, and there are all gradations from massive chromite to scattered chromite grains in dunite. The contrast between green or brown serpentine and specks or grains of black chromite gives most of the ore a spotted appearance. Chromite crystals are rare in the Grant County deposits, and in most of the spotted ore the chromite grains are angular or rounded. In a few deposits the chromite forms ellipsoidal globules from a quarter to an inch in diameter; this type of chromite, illustrated in figure 12, constitutes the so-called nodular ore. The chromite specimens shown in figures 12 and 13 were so treated and photographed as to obtain maximum contrast between serpentine and chromite. Where the serpentine was dark and failed to give good contrast, the specimen was treated with hydrofluoric acid, which etches and whitens the serpentine but does not attack the chromite.

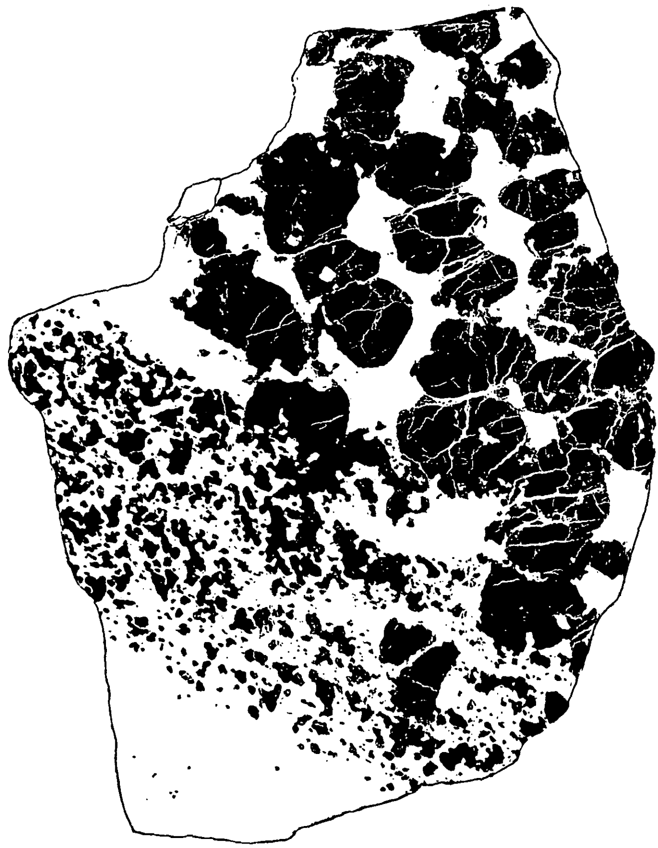


Figure 12.--Specimen from dump of Ward mine showing relations between nodular ore, spotted ore, and barren dunite.

Structural character

Banding is developed to some degree in nearly all the chromite deposits. In most of the deposits only one type of banding, either planar or linear, is shown, but in a few places, as for example the Iron King mine, linear banding is superimposed on planar banding.

Linear banding is well-shown in the Big Bertha deposit, where the ore shows marked vertical stripes in two adjacent walls of the prospect pit yet appears evenly disseminated in the floor. In the Ajax deposit the chromite aggregates are arranged like beads on strings, and some appear as flattened

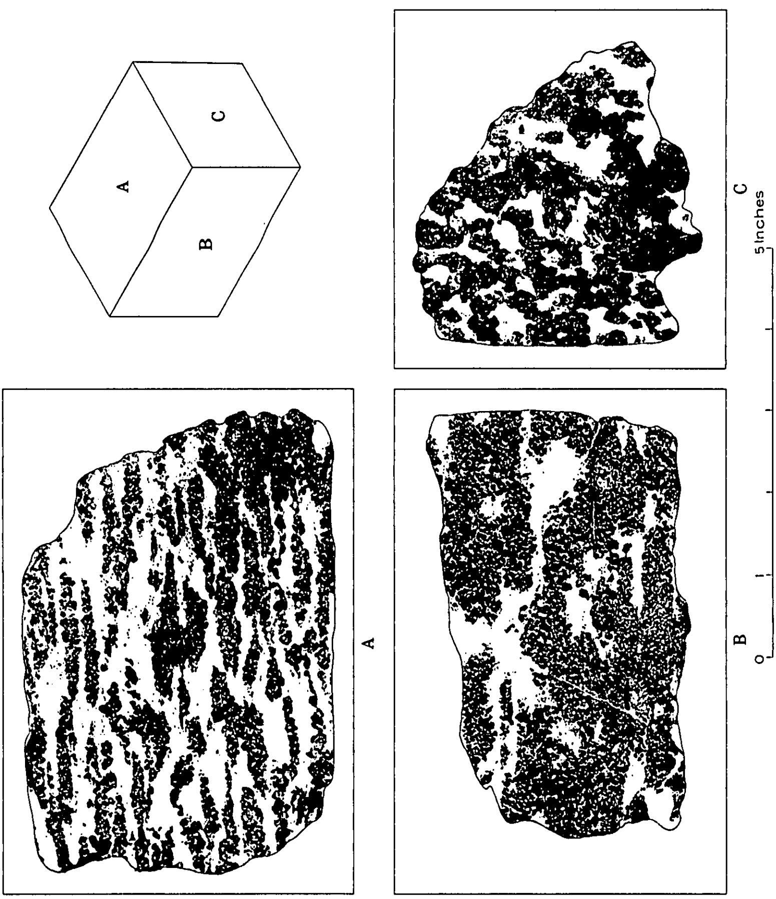


Figure 13.--Superimposed linear and planar banding in nodular chromite ore in serpentinized dunite. Mutually perpendicular photographic projections of a specimen from Ajax mine.

torpedo-shaped masses; this flattening of the chromite nodules extends along parallel planes and constitutes an obscure planar banding (fig. 13).

Planar banding, or alternation of layers of high- and low-grade ore, is best shown at the Dry Camp deposit, where massive chromite occurs in layers from a quarter of an inch to 2 inches in thickness. The chromite of the thinnest layers occurs in closely spaced grains or in irregular tabular masses such as might be formed by stretching of a thin, brittle sheet. In deposits devoid of massive ore the banding consists of alternating medium- or low-grade spotted ore and barren rock.

At the Iron King mine the major banding in the quarry face is planar, but ore specimens show prominent linear banding. The longitudinal axis of the linear banding is parallel to the planar banding, as it is wherever the two types of bands have been seen together.

Although zones of higher-grade ore can be mined selectively in deposits that show planar banding, the thinner individual bands cannot be sorted effectively by hand. Separation of ore and barren rock in deposits in which linear banding is dominant is especially difficult, because pipelike or torpedo-shaped masses of gangue occur in the ore, and cone-shaped masses of spotted ore extend out into the walls of the deposit.

Relations of ore bodies to enclosing rocks

The relations between the chromite bodies and the country rock of this region may be summarized in the statement that the chromite is as truly a component of the ultramafic rocks as olivine and pyroxene, and its occurrence is governed by the same laws. Just as there are gradations between dunite and pyroxenite, so there are all gradations between massive chromite and dunite or olivinite. None of the commercial chromite bodies in the Strawberry Range occur in peridotite or pyroxenite. In some places, transition from good ore to virtually barren rock takes place within a few inches; in other places the transition is so gradual that the deposit, in mining parlance, has "assay walls." Where the deposit is bounded by faults, as is common where the country rock is sheared serpentine, the walls are likely to be definite.

Banding in the chromite is generally parallel to the longer dimensions of the ore body and to the banding in the country rock. It cannot safely be assumed, however, that an ore body will extend far in the direction of banding, because ore may be cut off sharply across banding without faulting (fig. 14). Many small chromite deposits are merely irregular lumps of high-grade ore. The larger deposits are mainly irregular lenses whose long axes may plunge at angles between 15° and 90° in any direction.

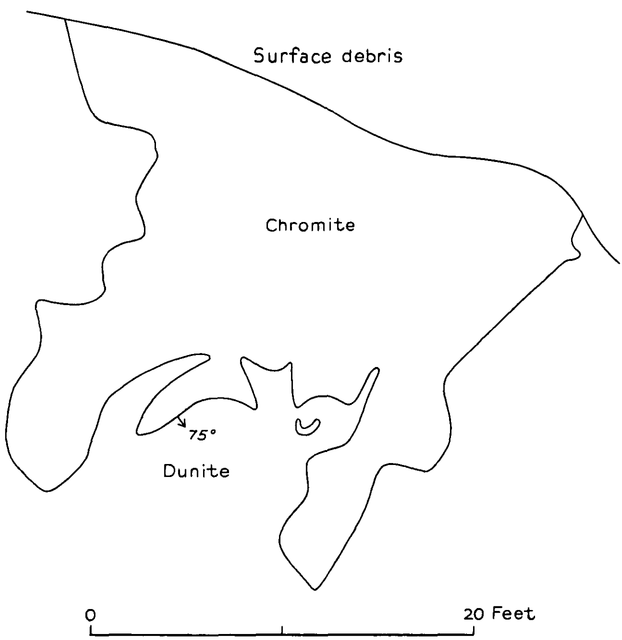


Figure 14.--Plan of southwest end of southwest ore body at Chambers mine showing irregularity of contact between chromite and dunite country rock. Except where dip is indicated the contact appears vertical.

The forms of the chromite bodies of this region are so irregular that estimates of ore reserves from surface exposures, even in well-banded deposits, must be made with great caution. The attitude and size of most of the bodies can be determined only by diamond drilling or actual mining operations.

Origin

The chromite that occurs in bodies large enough to be of commercial interest is clearly of early magmatic origin. Massive chromite in the upper deposit at the Dry camp mine is cut by numerous fractures that are filled with serpentine in which residual olivine pseudomorphs are preserved. Near the southwest end of the same deposit, the banded ore is cut by a dunite dike 2 inches thick. The relations between nodular and spotted ore in serpentinized dunite at the Ward mine (fig. 12) suggest that the spotted ore was formed by fragmentation of the nodular chromite as a result of flowage while the dunite magma was plastic. Remnants of olivine are here preserved in the serpentine, which shows unsheared mesh structure. The linear banding in deposits like the Ajax seems best explained by magmatic flowage that occurred after crystallization of the chromite and before solidification of the dunite.

Distribution

As the chromite bodies were formed by magmatic processes far below the surface, their relation to the present surface is entirely accidental. As chromite is very insoluble and resistant to surface weathering, secondary enrichment does not occur, and the chromic oxide content varies no more vertically than it does horizontally. The distribution of chrome lenses on the surface appears to be haphazard, like that of raisins in a pudding, and the same haphazard distribution probably holds in depth. Although an affinity between chromite and dunite is shown both by localization of chromite deposits in dunite lenses and by the dunitic character of the matrix of most of the chromite ore, some of the largest deposits occur in olivinite.

In general, it seems that the edges of the ultramafic belt, where peridotite and pyroxenite prevail, are unfavorable areas for prospecting and that attention should be concentrated on the areas underlain by dunite and olivinite.

ORE RESERVES

The chromite deposits of Grant County probably cannot now compete with chromite from foreign sources in present American markets. The known high-grade deposits are so small that mining costs are high. The large deposits are subcommercial in grade, and the minable product must be concentrated to be acceptable at any price in an open market, and transportation costs to present consuming centers are high. The only ore shipped from the district since 1920 was used solely for milling tests. However, the known deposits do constitute important reserves that would be usable in times of national emergency, when economic restrictions of grade and price would be relaxed.

From the figures quoted in Westgate's field notes, which contain data gathered from the mine owners and operators in August 1918, high-grade ore, containing more than 40 percent of chromic oxide (Cr_2O_3), constituted about one-fourth of the total ore shipped. Although only four mines produced 300 tons or more each of high-grade ore, about 90 percent of the total production of low-grade ore, which averaged about 32 percent of chromic oxide, came from three mines. In future shipments of crude ore from the district, the ratio of low-grade to high-grade ore will be greater than in the past, because most of the high-grade deposits exposed at the surface have been mined out.

Surface trenching and shallow diamond drilling of three deposits--Chambers, Iron King, and Dry Camp--by the Bureau of Mines indicate between 80,000 and 130,000 tons of chrome ore averaging 25 percent of chromic oxide above the depth drilled. With sufficiently high prices and establishment of custom mills for concentrating low-grade ore, probably 200,000 tons of material averaging 25 percent of chromic oxide could be mined from known ore bodies.

MINES AND PROSPECTS

Nearly 100 chromite prospects are known in the area east of Canyon Creek alone. Only the more productive mines, the larger prospects, and the prospects in which the relations of chromite are unusually well shown will be described. Several deposits described by Westgate are here omitted either because they were not visited or because the workings are inaccessible and no additional information was obtained. The reader is referred to Westgate [10/] and Allen [11/] for descriptions of the deposits in the Greenhorn and Granite districts and of several mines in the Canyon City district which were not visited by the writer or which are now caved. Production figures for individual mines are quoted from Westgate's field notes or records of the United States Bureau of Mines.

Deposits in dunite and olivinite

Chambers mine (38) [12/].--The Chambers mine is at an altitude of about 6,500 feet on the northwest end of Bald Mountain, in the southeast corner of sec. 13, T. 14 S., R. 32 E. The mine is 13 miles by road from John Day, 8 miles of which is dirt road. Mining operations began in June 1918, and total

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10/ Westgate, L. G., Deposits of chromite in eastern Oregon: U. S. Geol. Survey Bull. 725, pp.37-60, 1921.

11/ Allen, J. E., Chromite deposits in Oregon: Oregon Dept. Geology and Min. Industries Bull. 9, pp. 53-69, 1938.

12/ Numbers in parentheses are those used on the map (pl. 12) and in the reports by Westgate and Allen.

production was probably about 6,000 tons. The ore shipped averaged 30 to 33 percent of chromic oxide. All ore under 28 percent, which included about one-fourth of the total ore mined, was discarded. Practically all ore shipped was mined from the glory hole shown on plate 14. The sample trenches and diamond drill holes were made by the Bureau of Mines.

The ore is mainly coarse spotted chromite in dunite that grades into massive chromite. In places it shows rude planar banding, best shown in the southwest ore body, where the bands dip about 70° SE. The matrix of the ore is serpentinized dunite, and, as shown in the cross sections, the ore bodies are almost surrounded by a shell of serpentinized dunite. The ore grades abruptly into the dunite where the contacts are not faulted, and the dunite grades outward into olivinite. Even where the chromite is in frozen contact with olivinite the matrix, between the chromite grains, is dunite. Small veins or dikes of green pyroxene from one-eighth of an inch to 1½ inches wide are common. They are probably genetically related to the larger gabbro and gabbro pegmatite dikes that cut the chromite in the glory hole. The pegmatite contains angular blocks of spotted chromite, and diamond drill hole No. 13 passed through about 10 feet of gabbro that cuts good ore. The gabbro is readily removed by hand sorting during mining. Many small faults cut the ore but thus far have not seriously interfered with mining operations.

Three major ore bodies and some smaller unworkable lenses are known on the Chambers ground. The size and general relations of the ore bodies are shown on plate 14. The southwest ore body is a lenticular mass dipping steeply southward and plunging northeastward. Most of the central ore body, which appears to be in the form of a short kidney, probably has been mined out. A tunnel, now caved, under the western edge of the glory hole was reported by Westgate to be in barren serpentine. Diamond drill holes Nos. 6 and 10 were barren, which indicates that the ore body does not extend to any great depth. The northeast ore body may consist of two overlapping lenses, but it seems more probably to be one large lens that has been faulted, for faulting at the edge of the ore is evident in cores from drill holes Nos. 12 and 16. Between drill holes Nos. 13 and 17 the ore either pinches out or is dropped along a fault parallel to the one indicated on plate 14. The average tenor of the ore, judged on the basis of past production and Bureau of Mines assays, is between 20 and 30 percent of chromic oxide.

Iron King mine (43).--The Iron King mine is at an altitude of 5,400 feet, in the SW$\frac{1}{4}$ sec. 18, T. 14 S., R. 32 E., on the west slope of the northwest spur of Canyon Mountain. The mine is served by a dirt road, 5$\frac{1}{2}$ miles long, from Canyon City. The workings, which consist of an open quarry, a tunnel, and small open pits, are shown on plate 15.

Mining at the Iron King deposit began in 1916, and 500 tons of ore was shipped by the end of the year. About 3,000 tons was shipped annually during 1917 and 1918, making the total production approximately 6,500 tons. The ore was hand-sorted, and there are now several hundred tons of low-grade ore in the dump. The shipping ore averaged about 32 percent of chromic oxide.

The ore at the Iron King mine is fine-grained spotted chromite in a matrix of serpentine derived from dunite. The ore is banded and gradates all the way from massive black ore containing, according to Bureau of Mines analyses, about 43 percent of chromic oxide to barren serpentinized dunite. Although planar banding is most apparent in the quarry face, dump specimens show well-developed linear banding. The primary, magmatic character of the banding is still evident despite serpentinization and complex faulting. Mainly because of such complex faulting, the distribution of the ore, as shown on plate 16, is very irregular. The dunite mass in which the ore occurs is surrounded by olivinite in which irregular bodies of peridotite and pyroxenite occur. These pyroxenic masses are related to the pyroxenic border facies of the ultramafic rocks, and about 200 feet south of the mine a large east-west block of gneissic basement complex is included in the olivinite. The main contact of the intrusive mass with the basement complex is about 1,600 feet south of the mine. Small veins of magnesite occur in the serpentine, and large crystals of aragonite occur in open fractures in the chromite.

The ore body in the Iron King deposit appears to be a nearly horizontal tabular mass, which is bounded laterally by faults and has been broken into several blocks that rise northward in a series of steps. The apparent dip of the banding in the individual fault blocks exposed in the quarry face is less than 15° NW. or SW., the dips in adjoining blocks being commonly in opposite directions. The chromite is cut off on the west by a fault that strikes N. 40° E. and dips 41° SE. The footwall of this fault forms the west wall of the quarry and was penetrated at a depth of 56 feet in diamond drill hole No. 24. The southeastern edge of the ore body is faulted against sheared and slickensided serpentine in the quarry face, and the northeastern limit of the ore-bearing block is probably a fault that brings serpentinized dunite against peridotite and pyroxenite. Drill hole No. 29 reached the hanging wall of a breccia zone containing fragments of chromite ore at a depth of 63 feet, and from this fact and the surface exposures it is inferred that the fault trends about N. 50° W. and dips 50° NE. The small chromite blocks exposed southeast of the main ore body appear to be in the breccia, and the highest chromite exposure northwest of the quarry lies close to the northwesterly projection of the fault, on the footwall side. The intersection of the breccia zone with the footwall fault presumably determines the northwesternmost extension of the ore-bearing block. The total width of the ore in the quarry face is 115 feet, and the total exposed thickness ranges between 10 and 25 feet. The chromite exposed in the quarry floor is a thin band dipping 10° or 15° toward the quarry face. The tunnel east of the quarry is in barren serpentine, and no indications of minable ore were found southeast of the quarry or below the quarry level. The record of shipments indicates that the ore averages 25 to 30 percent of chromic oxide (Cr_2O_3), including low-grade ore thrown on the dump.

Black Velvet deposit.--The Black Velvet claim is about 750 feet northwest of the Iron King mine and 50 feet above the road. Figure 15 shows the size and shape of the ore body. The ore is spotted chromite with planar banding that dips parallel to banding in the enclosing olivinite. At the north end the chromite pinches out. Along the fault in the northern trench the spotted chromite and serpentine have been ground to a streaked gray and brown massive rock that is fully as hard as the adjoining serpentinized olivinite. Elsewhere the contacts are gradational. Ore with a vertical thickness of 6 feet is exposed in the north trench, and the limits of the body were fairly accurately located in small pits. The ore probably contains between 15 and 25 percent of chromic oxide.

Dry Camp mine (33).--The Dry Camp mine is in the southern part of the SW¼ sec. 8, T. 14 S., R. 33 E., a short distance east of Little Indian Creek. The deposit is 7½ miles by dirt road from the John Day Highway.

VIEW OF QUARRY AT IRON KING MINE.

Shows the footwall fault and the distribution of ore in the face. The drilling rigs are set up at drill holes 24 and 25.

The ore in the Dry Camp deposit consists of spotted chromite in a matrix of serpentinized dunite and shows the most perfect planar banding seen in the district. The general relations and extent of the deposits are shown on plate 17. The mine was first worked in September 1917, and the first ore was shipped two months later. Shipments to July 31, 1918, are reported as 300 tons of ore containing 40 to 42 percent of chromic oxide

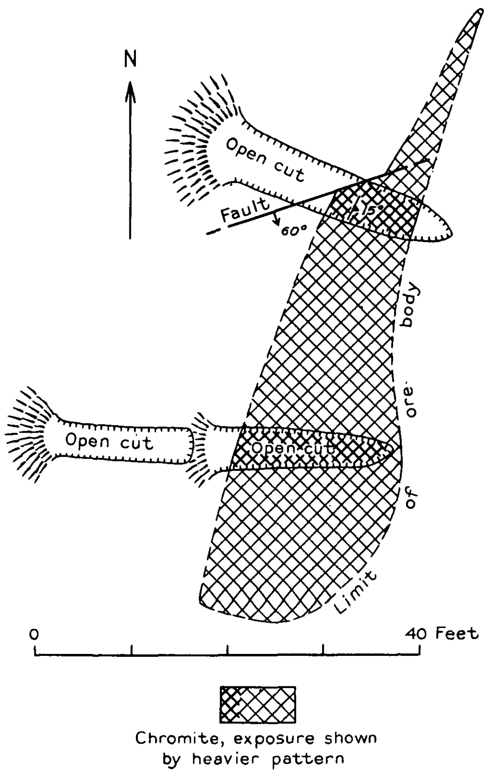


Figure 15.--Plan of Black Velvet chromite deposit showing attitude of chrome body and contact relations.

and 63 tons of 35-percent ore; 100 tons of mine-run ore was shipped late in 1939 for concentration tests. Although the banding in the two deposits dips 45° to 75° SE., the deposits are very shallow. As shown in the sections, no ore was found in any of the diamond drill holes. Test pits in the lower deposit were sunk 8 feet in broken ore, and the exposed thickness of ore in the upper deposit is about 20 feet. The tenor of the ore is between 15 and 30 percent of chromic oxide, which is considerably below that of past shipments taken from the rich central part of the upper deposit.

Marks & Thompson mine (27).--The Marks & Thompson mine is in the northern part of the SW¼ sec. 10, T. 14 S., R. 33 E., about 300 feet above Indian Creek. The mine was operated from November 1916 to August 1917, and 400 tons of 30-percent chromic oxide ore was shipped.

The workings and general relations of the ore body are shown in plate 18. The ore consists of rather low grade spotted chromite in which both planar and linear banding are developed parallel to the walls of the ore body, which dip 40° to 50° SE. At contacts that are not fault contacts the ore grades abruptly into the olivinite country rock. Although three prominent faults cut the ore body, the ore is comparatively massive The entire surface extent of the chromite body is not exposed, and ore may extend some distance beyond the northwestern side of the open cut. If movement on the northern transverse fault were normal, so that the northern segment of the ore body was dropped, the total reserve may be several thousand tons. The southern end of the mine appears to be worked out. The chromite in the trenches to the northeast is much faulted and is noteworthy mainly in that it shows that other chromite deposits of minable size may be present. The average tenor of the ore is probably between 15 and 25 percent of chromic oxide.

Ray mine (39).--The Ray mine is on the east end of Bald Mountain, at an altitude of 6,950 feet, about 2,000 feet a little west of north from the southeast corner of sec. 20, T. 14 S., R. 33 E. The mine is 17 miles from John Day by road, 4 miles of which is very steep and rough. The deposit was discovered in May 1918, and some ore was shipped. Westgate reports that the ore assayed 32 to 44.70 percent of chromic oxide.[13]

The workings and the exposures of the chromite remaining in the mine are shown on plate 19. The ore body that Westgate described has been mined out except for small masses of low-grade spotted ore, which shows some banding. The chromite is surrounded by a dunite shell, and the country rock is jointed olivinite. The tunnel penetrates about 20 feet of crushed chromite, which may or may not be continuous with the small chromite lens over the tunnel. No ore is exposed in the two prospect pits northwest of the Ray mine.

Ajax mine (54).--The Ajax mine is in the SE$\frac{1}{4}$ sec. 16, T. 14 S., R. 33 E., 1,000 feet above Indian Creek. The workings consist of three open cuts about 25 feet long and 40 feet apart. The chromite occurs in several lenses that range in size from 2 by 3 by 4 feet to 3 by 15 by 12 feet and are arranged in echelon in a narrow dunite zone in olivinite, the long axes of the lenses being parallel to the dunite contacts. The ore includes spotted and nodular types in which conspicuous linear banding has been produced by fracturing and elongation of the chromite nodules. The spotted ore, particularly in the southernmost cut, fingers out into the dunite in a series of irregular cones extending parallel to the linear banding, which trends N. 80° E. and pitches about 50° E. The ore on the dump is reported to contain 35 to 41 percent of chromic oxide.

13/ Westgate, L. G., op. cit., p. 42.

Bald Eagle deposit (53).--The Bald Eagle deposit is 1,000 feet northwest of the Chambers mine, at a 6,100-foot altitude, in the NE$\frac{1}{4}$SW$\frac{1}{4}$ sec. 13, T. 14 S., R. 32 E. The workings and general geologic relations are shown in figure 16. The chromite occurs in banded, spotted, and nodular ore, in which the nodules average three-eighths of an inch in length and about three-sixteenths of an inch in thickness. The south end of the ore body, although badly shattered, is clearly intrusive into an inclusion of diorite that belongs to the basement complex. The banding in the chromite is essentially perpendicular to the diorite contact, and the juxtaposition of the chromite body and the inclusion seems accidental. The contacts of dunite and ore show abrupt transitions; the surrounding country rock is olivinite. The average exposed thickness of ore is about 5 feet, and the ore appears to be of good milling grade.

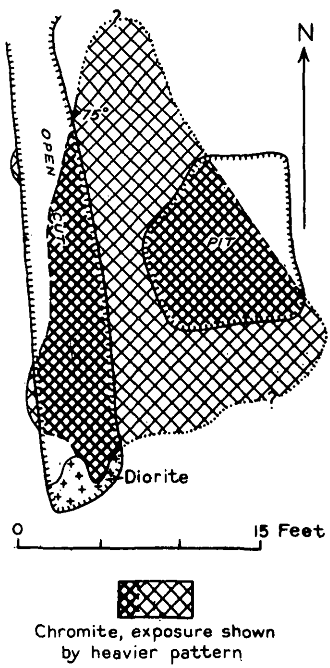


Figure 16.--Plan of Bald Eagle chromite deposit.

Celebration mine (52).--The Celebration mine is about 500 feet south of the East Fork of Pine Creek, in the northwest corner of sec. 30, T. 14 S., R. 33 E. The workings and exposures of chromite are shown in figure 17. The country rock is dunite, largely altered to serpentine, which a short distance to the west is intimately mixed with banded gabbro. The ore is high-grade nodular chromite in which equidimensional $\frac{1}{4}$-inch nodules of chromite occur in a matrix of fresh green monoclinic pyroxene. The ore averages about 5 feet in thickness and is considerably broken; the tunnel follows a shatter zone that dips about 20° S. parallel to the ore body.

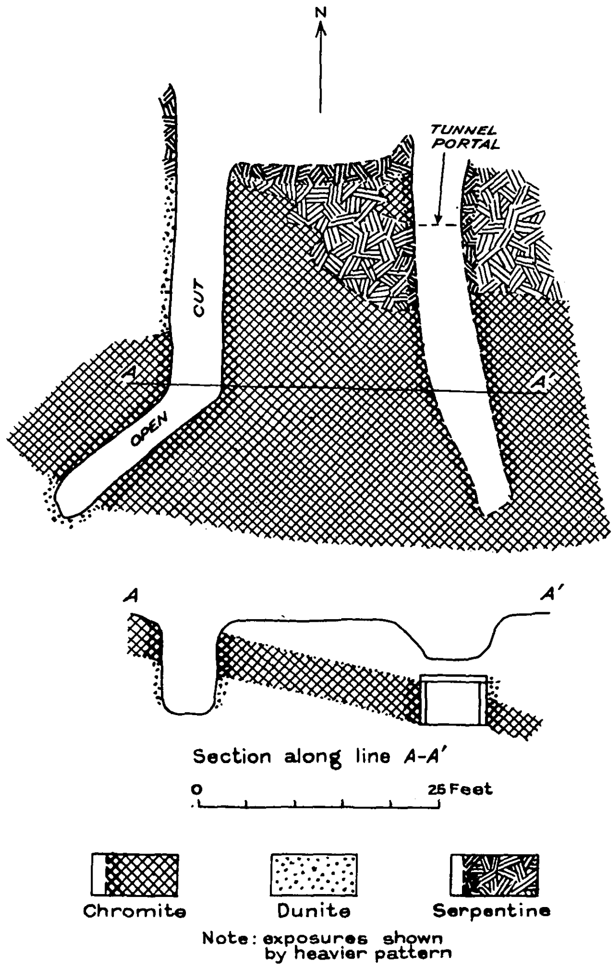


Figure 17.--Plan and section of Celebration mine.

Ward mine (28).--The Ward, Kingsley (30), Howard (26), Powers (21), and Big Bertha No. 1 (40) mines and the deposits west of Pine Creek (58) are similar in that the chromite occurs in thin tabular bodies or irregular stringers that appear to be schlieren.

The Ward mine is in the SE¼ sec. 5, T. 14 S., R. 32 E., about a third of a mile west of Dog Creek. The deposit was first worked in 1916 and was mined out late in 1918. Total production was between 2,000 and 2,500 tons. About a quarter of this was high-grade black ore averaging between 38 and 45 percent of chromic oxide in carload lots; the remainder averaged 31 to 32 percent chromic oxide. Massive black ore, spotted ore, and nodular ore were present. The relations between nodular ore, spotted ore, and barren dunite are shown in figure 12. The ore body was a vertical mass about 80 feet long, 70 feet deep, and not more than 10 feet thick. The east end was faulted off against olivinite, and the west end pinched and faded out into barren dunite. The remaining ore in the mine shows well-developed vertical planar banding parallel to the walls. Where exposed in a cross-cut trench the spotted ore at the north edge of the ore body grades into 8 feet of barren dunite, which in turn grades into vertically banded olivinite. Evidence of post-chromite pegmatitic activity is revealed by dump specimens that contain brecciated chromite enclosed in very coarse grained pyroxene.

Kingsley mine (30).--The Kingsley mine is in the SE¼SW¼ sec. 9, T. 14 S., R. 32 E., in the headwaters of Dog Creek, about 5,300 feet above sea level. The mine was operated from November 1, 1917, to November 1919. The 200 tons of ore shipped in 1918 averaged 45 percent of chromic oxide; some assays are reported to have run as high as 49.78 percent. The ore consists of black to spotted chromite and forms irregular bunchy stringers, from a few inches to 5 feet wide, in a dunite zone in olivinite. The stringers, which are essentially parallel, strike N. 50° W. and dip 60° NE. The zone has been explored about 100 feet along the strike and 35 feet vertically by an open cut and four tunnels. Imperfectly banded spotted ore was found in a prospect pit 50 feet southwest of the main workings.

Powers mine (21).--The Powers mine is on the ridge west of Dog Creek, near the middle of the west edge of sec. 4, T. 14 S., R. 32 E. The mine was in operation from January 1917 to August 1918, and a total of about 480 tons of ore containing 40 percent or more of chromic oxide was shipped. The ore consisted of about equal parts of high-grade massive chromite containing about 50 percent of chromic oxide and low-grade spotted ore averaging 25 to 30 percent. The workings, which consist of a series of trenches and open cuts and two tunnels, all on the east slope of the ridge, extend over a horizontal distance of 250 feet and have a vertical range of 50 or 60 feet. The chromite-bearing zone is irregular in thickness, its thickest part being 8 feet wide and its average about 3 feet. The chromite occurs in a dunite band that is little wider than the chromite body. The ore and dunite trend N. 50° W. and dip 60° or more southward. Planar banding is well-developed parallel to the walls. At the northwest end of the deposit the chromite grains string out into dunite and olivinite. A small amount of fresh enstatite was found in some of the ore.

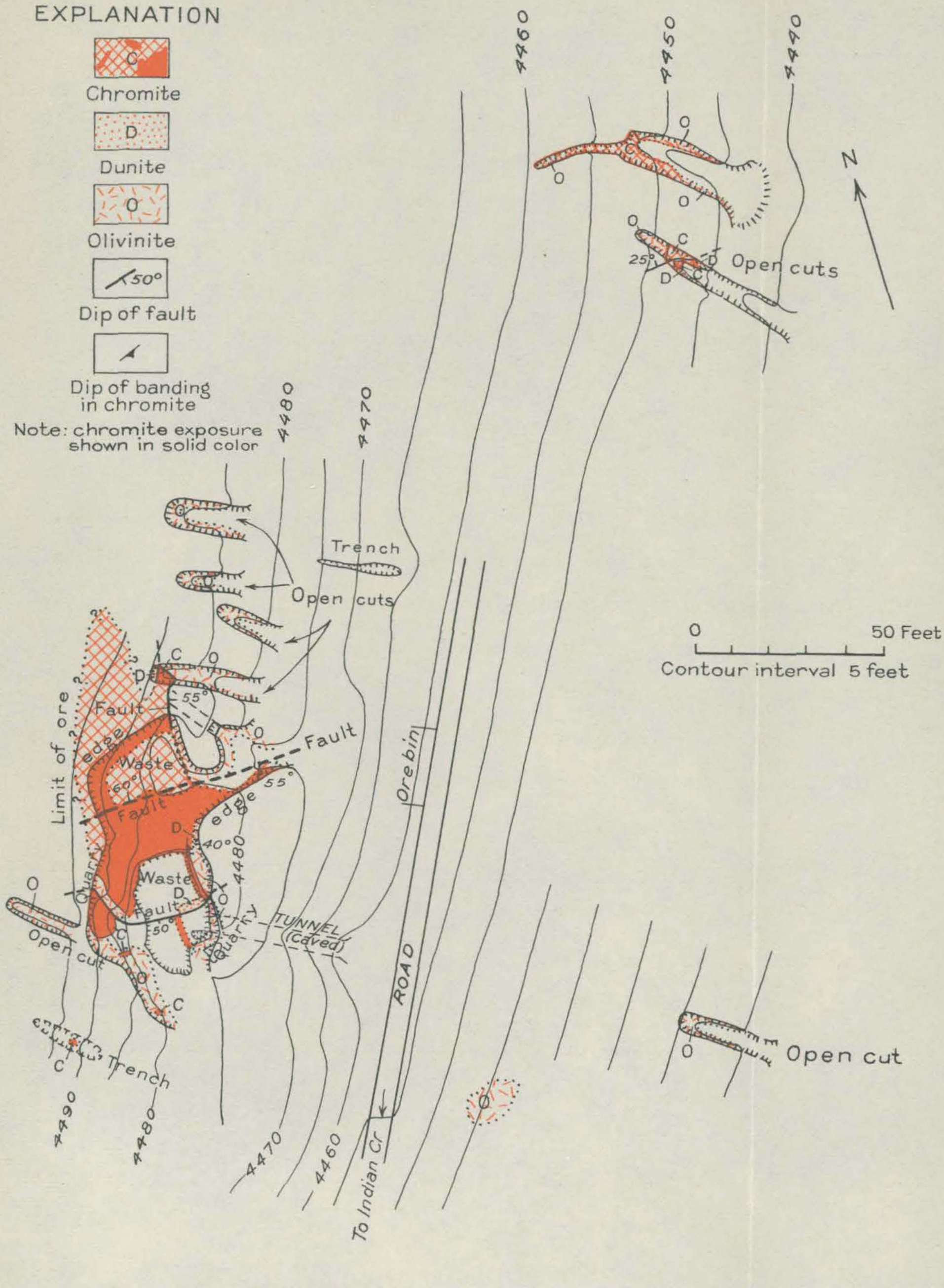
Howard prospects (26).--The Howard prospects are 3,500 feet northeast of the Dry Camp mine, near the center of sec. 8, T. 14 S., R. 33 E. The upper of the two principal prospects is a T-shaped open cut with the bottom of the T pointing northward. Small lenses of massive chromite and irregular masses of pyroxene occur in partly sheared and serpentinized dunite. Most of the ore contacts are faulted. The lower opening is a 75-foot trench along a chromite body trending N. 25° W. The main part of the cut is 35 feet long, 4 to 12 feet wide, and 10 feet deep. The ore forms a veinlike stringer of spotted and massive chromite in an irregular body of dunite, which grades into the olivinite country rock. The distribution of chromite in the ore and of pyroxene in the olivinite suggest linear banding and are remarkably similar. About 10 tons of low-grade ore is on the dump.

Prospects west of Pine Creek (58).--The prospect pits west of Pine Creek, in the center of the S½ sec. 11, T. 14 S., R. 32 E., reveal small chromite bodies enclosed in a lens of unsheared dunite, which is nearly 2,000 feet long and 200 to 400 feet wide. The dunite is itself enclosed in olivinite. The contacts between the two rocks are rather well exposed and indicate that the dunite strikes northwestward and dips 20° to 30° NE. The chromite forms only small irregular lenses, and no minable ore is exposed. The outstanding feature of the deposits is a band of spotted chromite between one-half inch and 3 inches thick, which is exposed near the upper end of the dunite mass. This chromite band is traceable continuously on a vertical rock face for upwards of 40 feet and was followed for nearly 35 feet in a tunnel at right angles to the rock face. The chromite lies parallel to the contacts of the dunite mass and apparently is a schlierenlike body whose lateral extent is great in comparison with its thickness.

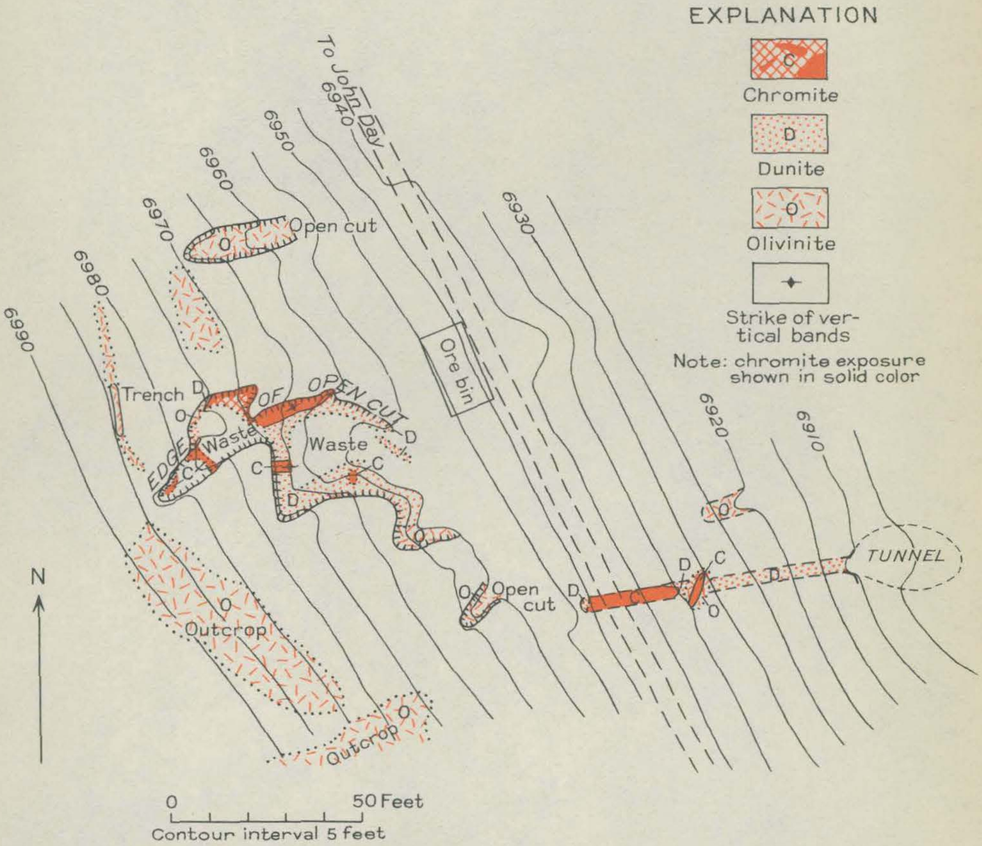
Sheep Rock deposits (37, 40).--Three chromite deposits on Sheep Rock, in prospects called the Hanenkrat, Morgan, and Campbell, were described by Westgate,[14] but because of mining since Westgate's visit, there is some difficulty in fitting his descriptions to the present prospects. The Hanenkrat (40) prospect has been renamed the Big Bertha No. 1; the Morgan and Campbell prospects were not definitely identified.

The Big Bertha (37) deposit may be the same as the Campbell claim of Westgate. The ore is exposed in an open cut about 20 feet long, 10 feet wide, and 5 feet deep. The ore is low grade,

14/ Westgate, L. G., op. cit., p. 43.



GEOLOGIC MAP OF THE MARKS THOMPSON CHROMITE DEPOSIT



PLAN OF THE RAY MINE

is spotted,and shows distinct vertical linear banding combined with planar banding striking N. 60° E. The chromite is in dunite, and although the planar bands feather out lengthwise, the lateral contacts are commonly well defined. In small irregular bunches and stringers of higher-grade chromite that occur outside of the main body of spotted ore, only vertical linear structure is apparent.

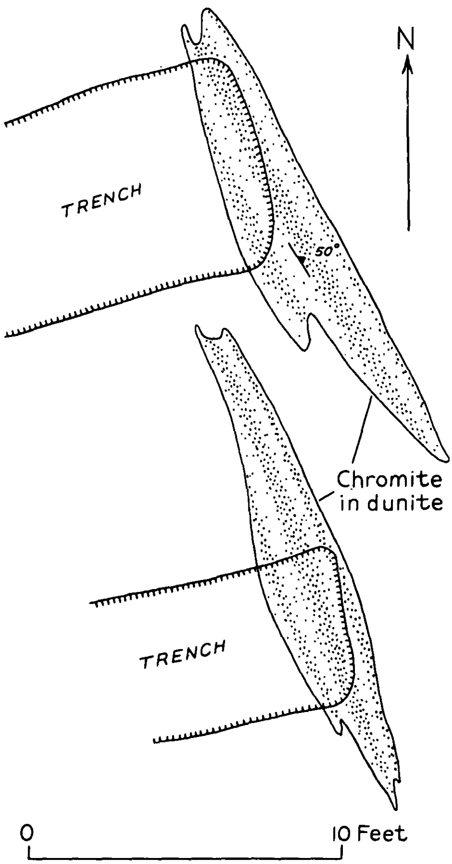


Figure 18.--Plan of Ray chromite prospects between Overholt and Indian Creeks showing attitude of banding. The country rock is olivinite.

Ray prospects (55, 56).--Several prospect pits have been dug in small chromite lenses in the west fork of Overholt Creek in the SE¼ sec. 10 and the NE¼ sec. 15, T. 14 S., R. 33 E. The relations of the two largest lenses, which are in sec. 10, are shown in figure 18. The ore is well-banded, partly massive and partly spotted. It is enclosed in dunite, which grades into olivinite within a few inches from the ore. The other lenses that have been prospected are much smaller. The average tenor in chromic oxide is probably about 20 percent.

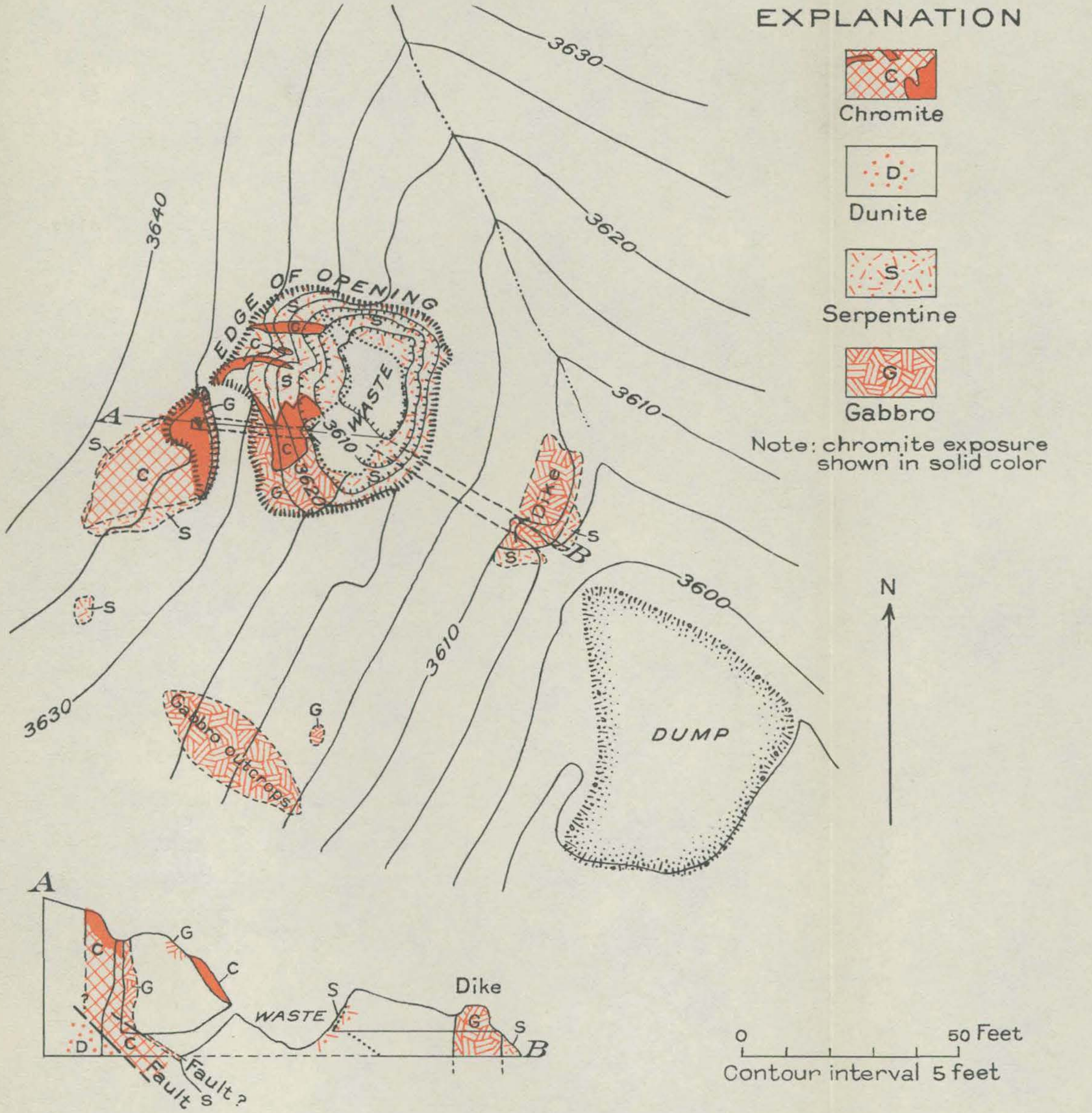
Reed (13) and Campbell mines (14).--The Reed and Campbell properties are among the prospects in the NE$\frac{1}{4}$ sec. 2., T. 14 S., R. 32 E., and are indicated on plate 12 by the number (59). The openings are now slumped, and the only visible ore occurs in two 1-inch stringers of spotted chromite in dunite and olivinite at the Campbell prospect.

Deposits in serpentine

Canyon City-Mount Vernon belt

Silver Lease mine (10).--The Silver Lease mine is about 3 miles northwest of John Day near the middle of the west edge of sec. 17, T. 13 S., R. 31 E. The workings and the distribution of the ore are shown on plate 20. About 700 tons of ore averaging 28 percent of chromic oxide is reported to have been shipped in 1918. The ore consists of lenses of dark spotted chromite bounded by slickensided contacts against serpentine. The serpentine contains pyroxene and is probably altered olivinite. The ore remaining in the glory hole consists only of small lenses and a shell of chromite perhaps 3 feet thick that lies against the gabbro (?) dike. The main ore block is west of the gabbro (?), which evidently cut squarely across the original chromite lens.

Norway (20) and Smith & Geitsfield mines (18) and prospect (60).--The Norway and Smith & Geitsfield mines, in the NW$\frac{1}{4}$ sec. 3, T. 14 S., R. 31 E., were described by Westgate, but the lode deposits on the Norway ground had not been mined at the time of his visit.



PLAN AND CROSS SECTION OF THE SILVER LEASE CHROMITE DEPOSIT

The Smith & Geitsfield produced 48 tons of 35-percent chrome ore in 1917, and the Norway mine produced 922 tons of ore containing more than 40 percent of chromic oxide (Cr_2O_3) in 1918. Four principal bedrock deposits were mined at the Norway, the largest of which is shown in figure 19. The ore ranges from massive high-grade to spotted low-grade chromite and includes some nodular ore. The chromite contacts are slickensided, and in one opening the chromite is sheared out in small lenses along a fault zone. The dumps contain about 400 tons of low-grade ore averaging 15 to 25 percent of chromic oxide and about 10 tons of higher-grade ore probably averaging 35 percent of chromic oxide. Not more than 50 tons of ore is visible in the ground.

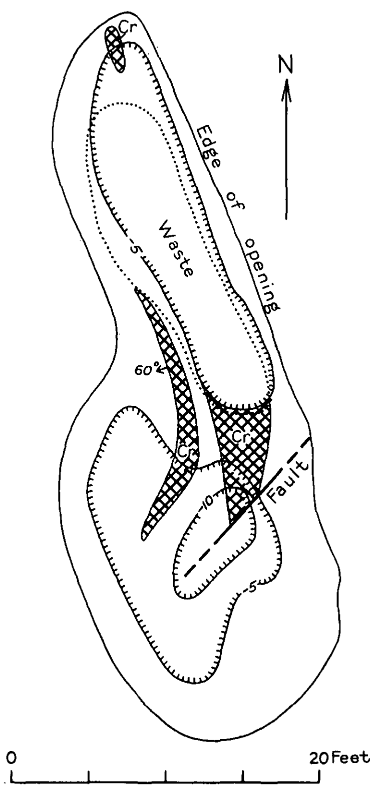


Figure 19.--Plan of principal opening on Norway claim. Cr, chromite.

At the prospect (60) southwest of the Norway, in the NE¼ sec. 8, two shafts were sunk 25 feet apart along a shear zone in pale-green serpentine. The zone trends N. 75° E. and dips 60° S. Spotted chromite is found on the dump as thin flaky pieces as much as half an inch thick, and it is inferred that the ore occured in thin irregular bands, possibly as schlieren.

Murderers Creek belt

Glasscock claims (15, 16, 17).--The Uncle Sam (15), Queen of the May (16), and Stone & Hankins (17) mines, collectively referred to as the Glasscock claims, are in the E½ sec. 10, T.

14 S., R. 28 E., about 1½ miles west of Fields Creek. The workings are caved and all the deposits are reported to be mined out, except possibly the Stone & Hankins, which is now held by Roy Glasscock as the Another Chance claim. The Uncle Sam and Queen of the May deposits, which are in dense serpentine derived from dunite and olivinite, produced about 40 and 80 tons, respectively, of ore containing more than 40 percent of chromic oxide. The Stone & Hankins mine produced about 300 tons of ore that averaged slightly more than 40 percent of chromic oxide and ran as high as 45 percent. Boulders of high-grade ore are exposed in small cuts near the Stone & Hankins workings, although no sizable bodies were found in place.

Hankins (Spring and Chrome Ridge) mine (45).--The Hankins mine, described by Allen as the Spring and Chrome Ridge mine, is in the NE¼ sec. 12, T. 15 S., R. 28 E., about a mile north of Murders Creek on the crest of the divide west of Oregon Mine Creek. About 65 tons of high-grade ore was shipped in 1918. The ore consists of massive black chromite that occurs in small lenses with slickensided contacts against the enclosing dense dunitic serpentine. The main body of serpentine is somewhat pyroxenic and probably derived from olivinite. No minable ore was seen.

Delore prospects (47).--The Delore prospects are on a bare serpentine ridge between Deer Creek and the South Fork of Murderers Creek, in the W½ sec. 27 and the SE¼ sec. 28, T. 15 S., R. 28 E. Total shipments amounted to about 50 tons of ore, said to average 54 percent of chromic oxide. The commercial chromite occurs as small sheared lenses in the serpentine. In the lowest cut, fine-grained brown chromite coatings on slickensided surfaces in the serpentine are unusually prominent. The workings include seven open cuts on the northwest side of the ridge, in sec. 27, and one cut on the southeast side of the same ridge, in sec. 28, where the only ore in place was seen. Here a lens of dense black chromite 3 feet long and 8 inches in greatest thickness trends N. 15° E. and stands vertical in serpentine. This ore is somewhat magnetic and contains about 21 percent of iron.

Prospects near Bull Spring (61).--Three prospects are situated in the vicinity of Bull Spring, which is near the common corner of secs. 15, 16, 21, 22, T. 15 S., R. 28 E. The workings are in the serpentine that forms a bare ridge northwest of the road between Murderers Creek and the South Fork of Murderers Creek. No chromite besides that forming thin coatings on slickensided surfaces was seen in place, although a few small pieces of slickensided black ore were found on the dumps.

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UNITED STATES DEPARTMENT OF THE INTERIOR
Harold L. Ickes, Secretary

GEOLOGICAL SURVEY
W. C. Mendenhall, Director

Bulletin 922-J

CHROMITE DEPOSITS IN THE SEIAD QUADRANGLE SISKIYOU COUNTY, CALIFORNIA

BY

G. A. RYNEARSON AND C. T. SMITH

Strategic Minerals Investigations, 1940
(Pages 281-306)

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1940

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - Price 30 cents

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ILLUSTRATIONS

CHROMITE DEPOSITS IN THE SEIAD QUADRANGLE
SISKIYOU COUNTY, CALIFORNIA

By G. A. Rynearson and C. T. Smith

ABSTRACT

The chromite deposits described in this report are in the Klamath Mountains of northern California. The oldest rocks in the area are mica, chlorite, and hornblende schists of pre-Cambrian (?) age, which are overlain by a complex series of metamorphosed volcanic and sedimentary rocks of Paleozoic (?) age. Into all these rocks quartz diorite, peridotite, and granodiorite were successively intruded. Auriferous terrace gravels, possibly of Pleistocene age, Recent gravels, and alluvium partly fill some of the larger canyons.

The chromite deposits, which occur in peridotite, range in size from a few tons to more than 100,000 tons. The ore of minable grade has an average chromite content of 35 percent. Reserves in the district, as estimated from known outcrops, are believed to be approximately 125,000 tons. At current prices of $20 to $25 a ton it is unlikely that any of the deposits can be profitably worked. Though the major part of the tonnage is of low grade (20 percent of chromite), the material could be concentrated to a 45- or 50-percent product. Hand sorting would yield small tonnages of shipping ore.

INTRODUCTION

Location.--The chromite deposits described in this report are in the northeastern part of the Seiad quadrangle, Siskiyou County, California (see fig. 41). The nearest railroad shipping point is Hornbrook, 51 miles up the Klamath River from Seiad Valley. The first 24 miles of the route from Seiad Valley to Hornbrook is a narrow, graded dirt road; the remaining 27 miles is paved and oiled.

Basis of report.--The field work for this report was carried on from July 25 to November 8, 1938, and from May 22 to July 13, 1939, under an allotment from the Public Works Administration for the investigations of strategic minerals.

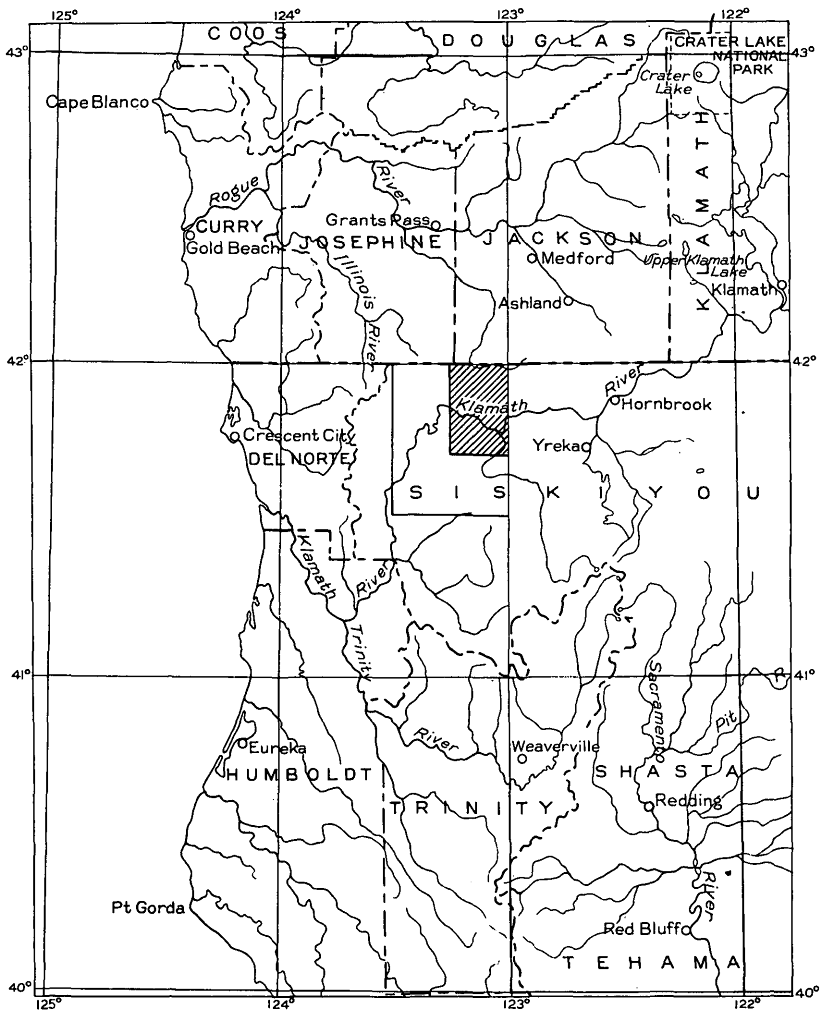

Figure 41.--Index map of northern California showing location of the northeastern part of the Seiad quadrangle.

The writers are indebted to Mr. H. F. Byram and the Rustless Mining Corporation for permission to study their properties. The aid of J. R. Bovyer in mapping the Seiad Creek chromite deposit and the constant cooperation of the U. S. Forest Service and the local inhabitants are gratefully acknowledged.

History of mining.--The deposits of the district were located during the intensive search for chromite in the last years of the first World War. Mining began in 1917, and a year later 10 mines in the district were producing ore. Mining stopped when chromite prices fell at the end of the war. Interest in the chromite resources of the district has been revived in the past few years. The Rustless Mining Corporation has acquired control of most of the deposits and is prospecting its holdings.

Earlier investigations.--Prior to the present investigation the area had not been mapped geologically. J. S. Diller briefly studied the chromite deposits during their early development in 1917;[1] and W. D. Johnston, Jr., spent several days in the area in 1931, examining some of the chromite properties and collecting specimens which he later described.[2] C. V. Averill has briefly described several of the mines.[3]

1/ Diller, J. S., Chromite in the Klamath Mountains, California and Oregon: U. S. Geol. Survey Bull. 725, pp. 1-84, 1921.

2/ Johnston, W. D., Jr., Nodular, orbicular, and banded chromite in northern California: Econ. Geology, vol. 31, pp. 417-427, 1936.

3/ Averill, C. V., Mines and mineral resources of Siskiyou County: California Jour. Mines and Geology, vol. 31, no. 3, pp. 255-338, 1935.

GEOLOGY

Metamorphic rocks

Older rocks.--The older metamorphic rocks of the area are mica, chlorite, and hornblende schists, not differentiated on the geologic map (pl. 40). The areas underlain by them, mainly in the east half of the region mapped, are densely covered with trees and underbrush and contain few good exposures, but the gray to brown soil derived from them is rather distinctive.

The mica schist ranges in color from light gray to nearly black. It contains both colorless and black mica and quartz. Some of the quartz occurs in small lenticular masses that lie parallel to the planes of schistosity. Thin bands of nearly pure quartzite, which also lie parallel to the schistosity, suggest that bedding and schistosity coincide and that the mica schists were derived from sandy argillaceous sediments.

The chlorite schist is light to dark grayish green and strongly foliated. It contains much more feldspar than the mica schist and is believed to have been derived from andesitic volcanic rocks. The relations between the chlorite and mica schists were not determined.

The hornblende schists are commonly found near contacts between chlorite schist and later intrusive rocks and appear to be a product of igneous metamorphism. They are dark green or gray where fresh and brownish where weathered.

Younger rocks.--Metamorphosed volcanic rocks whose relations and character indicate that they are younger than the mica and chlorite schists occur in the Marble and Siskiyou Mountains and occupy two areas in the west half of the region mapped. The area occupied by similar rocks north of the Klamath River extends northward into Jackson County, Oregon.

The original character of these rocks is best indicated in places north of the Seiad quadrangle, where they have been only moderately metamorphosed. Amygdaloidal and other volcanic textures may there be recognized, and the series appears to have consisted mainly of andesitic and basaltic flows and sills, though it also contained thin layers of sandstone, tuff, and shale, and some thick layers of limestone, now altered to marble. Within the Seiad quadrangle the volcanic rocks have mostly been altered, probably by intrusive processes, to schists and gneisses, though bedding is still recognizable in some of the sedimentary layers.

The marble occurs as lenses and layers, in places nearly 1,000 feet thick. The rock is coarse-grained and grayish white. Chert bands and thin quartzite beds, which are found in many parts of the exposures, give clues to the original bedding, much of which has been obscured by metamorphism. The marble is well-exposed on the west side of Grider Creek Canyon, where it forms cliffs more than 500 feet high.

Igneous rocks

Quartz diorite.--Quartz diorite, exposed in the southern half of the region, has been intruded into the schists and other metamorphic rocks and is older than the peridotites and the granodiorite. Its geologic age is not known more definitely than these relations indicate. It is medium-grained and medium gray, with a greenish cast in places. It consists mainly of andesine, hornblende, and quartz and contains a little biotite.

Gneissic structure resembling flow banding is commonly present but is not conspicuous everywhere. Both the gneissic quartz diorite and the volcanic rock have been so intensely metamorphosed that in several places the contact between them is not readily recognized. These rocks, therefore, are not distinguished on some parts of the map. Much of the area near Canyon Creek and Devils Peak mapped as younger metamorphic rocks is quartz diorite.

Peridotite and serpentine.--The largest body of peridotite wholly within the region extends north-northwest from the mouth of McGuffy Creek to Schutts Gulch, but many other bodies crop out in the western part, and two small ones are exposed in the northeastern part of the region. Some of the bodies are sill-like, but most of them are dikes.

The peridotite is mainly the variety dunite, a rock consisting essentially of olivine, but locally it grades into saxonite by an increase in the percentage of enstatite. The peridotite is for the most part relatively fresh, although it is largely altered to serpentine along fractures and shear zones. The small bodies of completely serpentinized rock may represent a different period of intrusion. The rock, where it is not much serpentinized, is yellowish green to greenish black on fresh surfaces and weathers to brown or brick red. Accessory minerals, such as pyroxene and magnetite, are relatively resistant to weathering and stand out in relief on weathered surfaces. The peridotite may usually be recognized in the field by its reddish outcrops and soil and by the sparse vegetation that it supports. The serpentines and the more highly serpentinized peridotites weather to a light-green or greenish-brown color and are characterized by slick, curved surfaces with a waxy luster.

The mineral composition of the peridotite varies only slightly. Olivine is the chief constituent, usually forming about 95 percent of the rock. Enstatite also occurs in varying amounts. Chromite and magnetite are, for the most part, accessory minerals, occurring as sparsely disseminated grains, although in places chromite forms masses large enough to be of economic importance. Tremolite, talc, anthophyllite, chlorite, magnetite, and serpentine minerals occur as products of metamorphism and hydrothermal alteration.

The peridotite bodies are intruded into all of the metamorphic rocks, including the quartz diorite, and granodiorite and associated pegmatites are in turn intruded into them. Their geologic age is tentatively classified as late Jurassic or early Cretaceous, on the basis of observations made in other parts of the Klamath Mountains.[4/]

Granodiorite.--The granodiorite is a light-colored, medium-grained plutonic rock, possibly equivalent to the "Siskiyou granodiorite" described by Maxson.[5/] It crops out east of Seiad Valley and between Walker and Grider Creeks. The principal minerals are quartz, plagioclase, orthoclase, muscovite, and biotite. Considerable variations in the percentages of the different minerals result in facies that approach quartz monzonite or quartz diorite in composition. Border facies commonly contain large inclusions of the younger metamorphic rocks. These inclusions have been partly assimilated, and some contain much garnet.

Small pegmatitic bodies occur within the main mass. They are composed of coarse-grained quartz and sodic plagioclase, books of muscovite and biotite, and occasional garnet crystals. At many places in the area pegmatite dikes, thought to be related to the granodiorite, invade the peridotite and younger metamorphic rocks. The granodiorite is slightly affected by dynamic metamorphism.

4/ Diller, J. S., U. S. Geol. Survey Geol. Atlas, Port Orford folio (No. 89), p. 4, 1903. Diller, J. S., U. S. Geol. Survey Geol. Atlas, Riddle folio (No. 218), p. 4, 1924. Shenon, P. J., Geology and ore deposits of the Takilma-Waldo district, Oregon: U. S. Geol. Survey Bull. 846, p. 160, 1933. Maxson, J. H., Economic geology of portions of Del Norte and Siskiyou Counties, northwesternmost California: California Jour. Mines and Geology, vol. 29, p. 131, 1933.

5/ Maxson, J. H., idem.

Quaternary deposits

Gravels.--Some of the gravel terraces along the Klamath and Scott Rivers are as much as 1,000 feet above the present river beds. The gravels contain boulders of peridotite, schist, and quartz diorite in a partly consolidated sandy matrix. Some of the deposits are nearly 100 feet thick, but present-day hydraulicking operations for the recovery of gold are rapidly removing them.

The age of the gravel terraces has not been definitely determined. Repeated rejuvenation of the rivers, perhaps beginning in Pleistocene time, is indicated by the various terrace levels. No fossils were found, and no measurements or correlations were attempted.

Alluvium.--Unconsolidated mixtures of sand and gravel with a few large boulders partly fill many of the canyon bottoms in the area. A small alluvial plain underlain by as much as 30 feet of alluvium forms the floor of Seiad Valley.

Structure

The structure of the area is complex and far from being completely understood, but some of its main features may be stated. The most notable structural feature is the northerly trend of the rocks.

The schists, for the most part, strike from N. 40° E. to N. 25° W. and dip moderately or steeply to the northwest or northeast. Interbanding of the various kinds of schists suggests that isoclinal folding may have occurred.

The younger metamorphic rocks are relatively undeformed. Their dips are generally low and are influenced by the proximity of intrusive bodies. Broad plunging folds are traceable in a few places. In general the rocks dip to the northwest and strike about N. 30° E.

The quartz diorite was intruded as an elongate body trending west of north. Gneissic structure resembling flow-banding is indicated by alinement of the mafic minerals. The well-developed gneissic structure in the northern part of the area is believed to be due in part to later deformation. North of Seiad Creek the quartz diorite has permeated the schist along the contact, forming a wide band of injection gneiss.

The larger bodies of peridotite also follow a north to northwest trend, closely parallel to the structure of the other rocks. In some places peridotite has been injected along planes of foliation in the quartz diorite to form alternating bands of the two rocks through a zone 500 feet in width. Foliation is prominent in the peridotite and is best developed near contacts with earlier rocks.

Fractures cut some of the chromite deposits, but the displacements on them are generally not more than a few feet. One fault zone was observed along Seiad Creek in sec. 33, T. 47 N., R. 11 W., but the amount of displacement could not be measured. Some mineralization is associated with this fault, and a number of gold prospects are located along it. Landslides in the peridotite and serpentine are numerous, and two of the smaller chromite deposits are in landslides.

ORE BODIES

The chromite deposits are enclosed in zones of partly serpentinized peridotite containing 50 to 90 percent of the original olivine. In this respect they contrast with the deposits in Del Norte County, which are in wholly serpentinized rock.[6/] The ore bodies, most of which are tabular, contain several distinctive types of ore. The most prominent ore bodies in the Seiad Creek and some smaller deposits are composed of massive

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6/ Maxson, J. H., op. cit., p. 149.

or layered chromite-bearing rock. Individual layers taper out and become ill-defined toward the ends and are most sharply defined at the sides. A few claims contain small amounts of orbicular and nodular ore, but massive or banded chromite constitutes the main ore bodies in all the deposits visited.

The ore deposits strike approximately parallel to the elongation of the peridotite areas, but they are not confined to any single zone.

The lengths of individual ore bodies, except in the Seiad Creek deposit, are at most only a few hundred feet. The chromite zones are discontinuous individual lenses of ore only a few feet or a few tens of feet in length. The chrome-rich zones contain between 20 and 40 percent of chromite, analyses of which average more than 50 percent of Cr_2O_3.

Mineralogy

The only ore mineral found in the deposits is chromite, whose formula is generally written as $FeO.Cr_2O_3$. Pure chromite contains 68 percent of chromic oxide and 32 percent of ferrous oxide, but in nature this ideal composition seldom occurs owing to the presence of aluminum, ferric iron, and magnesium in the chromite molecule. Because of the presence of these other elements the formula for chromite is more accurately written as $(Fe,Mg)O.(Cr,Al,Fe)_2O_3$. An analysis of chromite from the district follows:

Analysis of chromite from the Seiad Creek deposit 1/

/Charles Milton, analyst/

	A	B		A	B
Cr_2O_3	57.92	59.19	NiO	0.06	0.06
Al_2O_3	5.84	5.97	MgO	13.12	12.73
Fe_2O_3	6.40	6.54	CaO	.26	
FeO	14.83	15.16	SiO_2	1.29	
MnO	.25	.25	Total	99.97	99.90

1/ Johnston, W. D., Jr., op. cit., p. 425.

A. As analyzed.

B. After deducting 2.2 percent for $(Ca,Mg)SiO_3$, assumed to be present as an impurity.

The chief gangue minerals are olivine and serpentine, with olivine usually predominant. Small amounts of carbonate (magnesite?), kaemmererite, and uvarovite occasionally accompany the serpentine. Separation and concentration of the ore is made difficult by this type of gangue. The small difference of about 1.0 between the specific gravities of chromite and olivine is especially unfavorable to gravity concentration. Averill 7/ has described the results of some metallurgical work on ore from the Seiad Creek deposit. Concentration experiments were made that involved three types of magnetic separation, two types of flotation, and a method of tabling. The results are shown graphically in figure 42. The most satisfactory results were obtained by flotation of the chromite in an ore that assayed 32.17 percent of Cr_2O_3; one cleaner furnished concentrates that assayed 56.35 percent of Cr_2O_3, with a recovery of 89.7 percent.

7/ Averill, C. V., op. cit., p. 268.

Character of ore

Four distinct types of ore--banded, massive, nodular, and orbicular--are found in the deposits in the quadrangle. The types most important economically are the massive and banded ores (pls. 41, A, B, and 42, B), both of which are represented in the Seiad Creek deposit.

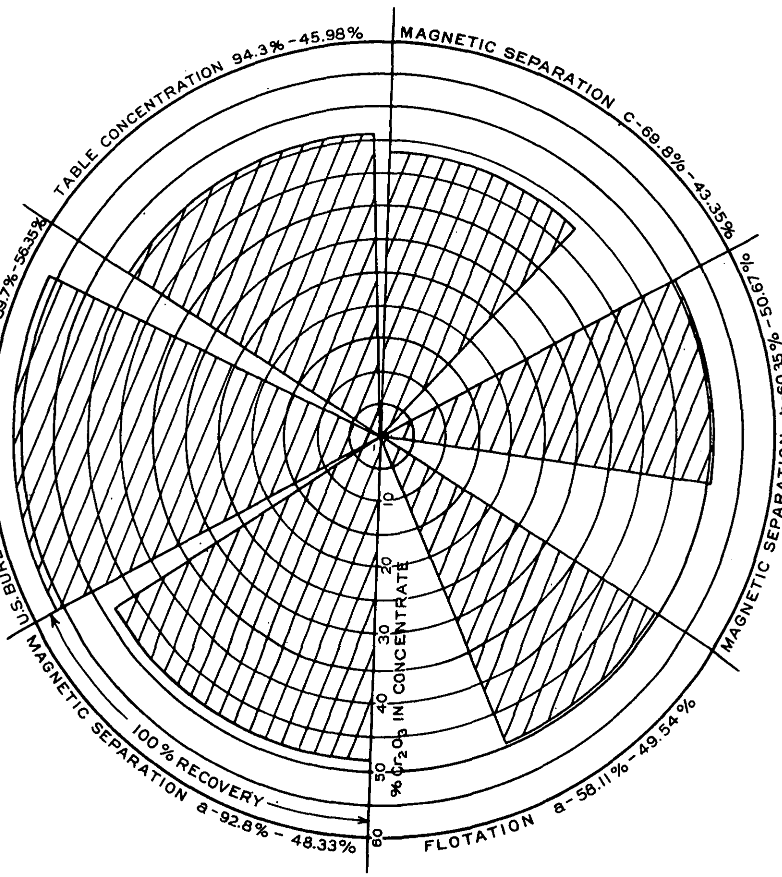
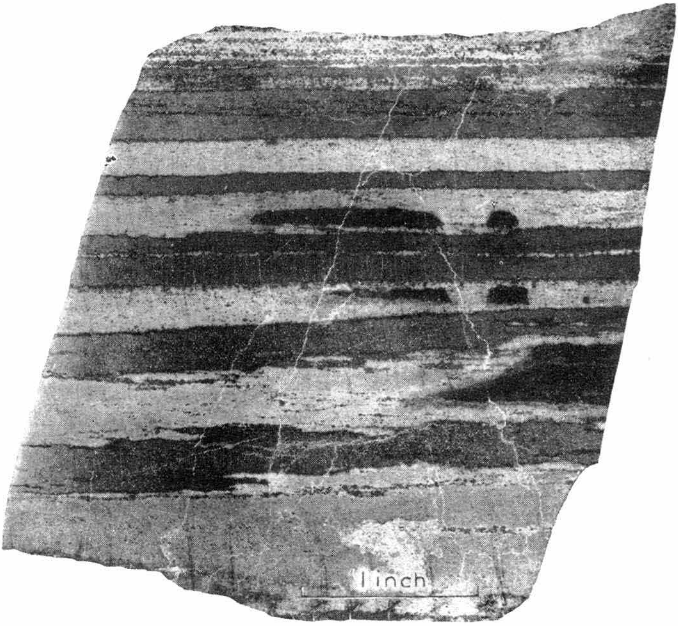
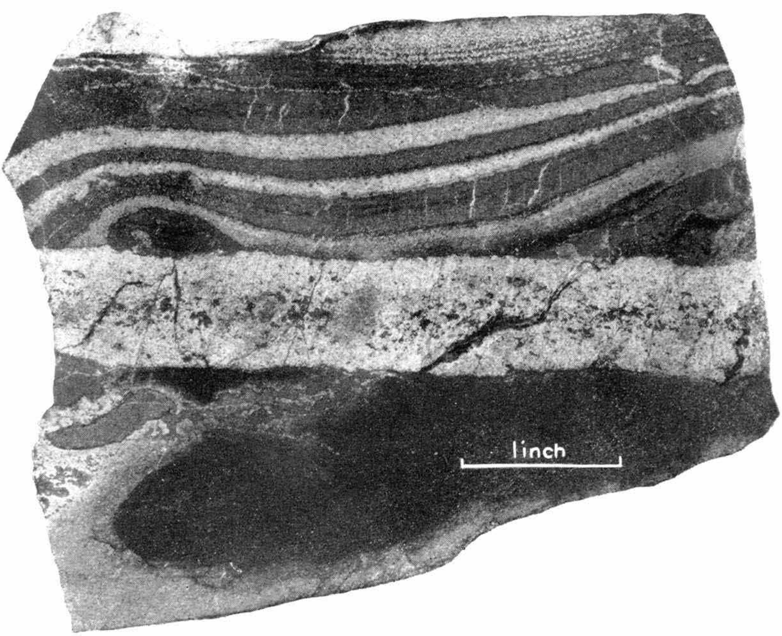


Figure 42.--Diagram showing results of metallurgical tests on Seiad Creek ore in percentage of recovery and percentage of Cr_2O_3 in concentrate, by six different methods. (After Averill.)

The banded ore consists of more or less continuous layers of chromite alternating with layers of partly serpentinized dunite. The chromite bands are mostly about a quarter of an



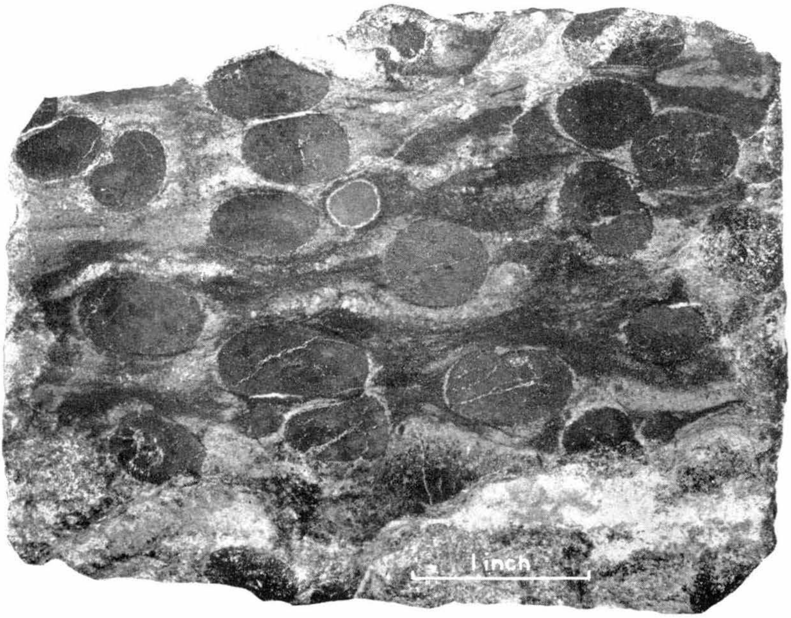
A. WELL-BANDED CHROMITE ORE SHOWING SMALL BLACK PATCHES OF UNWEATHERED PERIDOTITE.



B. BANDED CHROMITE ORE CUT BY DIKE OF SAXONITE.

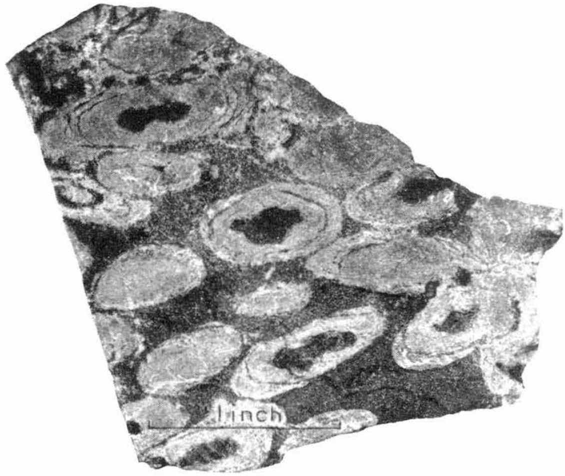
Saxonite is cut by later veinlets (black) of serpentine and carbonate. Cross fractures in the chromite are also filled with serpentine and carbonate. The dark area in the lower part of the specimen is unweathered peridotite.

CHROMITE ORE FROM THE JUMBO CLAIM.

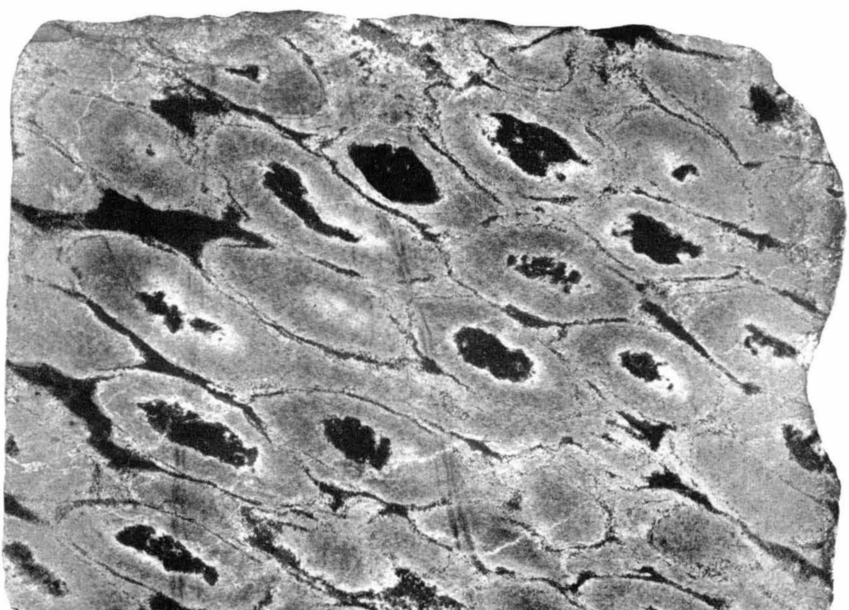


A. NODULAR CHROMITE FROM THE BLACK SPOT NO. 1 CLAIM.

B. RUDELY BANDED CHROMITE ORE FROM THE SEIAD CREEK DEPOSIT.



A. ORBICULAR CHROMITE ORE FROM THE OCTOPUS CLAIM.
Note successive shells of chromite and the abundance of inter-orbicular chromite.



B. ORBICULAR CHROMITE ORE FROM THE OCTOPUS CLAIM.

inch wide but may attain a width of 3 inches. In general they appear to have sharp boundaries, and the chromite grains are seen on close inspection to crosscut the olivine grains along the edges of the bands. Any single band extends for 15 or 20 feet at most and tapers out where another band a few inches to one side displays its maximum width.

Massive ore, averaging 60 percent of chromite, is found in several deposits, but only at the Seiad Creek deposit does it form ore bodies of noteworthy size. The banded ore grades into massive ore where the bands merge, but traces of banding are visible in even the most massive ore.

Nodular ore (pl. 42, A) occurs in two prospects. The nodules of chromite are embedded in a matrix of partly serpentinized olivine and pyroxene. The relation of the nodules to the foliation of the peridotite could not be determined.

Orbicular ore, consisting of close-spaced orbicules embedded in a matrix of serpentine, chromite, and serpentinized olivine (pl. 43, A, B), occurs in one deposit. The center of each orbicule consists of a mass of chromite crystals, which is surrounded by a shell of olivine. Some of the orbicules consist of several alternating shells of chromite and olivine. Where the chromite interstitial between the orbicules is abundant (pl. 43, A) the orbicular rock is good ore; elsewhere it averages only about 20 percent of chromite.

Origin

Chromite deposits have long been regarded as products of magmatic segregation. The universal association of chromite with ultrabasic rocks indicates a close genetic relationship.

Recent workers [8/] have questioned the magmatic segregation theory and have suggested that some of the chromite ores may be hydrothermal, or at least formed during a later magmatic stage than had previously been supposed.

Thin sections of the ores from the Seiad quadrangle are interpreted to indicate that chromite has replaced the olivine and pyroxene of the peridotite, for inclusions of olivine and of serpentine probably derived from olivine are common in the chromite, whereas the nearly complete absence of chromite inclusions in olivine implies that the olivine had almost completely crystallized before the chromite was formed. Chromite is always accompanied by serpentine, and olivine and chromite crystals are everywhere separated by thin sheaths of serpentine. Crystallization is believed to have yielded aqueous, chromite-rich residual liquors, which were introduced by a filter-pressing process into adjacent parts of the newly consolidated magmatic mass.

Most of the serpentinization accompanied the introduction of chromite in the late magmatic period. Later hydrothermal activity formed crosscutting veinlets of serpentine accompanied by carbonate, kaemmererite, and a little uvarovite. The distinction between the late magmatic and the hydrothermal serpentinization is emphasized by a small dike of relatively fresh saxonite that crosscuts the serpentinized banded ore and is cut in turn by hydrothermal veinlets of serpentine and carbonate (pl. 41, B).

Structural control is believed to have influenced the emplacement of the banded ores. Differential stresses set up in the partly consolidated magmatic mass could conceivably

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8/ Sampson, Edward, May chromite crystallize late?: Econ. Geology, vol. 24, pp. 632-641, 1929. Ross, C. S., Is chromite always a magmatic segregation product?: Econ. Geology, vol. 24, pp. 641-645, 1929. Fisher, L. W., Origin of chromite deposits: Econ. Geology, vol. 24, pp. 691-721, 1929. Sampson, Edward, Varieties of chromite deposits: Econ. Geology, vol. 26, pp. 833-839, 1931. Eskola, P., On the chrome minerals of Outokumpu: Finland Geol. Comm. Bull. 103, pp. 26-44, 1933.

produce marginal zones of weakness into which, by a filter-pressing process, the chromite-rich liquid could migrate and replace the olivine and pyroxene. Osborne [9/] has deduced a similar origin for certain titaniferous iron ore deposits. The original nature of the marginal zones is not apparent, being obscured by serpentinization, but it is suggested by the foliation of the peridotite and by evidence of protoclastic structure and, possibly, of some recrystallization of the olivine. Such structure could result from differential flowage or fracture, or both, in the partly consolidated magma. The relative importance of the two processes is uncertain, but flow was probably dominant at first and fracture later. Evidence that stresses continued after the emplacement of the chromite is given by folding in the banded ore and by thin cross veins of serpentine and carbonate (pl. 41, B) in the chromite.

The orbicular and nodular chromite is believed to have resulted from the replacement of the original structure in the peridotite, although the nature of the original structure is not understood, having supposedly been obscured beyond recognition by serpentinization. Marginal facies of the nodule-bearing rock exhibit structural features similar to the orbicular chromite; both types, therefore, are believed to have originated from similar processes. Flattening and elongation of the orbicules is probably due to the same stresses that affected the banded ore.

The exact stage at which the chromite was crystallized has little economic importance. It is important, however, that the chromite is a part of the enclosing dunite, so that its occurrence bears no relation to post-dunite fissures or to the present topographic surface.

9/ Osborne, F. F., Certain magmatic titaniferous iron ores and their origin: Econ. Geology, vol. 23, no. 7, pp. 750-752, 1928.

Localization

The chromite ore bodies lie parallel to the foliation of large peridotite bodies that trend about N. 20°-30° W. across the area. The foliation strikes N. 26°-64° W. and dips 37° to 75° SW. Two joint systems are present in places; one system is normal to the planes of foliation; the other is perpendicular in strike to the foliation and its dips are steep.

The chromite deposits are not found at any particular position within the peridotite masses, and there is no apparent relation between the sizes or distribution of the deposits and their distances from contacts.

The four types of ore--banded, massive, nodular, and orbicular--grade into one another without apparent change in the structure or mineralogy of the peridotite.

The largest ore bodies are roughly tabular masses rich in chromite which occur in partly serpentinized peridotite. At the Seiad Creek deposit individual layers and groups of layers lie parallel to the foliation but are arranged en echelon, so that the deposit as a whole cuts across the foliation of the peridotite at a small angle. In other deposits the relations are undetermined because of small outcrops and poor exposures, but individual ore bands appear to be parallel to the foliation.

Chromite is unevenly disseminated throughout the peridotite. In places disseminated chromite increases in amount until it constitutes 60 percent of the rock. Massive ore results where such concentration has been attained between several adjacent chromite bands. No structural control that influenced the distribution of massive ore could be found.

The orbicular ore is scant. Its mode of occurrence is similar to that of the banded ore.

Size and grade of known ore bodies

In this report ore bodies that are exposed on the surface and are intersected by an adit, although blocked on two sides only, are considered as probable ore. In open cuts exposing banded ore a depth of not more than 5 feet is assumed unless added information about the extent in depth was obtained.

Assays and measurements of grade were unavailable for most of the deposits. At the Seiad Creek deposit, grab samples taken across the strike of chromite-rich bands averaged 38 percent of chromite and gave a concentrate averaging 52.37 percent of Cr_2O_3. The amount of magnetite was believed not to exceed 5 percent in any of the samples, and it may be as low as 1 percent in some. An analysis of chromite in the orbicular ore showed an average Cr_2O_3 content of 51 percent.[10/] These analyses come from widely separated deposits and are believed to be representative for the area.

Reserves

Surface mapping and grab sampling at the Seiad Creek, McGuffy Creek, and Fairview deposits indicate about 45,000 tons of 35-percent ore. Geologically reasonable assumptions of continuity along the strike between exposures indicate an additional 60,000 tons of 35-percent ore. Deeper exploration by adits or diamong drilling would doubtless increase these estimates.

In the same deposits an estimated 200,000 tons of 20-percent ore lying above the lowest working or outcrop is indicated. The tonnage of 5-percent ore is much larger.

10/ Johnston, W. D., Jr., op. cit., p. 420.

MINES

Seiad Creek deposit

The Seiad Creek deposit, owned by the Rustless Mining Corporation, is in sec. 20, T. 47 N., R. 11 W., on a ridge between the forks of Seiad Creek (pl. 44), 7 miles by mountain road from Seiad Valley. Seiad Creek carries a good flow of water the year round, and the neighboring slopes are well-timbered.

The deposit is developed by 500 feet of underground workings in two adits (fig. 43) and by 27 open cuts and pits. Another adit is very short and has caved. Several foot trails and a sled trail make the adits and cuts accessible from the end of the road. In 1938 and 1939 the owners improved the road and trails and opened up several new cuts.

The country rock is peridotite originally consisting almost entirely of olivine, which is now partly altered to antigorite and talc. The peridotite has a well-developed foliation striking N. 26°-64° W. and dipping 37° to 75° NE. It is cut by a set of joints with a strike parallel, and a dip approximately perpendicular, to the foliation. The peridotite is in contact with chlorite schist along the east fork of Seiad Creek and with quartz diorite on the west slope of the west fork of Seiad Creek. At the contact with the diorite the peridotite has been injected along the gneissic planes of the diorite to form a zone of alternating sheets of the two rocks, in places 500 feet wide. Pegmatite dikes crop out on both sides of the ridge between the forks of the creek at an elevation of about 4,000 feet.

The chromite-bearing zone, which transects the foliation of the peridotite at a small angle, consists of a series of elongated bodies arranged en echelon. Exposed bodies of chromite from 2 to 15 feet in thickness extend discontinuously for

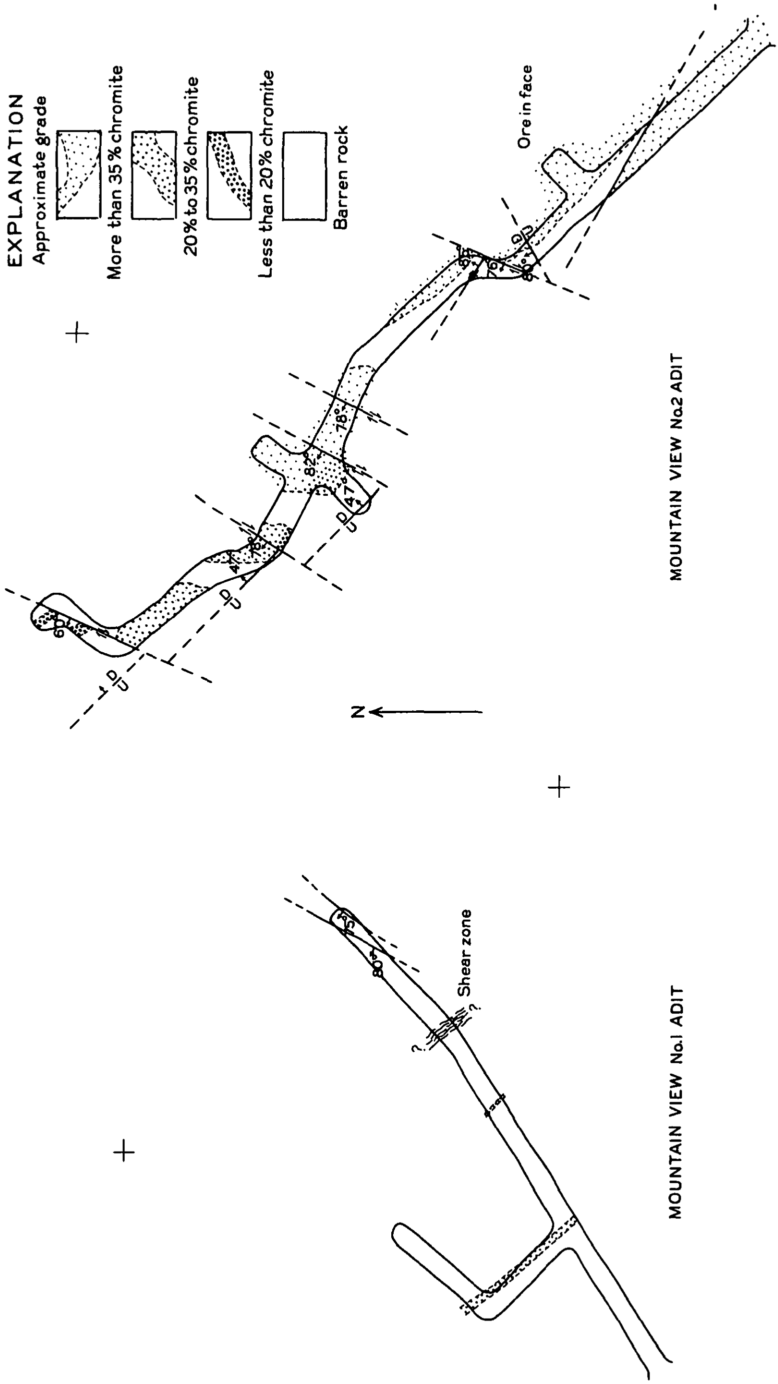

Figure 43.--Plans of underground workings at the Seiad Creek chromite deposit.

a distance of 3,000 feet. In general the ore is rudely banded and consists of small lenses of chromite intermixed with olivine. Most of the bands range from a fraction of an inch to a few inches in width, but individual bands of massive ore attain a width of 2 feet. Grab samples taken across chromite-rich zones in various parts of the deposit contained 17 to 64 percent of chromite and less than 5 percent of magnetite. The concentrate from these samples averaged 52.37 percent of Cr_2O_3. The grade of some of the ore sampled could be substantially raised by mechanical concentration or hand sorting. Kaemmererite, antigorite, and talc occur in cross fractures.

Minor post-chromite faulting was observed in the underground workings, but measurable displacements were not more than a few feet. Although surface indications are obscured by serpentinization and weathering, faulting has undoubtedly occurred in other parts of the deposit. Whether the faulting is of sufficient magnitude to displace chromite bodies into unexposed positions could not be definitely determined.

Chromite-rich bodies from 2 to 15 feet in width are exposed in several open cuts and adits, commonly as alternating bands of "high grade" and barren rock. The widths can be stated only approximately, as the "assay boundaries" of the ore would vary with the mining and milling methods used. Many of the bodies are pod-shaped and consist of massive chromite with little or no olivine; others are of relatively low grade, containing from 5 to 20 percent of disseminated chromite. Variations in shape and grade are great and unpredictable. The ore bodies show both lateral and vertical thinning, and chromite bodies are exposed underground that do not appear on the surface.

In calculating the reserves of this deposit, several assumptions are made that apply to all the deposits described.

1. The ore is assumed to average 9 cubic feet to the ton.

2. The ore exposed in each open cut is considered to be a separate unit except where ore is exposed on the surface between cuts.

3. The widths of the ore bodies are only approximate, as they would vary with such factors as assay boundaries, hand sorting, and mining and milling methods.

4. Ore was assumed to extend at least to the two adit levels unless a shallower depth was indicated by other evidence; and in some places it was proved this deep.

5. Probable ore is defined as ore in sight from adits, open cuts, and surface exposures.

6. Possible ore is defined as ore that is not exposed on the surface or cut by adits but assumed to be present along the strike of the ore zone.

On the above assumptions, indicated reserves, in tons, of the Seiad Creek deposit, averaging 35 percent of chromite, are estimated in the table below.

	Assuming vertical ore shoots	Assuming average dip of ore shoots as 50°
Probable ore	38,000	49,000
Possible ore	51,500	67,000
	89,500	116,000

Fairview group (Hamburg Bar mine)

Five claims (fig. 44) located on both sides of the ridge in sec. 34, T. 46 N., R. 11 W., are owned by Mary F. Reddy, of Medford, Oreg., and are under option to the Rustless Mining Corporation. Two miles of graded road connect the property with the Klamath River highway. The workings consist of five open cuts in ore. This deposit has not been worked since the first World War.

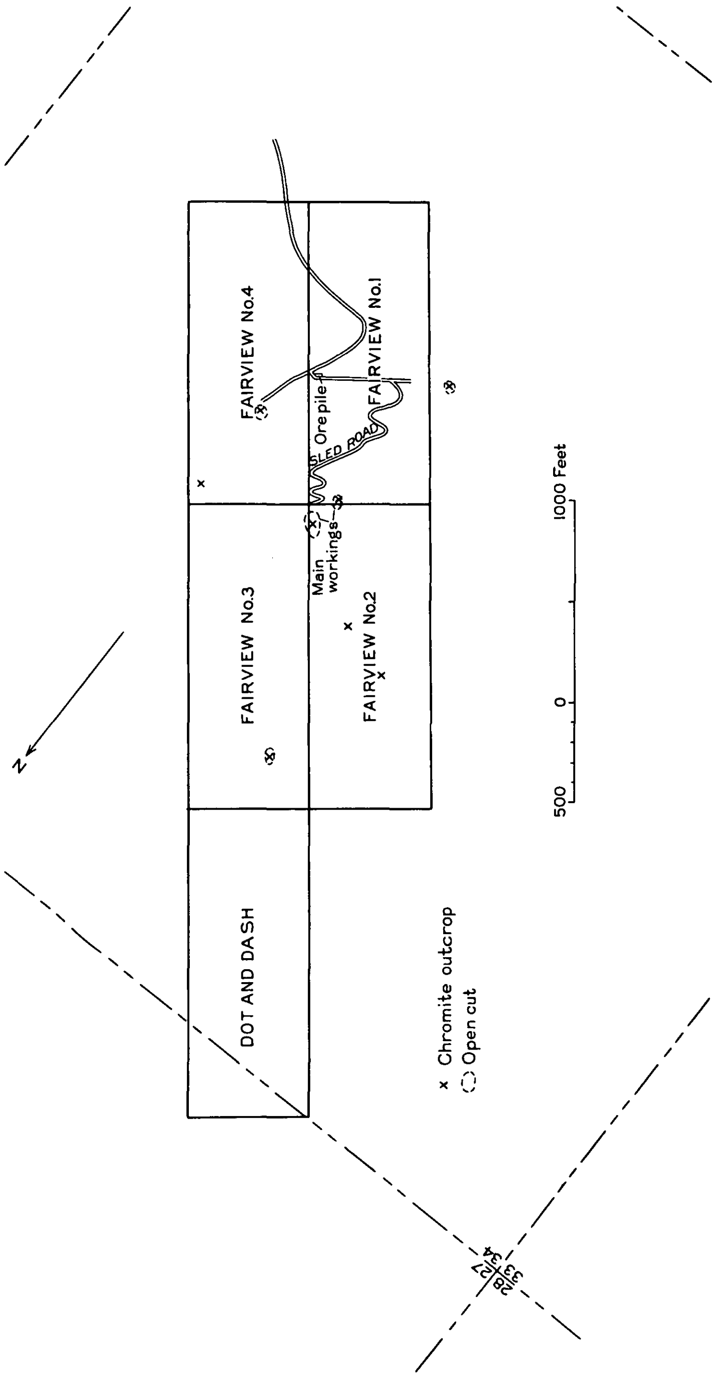

Figure 44.--Map of the Fairview group of chromite claims.

The chromite occurs in layers and in disseminated grains along zones parallel to the foliation of the peridotite country rock. The largest concentrations of chromite are exposed in two open cuts near the common corner of Fairview claims Nos. 1, 2, 3, and 4. The larger cut, which is on top of the ridge, exposes two zones of banded ore containing 20 to 25 percent of chromite, each zone 2 to 3 feet wide, 75 feet long, and separated by 3 to 6 feet of barren rock. The bands strike roughly N. 50° W. and dip 40° SW. About 10 tons of 20-percent ore is stacked on the dump. The other open cut also exposes two zones of chromite bands, which may represent the displaced extension of the bands in the upper cut. The zones are of lower grade in this cut than in the other; they range from 6 inches to 4 feet in width.

There are scattered outcrops of chromite at other places on the claims, but they are small and the major part of the chromite has already been mined.

Indicated reserves are estimated to be about 1,800 tons of 35-percent ore, of which 1,250 tons is probable ore and 550 tons is possible ore.

McGuffy Creek deposits

Several chromite deposits, known collectively as the McGuffy Creek deposits, occur in the northern part of sec. 25, T. 45 N., R. 11 W., and in the western part of sec. 30, T. 45 N., R. 10 W. Ore was shipped from three of these deposits during the first World War. Since that time four of the claims have been resurveyed and are now leased by H. W. Gould to the Rustless Mining Corporation. A sled trail and several foot trails connect the deposits with the Scott River road. The claims are described under their former names because it is not known whether the new claims include all the old workings. Where it is possible the new names also are given.

Octopus claim (Mary Lou, Chromite).--The Octopus claim was later relocated as the Mary Lou claim by Gus Kehrer, of Scott Bar, and is now known as the Chromite claim of the Rustless Mining Corporation. Workings consist of three open cuts and a short adit that is thoroughly caved. Much faulting and slipping are indicated in the peridotite. The chromite occurs in layers striking N. 38° W. and dipping 50° SW., parallel to the foliation of the peridotite. On the western margin is a small quantity of orbicular chromite, with the orbicules flattened in this same plane. Chromite bands are exposed over a width of 20 feet, a depth of nearly 50 feet, and a length of at least 25 feet along the strike, but more than half of the exposed width of the zone consists of barren rock. The richest part of the zone contains 25 to 35 percent of chromite. About 1,390 tons of ore averaging 35 percent of chromite is indicated.

Red Butte claim (Veta Grande).--The Red Butte claim is now known as the Veta Grande claim of the Rustless Mining Corporation. Workings consist mainly of two large open cuts. In only one are appreciable amounts of chromite exposed, and a short adit, now caved, has been driven across the chromite zone at the end of this cut. As in the Octopus claim, the chromite occurs as bands in peridotite. Individual bands range from a fraction of an inch to an inch in width and occur in a zone about 10 feet wide. Chromite is exposed in this cut along the strike for 150 feet, and it may extend discontinuously to the other cut. The average grade is about 20 percent. Large crystals of kaemmererite occur with talc and serpentine in cross-fractures in the chromite zone. About 3,340 tons of ore averaging 35 percent of chromite are indicated.

Liberty claim (Cerro Colorado).--The Liberty claim is now the Cerro Colorado claim of the Rustless Mining Corporation. The workings on the old Liberty claim consist of two open cuts on the west side of McGuffy Creek. The chromite occurs in bands that conform to the contorted foliation of the peridotite, suggesting that the rocks were contorted after the chromite was introduced. The bands are, on the average, approximately vertical and strike S. 10° E. into the side of the hill. Chromite is exposed in a zone 50 feet wide, about 10 percent of which would be minable. About 10 tons of 20- to 30-percent ore is stacked on the dump. About 139 tons of ore averaging 35 percent of chromite is indicated.

Jumbo claim.--Workings on the Jumbo claim consist of an open cut with a 15-foot adit. The ore is of the banded type and is contorted as in the Liberty claim. No ore has been shipped, but about 25 or 30 tons containing 30 percent of chromite has been mined and stacked on the dump. No estimate of additional reserves was made.

Neptune claim (Napatama ?).--Two open cuts and several prospect holes are opened up on the Neptune or Napatama (?) claim. The chromite rock is banded and occurs in a zone 5 feet wide and more than 100 feet long that trends N. 17° W. and dips 60° SW. No ore has been shipped, and because of the spotty distribution of the chromite the reserves are not believed to be large.

Black Spot claims.--Two chromite claims, Black Spot No. 1 and No. 2, have been located by Elmer Weeks, of Scott Bar, on the ridge north of McGuffy Creek. In both claims the chromite occurs as nodules. The chromite of Black Spot No. 1 was found in a slide and that of Black Spot No. 2 in a small outcrop on the top of the ridge.

Reliable tonnage estimates of the McGuffy Creek claims could be made only after extensive development. Trenching along the side of the ridge between the Red Butte and Liberty workings has uncovered small outcrops of chromite, indicating the possible presence of other chromite bodies.

Dolbear mine

The Dolbear mine is about 800 feet above the Klamath River, on the line between secs. 16 and 21, T. 46 N., R. 11 W. The property is patented by the Reddy interests of Medford, Oreg. There are several open cuts in ore, but they are so much caved that the extent of the ore in the deposit is concealed. Outcrops were observed along the ridge to an elevation of about 3,000 feet. A small amount of uvarovite was noted in cross fractures of the chromite. Reserves are roughly estimated to be 2,000 tons of rock averaging 35 percent of chromite.

Barton claim

The Barton claim, near the northern edge of sec. 9, T. 46 N., R. 12 W., is developed by two open cuts. The chromite left in these cuts is in part massive, in part disseminated. Ore was shipped during the first World War, and nearly all of it seems to have been mined out, as the reserves appear to be negligible.

Unidentified prospects

Near the southern edge of sec. 3, T. 46 N., R. 13 W., is an open cut in massive chromite, nearly all of which has been removed. About a ton of ore remained on the dump. Some kaemmererite accompanies the chromite, which occurs in black serpentine. No minable ore is thought to remain.

Three open cuts in disseminated and banded chromite on the eastern edge of sec. 19, T. 45 N., R. 10 W., were visited. Some of the chromite bands are 2 inches wide, but the total amount of chromite cannot be more than a few tons.

THE BIOSTRATIGRAPHY OF GLYCYMERIS VEATCHII IN CALIFORNIA

A thesis

by

Clay T. Smith

In partial fulfillment of the requirements

for the degree of Doctor of Philosophy

California Institute of Technology

Pasadena, California

1943

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ILLUSTRATIONS

THE BIOSTRATIGRAPHY OF GLYCYMERIS VEATCHII IN CALIFORNIA

ABSTRACT

The stratigraphy and correlation of upper Cretaceous rocks comprise one of the major problems of Pacific Coast geology. It is particularly significant as the search for petroleum penetrates into progressively older rock formations in California. As a step toward clarification of the problem this paper attempts to indicate the possible evolution and variation in a single fossil molluscan species during upper Cretaceous and early Tertiary time.

The results of the present study are three-fold; (1) The evolution of *Glycymeris veatchii* has been traced. (2) The number of ribs on a valve is found to vary inversely with the geologic age of the specimen. (3) Two new varieties, *Glycymeris veatchii reddingensis*, and *G. veatchii anae*, and one new species, *G. meganosensis*, have been recognised, and *G. major* is shown to be an invalid species.

A tentative correlation of the upper Cretaceous localities used in this paper is presented, and systematic description of the species and varieties described included.

THE BIOSTRATIGRAPHY OF GLYCYMERIS VEATCHII IN CALIFORNIA

INTRODUCTION

The stratigraphy and correlation of upper Cretaceous rocks comprise one of the major problems of Pacific Coast geology. Information bearing on this subject is rapidly assuming added economic significance as the search for petroleum penetrates into progressively older rock formations in California. Although general relationships of the various Cretaceous strata are well-known, little has been done with detailed subdivision into series, stages, and zones, so essential to economic exploitation. As an aid to a better understanding of the sequence and correlation of the stratigraphic units that are grouped in the late Cretaceous and early Tertiary, the present paper attempts to indicate the possible evolution and variation in a single fossil molluscan species during this portion of geologic time.

This study is primarily paleontologic, one of its purposes being to determine the time-stratigraphic positions of the varieties and subspecies of Glycymeris veatchii which have been listed, described, or figured since Gabb's original work. Large collections were examined from widely separated localities in California, representing the few established horizons in the upper Cretaceous section.

The evolutionary trends of Glycymeris veatchii indicated by this study were traced with the use of additional collections, until nearly all well-exposed upper Cretaceous sections that yield fossil specimens in the state had been assigned positions in the stratigraphic column (see table 1).

Stratigraphic subdivision or correlations established on the basis of a single species should be modified by a consideration of the trends within the faunas as a whole. The evolution of any individual or group of related individuals, while paralleling the evolution of the entire fauna, may be accelerated or retarded with respect to the rate at which the assemblage as a whole evolves. For this reason the tentative correlation chart (table 2) combines the results of this paper and unpublished work by Dr. W. P. Popenoe.

Acknowledgments.- I am indebted to Dr. Willis P. Popenoe of the California Institute of Technology for suggesting the problem, and for counsel and advice throughout the period of its investigation. In addition, Dr. Popenoe has furnished a large portion of the stratigraphic data and has generously made available much unpublished material. Dr. Chester Stock criticised the manuscript and gave generously of his time during its preparation. I am indebted to George P. Zebal for unpublished information on the stratigraphy of the Simi Hills.

STATEMENT OF PROBLEM

Glycymeris veatchii is a very abundant pelecypod in most of the fossiliferous upper Cretaceous deposits of the Pacific Coast. Similar forms, some described as variants, others as new species, are found in the Martinez Paleocene and in the Meganos of the Eocene. The problem presented by these molluscs may be stated as follows: Do the several forms referred to *Glycymeris veatchii* in the Cretaceous and Eocene comprise a genetic line? If evolutionary trends exist, are the forms to be related to one restricted species, several varieites of a species or to several new species? Finally, to what extent can evolutionary trends and variations be related to stratigraphy?

TABLE 1

Stratigraphic Sequence of Upper Cretaceous and Lower Tertiary Strata Based on the Evolution of G. veatchii.

Age	District	Formation	Member
LOWER EOCENE	Mt. Diablo quadrangle	Meganos	Type locality
	Lower Lake, Calif.	Martinez	Not designated
	Simi Valley, Calif.	Martinez	Marine member
Unconformity			
UPPER CRETACEOUS	Los Banos, Calif.	Garzas	Type locality
	Los Banos, Calif.	"Quinto B" reef beds	Los Banos Creek
	Santa Ana Mts.	Williams	Pleasants sandst.
	Simi Hills	"Upper Chico"	Not designated.
	Santa Monica Mts.	"Chico-Martinez"	Not designated.
	Tuscan Springs, Calif.	"Chico"	Not designated.
	Penz ranch, Calif.	"Chico"	Not designated.
	Santa Ana Mts.	Ladd	Upper Holz shale
	Santa Ana Mts.	Ladd	Middle Holz shale
	Chico Creek, Calif.	Type Chico	Upper member
	Chico Creek, Calif.	Type Chico	Lower member
	Redding, Calif.	"Lower Chico"	Member VI
	Redding, Calif.	"Lower Chico"	Upper half mbr. V
	Redding, Calif.	"Lower Chico"	Lower half mbr. V
	Redding, Calif.	"Lower Chico"	Member IV
	??	??	??
Base of upper Cretaceous on Pacific Coast			

METHOD OF INVESTIGATION

The principles involved in a solution of this problem have been applied in several similer investigations. They are found for example, in the comprehensive study of the genus, Spirifer, by Fenton[1], and likewise in

1/ Fenton, C. L., Publ. Wagner Free Inst. Sci., vol. 2, 1931.

the work by Rowe[2] on the echinoid genus, Micraster. In

2/ Rowe, A. W., Quart. Jour. Geol. Soc. London, vol. 55, p. 494, 1899.

this connection reference should be made also to the detailed studies of Mesozoic oysters by Trueman[3], and those on

3/ Trueman, A. E., Geol. Mag., vol. 59, pp. 256-268, 1922.

corals by Carruthers[4]. In each of these investigations

4/ Carruthers, R. G., Quart. Jour. Geol. Soc. London, vol. 66, pp. 523-538, 1910.

two fundamental features were stressed. (1) Evolutionary changes which particular fossil forms undergo were used to establish biostratigraphic zones, facilitating the correlation of various lithologic units. (2) The systematic classification was simplified by an elucidation of evolutionary lines. Thus forms were determined to be closely related that had previously been assigned to new species without good reason or because identification was based on single or damaged specimens.

In the investigations cited above as well as in the present study certain qualifications must be met before the results obtained and the conclusions drawn can be regarded as justifiable.

(1) The species of the genera chosen for investigation must be represented by an abundance of individuals at all stages throughout its geologic range. Most of the structural differences observed on two given specimens are small and individual variations are often misleading. It is the average variation shown by cumulative changes occurring in a large number of individuals which is found most useful.

(2) The geologic position or stratigraphic occurrence of individual samples must be established as accurately as possible. Obviously the course in evolution of a character can be determined only when the relative stratigraphic age or position of individual stages in the modification of this feature is known. Once the trend and rate of evolution are determined, stratigraphic correlations can be established with even greater certainty.

(3) Only well-preserved or carefully prepared specimens should be used. Conclusions based on poorly preserved or fragmental material are often not valid since the evolutionary changes may be masked or completely destroyed.

(4) The methods employed in making measurements or in recording descriptions should be applied as uniformly as possible. Constant vigilance must be exercised to reduce or avoid human error. Thus, Rowe[5/] took

5/ Rowe, A. W., op. cit., p. 494, 1899.

photomicrographs of specimens he was concerned with and made his measurements from the photographs to obviate mistakes.

(5) A standard basis for comparison of different forms must be devised, either by direct measurement or through calculation. In making comparisons it is important to utilize characters independent of those which may vary among individuals, as for example, those of size and shape.

In the present study more than 2000 specimens were examined, of which over 750 were measured. These pelecypods were identified as Glycymeris veatchii, G. veatchii, var. major Stanton, G. major Stanton, and G. major, subsp. meganosensis Clark. Measurements were made of the thickness, length, and height of the shell, as well as of the widths of the ribs and of the rib interspaces. In addition, the number of ribs was counted, character and amount of concentric sculpturing on each valve were observed, degree of development of posterior groove noted, and the position of the beaks established where this was possible.

Ratios of length to thickness, height to thickness, and height to length were calculated in order to reduce these data to certain common denominators by which the comparisons might be more readily comprehended. In this way, variations which are magnified by the size of the animal come to be seen in proper perspective, while evolutionary trends are more clearly indicated. Also, local variations due to possible environmental influences rather than evolution are thus more readily recognized. All specimens less than 6 mm. in thickness were considered immature and calculated separately. This separation was made (1) because it became evident early in the investigation that a specimen with a thickness or convexity of shell of about 6 mm. marked a rather sharp break within the growth series; all specimens of less thickness tended to have much higher ratios of length to thickness and height to thickness than did larger and more convex specimens; and (2) measurements of valves which were less than 6 mm. in thickness were subject to considerable error, in some cases sufficient to invalidate the results obtained from such measurements.

The stratigraphic succession of the localities from which individual specimens were measured was determined by reducing individual shell ratios to average values for a single locality. Localities representing the same time stages or narrow time-stratigraphic zones were combined by weighing the average ratios with the number of specimens measured from each locality. Where satisfactory stratigraphic information is available this procedure is simple, but in instances where the stratigraphy is little known or unknown altogether, the relative age of the locality is based on the apparent evolutionary stage of the individual specimens. This, obviously, does not furnish the most accurate results, but appears to be the only method available to the investigator under the circumstances.

EVOLUTIONARY TRENDS AND VARIANTS

The results of the present study are threefold: (1) The evolution of *Glycymeris veatchii* is found to continue in an unbroken line, throughout the time-range of the species from lower upper Cretaceous rocks in the vicinity of Redding to Martinez rocks, near Lower Lake, California. (2) The number of ribs on a valve is found to vary inversely with the geologic age of the specimen. (3) *Glycymeris veatchii*, species *sensu stricto*, has a much more restricted range than heretofore determined. Particular variants may be recognized at nearly every upper Cretaceous locality, other than those correlated with the type locality. The variants are listed as follows: *G. veatchii reddingensis*, *G. veatchii anae*, and *G. veatchii major*. A description of each of these and a detailed account of *G. veatchii s. s.* will be found in the systematic catalogue in the latter part of the paper.

Glycymeris major Stanton is apparently not a valid species. However, the form may show sufficient distinctiveness from the type *G. veatchii* to warrant its recognition as a separate variety. Accordingly, *G. major* should be regarded as a synonym of *G. veatchii*.

G. major subsp. *meganosensis* Clark is thought to exhibit features which digress markedly from the evolutionary trends shown by *G. veatchii* and is therefore raised to species rank and recognized as *G. meganosensis* (Clark).

STRATIGRAPHY

The stratigraphic sequence and correlation of the various upper Cretaceous localities as based upon paleontological evidence are summarized in table 2. Fossil specimens were measured from 22 localities in the Redding district, 24 localities in the Santa Ana Mountains, 6 localities in the Simi Hills, 6 localities in the Santa Monica Mountains, 4 localities from the Chico Creek section, 8 localities in the Los Banos region, 2 localities in the "Martinez" of the Simi Hills, 1 locality at Lower Lake, California, and from 1 locality in the type Meganos formation as defined by Clark and Woodford[6/]. Unfortunately, the representation of Eocene forms is not as full as it might be. However, direct comparison can be made by referring to the averages obtained from the specimens measured (see table 3).

Detailed information is available concerning the stratigraphy of many of the regions which furnished material; these areas will be described as fully as seems necessary. The additional districts from which collections have come are incompletely known in so far as published information is available.

6/ Clark, B. L. and Woodford, A. O., Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 17, no. 2, pp. 63-142, 1927.

TABLE 2

Tentative Correlation Chart Showing Relationships of Late Cretaceous and Eogene Deposits*.

<table>
<tr><th>Age</th><th>Southern Calif.</th><th>West side Great Valley</th><th>East side Sacramento Valley</th><th>Redding District.</th></tr>
<tr><td rowspan="2">EOGENE</td><td rowspan="2">Simi Valley
"Martinez"</td><td>Type Meganos</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Lower Lake
"Martinez"</td></tr>
<tr><td rowspan="6">UPPER CRETACEOUS</td><td></td><td>Type Garzas
"Quinto B"
reef beds</td><td rowspan="2"></td><td rowspan="4"></td></tr>
<tr><td>Upper zone, Santa Ana Mts., Simi Hills
Santa Monica Mts.</td><td rowspan="5"></td></tr>
<tr><td>Middle zone, Santa Ana Mts.
Lower zone, Santa Ana Mts.</td><td>Tuscan Springs
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<tr><td rowspan="3"></td><td rowspan="2">Type
Chico</td></tr>
<tr><td>Member VI
Member V upper half
Member V lower half</td></tr>
<tr><td></td><td>Member IV</td></tr>
</table>

*Based on unpublished work of Dr. W. P. Popenoe and others and studies of Glycymeris veatchii presented in this paper.

Redding district.- The principal Cretaceous exposures in the Redding district lie on the eastern border of the Redding quadrangle, about 15 miles north and east of the town of Redding, California. The exposures occur along the valleys of little Cow Creek, Swede Creek, Oak Run, Clover Creek, Old Cow Creek, and South Cow Creek. According to Dr. W. P. Popenoe[7] these Cretaceous rocks are

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7/ Popenoe, W. P., Bull. Amer. Assoc. Petrol. Geol., vol. 25, no. 11, p. 2095, Nov., 1941.
Bull. Amer. Assoc. Petrol. Geol., vol. 27, no. 3, pp. 306-312, Mar., 1943.

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divisible into six members, but since mapping in this area is incomplete, the relations of the various members are not completely known. The entire section is probably more than 4000 feet in thickness and comprises some of the earliest known upper Cretaceous deposits in the state.

In the present investigation attention is directed to the upper members since *Glycymeris veatchii reddingensis* has not been found stratigraphically below member IV. According to Dr. Popenoe[8] the presence of *G. veatchii*

8/ Popenoe, W. P., Personal communication.

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reddingensis at one locality near the base of member IV of the Redding series is the oldest occurrence of this species known to him in the Cretaceous of the Pacific Coast. As may be noted from the stratigraphic column (table 1), member V is divided into an upper and a lower part. While there is no stratigraphic basis for this division except an abundance of coarse conglomerate in the lower half, the division is recognized because of a recognizable modification in the evolutionary trends of G. veatchii reddingensis.

Member IV is a series of dark-gray sandy shales and shaly sandstones with a few thin coarse sandstone beds. This member is over 1000 feet thick and is well-exposed on Oak Run and Clover Creek. Abundant specimens of G. veatchii reddingensis were found at most of the localities in this member.

Member V is a coarse, arkosic gray sandstone alternating with finer-grained sandstone layers. Numerous thick beds of coarse conglomerate are developed in the lower half of the member. Member V is about 900 feet thick and appears to be unconformable on member IV. Member V is well-exposed in the upper part of Oak Run, the central and lower portions of Clover Creek and Old Cow Creek, and along most of South Cow Creek.

Member VI consists of dark-gray sandy shales with numerous thin-bedded sandstone layers. It is over 400 feet thick and rests conformably on member V. It is best exposed in the upper reaches of Clover Creek.

Chico Creek section.- The section at Chico Creek, Butte County, California[9/], consists of approximately

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9/ Taff, J. A., Hanna, G. D., and Cross, C. M., Bull. Geol. Soc. America, vol. 51, no. 9, pp. 1311-1315, Sept., 1940.

2000 feet of strata forming a monocline in which the strata dip to the west away from the mountains. It is essentially comprised of sandstone, except for a heavy conglomerate at the base. On the basis of measurements of G. veatchii reddingensis, the localities are grouped in an upper and a lower member. However, this division does not receive solid support from the paleontological evidence, since only four specimens are recorded from the upper zone. It is recognized here in order to indicate possible evolutionary progress in G. veatchii during deposition of this section.

Santa Ana Mountains (lower and middle zones).- The occurrences of G. veatchii in the Santa Ana Mountains are grouped in three zones. Similar grouping of these beds is suggested by the relationships of other parts of the fauna[10/]. The third zone overlies the lower two with

10/ Popenoe, W. P., Bull. Amer. Assoc. Petrol. Geol., vol. 26, no. 2, pp. 162-187, Feb., 1942.

disconformity and in this instance again, the time break is suggested by the fauna.

The lowermost occurrence of G. veatchii in the Santa Ana Mountains is in the upper half of the Holz member of the Ladd Formation. The Holz member consists of dark bluish to brownish gray micaceous sandy shale or siltstone with interbedded arkosic sandstones, calcareous concretionary beds, and non-persistent coarse conglomerate lenses; its total thickness probably exceeds 1500 feet. The Holz shale is a persistent and widespread member of the Santa Ana Mountains section, outcropping virtually continuously from Santa Ana Canyon south to Trabuco Canyon[11/].

11/ Popenoe, W. P., *op. cit.*, p. 171, 1942.

The upper half of the Holz shale is highly fossiliferous. There is but slight lithologic evidence for separating the upper half of the Holz shale into two zones, but the fauna shows a distinct break. The lower zone ranges from midway in the section to approximately 200 feet below the top of the shale; the middle zone comprises the upper 200 feet.

Penz ranch.- The section at Penz ranch on the eastern side of the Sacramento Valley, south of Chico Creek, is not too well-exposed, but good collections can be obtained at many points where exposures occur. The rocks are primarily sandstones and conglomerates, similar to those exposed on Chico Creek.

Tuscan Springs.- Tuscan Springs is the type locality for *Glycymeris veatchii* and is located on little Salt Creek about eight miles northeast of Red Bluff, California. The rocks at Tuscan Springs are a northward continuation of those found in the section exposed on Chico Creek, and for the most part are pebbly or silty sandstones and conglomerates. It is peculiarly fortunate that the type and associated specimens of G. veatchii come from a section which appears to lie almost midway in the geologic range of the species.

Santa Monica Mountains.- Hoots[12] published a general geological report on the Santa Monica Mountains, and his work on the Cretaceous rocks has been expanded and revised by H. D. B. Wilson[13]. The upper Cretaceous rocks comprise about 8000 feet of conglomerate, arkose and sandstone. The only fossiliferous horizon is a well-bedded, fine-grained sandstone, 300 feet in thickness and approximately 1000 feet below the top of the section. Wilson[14] has shown that all the fossil collections obtained in the upper Cretaceous of the Santa Monica Mountains come from this one horizon. An interesting feature of G. veatchii found here is the large size attained by the specimens; some exceed 70 mm. in height and length.

Simi Hills.- Popenoe[15] in his paper states: "Accord-

12/ Hoots, H. W., U. S. Geol. Surv. Prof. Pap. 165-C, 1930.

13/ Wilson, H. D. B., Minor thesis for the doctorate. Calif. Inst. of Tech., 1941.

14/ Wilson, H. D. B., op. cit., 1941

15/ Popenoe, W. P., opl cit., p. 176, 1942.

ing to Kew the Cretaceous sediments of the Simi Hills are divisible into two members. The lowest member consists of 250 feet of calcareous sandstone at the base and an equal thickness of gray shale above. The upper member, overlying the gray shale, consists of approximately 5500 feet of alternating thick beds of massive brown sandstone and thin beds of shale. Later unpublished work suggests that the lower member is much thicker and more complex than Kew suggests; but the details are not yet available......All the fossils so far recovered from this region are from the calcareous sandstones of the lower member."

Popenoe[16/] further suggests that the fossiliferous

16/ Popenoe, W. P., op. cit., p. 186, 1942.

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horizon may be divided into an upper and a lower member, but detailed mapping by G. P. Zebal[17/] has shown that the

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17/ Zebal, G. P., Unpublished Master's thesis, Calif. Inst. of Tech., 1943.

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several fossil localities which furnish the collections belong to the same bed. The evolutionary characters developed by *Glycymeris veatchii anae* substantiate Zebal's detailed mapping.

Santa Ana Mountains (upper zone).- The upper zone in the Santa Ana Mountains comprises what Popenoe[18/]

18/ Popenoe, W. P., op. cit., p. 173-175, 1942.

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has called the Williams formation. This formation consists of two members--the Schulz conglomerate at the base, and the Pleasants sandstone above. The Schulz conglomerate is unfossiliferous, and consists of light-colored, coarse arkosic sandstones with numerous beds of well-rounded boulders. The Pleasants sandstone is highly fossiliferous, although the preservation is poor, and consists of light-colored shaly sandstones with many intercalated beds of calcareous fossiliferous sandstone. The Williams formation is about 500 feet thick with approximately 200 feet comprising the Schulz conglomerate and the remainder representing the Pleasants sandstone. The distribution of the Williams formation in the Santa Ana Mountains is discontinuous, due principally to an overlapping by Martinez beds and to complex faulting.

"Quinto B" Reef Bed. 19/ - The uppermost upper Cretaceous in California is exposed for many miles along the west side of the San Joaquin Valley, north of Coalinga. The rocks are sandstones and sandy shales with some conglomerate outcropping in thick sections on Los Banos Creek, Garzas Creek, Moreno Gulch, and along other streams which flow into the valley. Most of the fossils come from high in the section, chiefly from the upper 2500 feet. The "Quinto B" reef bed is exposed on Los Banos Creek, west

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19/ Bennison, Alan, Unpublished thesis, Univ. Calif.

of Los Banos, California, and contains almost entirely *Glycymeris veatchii major*. Shells of this variant usually exceed 20 mm. in height and average between 40 and 45 mm. in height.

Type Garzas.- The type Garzas furnishes the youngest upper Cretaceous specimens available for measurement. These come from two localities on Garzas Creek, northwest of Los Banos, California. The section is in all respects similar to those on Los Banos Creek or in Moreno Gulch.

"Martinez" of the Simi Valley.- The specimens from the Simi Valley "Martinez" are few in number and hence do not yield altogether satisfactory data which may be considered of stratigraphic significance. The rocks are sandstones and shales and have been described by Kew[20/]. Preservation of the fossils is poor and an

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20/ Kew, W. S. W., U. S. Geol. Surv. Bull. 691, pp. 323-347, 1919.

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analysis of their characters is difficult. All the fossils come from the Martinez marine member of the formation as described by Nelson[21/].

21/ Nelson, R. N., Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 15, no. 11, pp. 399-402, 1925.

Lower Lake, California.- One specimen from the Martinez near Lower Lake, California, was measured.

The Martinez rocks in this region were described by Dickerson[22] as comprising from 3000 to 3500 feet of

[22] Dickerson, R. E., Univ. Calif. Publ., Bull. Dept. Geol., vol. 8, no. 6, pp. 89-99, 1914.

sandstone, overlain by 300 to 500 feet of shale. The principal fossilliferous horizon occurs approximately 100 feet above the base of the formation. It is unfortunate that only one specimen is available by which to judge the evolution of the type *Glycymeris veatchii* in this area originally recognized under the variety name *major*.

Type Meganos.- Specimens were measured from one locality in the type Meganos as defined by Clark and Woodford[23]. The rocks here consist of about 1000 feet

[23] Clark, B. L. and Woodford, A. O., *op. cit.*, pp. 63-142, 1927.

of sandstone with a heavy basal conglomerate and narrow shale layers near the top. Overlying the sandstones are alternating sandstones and shales approximately 2000 feet thick; the fossiliferous horizon occurs in calcareous lenses approximately 1500 feet below the top of the formation. Ten specimens were available for measurement.

TENTATIVE CORRELATION OF UPPER CRETACEOUS LOCALITIES

The suggested sequence of the upper Cretaceous localities described in this paper is given in table 2. This correlation chart is based on the views expressed in this paper regarding the evolution of *Glycymeris veatchii* as well as on much unpublished stratigraphic work by W. P. Popenoe and others.

The rocks of the first three members of the Redding district probably represent some of the oldest upper Cretaceous formations on the Pacific Coast. It is possible that the fossiliferous zones below Popenoe's[24/] *Glycymeris veatchii* zone in the Santa Ana Mountains correlate with these beds.

Glycymeris veatchii reddingensis first appears in member IV of the Redding section. In specimens from this area the number of ribs averages less than 32, the valves are slightly longer than high, and they are not particularly inflated as compared with those of *G. veatchii* species *sensu stricto* from Tuscan Springs. A curious anomaly appears in forms found higher in the section. Although throughout the entire range of upper Cretaceous time the average number of ribs increases as one proceeds toward the top of the deposits, in shells found locally in the

24/ Popenoe, W. P., *op. cit.*, p. 182, 1942.

Redding section the number of ribs decreases slightly from bottom to top of the stratigraphic section. No explanation is offered for this peculiarity, although it may be noted that the decrease is slight and not uniform throughout the section. Since mapping is incomplete in this region, additional work may revise the actual stratigraphic position of some of the localities, and this may be found to reverse the trend. There is also a tendency for the valves to become more inflated in members IV and V, but only slightly so. Member VI is represented by only nine specimens and this number does not adequately determine the evolutionary potision of Glycymeris veatchii reddingensis in this section.

Popenoe[25/] has suggested that member V of the Redding section may be correlated with the base of the type Chico on Chico Creek farther south. This correlation is substantiated by the position of G. veatchii reddingensis in the evolutionary series at both localities. Actually, there is a suggestion that G. veatchii reddingensis from member IV at Redding represents the same evolutionary stage as that of forms in the lower parts of the type Chico section on Chico Creek. The four specimens assigned to the "upper Chico" on Chico Creek seem to be higher than anything found in the Redding section.

25/ Popenoe, W. P., op. cit., p. 312, 1943.

The lowermost zone containing G. veatchii anae in the Santa Ana Mountains appears to be slightly younger than any horizon examined on Chico Creek or at Redding. Furthermore, both the lower and middle zones in the upper Cretaceous of the Santa Ana Mountains appear to be slightly earlier in time than the occurrence at Penz ranch and at the type locality of Tuscan Springs. However, the specimens from the Santa Ana Mountains show a local, apparently environmental, variation, which may mask somewhat the evolutionary features. In contrast to specimens from the type locality, those from the Santa Ana Mountains are considerably longer than they are high and show a marked reduction in convexity. These features give the shells a decidedly different shape and furnish the basis for the description of the new variety, anae. This shape of shell appears to be confined to the Santa Ana Mountains, but it is exhibited to a lesser degree by specimens from the Simi Hills. The Eocene specimens also suggest a trend in this direction, but since the highest Cretaceous forms that are found appear to be typically rounded and equilateral, this feature may be considered the result of an environmental or facies factor, rather than due to evolutionary change.

The specimens from Penz ranch appear to be only slightly older geologically than those from the type locality at Tuscan Springs, but since the differences are slight, they are regarded as of the same, or nearly equivalent, stage in time.

The fossiliferous horizon in the upper Cretaceous of the Santa Monica Mountains appears to be slightly older than the upper zone of the Santa Ana Mountains, and fauna from the Simi Hills. However, the differences are so slight as to suggest that all should be relegated to the same time stage. All are considered slightly younger than the faunas from Tuscan Springs and Penz ranch. These conclusions are in accord with Popenoe[26/] and Zebal[27/], except

26/ Popenoe, W. P., *op. cit.*, p. 186, 1942.

27/ Zebal, G. P., *op. cit.*, 1945.

that the forms from the Simi Hills appear to correlate directly with those of the uppermost zone of the Santa Ana Mountains rather than with those of a slightly older horizon as Popenoe[28/] suggests. This probably indicates

28/ Popenoe, W. P., *op. cit.*, p. 186, 1942.

a local acceleration in the evolution of *Glycymeris veatchii anae* with respect to the rest of the fauna from that locality.

The youngest Cretaceous forms of *G. veatchii major* that were measured come from the "Quinto B" reef bed and from the type Garzas beds on the west side of the San Joaquin Valley, west and north of Los Banos, California.

In contrast to the earliest forms from member IV at Redding, these specimens average more than 40 ribs and are slightly less inflated. The difference may be ascribed by some to a variation in size alone, but specimens of comparable size from the two districts possessed 32 and 36 ribs respectively. At any one locality shells may be found that can be assigned to either the top or bottom of the evolutionary sequence on the basis of their characters. Greater assurance of the time allocation of such materials is furnished when the structural characteristics of the average of 20 or more specimens from a single locality are analyzed.

An insufficient number of specimens available from the Eogene localities permits only recognition of a continuation of evolutionary trends in post-Cretaceous time. The structural feature which Stanton[29/] listed

29/ Stanton, T. W., U. S. Geol. Surv. 17th Ann. Rep., vol. 1, pp. 1005-1060, 1896.

as an aid in identifying *G. veatchii major*, namely, the wider ribs than interspaces, is certainly valid and well-marked, but the character is little if any more defined than on several of the Cretaceous forms.

CONCLUSION

In conclusion it may be stated that where the stratigraphic succession has been completely established over a considerable period of geologic time, evolutionary trends in *Glycymeris veatchii* are indicated. These trends appear to be valid for the entire range of occurrences of *G. veatchii*, at least on the face of the limited knowledge available concerning the upper Cretaceous stratigraphy of the Pacific Coast. Indeed, the suggestions of stratigraphic position made in the present paper may assist in throwing needed light on obscure correlations.

Detailed correlations on the basis of a single species have not been attempted for reasons stated previously, but it is noteworthy that previously suggested correlations, for which there is some evidence, appear to be substantiated by this study.

SYSTEMATIC DESCRIPTIONS

PHYLLUM MOLLUSCA

CLASS PELECYPODA

Order Prionodesmacea

Superfamily Arcacea

Family Arcidae

Genus Glycymeris da Costa

Glycymeris veatchii (Gabb) sensu stricto
(Plate I, figure 4, plate II, fig. 2)

1864 *Axinaea veatchii* n.s., Gabb, Pal. Calif., vol.1, p. 197, pl. 25, figs. 183, 183a.

1896 *Pectunculus veatchii* Gabb, Stanton, 17th Annual Rep., U. S. Geol. Surv., pt. I, p. 1039, pl. 64, fig. 1.

1900 *Pectunculus veatchii* Gabb, Whiteaves, Geol. Sur. Canada, Mes. Foss., vol. 1, p. 391, pl. 47, figs. 3, 4.

1902 *Pectunculus veatchii* Gabb, Anderson, Calif. Acad. Sci. Proc. (3), vol. 2, p. 35, no. 1.

1917 *Glycymeris veatchii* (Gabb), Waring, Calif. Acad. Sci. Proc. (4), vol. 7, no. 4, p. 61, pl. 8, figs. 2, 7, 8.

1930 *Glycymeris veatchii* (Gabb), Stewart, Acad. Nat. Sci. Phil., Spec. Pub., no. 3, p. 70, text fig. 1, pl. 1, fig. 7.

Description: The original description by Gabb (supra) is as follows: "Shell thick, subglobose, equivalve and nearly equilateral; beaks large, incurved, central, approximate, with the sides sloping downwards; anterior and basal margins regularly rounded; posterior end rounded or subtruncate. Surface marked by from thirty-six to forty radiating ribs, very regular in size, a little the smallest anteriorly and obsolete behind; a faint depression usually exists on the posterior side of the umbones, which passes down and strikes the middle of the posterior margin. Internal margin coarsely crenulated. Hinge robust; teeth arranged radiately; the lateral teeth largest and most widely separated. Area very narrow and short."

Stanton (supra) adds, "The radiating ribs are sometimes narrower than the interspaces and sometimes broader. The length of the shell is a little less than the height. A large specimen measures 49 mm. in length, 51 mm. in height, and the convexity of the single valve is about 21 mm."

Stewart (supra) gives more detail on the hinge area as follows: "..........showing ten prominent, widely-spaced taxodont teeth anterior and eight posterior. The six central teeth are smaller and closer together and almost vertical, though the anterior three slope slightly posteriorly and the posterior three slope anteriorly. The coarse crenulations of the margin gradually disappear dorsally, and are entirely absent at the extremities of the hinge."

Measurements of 12 perfectly preserved specimens of Glycymeris veatchii from the type locality show that the valves are either longer than high or higher than long, the average of all shells being equilateral. The number of ribs varies from 35 to 42, averaging slightly less than 38. The ribs are from 0.2 to 0.6 mm. wider than the interspaces, and somewhat variable in size anteriorly and posteriorly. Umbo either prosogyral, or opisthogyral; posterior depression well-marked; ventral margin of shell slightly crenulate from concentric growth sculpturing. Average specimen, 30.6 mm. high, 30.8 mm. long, and 13.7 mm. thick.

Discussion.- Measurements of specimens from all localities are summarized in table 3 in the form of averages and ratios. In preparing this table it was noted that the range in size of the shells is reflected by the average widths of the ribs and interspaces. Average rib widths in excess of 1.0 mm. are found in valves with lengths and heights in excess of 30 mm.; average rib widths between 0.8 mm. and 1.0 mm. are characteristic of valves with lengths and heights between 20 mm. and 30 mm.; average rib widths of less than 0.8 mm. are found in valves with heights and lengths of less than 20 mm. In determining the degree of convexity reference should be made to the ratios, length to thickness or height to thickness.

The largest valves measured in the entire series come from the Santa Monica Mountains and from one locality in the Santa Ana Mountains. These specimens measured approximately 75 mm. in length, more than 70 mm. in height and more than 30 mm. in thickness. A few large valves were found at almost every locality, regardless of its stratigraphic position.

The smaller valves were subdivided into immature and mature specimens, the basis of the division being a 6 mm. thickness of the valve. Valves thinner than 6 mm. show uniformly very high ratios of length and height to thickness as compared to valves with thicknesses of 6.5 mm. to 7mm. or more. The division at 6 mm. is of ccurse arbitrary, but it was found that few specimens having smaller values could be measured with those standards of accuracy that were applied to adult specimens.

Statistical information regarding the immature valves is given in table 4.

In what follows the descriptions of variants are based on forms exceeding 6 mm. in thickness.

Glycymeris veatchii var. reddingensis n. var.
(Plate I, figures 1, 2)

Description.- Compared with the typical form of the species this variety is smaller. The valve possesses, on the average, less than 33 ribs. Individual specimens may be indistinguishable from those of the typical form when the number of ribs is greater than 36, but valves with that number of ribs are rarely found where this variety occurs. A typical specimen measures 18.3 mm. in length, 19.2 mm. in height and 7.5 mm. in thickness. In this valve 30 ribs are present.

Syntype:- C. I. T. Invertebrate Paleontology cat. no. 4741.

Type Locality:- C. I. T. Invertebrate Paleontology loc. no. 1233.

Glycymeris veatchii var. anae n. var.
(Plate I, figures 3, 5)

Description.- Compared with the typical form this variety may have either more or fewer ribs, the number ranging from 33 to 45 or more. The chief distinguishing feature is the proportionally longer valve. Where the typical form of the species is very nearly equilateral,

TABLE 3

Average Measurements and Ratios of Varieties of G. veatchii

Locality	No. of Spec.	No. of Ribs	Width of Rib in mm.	Width of Rib inter-space in mm.	H/L	L/T	H/T
Type Meganos	10	37.00	0.950	0.300	0.94	2.57	2.42
Lower Lake "Martinez"	1	45.00	1.700	1.100	0.92	2.17	1.99
Simi Valley "Martinez"	12	40.14	0.940	0.480	0.94	2.55	2.40
Garzas Creek Type Garzas	15	40.64	1.583	1.625	0.98	2.54	2.51
Los Banos Creek "Quinto B" beds	117	40.18	1.139	1.179	0.99	2.57	2.50
Santa Ana Mts. Upper zone	66	39.67	0.610	0.506	0.92	2.46	2.27
Simi Hills	58	39.48	0.605	0.560	0.95	2.42	2.28
Santa Monica Mts.	29	38.72	1.309	1.082	0.98	2.38	2.31
Tuscan Springs	12	37.92	1.092	0.858	1.00	2.23	2.21
Penz Ranch	24	36.74	1.145	0.968	0.99	2.26	2.22
Santa Ana Mts. Middle zone	113	35.79	0.597	0.495	0.92	2.51	2.33
Lower zone	69	34.48	0.510	0.500	0.94	2.63	2.41
Chico Creek Upper zone	4	33.50	0.850	0.750	00.98	2.25	2.10
Lower zone	32	31.83	0.686	0.529	0.99	2.32	2.29
Redding district Member VI	9	29.83	0.725	0.450	0.97	2.35	2.27
Member V Upper half	189	29.31	0.695	0.484	1.01	2.19	2.21
Lower half	61	30.43	0.655	0.389	0.99	2.16	2.14
Member IV	41	32.00	0.809	0.463	1.02	2.18	2.21

TABLE 4

Average Measurements and Ratios of Immature Specimens of *G. veatchii**

Locality	No. of Spec.	No. of Ribs	Width of Rib in mm.	Width of Rib inter-space in mm.	H/L	L/T	H/T
Santa Ana Mts. Upper zone	37	39.16	0.425	0.400	0.88	3.22	2.84
Simi Hills	31	36.45	0.420	0.380	0.90	2.83	2.54
Penz Ranch	22	38.00	0.400	0.3500	0.89	2.91	2.57
Santa Ana Mts. Middle zone	69	32.96	0.413	0.347	0.90	2.75	2.46
Lower zone	19	33.11	0.300	0.300	0.91	2.86	2.61
Chico Creek Lower zone	1	33.00	--	--	0.99	3.14	3.12
Redding district Member VI	1	--	--	--	0.92	2.34	2.16
Member V Upper half	31	32.17	0.425	0.325	0.96	2.93	2.80
Lower half	39	41.00	0.500	0.200	0.97	2.68	2.58
Member IV	3	37.50	--	--	0.95	2.94	2.82

* No immature specimens found in collections from Type Meganos, Lower Lake "Martinez", Simi Valley "Martinez", Garzas Creek Type Garzas, Los Banos Creek "Quinto B" reef beds, Santa Monica Mts., Tuscan Springs, Chico Creek upper zone.

the new variety has a ratio of height to length that averages less than 0.95 and may be as low as 0.80. This proportion yields a characteristic shape even in valves that are badly damaged or deformed. An average specimen measures 20.2 mm. long, 18.8 mm. high, and 7.9 mm. thick.

<u>Syntype</u>:- C. I. T. Invertebrate Paleontology cat. no. 4742.

<u>Type Locality</u>:- C. I. T. Invertebrate Paleontology loc. no. 974.

<u>Glycymeris</u> <u>veatchii</u> var. <u>major</u> (Stanton)

1896 <u>Pectunculus</u> <u>veatchii</u> var. <u>major</u> n. var., Stanton, 17th Ann. Rept., U. S. Geol. Surv., pt. 1, p. 1040, pl. 64, figs. 2, 3.

<u>Description</u>:- The original description of the variety is as follows: "Compared with the typical form of the species, this variety is larger, less convex, and proportionally longer; the ribs are broader than the interspaces and the posterior end is more sinuous. Length of a large specimen, 65 mm.; height 64 mm.; convexity of one valve, about 22 mm."

Measurements on a large number of specimens from the "Quinto B" reef bed and the type Garzas formation indicate that this variety, compared with the typical form of the species, has on the average 2 or 3 more ribs; the interspaces are often slightly wider than the ribs, and the shell is considerably larger and slightly less convex. A typical specimen measures 46.5 mm. in length, 46 mm. in height, and 18.6 mm. in thickness. This valve has 42 ribs.

Discussion.- The variety is difficult to distinguish from G. veatchii s. s. unless large numbers of specimens are available for study. Measurements of individual shells indicate that the ribs are commonly wider than the interspaces in all the varieties of G. veatchii. Large and small forms occur together, making size of little value in the determination of a distinct variety. However, when more than twenty specimens are considered, the additional ribs, the larger average size, and the reduced convexity, are thought to establish the validity of this variety, major.

Nelson[30/] in a description of the Simi Valley

30/ Nelson, R. N., Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 15, no. 11, p. 403, 1925.

"Martinez" marine rocks lists the name Glycymeris major as one of the fossil pelecypods found in these deposits. The species does not appear to have been figured or described. Nelson perhaps intended to recognize the variety major as a distinct species, but the results of this study indicate that specific variation is lacking, and G. major is not a valid species.

Glycymeris meganosensis (Clark)

1927 Glycymeris major meganosensis n. subsp., Clark, Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 17, no. 2, pp. 86-87, pl. 14, figures 4, 5.

Description.- The original description by Clark is as follows: "Shell heavy, fairly large, ventricose, subcircular in outline; beaks prominent, strongly inturned; dorsal margins straight or nearly so, approximately at right angles to vertical between the beaks and the ventral edge; posterior dorsal margin strongly depressed, or flexed. Main surface of shell sculptured by about 30 broad, flat-topped, low ribs with interspaces much narrower than the ribs. The ribbing becomes obsolete on a narrow, anterior dorsal margin, on the flexed posterior dorsal margin it is somewhat finer than on the main surface of the shell, becoming obsolete near the posterior dorsal edge. On the larger uneroded specimens the ribbing near the ventral edge tends to become obsolete and covered over by heavy lines of growth. On adult specimens the ligamental area is wider and narrow, and there are about 20 taxodont teeth which extend continuously across the hinge plate and for about two-thirds the distance in the middle they are in a straight line curving gently downward on each end. Dimension.- Type: Length 44 mm., height 43 mm., thickness of one valve 21 mm..........The subspecies meganosensis differs from the typical form principally in the type of ribbing. On the majority of specimens of the latter the ribbing is more prominent and the interspaces are wider, and on the adult specimens the ribbing does not become obsolete as on meganosensis. Weathered specimens of the typical form are often hard to distinguish from the subspecies."

Measurements of a limited number of specimens show that the ribs average more than 0.6 mm. wider than the interspaces and the difference is often considerably greater than this. In most specimens of typical Glycymeris veatchii the ribs are not more than 0.4 mm. to 0.6 mm. wider than the interspaces. In G. meganosensis the number of ribs averages less than 35. Thus, the distinction between the typical form and the new species is quite marked.

Discussion.- Insufficient specimens are available to demonstrate adequately the amount or degree of obsolescence of the ribs. On ten specimens measured the rib counts were considerably higher than 30, the number given by Clark (supra). However, the number of ribs is far less than that which would be expected from a consideration of the evolutionary trends shown by shells from older horizons. Obsolescence of the ribs on the ventral edge, due to concentric line of growth, was not observed.

Since the ribs indicate the evolution of *G. veatchii* more clearly than any other single characteristic of the shell, the abrupt reduction in rib count is taken to indicate the substitution of other evolutionary characteristics for those which controlled the evolution prior to Meganos time. Markedly narrower interspaces, in some cases so narrow as to appear merely as lines on the shell, as well as a reduction in number of ribs below that which might be expected in specimens so far along the evolutionary scale, furnish a satisfactory basis for recognition of this former subspecies as a new species, *Glycymeris meganosensis* (Clark).

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Explanation of Plate I

Figure 1. *Glycymeris veatchii reddingensis*, typical form from the earliest known occurrence of the species in the California Cretaceous.

2. *Glycymeris veatchii reddingensis* n. var., Syntype.

3. *Glycymeris veatchii anae* n. var., Syntype.

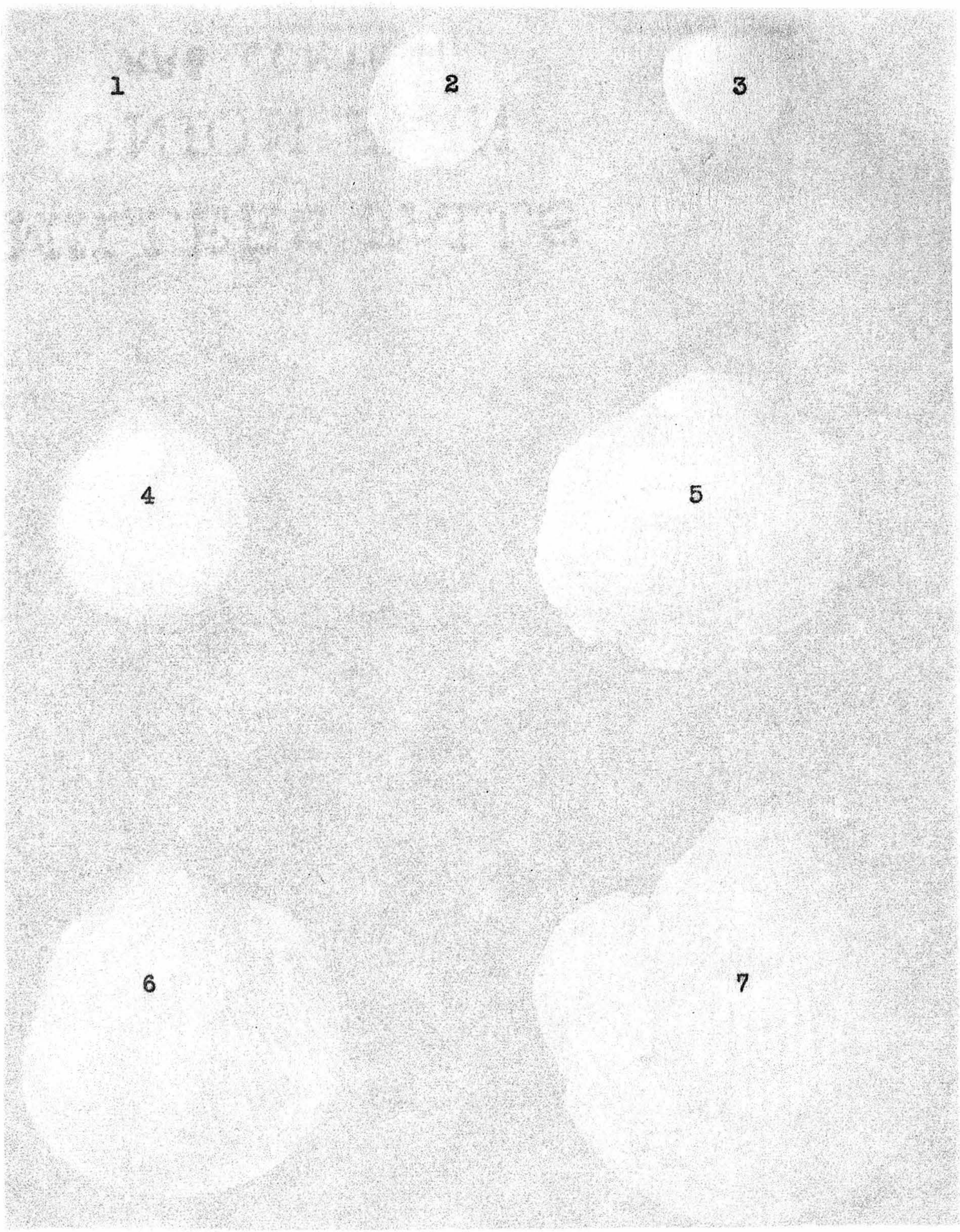
4. *Glycymeris veatchii sensu stricto*, typical form from Tuscan Springs.

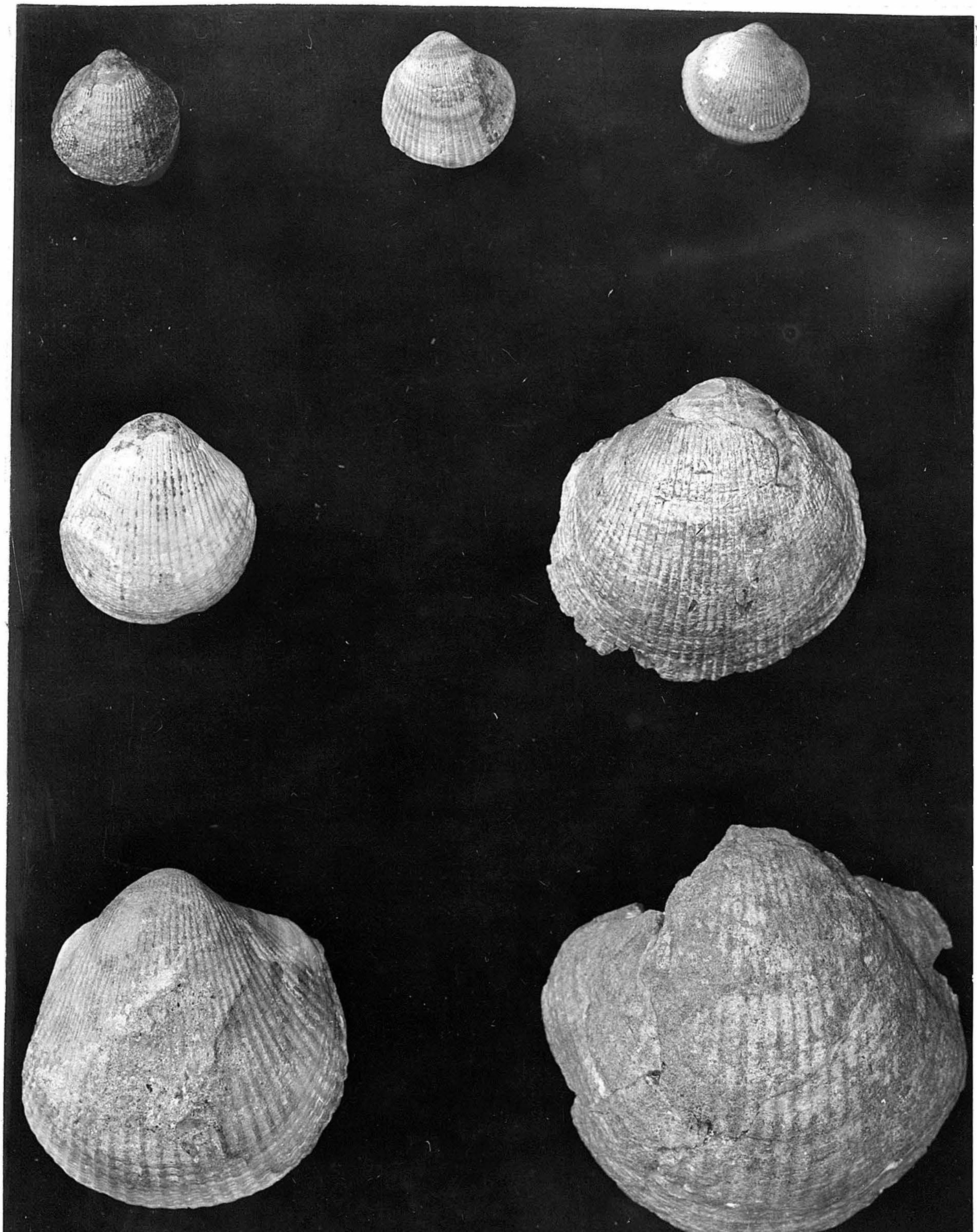
5. *Glycymeris veatchii anae*, large variety.

6. *Glycymeris veatchii major*, typical Cretaceous form from Los Banos Creek, Los Banos, California.

7. *Glycymeris veatchii s. s.*, giant form from the Santa Monica Mountains.

PLATE I





Explanation of Plate II

Figure 1. *Glycymeris veatchii major*, typical form from Martinez of the Simi Valley.

2. *Glycymeris veatchii sensu stricto*, typical form from the type locality at Tuscan Springs, California.

3. *Glycymeris meganosensis n. sp.*, typical form from the type locality of the Meganos formation, Mt. Diablo Qudrangle, California.

PLATE II