Geological and Geophysical Studies of Chromite Deposits in the Josephine Peridotite, Northwestern California and Southwestern Oregon

U.S. GEOLOGICAL SURVEY BULLETIN 1546 A–D

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Structure of Part of the Josephine Peridotite, Northwestern California and Southwestern Oregon

By JAMES G. EVANS

Geology and Chromite in the Low Plateau Area, Del Norte County, California

By JOHN P. ALBERS

A Magnetic Interpretation of the Josephine Peridotite, Del Norte County, California

By ANDREW GRISCOM

Geophysical Studies of Chromite Deposits in the Josephine Peridotite of Northwestern California and Southwestern Oregon

By JEFFREY C. WYNN *and* WILFRED P. HASBROUCK

U.S. GEOLOGICAL SURVEY BULLETIN 1546 A-D

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1984

DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, *Secretary*

U. S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publications Data

Main entry under title:
Geological and geophysical studies of chromite deposits in the Josephine Peridotite, northwestern California and southwestern Oregon.

(U.S. Geological Survey Bulletin 1546 A-D)
Contents: Evans, James G., Structure of part of the Josephine Peridotite, northwestern California and southwestern Oregon; Albers, John P., Geology and chromite in the Low Plateau area, Del Norte County, California; Griscom, Andrew, A magnetic interpretation of the Josephine Peridotite, Del Norte County, California; Wynn, Jeffrey C. and Hasbrouck, Wilfred P., Geophysical studies of chromite deposits in the Josephine Peridotite of northwestern California and southwestern Oregon.
Bibiographies: p. 5, 34-37, 52,86.
Supt. of Docs. no.: I 19.3:1546 A-D
1. Chromite—California, northern. 2. Chromite—Oregon. 3. Peridotite—California, northern. 4. Peridotite—Oregon. I. Title. II. Series: United States. Geological Survey. Bulletin 1546 A-D.
QE75.B9 no. 1546 A-D 537.3s 84-600093
[QE391.C65] [549'.526]

For sale by the Distribution Branch, U.S. Geological Survey,
604 South Pickett Street, Alexandria, VA 22304

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INTRODUCTION

By JOHN P. ALBERS

The United States is the world's largest user of chromite but has virtually no economic deposits of this mineral at present (1981). Most of the world's chromite is produced from stratiform deposits in South Africa and Rhodesia and from podiform deposits in alpine peridotites in the Soviet Union. The Stillwater Complex, a stratiform complex in Montana, contains substantial tonnages of chromite, but the ore has a low Cr_2O_3 content and is high in iron; if the United States' industry were to become dependent on it, major shifts and inefficiencies in metallurgy would be inevitable (Thayer, 1973).

Ultramafic rocks of the alpine peridotite type are common in both the Western and Eastern United States, and diligent search by prospectors over the last 100 years has yielded a large number of small deposits that were economically exploitable only during periods of national emergency. Through the efforts of prospectors virtually all exposed podiform chromite occurrences probably have been found. But how many podiform deposits are concealed at shallow to moderate depths (from a fraction of a meter to, say 50 m) beneath the erosion surface and is there any geological or geophysical method or combination of methods that will detect these concealed deposits? Are there any large deposits present at shallow to moderate depths?

Deposits yielding millions of tons do occur in alpine peridotites in the Philippines, Turkey, and in the U.S.S.R., and there seems to be no compelling geologic evidence to preclude their presence in similar peridotites in the United States. The principal objective of the project reported on here has been to test various techniques in an attempt to develop a method for detection of concealed podiform chromite deposits in alpine peridotites.

The studies have focused on areas in the Josephine Peridotite in northwestern California because of the presence in this region of a few unmined or partially mined podiform chromite bodies. These were the "field laboratories" where detection experiments were conducted. However, the deposits have been less than adequate because (1) their size is small, and (2) in the case of underground deposits, maps are inadequate, and (3) the location and amount of chromite remaining unmined is not precisely enough known. Furthermore, one promising deposit, Brown's mine, is more than 40 m below the surface. Nevertheless, this area seems to be the best "field laboratory" available in the conterminous United States, and no other options were known to us.

Geologic work included the following:

(1) Compilation by J. G. Evans of a photogeologic map (pl. 1) of essentially the entire area of the Josephine Peridotite that lies within California (published scale 1:125,000) was done by interpreting 1:15,840-scale aerial photographs. About one month was spent by Evans field checking the map. In addition, the Low Plateau and Low Divide areas, mapped in detail by Albers and Evans, respectively, were incorporated into this map, as was the geology of a much larger area of the ophiolite associated with the Josephine Peridotite mapped by G. D. Harper for his Ph. D. dissertation at the University of California, Berkeley.

(2) An area of about 2 mi^2 containing numerous chromite pods including the remaining unmined part of the Brown's mine deposit (Low Plateau area) was mapped in detail by Albers at a scale of 1:15,840 on color aerial photographs.

(3) Thirteen small areas (fig. 1) that are well exposed and exhibit small-scale structures within the peridotite were studied by Evans, who made detailed structural measurements and analyses.

Geophysical investigations were conducted at three localities within the Josephine Peridotite. These localities contain known chromite pods. They are identified on figure 1 and are referred to as: (1) Brown's mine, (2) Tyson mine, and (3) Red Mountain deposit. Field geophysical studies carried out in these areas include magnetic, electromagnetic, complex resistivity, and seismic reflection and refraction. Prior to field studies, the physical properties of a suite of ultramafic rocks and chromites were determined in the laboratory. Also included was a study of spectral reflectance characteristics that might be used to discriminate chromium-rich areas by remote-sensing techniques

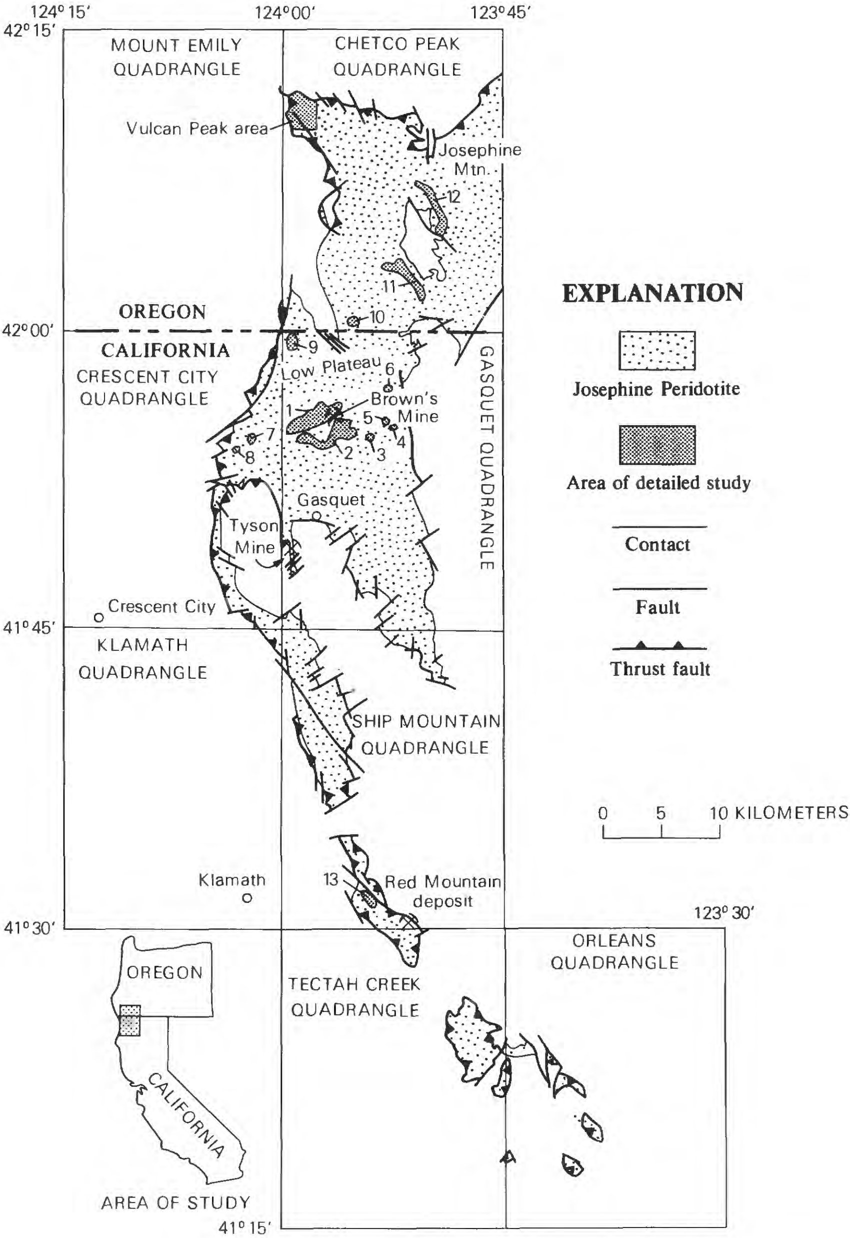

FIGURE 1.—Location of Josephine Peridotite and 15-minute quadrangles constituting study area. Numbered areas were studied in detail.

(Hunt and Wynn, 1979). J. C. Wynn was in charge of the overall geophysical work and carried out a number of the investigations himself. Complex resistivity studies were made by contract with Zonge Engineering, and seismic work was done by W. P. Hasbrouck.

In addition to the geophysical investigations noted, an aeromagnetic survey of the area of the Josephine Peridotite between latitudes 41°45′ N. and 42°00′ N. was made for the purpose of determining the configuration of the Josephine Peridotite at depth. Andrew Griscom was responsible for this part of the project work.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the cooperation of property owners in areas where our studies were conducted. Mr. and Mrs. Eugene Elliott of O'Brien, Oregon, owners of Brown's mine, not only gave permission to work on the property, but supplied information on the amount and location of unmined chromite remaining underground, and were helpful in many other ways during our fieldwork. Lee Hescock, co-owner of the Tyson mine and the Red Mountain deposit, was similarly helpful, and Bill Whippo, foreman at the Tyson mine when it was last operated in the 1950's, provided information on the location of remaining underground chromite.

Our thanks are also due C. H. McClendon and Barney McClendon for information they provided on the history and present physical status of a number of other chromite properties in the area, some of which were considered for study.

Richard Ellis provided a copy of his Master's thesis on the geology of selected chromite deposits in the Josephine Peridotite and also pointed out a number of pertinent geologic features to us in the field. We are most grateful to Gregory D. Harper, University of California, Berkeley, for providing us with a preliminary copy of his map covering a significant part of the Josephine Peridotite. This map is incorporated in simplified form in plate 1 of this report.

Finally, thanks are due Edward von Dohlen, Donald F. Huber, Luis Fraticelli, and Steve Manydeeds for their excellent assistance in various aspects of the fieldwork. Laurence J. Cummings is responsible for most of the petrographic work.

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Structure of Part of the Josephine Peridotite, Northwestern California and Southwestern Oregon

By JAMES G. EVANS

GEOLOGICAL AND GEOPHYSICAL STUDIES OF CHROMITE DEPOSITS IN THE JOSEPHINE PERIDOTITE, NORTHWESTERN CALIFORNIA AND SOUTHWESTERN OREGON

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STRUCTURE OF PART OF THE JOSEPHINE PERIDOTITE, NORTHWESTERN CALIFORNIA AND SOUTHWESTERN OREGON

By JAMES G. EVANS

ABSTRACT

The study area includes rocks of three major lithic belts, Coast Ranges belt, western Jurassic belt, and western Paleozoic and Triassic belt. The focus is on the western Jurassic belt, especially the Josephine Peridotite, the basal member of an ophiolite sequence. The peridotite consists of a harzburgite tectonite containing dunite bodies that have been deformed to varying degrees. It is not known whether the harzburgite is a residuum of partial melting or a product of primary precipitation from an ultramafic magma. Some chromitiferous dunite in the harzburgite may have formed as a cumulate ultramafic rock.

Overlying the peridotite in the ophiolite sequence are, in ascending order, cumulate ultramafic rocks, gabbro, a dike complex, and pillow lava. Late Jurassic metasedimentary rocks overlie the ophiolite. In the Late Jurassic, the ophiolite and metasedimentary rocks were thrust over metavolcanic rocks, gabbro, and gneiss and were subsequently thrust generally westward over the Late Jurassic and Early Cretaceous Franciscan Complex during the Late Cretaceous Coast Range orogeny. The Lower Coon Mountain pluton (ultramafic), which may have intruded the metasedimentary rocks in Early Cretaceous time, was folded, along with the older rock units, into an open syncline with its axis plunging at a low angle southeast. This folding may be related to the Late Cretaceous orogeny. The thrust at the west edge of the peridotite correlates in part with the South Fork Mountain fault. Part of the basal contact of the peridotite southeast of Rattlesnake Mountain may be the flat-lying thrust that is inferred from aeromagnetic data to underlie the peridotite. Steep faults occur in three major groups: (1) a dominant set striking N. 5° E.; (2) a large group with mean strike N. 35° W.; (3) a set striking N. 45° E. Faults of groups 2 and 3 are subparallel to the San Andreas and Garlock faults, respectively, and may have resulted from a regional stress regime like the one which produced the two major faults in southern California.

Subpopulations of layers and foliations in harzburgite are widely variable in orientation, but appear to define a beta axis plunging northeast. Subpopulations of folds and rods within the tectonite peridotite are divided into four groups based on style and orientation: (1) early isoclinal folds plunging generally northwest at a low angle; (2) open folds plunging generally northeast; (3) open folds plunging at low angles east and west; (4) steep folds. Fold groups 1 to 3 are listed in order of age, oldest to youngest. The relation of group 4 to the other three groups is unknown. Refolding of early isoclinal folds is indicated prior to development of folds of group 2.

Dunite dikes intruded harzburgite in several stages: some dikes intruded prior to development of harzburgite foliation and early isoclinal folds; other dikes cut harzburgite foliation, but underwent later stages of open folding; some dikes may not have been affected by folding. Apophyses of some dikes intrude harzburgite along orthopyroxene layers and suggest that some dunite layers parallel to harzburgite foliation may be intrusive. Orthopyroxene dikes cut dunite dikes and are locally warped and faulted.

Chromite deposits occur in intensely serpentinized dunite, granulated dunite, sheared serpentinite, sheared gabbro, and chromite breccia with diopside matrix. Ore bodies may be tabular, elongate parallel to fold axes, or have other controls. No clearly defined structural controls were found. Structural analysis may aid in prospecting small areas.

Chromite deposits appear to be confined to a crudely defined tabular zone below the gabbro. Projections of the chromite-bearing zone in the peridotite are drawn on a map. The array of chromite deposits implies possible contemporaneity of the chromitiferous dunite intrusions and overlying igneous units of the ophiolite, possible contemporaneity of part of the folding in the peridotite with formation of the overlying units, tectonic uncoupling between the harzburgite and dunite tectonites and the cumulate ultramafic rocks below the gabbro, and the possibility that some of the rock mapped as peridotite above the chromite-bearing zone is deformed cumulate ultramafic rock.

INTRODUCTION

The Josephine Peridotite extends north-south for 130 km through the mountains of southwest Oregon (Curry and Josephine Counties) and northwestern California (Del Norte and Humboldt Counties). The outcrop width of the peridotite is 1 to 19 km east to west in California and exceeds 30 km in this direction in Oregon. The area of this study includes the segment of peridotite 72 km long in California, an adjoining segment 19 km long in Oregon, and the rocks in the vicinity of the peridotite (fig. 1; pl. 1).

A geological reconnaissance of the Josephine Peridotite was made by J. G. Evans, assisted by E. Von Dohlen in fall 1977, by D. Huber in summer 1978, and by L. Fraticelli in spring 1979. A photogeologic interpretation of the peridotite was made by Evans in 1978 and checked in the field in 1979. The great contrasts in many places between sparsely vegetated peridotite terrain covered with reddish soil and heavily forested terrain underlain by other kinds of rocks are clearly seen in the field and generally show well on the color aerial photographs used in this study. The vegetation characteristics were used to make the photogeologic interpretation of the Josephine Peridotite and the nearby peridotite at the base of the Preston Peak ophiolite (pl. 1). Intensely serpentinized and sheared harzburgite and wehrlite were difficult to distinguish from nonperidotite rocks. Additional uncertainty in photointerpretation is due to variation in bulk composition of the regolith above peridotite. Locally, as on South Red Mountain, vegetation on peridotite terrain is as lush as vegetation on nonperidotite terrain.

The reconnaissance geologic map of the Josephine Peridotite (pl. 1) not only includes the photogeologic interpretation, modified by field interpretations, but also published and unpublished geologic mapping: published maps of the Gasque quadrangle (Cater and Wells, 1953) and for the Chetco Peak quadrangle (Wells and others, 1949; Ramp, 1975; Page and others, 1981); unpublished maps of the Low Plateau (Albers, 1977), the North Fork Smith River area (Cornwall, 1979), and the Middle and South Forks Smith River area (Harper, 1980a). (See pl. 1 for map credits by area.) Field interpretations were generally given priority over photointerpretation in the geologic compilation, especially in the Middle and South Fork area mapped by Harper. Locations of mines and prospects were determined in the field, taken from aerial photographs and from published information by Wells and others (1946), by Cater and Wells (1953, pl. 11), and by Ramp (1961, pl. 1).

GEOLOGIC SUMMARY

The area covered by plate 1 includes parts of two of the belts of pre-Nevadan basement rocks recognized by Irwin (1960, p. 10–30; 1966, p. 21–25): (1) the western Paleozoic and Triassic belt and (2) the western Jurassic belt. Rocks of these belts are discussed separately and are grouped on the explanation of plate 1, which also includes a Coast Range belt for rocks lying west of the western Jurassic belt.

The western edge of the western Paleozoic and Triassic belt is the thrust at the base of the peridotite on Ship Mountain (pl. 1). Snoke (1977) named the thrust the "Preston Peak thrust" and referred to the peridotite and the overlying metavolcanic and metasedimentary rocks as the Preston Peak ophiolite. The metavolcanic and metasedimentary rocks are intruded by a Late Jurassic ultramafic pluton. Emplacement of the Preston Peak ophiolite is post-Late Jurassic, as the overridden metasedimentary rocks are Late Jurassic. Changes in attitude of the Preston Peak thrust (pl. 1, cross section A-A′) are derived from map relations and an attempt to draw the peridotite in the hanging wall with a uniform thickness. The result suggests that the thrust is warped. The gentle dip of the thrust at the surface may be due to faulting or large scale slumping of relatively dense peridotite on relatively incompetent metasedimentary rocks, a near surface process postdating tectonic emplacement.

The western Jurassic belt is divided from the Coast Ranges belt on the west by a thrust fault, part of which may be the northern extension of the South Fork Mountain fault, the major thrust along which rocks of the western Jurassic belt were thrust westward over the Franciscan Complex in the Late Cretaceous (Irwin, 1964, p. C9; 1966; Blake and others, 1967; Hotz, 1969). Bailey and others (1970) concluded that the South Fork Mountain fault is continuous with the Coast Range thrust to the southeast along which serpentinite and the Great Valley sequence were thrust westward over the Franciscan rocks.

Vail and Dasch (1977) recognized rocks of the western Jurassic belt as an ophiolite sequence. Harper (1980b) and Harper and Saleeby (1980) used the name Josephine ophiolitic complex for rocks below the metasedimentary rock unit. These workers conclude that this ophiolite formed in proximity to an active volcanic arc and a continental margin, probably within a marginal basin during early stages of rifting of an arc complex. Harper (1980b) considers the ophiolite to be part of a complex continental-margin arc, island-arc, and marginal-basin system developed along part of western North America during Jurassic time, probably as a response to eastward subduction.

The basal member of the Josephine ophiolite of Harper (1980b) is a peridotite, named the Josephine peridotite sheet by Wells and others (1949, p. 9), and referred to informally as the Josephine peridotite by Himmelberg and Loney (1973, p. 1585) and formally as the Josephine Peridotite by Loney and Himmelberg (1977, p. 761).

Structures, textures and coexisting phases (Himmelberg and Loney, 1973) and olivine fabrics (Loney and Himmelberg, 1976) of the peridotite in the Vulcan peak area, northwest Chetco Peak quadrangle, are consistent with high-temperature (1,000°–1,200° C) deformation and recrystallization in the upper mantle. According to Himmelberg and Loney (1973, p. 1596) the best pressure estimate for formation of the mineral assemblages is at least 5 to 7 kb. No conclusive evidence was found bearing on the origin of the harzburgite as either a residuum of partial melting or a product of crystallization of an ultramafic or picritic magma in this or in other studies (Himmelberg and

Loney, 1973). Enstatite textures, however, suggest a magmatic stage in the history of the harzburgite. Dick (1976, p. 331; 1977a, 1977b) cites textural, mineralogical, geochemical, and field evidence to support his conclusions that the Josephine Peridotite underwent at least two periods of fractional partial melting.

Chromite, a common accessory mineral in the peridotite, is locally abundant in dunite. Deposits of chromite (pl. 1), presently subeconomic, are scattered seemingly at random in dunite bodies and in serpentinized dunite. Some chromitiferous dunite exhibits chromite net and occluded silicate texture (fig. 2), terms introduced by Thayer (1969, p. 133–134). These textures are very similar to primary textures in the Stillwater Complex (Thayer, 1969, fig. 1; Jackson, 1961, figs. 9, 10, and 30) and strongly suggest that some chromitiferous dunite originated as cumulate ultramafic rock. Dunite, with and without chromite, was deformed. A major goal of this project was detailed study of structures associated with chromite in order to determine chromite ore zones in the peridotite.

The upper members of the Josephine ophiolite of Harper

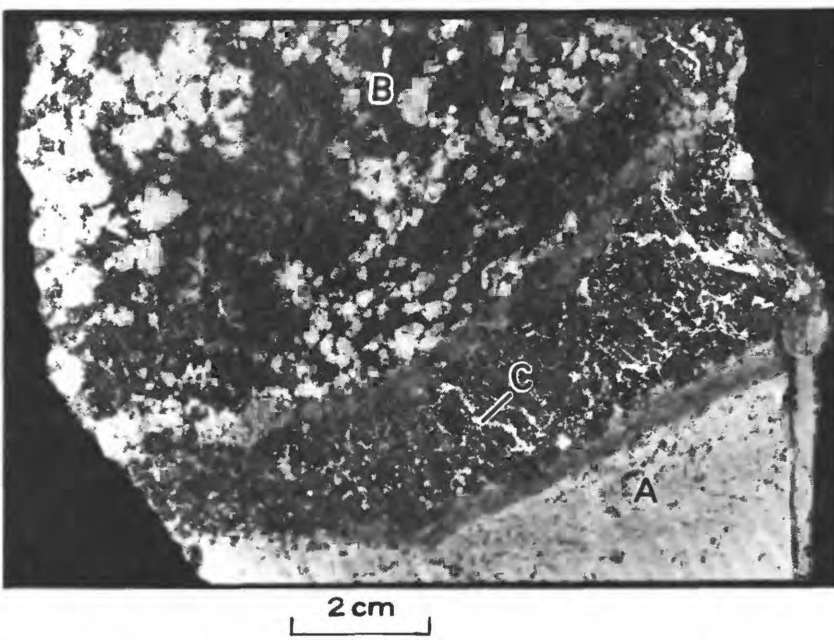


FIGURE 2.—Cumulate textures in chromitiferous dunite. Sample from Skyline mine on Low Plateau (pl. 1). Chromite (black) net (A) and occluded silicate (B) texture adjacent to a massive chromite layer with pull-apart texture (C). Tension cracks (leaders) filled with serpentinized olivine are at high angles to the massive chromite layer but are rare in the rest of the rock.

(1980b) are, in ascending order, cumulate ultramafic rock, gabbro, a dike complex, and pillow lava, all assigned a Late Jurassic age. Late Jurassic metasedimentary rocks overlie the ophiolite.

Blocks of gabbro occur on the dump at the Judy mine, Low Plateau. The gabbro may range from Middle Jurassic to Late Cretaceous, assuming that the gabbro is contemporaneous with dikes dated by Dick (1973) west of Cave Junction. Some of the gabbro is mylonitized and contains chromite breccia. Mylonitization was probably local, because no mylonitized rocks were found elsewhere in the Josephine Peridotite in this study.

In northern Chetco Peak quadrangle, the Josephine Peridotite is thrust over Jurassic metavolcanic rocks assigned to the Rogue Formation (Dick, 1973; Ramp, 1975; Wells and others, 1949) and a complex of Late Jurassic ultramafic rock, gabbro, and gneiss (Wells and others, 1949; Page and others, 1981) informally named the Chetco River complex by Hotz (1971, p. B3, fig. 2*A*, table 1). Ramp (1975) named the thrust the Madstone Cabin thrust, which is post-Late Jurassic because of the Late Jurassic rocks in the lower plate. The Madstone Cabin thrust is truncated by a generally north-trending thrust, possibly a segment of the South Fork Mountain fault.

The South Fork Mountain fault, underlying part of the Josephine Peridotite, dips eastward generally less than 45°. In the cross sections A-A′ and B-B′ (pl. 1) the fault dips 20°–25° east. A segment of the fault in the vicinity of the Smith River is approximately vertical. On the basis of interpretations of aeromagnetic data by Griscom (this volume), the Josephine ophiolite of Harper (1980b) is drawn as a sheet approximately 2.5 km thick lying on the Franciscan Complex and its metamorphosed equivalent. Uncertainty exists as to whether the gently dipping to flat-lying thrust under the peridotite is part of the South Fork Mountain fault, or is truncated by the fault. In section B-B′ the South Fork Mountain fault is shown truncating the flat thrust.

South of Rattlesnake Mountain, the thrust under the peridotite dips very gently eastward, and the Josephine Peridotite comprises two large klippen (1) on Red and South Red Mountains and (2) on part of Blue Creek Mountain Ridge (pl. 1). In these areas the Franciscan Complex cannot be clearly divided from metasedimentary rocks of the western Jurassic belt. Cross section C-C′ (pl. 1), based on aerial photograph and field interpretations, shows one structural interpretation of the klippe at South Red Mountain and the adjoining rocks. The rocks below the peridotite are intensely sheared metasedimentary rocks, unidentifiable as to formation. Assuming that these sheared rocks underlie the peridotite in a zone at least 690 m thick (vertical thickness of sheared rocks beneath the thrust along Blue Creek), approximately parallel to the thrust beneath the peridotite, the resulting geometry, shown in cross section C-C′, suggests that a 5-km-wide exposure of sheared rock (not mapped) lies between the west side of Starwein Ridge and South Red Mountain. An extension of this shear zone (not mapped) beneath South Red Mountain would project for a distance of 5 km east of the mountain and may be overlain by one or more rock units which are stratigraphically above the Josephine Peridotite. The sheared metasedimentary rocks in this zone are likely to have been derived mostly from the Franciscan Complex, although the Jurassic metasedimentary rock unit could also be present. The shear zone at the base of the Josephine Peridotite south of Rattlesnake Mountain may be part of the thrust inferred from aeromagnetic data farther north. The Blue Creek Mountain Ridge klippe is faulted on the southeast. Southeast of these faults the peridotite occurs as fault blocks and slivers as much as 3 km long and 1.5 km wide in a matrix of intensely fractured metasedimentary rock, chiefly slate.

Steep faults cutting the Josephine ophiolite and surrounding rocks must postdate tectonic emplacement of the ophiolite. In order to study the variation in attitudes of these faults, the dip angles were assumed to approximate 90°. Azimuths of the trends of the faults were measured from the geologic map (pl. 1) and assumed to approximate the strikes of the faults. Each fault was weighted by the length of its exposed or inferred trace. The faults were then separated into groups in which the strike of the faults are within 10 intervals. Total length of the faults in each group were plotted in fault-kilometers in a rose diagram (fig. 3). Three groups of steep faults are well developed in the study area: (1) the dominant group striking N. 5° E.; (2) a large group of faults with mean strike of N. 35° W.; and (3) a narrowly defined group striking N. 45° E. The faults of group 2 are subparallel to the San Andreas fault zone in the Coast Ranges and could have developed as a result of a regional stress regime similar to the one under which the San Andreas fault developed. The faults of group 3 are parallel to the general strike of the Garlock fault in southern California. These faults could be a fault set conjugate to group 2 and due to the same regional stress regime as the faults of group 2.

Rocks of the western Jurassic belt are folded into an open syncline (pl. 1, cross section A-A′) first recognized by Harper in the Lower Coon Mountain area. Poles of bedding in the metasedimentary rocks in the core of the syncline define a beta axis plunging approximately 10° nearly due north, although the map suggests that the syncline plunges southeast. Harper (1980b) attributes this deformation (and related metamorphism) to the Late Jurassic Nevadan orogeny, although the Early Cretaceous age of the folded Lower Coon Mountain pluton indicates that the syncline developed after the Nevadan orogeny. Final emplacement of the ophiolite occurred by Late Cretaceous, and, therefore, the syncline may be as old as or older than the thrust at the base of the Josephine ophiolite.

Slaty cleavage is developed, generally subparallel to bedding and to axial planes of early isoclinal folds of bedding. The mean orientation of these cleavages is N. 50° W., 25° SW. Poles of cleavage in the vicinity of the synclinal axis define a beta axis plunging approximately 20° S. 10° E. This direction is close to the apparent direction of plunge of the syncline on the geologic

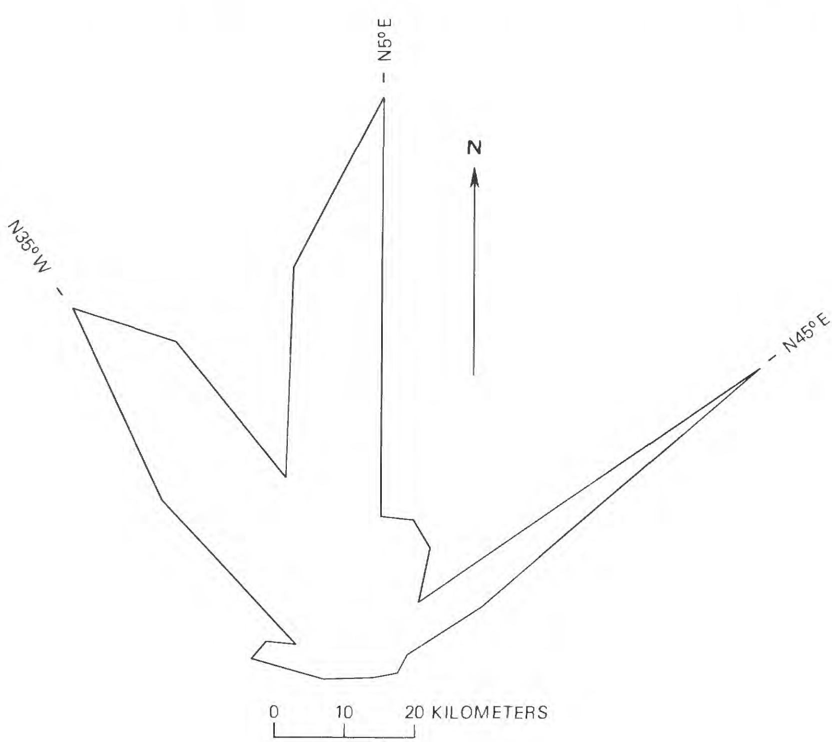


FIGURE 3.—Rose diagram of steep faults cutting the Josephine ophiolite of Harper (1980b) and surrounding rocks.

map and to many minor folds of cleavage. The minor folds, however, show much scatter in the southeast and northwest quadrants. The small angular difference in orientation of the folds of bedding and cleavage suggests that they could have developed as stages in a single tectonic episode.

Harper and Saleeby (1980) propose that some of the folding of the metasedimentary rocks was associated with thrusting of the Josephine ophiolite over the Franciscan Complex. Because Harper (1980b) dates folds of bedding as Late Jurassic, Harper and Saleeby (1980) may mean that folds of cleavage are contemporaneous with thrusting.

STRUCTURAL ANALYSIS

Most of the Josephine Peridotite is harzburgite that is massive, or is layered and foliated. Complexly deformed layers and foliations occur in many parts of the peridotite. In general, however, mesoscopic deformation is not penetrative in domains of more than a few square meters. One area of folded layers and foliations in the Vulcan Peak area, northwest of the Josephine Peridotite, was analyzed by Loney and Himmelberg (1976). In the present study the internal geometry of a larger part of the peridotite was analyzed to determine whether structural analyses could be used as a technique of chromite prospecting in the peridotite. Less than 1 percent of the area underlain by the peridotite was suitable (fig. 4). Most good exposures are on or near ridgetops and at some chromite mines where removal of regolith is extensive. Thirteen areas of well-exposed harzburgite tectonite and dunite were studied (fig. 1): twelve of the areas occur 6 to 30 km north of the town of Gasquet; the other area is at Red Mountain, 35 km south of Gasquet. The mesoscopic structures of each of these areas was analyzed separately. Standard techniques of structural analysis were used (Turner and Weiss, 1963; Ramsay, 1967): gathering numerous attitudes of layers, foliations, axial planes, lineations and fold axes, and detailed observations of fold types and styles and their geometric relations. Fabric elements described below were correlated between study areas, and inferences were made regarding the deformation history of the peridotite as a whole. The following description of the internal structure of the peridotite is a summary. Detailed structural data, including petrofabric studies, will be presented in a subsequent report.

LAYERS AND FOLIATIONS

The most common structures in harzburgite are orthopyroxene-rich layers and olivine-rich layers such as those shown in figure 5. Orthopyroxene layers are as much as 10 cm thick; dunite, as much as 30 cm. Some layers in harzburgite consist of dunite or orthopyroxene-poor harzburgite containing pods of coarse-grained (greater than 2 cm) orthopyroxenite (fig. 6). The orthopyroxenite pods appear to be segments of formerly continuous layers. These layers must have been pulled apart; some of the segments of orthopyroxenite were deformed. The pull-apart structures, pointing to large extensional strain in the plane of the layers, could have resulted from (1) extreme plastic deformation of the rock or (2) from flow of a partially liquid (or less viscous) phase having composition of dunite or orthopyroxene-poor harzburgite and containing orthopyroxenite as a solid (or more viscous) phase. Chromite-rich layers or schlieren in dunite are most commonly in the central parts of dunite layers. In places, the chromite layers are at an angle to the external contacts of the dunite body.

FIGURE 4.—View northeast across Peridotite Canyon, Calif. showing sparsely vegetated terrain. Apparent continuous exposures on flanks of ridges are commonly poor for structural study because the blocks of peridotite have been rotated. Distance between foreground and skyline is 2.5 km. Total relief shown is 300 m.

A foliation defined by planar arrays of orthopyroxene grains is present in many places in harzburgite. Typically the foliation is subparallel to layering in the same outcrop and to the axial planes of isoclinal folds of layers. Chromite schlieren in

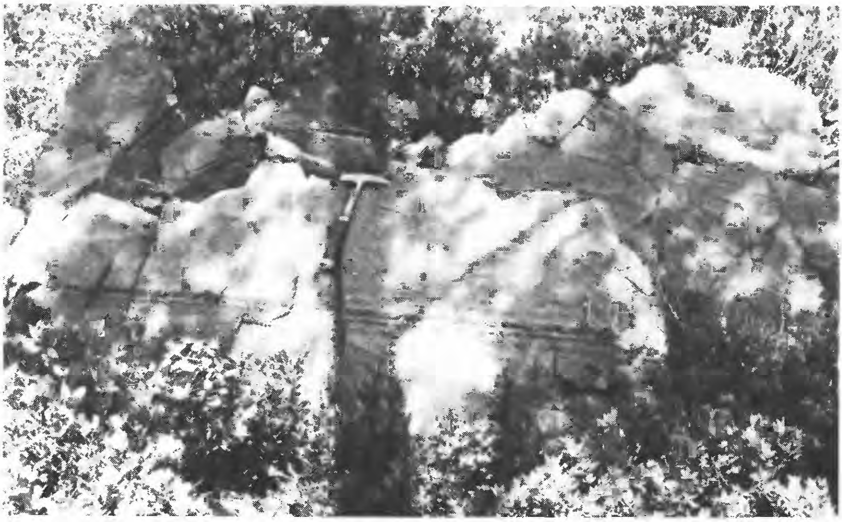


FIGURE 5.—Orthopyroxene layers in harzburgite.

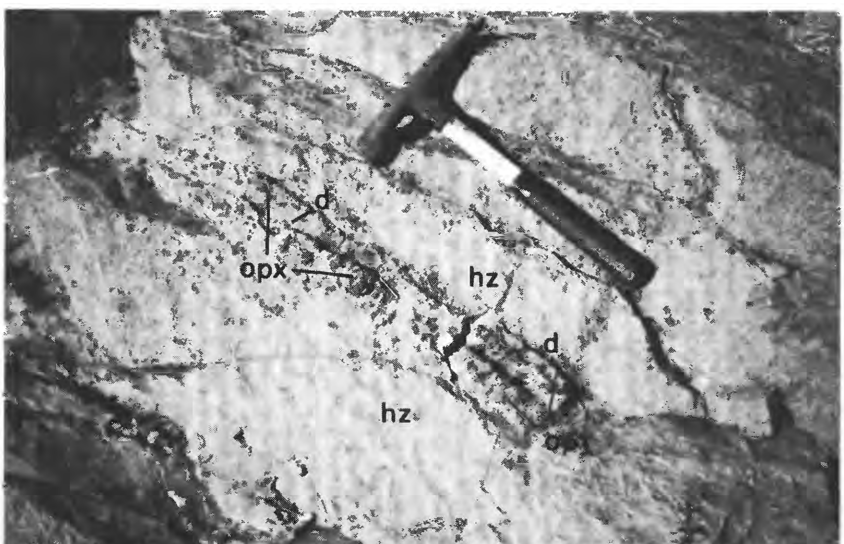


FIGURE 6.—Dunite layer (d) with discontinuous zone of orthopyroxenite (opx) in harzburgite (hz). Orthopyroxenite appears to be pulled apart segments of formerly more continuous orthopyroxenite layers.

dunite locally contain an internal foliation defined by planar arrays of chromite grains. These chromite foliations are oriented at a high angle to the general attitude of the schlieren (fig. 7) and are subparallel to the axial planes of nearby minor folds, described below. Olivine grains near axial plane chromite foliations of folded chromite schlieren are flattened in the plane of foliation. In places planar arrays of flattened chromite rods define a foliation in dunite (fig. 8). On Red Mountain this kind of foliation is subparallel to orthopyroxene foliation in harzburgite and at an angle to the dunite-harzburgite contact. These relations suggest deformation following an episode of dunite intrusion.

FOLDS

Folds of dunite, orthopyroxenite, and chromite layers have amplitudes generally 5 cm to 1 m. Folds with amplitudes greater than 1 m are difficult to recognize because the fold hinges are not exposed. A few dunite folds with amplitudes as much as 100 m were mapped by J. P. Albers on Low Plateau.

Isoclinally folded dunite bodies with greatly thickened

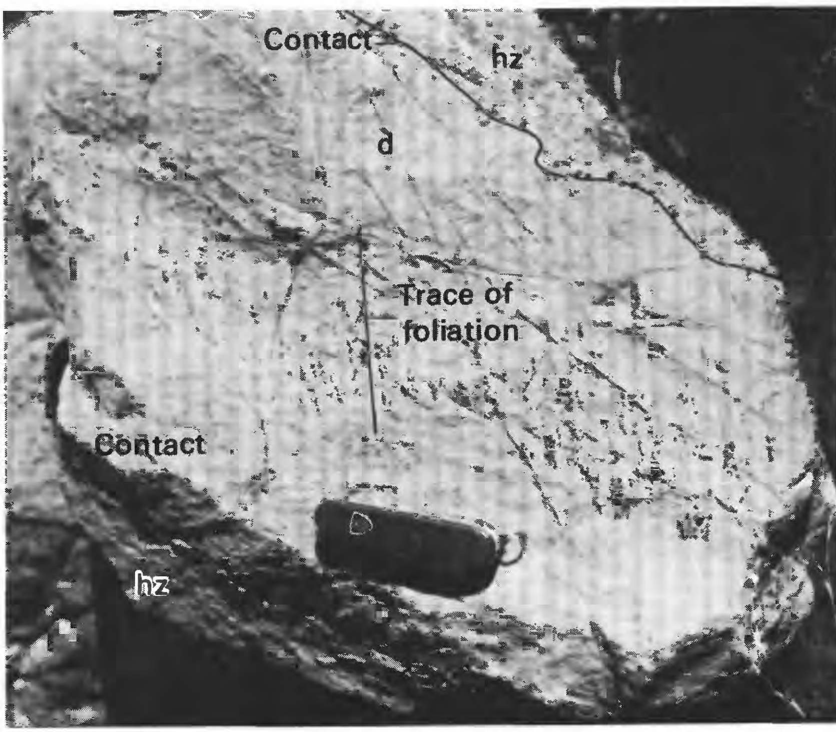


FIGURE 7.—Chromite foliation in dunite at high angle to dunite-harzburgite contact. Dunite, d; harzburgite, hz. Knife is 10 cm long.

hinge zones and detached hinges are probably the oldest kind of folds (fig. 9*A*). They generally plunge at low angles north-northwest and northwest. Axial planes of these folds are subparallel to orthopyroxene foliation in adjacent harzburgite. Some of the axial planes are refolded about axes with nearly the same orientation as the isoclinal fold hinges (fig. 9*B*). The isoclinal folds and the detached fold hinges indicate large extension in the plane of the harzburgite foliation. Assuming that these structures formed by plastic deformation with no volume change, the extension implies a compression oriented at a high angle to the plane of extension. This early deformation could be (1) an early pervasive plastic deformation in which preexisting folds were drastically altered or obliterated or (2) a deformation confined to narrrow zones in the peridotite. The widespread similarity in orientations of the axial planes of the isoclinal folds and the orientations of layering and foliation in harzburgite is consistent with a pervasive character for the deformation.

Other folds are more open in general profile, with little or moderate amounts of tectonic thickening or thinning of folded layers (fig. 9*C*, *D*, *E*, *F*). These folds are probably younger than the isoclinal folds because (1) in some outcrops the early isoclinal folds have a small circle distribution about an axis coincident with the axes of open folds when plotted on an equal area net; (2) the axial planes of the open folds are usually at high angles to the early harzburgite foliation and layering which are

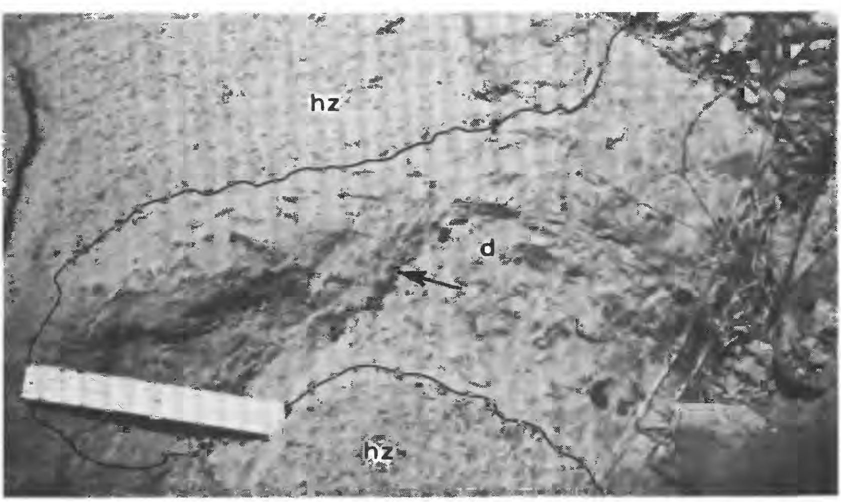


FIGURE 8.—Flattened chromite rods in dunite plunge 30° N. 15° W., at an angle to the dunite-harzburgite contact. Dunite, d; harzburgite hz. Arrow shows direction of plunge of rods. Scale is 20 cm.

subparallel to axial planes of isoclinal folds; and (3) the more open folds would have been unlikely to survive the early extension and flattening described for the isoclinal folds, unless the isoclinal folding only occurred locally in the peridotite.

The open folds are divided into three groups based on orientations: folds plunging gently to moderately mostly in the northeast quadrant; folds plunging at low to moderate angles both east and west; and folds plunging steeply. On Low Plateau, the northeast-trending folds are rotated in a small circle about a nearly east-west axis, and, therefore, comprise the older of the two groups. The steep folds could have formed contemporaneously with one or more of the other groups of folds either as a conjugate fold set or due to locally unusual orientation of the layering.

Ductility or viscosity contrasts between two masses of peridotite of differing composition may have existed and could account for some of the complex structure of the peridotite.

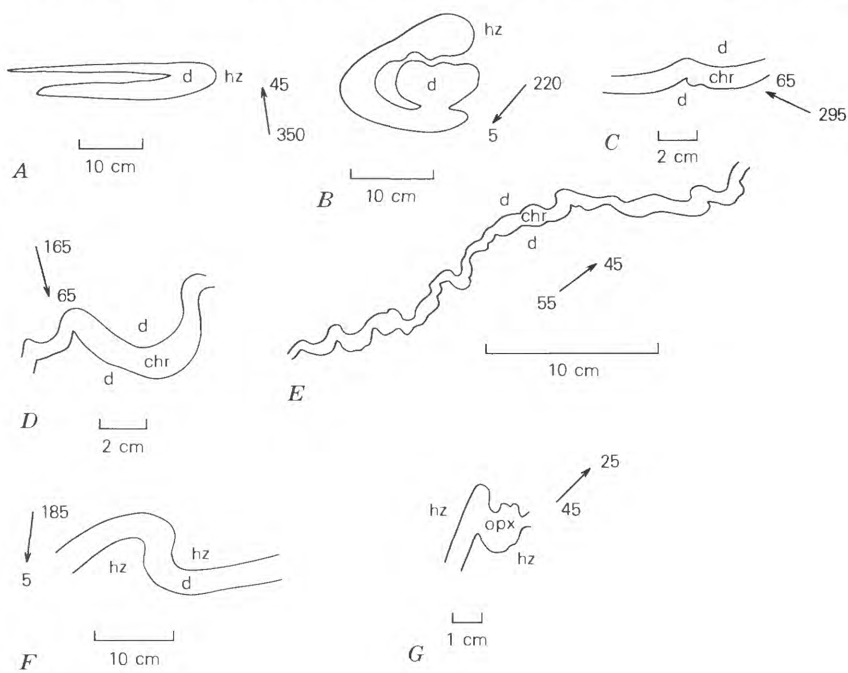


FIGURE 9.—Profiles of folds. Top of page is "up" direction; page surface is perpendicular to down-plunge direction. Trends of minor structures shown by arrows are referred to a 360° compass with 0°=north=top of page. Numbers at heads of arrows are angles of plunge. *A*, Detached isoclinal fold hinge. *B*, Detached, refolded isoclinal fold hinge. *C*, *D*, *E*, *F*, Types of open folds. *G*, profile of orthopyroxene rod. Dunite, d; harzburgite, hz; chromite, chr; orthopyroxene, opx.

Locally, on High Plateau, for example, plastically deformed chromite layers are adjacent to angular and subangular blocks of dunite surrounded by chromite (fig. 10). Either minor deformation, or possibly replacement of olivine by chromite, has resulted in a mismatch of opposing edges of the dunite fragments. The dunite blocks appear to be segments of a formerly continuous lens. No fault zone lies between the chromitiferous dunite deformed in the ductile mode and the chromitite and dunite deformed in the more brittle mode. Concentration of chromite in the rocks under discussion varies from 95 percent in the chromitite to nil in dunite. This variation in bulk composition may possibly influence the mechanical properties of the rocks and the mode of local deformation under certain conditions. Compositional contrasts in chromitiferous dunite that originated as a cumulate ultramafic rock may also imply differences in

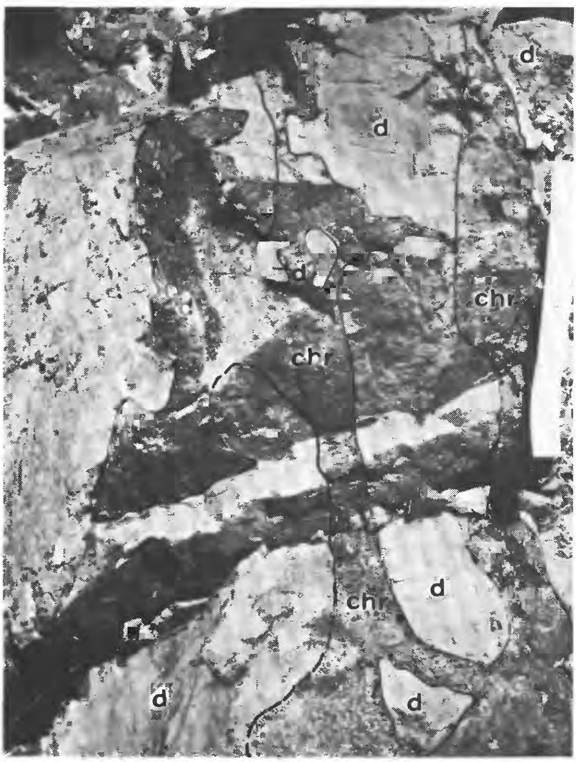


FIGURE 10.—Structure in chromitiferous dunite. Solid lines represent sharp dunite-chromite contacts. Dashed lines are gradational contacts between zones of disseminated chromite and ordinary dunite. Chromite-rich body labelled "chr"; contains chromite (black) and dunite with disseminated chromite (gray). Large dunite pod (labelled "d") on right appears to have been pulled apart, with chromite filling the spaces between the segments. Chromite near the upper left is folded. Scale is 20 cm.

amounts of liquid phase present, which could also influence mechanical properties and deformation mode of the rock material.

RODS

Rods of dunite (1 m long maximum), orthopyroxene (2 m long maximum), and chromite (10 cm long maximum) have oval to irregular profiles (fig. 9*G*). Some of them have profiles of folds and are clearly detached fold hinges. Rods are most common parallel to early northwest-trending isoclinal folds, but also occur parallel to folds in the other three fold groups. Rods of chromite (fig. 8) are found parallel to folds of all groups, but are the kind of rods most common parallel to axes of the open folds. These relations suggest that chromitiferous dunite behaved more plastically than other rock types during the episodes of open folding.

DIKES

Dunite dikes ranging in width from 1 cm to 300 m cut across the foliation and layering of the harzburgite. Dikes are most abundant in the Low Divide- High Divide area and on Red Mountain. Several episodes of dunite intrusion may have occurred prior to development of folding of foliation and layering in harzburgite. Other dikes cut across layering and foliation. Some of these dikes have apophyses that intrude along orthopyroxene layering and foliation (fig. 11), which suggests that some dunite "layers" may be intrusive in origin. Some dikes have centrally located chromite-rich schlieren, also suggesting that dunite layers with these kinds of chromite schlieren could be intrusions. Some dikes contain folded chromite layers with fold axes correlated with the three groups of open folds described above. These dikes must have been emplaced after the early intense plastic deformation and before development of the open folds or at least syntectonically with the earliest set of open folds. Some dunite dikes cut across others, further indicating more than one episode of dunite intrusion. Dunite dikes which appear unaffected by folding may have intruded after much of the folding in the peridotite.

Orthopyroxenite dikes, 1/2 cm to 3 m thick, cut across layering and foliation in harzburgite and cross most dunite dikes. Some orthopyroxenite dikes cut across others, indicating more than one episode of intrusion. Some of the dikes are broadly warped and faulted, reflecting low intensity ductile and brittle deformation.

Composite dunite-orthopyroxenite dikes consisting of tabular segments of dunite separating other tabular segments of orthopyroxenite intrude harzburgite. Evidence does not establish whether orthopyroxenite intruded dunite, or vice versa in these dikes.

FABRIC

The mean poles of layers and foliations in harzburgite in areas 1–13 are shown in figure 12*A*. In certain areas subpopulations of these planar fabric elements were defined. The mean of each of the subpopulations was included in the figure. The resulting preferential representation of certain areas was preferred to ignoring the subpopulations. Attitudes vary from gently dipping to nearly vertical. Poles of the mean orientations are approximately distributed in a northwest-southeast girdle with a beta axis plunging 10° N. 40° E.

Mean attitudes of subpopulations of linear elements were determined for most of the thirteen subareas (fig. 1). The data are shown in figures 12*B*, *C*, *D*, and *E*. No mean orientations were determined in those subareas in which the subfabrics do

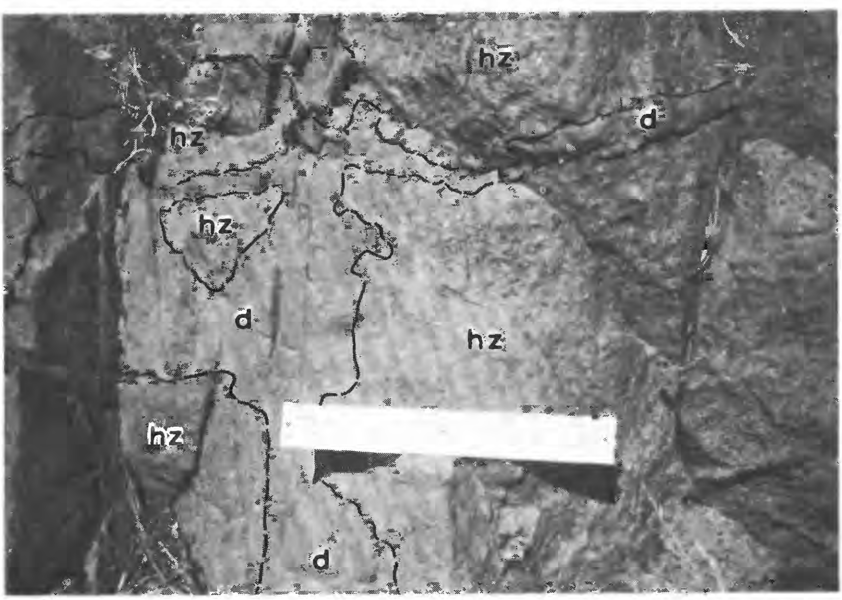
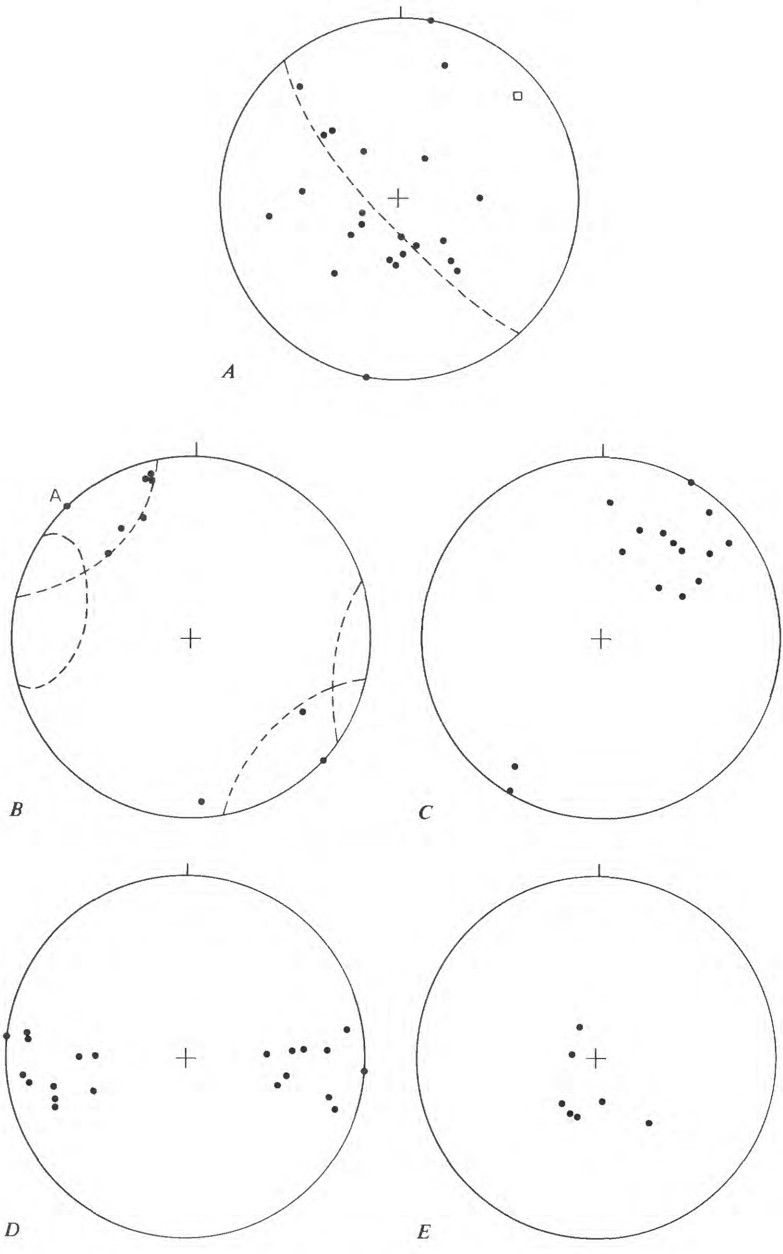


FIGURE 11.—Dunite intrudes harzburgite. Although outcrop is intensely serpentinized, textures and mesoscopic structures are well preserved. Harzburgite, hz; dunite, d. Subhorizontal dunite vein follows layering in harzburgite. Scale is 20 cm.

not comprise moderately well-defined sets. The means are divided into four groups defined in part by orientation and in part by fold style. The four groups correspond to the fold groups described above: (1) early folds generally trending north-



northwest and northwest (fig. 12*B*); (2) northeast-trending folds (fig. 12*C*); (3) west-trending folds (fig. 12*D*); and (4) steep folds plunging in many directions (fig. 12*E*). Some of the variations in attitudes of the mean orientations of the linear elements could be due to random rotation of large blocks of peridotite by faulting during or after Late Cretaceous thrusting, and (or) broad-scale heterogeneity of the deformations.

Refolding of early isoclinal folds is indicated by field observations and is implied in the dispersion of the mean attitudes of linear elements of group 1 in a small circle (fig. 12*B*). The axis of the small circle is horizontal and trends N. 45° W. Therefore, early isoclinal folding was followed by flexural-slip-type folding on a broad as well as a minor scale. Large folds of this kind are not mappable, owing to a lack of marker horizons in harzburgite. Broad-scale folding of layers and foliations may account for some of the wide spread of poles in fig. 12*A*.

A beta axis approximated from the distribution of poles mean orientaions of subpopulaions of planar elements plunges northeast like the folds of group 2 (fig. 12*A*, *C*). This relation points to a broad-scale folding of peridotite during development of minor northeast-trending folds. This folding event does not appear to have affected some domains in which poles of layering and foliation are far from the broad northwest-southeast band of poles (fig. 12*A*) and was not strong enough to alter greatly the orientaions of early northwest-trending folds.

Mean attitudes of subpopulations of linear elements with generally east-west trends are shown in figure 12*D*. Scatter is great along a steep east-west great circle. In some areas, like area 1, mean attitudes of the subpopulations are very different and may be due to systematic differences in orientation between large and small folds, or, possibly, to heterogeneity of the deformation.

Subpopulations of steep linear elements occur in only seven of the areas (fig. 12*E*). Relative development of steep linear ele-

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FIGURE 12.—Fabric diagrams. Structural data plotted on lower hemisphere equal area projection. North indicated by short line pointing toward top of page; vertical indicated by cross in center of circle. *A*, Poles to mean orientations of subpopulations of layering and orthopyroxene foliation in harzburgite. Beta axis (square) of poles plunges 10° N. 48° E. *B*, Mean orientations of subpopulations of early northwest-trending linear elments. Dot labelled "A" is axis of 30° small circle. Axis trends N. 45° W. *C*, Mean orientations of subpopulations of northeast-trending linear elements. *D*, Mean orientations of subpopulations of west-trending linear elements. *E*, Mean orientation of subpopulations of steep linear elements.

ments varies from area to area in the peridotite. At some localities in area 1, steep folds may be a conjugate set at right angles to northeast-trending folds (B-B′ tectonite) and possibly formed contemporaneously with those folds. In area 12 steep elements comprise the dominant set and are not clearly related to any other group of elements. Possibly the steep linear elements include elements formed during more than one episode of deformation; the episodes need not correspond with episodes of northwest-, northeast- or west-trending folding.

Findings in this study generally accord with the analysis of the Vulcan Peak area (Loney and Himmelberg, 1976). In the subareas south of Vulcan Peak, however, late northeast- and west-trending folds, which are absent farther north, are well developed.

TYPES OF CHROMITE DEPOSITS

Most chromite deposits are in dunite, which is usually much serpentinized even if the primary and tectonic structures described above can still be recognized. Many of the large deposits are in serpentinite which has been intensely fractured (fig. 13) and in which few preserpentinization structures and textures are preserved. The associated serpentinite typically breaks into small angular to subrounded fragments with surfaces which are curved as well as plane. The chromite is black and coarse grained or is dark brown and very fine grained with angular fragments of black coarser grained chromite. Tension cracks and pull-apart structure, commonly at high angles to the long dimensions of the chromite pods, are filled with serpentinite and may be related to the late shearing deformation.

The primary occurrence of chromite in dunite sets the stage for development of sheared chromite-bearing serpentinite. Preferential serpentinization of dunite, as observed in outcrop, resulted in development of serpentinite, a relatively incompetent rock that typically responds to near surface strain by brittle fracture. Shearing of the serpentinite can result in dispersal of chromite concentraions and in shear-polished chromitite pods several tens of meters in length. Zones of serpentinized dunite would comprise incompetent zones in the peridotite which could control location and attitude of large fault zones (see also discussion in Wells and others, 1946, p. 14).

The Sunrise and Gilmore mines, located 3 km south of Gordon Mountain (pl. 1) contain a breccia of generally coarse-grained black chromite in a matrix of coarse-grained lightgreen diopside with numerous intergranular voids (fig. 14). The subrounded to angular fragments of chromite are cut by numerous thin diopside veins; some fragments appear pulled apart. The diopside could have been residual magma remaining from crystallization of part of the peridotite. The intensely fractured character of the chromite suggests that the clinopyroxenite magma was forcibly emplaced in a chromitite body.

Chromite occurs in partly mylonitized gabbro at the Judy mine on Low Plateau (pl. 1), as well as in dunite. Coarse-grained

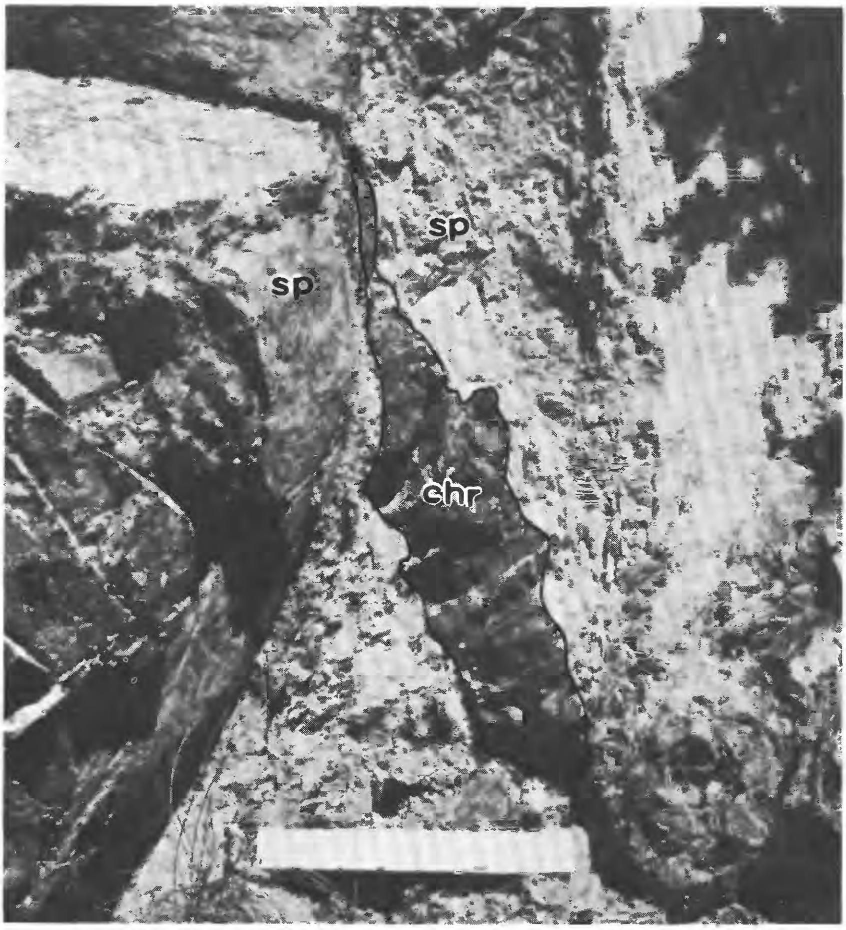

FIGURE 13.—Tabular pod of chromite in sheared and serpentinized peridotite. Pod has irregular contacts with sheared serpentine and has serpentine-filled fractures at high angles to the pod. Chromite in shear zones tends to be very fine grained, probably due to granulation. Chromite, chr; serpentinite, sp. Scale is 20 cm.

gabbro engulfed chromitiferous dunite; olivine was serpentinized; and chromite layers were folded and faulted (fig. 15). Localized mylonitization of the gabbro (not shown here) later resulted in further fragmentation of the chromite-rich xenoliths.

At the Bar Rick mine on Little Rattlesnake Mountain (pl. 1) chromitiferous dunite is granulated by shearing, but not intensely serpentinized. Original chromite structures are usually obscured by shearing and minor serpentinization at chromite-olivine interfaces. In places chromite net texture is faulted and olivine grains are flattened in a plane subparallel to minor faults (fig. 16). Age of granulation could be as old as Late Cretaceous, if shearing is related to tectonic emplacement of the peridotite, or younger than Cretaceous, if shearing is related to postemplacement faulting.

STRUCTURE OF CHROMITE DEPOSITS

Chromite in the Josephine Peridotite is widely scattered as an accesory mineral in harzburgite, dunite, and orthopyroxenite. Anomalous (>1 percent) concentrations of chromite are nearly all in dunite, or serpentinized dunite.

Chromite layering, folds, lineations, foliations, rods, and pods exhibit a wide range of orientations; minor folds of many

FIGURE 14.—Chromite (gray) breccia in matrix of coarse-grained pale-green diopside. Scale is 20 cm.

styles occur in dunite. Chromite occurs in rocks exhibiting primary textures, in tabular lenses, or in linear bodies elongate parallel to one or more fabric direction or the rock. In some outcrops primary textures and later deformation fabrics are both present. If the chromite deposits were ever originally part of a formerly continuous primary chromitiferous dunite zone in

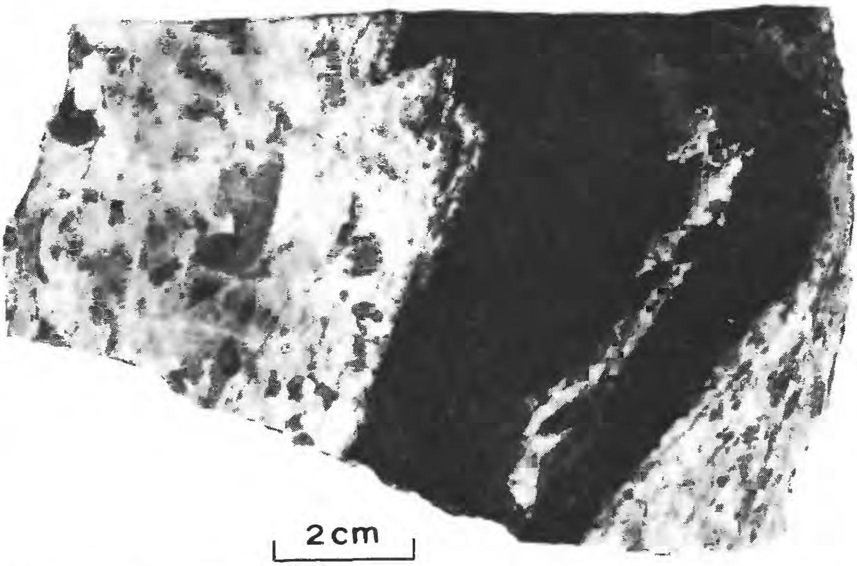

FIGURE 15—Gabbro with deformed (sheared and folded) bands of chromite (black). Dark-gray zones in and near chromite are green serpentine.

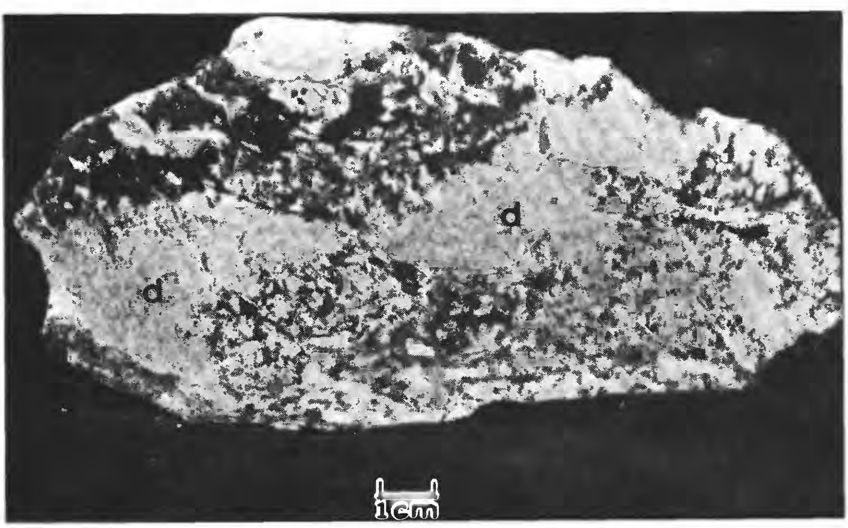

FIGURE 16.—Faulted dunite layer (d) in chromitiferous dunite.

the peridotite, deformation of this hypothetical zone has obliterated any clear evidence of its former continuity. No particular kind of structure is uniquely associated with the chromite deposits, and no ore zones were clearly indicated from the structural studies.

Little structural information is available to use in determining what structural elements are important in localizing chromite ore bodies in the peridotite. Ramp (1961, p. 10) concluded that chromite deposits in southwest Oregon are predominantly planar and are oriented subparallel to dunite-harzburgite contacts. By this hypothesis discovery of new deposits is likely to occur along the line of strike of the known deposits.

At the Judy mine, Low Plateau (pl. 1) elongaion of the chromite deposit appears to be parallel to the axis of a west-plunging folded chromite lens. On the surface both limbs of the fold pinch out within a few meters of the hinge. Extensions of ore along axes of folded chromite layers were described at the Kandak mine near Karabortlan, Turkey (Thayer, 1964, p. 1510, 1511), and in the Hindubagh area, Pakistan (Terry W. Offield, unpub. data). Such larger chromite folds, however, do not seem to be typical of the Josephine Peridotite.

At Low Divide the dunite dike contains several occurrences of chromite ore bodies, which are shown in figure 17 in a profile view of north-northeast- plunging axis of the intrusion. Irregular and flat-lying chromite-rich bodies occur one above another near the east side of the dike and outline a chromite zone which may be tabular. Knowledge of only one of the occurrences would not be of use in predicting the attitude of the ore zone. Greenbaum (1977, p. 1184) described a similar situation in a mine on Cyprus, where ore body elongation diverges from the attitude of the ore zone. Individual ore bodies trend northwest and north-northwest and plunge nearly vertically, but the ore zone as a whole trends N. 12° E. and plunges 55° S., close to a dunite-harzburgite contact. He suggests that the ore bodies are remnants of a once more extensive layer segmented by faulting. This conclusion is not clearly applicable to the Low Divide chromite occurrences.

Elongation of ore bodies parallel to a lineation, as in the Uzun Damar deposit, Turkey (Thayer, 1964, p. 1519), in some deposits in Maryland and Pennsylvania (Pearre and Heyl, 1960, p. 744–745), and in several deposits in New Caledonia (Cassard and others, 1981, p. 813–815), and Domokos, Greece (Thayer, 1963, p. 144), may occur locally in the Josephine Peridotite and may be of use as a prospecting concept. However, the Josephine Peridotite has several lineations, more than one of which are present in many outcrops, and no evidence indicates which of the lineations may control ore elongation or ore zones.

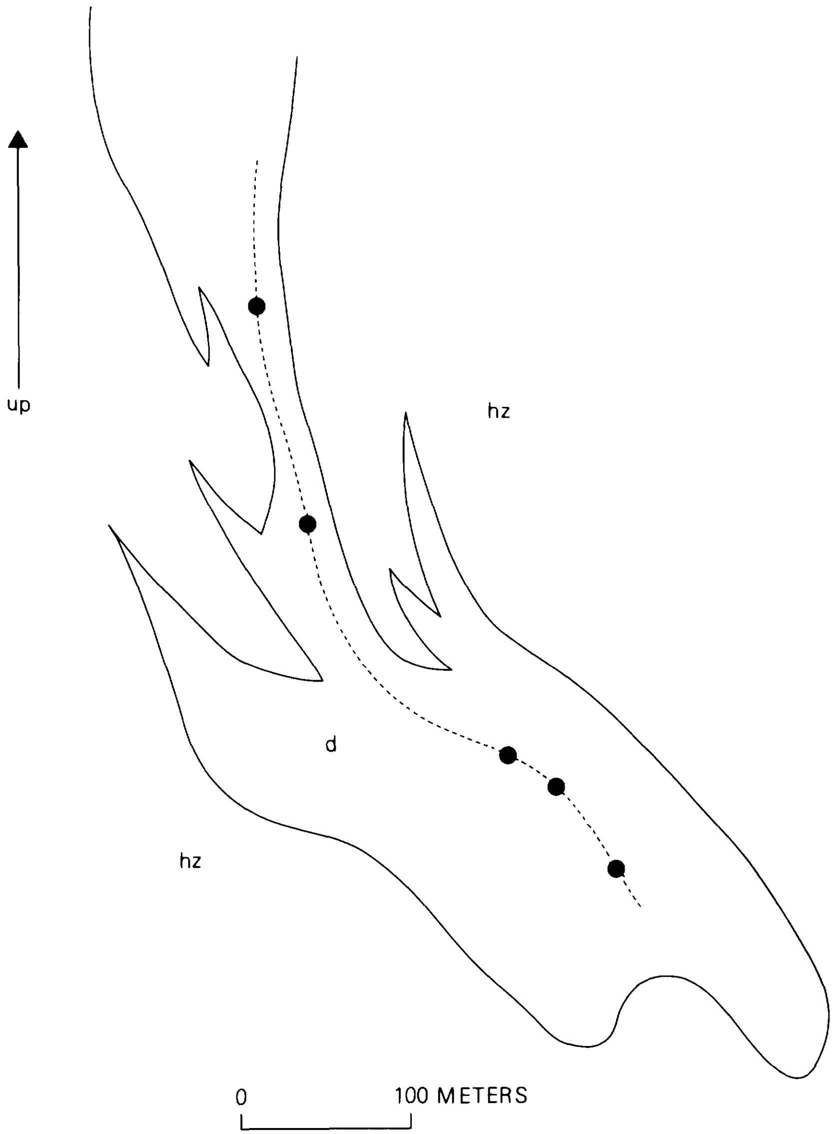

FIGURE 17.—View perpendicular to long axis of dunite intrusion at Low Divide, in direction N. 15° E., 20° NE. Plane of view dips 70° SSW. Large dots are projections of chromite ore bodies. Dotted line is trace of possible ore zone. Dunite, d; harzburgite, hz.

Structural analysis may be of limited use in chromite prospecting in the Josephine Peridotite, although its use in that regard was not clearly demonstrated in this study. Owing to the complex internal geometry of the peridotite, structural analysis should be confined to small areas, if it is to be useful.

On Low Plateau (pl. 1) the chromite mines and prospects seem to aline into two northeast-trending zones near the top of the northwest and southeast flanks of the mountain. These zones do not correlate well with any structural elements in the peridotite there, but do correspond to the zone of best exposure of the peridotite. Below the zone, the rocks are mostly covered by regolith and landslide deposits. Nevertheless, these relations coupled with the good exposures along Peridotite Canyon and along the cliffs on the northwest flank suggest that, over the whole mountain (relief of 2,000 ft), chromite deposits occur only in a 600-foot-thick zone near the top.

To examine the correlation of the mines and prospects with topographic elevation, the mines and prospects were plotted on cross section B-B′ (pl. 1) drawn from High Divide to Elk Camp. The chromite occurrences (mines and prospects) were projected onto the cross section from 3 to 5 km away. The occurrences are from 1,300 to 2,500 ft in elevation on the west end of the cross section and from 2,300 to 3,500 ft on the east. Considering the 3,000 ft of relief in the peridotite in the vicinity of cross section B-B′, the correspondence between elevation and chromite deposits is not as impressive as at Low Plateau. Lack of deposits near the bottoms of the deep canyons, such as North Fork Smith River, is consistent with the concept that the deposits occur in a flat-lying zone, but can also be explained by the generally poor exposures along the canyon walls due to thick regolith and landslide deposits. Elevations of the chromite deposits appear to decrease generally toward the core of the syncline mapped by Harper (1980b). If the mines and prospects can be said to occur in zones, however poorly defined, the zones have the gross appearance of dipping at low angles toward the trough of the syncline: on Little Rattlesnake Mountain, the dip is northeast; on south Gasquet Mountain, southeast; on upper Coon Mountain, southwest (pl. 1). According to this hypothesis, the chromite deposits occur within a flat-lying to synclinal zone as much as 1,200 ft thick. Deposits would not be found where the land surface is eroded below the zone either in the deep canyons or elsewhere in the harzburgite where the zone projects above the topographic surface.

Concentricity of the crudely defined chromite-bearing zone with the syncline mapped by Harper suggests that the chromite may somehow be related spatially to the overlying members of the Josephine ophiolite. Actually, stratigraphic distances between the deposits and the gabbro vary appreciably by an amount unknown because of faulting. Unless the chromitiferous dunite in the Josephine Peridotite is much older than the overlying members of the ophiolite, it is possible that the chromite precipitated from chromitiferous dunite magma in a particular range of pressure-temperature conditions located not far below the gabbro. These relations would imply a kind of stratigraphic control of the chromite deposits. Stratigraphic character of chromite deposits for other peridotites has been suggested (Flint and others, 1948, p. 56; Smith, 1953, p. 410–411; Stoll, 1958, p. 429; Greenbaum, 1972a, p. 39; Peters and Kramers, 1974, 1977, p. 1178; Dickey, 1975, fig. 1, Panayiotou, 1978, George, 1978, fig. 4; Cassard and others, 1981, p. 823–826).

Plate 2 is a map of the chromite-bearing zone which is assumed to be about 1,000 ft thick. Although most of the zone is shown as horizontal or gently dipping, in places dips greater than 20° (55° maximum) are suggested, and anticlines and synclines within the peridotite are inferred. The map shows the approximate outcrop pattern of the zone inferred and speculated from known deposits and projected into some areas in which no chromite deposits are known. This hypothetical outcrop pattern outlines areas having potential for chromite deposits. Peridotite below the chromite-bearing zone, having no potential for chromite deposits, comprises much of the Josephine Peridotite. Peridotite above the chromite-bearing zone also has no potential for chromite deposits, but deposits would be expected in the chromite-bearing zone beneath these rocks where it has not been removed by faulting. Chromite deposits may also occur in the chromite-bearing zone beneath the overlying rocks of the upper members of the ophiolite. No attempt was made to infer areas of possible subsurface chromite potential below units which overlie the peridotite.

Three large inferred folds of the chromite zone trend west and west-southwest and plunge east and west. They can be tentatively correlated with the west-trending group of minor folds which are nearly ubiquitous in the peridotite. A northeast-trending syncline is inferred in the Low Plateau-High Plateau area and may be related to northeast-trending minor folds in the peridotite. The major syncline, trending north-northwest and plunging southward, is coincident with the large fold of the Late Jurassic ophiolite and metasedementary rocks.

Plate 2, when compared with figure 1, suggests that the 13 study areas are in the chromite zone and (or) in peridotite not far below the zone. The Vulcan Peak area, studied by Loney and Himmelberg (1976), is partly in the chromite zone and in peridotite just above the zone.

The stratigraphic character of the chromite deposits implies that some of the deformation in the Josephine Peridotite, possibly including development of northeast-trending and later folds, occurred penecontemporaneously with development of the overlying ophiolite (See model of Greenbaum, 1972a, p. 125–130, 1972b.) If so, the existence of the cumulate ultramafic rocks between the gabbro and the harzburgite tectonite implies some kind of tectonic uncoupling between the two units. George (1978) has examined an ultramafic sequence on Cyprus that is more complete than the one in the western Klamath Mountains. He documented a gradation in tectonic intensity from undeformed cumulate ultramafic rock through ultramafic metacumulates to harzburgite tectonite. In the study area of plate 1, the rocks in this critical interval are sheared and serpentinized. However, it is possible that some of the poorly exposed rocks mapped as the Josephine Peridotite and lying above the chromite zone, such as in the Oregon Mountain area, are equivalent to the deformed ultramafic metacumulates recognized by George in Cyprus.

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Geology and Chromite in the Low Plateau Area, Del Norte County, California

By JOHN P. ALBERS

GEOLOGICAL AND GEOPHYSICAL STUDIES OF CHROMITE DEPOSITS IN THE JOSEPHINE PERIDOTITE, NORTHWESTERN CALIFORNIA AND SOUTHWESTERN OREGON

U.S. GEOLOGICAL SURVEY BULLETIN 1546-B

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GEOLOGY AND CHROMITE IN THE LOW PLATEAU AREA DEL NORTE COUNTY, CALIFORNIA

By JOHN P. ALBERS

INTRODUCTION

The Low Plateau area, in the central part of the Josephine Peridotite (fig. 1, pl. 1), is bounded by deep canyons—North Fork of Smith River on the west, Diamond Creek on the north, High Plateau Creek on the east, and Peridotite Canyon on the south. The southern part of Low Plateau contains at least 24 podiform chromite deposits and occurrences and is moderately well exposed. The best known and most productive deposits in the area are the Brown's (High Plateau), Bonanza, Judy, Bluebird, and Skyline. The Brown's deposit reportedly still contains a substantial amount of unmined chromite and therefore was selected for detailed geological and geophysical investigation.

About 2 mi^2 in the southern part of Low Plateau were mapped at a scale of 1:15,840 (pl. 3) on the U.S. Forest Service color aerial photographs in an attempt to determine whether the known chromite deposits are controlled by a stratigraphic and (or) structural pattern within the tectonite peridotite. In addition, J. G. Evans examined and measured in detail structural features in several specific localities within the Low Plateau area. His results are reported elsewhere in this volume.

LITHOLOGY

At least 95 percent of the Low Plateau area (pl. 3) is underlain by harzburgite. Dunite, and altered diorite and gabbro dikes that intrude the peridotite, underlie the remaining part of the area. The dunite and harzburgite are moderately to highly serpentinized. Modal analyses of 55 thin sections collected from throughout the area show that the percentage of serpentinization ranges from about 18 to 100 percent (fig. 18). The most highly serpentinized rocks are in the eastern part of the area, roughly east of the longitude of the bonanza mine (pl. 3), where the rocks have a light- to dark-gray coloration, in contrast to the dark yellowish orange and pale reddish brown of the less serpentinized rocks west of the Bonanza mine. Another area of highly serpentinized rock is elongate north-south and affects the ultramafic rocks that enclose the diorite dikes in the central part of the map area, and a third area is in the extreme southwestern part. Areas where rocks are more than 50 percent serpentinized, on the basis of thin-section examination, are shown on plate 3. The texture of the harzburgtite is xenoblastic granular. Orthopyroxene is present in amounts up to about 30 percent in the harzburgite. Commonly it ranges from 12 to 20 percent, in grains 2 to 4 mm long. Clinopyroxene is also present in some samples, mainly as exsolution lamallae in orthopyroxene. Olivine grains about 1 to 3 mm in maximum dimension interlock with the pyroxene. In the least serpentinized specimens olivine makes up about 65 percent of the rock. Black opaque minerals, most of which are magnetic, are present commonly in amounts of 3 to 5 percent. They occur mainly as irregularly shaped grains, many microscopic in size, that are commonly disseminated throughout the harzburgite but that may also be concentrated in small stringers or be localized around the edges of or within orthopyroxene crystals. The olivine in partially serpentinized harzburgite locally displays strain shadows, and kink band boundaries divide olivine grains into subgrains. Serpentine minerals typically exhibit mesh texture, but fibrous textures are common in the more highly serpentinized rocks. The various serpentine minerals were not identified. Accessory chromite is present in most harzburgite in quantities less than 1 percent. Minerals more rarely present include calcite, fuchsite, chlorite, pargasitic amphibole, sericite(?), and secondary iron oxide.

Dunite occurs sporadically throughout the ultramafic body as layers, dikes, and highly irregular bodies. Some dunite may form dikes, whereas other dunite bodies may represent complex fold hinges, as described by Evans (this volume). Some dunite-rich zones are as much as 50 m thick and a kilometer long (pl. 3), but most bodies are from less than a square meter to a few square meters in size.

Dunite shows about the same degree of serpentinization as harzburgite and involves about the same mineral content except for pyroxene, which is less than 5 percent in dunite. All the podiform chromite deposits are in dunite, and the only disseminated chromite in the Low Plateau area in amounts greater than 1 percent is also in dunite.

Dike rocks in the Low Plateau area are sparse and poorly exposed. However, the larger and more continuous dikes show up prominently on aerial photographs because they are marked by narrow belts of dense vegetation. Most conspicuous is a pair of apparently steep dipping north-trending dikes in the central part of the area (pl. 3), which although only a few meters thick, extend for approximately 1 km along strike. Thin sections show that hornblende in grains up to 1 mm in longest dimension makes up from 50 to 65 percent of the rock and plagioclase 12 to 17 percent. Alteration products are present in amounts up to 25 percent, and black opaques up to 4 percent.

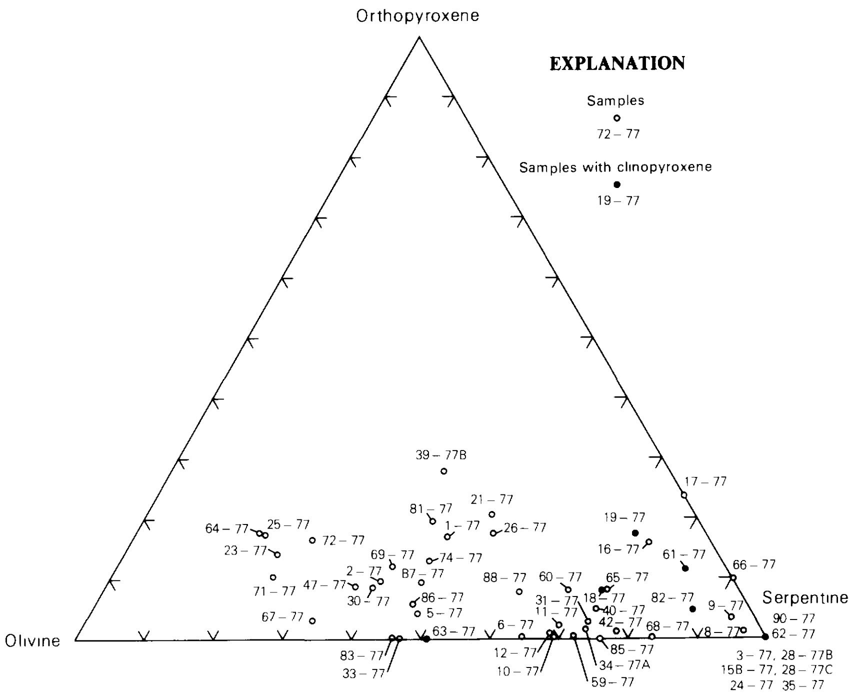


FIGURE 18.—Plot showing modal amounts of olivine, orthopyroxene, and serpentine in rocks of the Low Plateau area.

STRUCTURE

Although the bulk of the harzburgite in the Low Plateau area appears to be structureless, a prominent though discontinuous layering, formed by alternating orthopyroxene-rich layers and olivine-rich layers, is present in many localities. The orthpyroxene-rich layers are commonly 1 to 2 cm thick, but rarely they are as much as 10 cm thick (see fig. 5). Intervening dunite layers are generally a few centimeters thick but range up to about a third of a meter. Some dunite layers have chromite-rich zones or schlieren within them. These may be parallel to the contacts between olivine and pyroxene-rich layers or at a low angle to them. In most places the layering is discernible only in an individual outcrop, and nearby outcrops along stike are massive harzburgite. But in a few localities where dunite and harzburgite are interlayered over a substantial thickness of perhaps several meters, the layering can often be traced for several tens or hundreds of meters along strike. Although rarely observable in outcrop, the layering evidently ends very abruptly rather than gradually fading out. Also, the discrete layers nearly everywhere maintain a remarkable degree of parallelism and are rarely seen to merge. The abrupt endings strongly suggest that the layered material was pulled apart, perhaps while in a plastic condition, during a period of extensional deformation. It is tempting to consider the parallel interlayered olivine and orthopyroxene as remnants of original cumulate layered material in an otherwise completely tectonized and recrystallized protolith. On the other hand, Himmelberg and Loney (1973), in describing the peridotite of the Vulcan Peak area a few miles north of Low Plateau, interpreted concordant tabular bodies of dunite with anhedral chromite grains in harzburgite to have been probably derived by metamorphic differentiation of homogeneous harzburgite.

Himmelberg and Loney (1973) also recognize a second type of dunite with euhedral to subhedral chromite grains. This type of dunite forms irregular and discordant tabular bodies as well as concordant tabular bodies in harzburgite. This type of dunite is also common in the Low Plateau area. Himmelberg and Loney (1973) believe this second type of dunite may be fundamental to the petrogenesis of the peridotite. Evans (this volume) describes what he considers to be dunite dikes that cut across foliation and layering in harzburgite. These dikes are similar to the discordant dunite bodies described by Himmelberg and Loney (1973) and are common in the Low Plateau area. Because some of the dikes contain folded chromite layers or schlieren with fold axes correlated with three groups of open folds, Evans (this volume) believes the dikes must have been emplaced after early intense plastic deformation and before development of the open folds, or at least syntectonically with their development.

The strikes and dips plotted on the geologic map (pl. 3) represent the attitude of the various types of layering described above. It must be mentioned that, despite the relatively good outcrops, a persistent problem confronting the geologist in the Low Plateau area is deciding whether each given exposure is really in place or whether it is detached and moved. Because of the ubiquitous jointing and blocky nature of the peridotite, this problem exists on the relatively flat surface atop the plateau as well as on its steep flanks. Even though we followed a very cautious policy with regard to what we accepted as being in place, it is still possible that some of the layering attitudes on plate 3 were measured on rocks slightly out of place. However, the good continuity of structural trends in various parts of the map (pl. 3) gives confidence that the bulk of the measurements are truly representative of in situ bedrock.

In the general vicinity of Brown's mine and to the north and west, the attidudes show a surprisingly consistent north-northwest trend and gentle to moderate eastward dips. About a mile northwest of the mine this trend is truncated, apparently rather abruptly, by an east-northeast trend with moderate southward dips. The nature of the truncation is not clear. The outcrops give no indication of a fault, and no evidence of an ancient shear zone or other deformational feature was recognized. In the immediate vicinity of the Judy mine (pl. 3) east-northeast trends predominate, but dips are mostly toward the north at gentle to moderate angles. Southwest of the Judy mine the dips change again to the southeast and east. Much of the area south of the Judy mine is landslide disrupted, and the overall structural pattern in this area is unknown.

Open folds of mappable scale were seen in only two or three places. The clearest example is about three quarters of a mile S. 75° W. of Brown's mine (pl. 3), where a dunitic layer is folded into a gentle eastward-plunging syncline. Another open fold in well-layered dunite-harzburgite may be present about half a mile N. 75° W. of Brown's mine, as indicated by a rather abrupt change in strike from northwest to northeast in neighboring outcrops. However, this discordance is so abrupt that some alternative explanation is more likely. Outcrops, although good, are inadequate to permit resolution of the problem.

One objective of this study was to attempt to determine whether the distribution of podiform chromite bodies is controlled by structure in the peridotite. Locally, as at the Brown's and Judy deposits, the tabular faulted chromite body appears to be at least approximately concordant with recognizable structure. The tabular Brown's deposit seems to have trended nearly north and dipped east at a low angle. This would be about parallel to the fairly consistent layering shown by olivine and pyroxene in surface outcrops several tens of meters above the deposit (pl. 3, fig. 19). The chromite body at the Judy mine, on the other hand, appears to be elongate parallel to the axis of a west-plunging fold (see Evans, this volume). The chromite in all the other deposits in the Low Plateau area has been removed by mining, and possible local structural control of these deposits, if it existed, was not detected.

Overall distribution of the deposits on Low Plateau suggests two possible northeast alinements, one about parallel to the northwest edge of the plateau and the other mainly on or near the southeast flank. However, these "alinements" may be due to the present topographic configuration and thus have no structural or stratigraphic significance. They clearly cut across the structural grain as shown by the dunite-harzburgite layering, and if they do reflect a large-scale structural or stratigraphic control in the peridotite, it is not recognizable within the Low Plateau area. Consequently, detailed structural and stratigraphic studies within this area appear to be of little value in exploring for concealed chromite bodies; nevertheless, Evans (this volume), who based his analysis of the distribution of chromite deposits in the Josephine Peridotite as a whole, believes that there is an overall stratigraphic control of chromite in a zone beneath the cumulate rocks.

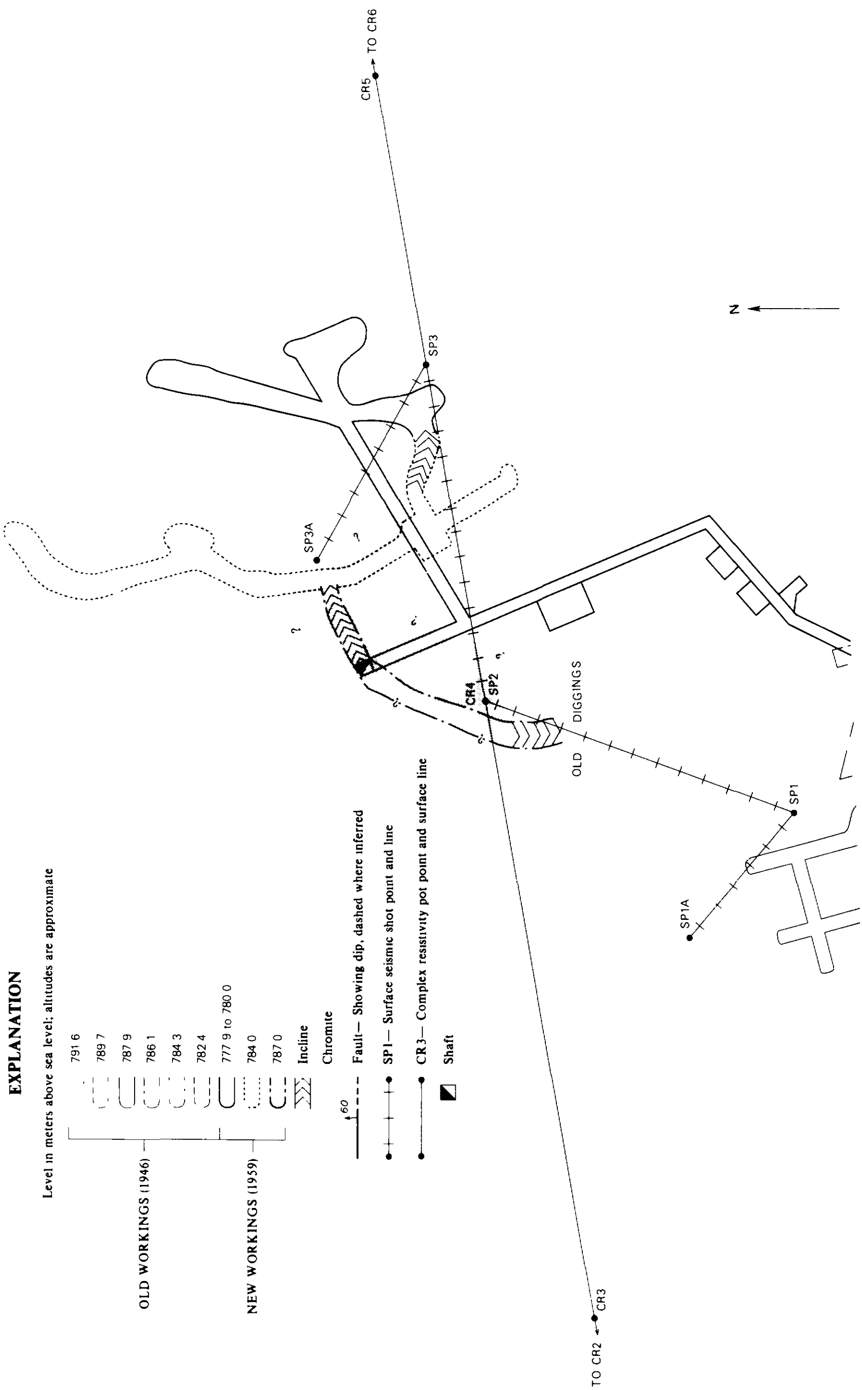
Harper (1980) also recognized this relationship noted by Evans in a large area of the peridotite. In Harper's area the distribution and internal structure of cumulates show that in gross aspect dips are very gentle and that the principal fold recognized is a broad and open syncline. Cumulate rocks occur only a short distance north and east of Low Plateau (see Vail, 1977), and it is certainly possible that the chromite-bearing rocks in the upper part of the plateau represent the same rather thin chromite-bearing stratigraphic zone recognized by Harper (1980) a few kilometers south. In theory, a nearly horizontal cover of cumulate rocks, now eroded away, would have been present perhaps only a few tens of meters above the present surface of erosion, a concept which would neatly fit Evan's (this volume) proposal of a flat-lying chromite zone on Low Plateau, but it would require a markedly conformable relationship between the cumulate rocks and the layering in the underlying tectonite peridotite (pl. 3), a layering which at least some chromite bodies (Brown's deposit) seem to parallel. In summary, marked structural discordance between cumulates and tectonites is apparent in virtually all well exposed unfaulted sequences that have been studied, and so it would be surprising if a concordant relationship exists in the Josephine Peridotite.

CHROMITE DEPOSITS

About 20 podiform chromite deposits have been worked on Low Plateau but probably fewer than half of these have had any production, and only at the Judy mine is any unmined chromite exposed. Most of the productive deposits were worked during World War II and were examined and described by the geologists of the U.S. Geological Survey (Wells and others, 1946); these include the Brown's (High Plateau), Bonanza, Judy, and Skyline deposits (pl. 3). A great deal of prospecting was done during the 1950's, and a few additional deposits were found. Some of these may have produced some chromite, but all one has to judge by is the size of the excavation and the few pieces of chromite that may be scattered around.

The largest production by far has come from the Brown's (High Plateau) ore body. Incomplete records indicate that Brown's deposit has produced between 20,000 and 25,000 short tons of massive high-grade ore, and the present owners, Mr. and Mrs. Eugene Elliott of O'Brien, Oregon, report (1977, oral commun.) that some ore still remains unmined in underground workings that were inaccessible in 1977. The location of this chromite is shown on the mine map (fig. 19).

According to Wells and others (1945), the High Plateau (Brown's) deposit consisted originally of a single continuous tabular body of pure, massive chromite, which has been broken by faulting into two or three separate bodies. The strike of the tabular bodies was a little west of north and the dip 10° to 15° east. This attitude is in general agreement with the attitude of the sporadic layering exhibited by the harzburgite with dunitic layers seen in nearby surficial outcrops. It also coincides approximately with what must be the general attitude of the remaining unmined chromite, based on the Elliotts' description and on the configuration of the underground workings (fig. 19). The amount of unmined chromite may be as much as 4,000 tons


EXPLANATION
Level in meters above sea level; altitudes are approximate
OLD WORKINGS (1946)
NEW WORKINGS (1959)
791 6
789 7
787 9
786 1
784 3
782 4
777 9 to 780 0
784 0
787 0
Incline
Chromite
60
Fault— Showing dip, dashed where inferred
SP1— Surface seismic shot point and line
CR3— Complex resistivity pot point and surface line
Shaft
N
CR5
TO CR6
SP3
SP3A
CR4
SP2
OLD DIGGINGS
SP1
SP1A
CR3
TO CR2

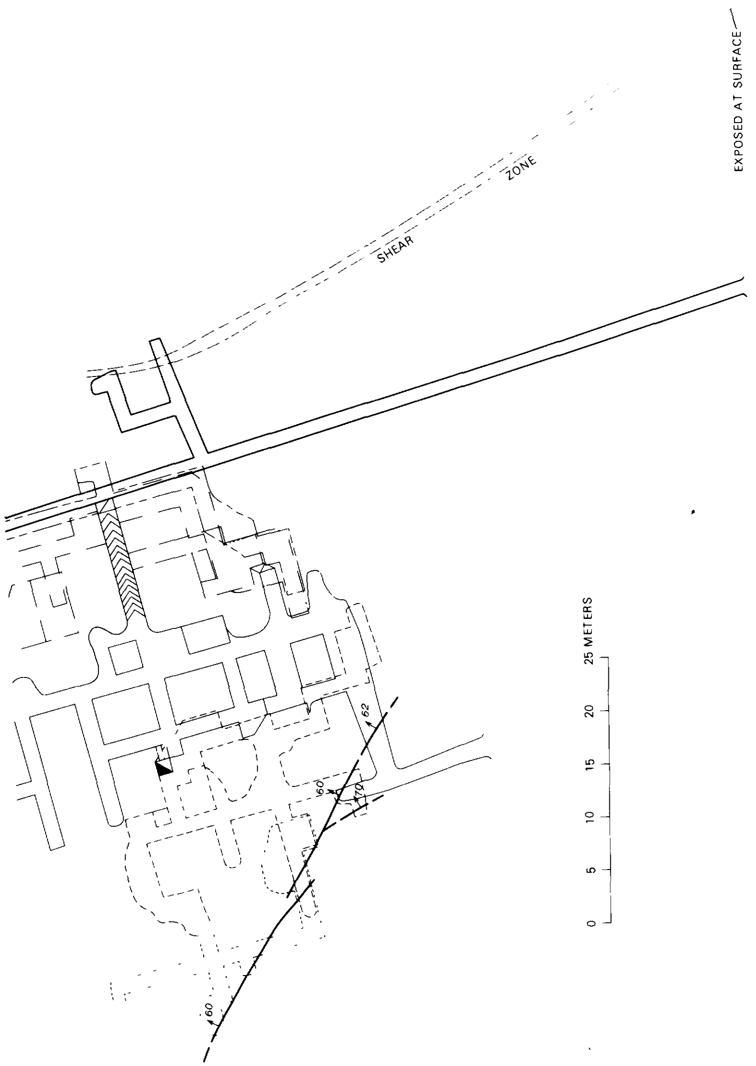


FIGURE 19.—Plan of Brown's mine, Del Norte County, California, showing approximate location of unmined chromite and position of geophysical traverse lines on the surface. Compiled by J. P. Albers from Wells and others (1946) and mine owner's maps (1959, incomplete).

TABLE 1.—*Semiquantitative six-step spectrographic analysis for 54 elements in chromites from Low Plateau and elsewhere in the Josephine Peridotite*

[Si, Al, Fe, Mg, Ca, and Ti are reported in percent, all others in parts per million (ppm). Results are to be identified with geometric brackets whose boundaries are 1.2, 0.83, 0.56, 0.38, 0.26, 0.18, 0.12, etc., but are reported arbitrarily as midpoints of these brackets: 1.0, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, etc. The precision of a reported value is approximately plus or minus one bracket at 68 percent, or two brackets at 95 percent confidence. Symbols used are: G, greater than 10 percent, or greater than value shown; L, level of detection too low to determine; --, not looked for. Elements looked for but not detected or at limit of detection included Ag, As, Au, B, Be, Bi, Cd, La, Mo, Nb, Pb, Pd, Pt, Sb, Sn, Sr, Te, U, W, Y, Zn, Zr, Na, K, P, Ge, Hf, In, Li, Re, Ta, Th, Tl, Pr, Nd, Sm, Eu. Analyst, L. A. Bradley, I. Samples D195040–D195052, D195061–D195062 are chromites from Low Plateau; samples D195053–D195060, D195063–D195064 are chromites from elsewhere in the Josephine Peridotite]

	Chromite ore											
Field sample	7–77	10–77	13–77	20–77	27–77	28–77	32–77	33–77	34–77	36–77	37–77	38–77
Lab No.	D195040	D195041	D195042	D195043	D195044	D195045	D195046	D195047	D195048	D195049	D195050	D195051
Fe	7.0	10.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	10.0	7.0	7.0
Mg	10.0	10.0	10.0	G	10.0	G	7.0	G	10.0	7.0	10.0	10.0
Ca	.05	.07	.05	.3	.02	.07	.007	.15	.07	.15	.015	.1
Ti	.07	.07	.05	.05	.03	.03	.07	.03	.07	.07	.05	.05
Mn	700	300	300	300	300	500	300	300	300	300	300	300
Ba	--	--	15	--	--	--	--	--	15	20	7	15
Co	200	200	200	150	150	200	300	200	200	200	150	150
Cr	G	G	G	G	G	G	G	G	G	G	G	G
Cu	5	3	2	1	5	7	3	30	7	7	7	7
Ni	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	3,000	1,500
Sc	10	10	70	15	7	7	10	15	7	10	7	7
V	1,000	700	700	700	300	300	700	1,500	700	1,000	700	1,500
Si	1.0	1.0	.3	1.5	7.0	5.0	1.5	1.0	3.0	1.5	3.0	1.5
Al	G	7.0	G	10.0	7.0	7.0	10.0	G	G	10.0	10.0	G
Ce	--	--	--	--	--	--	--	--	--	--	--	--
Ga	20	20	15	15	15	15	20	30	20	30	20	30
Yb	--	--	--	--	--	--	--	--	--	--	--	--

Chromite ore—Continued											Spinel crystal	Chromite ore
41–77 D195052	43–77 D195053	44–77 D195054	51–77 D195055 East	51–77 D195056 West	52–77 D195057	53–77 D195058	54–77 D195059	55–77 D195060	56–77 D195061	57–77 D195062	58–77 D195063	DN-8-76 D195064
7.0	7.0	7.0	10.0	10.0	10.0	10.0	7.0	G	10.0	10.0	G	7.0
10.0	G	10.0	10.0	10.0	10.0	10.0	10.0	7.0	7.0	7.0	7.0	G
.01	.02	.05	.3	.3	.01	.01	.03	.5	.15	.07	L	.02
.05	.07	.1	.15	.15	.07	.05	.07	.3	.07	.07	.15	.03
500	300	300	700	300	500	500	700	700	300	300	5,000	300
10	10	--	--	--	15	--	15	--	15	7	L	--
150	150	150	200	200	150	150	200	150	150	150	50	100
G	G	G	G	G	G	G	G	G	G	G	2,000	G
7	3	5	3	7	7	5	15	200	3	3	1.5	7
1,000	1,000	2,000	1,000	1,500	1,500	1,000	1,500	700	1,500	1,500	500	2,000
5	10	10	15	15	15	7	15	30	7	7	L	7
1,000	1,000	1,000	700	1,500	700	1,500	1,500	1,500	1,000	1,000	150	700
2.0	1.0	1.5	3.0	1.0	3.0	1.0	3.0	10.0	1.5	.3	.03	7.0
10.0	G	G	7.0	G	7.0	G	7.0	7.0	7.0	G	.15	7.0
--	--	--	--	--	--	--	--	--	--	--	--	--
30	30	30	20	30	15	30	30	30	20	30	--	15
--	--	--	--	--	--	--	--	--	--	--	--	--

in a tabular body 1 to 1.5 m thick and 40 to 45 m beneath the surface. In the absence of any known podiform chromite deposit of this size in the United States, the Brown's deposit was one of those selected for the geophysical investigations reported elsewhere in this volume by Wynn and Hasbrouck.

Although the chromite at Brown's mine is not visible in situ, abundant float is present along a trail below the mine. The texture of different specimens varies, but nearly all appears to contain more than 90 percent chromite, with very little serpentine or other minerals. Uvarovite and kammererite are common along fractures in some specimens of the ore but appear to make up an insignificant part of its bulk. Wells and others (1945) report that the chromite in the deposit is nearly pure, assays 50 to 55 percent Cr_2O_3, and has a chrome-iron ratio ranging from 2.94 to 3.74.

According to information in Wells and others (1945) the Judy, Bonanza, Bluebird, and Skyline deposits together had produced a total of about 600 tons of chromite by sometime in 1943. The Cr_2O_3 content ranged from 41.83 to 50.55 percent, and chrome-iron ratios were from 2.55 to 3.52 in these deposits. During the present work we have not had any ore samples chemically analyzed for major elements.

A total of 18 samples of chromite float collected from the various deposits on Low Plateau were analyzed by the semiquantitative six-step spectrographic method. None of the 54 elements looked for are present in abnormally high amounts (table 1). Additionally, the 18 samples were analyzed for platinum group metals by Joseph Haffty and A. W. Haubert. The results are given in table 2. It is noteworthy that five chromite samples (pl. 3, locs. 10-77, 20-77, 32-77, 33-77, 52-77), including one from the Judy mine, are anomalously high in ruthenium. The Judy sample is also high in platinum, rhodium, ad iridium, and an unnamed deposit about a mile northeast of the Judy mine (pl. 3, loc. 52-77) stands out as being unusually high in platinum, rhodium, iridium, and ruthenium. Three of the five samples are close to the northwest edge of Low Plateau above the North Fork of the Smith River. In addition to the 18 samples from Low Plateau deposits, 7 samples from other chromite deposits elsewhere in the Josephine Peridotite are included in tables 1 and 2.

TABLE 2.—*Analyses of chromites for platinum-group metals from Low Plateau and elsewhere in the Josephine Peridotite*

[Tr, trace. Varying limits of determination for Pd, Pt, and Rh are due to the dilution factor. Method used to determine Pd, Pt, and Rh from Haffty and Haubert (1968)]

Lab No.	Field sample	Pd (ppm)	Pt (ppm)	Rh (ppm)	Ir (ppm)	Ru (ppm)	Deposit
D195040	7-77	<0.004	<0.010	0.008	0.044	0.11	
D195041	10-77	Tr	.047	.027	.14	.28	
D195042	13-77	.006	<.010	.011	.042	.12	
D195043	20-77	<.004	.015	.018	.14	.33	
D195044	27-77	.012	.038	.007	.044	.12	
D195045	28-77	<.004	<.010	.015	.066	.19	
D195046	32-77	<.004	<.010	.015	.11	.27	
D195047	33-77	.010	.059	.039	.25	.41	Judy
D195048	34-77	<.004	<.010	.011	.061	.18	
D195049	36-77	<.004	<.010	Tr	.052	.17	
D195050	37-77	<.009	<.022	Tr	.052	.15	
D195051	38-77	.006	.011	.014	.073	.22	
D195052	41-77	Tr	<.010	Tr	<.030	<.10	
D195053	43-77	<.008	<.020	.021	.091	.27	Bar Rick
D195054	44-77	Tr	<.020	.008	.040	<.10	Buckskin
D195055	51-77 (East)	.018	.012	Tr	.040	<.10	Tyson
D195056	51-77 (West)	Tr	.010	.018	.052	.18	Tyson
D195057	52-77	Tr	.076	.061	.85	1.40	
D195058	53-77	Tr	<.010	.006	.056	.18	
D195059	54-77	<.004	.016	Tr	.040	<.10	Tangerine
D195060	55-77	.007	.011	Tr	<.030	<.10	Last Drink
D195061	56-77	<.008	.014	.010	.056	.15	Brown's
D195062	57-77	<.004	<.010	.011	.054	.18	Brown's
D195063	58-77	<.004	<.010	<.005	<.030	<.10	"magnetite"
D195064	DN-8-76	Tr	<.020	.006	.046	.13	Mountain View

CONCLUSIONS

Although podiform chromite deposits were once relatively abundant in Low Plateau, those discoveries are nearly all mined out, and the detailed stratigraphic and structural relations of most deposits to the enclosing rocks can only be vaguely inferred. Nevertheless, it appears that the large tabular body forming the Brown's deposit lies in gross concordance with a possible primary layering that is visible sporadically in the enclosing harzburgite. However, this intepretation cannot be verified directly, owing to lack of chromite surface exposures and the inaccessibility of underground workings. Thayer (1969) has suggested that the podiform chromites formed as layers by gravitational differentiation of magma in the upper part of the mantle in supercomplexes analogous to those known to have produced stratiform type chromite. Perhaps the tabular body at Brown's mine is a remnant of a once more continuous sheet formed in this manner and was pulled apart by subsequent extensional deformation. If so, the trend of layering in the surrounding harzburgite might be a clue to the likely target areas for additional detached remnants of such a sheet, but the absence of recognizable internal stratigraphy in the harzburgite and the sporadic distribution of layered material frustrates any attempt to follow for significant distances what might be favorable stratigraphic-structural zones. Therefore, it must be concluded that in the Low Plateau area stratigraphic and structural studies are of limited use in identifying target areas for concealed podiform chromite.

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A Magnetic Interpretation of the Josephine Peridotite, Del Norte County, California

By ANDREW GRISCOM

GEOLOGICAL AND GEOPHYSICAL STUDIES OF CHROMITE DEPOSITS IN THE JOSEPHINE PERIDOTITE, NORTHWESTERN CALIFORNIA AND SOUTHWESTERN OREGON

U.S. GEOLOGICAL SURVEY BULLETIN 1546-C

CONTENTS

A MAGNETIC INTERPRETATION OF THE JOSEPHINE PERIDOTITE, DEL NORTE COUNTY, CALIFORNIA

By Andrew Griscom

MAGNETIC DATA AND INTERPRETATION

An aeromagnetic survey (pl. 4) of the area in northwestern California underlain predominantly by the Josephine Peridotite was performed in 1977 and mapped (pl. 5) at a scale of 1:62,500. The purpose of this survey was to study the relationship between the local chromite deposits and the aeromagnetic data. Flight traverses were oriented east-west at a spacing of 0.8 km (0.5 mi) and at an altitude of 1,200 m (3,800 ft) above sea level, except where necessary to clear higher ridges. Contour intervals of the map are 25 and 100 gammas, depending upon the steepness of local gradients in the Earth's magnetic field. An average regional field of 53,038 gammas plus a regional trend of 4.72 gammas/km north and 2.78 gammas/km east were removed from the data before contouring, on the basis of the International Geomagnetic Reference Field (IGRF) 1975.

The local topographic relief for much of this area is substantial, ranging from 500 to 1,000 m. Valleys are generally narrow and steep sided. Because the near-surface rocks are highly magnetic, there is a correlation of topography with magnetic anomalies, magnetic lows tending to be associated with valleys. This correlation complicates the anomaly patterns and partly obscures the features caused by variations in magnetic properties between adjacent rock units. Continuously recorded radar altimeter data are available for most flight lines, but the data indicate the heights above ground only where the distance is less than 500 m.

Certain problems are evident with the contoured aeromagnetic map. A significant difficulty is the presence of certain highs and lows with steep sides and flat tops or bottoms. Inspection of the original analog data records on traverses crossing such anomalies has shown that the form of these anomalies is more rounded than that depicted on the contour map. Apparently the process of computer contouring these data has distorted the form of the anomalies, although their location and shapes outside the flat regions are approximately correct. Another effect of the computer countouring is the elimination of certain magnetic features from the contoured data where the wavelength of the feature is shorter than the grid spacing.

The magnetic anomalies and patterns on the magnetic map are caused not only by topography composed of magnetic rocks but also by variations in the amounts of magnetic minerals, commonly magnetite, in the various rock units. Many of the anomalies are therefore closely related to geologic features. The source of most magnetic anomalies on the map appears to be ultramafic rocks, all serpentinized to a varying degree.

The aeromagnetic interpretation map (pl. 5) was compiled from the aeromagnetic map with very little reference to any geologic data. At these latitudes, the inclination of the Earth's magnetic field (65°) is sufficiently steep so that boundaries between magnetic and relatively nonmagnetic rock units are in general located on the flanks of the magnetic anomaly, approximately at the steepest gradient. The interpretation map contains many such interpreted boundaries drawn around characteristic magnetic anomalies. As a constraint upon the interpreted locations of the magnetic boundaries, a series of magnetic profiles were calculated from models representing geologic cross sections through the map area. These models also take into account the magnetic effects of topography and geologic structure and are discussed in greater detail in a subsequent section.

A truck-mounted magnetometer was driven along most roads crossing the map area. These continuously recorded magnetic data change abruptly from a very jagged to a very smooth profile over boundaries between magnetic and nonmagnetic rocks. A total of 12 such boundaries are indicated on the interpretation map (pl. 5) and serve as additional constraints upon the interpretation.

No rock samples were collected for the investigation of magnetic properties. Unpublished data of the author on ultramafic rocks from other areas in California has shown that these properties in ultramafic rocks commonly vary at least by a factor of 10 even in the same outcrop. The data of the truck-mounted magnetometer confirm this observation here as well. The profiles indicate hundreds of magnetic anomalies with wavelengths of 100–200 m and with amplitudes of 100–3,000 δ or more. To sample adequately such diverse magnetic properties would be difficult and time consuming, even if adequate outcrops were available. The model calculations on the aeromagnetic map provide average magnetic properties far more easily.

GENERAL GEOLOGY AND MAGNETIC EXPRESSION OF ROCK UNITS

The details of the geology are discussed by Evans in this volume but some general tectonic and lithologic data that relate to the aeromagnetic interpretation are described here. Three broad generalized belts of rocks extend from north to south across the area of the magnetic map: (1) a western belt of weakly metamorphosed nonmagnetic sedimentary rocks of Late Jurassic and Cretaceous age, mostly graywacke and shale, correlative with the Franciscan Complex in California and the Dothan Formation in Oregon; (2) a broad central belt of magnetic ultramafic and mafic rocks collectively termed by Harper (1980b) the Josephine ophiolite, of Late Jurassic age; this rock assemblage is complexly faulted and folded particularly in the south-central part of the map area, and the entire ophiolite together with its overlying rocks were thrust over the rocks of the western belt; and (3) conformably overlying the ophiolite, an eastern belt of weakly metamorphosed nonmagnetic sedimentary rocks, interbedded black slate and graywacke of the Upper Jurassic Rogue and Galice Formations, deformed by numerous faults and folds that locally have brought the underlying ophiolite to the surface. A Jurassic ultramafic intrusion(?) of wehrlite cuts the Galice Formation at the south center of the map, and various small intrusions of hornblende diorite and quartz porphyry occur elsewhere cutting the Josephine ophiolite.

The Josephine ophiolite of Harper (1980b) contains the following sequence of units from bottom to top: (1) Harzburgite tectonite with subordinate dunite; (2) cumulate ultramafic rocks; (3) gabbro; (4) sheeted diabase dike complex; and (5) pillowed basalt flows. Of these rocks only units (1) and, in some places, (2) appear to display significant magnetic anomalies, whereas units (3) through (5) are at most only weakly magnetic.

The most important magnetic mineral in serpentinites is generally magnetite which has formed during the serpentinization of the olivine and pyroxene in tectonite and cumulate ultramafic rocks. Most of the cumulate rocks do not display magnetic anomalies and may not contain large amounts of serpentine. Accordingly, for the purpose of the generalized geologic map of plate 5, the weakly magnetic units (3) through (5) have been combined under the heading, mafic igneous rocks, while units (1) and (2) are retained. A small area of hornblendite within the Josephine Peridotite at the north border of the map appears to be nonmagnetic and is therefore indicated on plate 5.

CALCULATED MODELS

In order to obtain a better understanding of the aeromagnetic map, a series of three models (I, II, III) were calculated across the Josephine ophiolite and one more model (T-T′) (pl. 5) was calculated as part of an investigation of topographic effects. The observed magnetic data for the profiles were taken both from the original records of the data and from the contoured magnetic map (pl. 4). No geologic constraints were imposed on the models; contacts were located at the best positions to satisfy the geophysical data. The direction of magnetization in the models is assumed to be appropriate for induced magnetization, that is, parallel to the present magnetic field of the earth. This assumption has been found on the basis of physical properties measurements to be approximately correct for serpentinized ultramafic rocks elsewhere in northern California (Griscom, unpub. data). The thickness of the magnetic rocks is rather uncertain; the models show a minimum thickness of about 2 km, as illustrated, but locally could be as thick as 4 km. The calculations are not especially sensitive to variations in the form of the bottom of the magnetic rock masses, and a horizontal surface is used, although both faulting and folding of this boundary unquestionably occur. The magnetic model calculations assume that the models are two dimensional, which means that all contacts and topography, as well as the form of the observed magnetic field, extend identically to infinity normal to the plane of the model. In other words it is assumed that a similar parallel model located 1 or 2 km to the north or south of the calculated one would be identical in all respects. This assumption is clearly not correct in general, but it is approximately correct for certain critical portions of these models; the problem will be evaluated more carefully in the specific discussion of each profile. Computed and observed magnetic profiles are matched together with respect to shape and without regard for datum differences, the map datum being rather arbitrary.

TOPOGRAPHIC MODEL T-T′

Model T-T′ (pl. 5) examines the problem of whether the magnetic anomalies are caused by the topography. The model uses the original analog data of flightline 20 and not the data of the magnetic contour map. The data indicate a major magnetic high, flanked by two lows; these features are associated with a major topographic high flanked in turn by two topographic lows. The magnetic and topographic features in the central part of the profile strike approximately north-south for sufficient distances normal to the model that the two-dimensional condition is approximately met. The condition is not adequately met at the two ends of the model. The results indicate that even though the magnetic profile and the topography appear to correlate with each cother, the form of the topography is not the major cause for the variations in the aeromagnetic profile. The magnetization in profile T- T′ (pl. 5) is set at 2.1×10^{-3}emu/cm^3 to give reasonable calculated values of the magnetic field along the entire profile and hence fails to match the amplitude of the large central magnetic high. If the magnetization is increased to about 5x10^{-3}emu/cm^3, then the observed central anomaly will indeed match the calculated anomaly but the adjacent computed anomaly at 10 km will then have an amplitude of over 1,000 gammas, thus causing a considerable mismatch. It is concluded that there are major lateral variations in the magnetic properties of the rocks along the model in order to cause the observed magnetic field.

PROFILE I

Profile I (pl. 5) extends across the northern part of the map area and for the west end uses a portion of the original recorded data of flight line 34 projected parallel to strike onto profile I. The remainder of the magnetic data of profile I are taken from the aeromagnetic map (pl. 4). The condition that the data be two dimensional is approximately met except at the east end of the profile east of 15 km, where the location of contacts at the surface is approximately correct but the calculated dips and magnetizations are not especially accurate. The agreement between the computed and observed anomalies at 6 km is not good, but the calculation and model indicate that the west contact of the Josephine ophiolite dips east at about 45°. The magnetic low at 11 km is modeled by assuming the presence of a large mass of nonmagnetic rocks about 1 km thick. Evidence for the presence of these nonmagnetic rocks was obtained on the truck-mounted magnetometer travese across this same magnetic low about 1 km to the north of the profile and is plotted on plate 5. It is possible that these nonmagnetic rocks may actually represent upfolded rocks below the ophiolite because the magnetic low strikes north into an antiformal area where the nonmagnetic Dothan Formation is exposed at the north border of the map area (pls. 4 and 5). The east contact of the ophiolite at 18 km is a steep boundary, presumably a fault. The discrepancy between this calculated east boundary and that shown on the geologic map in the same general area (pl. 5) will be discussed later.

PROFILE II

Profile II (pl. 5) extends across the central portion of the map and, because of discrepancies between observed data and the contour map at the west end, uses a portion of the original recorded data of flight line 25 projected parallel to the strike of the geology onto profile II. The remainder of the magnetic data of profile II are taken from the aeromagnetic map (pl. 4). Between 8 km and 12 km the data are not two dimensional, and so here the details of the model are not reliable but only generally correct. Profile II presents a similar geometry to that of profile I. The west contact of the ophiolite dips east at relatively low angles, and a magnetic low (not the same low as that of profile I) is interpreted as caused by a relatively thin mass of nonmagnetic rocks overlying the magnetic ultramafic rocks of the ophiolite. The strongly magnetic block of rock located between 13 and 15 km has boundaries that dip vertically and presumably represent normal faults.

PROFILE III

Profile III (pl. 5) extends east-west across the south portion of the map and uses the original data of flight line 9 projected onto the profile. The profile is composed of two separate segments chosen to cross the topography and the geologic map in such a way as to fulfill approximately the condition of two dimensionality. Along profile III (pl. 5) this condiiton is not very well satisfied by the magnetic low at 17 km, where the small mass of nonmagnetic rocks shown on the model is probably thinner than would result from a more sophisticated calculation. Again, the west contact of the ophiolite dips east at a relatively low angle. Overlying the magnetic rocks are flat-lying masses of nonmagnetic rocks located between 4 and 13 km; these nonmagnetic rocks are the mafic upper portion of the ophiolite. At 9 km a small mass of exposed magnetic rocks corresponds with the upfaulted sliver of basal ultramafic rocks shown on the geologic map (pl. 5). At the east end of the profile between 16 and 23 km most of the magnetic rocks are overlain by both nonmagnetic and relatively less magnetic (1.8×10^{-3}emu/cm^3) rocks. Perhaps these rocks represent the ultramafic cumulates or the lower portion of the gabbro layer.

SUMMARY OF PROFILE RESULTS

Some general conclusions can be drawn from the analyses of the profiles.

1. Topographic effects, although important, are not the major source of the magnetic anomalies.
2. The west contact of the Josephine ophiolite dips east at angles less than 45°, consistent with the idea that the contact is a thrust fault.
3. Modeling studies indicate that the form of the ophiolite is that of a flat-lying sheet, the peridotite tectonite portion being generally at least 2 km thick, but probably in general not thicker than 4 km.
4. The east contact of the ophiolite where modeled is steeper than the west contact and probably is faulted south of lat 41°51′ N. and north of lat 41°56′ N., judging from the continuously steep linear magnetic gradients along the east contacts in these areas. The structure of the east contact is more complex elsewhere, on the basis of the more complex associated magnetic patterns.
5. Internal magnetic boundaries within the magnetic rocks of the ophiolite are generally rather steep, suggesting that the complex structures mapped by Harper (1980a, 1980b) in the south portion of the area probably continue throughout the rest of the ophiolite to the north.
6. The models indicate that various major magnetic lows within the area of the ultramafic rocks are probably the result of associated nonmagnetic rocks at the surface. These nonmagnetic rocks extend down only to relatively modest depths of less than 1 km. One magnetic low on profile I at the north border of the map may be caused by nonmagnetic rocks from below the ophiolite, which is very thin here because of antiformal folding and erosion.

7. The modeling results of profile III confirm the geologic interpretation that the ultramafic rocks continuously underlie at shallow depth the exposed upper mafic rocks of the ophiolite as mapped by Harper.

DISCUSSION OF INTERPRETIVE MAP

By using the computed models of profiles I, II and III as a guide, an interpretive map (pl. 5) was prepared from the aeromagnetic map (pl. 4). This interpretive map accepts the magnetic boundaries from the profiles and extends them laterally in plan along the steepest magnetic gradients, where such boundaries are ordinarily located at these magnetic latitudes. The various magnetizations calculated from the models are plotted along each profile (pl. 5) and have been arbitrarily divided into the three general classes listed in the table below. The numbers in parentheses represent the magnetizations of material at depth below the nonmagnetic material (magnetization of 0.0) at the surface.

Calculated magnetizations of rock units in profiles I, II, and III

Class	Range of magnetization (emu/cm^3)	Definition
A	0	Weakly magnetic.
B	$0.9–2.3 \times 10^{-3}$	Moderately magnetic.
C	$3.0–5.0 \times 10^{-3}$	Strongly magnetic.

These classes are used as labels for the three different magnetic units outlined by the magnetic interpretation map. Comparison between the outer boundaries of the magnetic units and the geologic contacts of the Josephine Peridotite indicates good general agreement, although the magnetic boundaries lack detail and may commonly be displaced by as much as 0.5 km from the geologic contacts. Reasons for these discrepancies include: The 1-km flightline spacing of the aeromagnetic map, computer contouring problems with the data, minor location error of the aircraft, and the generally qualitative nature of the magnetic interpretation. Some local discrepancies are, however, so severe that they generate questions with regard to the local accuracy of the geologic mapping. An example is the east contact of the peridotite north of lat 41°53′ N., in particular where crossed by profile I. The discrepancy here between the magnetic interpretation and the geologic contact is about 1 km. It seems unlikely that either the magnetic interpretation or the magnetic map could be in error by such a large amount.

Comparisons between the interpretive map and the geologic map in the southern portion of the area provide information concerning the magnetic properties of the various units of the Josephine ophiolite. In the south the only magnetic rocks (magnetic units B and C) are the ultramafic tectonite of the Josephine Peridotite and, to a lesser extent, the ultramafic cumulates. The mafic components of the ophiolite (gabbro, sheeted dikes, and pillowed basalt flows) do not appear to generate any magnetic anomalies and therefore are members of class A (weakly magnetic rocks). The above observations on physical properties of rock units can be applied to the remaining area of the interpretive map. Units B and C are considered to represent ultramafic tectonite for the most part and possibly small amounts of ultramafic cumulate. Unit A, however, is probably not ultramafic tectonite (unless there are zones of low serpentinization) and may be in part weakly magnetic ultramafic cumulate or even one of the mafic components of the ophiolite, assuming that the unit is not composed of sedimentary rocks inadvertently missed during the mapping.

Certain linear boundaries associated with steep magnetic gradients are interpreted to be faults. The interpretive map (pl. 5) shows two north-south faults on the east side of the ultramafic rocks and two minor east-west faults interrupting the west boundary. These latter two faults do not correspond to mapped faults on the geologic map and may be artifacts of the geophysical data, perhaps caused by the contouring program. A series of major northeast-trending faults are also interpreted from the aeromagnetic data and, although not all of these interpreted faults correspond to faults on the geologic map, there is good evidence of many northeast-trending faults on the geologic map.

The curvilinear boundaries between magnetic units A, B, and C deserve explanation in terms of the known geology. Although some of these boundaries are steeply dipping, their general lack of sustained linear extent suggests that they are not major faults. There are at least two other possible explanations for these forms. (1) The boundaries represent changes in the degree of serpentinization of the Josephine Peridotite, because it is the serpentinization process that has made these rocks magnetic in the first place (olivine or orthopyroxene plus water altered to serpentine plus brucite plus magnetite). The irregular patterns then represent the irregular distribution and degree of serpentinization. (2) The boundaries define original compositional differences, possibly crude layering, in the ophiolite (this hypothesis is not supported by the geologic mapping). Magnetic unit A has already been interpreted in this fashion as possibly being part of the mafic rocks of the ophiolite sequence. The writer believes that both explanations are probably correct here. Units A and B tend to be associated with topographic lows, whereas unit C tends to be associated with topographic highs, particularly the high-level erosion surfaces of Pine Flat Mountain, High Plateau, Low Plateau, Elk Camp Ridge, and Upper Coon and Gordon Mountains. These topographic differences suggest that significant lithologic differences may well exist between unit C and unit B. The general north-south trend or "grain" of the magnetic patterns parallel to regional structure might be caused by either explanation but the writer believes that explanation (2) is the more likely cause of these trends and that the magnetic units generally represent some primary lithologic differences rather than later variations in degree of alteration. This latter explanation is also consistent with the diagonal interruption of magnetic units B and C by the western border fault at the north portion of the map area; in other words the primary stratigraphy of the ophiolite is older than the thrust faulting.

The structure of the east contact of the ophiolite is a major tectonic problem in this area. The main question is whether the ophiolite is an east-dipping thrust sheet or is an isolated klippe. The calculated profiles T-T′ and II (pl. 5) do not clearly answer the question because the steep faults and large magnetic highs on the east side of the ophiolite may obscure the presence of a possible east-dipping extension of the body at depth. The eastern magnetic high is very small, however, at two places near the center of the map, and so here there may be no east-dipping continuation at depth. In conclusion, the calculated profiles and the magnetic map are consistent with the interpretation that the ophiolite is an isolated klippe, but the data do not completely exclude the possibility that there may instead be an east-dipping extension of the ophiolite in the subsurface.

ECONOMIC IMPLICATIONS

The prior discussion of possible causes for the various magnetic units has direct application to the use of the magnetic data as a guide to chromite deposits in this area. Individual chromite mines and prospects are plotted on plate 5. The relationship between the deposit locations and the magnetic map is not clear, but the data from the southeast corner and profile III suggest one possibility, namely that the chromite may be concentrated in certain layers, such as in the upper part of the Josephine Peridotite (magnetic unit C). Similar relations may hold for the cluster of four deposits near the east end of profile I and also for the deposits located adjacent to the north limits of the mafic rocks of the ophiolite.

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Geophysical Studies of Chromite Deposits in the Josephine Peridotite of Northwestern California and Southwestern Oregon

By JEFFREY C. WYNN *and* WILFRED P. HASBROUCK

GEOLOGICAL AND GEOPHYSICAL STUDIES OF CHROMITE DEPOSITS IN THE JOSEPHINE PERIDOTITE, NORTHWESTERN CALIFORNIA AND SOUTHWESTERN OREGON

U.S. GEOLOGICAL SURVEY BULLETIN 1546-D

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ABSTRACT

Laboratory and field measurements were made in a study of a small number of chromite deposits in the Josephine Peridotite of northwest California to examine their physical properties and to search for possible diagnostic geophysical signatures. Though the sample was small, the results show that no single geophysical method gives unequivocal identification of buried massive pods of chromite but that a combination of gravity, magnetic, and seismic data, and complex resistivity, might be used to explore successfully if used in a systematic fashion. Some of the geophysical signatures appear to be secondary or associative in nature, indicating that a specific method or combination of methods might have to be modified for application in an area other than where they were developed.

INTRODUCTION

Laboratory and field geophysical studies were carried out in 1978 in an investigation of three podiform chromite deposits in the Josephine Peridotite of northwestern California. Laboratory measurements of a wide range of physical properties were made on a suite of 27 rocks from the area in order to give direction to followup investigations. Additionally, three known deposits were tested with several field methods. Correlations were made between the geophysical data and the reported structure and geology of the ore bodies. The field sites were chosen with the help of local mine owners, with the intent to geophysically examine known (identified) chromite deposits. The three deposits chosen were the Red Mountain outcrop, Tyson's mine, and Brown's mine (see fig. 1, this volume). Descriptions of these sites are available in Wells and others (1946).

PREVIOUS STUDIES

Studies (Hammer and others, 1945; Yungul, 1956; Davis and others, 1957; Jancovic, 1963; Bosum, 1970) indicate that although the gravity method is often effective in the search for podiform chromite, it can be tedious and expensive and it has limitations tha make it sometimes unreliable in complex, dissected areas, especially when used by itself.

Magnetic studies have been carried out by several investigators on chromite bodies all over the world (Hawkes, 1951; Yungul, 1956; Bosum, 1963, 1970). These studies indicate that podiform chromite might be detectable with magnetic methods at greater depths than with gravimetric methods, perhaps more than twice the depth, in some cases. Different magnetic susceptibilities and remanent magnetization levels in different regions appear to make this method somewhat site specific, however; that is, a geological signature, empirically determined from measurements over known deposits, can be used effectively in the local environment where it was determined but may have only limited usefulness in other localities. In addition, magnetite content in surrounding rocks and in intergrowth contact with chromite nodules will ordinarily vary from area to area. Variations in degree of serpentinization will also lead to extreme fluctuations in the magnetic field over short distances in otherwise homogeneous peridotites.

A single study using induced polarization (IP) in Yugoslavia (Jancovic, 1963) gave equivocal results, mainly because of an insufficiency of IP and geological data. Other geoelectrical studies have come to the authors' attention, but these have been unpublished (and usually proprietary) contract survey reports.

LABORATORY STUDIES

Laboratory measurements were made on a suite of 27 rocks collected in and adjacent to the Josephine Peridotite. These studies included determinations of specific gravity, magnetic susceptibility, seismic velocity, resistivity and complex resistivity (CR), and spectral reflectance (Hunt and Wynn, 1979). The results were encouraging, especially with the magnetic susceptibility and CR studies, and suggested that field methods based on these properties be tested.

The magnetic susceptibility results (fig. 20) showed consistent lows for massive chromite samples. Increased magnetic susceptibility is associated with increased serpentinization; therefore, the more heavily serpentinized the host rock, the greater the anticipated contrast with the chromite should be. This encouraged us to search for magnetic lows associated with the chromite ore. Remanent magnetization, except in rocks where lightning has induced a strong local component, was generally not a significant factor.

Complex resistivity was another technique experimented with; though CR spectra are described in Zonge and Wynn (1975), a brief description of the method is warranted here. Complex resistivity is an advanced form of the induced polarization (IP) method. In the IP method a time-varying current is driven into the ground through two electrodes and the resultant voltage is picked up between two other electrodes. The results obtained are expressed as the apparent resistivity and polarization of the earth, as a function of frequency. The latter quantity may be expressed as phase shift or a number of other quantities depending on current wave forms and the receiver used. In the CR method measurements are made at many more frequencies than the ordinary IP method, and the results are expressed in terms of Argand diagrams as well as apparent resistivity and phase shift. In Argand diagrams the real (in phase) and imaginary (quadrature) parts of the response or "transfer function" of the Earth are plotted as a function of frequency. A sulfide-rich rock will give a different spectrum from a barren or unaltered rock because the electrochemical and electronic processes inside these rocks differ. Figures 21 and 22 are Argand diagrams representing the change caused by the Earth for each frequency of the input signal. We can empirically observe that chromite-rich rocks give "peaked" or bent curves different from those produced by dunite and harzburgite.

To intepret these different curves, we have assigned letters to the general shapes. Following a convention used in Zonge and Wynn (1975), we assign a capital "C" to spectral shapes whose imaginary component increases steeply with increasing frequency—in other words, the spectra slope up and to the left (direction of increasing frequency) in the Argand diagram. Now we assign a lower case "c" to spectra whose imaginary components increase slowly with increasing frequency—a shallower slope than those with the capital "C". A spectral shape whose imaginary component *decreases* steeply with increasing frequency (slopes

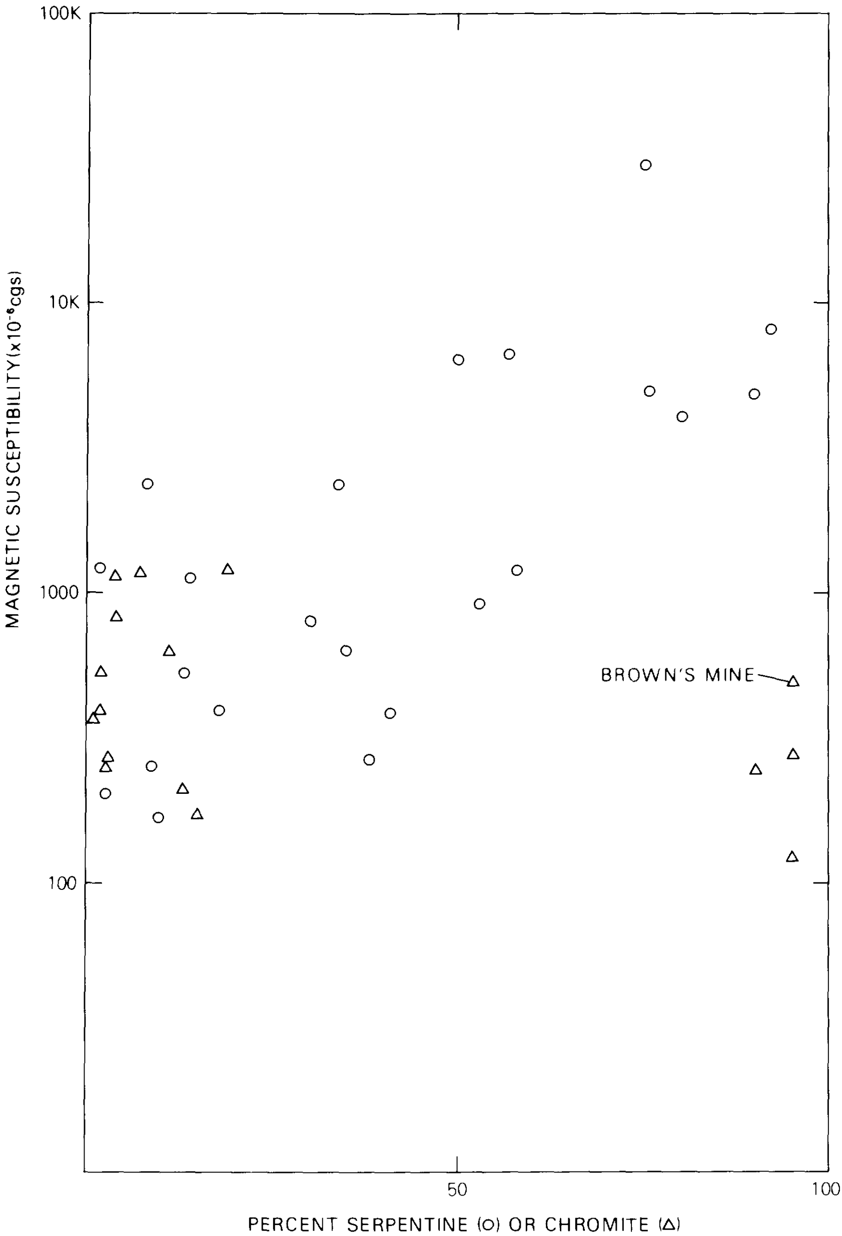

FIGURE 20.—Magnetic susceptibility as a function of serpentine and chromite content for samples collected in the Josephine Peridotite. Chromite samples generally have low magnetic susceptibility, whereas susceptibility shows a nearly exponential relationship with pecent serpentine, though with wide scatter.

down to the left) may be assigned an uppercase "A," while a "flat" spectra (imaginary component constant with frequency) may be labeled with a lowercase "b". The "peaked" or bent spectra associated with the chromite can be distinguished by a "Cc", "Cb", or "CA" label in the pseudosection. This is equivalent to a time constant in the range of 0.1 to 10 described by Pelton and others (1978). That of the dunite and harzburgite is in the 10^{-3} to 10^{-6} range. The laboratory distinctions described here led us to experiment with CR in the field at the three chromite sites.

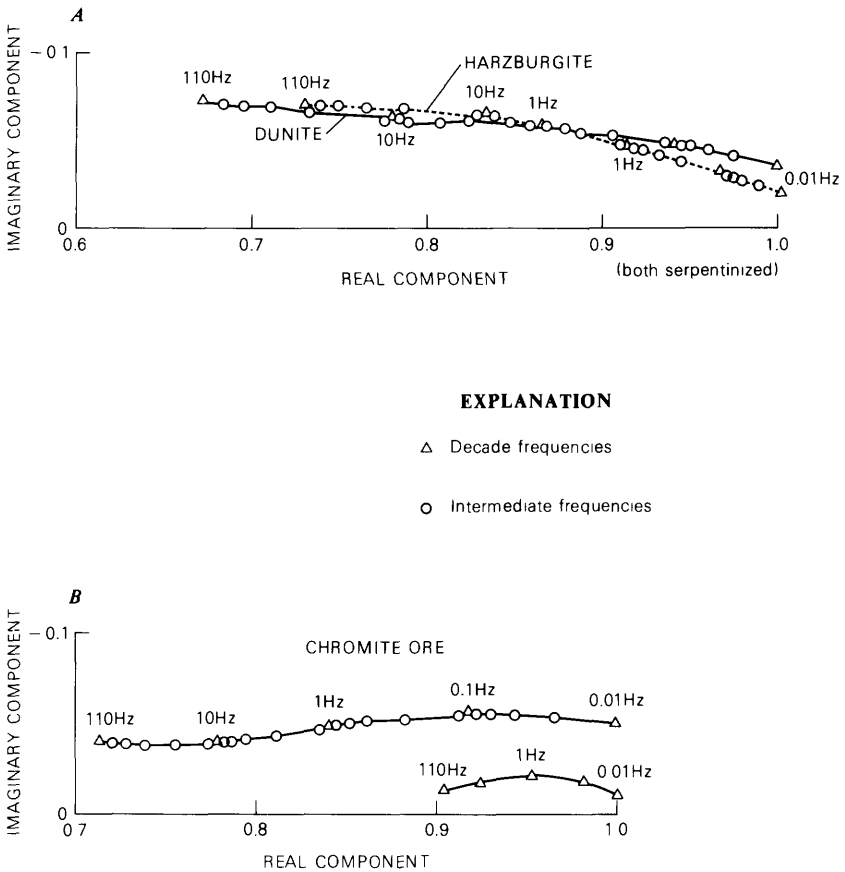

FIGURE 21.—Complex resistivity electrical spectra (Argand diagrams) for several samples from the Red Mountain area in the southern part of the Josephine Peridotite. In these samples, the dunite and harzburgite, *A*, appear to give identical spectra, but thin section data are unavailable and the samples all have some pyroxene content. The chromite samples, *B*, (both were massive) show a characteristic "peaked" spectral shape.

FIELD STUDIES

Podiform chromite deposits are found almost exclusively in dunite lenses in a larger matrix of harzburgite. The dunite and harzburgite are part of the differentiated mantle material at the base of the ophiolite sequence (Josephine ophiolite of Harper, 1980) and make up the tectonite peridotite, called the Josephine Peridotite, usually found beneath the cumulate and gabbro sections. A generalized ophiolite model, showing the approximate location of chromite deposits in the section, is shown in figure 23. An idealized geologic model showing the somewhat tabular shape typical of podiform and chromite bodies is shown in figure 24. These bodies are generally composed of 90 percent or more chromitite, usually in the form of grains or nodules packed together. The remaining interstitial material is derived from dunite but may be largerly serpentinized with a complex mineralogy dependent upon many different environmental factors. The chromite grains or nodules may themselves have an

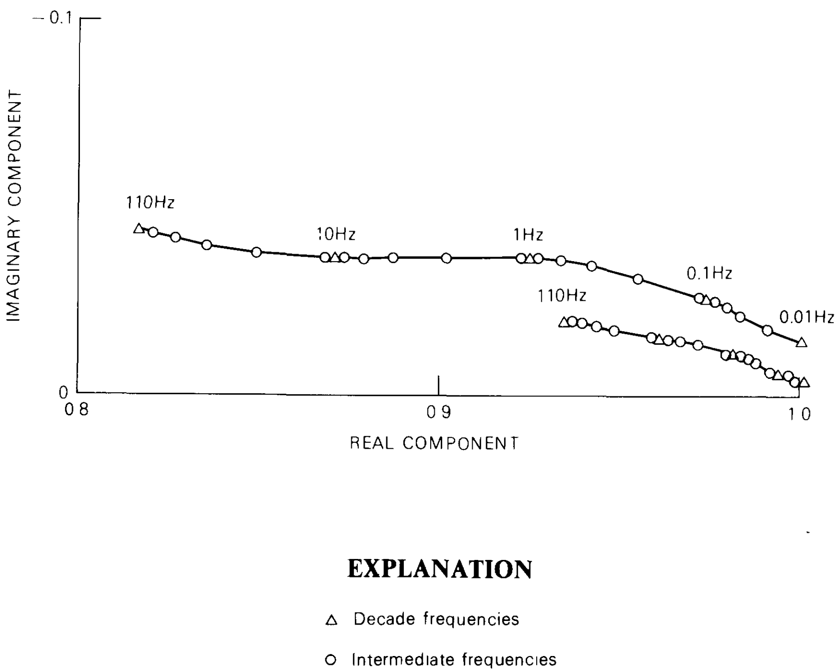

FIGURE 22.—Complex resistivity electrical spectra for two samples of massive chromite ore taken from the Brown's mine locality, Josephine Peridotite. The lower sample fails to show the "peaked" spectral shape (the spectrum is typical of an unmineralized and unaltered igneous rock instead), which may indicate that this shape is only indirectly related to the chromite.

alteration halo, typically composed of kammererite, that is derived from the serpentinization process. The more brittle chromite mass inevitably causes an increased degree of tectonization to its enveloping dunite lens. The consequence, therefore, of the emplacement tectonic process is that the dunite sur-

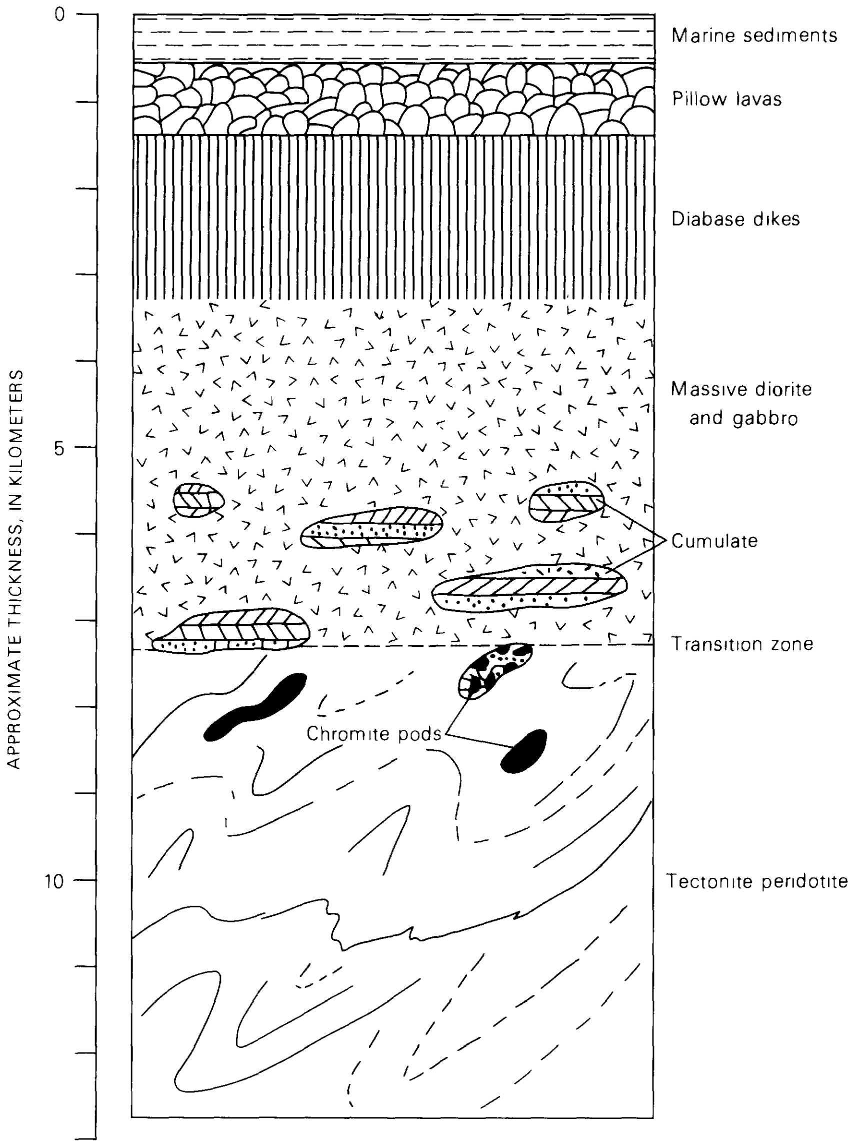

FIGURE 23.—Idealized ophiolite section, showing position of chromite pods, taken from Dickey (1975).

rounding a chromite pod is more heavily serpentinized, owing to an increased exposure of fracture surfaces to fluids, than the harzburgite country rock. This implies (though does not necessarily demand) that the magnetic susceptibility increases sharply in the immediate vicinity of a chromite pod but drops to negligible levels at the chromite mass itself (pure chromite having negligible susceptibility).

Ground magnetic, electromagnetic (EM, both VLF and slingram), and complex resistivity (CR) studies, as well as limited seismic refraction studies, were made at several locations in the Josephine Peridotite. The Very Low Frequency Electromagnetic (VLF-EM) method is described in Telford and others (1976), along with the magnetic and seismic methods. In areas where a target body is within 10–30 m of the surface, the VLF method is often effective in identifying it if sufficient resistive contrast exists, such as at Red Mountain. CR measurements were made at the three principal sites: Brown's mine, Tyson's mine, and the Red Mountain deposit. The Tyson's mine CR results were unusable, owing to instrumentation problems, and are therefore not included in this paper. The seismic data have not been completely processed becaus of an intermittent noise problem

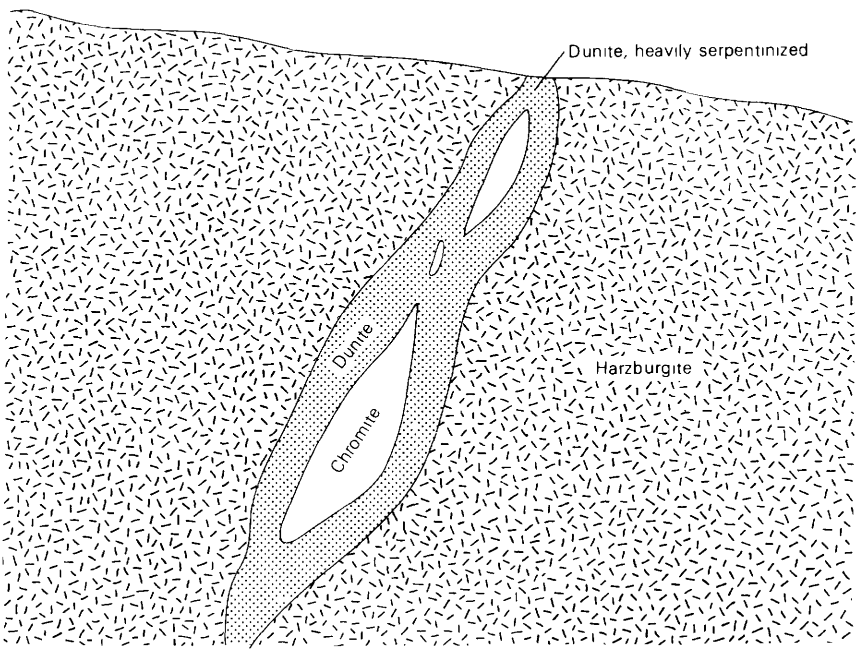

FIGURE 24.—Idealized conceptual model of a chromite deposit.

with the recorder system. These data are recoverable, however, and preliminary results are highly encouraging.

RED MOUNTAIN OUTCROP

The Red Mountain site consists of two small exposed outcrops below the crest of a steep hill near the southern tip of the Josephine Peridotite (fig. 1, this volume). Some dunite is found in contact with the chromite, but very little is visible elsewhere at the site, since the ground (except for the chromite outcrops) is mostly covered with harzburgite scree. The outcrops consist of massive (95+ percent chromite) ore, partly fractured and rehealed, in contact with strongly tectonized dunite. Serpentinization of the surrounding peridotite is typically 40 percent.

The VLF-EM apparent-resistivity profile (fig. 25*C*) shows resistive highs over both outcrops; crosslines and one parallel line show that these resistive highs are localized around the outcrops (fig. 25*A*). The total field magnetic data (fig. 25*B*) show a high at the western edge of the western outcrop, with a sharp 550 nT (nanoTesla, where 1 nT=1 gamma) magnetic low over the central and eastern parts of the outcrop. This magnetic low extends eastward through the other (easternmost) outcrop and then gives way to a high followed by another low that is unexplainable from the surface geology. The magnetic low may be caused by a remanent dipolar effect but is most likely due to the removal of peridotite displaced by the chromite mass. The sharp magnetic high at the western edge of the west outcrop could be caused by increased serpentinization of the dunite halo.

Figure 26 shows apparent resistivity and phase-angle pseudosections.[1] These are conventional data, a byproduct of the CR survey. The apparent-resistivity data show resistive highs associated with both outcrops, in agreement with the VLF-EM results of the previous figure. The phase-angle data indicate that the outcrops are somewhat more polarized than the surrounding peridotite. These data also indicate that the eastern outcrop (or at least the source of the polarization) extends below the range of the survey method. For a 10-m dipole spacing (distance between electrodes of the receiver), this implies a depth of at least 20 m in this kind of electrically resistive terrain; a larger dipole spacing would "see" deeper but would also provide less resolution.

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[1] Pseudosections are not true cross sections of the earth parameters, and should not be interpreted as such. A dikelike feature gives a pseudosection shape like pyramid centered over the dike, whereas a block of material with finite depth extent gives a "pants leg," totally different in shape from the source body. Further details about pseudosections can be found in Sumner (1976).

Figure 27*B* shows a pseudosection of spectral shape response interpreted from CR measurements taken along the traverse. Figure 27*C* shows two representative field CR spectra. At Red Mountain, only two spectral shapes were observed, the "C" and the "Cc". In the latter case, the lower frequency part of the spectral curve increased steeply but levéled off after 1.0 Hz—therefore the double character representation for a "bent" spectrum. Recalling the discussion about laboratory chromite samples, we were looking for a "peaked" or bent CR spectrum. The "Cc" spectral shape observed beneath the two outcrops is

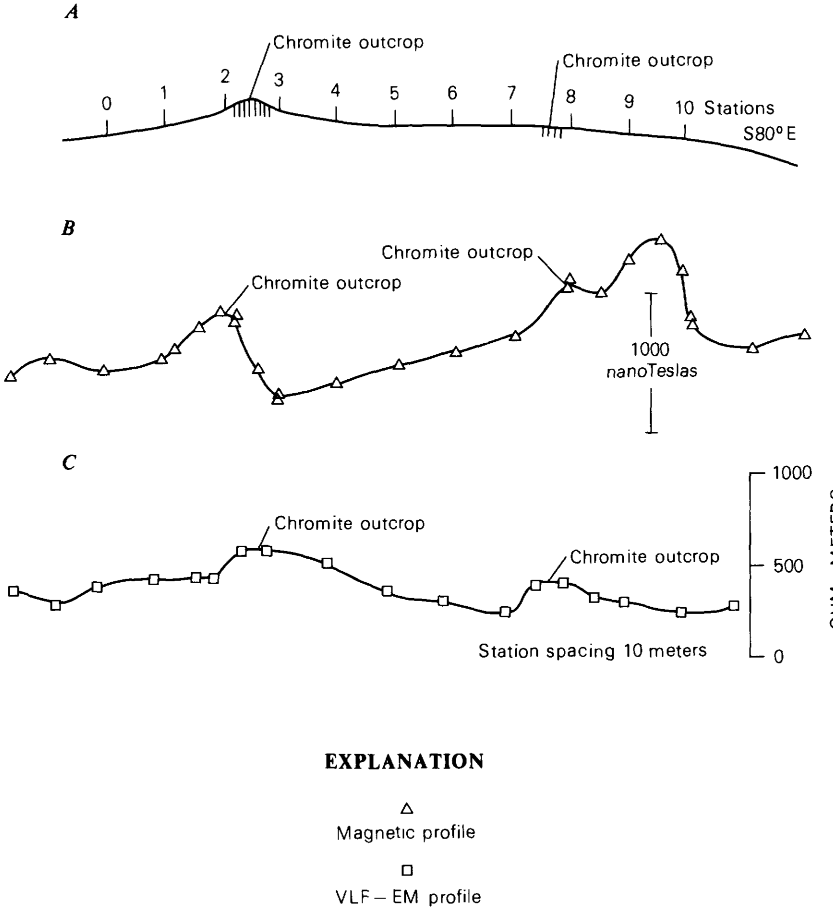

FIGURE 25.—Geophysical traverses over the chromite outcrops at the Red Mountain site, southern extreme of the Josephine Peridotite. *A*, Topography, unexaggerated scale, chromite outcrops shown with hachures; *B*, Total-field magnetic profile, showing a magnetic low delimited by the outcrops; *C*, VLF-EM apparent-resistivity profile, values in ohm-meters, showing resistive highs over both outcrops.

almost certainly the same spectral shape observed in the laboratory for chromite samples. The high-frequency end has not decreased as much in the imaginary component, because the field results are a weighted average of the results for chromite and a much larger volume of peridotite surrounding the chromite. The spectral-type pseudosection again shows the outcrop on the east to have limited extent, but the apparent chromite

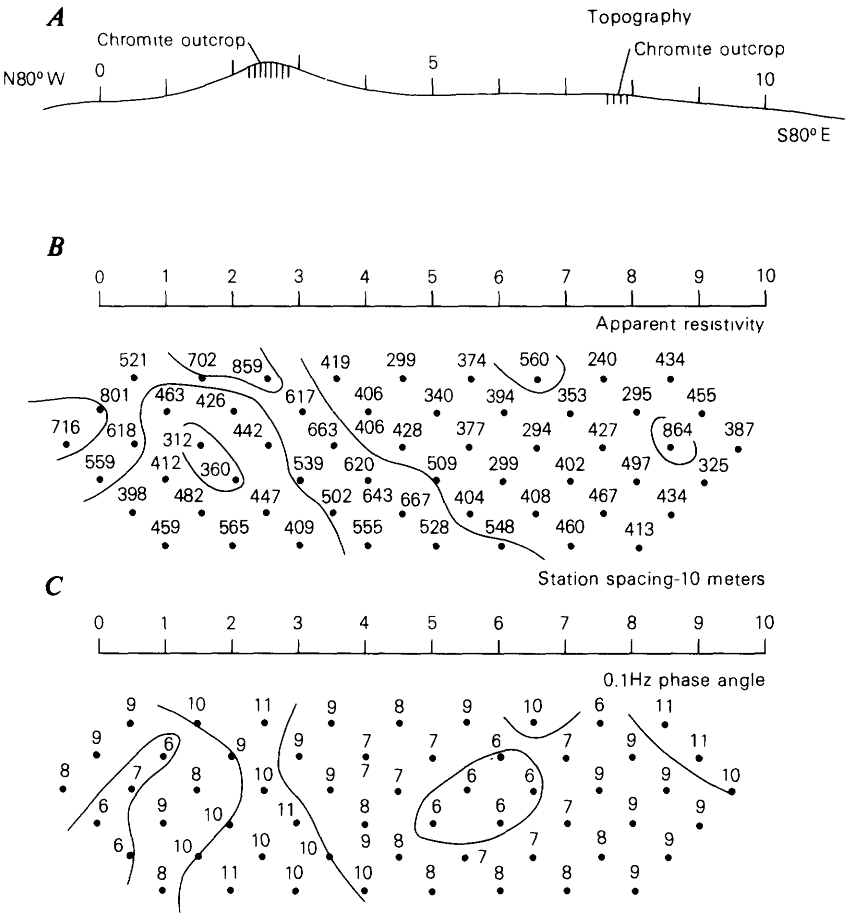

FIGURE 26.—Geophysical traverses over the chromite outcrops at the Red Mountain site, Josephine Peridotite. *A*, Topography; ticks indicate station locations spaced 10 m apart; *B*, Dipole-dipole apparent-resistivity pseudosection, values in ohm-meters, showing resistivity highs at each outcrop. The eastern outcrop has caused a modified "pants leg" shape of 500 OHM-M; *C*, Dipole-dipole phase-angle pseudosection, values in milliradians for 0.1 Hz, showing a moderate phase-angle anomaly going to depth beneath the western (larger) outcrop of chromite.

signature shows that the outcrop on the west side goes to depth. This apparent extension to depth is the same result obtained with the phase-angle data, but it is much more diagnostic.

Figures 28 and 29 show the results of two shear-wave refraction profiles using a 12-channel portable seismic system

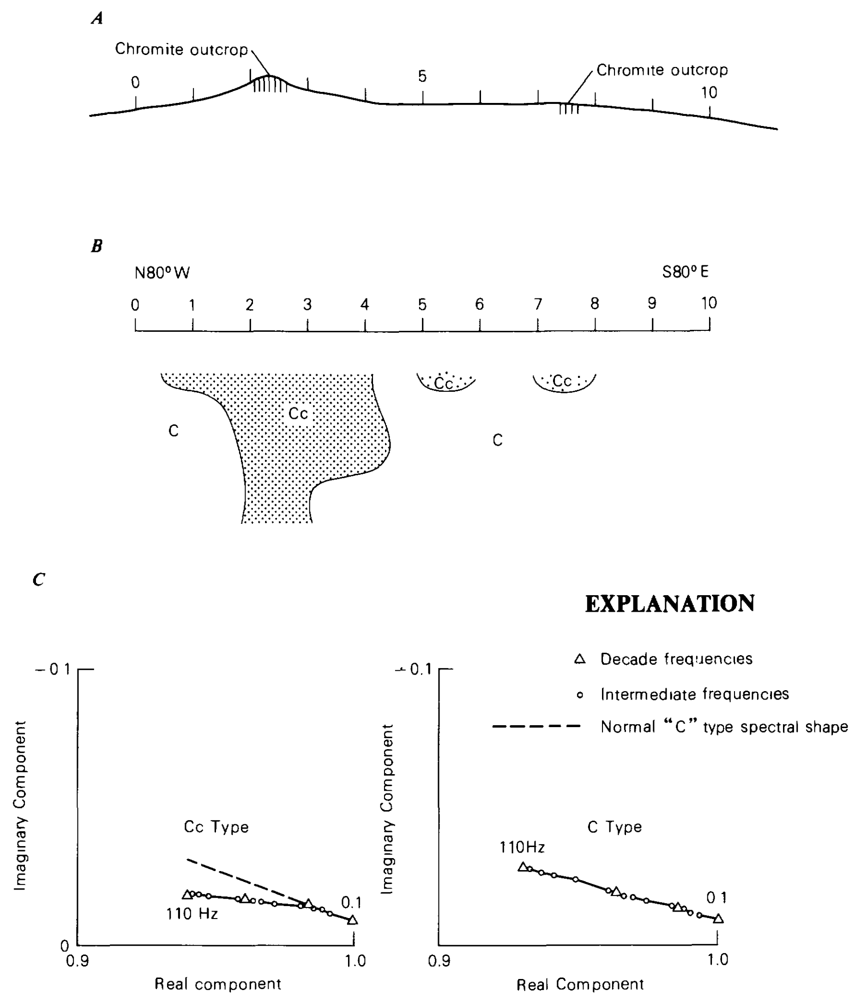

FIGURE 27.—Geophysical traverse over the chromite outcrops at the Red Mountain site, Josephine Peridotite. *A*, Topography; ticks indicate station locations spaced 10 m apart; *B*, Complex resistivity spectral-type pseudosection, showing a "Cc" spectral shape anomaly beneath each outcrop, going to depth beneath the western one; *C*, Example spectral types used to compile the pseudosection in *B* from the field data, showing both "C" and "Cc" spectral types. See text for discussion of spectral shape anomalies.

over the western outcrop at the Red Mountain site described previously. The data in figure 28 represent a two-layer earth with a sharp variation in the second segment of the traveltime curve over the outcrop. This bulge in the curve is caused by a substantial velocity increase in the chromite. Figure 29 is nearly identical to figure 28, except that the shotpoint is moved to the other side of the outcrop and geophone array to check against the possiblity of some purely geometrical effect.

The magnitude of the velocity increase (perhaps a factor of two) is such that a similar podiform chromite deposit might be readily identifiable at substantial depth, depending on its size and the presence of other inhomogeneities. The magnitude of the velocity anomaly may be enhanced by the degree of serpen-

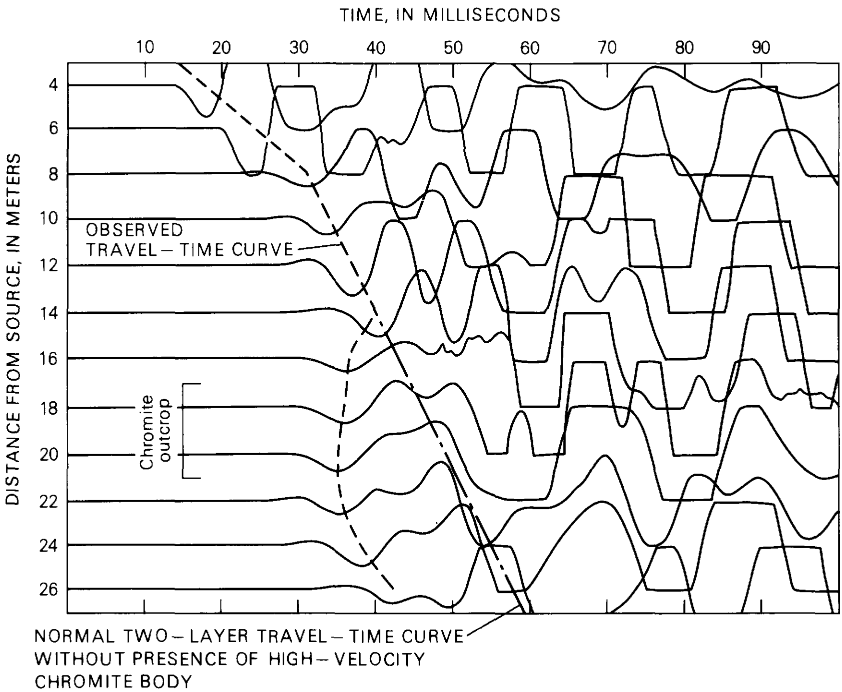

FIGURE 28.—Seismic field records taken over the westernmost (larger) chromite outcrop at the Red Mountain site, Josephine Peridotite. Each trace is for a single geophone, spaced 2 m apart, with the topmost traces being from the east side of the outcrop. A very pronounced velocity increase shows up at the chromite outcrop, seen here as a bulge in first-arrival times between meters 16 and 26, caused by a much shortened arrival time during this interval. The shot point is located 4 m to the east (top of sheet) of the number 4 (4 m) geophone-trace. A vertical compressional source 0.5 m deep was used.

tinization in the surrounding rock; consequently, an unserpentinized host peridotite might not provide so large a velocity contrast.

The full results of seismic measurements at the Red Mountain site, and results of the two mines and a fourth experimental location, would require extensive discussion; however, it appears that the chromite deposits at Red Mountain give resistivity, magnetic, phase-angle, spectral-shape, and shear-wave (Sv component) velocity anomalies. All the geophysical data are consistent with (but not necessarily indicative of) a dunite lens stretching from the west outcrop to the east outcrop, including in it a massive chromite outcrop on the west which extends to considerable depth.

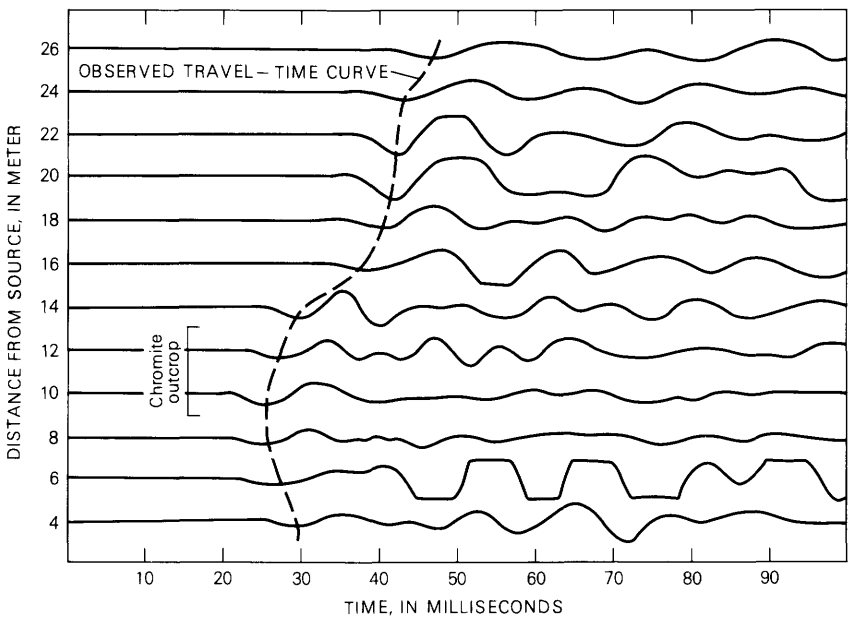

FIGURE 29.—Seismic field records taken over the westernmost chromite outcrop at the Red Mountain site, Josephine Peridotite. The only difference between figures 28 and 29 is the location of the shot point. Figure 29 is the reverse-direction analog of figure 28, with the shot point being located 4 m to the west of the number 12 (bottom) geophone-trace. The chromite shows again as a bulge, in this case between meters 4 and 14.

TYSON'S MINE

Tyson's mine is located on a steep slope where it has been exposed by hydraulic mining about 8 km southeast of Gasquet, Calif., in the south-central part of the Josephine Peridotite (fig. 1, this volume). Most of the original chromite ore has been mined out, but Mr. Whippo, the last mine foreman to work there, described a pod of chromite that had been encountered by a drift just as the mine was shut down. The pod is located in a white serpentinized mass of peridotite which lies stratigraphically beneath a layer of green serpentinized peridotite which in turn lies beneath a weakly metamorphosed greenstone. The greenstone unit apparently lies in fault contact with the underlying rock and probably represents the pillow-lava part of the ophiolite section. Serpentinization of the two units below the greenstone is nearly complete.

Figure 30 shows the topography, the geologic relationships, and the presumed location of the chromite pod. The total field magnetic profile shows a 500-nT low over the chromite pod, whose diameter and shape are not well defined. A 10-m horizontal dimension, however, is thought to be probable. The VLF-EM apparent-resistivity profile is interesting in that the resistivities are usually low in comparison to the other sites visited, over the entire length of the traverse. The entire surface has been exposed by hydraulic mining methods, and the serpentinization is extensive, often reaching 100 percent in hand-sample examination. There is a broad resistivity low over the exposed areas of white serpentine, but apparently no influence or effect from the chromite pod can be discerned in the resistivity data.

BROWN'S MINE

Brown's mine is on the southern flank of Low Plateau, about 6 mi north of Gasquet, Calif., and 3 mi south of the Oregon border. It lies in a harzburgite terrane that is cut by 10- to 50-m-wide dunite-rich zones that generally strike north-south. In the area of the mine, intercalated dunite and harzburgite layers dip gently to the east (Albers, this volume, pl. 3). The degree of serpentinization is generally on the order of 40 percent, but locally it abruptly approaches 100 percent. The chromite itself was exposed by erosion on the north side of a steep ravine. It is massive, typically 95 percent chromite, with 5 percent interstitial minerals. About half of the estimated 25,000 t of chromite ore was mined out by the end of World War II.

Figure 31 shows a topographic profile and the apparent-resistivity and phase-angle pseudosections. The data were ob-

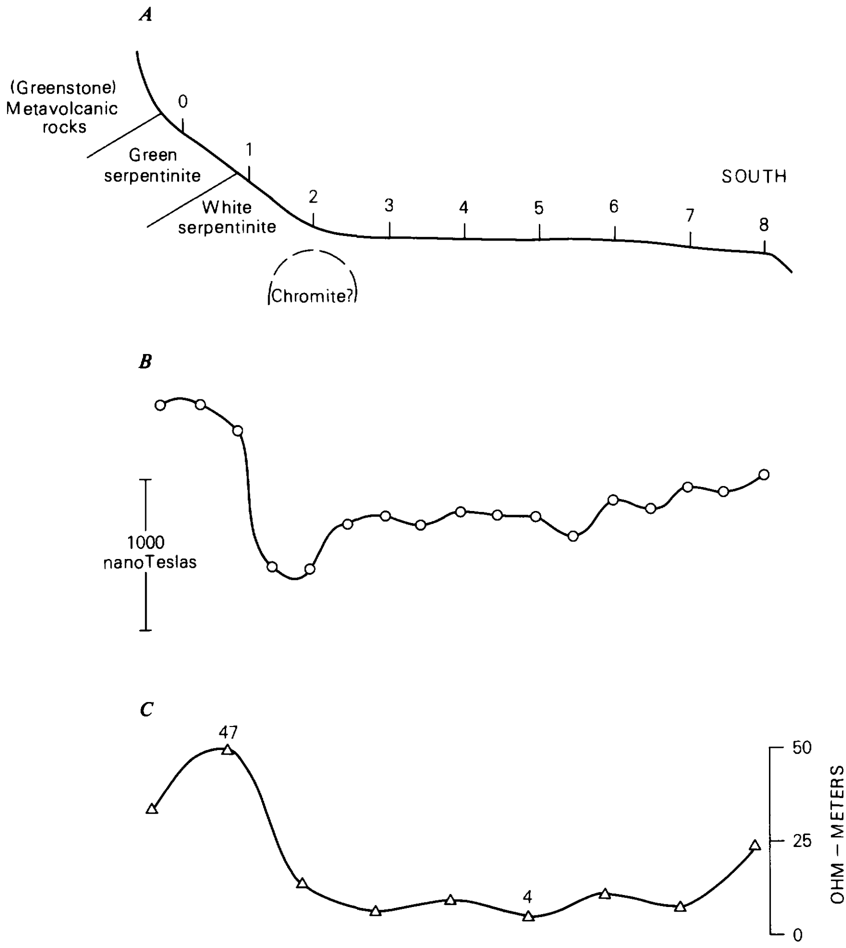

FIGURE 30.—Geophysical traverses at Tyson's mine, south-central part of the Josephine Peridotite. *A*, Topography and geology, unexaggerated scale showing inferred location of the chromite pod; ticks indicate station locations spaced 15 m apart; *B*, Total-field magnetic profile, showing a 500-nT low over the chromite deposit; *C*, VLF-EM apparent-resistivity profile, showing unusually low resistivities in the serpentinite, but no effect from the chromite pod.

tained on a line about 40 to 45 m above the known extensions of the remaining ore; the location was obtained from old mine maps and from onsite observations. The apparent-resistivity pseudosection shows resistivities ranging from 300 to 2,500 ohm-meters. These values are much higher than those obtained

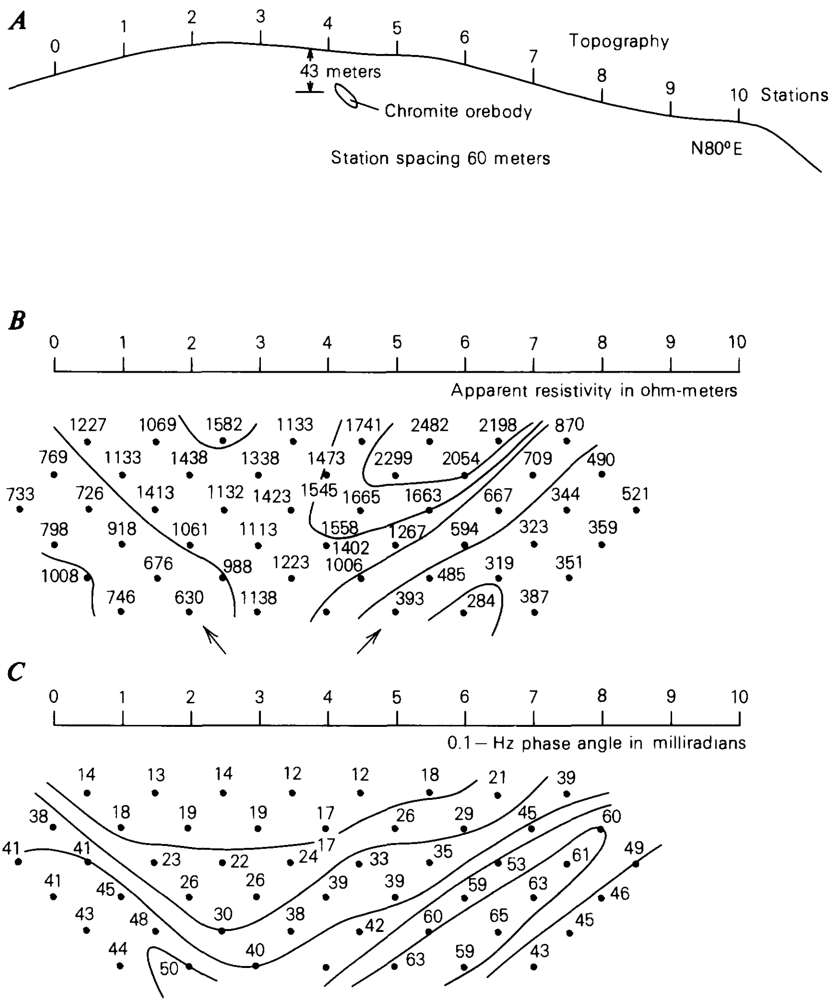

FIGURE 31.—Geophysical traverses over the chromite deposit at Brown's mine, central part of the Josephine Peridotite. *A*, Topography, unexaggerated scale, showing the inferred location of the orebody; *B*, Dipole-dipole apparent-resistivity pseudosection, values in ohm-meters, showing the strong effects of serpentine at each end (arrows); *C*, Dipole-dipole phase-angle pseudosection, values in milliradians for 0.1 Hz, showing an anomalous feature in the center at the 33 and 42 milliradian points.

at Tyson's mine, and even higher than the resistivities at the Red Mountain deposit but not reasonable for a mildly serpentinized peridotite. The two diagonals (indicated by arrows) in figure 31*B* show that lower resistivity values are caused by patches of highly serpentinized peridotite exposed at the surface and apparently extending to depth, at each end of the CR traverse.

Figure 31*C* shows the phase-angle pseudosection, where the same diagonals that showed lower resistivities in figure 31*B* also indicate higher polarization—this is the serpentine showing up again. To an experienced interpreter familiar with the gentle eastward dip of the foliation, the subtle but consistent 35° westward dip in the pseudosection contours would indicate a westward dip in the serpentine mass outcropping around stations 7 to 10. Geologic informaion at the surface and in the vicinity of the massive chromite body indicate no abrupt structural changes in the area, which means that the westward-dipping contours must be caused by some discrete polarizing feature nearly masked out by the strong serpentine effect. This feature coincides with and extends slightly east of the known chromite ore. A possible eastern extension of the ore zone downdip was suspected by the operators at the time the mine was shut down, but uncertainties in line location, the degree of serpentinization, and the imperfect two-dimensionality of the deposit make the chromite extension difficult to pin down more exactly, either geophysically or geologically.

Figure 32 shows representative Argand diagrams of CR spectra observed in field data from Brown's mine. These spectra are labeled according to the convention described previously, adding several new classifications to incorporate a *decreasing* imaginary component with increasing frequency ("A" and "a") and a null response typical of unaltered, unmineralized peridotite ("n"). The spectral shape of most interest is the "Cb" curve on top of the figure. If the laboratory and Red Mountain field observations are applicable to Brown's mine, this shape should correspond to the chromite ore.

Figure 33*B* shows the interpreted spectral shape pseudosection for Brown's mine. The "C" and the "A" contributions appear to be caused by an increase in serpentine, but why two different contributions exist is not understood; more complete subsurface geological information along the line might supply an explanation. In the center of the pseudosection a discrete block of "Cb" spectra is located at and extends slightly west of the known location of the chromite ore. There is another discrete block on the eastern edge of the pseudosection, just beyond the serpentine, but there is also insufficient geologic information to allow any identification of this eastern block. These results seem to bear out the laboratory observations that a spectrum with increasing, then decreasing, imaginary component as a function of frequency (a "peaked" spectrum in an Argand diagram) is indicative of the presence of massive chromite. The causal relationship between chromite and a peaked spectra is not understood at this time, and we should anticipate the possibility that the association is indirect and therefore at

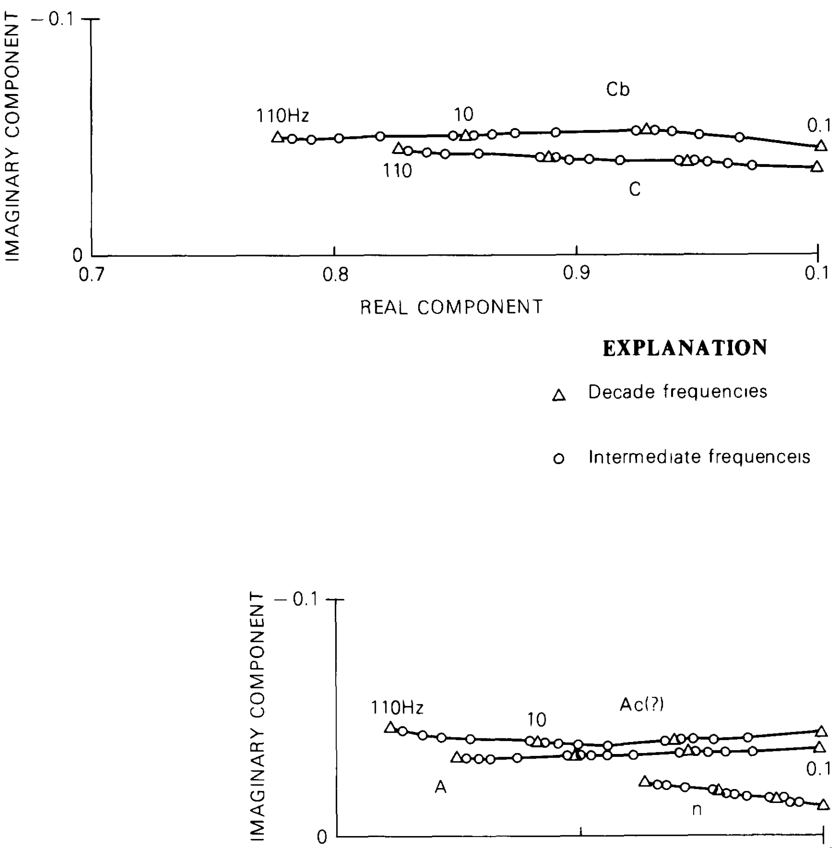

FIGURE 32.—Complex resistivity spectral types from the field data collected over Brown's mine, Josephine Peridotite. These spectra are arch types with letter designations plotted in figure 33*B* and discussed in the text.

least potentially site specific. Laboratory studies are underway to answer the question about the nature of the relationship between massive chromite ore and the apparent chromite CR signature.

For the sake of completeness, the total field magnetic pro-

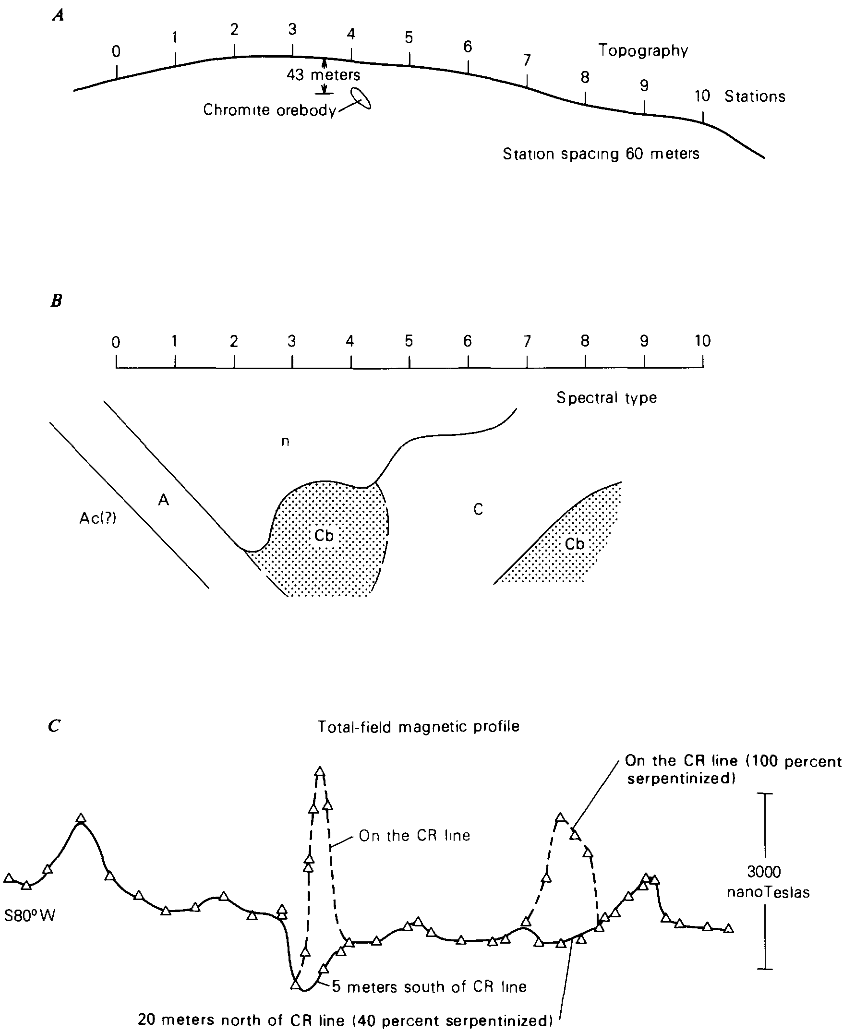

FIGURE 33.—Geophysical traverses over the chromite deposit at Brown's mine, Josephine Peridotite. *A*, Topography; *B*, Complex resistivity (CR) spectral-type pseudosection, showing the "Cb" shape apparently pinpointing the chromite deposit below the center of the profile (see text for discussion of spectral shape anomalies); *C*, Total-field magnetic profile, showing the strong effects of serpentine, partially masking a possible low over the chromite deposit.

file has been included in figure 33. Perhaps the most important piece of information contained in the traverse is a warning: in a serpentinized terrane, the magnetic field can be expected to vary wildly. The high-amplitude, short wavelength anomaly over the ore zone has a spatial variation (3,000 nT in only 15 m horizontal distance, measured 3 m above the surface) so short that the source must be virtually at the surface. Careful examination of the rocks showed no significant variation in rock type, percent serpentine, or structure. When a low-pass spatial filter was applied to the data, a magnetic low did remain over the ore zone and extended to the west as does the CR spectral anomaly. On the eastern side of the line a broad magnetic high was observed, which correlates with a patch of nearly 100 percent serpentine; a profile completed 20 m to the north of the serpentine did not give a similar anomaly.

The geophysical data at Brown's mine gave very encouraging results; the CR spectra, the phase-angle data, and the magnetic data all have correlatable anomalies. In all cases, however, the serpentine influenced the data and obscured its interpretation, sometimes to the point where if a massive pod of chromite existed, it might not be uniquely identifiable if only a single method tied to only one physical property were used.

CONCLUSIONS

In the Josephine Peridotite, chromite ore appears to be associated with magnetic lows. This is at variance with field observations from eastern Turkey and elsewhere. Bosum (1963) would say that the chromites from the Josephine Peridotite are probably from a "deeper" part of peridotite section, whereas chromites with magnetic highs would be from a "shallower" part, with thin magnetite haloes around individual chromite nodules.

Gravity has been used to explore from chromite, but it is tedious, expensive, and good only for shallow depths, by itself. In areas of severe topography (like most ophiolite terranes, for instance) terrain corrections with the necessary precision would be extremely difficult. The seismic field data are only partially processed at this time, but appear to show strong velocity highs for massive chromite contrasted against the surrounding serpentinized peridotites. This result did not show up in the preliminary laboratory study.

Electrical measurements are encouraging, showing a "peaked" or bent CR spectral shape associated with the chromite ore, both in laboratory samples and in the field. This effect might very well be secondary in nature, that is, caused by cogenetic accessory minerals, and should be studied by laboratory work on rocks from different environments. The complications in electrical and magnetic data caused by serpentine should be studied further, so that we might be able to separate its electrical and magnetic signatures from other rock types.

Though more work is required, it appears that buried podiform chromite might be detectable using several geophysical methods together, along with good geologic guidance.

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GPO 587-044/10019