UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOPHYSICAL STUDIES OF CHROMITE DEPOSITS IN THE JOSEPHINE ULTRAMAFIC COMPLEX OF NORTHWEST CALIFORNIA AND SOUTHWEST OREGON

BY

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ABSTRACT

Laboratory and field measurements were made in a study of a small number of chromite deposits in the Josephine ultramafic complex 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, magnetics, and seismics, 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, raising the possibility 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 ultramafic complex in collaboration with studies by John Albers and others (unpub. data). These studies are an integral part of a U.S. Geological Survey research effort directed at gaining a better understanding of the genesis and emplacement of podiform chromite deposits and determining whether an effective exploration method for chromite can be developed. 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 orebodies. The field sites were chosen with the help of local mine owners, the intent being to examine geophysically known (identified) chromite ore that still remains in the ground, though this has proven to be a difficult requirement to fill. The three deposits chosen were the "Red Mountain" outcrop, Tyson's mine, and Brown's mine (see fig. 1). Descriptions of these sites are available in Wells, Cater, and Rynearson (1946).

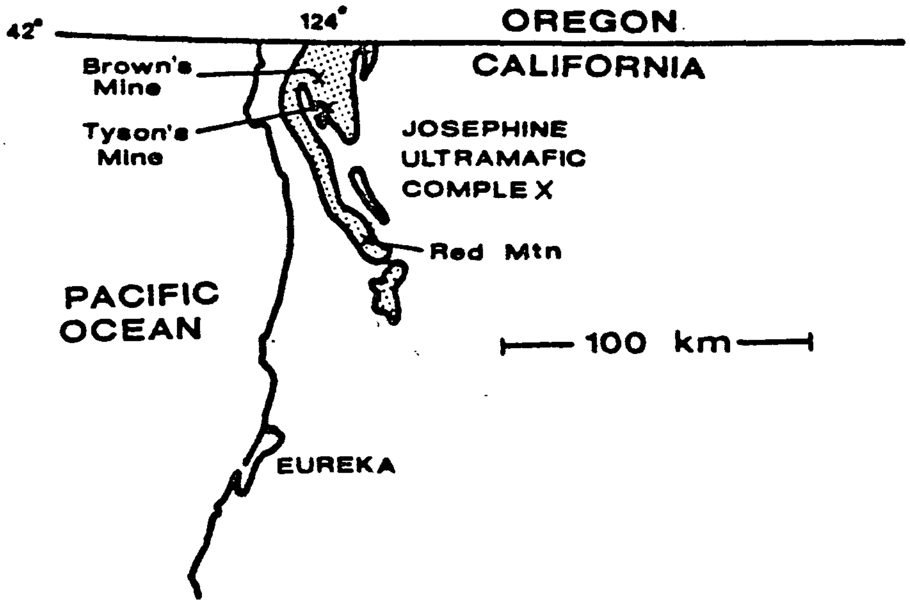
PREVIOUS GEOPHYSICAL WORK ON CHROMITE DEPOSITS

Gravity studies (Hammer and others, 1945; Yungul, 1956; David 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 that 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 gravimeteric 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 (A geological signature, empirally determined from measurements over known deposits, can be used effectively in the local environment where it as 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 author's

Figure 1. Location of the Josephine ultramafic complex, site of most of the fieldwork and areas sampled referred to in this report.


42°
124°
OREGON
CALIFORNIA
Brown's Mine
Tyson's Mine
JOSEPHINE ULTRAMAFIC COMPLEX
Red Mtn
PACIFIC OCEAN
100 km
EUREKA

attention, but these have been unpublished (and usually proprietary) contract survey reports.

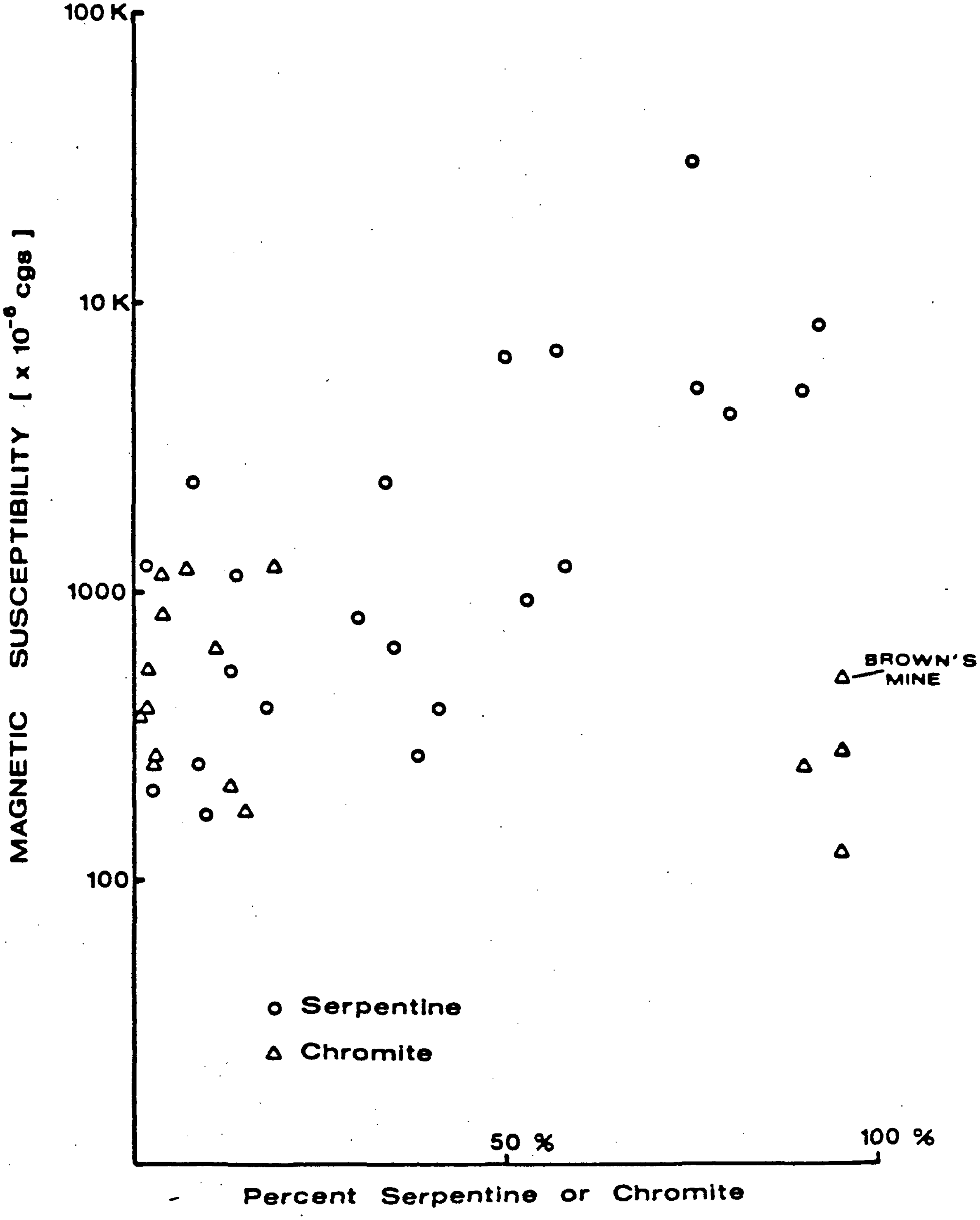
LABORATORY STUDIES

Laboratory measurements were made on a suite of 27 rocks collected in and adjacent to the Josephine ultramafic complex. 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. 2) 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 lghtning 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 complex resistivity method measurements are made at many more frequencies

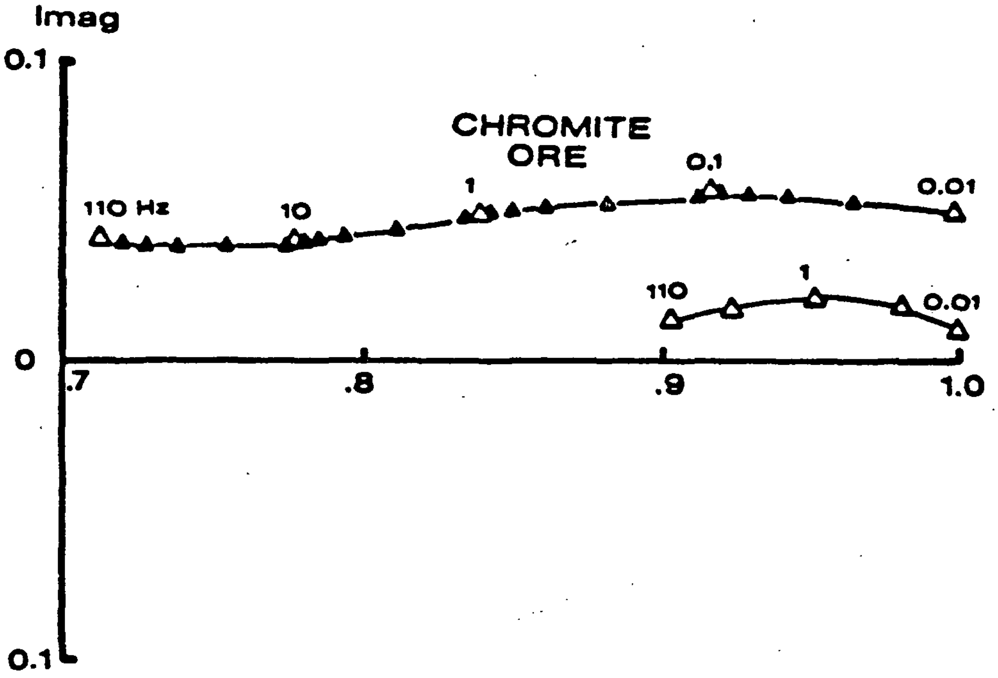
Figure 2. Magnetic susceptibility as a function of serpentine content and also for chromite content (combined in one figure) for samples collected in the Josephine complex. Chromite samples generally have low magnetic susceptibility, whereas susceptibility shows a nearly exponential relationship with percent serpentine, though with wide scatter.


MAGNETIC SUSCEPTIBILITY [x 10^{-6} cgs]
100 K
10 K
1000
100
o Serpentine
Δ Chromite
BROWN'S MINE
50 %
100 %
Percent Serpentine or Chromite

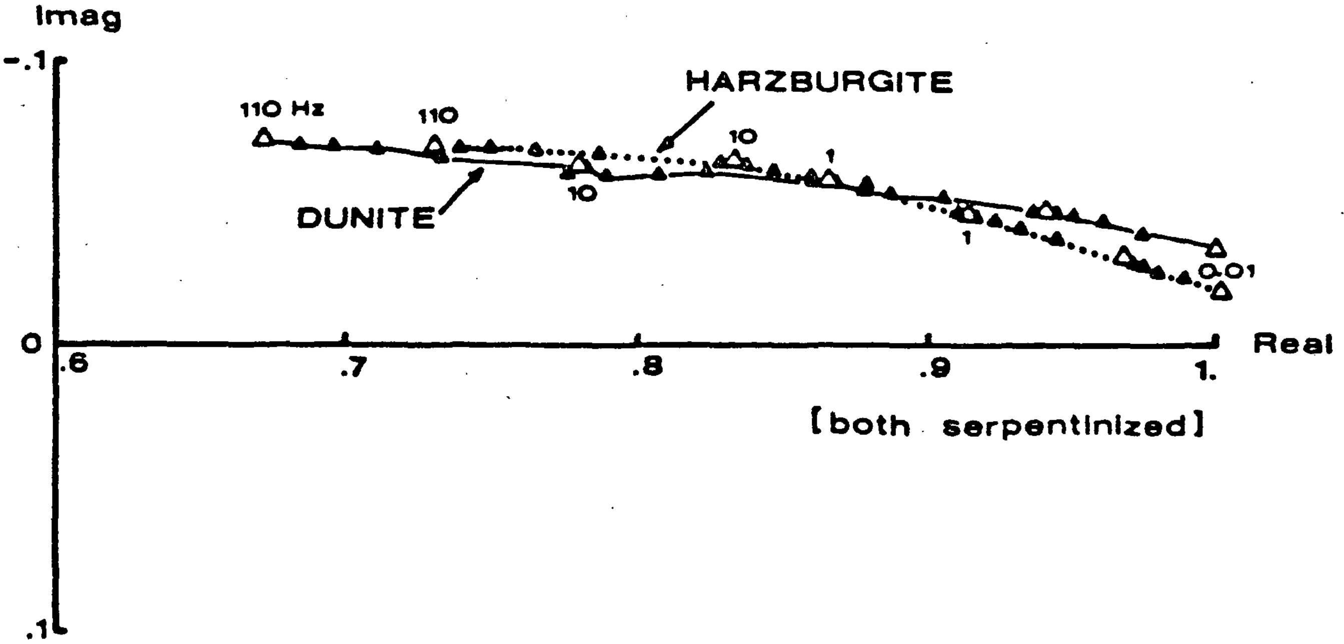
than in the ordinary IP method and the results are expressed in terms of Argand diagrams as well as apparent resistivity and phase shift. In Argand diagrams the real (in phase) and imaginary (quadrature) parts of the reponse or "transfer functin" of the earth are plotted as a function of frequency. A 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 3 and 4 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.

We may take a first cut at interpretation of these different curves by assigning letters to the general shapes. Following a conventio used in Zonge and Wynn (1975), we assign a capital "C" to spectral whose imaginary component increases steeply with increasing frequency--in other words, the spectral slope up and to the left (direction of increasing frequency) in the Argand diagram. Now we assign a lowercase "c" to spectra whose imaginary components increase slowly with increasing frequency--a shallower slope than the capital "C". A spectral shape whose imaginary component decreases steeply with increasing frequency (slopes 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). The 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 3. Complex resistivity electrical spectra (Argand diagrams) for several samples from the Red Mountain target area at the southern extreme of the Josephine complex. In these samples, the dunite and harzburgite appear to give identical spectra, but thin section data are unavailable and the samples all had some pyroxene content. The chromite samples (both were massive) show a characteristic "peaked" spectral shape.

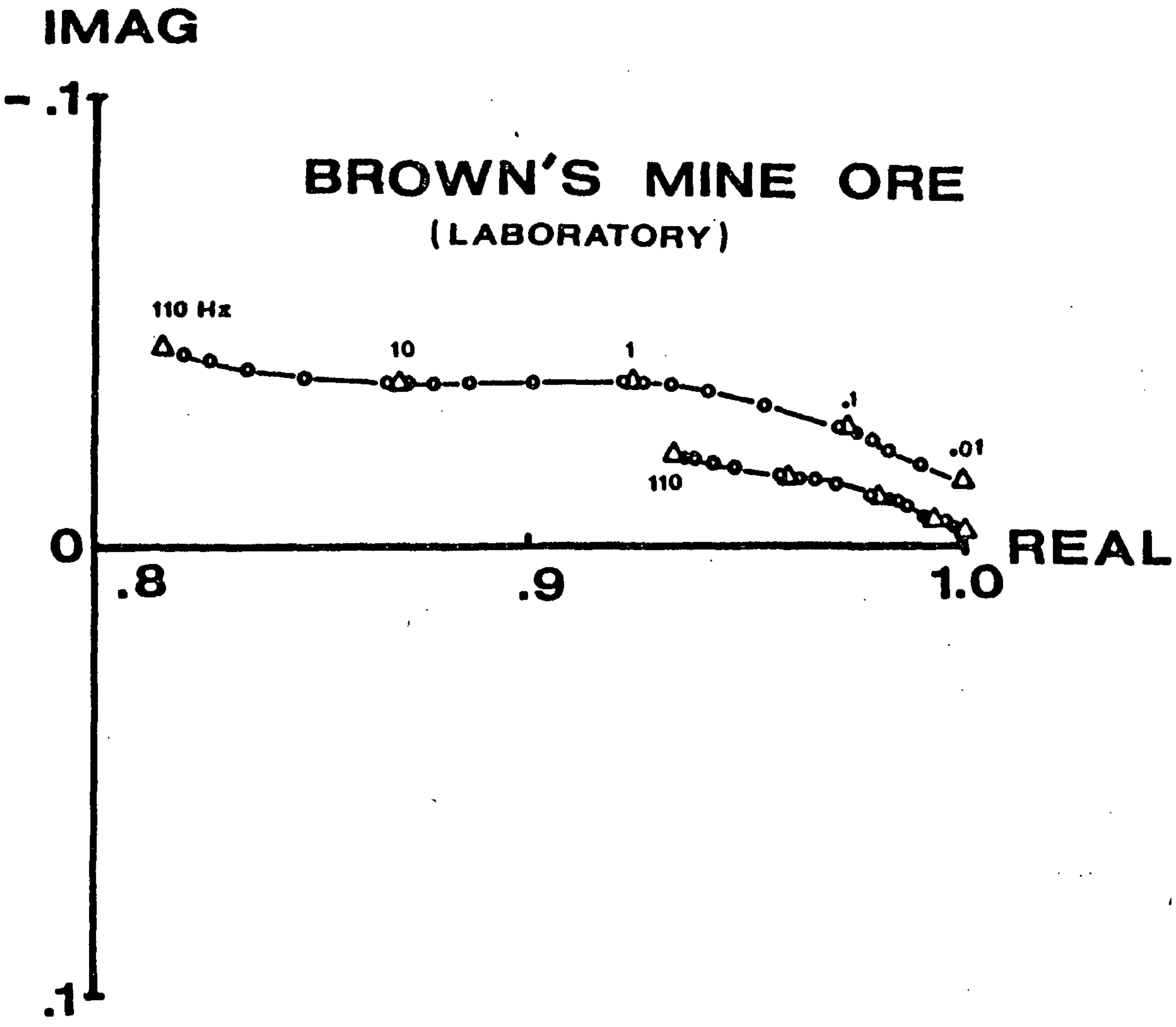


Red Mountain [Calif.] Laboratory Samples



3

Figure 4.. Complex resistivity electrical spectra for two samples of massive chromite ore taken from the Brown's mine locality, Josephine complex. One 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.


IMAG
- .1
BROWN'S MINE ORE
(LABORATORY)
110 Hz
10
1
.1
.01
110
0
.8
.9
1.0
REAL
.1

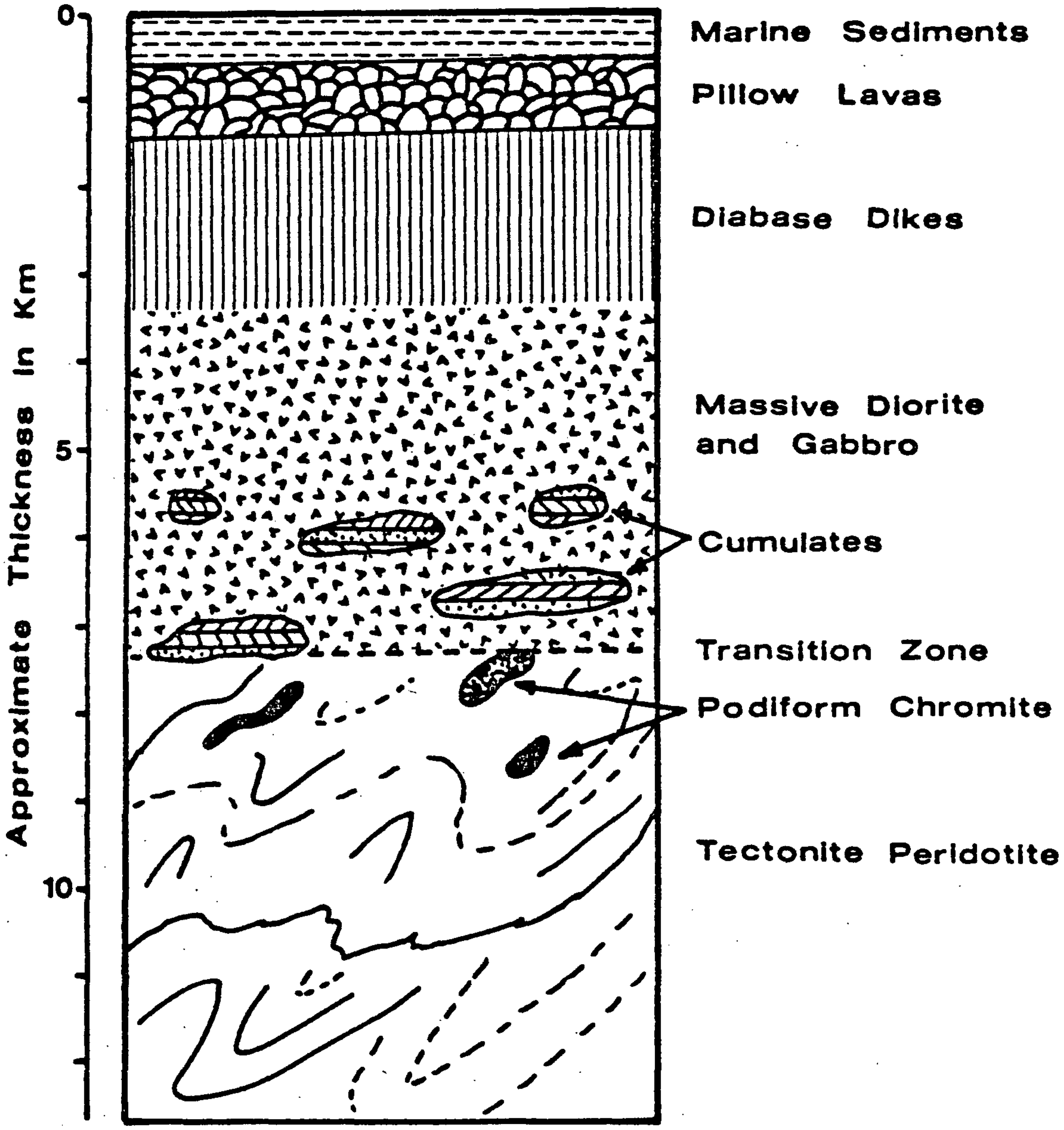
FIELD STUDIES

Podiform chromite deposits are found almost exclusively in dunite lenses in a larger groundmass of harzburgite. The dunite and harzburgite are part of the differentiated mantle material at the base of the ophiolite stratigraphic sequence, and make up the tectonite 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 5. An idealized geologic model, showing the somewhat tabular shape typical of podiform and chromite bodies, is shown in figure 6. 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 largely serpentinized with a complex mineralogy dependent upon many different environmental factors. The chromitite grains or nodules may themselves have an alteration halo, typically composed of kemererite, that derives 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 surrounding a chromite pod is more heavily serpentinized due 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 increase sharply in the immediate vicinity of a chromite pod, but drop 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 complex. The VLF-EM method is described in Telford and others (1976), along with the magnetic and seismic

Figure 5. Idealized ophiollite section, showing the position of the chromite pods, taken from Dickey (1975).

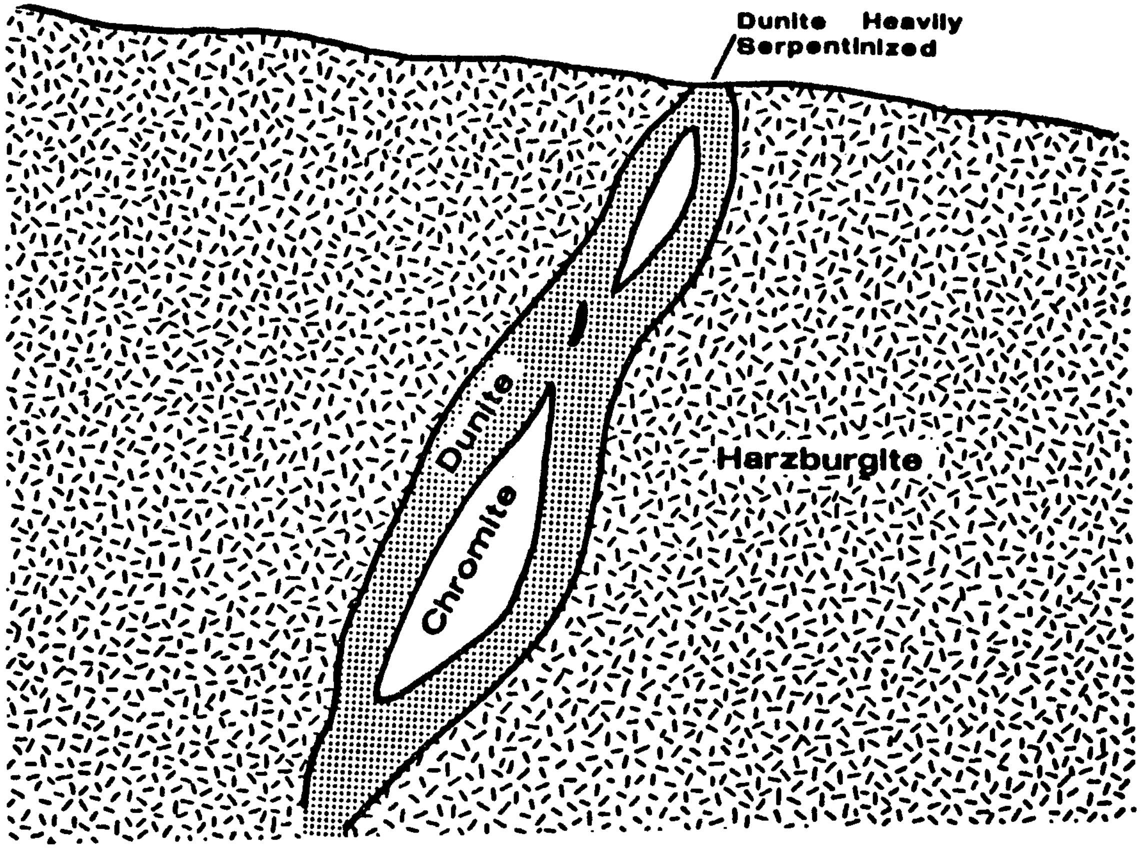
Idealized Ophiolite Section



From Dickey [1975]

Figure 6. Conceptual model (idealized) of a chromite deposit.

Idealized Geology



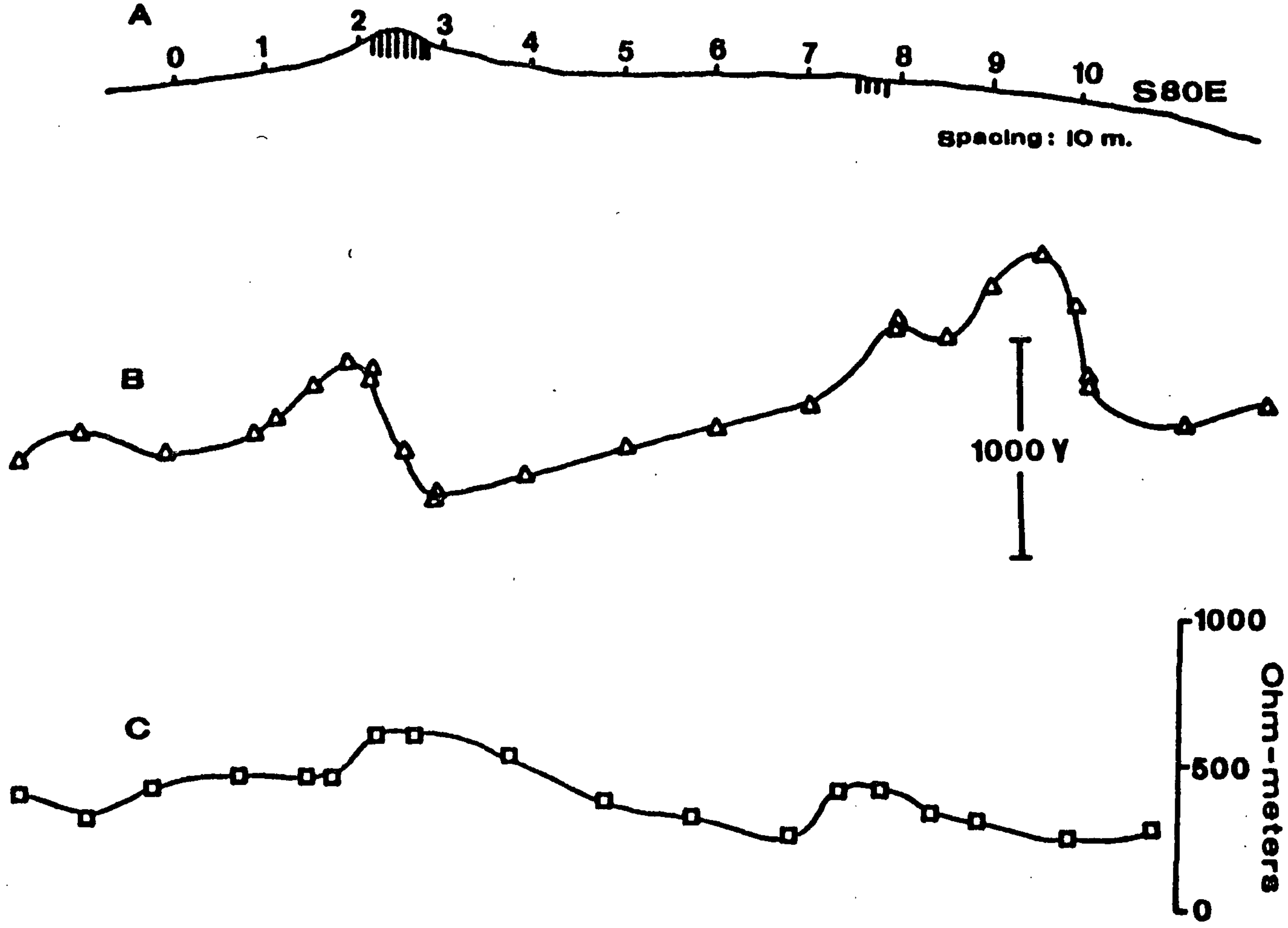
methods. In areas where a target body is within 10-30 m of the surface, the VLF method is often effective in identifying it if sufficient resistive contrast exists, such as at Red Mountain. CR measurements were made at the three principal sites: Brown's Tyson's, and the Red Mountain outcrop deposits. The Tyson's mine CR results were unusable, due to instrumentation problems, and are therefore not included in this paper. The seismic data have not been completely processed due to an intermittent noise problem with the recorder system. These data are recoverable, however, and preliminary results are highly encouraging. The following discussion will cover the Red Mountain outcrop, Tyson's mine, and the Brown's mine in that order.

A. 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 ultramafic sheet (fig. 1). Some dunite is found in contact with the chromite but very little is visible elsewhere at the site, where the ground (except for the chromite outcrops) is 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. 7c) shows resistive highs over both outcrops; crosslines and one parallel line show that these resistive highs are localized around the outcrops. The total field magnetic data (fig. 7b) 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 part of the outcrop. This magnetic low extends eastward through the other (easternmost) outcrop, and then given way to a high followed by another low that is unexplainable from the surface geology. The magnetic low may be

Figure 7. Geophysical traverses over the chromite outcrops at the Red Mountain site, southern extreme of the Josephine complex. A, Topography, unexaggerated scale, chromite outcrops shown with hachurs; B, total-field magnetic profile, showing a magnetic low delmited by the outcrops; C, VLF-EM apparent-resistivity profile, values in ohm-meters, showing resistive highs over both otcrops. Spacing is 10 m between station numbers.


A
0
1
2
3
4
5
6
7
8
9
10
S80E
Spacing: 10 m.
B
1000 γ
C
1000
500
0
Ohm-meters

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 8 shows apparent resistivity and phase-angle pseudosections.[1] These are conventional induced polarization (IP) 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 polarizable than the surrounding peridotite. These data also indicate that eastern outcrop has a finite depth extent, perhaps only 5 m, but that the western 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.

Figure 9b shows a pseudosection of spectral shape response interpreted from CR measurements taken along the traverse. Figure 9c 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 leveled off after 1.0 Hz; therefore the double character representation for a "bent" spectrum. Recalling the discussion about laboratory chromite samples, we were looking

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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 a pyramid centered over the dike, while 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 8. Geophysical traverses over the chromite outcrops at the Red Mountains site, Josephine complex. A, Topography; B, Dipole-dipole apparent-resistivity pseudosection, values in ohm-meters, showing resistivity highs at each outcrop. The eastern outcrop has caused a mdified "pants leg" shape of 500 m separated by the single station in the 200 m range; 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. Spacing is 10 m.

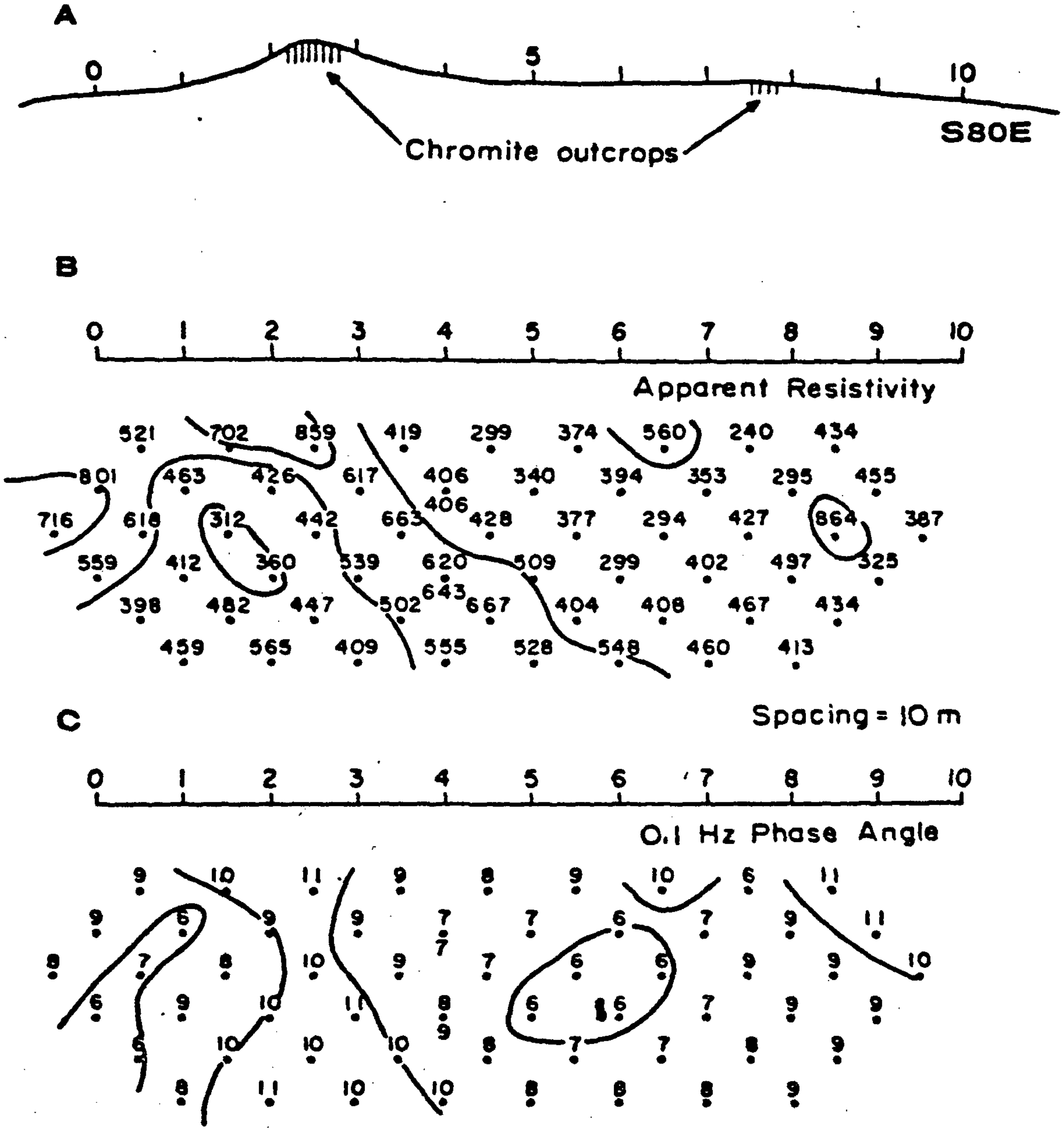
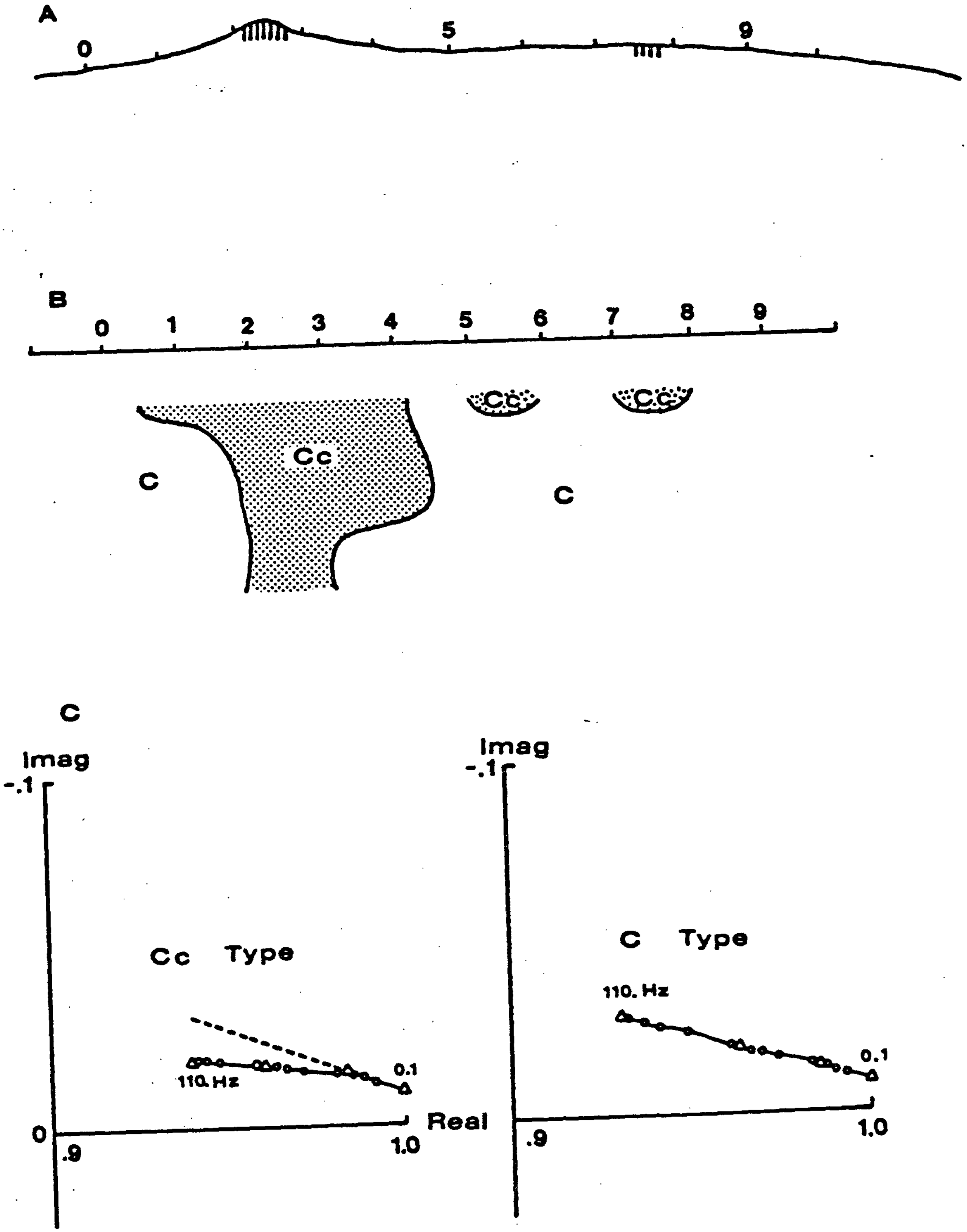

A
0
5
10
Chromite outcrops
S80E
B
0 1 2 3 4 5 6 7 8 9 10
Apparent Resistivity
521 702 859 419 299 374 560 240 434
801 463 426 617 406 340 394 353 295 455
716 618 312 442 663 406 428 377 294 427 864 387
559 412 360 539 620 509 299 402 497 325
398 482 447 502 643 667 404 408 467 434
459 565 409 555 528 548 460 413
C
Spacing = 10 m
0 1 2 3 4 5 6 7 8 9 10
0.1 Hz Phase Angle
9 10 11 9 8 9 10 6 11
9 6 9 9 7 7 6 7 9 11
8 7 8 10 9 7 7 6 6 9 9 10
6 9 10 11 8 6 6 7 9 9
6 10 10 10 9 8 7 7 8 9
8 11 10 10 8 8 8 9

Figure 9. Geophysical traverse over the chromite outcrops at the Red Mountain site, Josephine complex. A, Topography; 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 field data, showing both "C" and "Cc" spectral types.


A
0
5
9
B
0
1
2
3
4
5
6
7
8
9
Cc
Cc
Cc
C
C
C
Imag
-.1
Cc Type
110. Hz
0.1
0
.9
1.0
Real
Imag
-.1
C Type
110. Hz
0.1
.9
1.0

9

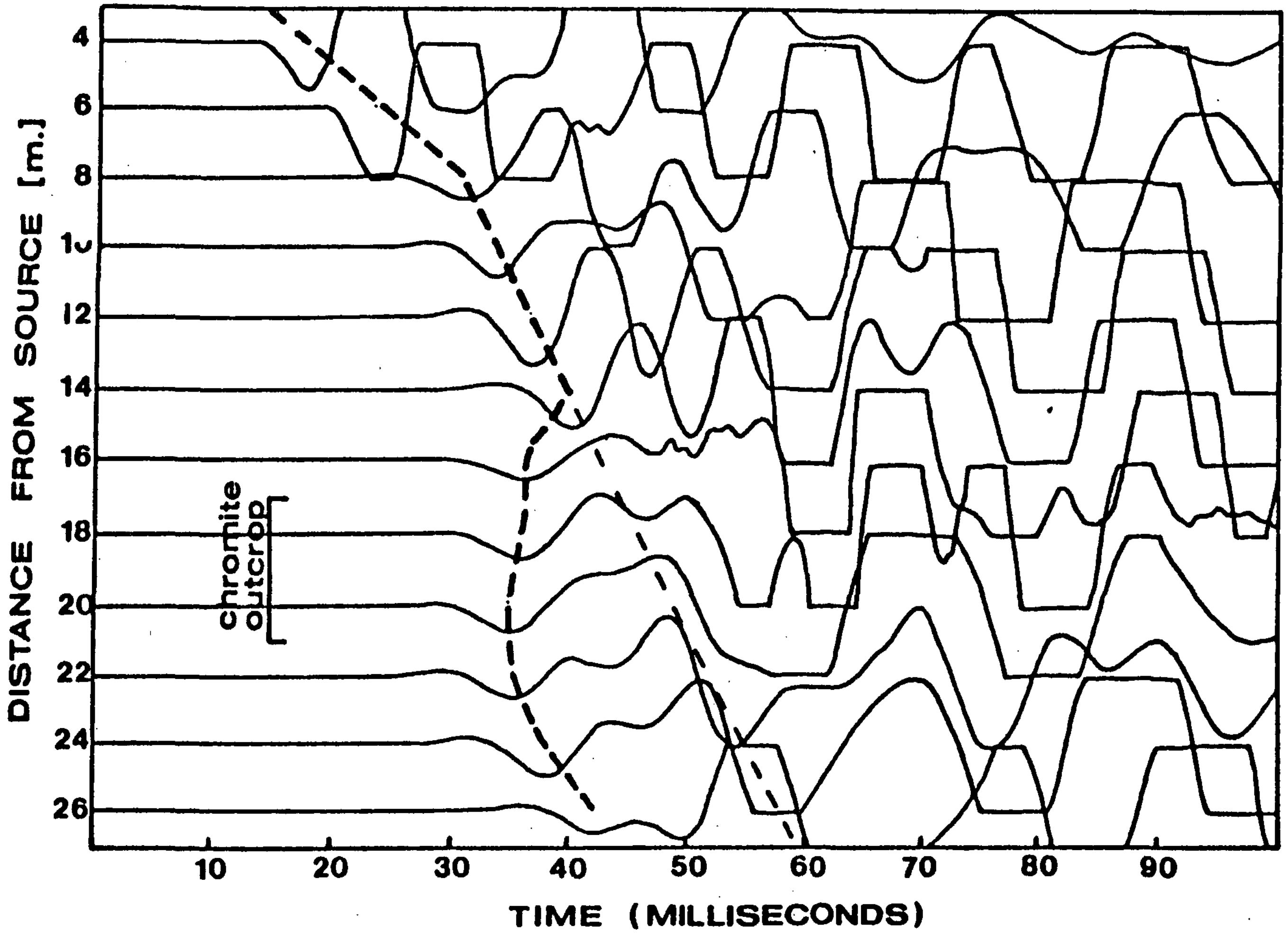
for a "peaked" or "bent" CR spectrum. The "Cc" spectral shape observed beneath the two outcrops is almost certainly the same spectral shape observed in the laboratory for chromite samples. The high-frequency end has not decreased as much in the imaginary component, because the field results are a weighted 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 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 10 and 11 show the results of two shear-wave refraction profiles using a 12-channel portable seismic system over the western outcrop at the Red Mountain (California) site described previously. The data in figure 10 represent a two-layer earth with a sharp variation in the second segment of the travel-time curve over the outcrop. This bulge in the curve is caused by a substantial velocity increase in the chromite. Figure 11 is nearly identical to figure 10, except that the shotpoint is moved to the other side of the outcrop and geophone array to check against the possibility 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 serpentinization in the surrounding rock, consequently an unserpentinized host peridotite might not provide quite so large a velocity contrast.

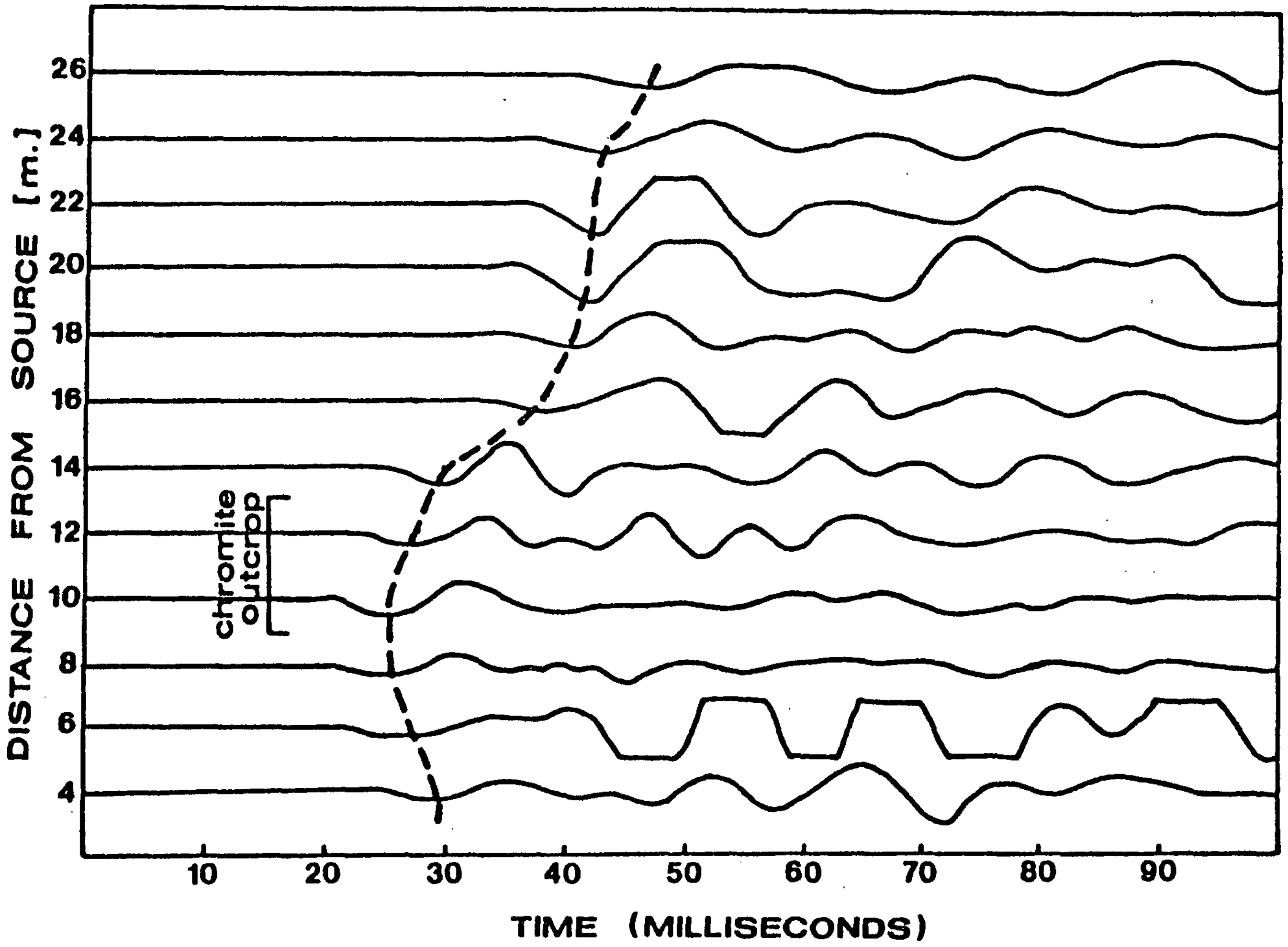
Figure 10. Seismic field records taken over the westernmost (larger) chromite outcrop at the Red Montain site, Josephine complex. Each trace is for a single geophone, spaced 2 m apart, with the topmost traces being from the east side of the outcrop. A very pronounced velocity increase shows up at the chromite outcrop, seen here as a bulge in first-arrival times between traces 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 geophone-trace. A vertical compressional source 0.5 m deep was used.

a)



DISTANCE FROM SOURCE [m.]
4
6
8
10
12
14
16
18
20
22
24
26
chromite outcrop
10
20
30
40
50
60
70
80
90
TIME (MILLISECONDS)

Figure 11. Seismic field records taken over the westernmost chromite outcrop at the Red Mountain site, Josephine complex. The only difference between figures 10 and 11 is the location of the shot point. Figure 11 is the reverse-direction analog of figure 10, with the shot point being located 4 m to the west f the number 12 (bottom of page) geophone-trace. The chromite shows up again as a bulge, in this case between traces 4 and 14.


DISTANCE FROM SOURCE [m.]
26
24
22
20
18
16
14
12
10
8
6
4
chromite outcrop
10
20
30
40
50
60
70
80
90
TIME (MILLISECONDS)

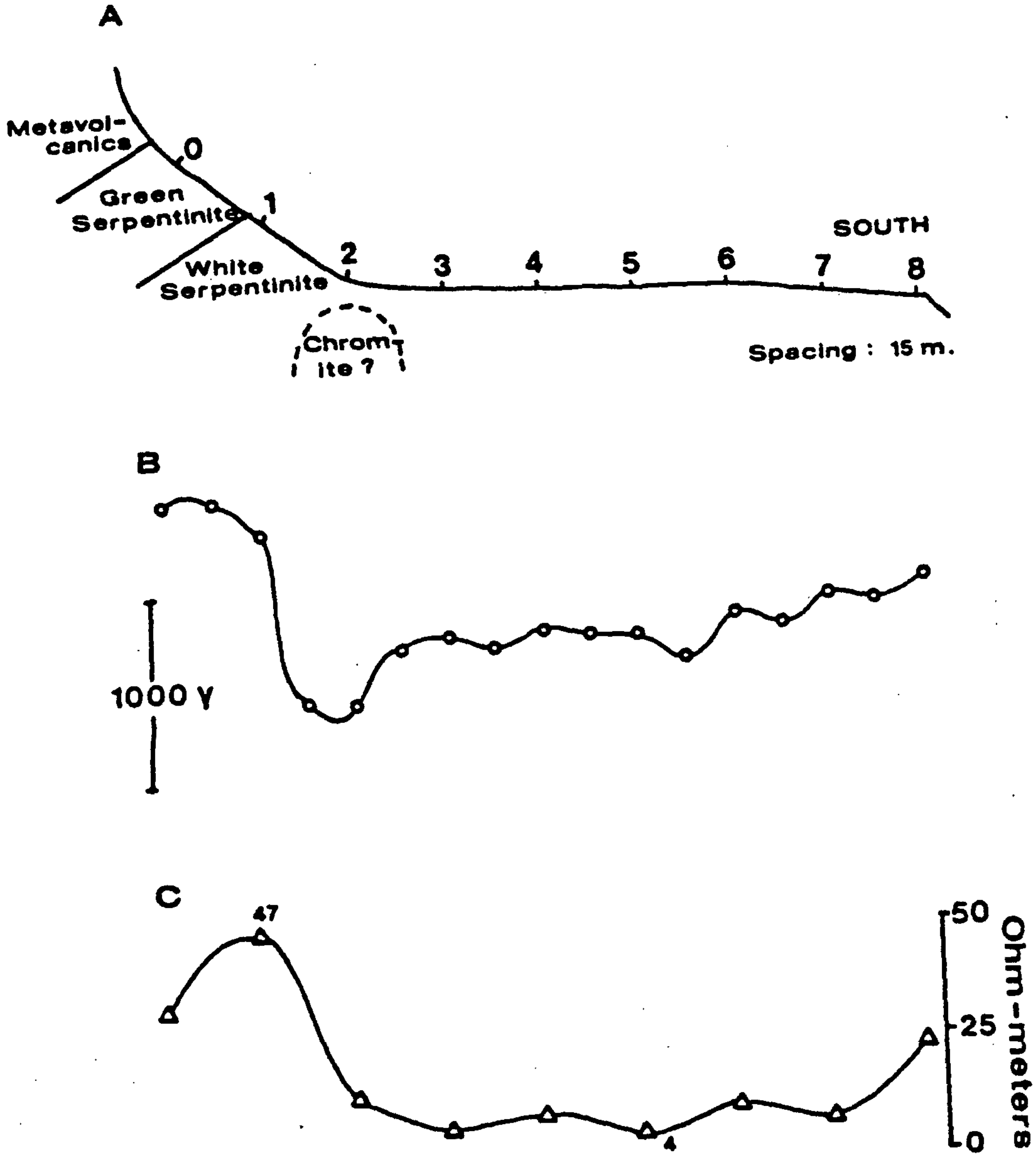
The full results of seismic measurements at the Red Mountain site, and results at the other two mines and a fourth experimental location, are the subject of a subsequent paper. It appears, however, that the chromite deposits at Red Mountain give resistivity, magnetic, phase-angle, spectral-shape, and 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.

B. 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 ultramafic sheet (fig. 1). 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 ohiolite stratigraphic section. Serpentinization of the two units below the greenstone is nearly complete.

Figure 12 shows the topography, the geologic relatioships, 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 unusually low in comparison to the other sites visited, over

Figure 12. Geophysical traverses at Tyson's mine, south-central part of the Josephine complex. A, Topography and geology, unexaggerated scale, showing inferred location of the chromite pod; B, Total-field magnetic profile, showing a 500 nT low over the chromite deposit; C, VLF-EM apparent-resistivity profile, values in ohm-meters, showing unusually laow resistivities in the serpentinite.


A
Metavol-
canics
0
Green
Serpentinite
1
White
Serpentinite
2
3
4
5
6
7
8
SOUTH
Chrom-
ite ?
Spacing : 15 m.
B
1000 γ
C
47
4
50
25
0
Ohm-meters

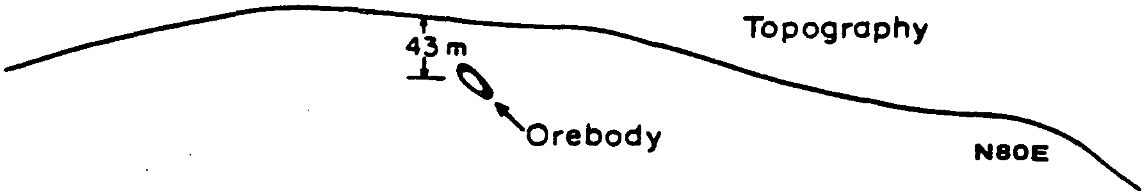
the entire length of the traverse. The entire surface has been exposed by hydraulic mining methods, and the serpentinization is extensive, often reaching 100 percent in hand-sample examination. There is a broad resistivity low over the expsed areas of white serpentine, but apparently no influence or effect from the chromite pod can be discerned in the resistivity data.

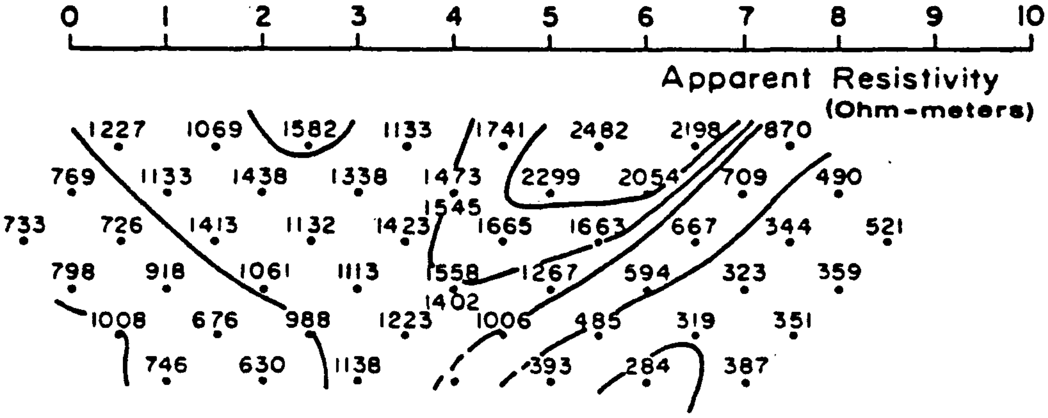
C. Brown's mine

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 bands of dunite that generally strike north-soth. In the area of the mine, there is a gentle 15° to 20° eastward dip in the foliation of pyroxene crystals in the harzburgite groundmass. The degree of serpentinization is on the order of 40 percent, with occasional sections where it abruptly approaches 100 percent. The chromite itself was exposed by weathering on the north side of a steep ravine. It is massive, typically 95 percent chromitite, with 5 percent interstitial minerals made up largely of pargasite(?) and zoesite. About half of the estimated 25,000 t of chromite ore was mined out by the end of World War II.

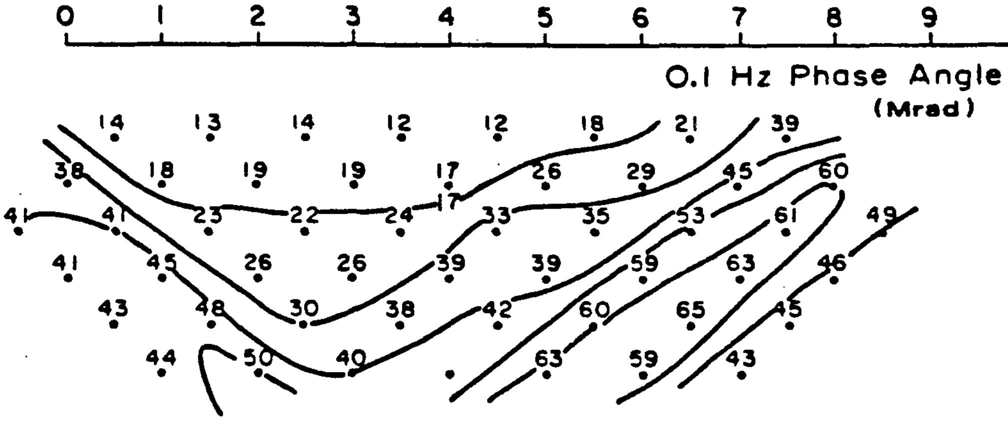
Figure 13 shows a topographic profile, and the apparent resistivity and phase-angle pseudosections. The data were obtained on a line about 40 to 45 m above the known extensions of the remaining ore; the location was obtained from old mine maps and from on-site observations. The apparent resistivity pseudosection shows resistivities ranging from 300 to 2,500 ohm-meters. These values are much higher than those obtained at Tyson's mine, and even higher than the resistivities at the Red Mountain outcrop, but not unreasonable for a mildly serpentinized peridotite. The two diagonals in figure 13B show that lower resistivity values are caused by patches of highly serpentinized

Figure 13. Geophysical traverses over the chromite deposit at Brown's mine, central part of the Josephine complex. A, Topography, unexaggerated scale, showing the inferred location of the orebody. There is a gentle 15° eastern dip in the foliation of pyroxene-rich zones in the harzburgite mass; B, Dipole-dipole apparent-resistivity pseudosection, values in ohm-meters, showing the strong effects of serpentine at each end; C, Dipole-dipole phase-angle pseudosection, values in milliradians for 0.1 hz, showing an anomalous feature in the center at the 45 milliradian point. Spacing between stations is 60 m.


Topography
43 m
Orebody
N80E


0 1 2 3 4 5 6 7 8 9 10
Apparent Resistivity
(Ohm-meters)
1227 1069 1582 1133 1741 2482 2198 870
769 1133 1438 1338 1473 2299 2054 709 490
1545
733 726 1413 1132 1423 1665 1663 667 344 521
798 918 1061 1113 1558 1267 594 323 359
1402
1008 676 988 1223 1006 485 319 351
746 630 1138 393 284 387

Spacing = 60 m


0 1 2 3 4 5 6 7 8 9 10
0.1 Hz Phase Angle
(Mrad)
14 13 14 12 12 18 21 39
38 18 19 19 17 26 29 45 60
17
41 41 23 22 24 33 35 53 61 49
41 45 26 26 39 39 59 63 46
43 48 30 38 42 60 65 45
44 50 40 63 59 43

peridotite exposed at the surface and apparently extending to depth, at each end of the CR traverse.

Figure 13C shows the phase-angle pseudosection, where the same diagonals that showed lower resistivities in figure 12B 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 information 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 down dip was suspected by the operators at the time the mine was shut down, but undertainties 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.

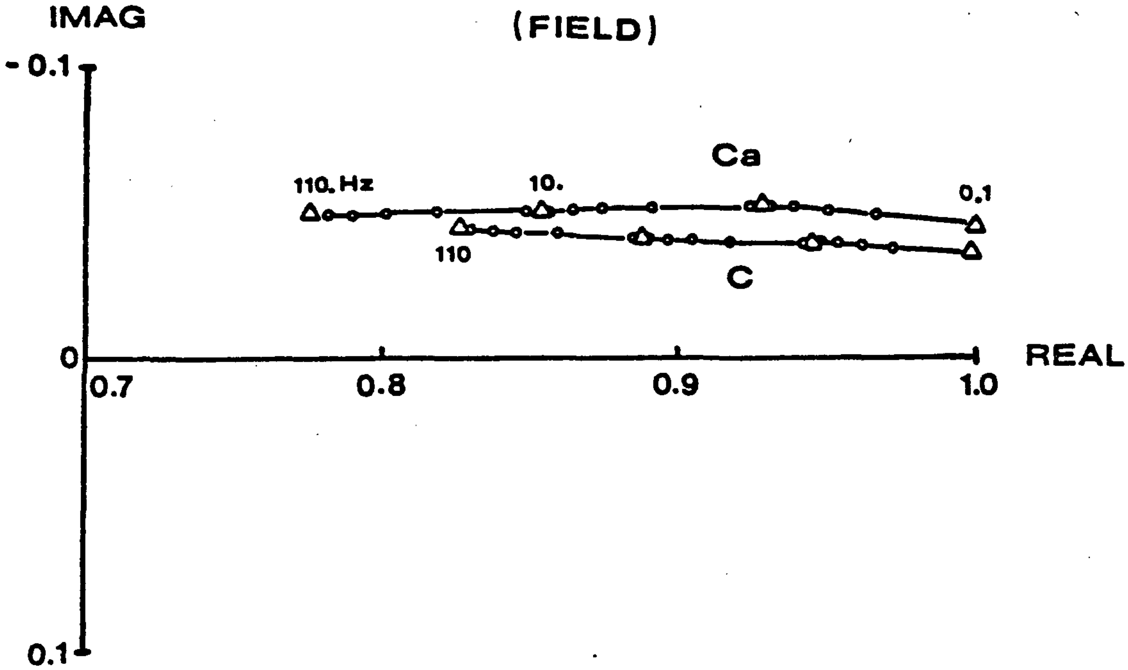
Figure 14 shows representative Argand diagrams of CR spectra observed in field data from Brown's mine. These spectra are labeled according to the convention described previously, adding several new classifications to incorporate a decreasing imaginary component with increasing frequency ("A" and "a"), and a null response typical of unaltered, unmineralized peridotite ("n"). The spectral shape of most interest is the "Ca" curve on the 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 14. Complex resistivity spectral types from the field data are collected over the Brown's mine target, Josephine complex. These spectra are arch types with letter designations plotted in figure 15 and discussed in the text.

BROWN'S MINE

SPECTRAL TYPE

(FIELD)



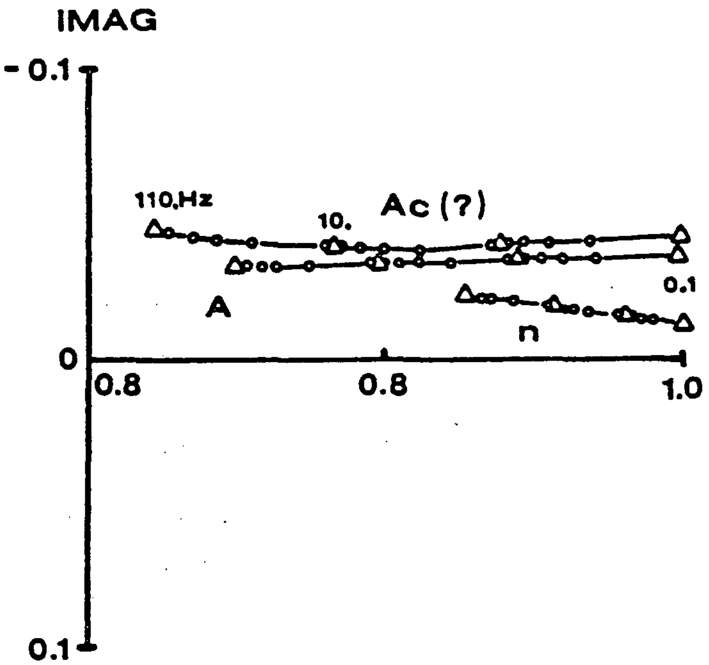
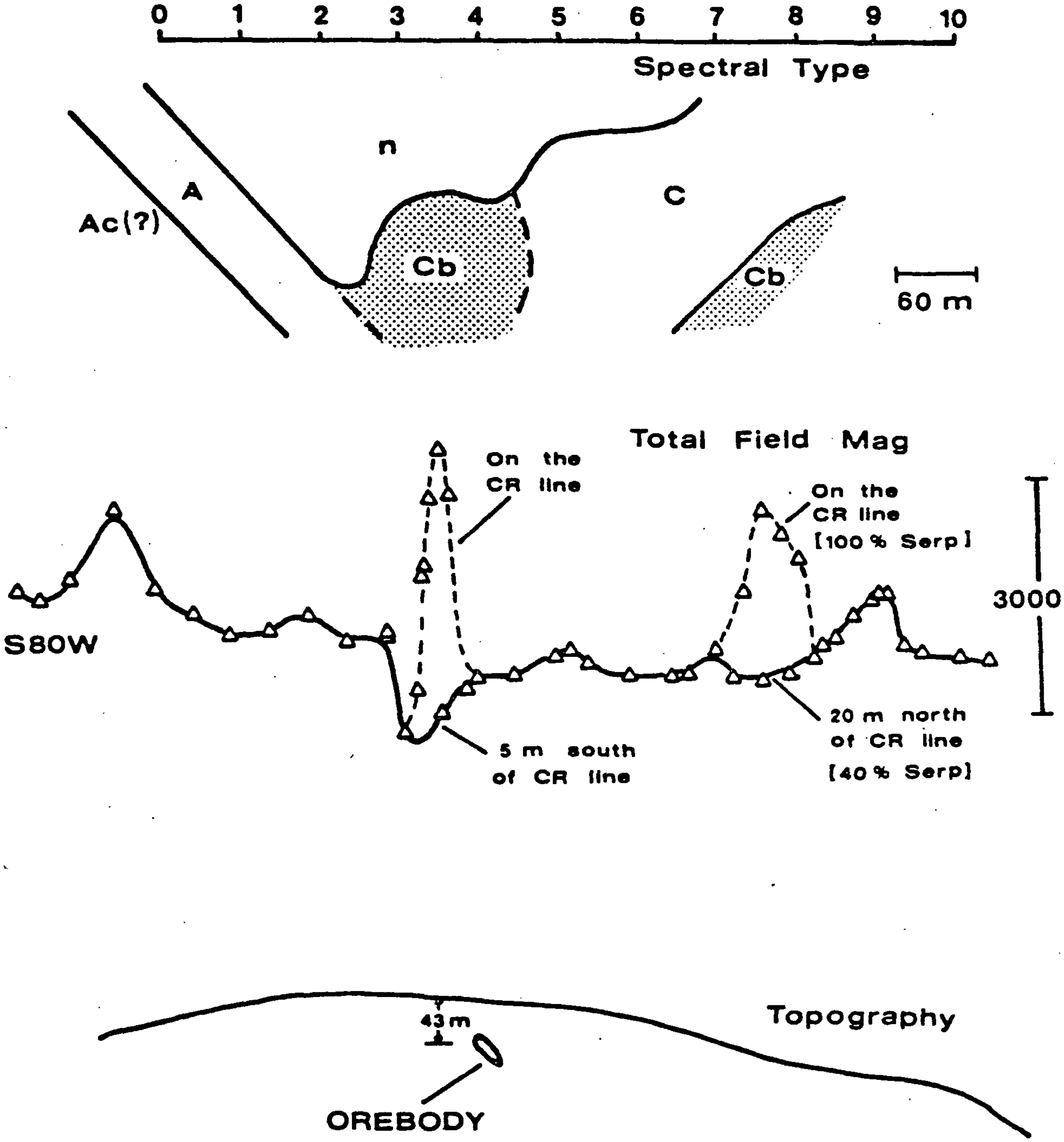


Figure 15 shows the interpreted spectral shape pseudosection for Brown's mine. The "C" and the "A" contributions appear to be caused by an increase in serpentine; why two different contributions exist is not understood; more complete subsurface geologic information along the line might supply an explanation. In the center of the pseudosection a discrete block of "Cb" spectra is located at and extending slightly <u>west</u> 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 <u>indirect</u>, and therefore at 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 completelness, the total field magnetic profile has been included in figure 15. 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

Figure 15. Geophysical traverses over the chromite deposit at Brown's mine, Josephine complex. A, Topography; B, Complex resistivity spectral-type pseudosection, showing the "Ca" shape apparently pinpointing the chromite deposit below the center of the lne; C, Total-field magnetic profile, showing the strong effects of serpentine, partially masking a possible low over the chromite deposit.

BROWN'S MINE


0 1 2 3 4 5 6 7 8 9 10
Spectral Type
n
A
Ac(?)
C
Cb
Cb
60 m
Total Field Mag
On the CR line
On the CR line [100 % Serp]
3000γ
S80W
5 m south of CR line
20 m north of CR line [40 % Serp]
Topography
43 m
OREBODY

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 dta all have correlatable anomalies. In all case, 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 ultramafic complex, 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 Josephine chromites 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 for 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 processes as of this writing, 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" 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 serparate its electrical and magnetic signature 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. Research is underway to add the important adverb "economically" to the previous sentence.

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