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Codicil to

The Geophysical Expression of Selected Mineral Deposit Models

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INTRODUCTION

by

William D. Heran

This compilation of geophysical mineral deposit models is an extension of USGS Open-File Report 92-557, The Geophysical Expression of Selected Mineral Deposit Models, D.B. Hoover, W.D. Heran and P.L. Hill editors. Open-File Report 92-557 was designed as a companion volume to U.S. Geological Survey Bulletin 1693, Mineral Deposit Models (Cox and Singer, 1986), USGS Open-File Report 91-11A (Orris and Bliss, 1991), and USGS Bulletin 2004 (Bliss, 1992). Mineral Deposit Models (Bulletin 1693) is a compilation of descriptive geologic attributes of approximately 90 mineral deposits, arranged in a litho-tectonic classification. The geophysical characteristics compiled here and in OF 92-557 are an important component of the continuously evolving deposit model compilation and therefore complement the previously published geologic characteristics. The purpose of the geophysical deposit models are to provide, where possible, quantitative values of physical properties and their ranges, of deposits and host rocks, in order to facilitate quantitative modeling of the geophysical response.

The use of multi-technique geophysical data allows a three-dimensional model of the subsurface, yet data acquisition usually leaves the surface undisturbed. Exploration for, and assessment of, mineral deposits has focused on deeper deposits or those that may be hidden by considerable cover. Geophysical methods can play an important part in the search for obscure or hidden mineral deposits and can optimize the selection of drilling-targets.

The geophysical models follow a similar format given in Bulletin 1693 and retain the same alphanumeric model numbers for the deposit types. The geophysical model format, briefly summarizes the geologic characteristics, given in Bulletin 1693, gives the regional scale geophysical expression, the deposit scale characteristics, physical property values of the deposit and host rocks, remote sensing characteristics and an extensive reference list. The physical properties covered include, density, porosity, magnetic susceptibility and remanence, seismic velocity, electrical properties, optical properties, thermal properties, and radioelement content. The quantitative values given for each deposit model are usually in-situ measurements and not laboratory or drill core values. The physical property values for many host and cover rocks are contained in the introductory section of OF 92-557. The reference list contains what the author considered the more relevant publications, and the reader may use it for further detail. Illustrations, some from the literature, showing typical responses of various methods over deposits are given for each model.

This report contains three new geophysical models which cover six of the Cox and Singer models and one revised geophysical model. The geophysical models may in some cases cover several related geologic models lumped together due to the similarity of geophysical signatures or lack of data on which to separate them geophysically. The models presented here are:

1. Geophysical Model of Massive Sulfides, covering; Cyprus type (Cox and Singer no. 24a); Besshi type (Cox and Singer no. 24b); Kuroko type (Cox and Singer no. 28a)
2. Geophysical Model of Chromite Deposits, covering; Bushveld type (Cox and Singer no. 2a); Podiform type (Cox and Singer no. 8)
3. Geophysical Model of Bedded Barite covering; Bedded Barite (Cox and Singer no. 31b)
4. Revised Geophysical Model of Diamond Pipes, covering Diamond Pipes (Cox and Singer no. 12)

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4. Orris, G.J., and Bliss, J.D., eds., 1991, Some Industrial Mineral Deposit Models: Descriptive Deposit Models: U.S. Geological Survey Open-File Report 91-11A, 73 p.

GEOPHYSICAL MODEL OF MASSIVE SULFIDE DEPOSITS

COX AND SINGER MODEL Nos. 24a, 24b, 28a Compiler - **W.D. Heran**

A. Geologic Setting
Three major deposit types are included:

- Cyprus - hosted in marine mafic extrusive rocks
- Besshi - hosted in marine mafic extrusive rocks
- Kuroko - hosted in marine felsic to mafic extrusive rocks

Cyprus Massive Sulfide: Within ophiolite assemblage, commonly above diabase dikes localized within pillow basalts or mafic volcanic breccia. Deposits are podlike massive, iron, copper and zinc sulfides with an underlying sulfide stringer zone. May be adjacent to steep normal faults and overlain by Fe-rich bedded marine sediments (ochre).

Besshi Massive Sulfide: Possibly related to submarine hot springs and associated basaltic volcanism within rifted basin of volcanic island arc or back arc setting. Usually hosted in thinly laminated clastic terrigenous sediments or mafic tuffs. Deposits are thin, sheetlike bodies of massive to well-laminated sulfides, laterally extensive and tend to cluster in en echelon patterns. All known deposits occur in strongly deformed metamorphic terranes.

Kuroko Massive Sulfide: Within calc-alkaline volcanic island arc systems and Archean greenstone belts. Common near center and felsic top of volcanic-sedimentary sequence with tendency to occur in close proximity to each other or clusters. Pyritic siliceous rock (exhalite) may be marker horizon. Distinctly vertically zoned, massive copper- and zinc-sulfide bearing, stratiform body with underlying veins and stockwork of disseminated sulfides.

Note: all three types upon weathering may produce yellow, red and brown limonitic gossans.

B. Geologic Environment Definition
Remote sensing methods can help detect and map the extent of ultramafic belts and intrusive complexes by overall reflectance (albedo), thermal properties and geobotanical changes (Harrington, 1991; Longshaw and Gilbertson, 1975). Landsat TM data have been utilized to map and subdivide units of the Semail ophiolite in Oman (Abrams, 1987). Landsat TM data have been used on a regional and local scale to recognize syn- and post-volcanic structures, including first and second-order lineament faults and shear zones in Canadian greenstone belts (Carboni and others, 1991). TM data were used to map lithologies, limonitic and gossan surfaces and integrated with panchromatic air photos providing structural data and locations of volcanic centers (Volk and others, 1987). Aircraft multispectral scanner data have successfully mapped the distribution of iron-oxide species over known gossan outcrop in Australia (Fraser and others, 1987).

Aeromagnetic and regional gravity data have been used to define tectonic terranes in northern Michigan and Wisconsin (Klasner and others, 1985). High-resolution aeromagnetic surveys were useful in interpreting Precambrian bedrock beneath glacial cover in Minnesota (Chandler, 1985). Enhanced high resolution aeromagnetic and VLF data were utilized to map lithology and regional faults in the central volcanic belt near Buchans, Newfoundland (Kilfoil, 1989). Ophiolite belts are characterized by aeromagnetic data as en echelon belts of short wavelength, high gradient anomalies (Heinz, 1989), and chains of narrow local positive and negative anomalies (Menaker, 1981). Greenstone belts may be defined in aeromagnetic surveys as a regional magnetic low if the belt is magnetite-deficient, in other cases a high if it is magnetite-rich (Grant, 1985; Isles, Harman and Cunneen, 1988). A statistical analysis of regional magnetic and gravimetric parameters were used to evaluate regional deposit potential in greenstone areas in Canada (Favini and Assad, 1974). Regional gravity was used to define thrust faults in an island-arc terrane in Canada (Wilson and Brisbin, 1960). Airborne electromagnetic surveys have been widely used in favorable terrains for finding conductors (Seigel, 1977; Klein and Lajoie, 1992; Ward, 1967; 1970) and can be credited for the discovery of numerous massive sulfide deposits in Canada (Paterson, 1966; 1967; Fleming and Brooks, 1960; Mackay and Paterson, 1959; Podolsky, 1966) and Wisconsin (Schnenk, 1977; May and Schmidt, 1982; Mudrey and others, 1991).

C. Deposit Definition

Massive sulfide bodies are defined as a single mass containing between 50-80% metallic sulfide minerals. This fact almost always lends to a higher electrical contrast relative to its host. A variety of ground EM methods have been successfully applied, as follow-up to airborne surveys, including the frequency and time domain methods utilizing a broad band of frequencies and employing several coil configurations (Ward, 1966, 1979; Crone, 1966, 1979; and Strangway, 1966; McCracken, 1981; Klein and Jajoie, 1992; Zonge, 1992; Sinha and Stephens, 1987). Other electrical methods such as SP (Cifali and Whiteley, 1981; Moss and Perkins, 1981), resistivity (Quick and Cifali, 1981; Tyne and Whiteley, 1981), and IP (Hallof, 1966; 1992) have been widely used to locate and define deposit parameters. The presence of pyrrhotite and/or magnetite in the mineral assemblage of the deposit (not always present) may cause a magnetic contrast with the host rock. Ground magnetic surveys are commonly used (Hood and others, 1979) if a subtle or strong airborne magnetic anomaly is obtained, to locate or outline ore zones. The magnetic method is credited for the discovery of the Pima ore body in Arizona (Heinrichs and Thurmond, 1956). Another inherent physical property of the massive sulfide is high density of the ore minerals. The gravity method although not normally used as a primary tool can play an important role in an integrated effort to check EM or electrical anomalies (Tanner and Gibb, 1979; West, 1992; Boyd and others, 1975; Barbour and Thurlow, 1982), outline the deposit, or estimate ore reserves (Templeton, 1981). A 2.8 mgal anomaly was obtained over the Faro deposit NWT Canada (Brock, 1973). Seismic refraction and reflection surveys have been used to map fault structures (Spencer and others, 1993) map ore zones (Cooksley, 1992) and as a screening method to distinguish between shallow orebodies and conductive shales or graphite zones (Hawkins and Whitely, 1981). Downhole electrical and gamma radiation methods were used at the Woodlawn deposit, Australia to effectively outline the deposit and log lithologies (Templeton and others, 1981; Hone and Young, 1981).

D. **Size and Shape of**	**Shape**	**Average Size/Range**
Deposit	lenticular to sheetlike; stringer, stockwork	$8.2\text{x}10^5\text{m}^3/5.1\text{x}10^4\text{-}8.7\text{x}10^6\text{m}^3$
Alteration	stringer zone or blanketing	

E. **Physical Properties** (units)	**Deposit**	**Alteration**	**Host**
1. Density (gm/cc)	3.9, 3-4.5[2]		*
2. Porosity (%)	.35, .2-.5[2]		*

3. Susceptibility (10^{-6} cgs)	1200, 0-5400[2]	*
4. Remanence (mA/m)	.8, .2-1.0[32]	*
5. Resistivity (ohm-m)	1, .01-6[2]	*
6. IP Effect chargeability (mv-sec/v)	45, 16-125[2]	*
percent freq. effect (PFE)	5, 0-200[32]	*
7. Seismic Velocity km/sec	1.4, 1.1-1.8[32] 3.2[10]	*
8. Radiometric		
K (%)	low-moderate	*
U (ppm)	low	*
Th (ppm)	low	*

F. Remote Sensing Characteristics

Visible and near IR: Iron-oxide species (goethite, hematite, etc.) have unique reflectance spectra and can be distinguished from other alteration or weathering products (Hunt, 1979). Near-infrared spectra (800-2500 nm) have been utilized to distinguish true and false gossans (Raines and others, 1985). Color composite images from Landsat MSS band ratio data have been used to successfully map ferric iron-bearing rocks (Segal, 1983). Airborne multispectral scanners have been applied to map rock types, soils, alteration and gossans in Australia (Fraser and others, 1987; Honey and Daniels 1986).

G. Comments

Ground follow-up surveys following regional exploration must eliminate extraneous sources of anomalies such as conductive graphitic zones. The choice of techniques to apply first will vary depending on host environment, minerals present, structural controls and target depth. The normally high electrical conductivity of massive sulfides makes the electrical or electromagnetic methods most frequently used (Ward, 1966). The electromagnetic method has been successfully used since the early 1920's (Ward, 1979; Moss and Perkins, 1981). Gravity, magnetics and seismic methods are commonly used in an integrated exploration program. In general massive sulfide bodies are very dense, typically very conductive and frequently magnetic (Ward, 1966). Several geophysical case histories to note are: SEG Mining Geophysics, 1966; Case Histories of Mineral Discoveries, v. 3, AIME, 1991; and Geophysical Case Study of the Woodlawn orebody, New S. Wales, Australia, 1981.

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AIRBORNE ELECTROMAGNETICS (AEM)

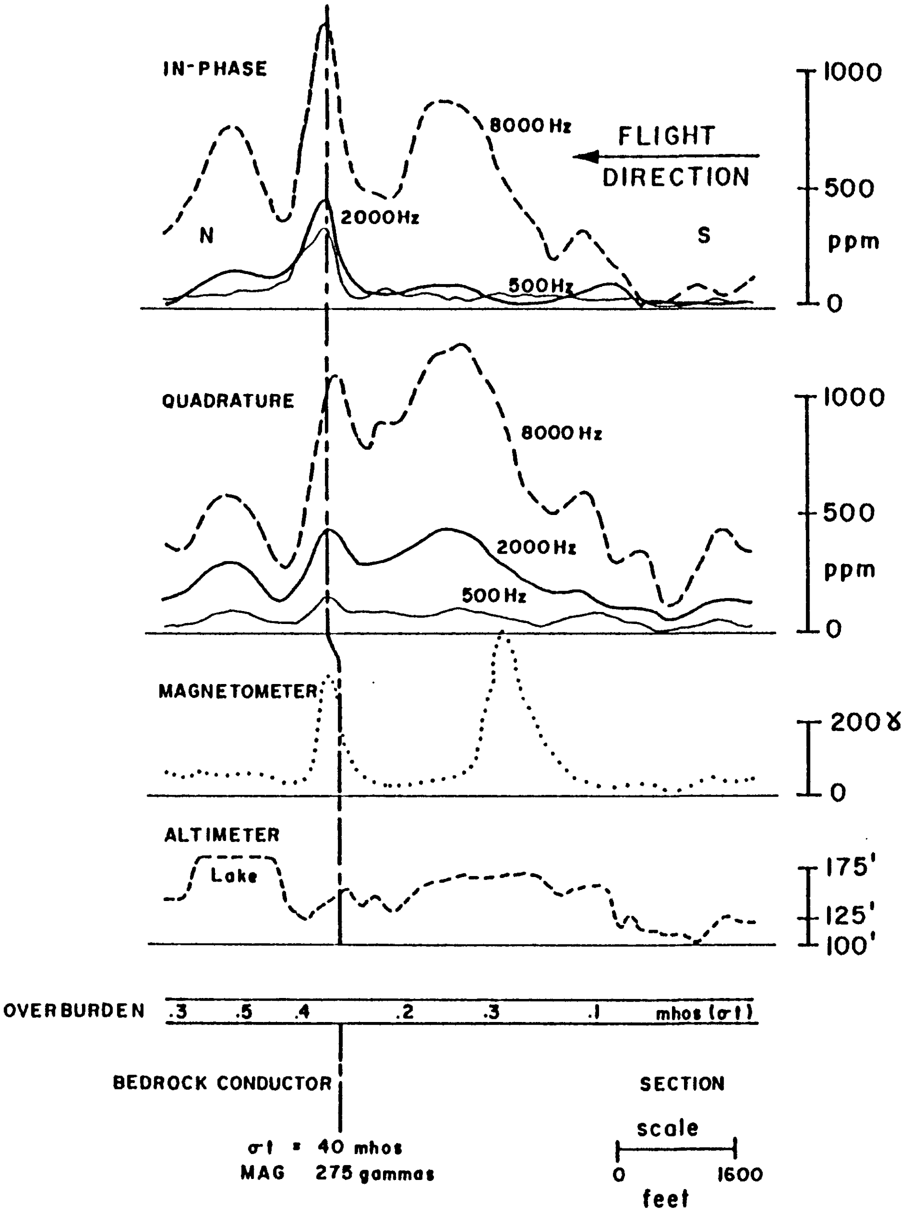


Figure 1. Three-frequency airborne electromagnetic (AEM), and magnetic data over the New Insco massive sulfide deposit, Quebec, Canada. (modified from Becker, 1979)

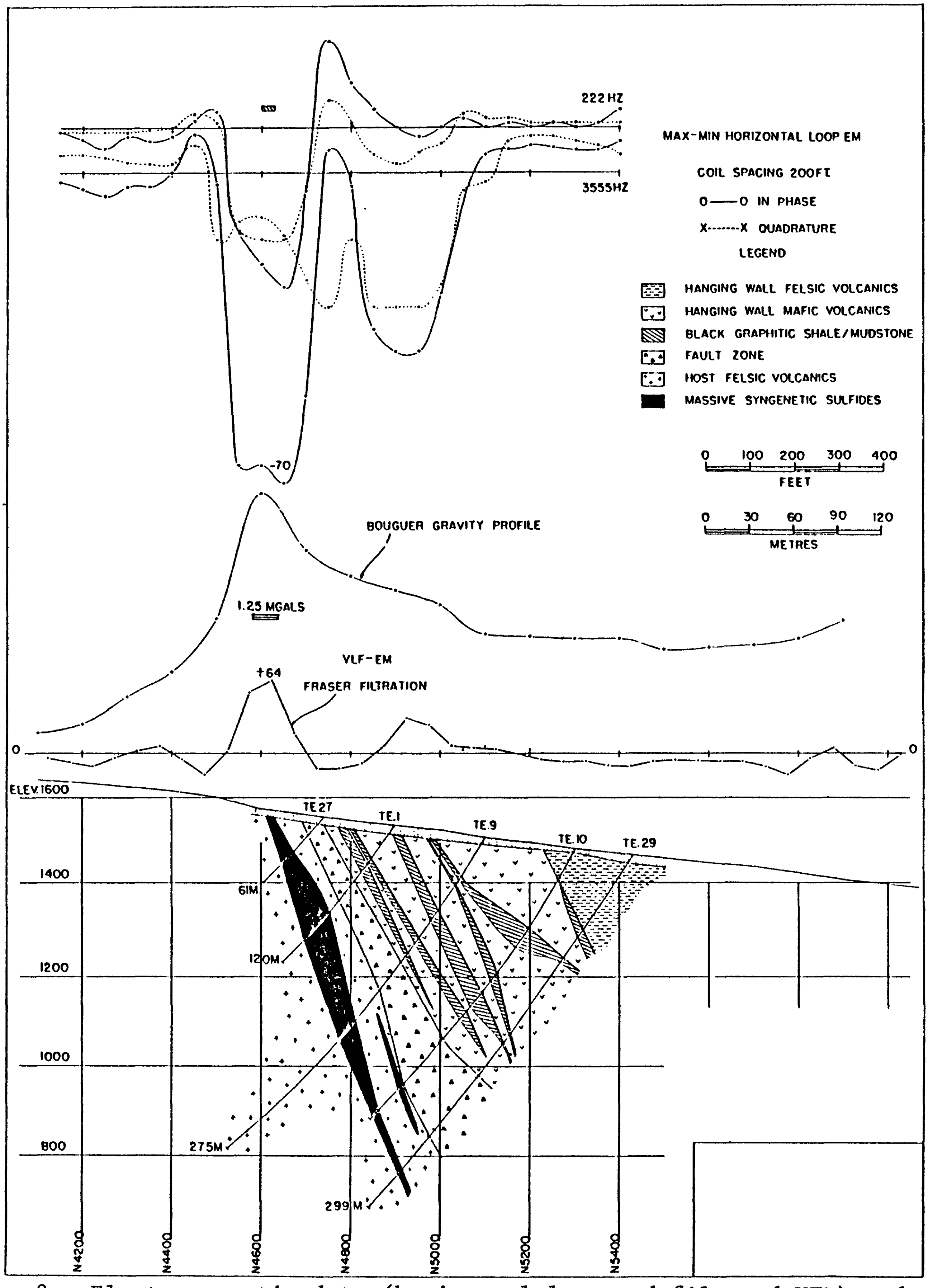
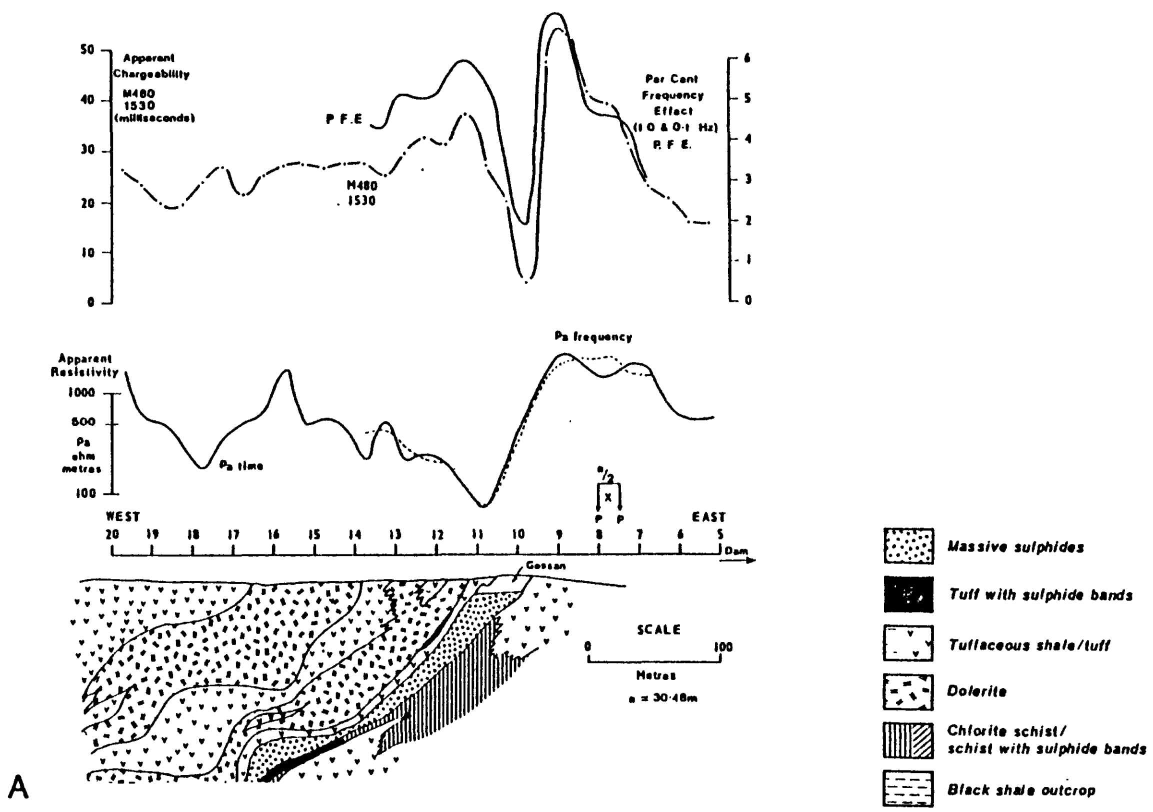


Figure 2. Electromagnetic data (horizontal loop and filtered VFL) and Bouguer gravity profile over the Tulks East massive sulfide, Newfoundland. (modified from Barbour and Thurlow, 1982)

INDUCED POLARIZATION



SELF POTENTIAL

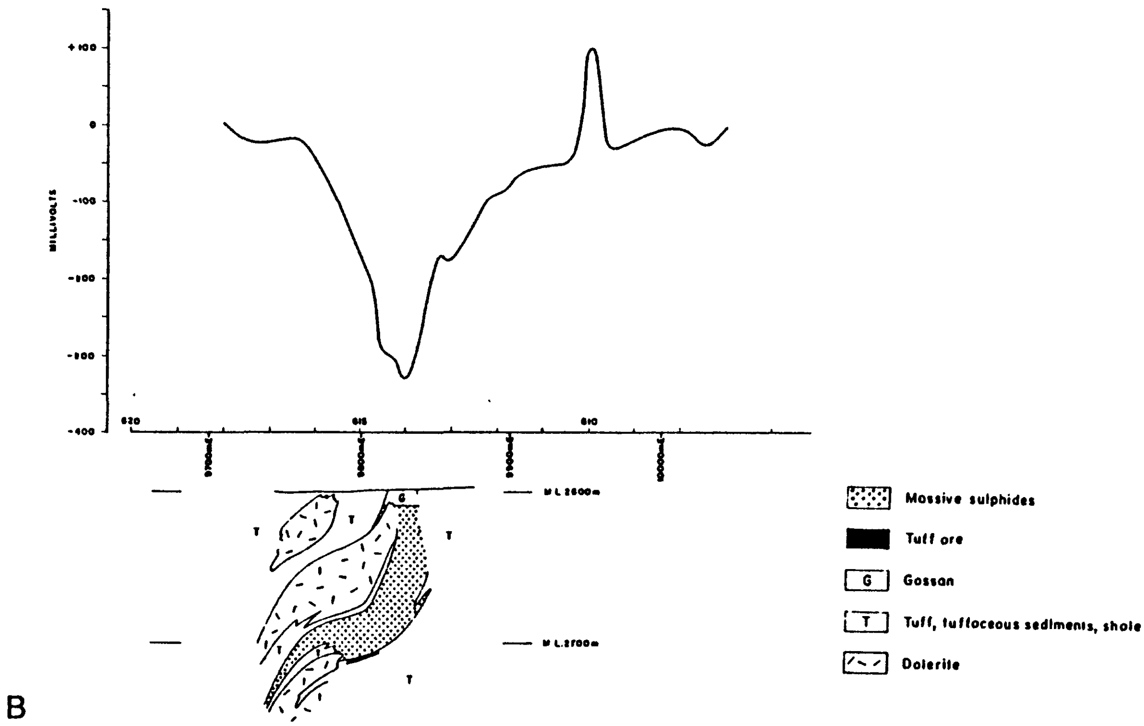


Figure 3. Electrical surveys over the Woodlawn orebody. New South Wales, Australia. (A) Induced Polarization (IP) using gradient array in both time and frequency domain. (B) Self-potential profile showing an intense negative anomaly with a magnitude of about 300 mV. (modified from Cifali and Whitely, 1981; Tyne and Whitely, 1981)

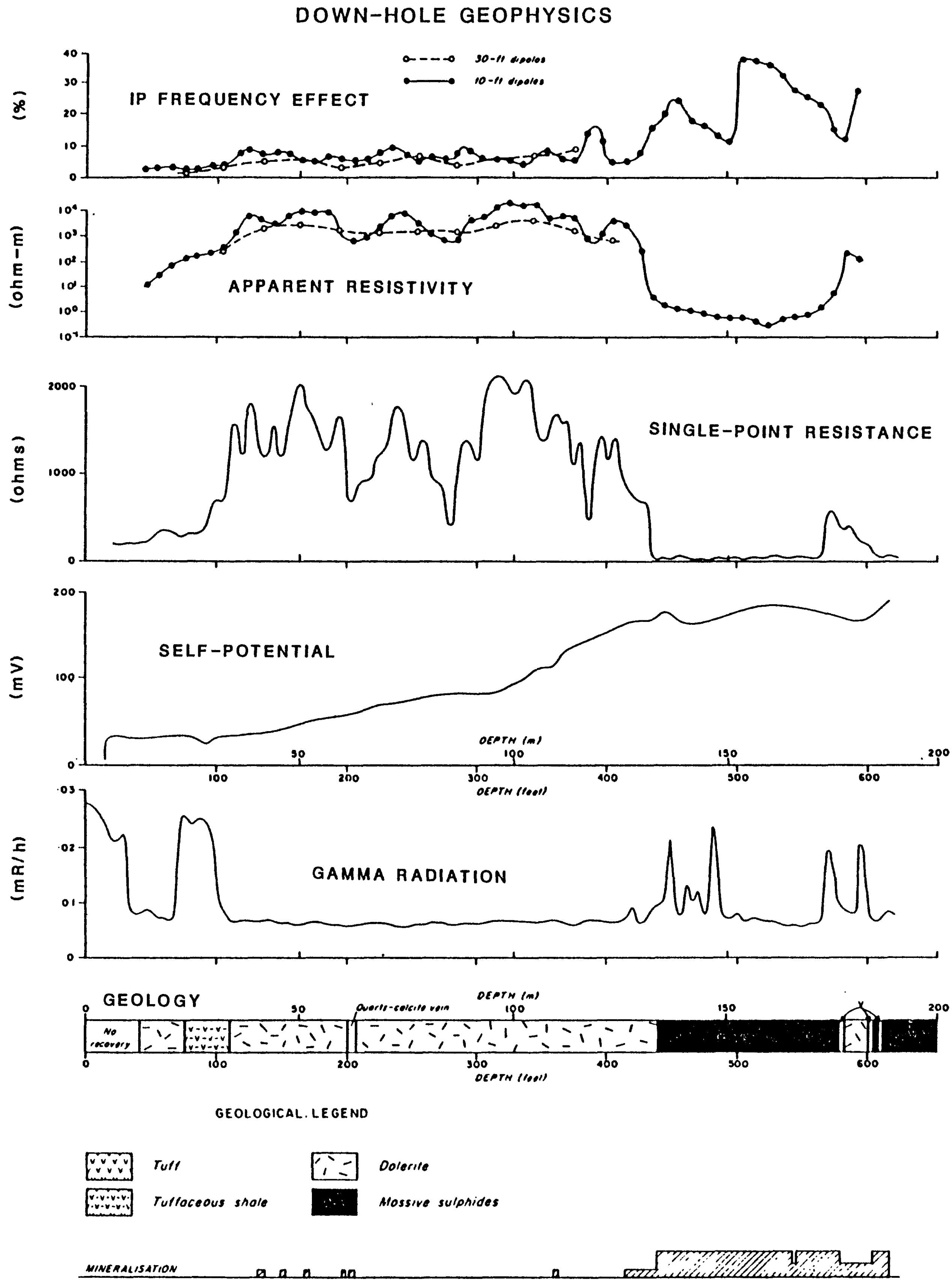


Figure 4. Drill hole electrical (frequency effect, apparent resistivity, single point resistance, self-potential) and gamma radiation logs along with drill core lithology from hole U256, Woodlawn orebody, New South Wales, Australia. (modified from Hone and Young, 1981)

GEOPHYSICAL RESPONSES OVER WOODLAWN

GEOPHYSICAL METHOD	NATURE OF GEOPHYSICAL RESPONSE				
	WEAK	MODERATE	STRONG	SIMPLE	COMPLEX
AIRBORNE					
Magnetics			NO ANOMALY		
HEM	###########				##########
Input		############			##########
Dighem II		##############		########	
GROUND					
Electromagnetic (cw)			#######	########	
VLF		#############		########	
AFMAG			#######	########	
Audio MT					#########
Dip Angle					
Broadside	###########				
Fixed Transmitter			#######	########	
Slingram			#######	########	
Turam					
Large Loop			#######	########	
Small Loop			#######	########	
Electromagnetic (pulse)					
Crone PEM			#######	########	
Newmont EMP			#######	########	
MPPO 1			#######	########	
SIROTEM			#######	########	
Electrical					
SP			#######	#########	
Resistivity			#######	#########	
IP		#############			#########
MIP	###########				#########
Potential Field					
Magnetics			NO ANOMALY		
Gravity		#############		#########	
Seismic Refraction			#######		##########
DOWNHOLE					
SP			#######	#########	
Gamma Ray		##############		###########	
EM	###########				##########
Resistivity			#######	#########	
Mise-à-la-Masse			#######	#########	

TABLE 1. Table 1 shows the wide variety of geophysical methods used at the Woodlawn orebody (New South Wales) Australia, and a subjective classification of the geophysical responses, based on the magnitude of the response relative to background (modified from Malone and others, 1981).

GEOPHYSICAL MODEL OF CHROMITE DEPOSITS

COX AND SINGER MODEL NO. 2a & 8a   Compilers- **A.K. Kospiri**[1]
W.D. Heran

A. Geologic Setting

Two major deposit types are included, both hosted within mafic-ultramafic complexes; stratiform and podiform types.

Stratiform: Within cratonal, mostly Precambrian shield areas, as repetitively layered mafic-ultramafic intrusions. Layered chromite in lower intermediate zone of layered gabbro-peridotite, which may be traced for miles. Chromite occurs in massive to disseminated layers with cumulate texture.

Podiform: Magmatic cumulates in elongate magmatic pockets occurring along spreading plate boundaries; exposed in accreted terranes as part of ophiolite assemblage. Autoliths in the tectonite peridotites (alpine) usually occur within the lower part of the ophiolite complex and are highly deformed and serpentinized. Pods may lie near the transition zone below magmatic cumulates in the sequence. Ore bodies are massive to disseminated chromite surrounded by a thin dunite halo in a harzburgite host, and the ore body host contact is generally sharp.

B. Geologic Environment Definition

Remote sensing techniques may be used to detect and map ultramafic belts and intrusive complexes by overall reflectance (albedo), thermal properties, and geobotanical changes (Harrington, 1991; Longshaw and Gilbertson, 1975). The Semail ophiolite in Oman has been mapped and its units subdivided using Landsat TM data (Abrams, 1987). Ophiolite belts are characterized by aeromagnetic data as en echelon belts of short wavelength, high gradient anomalies (Heinz, 1989), and chains of narrow local positive and negative magnetic anomalies (Menaker, 1981). Aeromagnetic surveys and regional gravity data have been used to delineate the extent and shape of large layered intrusions (Blakely, 1984; Gould and others, 1985; Kleinkopf, 1985; Blakely and Zientek, 1985). Detailed gravity data have been used to estimate thickness and subsurface form of ophiolite massifs (Sharp, 1989). Detailed magnetic prospecting has helped map ophiolite sequences under sedimentary cover (Bozzo and others, 1984). Integrated ground magnetic and gravity surveys have been successful in finding and determining the size and shape of buried ophiolite massifs (Babadzhanyan, 1983). Additionally integrated aeromagnetic, regional and detailed gravity and electromagnetic data were utilized to map the extent and structure of a layered intrusive in South Africa (Gould and others, 1985). Gravity and electrical data have helped determine horizon thickness and structure at the Bushveld complex (de Beer and others, 1987; Hattineh, 1980). Other examples of the utilization of integrated geophysical methods to aid in defining the size, shape or depth of ultramafic complexes are: the Great Dyke in Rhodesia (Weiss, O. 1940); ultramafic rocks in northern California (Irwin, W.P. 1962); ultramafic rocks in the Appalachian province (Zietz, I. and Bhattacharyya, B.K. 1975); Papuan ultramafic belt, New Guinea (Milsom, J., 1973); ultramafic rocks in the eastern Mediterranean (Rabinowitz and Ryan, W.B.F. 1970), ultramafic rocks in former U.S.S.R. (Nepomnyashchikh, A. 1959; Moskaleva, S.V. and Zotova, I.F. 1965); Camaguey ultramafic massif, Cuba (Shablinskiy, G.N. and Damian, F. 1987).

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[1]Geophysical Enterprise, Tirana, Albania

C. Deposit Definition

For several decades integrated geophysical methods have been used for chromite exploration. Gravimetric, magnetic, electrical, electromagnetic and seismic surveys have all been applied. The literature shows exploration surveys have been carried out in the U.S.A., former U.S.S.R., South Africa, Rhodesia, Albania, Turkey, Finland, Cuba, Greece, Philippines, Yugoslavia, New-Caledonia, China, Sudan, and other countries.

Test holes were drilled on the crests of 106 gravity anomalies in Cuba. The results of drilling revealed that ten anomalies overlie deposits of chromite (Davis, W.E. et al., 1957). Gravity methods have been successfully used for the exploration of chromite in the Urals and Kazakhstan. Positive gravity anomalies due to chromite ores, as a rule, have an intensity of 0.8-1.0 mgals, their areas ranging from 0.1-0.2 km^2. Chromite orebodies at a depth of 150 m were clearly identified from gravity data (Klichnikov, V.A., and Segalovich V.I., 1970). Large chromite deposits are readily identifiable using gravity techniques even in rugged topograhy (Yungul, 1956). Ground magnetic surveys have had varying results. Since chromite is moderately magnetic, direct detection may only be achieved if the host rock is uniformly nonmagnetic (Hawkes, 1951). Integration of gravity and magnetic techniques have proven to be useful. A combination of refraction seismic, ground magnetic, and complex resistivity methods was found to be effective in the identification of podiform chromite deposits (Wynn, J.C., 1981, 1983). Very Low Frequency Electromagnetic (VLF-EM) have yielded good resolution in exploration for podiform chromite in Maryland (Miller, J.P.,1981). Chromite deposits in Kazakhstan were identified in boreholes by means of nuclear logging. (Karanikolo, V.F. et al., 1968).

D. Size and shape of deposit

In stratiform complexes groups of layers are continuous and uniform in thickness and may be traceable for miles. Podiform chromite deposits are in the form of pods, lenses, veins, tabular, pencil-shaped, disseminated schlieren, or irregular in form. Most pods are small, but large bodies are known in Kazahstan, Kempirsai; Albania, Bulqiza deposit; Philippines, Coto orebody.

E. Physical Properties (units)	Deposit	Host rocks		
		Dunite	Peridotite	Serpentinite
1. Density (gm/cc)	3.0-4.6[42,63]	2.7-3.3[23]	2.8-3.33[82]	2.0-2.[32,82]
2. Porosity (%)	0.2-3.8[78]	0.3[13]	0.1-0.8	2.5-10
3. Susceptibility (10^{-5} SI)	20-9502[5,26]	30-200[52,63]	200-3000[52,63]	30-6000[26]
4. Remanence (10^{-5} SI)	100-8100[30]	10-1800[26]	20-1300[26]	10-9500[30]
5. Resistivity (ohm-m)	8500 average	64000	68000	10000
6. IP Effect (%)	0.2-18[26]	0.2-2.0	0.2-2.0	0.2-50[26]

7. Seismic Velocity Vp (km/sec)	4.5-9.5	5.7-8.9[13]	6.2-10	4.2-4.5[13]
8. Radioelements				
K (ppm)	very low	10-900[74]	1000-10000[74]	1000[74]
U (ppm)	"	0.001	?	1-0.1
Th (ppm)	"	1-0.001	0.1	0.001

F. Remote Sensing Characteristics

The rock spectra, indicate that chromite bearing host lithologies should be distinguishable from surrounding ultramafic and mafic rocks using remote sensing techniques (Hunt, G.R. and Wynn, J.C., 1979). Biogeochemical studies show that chromite poisons vegetation in a very distinctive manner, and the amount of serpentinization strongly controls both density and species of vegetation (Wynn, 1981). TM data were found to be extremely useful for mapping and subdividing the units making up the Semail ophiolite in Oman (Abrams, M., 1986).

G. Comments

Gravity studies in many different areas (Kazakhstan, Turkey, Cuba, Albania, Philippines, India, etc.) indicate that the gravity method is the most effective geophysical method for podiform chromite exploration. A typical podiform chromite deposit has a positive density contrast of about 0.8-1.5 gm/cc over the host rocks, which often produces recognizable gravity anomalies. Magnetic studies have been carried out by several investigators on chromite bodies world-wide. Results obtained in Turkey, Finland, Albania, India, Philippines indicate that this method may not be so discouraging as reported by some authors. Electrical and electromagnetic methods (IP, Complex resistivity, VLF-EM) have yielded good resolution in exploration tests over podiform chromite. Seismic field data appear to show strong velocity highs related to massive chromite contrasted with the surrounding, low velocity serpentinized peridotites (Wynn, J.C., 1981; Reid, A.B., and others, 1980).

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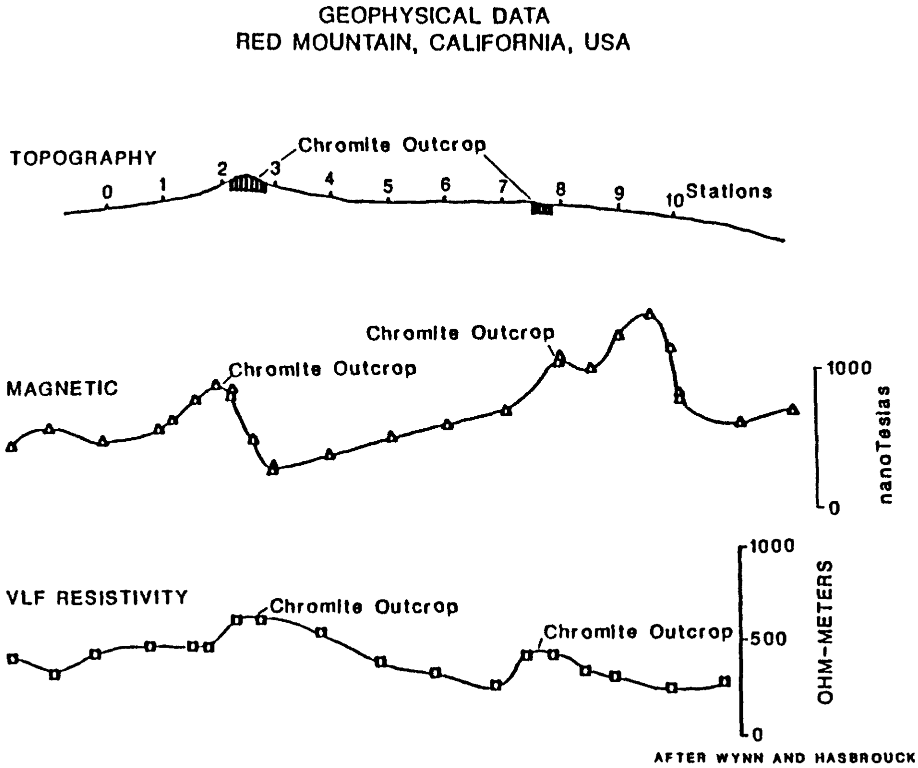


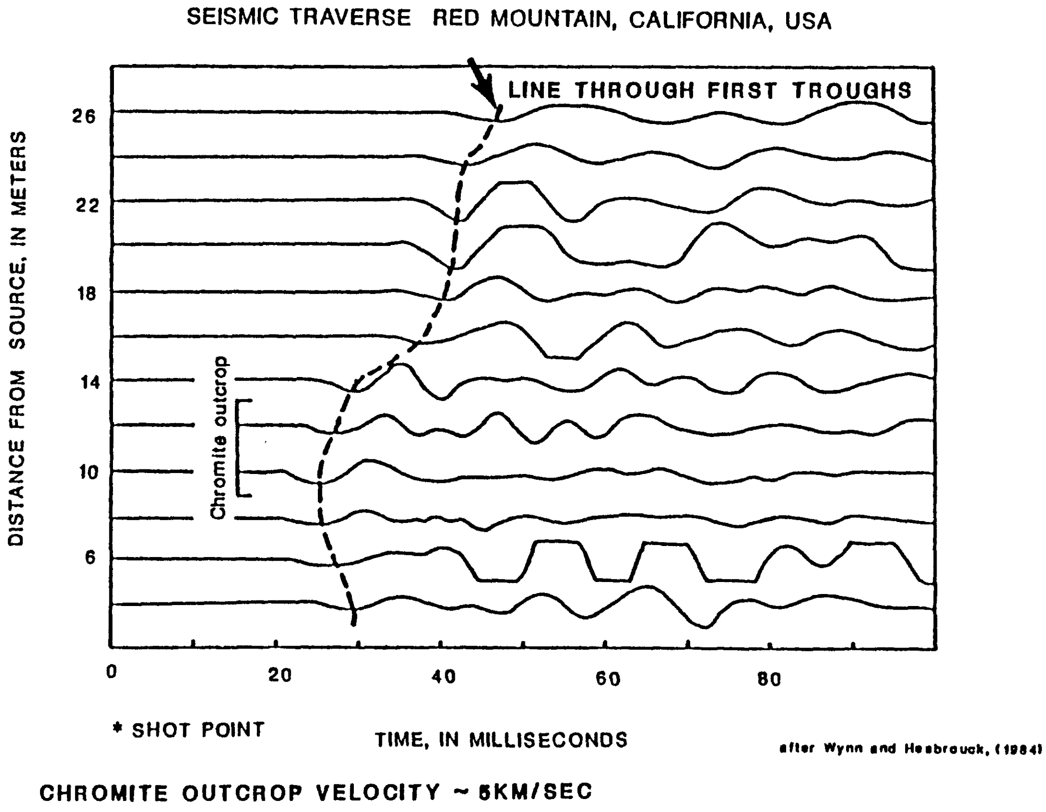


Figure 1. Magnetic data, electromagnetic data (VLF resistivity) and seismic data at the Red Mountain chromite deposit, California. (after Wynn and Hasbrouck, 1984)

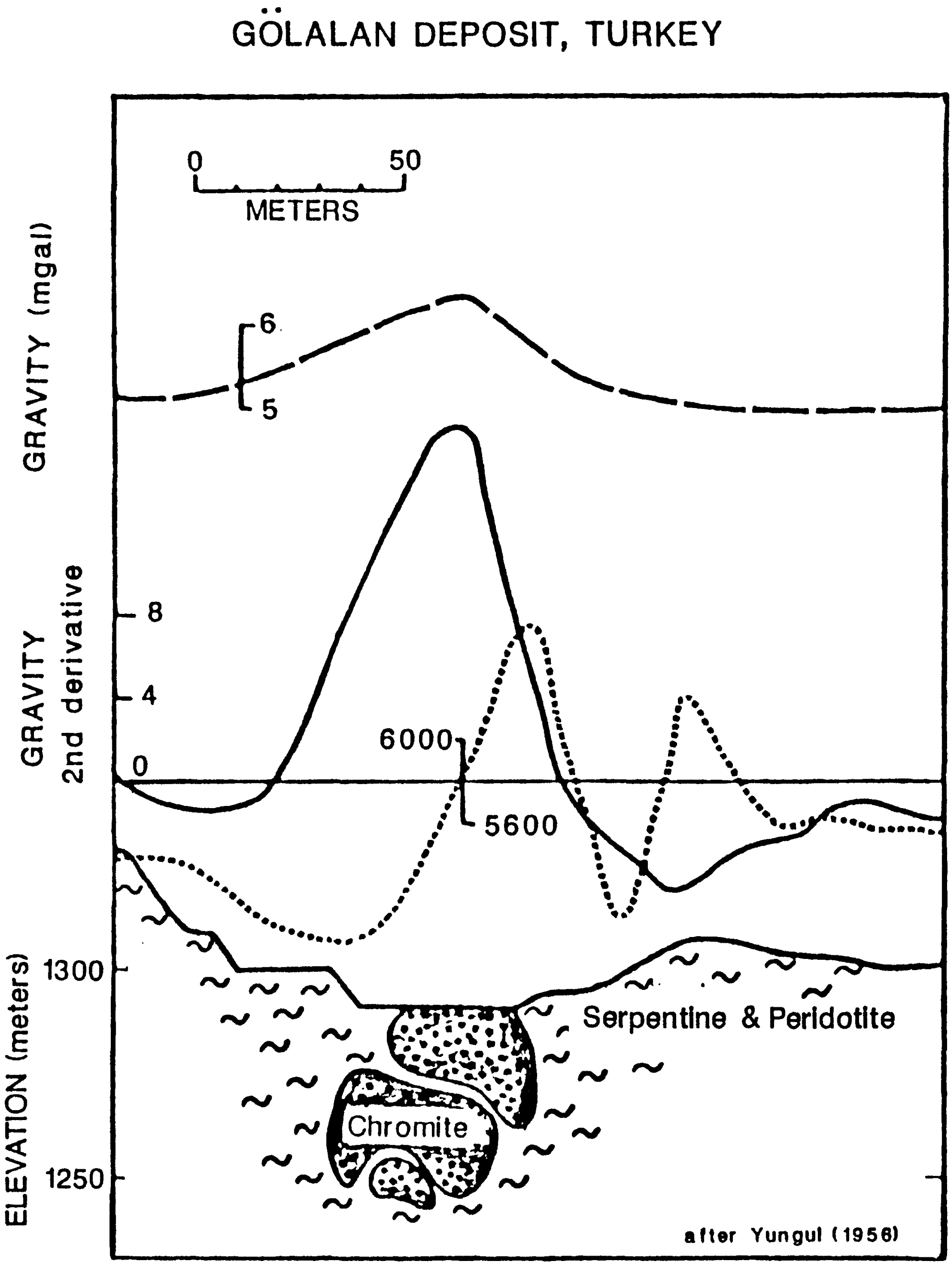


Figure 2. Bouguer gravity, 2nd derivative of gravity data, and the magnetic vertical intensity over the Golalan chromite deposit, Turkey. (after Yungul, 1956)

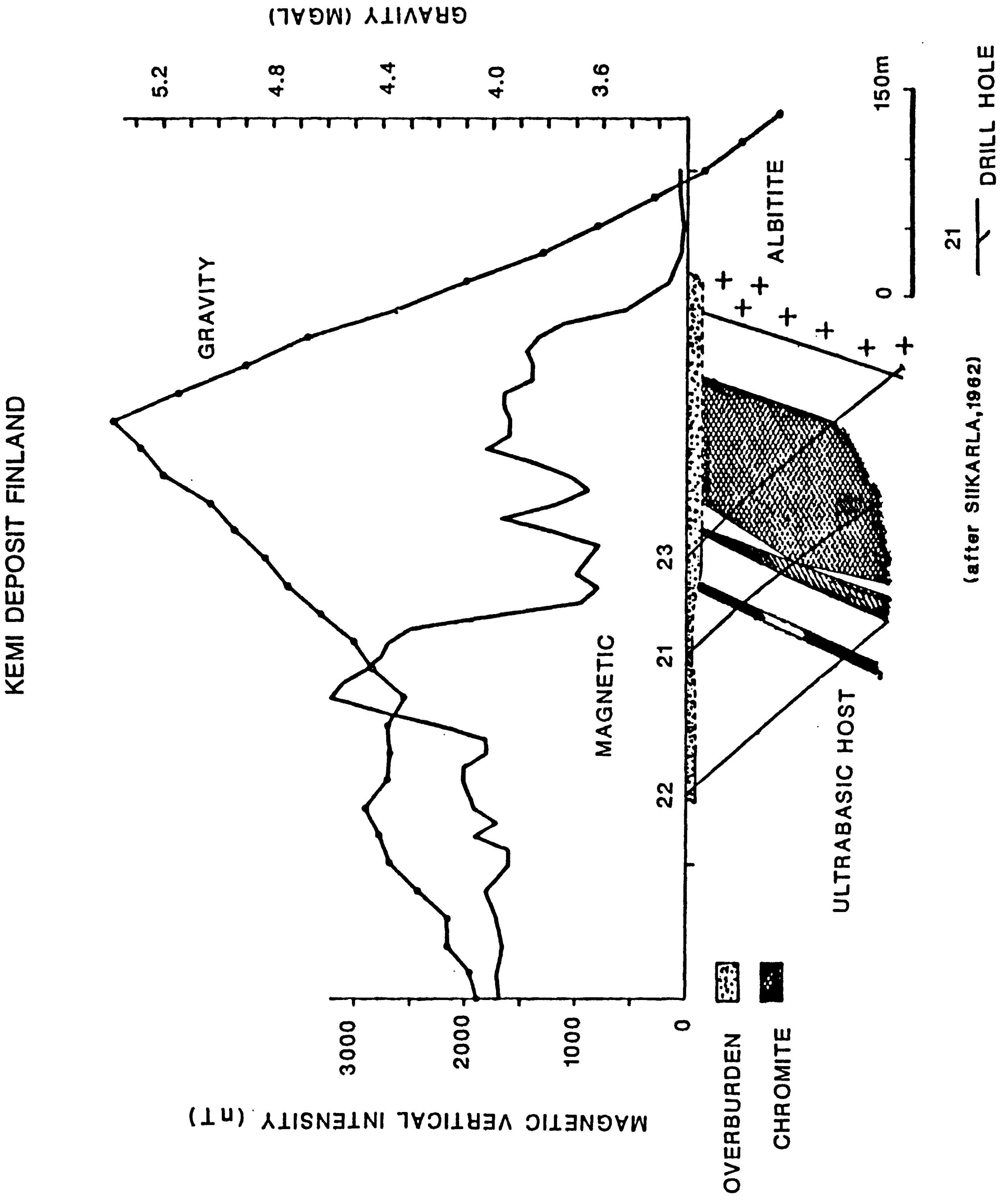
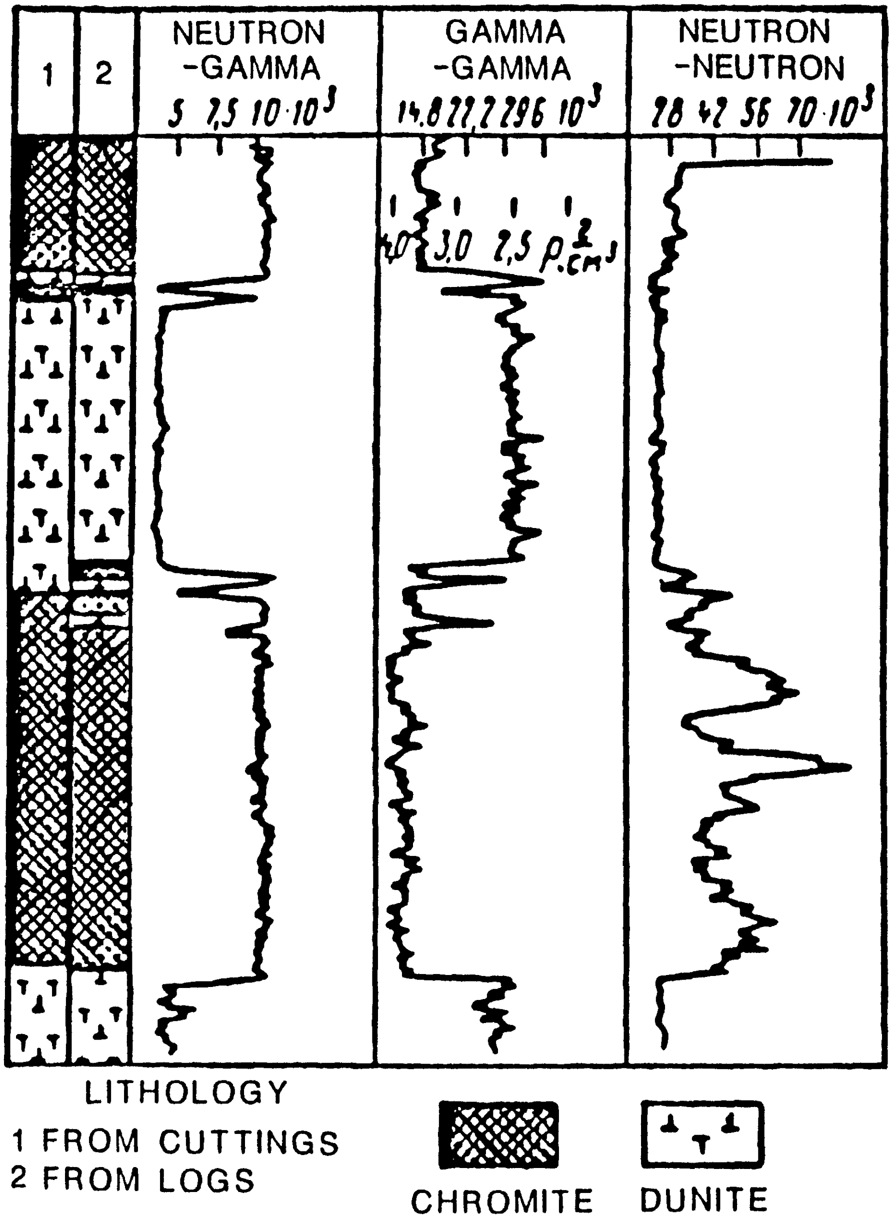


Figure 3. Bouguer gravity and magnetic vertical intensity profile data over the Kemi stratiform chromite deposit, Finland. (after Siikarla, 1962)

NUCLEAR LOGGING FOR CHROMITE



(after MILETSKIY and others,1973)

Figure 4. Borehole profiles using a combination of nuclear geophysical methods from a chromite deposit in Kazakstan. (Miletskiy and others, 1973)

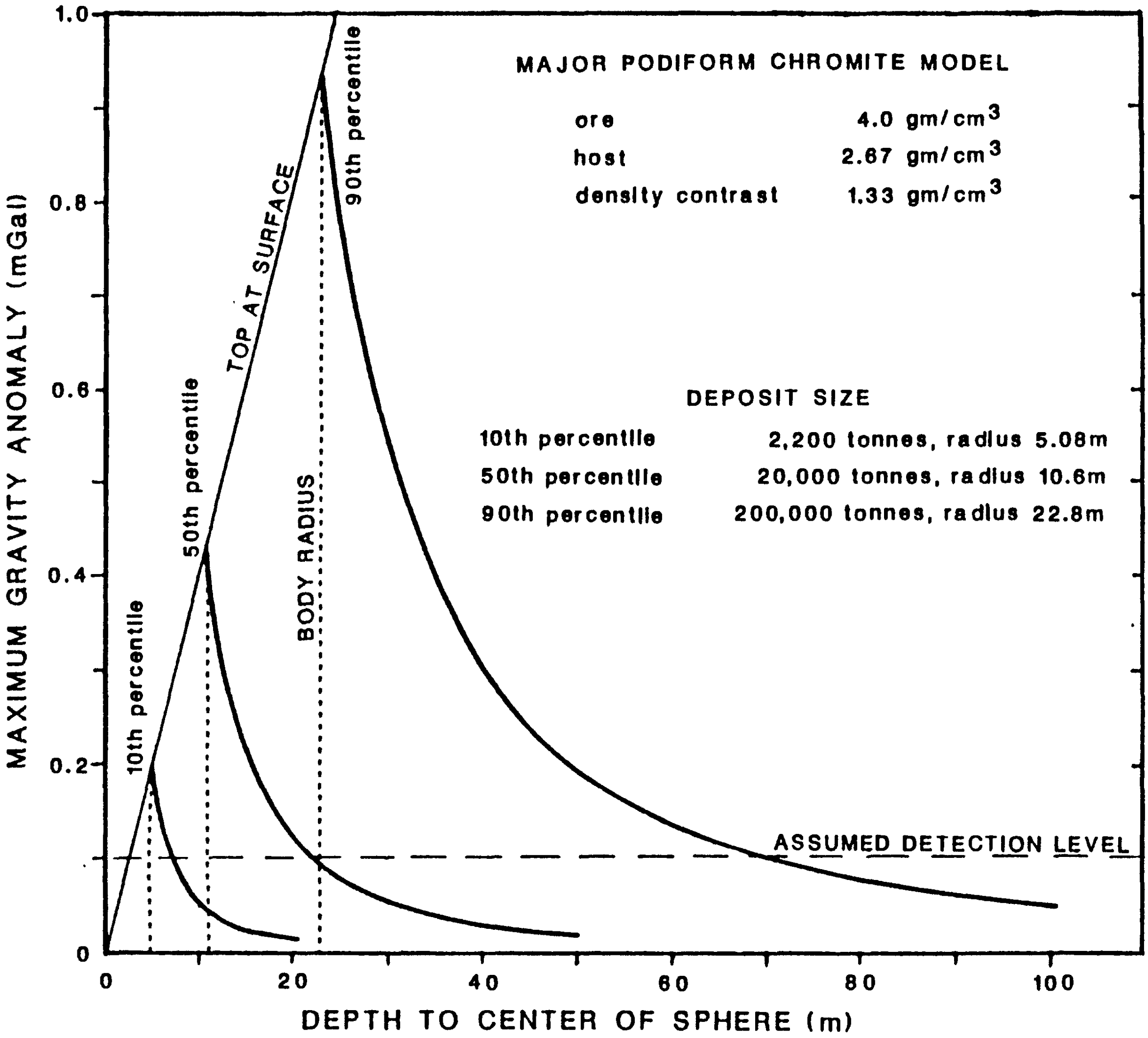


Figure 5. Graph showing the maximum gravity anomaly due to a spherical body of chromite, 4.0 g/cm^3 in a 2.67 g/cm^3 host as a function of depth of burial for bodies of 0.0022 M, 0.02 M, and 0.2 M tonnes. Size range of ore bodies represent the 10th, 50th and 90th percentiles of major podiform chromite deposits from Singer and others (1986).

GEOPHYSICAL MODEL OF BEDDED BARITE

COX AND SINGER Model No. 31b
Geophysically similar models-31a sedimentary exhalative Zn-Pb.

Compilers - **D.B. Hoover**
P.L. Hill
D.H. Knepper, Jr.
(Sept. 1993)

A. Geologic Setting
- Hosted within marine fine grained, typically siliceous or carbonaceous, sediments usually of Proterozoic or Paleozoic age.
- Stratabound deposits of limited areal extent related to exhalative processes controlled by high angle faults along which metal-rich brines were released to sea water.

B. Geologic Environment Definition

Geophysical methods appear to have had very limited application on a regional scale for old marine basins in which bedded barite deposits are found. However, airborne methods could have application to mapping of lithologies and structures, especially where cover or access present difficulties to conventional regional mapping. Barnes and Kelley (1991) note that 12 of 3500 gravity stations comprising a regional survey in Alaska need to be reexamined. These 12 stations, showing 2-4 mgal highs, had been rejected when compiling the regional map as due to simple errors or related to shallow sources. The shallow sources could be bedded barite deposits. Caveat emptor!

C. Deposit Definition

All conventional geophysical methods have been tried over bedded barite deposits but only two, gravity and electrical resistivity, methods have proven very effective. Gravity is most used due to the large density contrast between ore and host (+1.0 to 2.0 gm/cm^3 reported). Maximum anomalies at Mangampetta North and South, India, and Red Dog North, Alaska; three of the largest deposits are 2.1, 1.6, and 4.07 mgals respectively (Bose, 1980; Barnes and Morin, 1982; Barnes and others, 1982). Small deposits become difficult to identify with gravity methods because of limitations due to geologic noise (Bhattacharya and others, 1974; Miller and Wright, 1983; Moro, 1982; Parker, 1980; Visarion and others, 1974). Although, in favorable areas even small deposits may be identified (Uhley and Scharon, 1954).

Bedded barite deposits, like many other chemical sediments, are expressed as high resistivity units. Where these are hosted within carbonaceous or sulfide-bearing sediments, the resistivity contrast may be very large (Parker, 1978, 1980; Rao and Bhimasankaram, 1982; Bhattacharya and others, 1974). I.P. methods were used at the Mel deposit, Yukon territory, Canada (Miller and Wright, 1983) providing good definition because of the high sphalerite/galena content. Intrinsic chargeability was 60 msec from modeling. Moro (1982) presents S.P. results at the Ambiciosa mine, Spain, showing 100+ mv anomalies, but these are related to sulfide-and graphite-bearing host schists.

Magnetic methods are mentioned by Scull (1958), Vasserman and others (1980), Bose (1980), and Parker (1980) tried them at Aberfeldy, Scotland but results were inconclusive. Bose (1980) states that seismic refraction was tried but gives no results.

Scull (1958) using a total-count scintillometer across the Chamberlain Creek syncline noted that barite and associated black shales had low radioactivity contrary to expectations. He suggested airborne scintillometry could be an effective tool. However, many deposits show a sericite alteration zone (Papke, 1984) which might provide a target for gamma-ray spectrometry. Vasserman and others (1980) note that natural gamma-ray logs show a minimum in barite ore. Zimovets (1984) gives results for natural gamma-ray and gamma-gamma logs showing excellent correlation between each and low values for natural gamma and high values for gamma-gamma logs. Using these logs quantitative estimates of barite content could be obtained.

D. Size and Shape of Deposit	Shape	Average Size/Range
	lense	individual lenses 0.1 to several meters thick. Interbedded units up to 100 m thick. Strike length typically several 100s of meters but may be discontinuous up to 7 km. Volume 29-6800 m^3, ave. 440 m^3

E. Physical Properties (units)	Deposit	Alteration	Cap	Host
1. Density (gm/cm^3)	2.86-4.42;4.1[1,2,3,7,12,15,16]	?	N.A.	*
2. Porosity (%)	0.5-5%[15]	?	N.A.	*
3. Susceptibility (cgs)	very low-low	low	N.A.	*
4. Remanence	low	low	N.A.	*
5. Resistivity (ohm-m)	850[12] - 1400[(7)] 1000 - 1,000,000[15]	?	N.A.	*
6. IP Effect (msec.)	60[(7)]	?	N.A.	*
7. Seismic Velocity	high	?	N.A.	*
8. Radioelements				
K (%)	low	medium?	N.A.	*
U (ppm)	low	low?	N.A.	*
Th (ppm)	low	low?	N.A.	*

F. Remote Sensing Characteristics

No literature references to remote sensing techniques applied to barite exploration have been found. However, in some cases such methods may be relevant to lithologic, structural, and possibly alteration mapping in exploration for barite. In the visible and near infrared region the barite spectrum is featureless.

G. Comments

Because of the small average size and limited alteration haloe, if present, detailed surveys are required at the deposit scale. It is unlikely that airborne surveys would be of much help in deposit definition. A USGS AEM and gamma ray 400 m spaced survey in the Osgood Mtns., Nevada showed no definitive high resistivity body over the Barum deposit, nor a characteristic radioelement signature.

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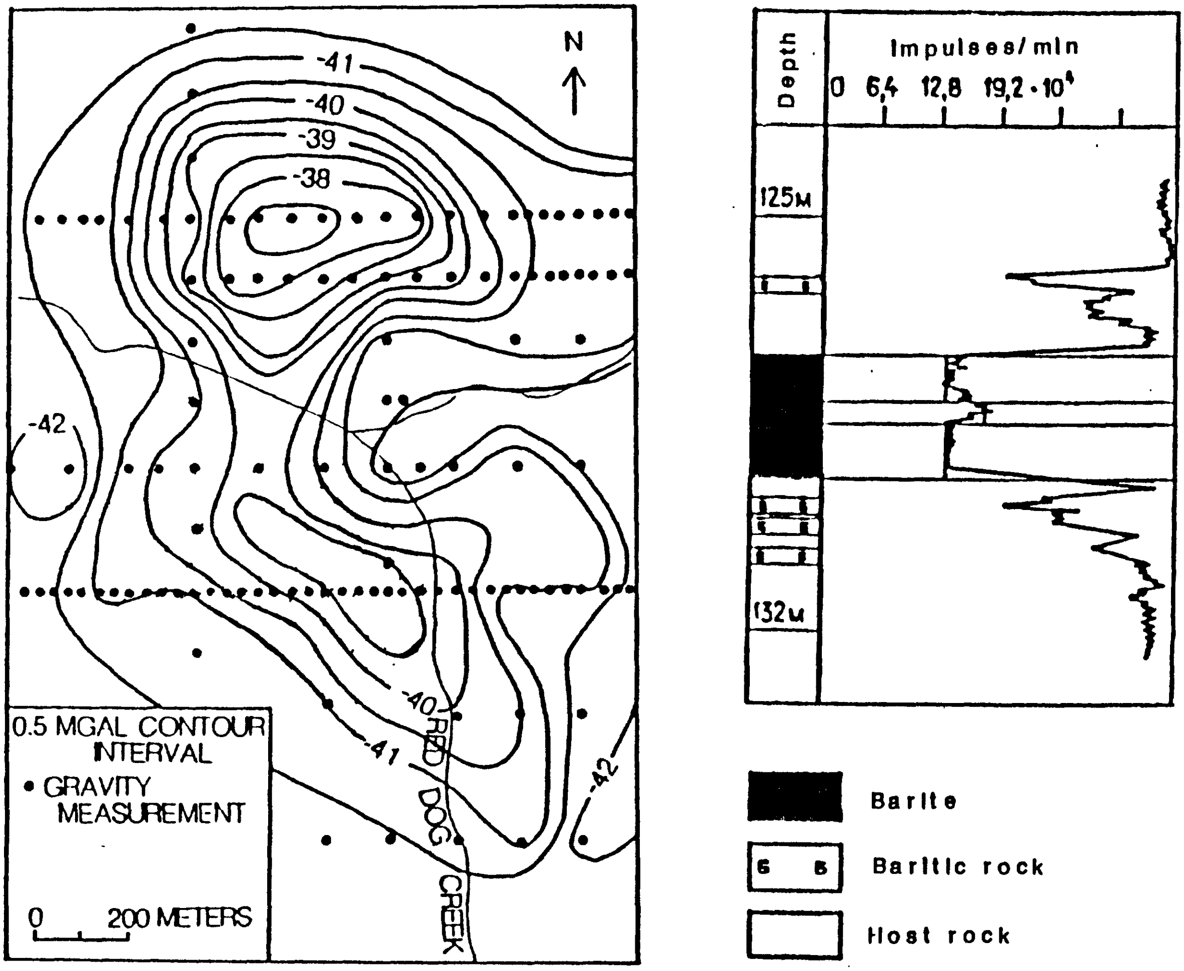

A B

Figure 1. A. Gravity contour map of the Red Dog deposit Alaska, adapted from Barnes and Morin (1984). B. Gamma-gamma log from a barite deposit in the northern Urals, adapted from Zimovets (1984).

GEOPHYSICAL MODEL OF DIAMOND PIPES

COX AND SINGER Model No. 12
Geophysically similar models-No. 10 Carbonatites;
No. 29b, Olympic Dam

Compilers - **D.B. Hoover**
D.L. Campbell
(Dec. 1993)

A. Geologic Setting
- •Kimberlite or lamproite diatremes emplaced along zones of basement weakness within or on the margins of stable cratons; (Dawson, 1971, 1980) often in groups of three or more.
- •Often spatially related to carbonatites, but not normally occurring along same zones of crustal weakness (Dawson, 1967; Garson, 1984). A genetic relationship is open to question.

B. Geologic Environment Definition

Regional magnetic, gravity, and remote sensing surveys may identify deep-seated fracture systems and related anteclises or syneclises that define zones of weak crust favorable for emplacement (de Boarder, 1982; Tsyganov, and others, 1988; Jennings, 1990).

C. Deposit Definition

Individual diatremes generally appear as circular to elliptical bodies in remote sensing images, and on magnetic, gravity, or resistivity maps. The diatremes may show as distinct magnetic highs (Yakutia, West Africa) of hundreds to a few thousand nT, but high remanence or magnetic host rocks can result in negative or no anomalies. Gravity (order of 1 mgal), resistivity, and seismic velocity anomalies generally show as lows over the diatremes related to serpentization and weathering of the mafic rocks. Radioelement surveys have generally not been effective, although in Yakutia Fedynsky and others (1967) report that they have been used to differentiate between diamond-bearing basaltic kimberlite from barren micaceous kimberlite and carbonatites (da Costa, 1989; Kamara, 1981; Gerryts, 1970; Macnae, 1979; Guptasarma and others, 1989; Jennings, 1990; Carlson and others, 1984).

D. **Size and Shape of**	**Shape**	**Average Size/Range**
Deposit	Vertical cone, carrot-like	0.1 to 5 km diameter; generally 0.4 to 1 km depth to about 2 km
Alteration haloe	Irregular about pipe	thin, not geophy. significant
Cap	Elliptical cylinder	0.1 to 5 km, 0-10's m thick

E. Physical Properties (units)	Deposit	Alteration	Cap	Host
	kimberlite or lamproite pipe	Si, CO_2, K metasomatism	clay-rich weathering zone-blue and yellow ground	any cratonic unit
1. Density (gm/cm^3)	2.75[10] 2.64-3.12[4,10,19] 2.35-2.55[16]	?	2.35?[21] 2.5-2.62[4]	*
2. Porosity	low-moderate	low?	high[4]	*
3. Susceptibility (cgs)	$1x10^{-4}$-$1x10^{-2}$[16] to $2.3x10^{-3}$[11]	?	$1x10^{-5}$-$1x10^{-3}$[16] to $2x10^{-5}$[11]	*
4. Remanence (Q)	variable 0-0.8-2.0[22]	?	variable	*
5. Resistivity (ohm-m)	100-2000[4,16,19,21]	medium-high	2-100[4,16,19,21]	*
6. IP Effect (msec.)	low	low?	low, 0-4[18]	*
7. Seismic Velocity (km/sec)	2.6-3.3[4]	high?	1.5[4] 0.3-2.4[2]	*
8. Radioelements				
K (%)	2.6 average 0.07-6.7[3] 1.9[2]	medium	medium?	*
U (ppm)	0.26, average 0.07-0.8[3] 3.8[2]	low	very low	*
Th (ppm)	0.44, average 0.17-0.9[3] 9.3[2]	low	low	*

F. Remote Sensing Characteristics

Visible and near IR-Remote sensing techniques can identify lineaments which may reflect zones of crustal weakness along which pipes were emplaced. Lineament intersections may be favored locations (Tsyganov and others, 1988). Vegetation anomalies related to drainage and lithologies can be used for location. Alteration products of kimberlite, such as serpentine, chlorite, and vermiculite show distinct spectral absorption features that can be detected by a variety of methods (Kingston, 1989; Jennings, 1990).

G. Comments

The relatively small size, 0.4-1.0 km, of most pipes requires detailed coverage for identification. The geophysical signature differs from carbonatites in, reduced amplitude of magnetic anomaly, and by a small negative gravity anomaly in contrast to the large positive anomaly of carbonatites. A combination of magnetic, gravity, and resistivity methods are most used in exploration. No single method is universally applicable. Radioelement methods have had relatively little use, although they should have some application in differentiating varieties of kimberlites and lamproite. Some Russian literature (Ratnikov, 1970), gives very low values of density for kimberlites. These probably refer to serpentinized or weathered samples and are not representative of unaltered rock. Gerryts (1967) gives a rule-of-thumb of 1 mgal/183 meters (200 yards) of pipe diameter for the gravity low. A broad gravity high ring about the central low, due to dense, deeper, kimberlite has not been observed. Guptasarma and others (1989) report both positive and negative gravity and magnetic responses over kimberlites in India. Jennings (1990) notes that less than 25% of kimberlite-like magnetic features in an area of Botswana were kimberlites, when drilled. Johnson and Seigel (1986) show airborne magnetic and EM data over three pipes in Tanzania, only two of which show a magnetic signature, but all three have a strong, positive conductivity anomaly. Bose (1980) suggests that gravity highs, magnetic highs and resistivity highs are seen over fresh unweathered kimberlites, while gravity, magnetic and resistivity lows are seen over weathered kimberlites in India. Carlson and others (1984) show results for gravity, magnetic, EM, galvanic resistivity, gamma-ray, and seismic refraction studies over several diatremes in the State-Line district of Colorado-Wyoming, concluding that magnetic, resistivity and EM methods were clearly the most effective. Their data appear to show fenitization up to 15 m around the pipe.

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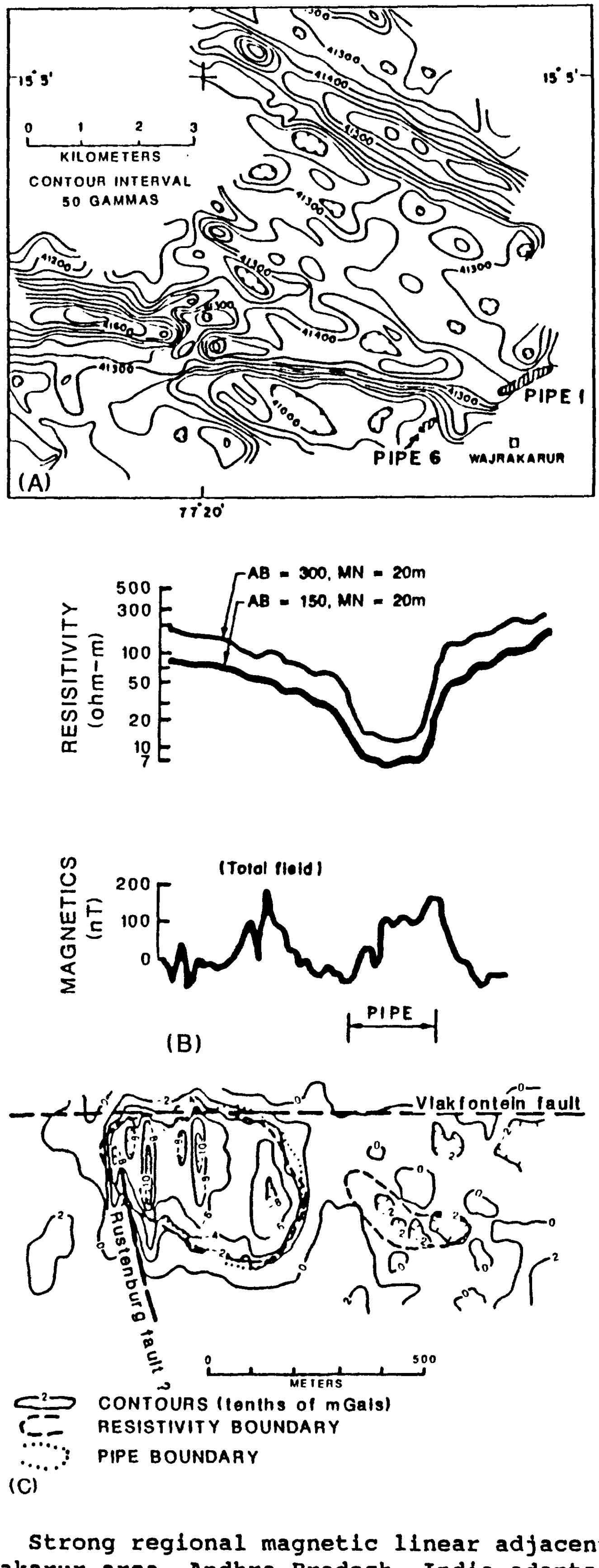

Figures A. Strong regional magnetic linear adjacent to two kimberlite pipe in the Wajrakarur area, Andhra Pradesh, India adapted from Guptasarma and others (1989). Contour interval is 50 gamma. B. Resistivity and ground magnetic traverse across the Palmietfontein pipe South Africa adapted from d Costa (1989). C. A residual gravity map of the Palmietfontein pipe also showing its emplacement at the junction of the Vlakfontein and Rustenburg faults, after da Costa (1989).