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GEOLOGY AND MINERALIZATION OF THE BULLFROG MINE AND VICINITY, NYE COUNTY, NEVADA

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The Bullfrog and Montgomery-Shoshone Au-Ag deposits, currently operated by Barrick Gold Corp., are located in the Bullfrog mining district 3 miles west of Beatty, NV, and are volcanic-hosted epithermal style vein deposits. Open pit mining of the Bullfrog deposit began in 1988 and was completed in late 1994; current production is from underground and is by underhand drift-and-fill. Open pit mining at the Montgomery-Shoshone deposit began in 1994. Total mine gold production through 1994 was 1,477,000 oz of refined Au from 15.2 Mmt of milled ore averaging 3.30 g/t Au. In 1994 the mine produced 301,000 oz Au at an average grade of 3.59 g/t. Essentially all the mine's production has been from the Bullfrog deposit. Year end reserves for 1994 were 13.0 Mmt grading 2.49 g/t Au (1,042,000 oz); the majority of the contained ounces are located underground in the Bullfrog deposit. Current production rates are approximately 6,500 mt/day of open pit ore (0.85 g/t Au cut-off), and 1,000 mt/day of underground ore (3.0 g/t Au cut-off). Life-of-mine stripping ratios are 8:1 for Bullfrog, and 6:1 for Montgomery-Shoshone. Ore is processed in a 7,500 mt/day CIL mill. Prior to mining these deposits contained over 2.7 million oz Au. This ranks the Bullfrog mine as one of the larger volcanic-hosted gold mines in Nevada.

Gold was first discovered in the district in 1904 at the Original Bullfrog mine located 4 miles west of Barrick's current operation. Historic recorded production in the district prior to 1989 was approximately 70,000 oz Au at an average equivalent grade of 0.52 opt Au, and was derived mainly from the Montgomery-Shoshone mine between 1907-1910. This property was acquired by St. Joe American Corp. in 1982 and exploration work through 1985 identified a marginal resource of approximately 270,000 oz Au. During this work an exploration model was developed by St. Joe geologists. One of the areas targeted was near the inactive Senator Stewart mine on the east flank of Ladd Mtn., 1 mile south of the Montgomery-Shoshone deposit near the projection of a large regional fault. The thirteenth and last hole of the drilling program designed to test this model discovered the current Bullfrog deposit under gravel cover. This hole contained an intercept of 1.20 g/t Au from 70 - 300 ft.

The southern Bullfrog Hills are composed mainly of Miocene rhyolitic ash-flow tuffs erupted between 15.25 and 11.45 Ma from several overlapping calderas near Timber Mtn. located about 20 miles to the northeast. Basalt and latite flows, bedded variably reworked tuffs, and volcaniclastic rocks are locally interlayered with the rhyolitic ash-flow tuffs. These rocks have been informally grouped into rhyolite units 1 - 10 and are as much as 10,000 ft thick. Basalt dikes, which typically occupy faults, intrude rocks as young as 11.45 Ma. The Rainbow Mtn. sequence, also known as the tuffs and lavas of the Bullfrog Hills, overlies the ash-flow tuffs derived from the Timber Mtn. area and consists of interbedded crystal-poor to porphyritic rhyolite lavas, airfall tuffs, lightly to moderately welded crystal-rich ash-flow tuffs, and variably reworked tuffs and tuffaceous sedimentary rocks. Also present are intercalated lenses of landslide breccia. At least some of the ash-flow tuffs and lavas of the Rainbow Mtn. sequence erupted from local sources marked by mineralogically similar rhyolitic plugs. The Rainbow Mtn. sequence is capped by porphyritic latite lavas. New $^{40}Ar/^{39}Ar$ ages indicate that the rocks of the Rainbow Mtn. sequence were laid down between 10.56 and 10.33 Ma.

Rocks of the southern Bullfrog Hills are complexly deformed by a series of mainly northerly and northeasterly striking normal faults. These faults dip mainly west, while the rock units dip mainly east. Because of opposing dips of faults, tilts of rock units can change abruptly from steeply east (60-90°) along moderately to gently west dipping faults to near flat-lying or moderately west in proximity to major east-dipping faults. In other areas both strikes and dips of rock units on either side of a fault can change by as much as 25-35° indicative of rotational movement along faults. Angular unconformities and discontinuous fault scarp breccias indicate at least four pulses of extensional deformation -- the earliest at ca. 16 Ma as evidenced by a coarse basal Tertiary breccia and conglomerate, another between 15.1 and 14.0 Ma, and another at ca. 12.5 Ma, and probably the most profound phase between 10.7 and 10.3 Ma. This last phase was most important for developing faults that host gold mineralization in the Bullfrog mine area. Extension and tilting of rock units appears to have ceased before 7.6 Ma.

The Tertiary volcanic and volcaniclastic rocks overlie lower Paleozoic sedimentary rocks and upper Proterozoic metamorphic rocks. The latter have been interpreted by other workers as part of a mid-Miocene metamorphic core complex, and the low-angle contact between the pre-Tertiary, as a regional detachment fault. Recent field work, however, indicates that this contact, at several localities is an unconformity rather than a single continuous fault.

Mineralization at the Bullfrog deposit consists of a series of crustiform banded veins, vein breccias and stockworks of quartz and calcite with Mn-oxides. Rhyolitic ash flows of the Rainier Mesa Tuff (11.6 Ma) are the principle host rocks and dip 45° east. Footwall rocks consist mainly of flow banded latite lavas (pre-14.0 Ma). The main ore controls are the MP and UP faults which are northerly striking, 30-45° west dipping faults with as much as 1000-2000 ft of cumulative displacement. These are interpreted to be normal faults which have been rotated during extension. Most of the high grade ore (>3 g/t Au) is in veins and vein breccias developed along and in the immediate hanging wall of the MP fault. Similar but narrow high grade ore is also developed along the UP fault which lies 100-150 ft in the hanging wall. Lower grade ore (>0.85 g/t Au) is developed in broader stockwork zones adjacent to these faults. Ore grades correlate with the density of stockwork and veining. The orebody extends for over 5,000 ft along strike, and over 1000 ft down-dip and vertically. Changes in the geometry and grade of the ore occur where the MP and UP faults change strike, and where these faults are intersected by a series northeast striking faults. The bulk of the ore is rather unremarkable in terms of its overall mineralogy and geochemistry, consisting mainly of native Au (generally <10 microns), electrum and acanthite, although the higher grades are associated with abundant sooty Mn-oxides and quartz after calcite replacement textures. Prior to oxidation, the veins contained only minor sulfides (<1-2%) and consisted mainly of pyrite. Silver:Au ratios average 2.5:1. A large halo of geochemically anomalous Au (>100 ppb) surrounds much of the deposit. Other Au pathfinder elements are generally low, especially when compared with many volcanic-hosted deposits; base metal concentrations are also generally low (<100 ppm). The mineralization may contain weakly anomalous As and Mo. Wallrock alteration consists of silicification-adularization mainly between the MP and UP faults and occurred prior to veining and associated main stage gold mineralization; weakly anomalous concentrations of Au are associated with this early stage of alteration. Bleaching and a weak argillic assemblage (kaolinite-smectites-illite) is developed outward from the more intense alteration. Carbon-pyrite and chlorite-pyrite alteration is present in the footwall of the deposit, and appears more intense beneath the center of the orebody where the alteration is often fracture controlled; maximum wallrock pyrite content ranges from 1-3%. The deposit has undergone oxidation which is nearly complete above the MP fault.

The Montgomery-Shoshone deposit is hosted in the Rainier Mesa Tuff and Ammonia Tanks Tuff (11.45 Ma) which dip 35-40° east. Mineralization is localized along two vein-filled fault zones and adjacent areas of stockwork. These faults, the Montgomery and the Polaris, strike northerly and dip moderately to steeply west, and have as much as 400 ft of cumulative normal displacement. The faults are located about 300-400 ft apart, but merge along strike to the south where the economic mineralization ends. Economic grades of mineralization persist for 500-650 ft vertically and 500-800 ft along strike. The deposit occurs in the footwall of the northeast striking Contact fault which is mainly post-mineral and has as much as 2000-3000 ft of displacement. In terms of overall style of mineralization, wallrock alteration and geochemistry, the deposit is similar to Bullfrog. However, Montgomery-Shoshone is lower grade and has a much higher Ag:Au ratio (15:1). Wallrocks are also more argillized and oxidized, and Montgomery-Shoshone lacks carbon-pyrite and strong chlorite-pyrite alteration in its footwall.

Adularia related to mineralization has yielded dates of 9.99 +/- 0.04 Ma ($^{40}Ar/^{39}Ar$) for Bullfrog and 9.5 +/- 0.2 Ma (K/Ar) for Montgomery-Shoshone. Textural and field relations, as well as laboratory studies suggest formation at paleodepths of approximately 2000 ft. Main ore stage fluids were low salinity. The deposits of the Bullfrog district are similar in mineralization style to other epithermal vein districts which have been termed adularia-sericite-type and low sulfidation, several of which are bonanza-type in terms of grades, notably Oatman AZ, Aurora NV and Republic WA. While these districts host similar styles of mineralization, they have not sustained the profound extensional faulting that is developed in the Bullfrog district. Although the Tertiary rocks of the Bullfrog district have been described as lying in the hanging wall of a regional low-angle detachment fault, mineralization at Bullfrog bears little resemblance to that typically associated with well documented detachment fault settings in the Mojave Desert and the Colorado River extensional corridor. The source of the gold for the Bullfrog deposits remains in question, as does the role of the low-angle fault which the deposits are regionally associated.

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Volcanic Centers of Southwestern Nevada: Evolution of Understanding, 1960–1988

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Since about 1960, geologists of the U.S. Geological Survey and, more recently, those of Los Alamos and Lawrence Livermore national laboratories, supported largely by the U.S. Department of Energy (DOE) and its predecessors, have been unraveling a complex series of ash flow sheets, lavas, and related calderas in the southwestern Nevada volcanic field in and near the Nevada Test Site (NTS). Extensive detailed geologic mapping aided in delineation of four major calderas: Silent Canyon (~14) Ma), Timber Mountain–Oasis Valley (~11.5 Ma), Black Mountain (~7.5 Ma), and Stonewall Mountain (~6 Ma). In the 1960s, key concepts that contributed to the understanding of volcanology were the recognition of vertical compositional zonation within ash flow sheets, the significance of caldera rim and moat lavas, the relation between caldera collapse and intracaldera breccias and ash flow facies, and the correlation of intracaldera and outflow-sheet facies. Deep drill holes within Silent Canyon and Timber Mountain calderas provided vital information on caldera geometry and intracaldera facies. Radiometric dating has produced nearly 100 dates that define the age of the field between about 16 and 6 Ma. During the middle part of that period a major ash flow eruption occurred once in about every half million years. Continuing support by the DOE for earth science at the NTS during the 1970s and 1980s has permitted a unique longevity of studies and provided opportunities to restudy mapped areas, revise some incorrect relationships, and work out important details of caldera history and structure that otherwise would not have come to light. Petrochemical and isotopic studies contributed to the understanding of the PT environment of the magma bodies that generated the major ash flow sheets. In the last decade, specialized work has continued on stratigraphic and petrologic problems, resulting in understanding of petrochemical cycles, in wider and more accurate correlation of certain units, and in understanding the time and spatial relationship between petrochemically very similar ash flow sheets from the Black Mountain and Stonewall Mountain calderas. Drilling and detailed Earth science studies in connection with preliminary characterization of a proposed nuclear waste repository at Yucca Mountain have greatly advanced knowledge of the older and younger parts of the volcanic sequence, including the basalts. A newly defined volcano-tectonic collapse area in Crater Flat, probably a caldera, is strikingly similar in structure, location, and geophysical expression to the Silent Canyon caldera to the north. Rhyolite lavas peripheral to the Timber Mountain–Oasis Valley caldera complex are intercalated with the major ash flow sheets from the complex, and analyses of the lavas fit well on compositional trends determined by the ash flow sheets. Renewed studies since 1981 include eruptive dynamics and magma chemistry of the major ash flow sheets and sources of mafic and intermediate volcanism. Hydrothermal alteration and mineralization occur after major magmatic pulses. New data on the age, structure, and distribution of the volcanic rocks have resulted in revised structural models involving volcano-tectonic and detachment faulting processes.

INTRODUCTION

This introductory paper is a review of past studies and the evolution of concepts on calderas and related magmas of the southwestern Nevada volcanic field during a period of protracted field, drilling, and laboratory investigations from 1960 to the present (1988). The name southwestern Nevada volcanic field was used first by *Christiansen et al.* [1977] to include the broad volcanic plateau underlain by tuffs and lavas of the Timber Mountain–Oasis Valley caldera complex and Silent Canyon and Black Mountain calderas (Figure 1). In this paper and those that follow in this special issue of the *Journal of Geophysical Research*, the southwestern Nevada volcanic field is expanded to include volcanic rocks from three adjacent areas: Stonewall Mountain caldera complex, a possible caldera complex in Crater Flat, and vents near Bullfrog Mountain west of the Timber Mountain–Oasis Valley (Figure 1). Tuffs and lavas from these outlying volcanic centers intertongue with those from the Timber Mountain–Oasis Valley caldera complex, and together they form a dissected, discontinuous, and faulted volcanic field. The eastern part of this volcanic field extends onto the Department of Energy (DOE) Nevada Test Site (NTS).

As early as the 1950s, geologists of the U.S. Geological Survey (USGS) began geologic mapping at the U.S. Atomic Energy Commission (AEC) Proving Grounds [*Johnson and Hibbard*, 1957], now the NTS, and conducted engineering studies of tuffs beneath Rainier Mesa at the request of the

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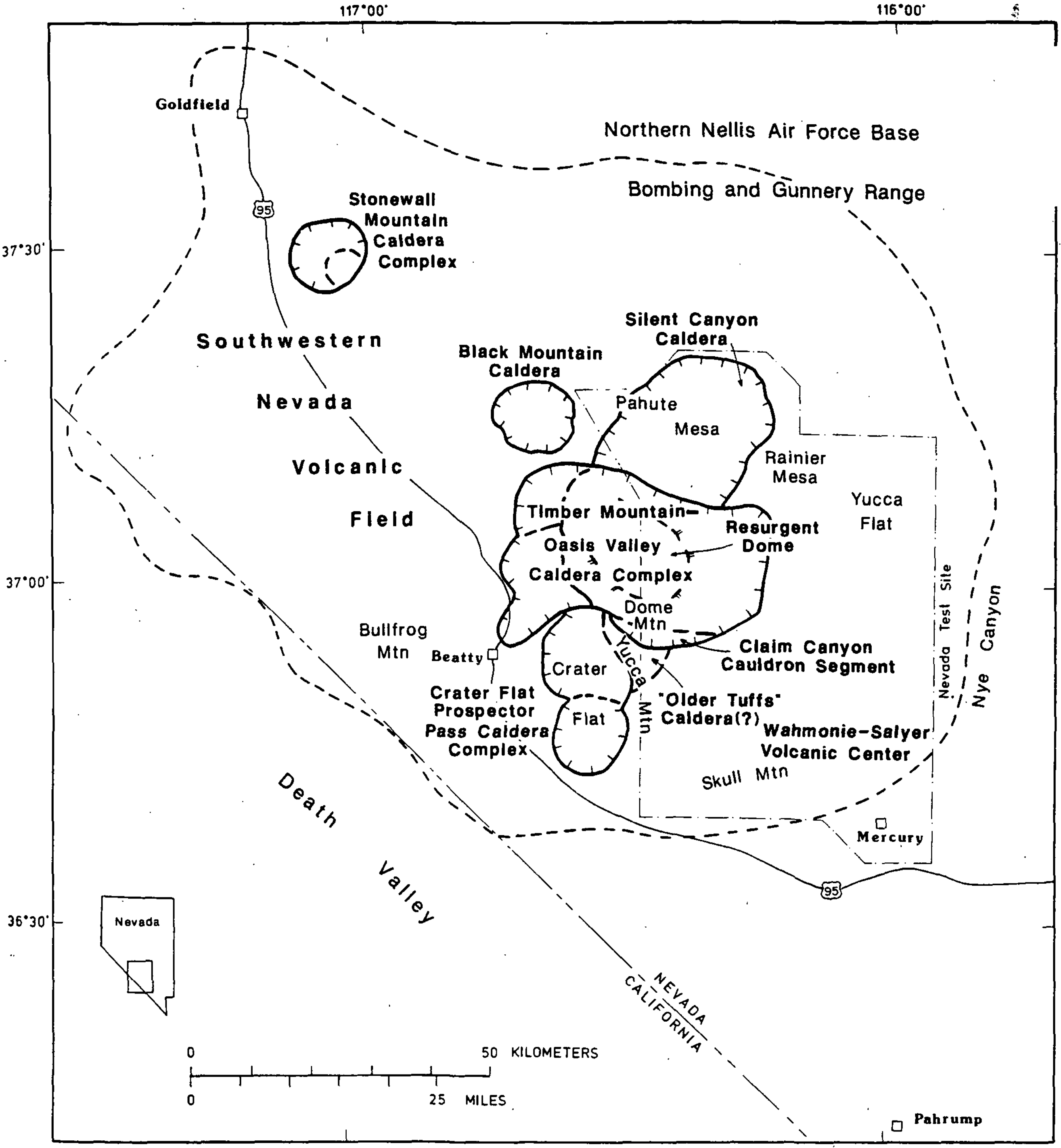

Fig. 1. Location of caldera and other geographic features of the southwestern Nevada volcanic field (dashed outline).

AEC, now the DOE [*Hansen et al.*, 1963; *Houser*, 1968; *Eckel*, 1968]. In 1958, geologic mapping of volcanic rocks was begun in two 7.5′ quadrangles: Rainier Mesa [*Gibbons et al.*, 1963] and Tippipah Spring [*Orkild*, 1963]. In the volcanic sequence at Rainier Mesa (Figure 1), several welded ash flow tuffs were recognized, but owing to the areally restricted study, no understanding of their source and regional stratigraphic relations was achieved. Most of the volcanic sequence at Rainier Mesa consists of bedded tuff in a relatively simple but laterally variable sequence; the variability is due in large part to topographic effects of underlying ridges of Paleozoic rocks.

Many later, more significant scientific contributions to volcanology resulted from the large-scale geologic effort at the NTS [*Byers et al.*, 1986]. The growth of our understanding from relatively simple layer-cake stratigraphy to complex volcanic and magmatic configurations within and near caldera centers will be outlined, as well as the appreciation of the magmatic evolution of major volcanic centers, such as Timber Mountain. Since 1981, Earth scientists from Los Alamos and Lawrence Livermore national laboratories have contributed to the geology, petrology, and geochemistry of the Timber Mountain–Oasis Valley caldera complex. The Lawrence Livermore contribution has come mainly from T. A. Vogel and his students from Michigan State University.

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not significant to NTS

Curie Temperature Isotherm Analysis and Tectonic Implications of Aeromagnetic Data From Nevada

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Estimates of the depth to the Curie temperature isotherm in Nevada are in accordance with other regional geologic and geophysical information and together can be explained in the context of present-day tectonism. A method to estimate the depth extent of magnetic sources from the statistical properties of magnetic anomalies was applied to a statewide compilation of aeromagnetic data from Nevada. Basal depths of magnetic sources show no apparent correlation with the so-called magnetic quiet zone, which trends northerly through the eastern part of the state, or with basin-and-range topography. However, certain correlations with published heat flow measurements are apparent and suggest that undulations in basal depth of magnetic sources are related in part to undulations in the Curie temperature isotherm. For example, an area of shallow basal depth (< 10 km) near Battle Mountain corresponds to an area of exceptionally high conductive heat flow and indicates a shallow depth to the Curie temperature isotherm in this region. A narrow zone of shallow basal depth extends south from the Battle Mountain area along the 118°W meridian to at least latitude 38°N, which also is a zone of historic surface offsets and high-magnitude earthquakes. The correspondence along the 118° meridian of shallow basal depth, high heat flow, high lower crustal seismic velocities, attenuated *P* and *S* wave arrivals, historic faulting, and large earthquakes suggests that they each are related to an active north trending spreading zone in this part of the Basin and Range province.

INTRODUCTION

During the last few decades, magnetic data acquired by aircraft have proven useful for extrapolating the location of magnetic rocks from outcrops to covered areas, for defining the shape of subsurface lithotectonic features, and for interpolating subsurface geologic information between more widely spaced geophysical measurements such as seismic reflection and refraction profiles. In this paper we examine a new compilation of magnetic data from the state of Nevada and relate it to other regional geologic, topographic, and geophysical information. In particular, the spectral properties of the magnetic field are used to infer depths to the Curie temperature isotherm in Nevada and to draw conclusions about the tectonic setting of the area.

Certain oxides and sulfides of iron, such as magnetite and pyrrhotite, possess a spontaneous magnetization at room temperature that is manifested in rocks as remanent magnetization and ferrimagnetic susceptibility. Above the Curie temperature (approximately 580°C for magnetite at atmospheric pressure), spontaneous magnetization vanishes, and these minerals exhibit paramagnetic susceptibility. Because paramagnetism is a small effect compared to spontaneous magnetization, rocks are essentially nonmagnetic at temperatures greater than the Curie temperature of the most important magnetic mineral of the rock. It should be possible therefore to estimate the depth and configuration of the Curie temperature isotherm from subtle characteristics of magnetic anomalies if magnetic lithologies exist at these depths.

Estimates of the depth to the Curie temperature should be treated with caution for both mathematical and geologic reasons. First, these estimates are inverse calculations and encompass all of the nonuniqueness and mathematical instabilities inherent in such methods. These calculations are especially difficult because estimates of Curie temperature depth attempt to define the nature of deep crustal sources that produce generally low-amplitude and long-wavelength magnetic anomalies compared to shallower sources. Second, techniques to estimate depth to the Curie temperature actually estimate the basal depth of magnetic sources. A surface that describes basal depths, however, may not be an isothermal surface because rock magnetic properties, and the Curie temperature, in particular, may vary from place to place due to lithologic or mineralogic changes.

With these caveats in mind, a Fourier domain technique was applied to the compilation of aeromagnetic data from Nevada in order to estimate the basal depth of magnetic sources in this region. The method uses the statistical properties of groups of magnetic anomalies within overlapping rectangular cells. The regional scope of the magnetic compilation allowed the state to be divided into numerous cells and permited an investigation of lateral variation of basal depth throughout the state. The estimates of basal depth show interesting comparisons with heat flow measurements, earthquake activity, recent faulting, and seismic data that are interpreted in terms of extensional tectonics of the Basin and Range geologic province.

GEOLOGICAL AND GEOPHYSICAL SETTING

The state of Nevada lies within the Basin and Range geologic province (Figure 1), which is characterized by approximately east-west extension, widespread volcanism, regionally elevated topography, thin crust, low upper mantle velocity, and high heat flow. As summarized by *Zoback et al.* [1981], modern topography and extensional tectonism of the Basin and Range reflect only a late stage episode in a more complicated history related to interaction between the Pacific, Farallon, and North American plates. An episode of continental rifting during the late Precambrian left a passive continental margin and a westward thickening wedge of shelf deposits along western North America [*Stewart*, 1972]. As inferred

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Overview of Geophysical Methods Applied to Precious Metal Exploration in Nevada

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Many of the geophysical methods are applicable to mineral exploration. Several are direct detectors of sulfide mineralization, but most are indirect, that is they respond to a geological environment, rather than a particular mineral suite. In precious metal exploration, the application of geophysics is indirect and use should be considered more as a mapping tool than just an anomaly finder.

The following is a review of where and how the various geophysical methods might be applied. All geophysical methods have some application to gold exploration in the Great Basin of Nevada, but not in a casual or routine sense. No geophysical method detects gold mineralization per se, with the possible exception of nuclear activation which has only limited application and is not specifically listed. Several methods can detect and map gold-bearing lithology or an associated alteration envelope; others can locate structures or lithologies that may be permissible for mineralization. No one method will work satisfactorily all of the time, and all methods will provide useful information under certain geologic conditions, and therefore will work some of the time.

In Nevada, gold deposits may occur in a wide variety of geologic units, including volcanic tuffs and flows, sandy sediments and carbonates, and along intrusive margins. Hydrothermal alteration is characteristic but complex; variations range from advanced argillic to pervasive silicification. On a broader scale, key indicators that simply characterize gold deposits are favorable lithology and alteration, structure which permits circulation of hydrothermal fluids, and intrusive activity which provides a source of metals, hot waters, and heat to drive the system.

The list of geophysical methods with potential application to gold exploration, Figure 1, includes the five main classifications, each responding to a different physical property of the earth (susceptibility, density, resistivity, velocity, and radioactivity). Two secondary properties, magnetic remanence and chargeability, have been added. Applied to an exploration project, the critical factor is the change or contrast in physical properties - lateral for some, vertical for others - in the shallow, near-surface crust that is detected and measured.

Many gold deposits are small targets, which in a bulk sample concept, have low physical property contrasts. Locally, however, the mineralization or alteration assemblages may vary widely in intrinsic properties, e.g. from silicic (high resistivity, low chargeability) to advanced argillic (low resistivity, high chargeability). Significant sulfide mineralization is only sometimes a significant component of an anomaly.

Geophysical surveys are not just aimed at producing anomalies over mineralized zones, but also may be designed to determine pediment depths, basement highs, location of buried faults, lithologic contacts under cover, or areas of significant alteration.

Range of Physical Properties

The range of physical properties, and their respective units, is shown in Figure 2. The range or variation of resistivity and susceptibility is tremendous, as much as 7-9 orders of magnitude for the former, and is usually plotted on a logarithmic scale. Susceptibility can range from >50,000 micro cgs for magnetite deposits to almost zero for alteration assemblages where the destruction of magnetite is complete. Density, on the other hand, has probably the least variability and least range for many of the common rock types. Certain minerals, gold (>19 g/cc) or metallic sulfides, for instance, have a high specific gravity but rarely do they occur in nature in the quantity or extent necessary to effect or cause a significant and measurable response at the surface. Massive sulfides, usually of relatively limited overall size, are probably the most dense of the common geologic features.

Susceptibility (k) is a function of the volume percent magnetite in a rock, and to a certain extent the size of the magnetite grains. While magnetite generally increases toward the mafic end of the petrologic sequence, susceptibility cannot be tied directly to rock composition. For instance granite may produce a relative high anomaly due to accessory magnetite or a relative low (with no accessory magnetite) if intruded into an intermediate or mafic host environment. Remanence, if present, causes unusual magnetic anomalies and, if recognized, limits the interpretation potential of the magnetic data.

Resistivity ρ, or its reciprocal conductivity σ, has the greatest range of any physical property. Massive sulfides and graphitic shales are on one end of the scale, metamorphics on the other. Most rocks, volcanics as well as sediments, can have widely variable resistivity, due primarily to porosity and permeability, and water content and salinity. No value is particularly diagnostic

List of Methods

Magnetics

- * Aeromagnetics

Gravity

Electrical

- * Resistivity
- * Induced Polarization - IP
- * Electromagnetic - EM
  - VLF - Very Low Frequency
  - Frequency Domain (Horizontal Loop)
  - Time Domain
  - MT - Magnetotelluric
  - CSAMT - Controlled Source Audio Magnetotelluric
  - Airborne EM
  - Self-Potential - SP

Seismic

- * Reflection
- * Refraction

Radiometric

- * Natural
- * Artificial

Well-Logging (all methods)

Remote Sensing Imagery

Figure 1. List of Methods.

until correlated with a particular unit in a particular environment. Significant changes within a project area are not unusual.

Massive sulfides are a low resistivity (high conductivity) target; porphyry systems with disseminated sulfides are high chargeability, generally low resistivity, targets. Precious metal targets cannot be so classified or defined and interpretation must consider both the highs and lows of anomalous response.

Density has the least variability over the types of rock composition. Silica and feldspars are similar in density. The mafic minerals are usually more dense, but the range of rock density is usually not more than 2.6 to 2.85 g/cc. Porosity and permeability of both carbonate and clastic rocks usually will have more effect on bulk density than mineral composition. Dry alluvium is usually the least dense unit of concern; ultra mafics and/or metamorphics the greatest. Sulfide minerals are dense, but commonly are disseminated and usually are so small a percentage that the effect on the bulk rock density is insignificant.

Seismic velocity is related to the "strength" (elastic moduli and density) of the rock unit. Sediments and large intrusives may be reasonably consistent within a mining district; volcanics flows, tuffs, and intrusives, on the other hand, may be limited in areal extent, show large changes in thickness over short distances, and vary widely in hardness and density. Alteration and mineralization show velocity anomalies both higher and lower than the host rock environment. Dry alluvium is the low end of the velocity scale, dense crystalline basement rocks are the high end in Nevada geology.

The effect of alteration on physical properties, Figure 3, is the modification of the normal or background value of the intrinsic physical property, which either increases or

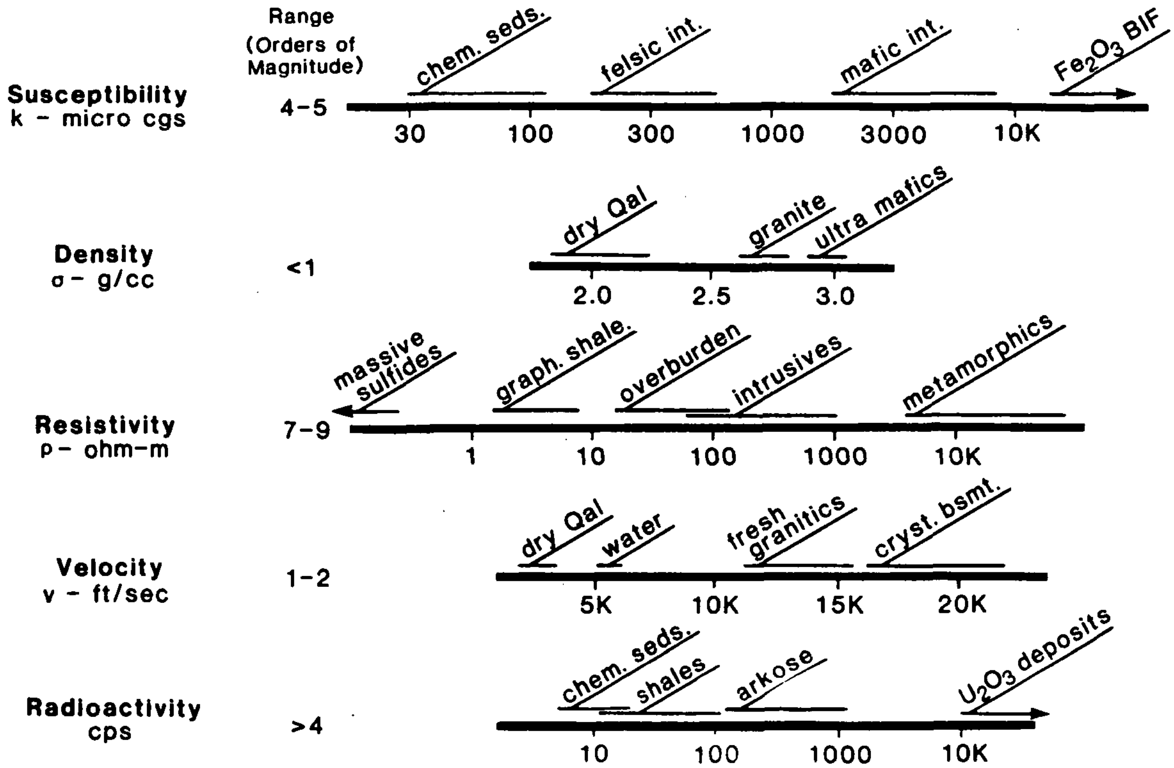

Figure 2. Range of Physical Properties

decreases it, producing anomalous highs or lows respectively. Magnetite is generally destroyed in many alteration processes, but can be formed with certain types of skarns. Resistivity can be increased by the addition of silica, or decreased by the formation of clays and related alteration products. For these reasons, particularly in gold exploration programs, an anomaly of interest cannot be assumed to be either a high or a low — both are feasible, and both may have exploration potential.

Applications

In this section, one or two typical applications of each method are shown in a simple schematic fashion. The word "schematic" is used because rarely are the applications this simple and straightforward. While simple, the examples are not trivial. The first (Geology, Figure 4) is a section of a "typical" basin-and-range environment at a "regional" scale. Volcanics, faulted sediments, buried intrusive rocks and a thick section of colluvium in the down-dropped basin-and-range valleys are characteristic.

Magnetics

A regional airborne magnetic survey will map the extent of volcanics under cover and, within limits, the location, depth and susceptibility contrast of intrusive bodies. Figure 5 shows a computer calculated profile of a 2½-D model of the magnetic response of the geologic section equivalent to that of a low level draped survey. The volcanics typically produce a strong anomaly; however, due to either topographic effects or magnetic remanence (or a combination of both), the resulting anomaly may be a dominant low. Because the intrusive may be small and at depth, as in the example, its anomaly has a low amplitude, broad profile. Therefore, such small indistinct anomalies should not be omitted from consideration.

The final product of an airborne survey is usually a contour map. Figure 6 is an example of a low level, fixed wing draped survey flown nominally 400 feet above the ground surface at one-quarter mile line spacing in a north-south direction. The resulting anomalies are, in part, small and tight, often intense, closures - some may say noisy - indicating surface volcanics. Helicopter surveys, often in conjunction with electromagnetics, are often flown at 0.1 mile spacing at 200 feet flight elevation.

Alternatively, magnetic surveys may be flown at a constant barometric elevation several thousand feet above the surface, either on a grid (typically 1.5 miles) or single line direction (at .5 to 1.0 mile spacing). Anomalies are relatively broad and smooth which reflects the increased distance between source and sensor. Line spacing necessary

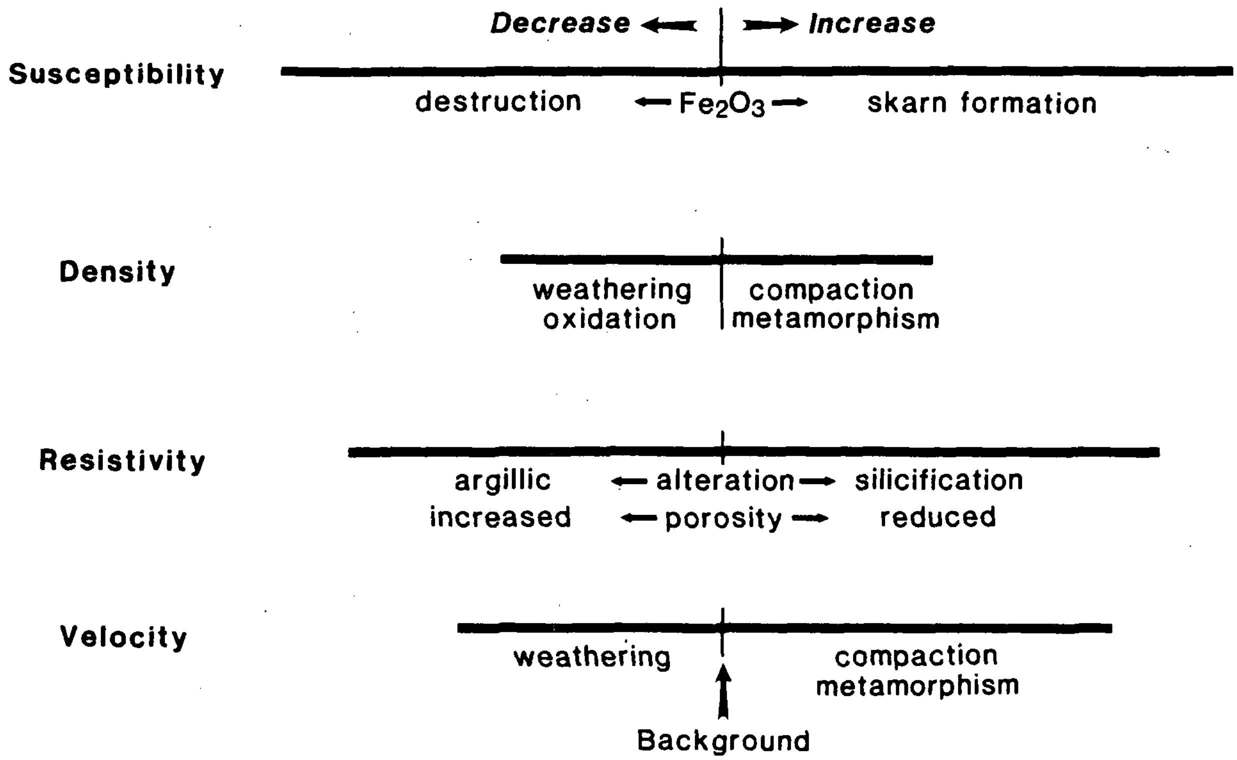

Figure 3. Effect of Alteration on Physical Properties.

to define small features may be opened up providing more areal coverage for the same dollar amount. Small, strong amplitude, features, such as in the example shown, would be smoothed or smeared simply because of the size-distance function implicit in potential field methods. Figure 7 shows the magnetic data of Figure 6 continued upward 1000 feet, which is approximately equivalent to a high level, constant barometric survey.

Similar broad patterns, linears and other equivalent features can be discerned in both contour maps. The differences, however, are in what can be interpreted from each contour map and the relative unit cost of the survey. The tight patterns in the west half of Figure 6 are a typical pattern indicative of surface volcanics, probably with some terrain effect. Closures on the "high level" (Figure 7) reflect the same sources, but are reduced in amplitude and broader when measured at the greater height. Linear features indicate faults or lithologic contacts. The sharp north-south demarkation in contour pattern in the center is a mapped fault throwing Paleozoic sediments on the east against volcanics on the west. North-northeast and west-northwest linears, in the west and north respectively, show well on both maps. With study other equivalent features can be discerned. One primary difference is that the signature of any small anomaly is attenuateed and smoothed when measured at a greater height. Other differences might be in the width and depth estimates of small anomalies with dimensions less than that of the flight elevation. On the other hand regional features are enhanced and near-surface effects (volcanics, or "noise" in some interpretations) are suppressed with high level surveys. Selection of type survey and flight specifications to be flown are based upon the area of interest, concepts of target size and depth, and budget. Either approach has advantages and limitations.

Filters, derivatives, and/or reduction-to-the-pole can be used to aid interpretation in either data set. Frequency filters, either low or high cut, to eliminate regional features or surface (or noise) effects respectively, or upward continuation can be useful to isolate certain types of anomalies and to otherwise enhance interpretation.

On either regional or detail scales, in addition to the contour map a number of other map products can be generated to aid in magnetic interpretation. Color maps, in particular, are very useful, and in effect when properly done, become an optical filter. Shaded relief or shadowgraphs with different illumination angles and azimuths are used to emphasize linear features such as structures. Individual and stacked profiles show the data without the smoothing effect of the contour algorithm.

Airborne magnetics is a sound basic geophysical mapping tool that can be effectively applied to most exploration prospects. Relatively inexpensive, it can provide data on the extent of certain lithologies, on

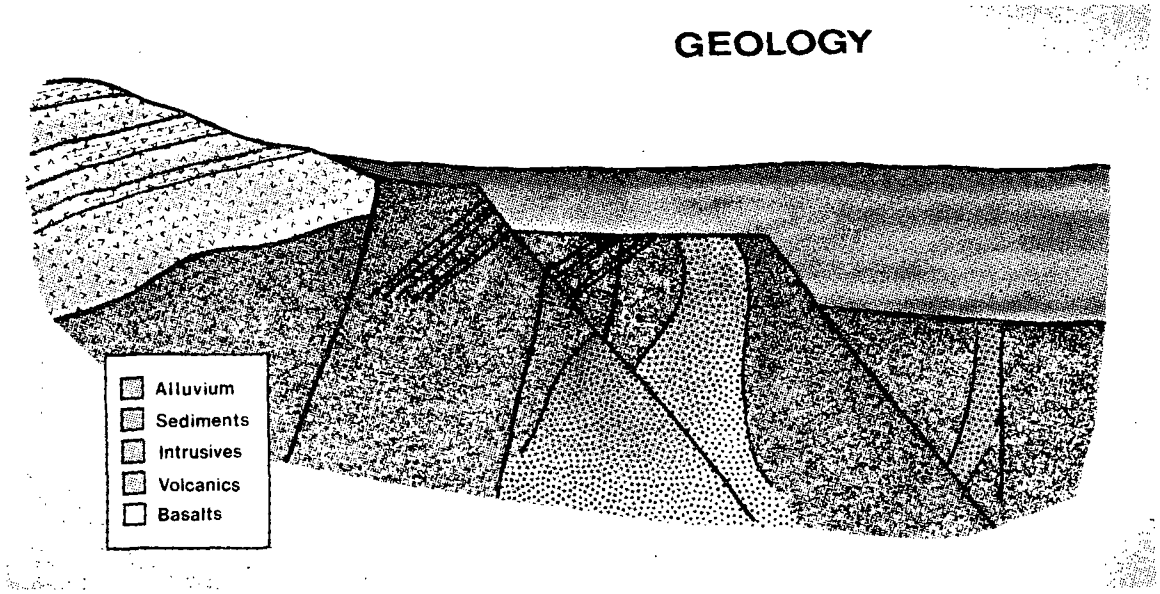

Figure 4. Geology.

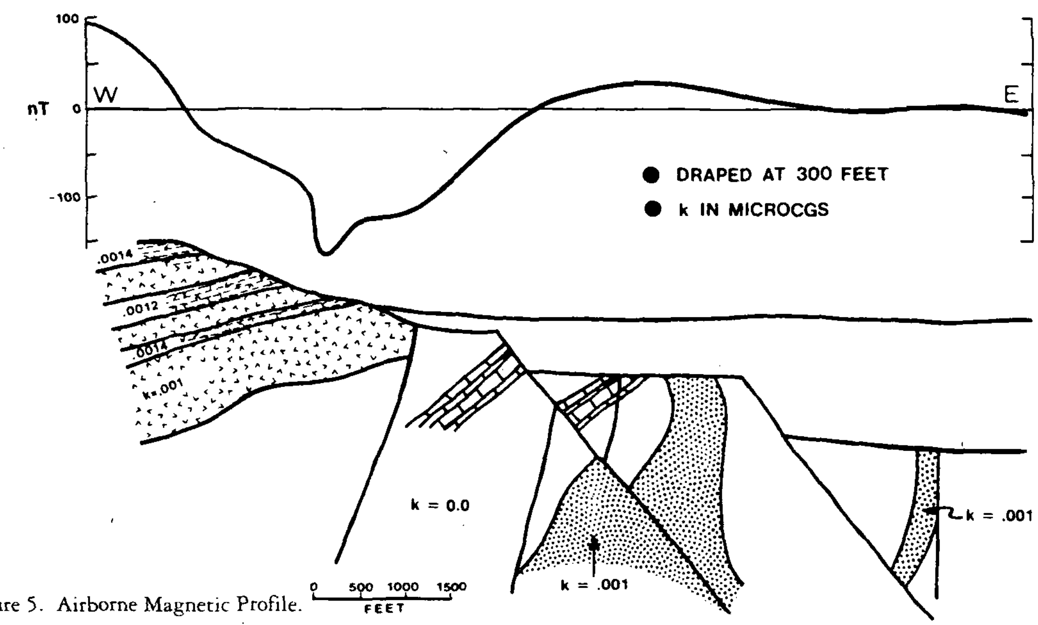

Figure 5. Airborne Magnetic Profile.

structure, and on the location, depth and susceptibility contrast (or composition to the extent that susceptibility is diagnostic) of the intrusive.

Ground mag in either a total field or vertical gradient configuration is a common follow-up technique. Use of the gradient enhances or sharpens broad features but can be a handicap if near-surface effects (volcanic noise) are high. The use of a 8-foot staff and a single sensor reduces the noisy effects of detrital magnetite on the surface or the magnetic noise produced by many surface volcanics, e.g. basalt flows.

Survey design - line separation and station spacing - can be crucial to an effective survey and satisfactory interpretation. Twenty-five foot stations on 200 foot lines are a typical detail specification. Too often lines are spaced on a budget basis and not on a realistic attempt to define the anticipated target.

Gravity

A gravity profile over the same geology section, with typical densities assigned to the rock units, shows the gravity low due to the "block" of low density alluvium, Figure 8. The locations of the faults, downdropping basement to the east, are indicated by a change in gradient of the profile. In this case the subtle changes are the significant characteristic of fault location. Under ideal circumstances depth to pediment surfaces can be calculated, but in most cases the variability of the

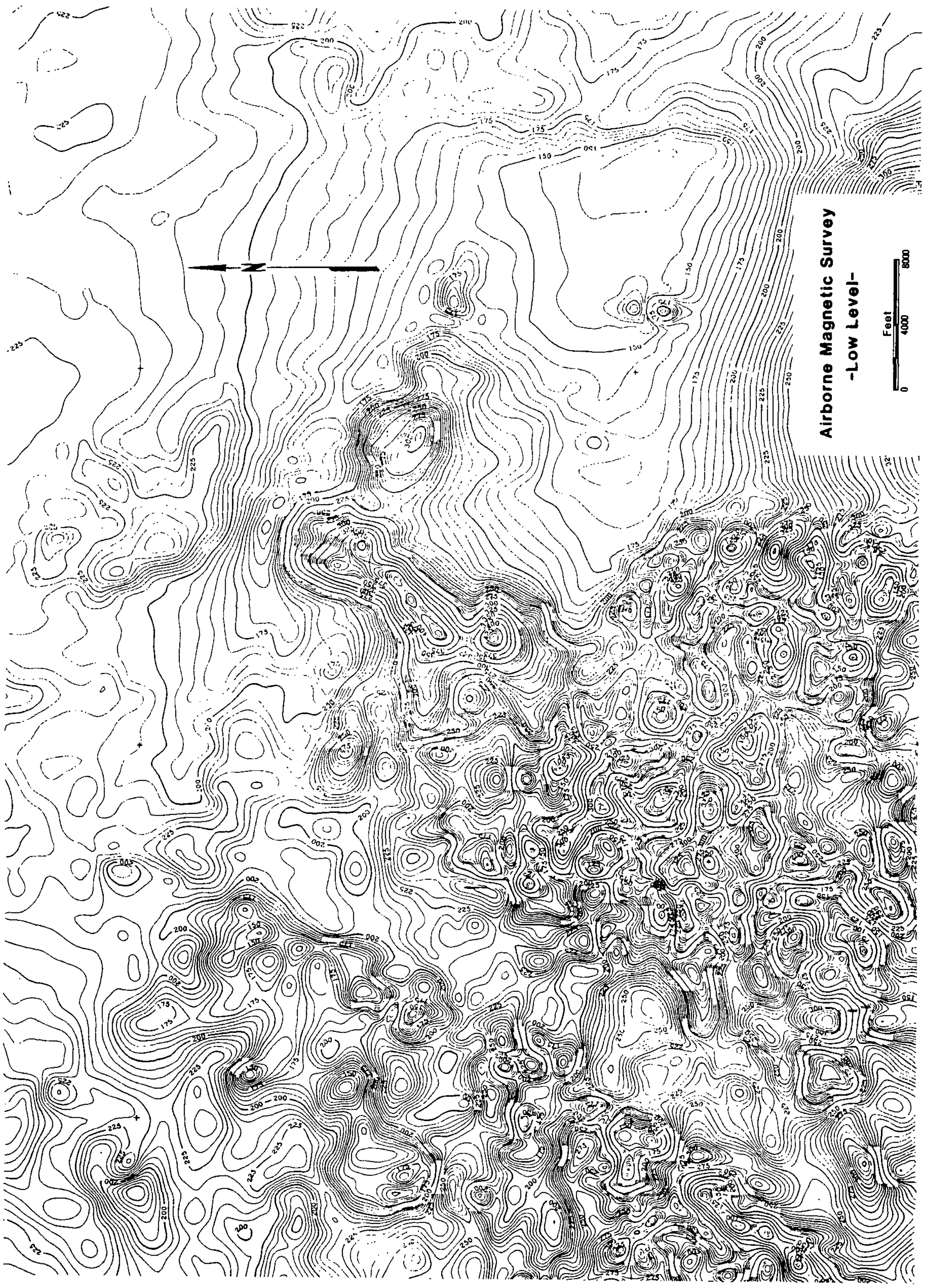

Figure 6. Airborne Magnetic Survey - Low Level.

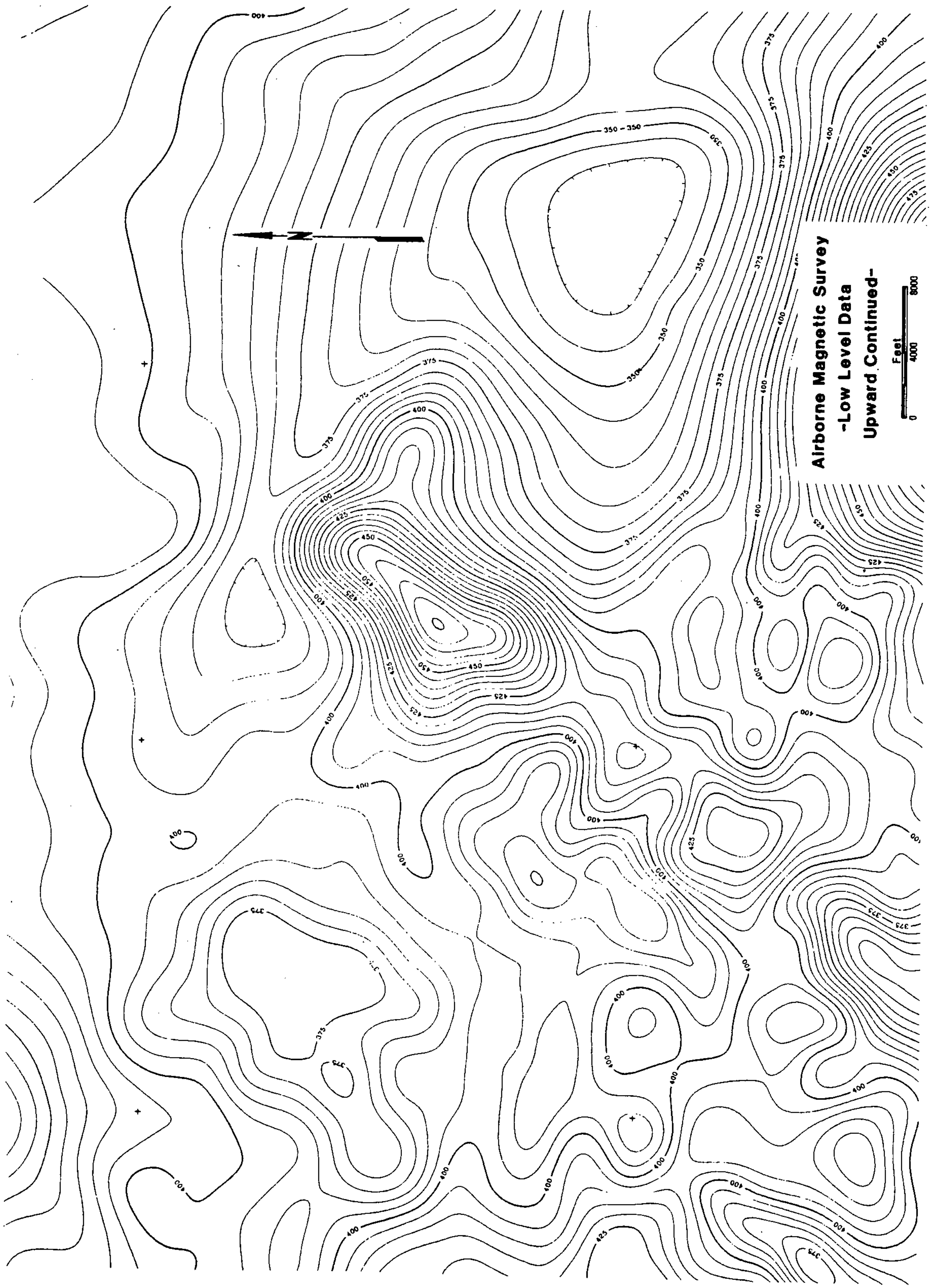

Figure 7. Airborne Magnetic Survey - Low Level Data Upward Continued

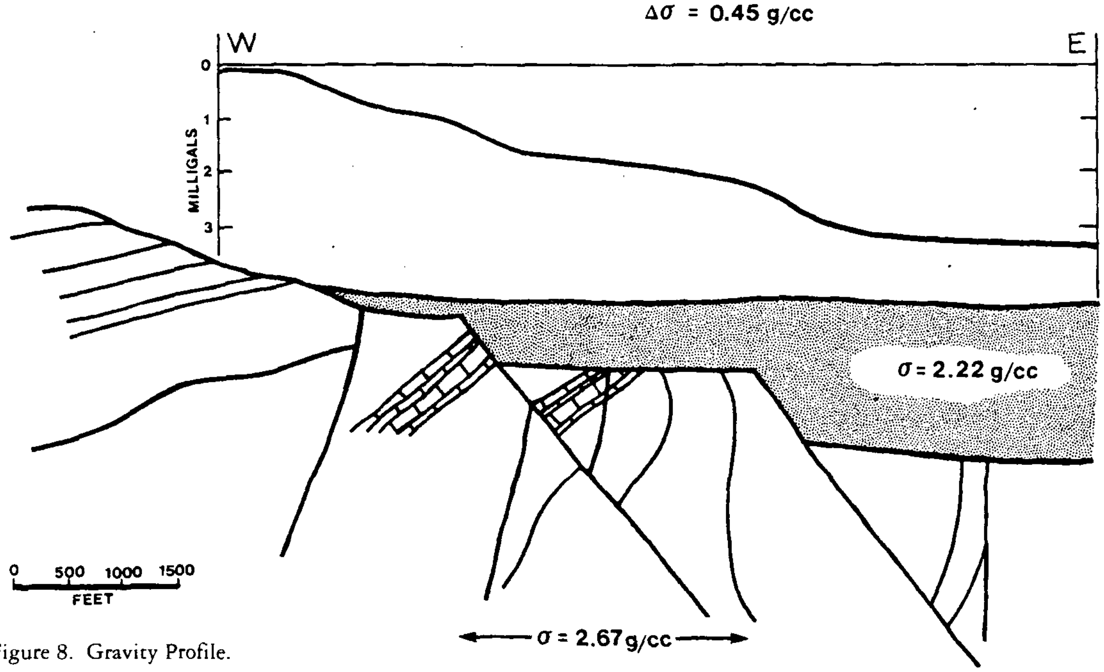

Figure 8. Gravity Profile.

alluvium density, due to compaction and grain size, water saturation, and intercalated volcanic flows, are such that a depth may be estimated, but accuracy is limited unless other constraints are available. On a regional basis, gravity can map the major offset structures within the basin-range valleys, outline many buried intrusive bodies, provide crude estimates of the depth of valley fill, and in correlation with magnetics provide constraints to the regional mapping of structure and lithology.

Electromagnetics

Using the same geologic model, possible applications of several of the inductive source electrical methods, Time Domain EM (TEM) and Controlled Source Audiomagnetotelluric (CSAMT), are shown, Figure 9. Measurement of intrinsic electrical properties is feasible, but usually the lateral and/or vertical changes in resistivity (conductivity), are the more important anomalous effect in an exploration context. In-loop TEM can map the geoelectric section to depths of perhaps +1500 feet but is dependent, as with all electrical methods, upon the resistivity of the overlying material and contrast with bedrock units. An estimate of the resistivity of the bedrock unit is determinable, so that interpretation of small changes in the bedrock are feasible. Large loop methods provide more signal and a greater depth of investigation.

The TEM soundings identified on the section are calculated and shown in Figure 10. Simple two layer cases are modelled. Water table, or interbedded volcanics could make any a multiple layer case. In this example the TEM curves appear quite similar, but are in fact related to different bedrock resistivities. In practice, careful field work by competent operators and use of inverse computations, relatively small contrasts in bedrock resistivities and/or changes in depths can be identified. Although there are a number of reasonable solutions that will fit the curve, such differences in depths and bedrock resistivity can be demonstrated. For instance, three layers can be forced to fit the two layer case shown without significant differences in the resulting curve match. Typically, however, a complex multiple layer section is replaced by a simplified three or four layer model - the principle of equivalence - with practically indistinguishable response. Often, however, the more significant interfaces (or resistivity values) are within reasonable limits. Interpretation implies knowledge of the principles, experience, and some understanding and appreciation of the local geology and geologic model.

CSAMT is a another alternative to map the electrical character of the subsurface, and has the potential to outline both conductive and resistive features (structures and/or lithologies) at greater depth with reasonable resolution. A grounded electric dipole is used for the transmitter. Located several miles away -the distance is dependent upon the resistivity of the area - the measurement of both the electric and magnetic fields is made. From the ratio of these two fields, an apparent resistivity is calculated. The next two figures show the calculated model of a deep conductive feature, Figure 11, the apparent resistivity, and Figure 12, the impedance phase shift between the electric and magnetic fields.

VLF

The next geological schematic, Figure 13, is that of a more detailed geological section with shallow bedrock and several buried alteration zones. The zones of the more productive application of several common geophysical methods are shown, Figure 14.

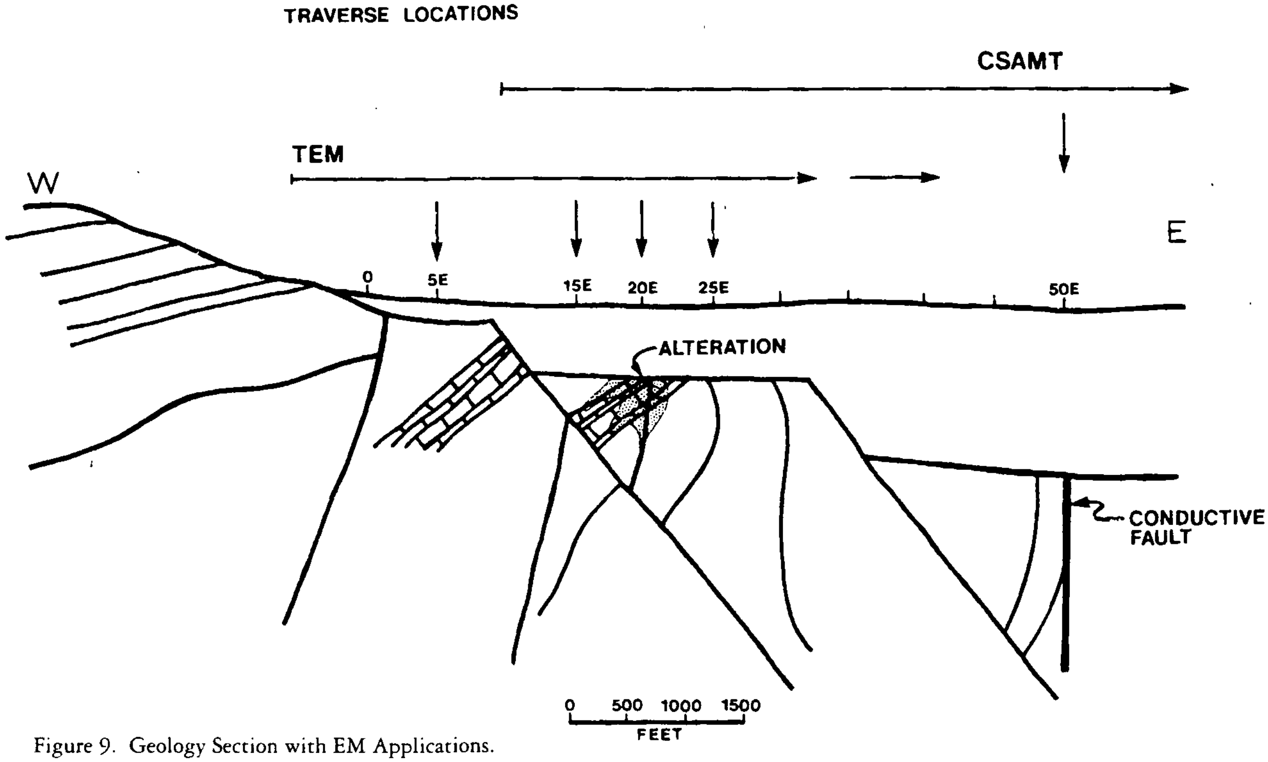

Figure 9. Geology Section with EM Applications.

Figure 15 shows a typical VLF (Very Low Frequency EM) profile derived from a ground survey and plotted in a tilt-angle format. Similar results would be obtained from an airborne survey. The number of conductors, which can arise from conductive faults, edges of water channels or bedrock edges in the alluvium are often a severe handicap to interpretation. In this plot the conductor location is at the inflection point between high and low tilt angle readings (or change in slope on the profile, sometimes called a "crossover"). Airborne and some ground systems will plot the percent intensity of the in-phase and quadrature rather than tilt angle.

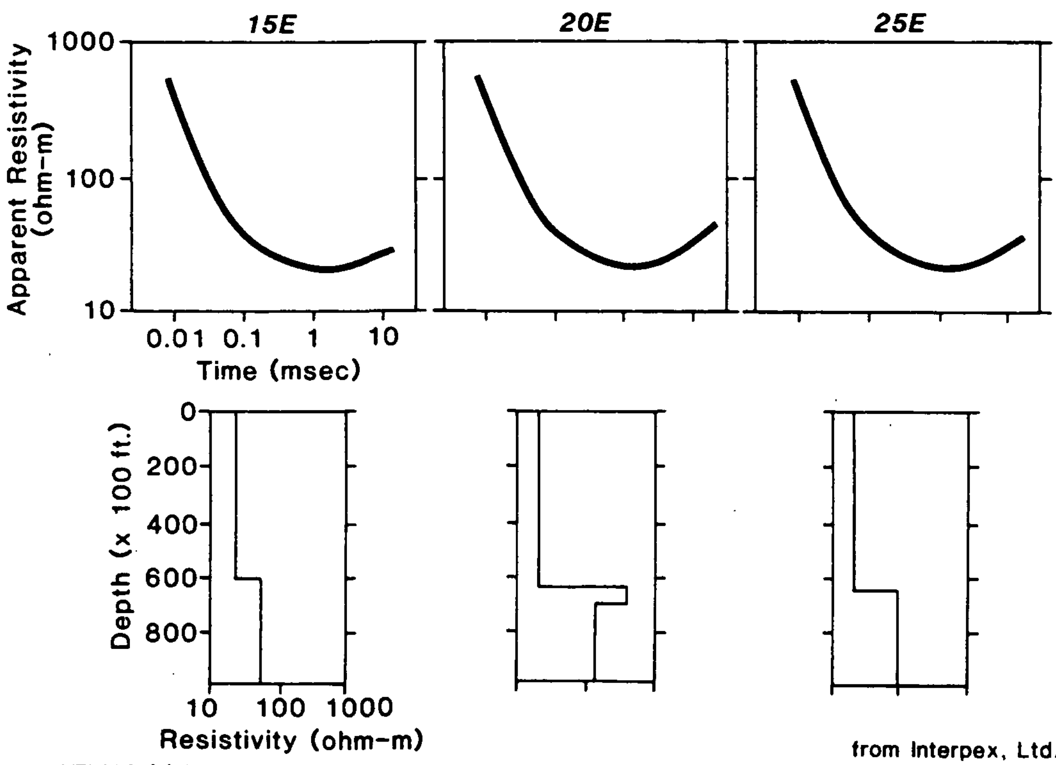

Figure 10. TEM Model A.

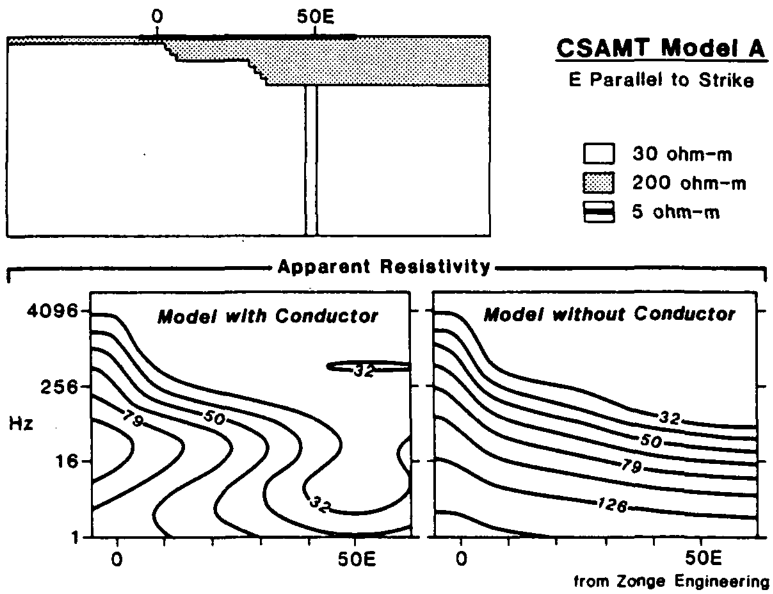

Figure 11. CSAMT Model A - Apparent Resistivity.

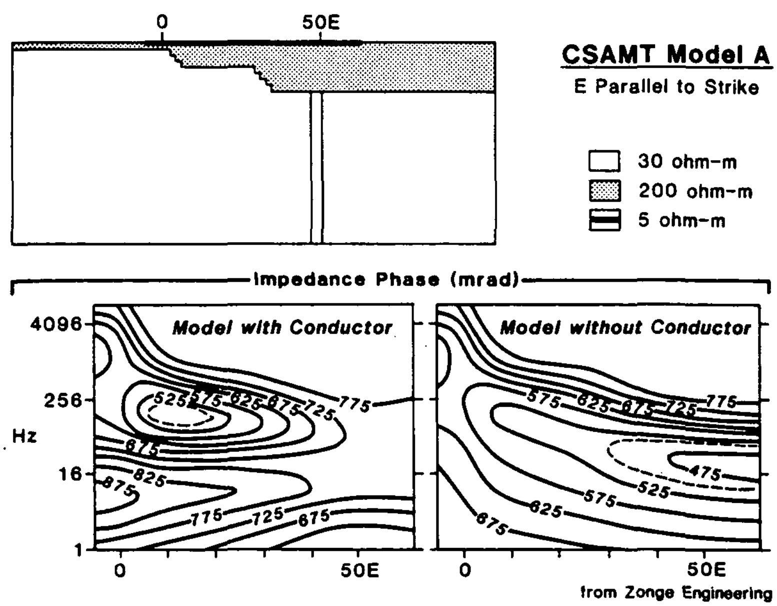

Figure 12. CSAMT Model A - Impedance Phase.

Air EM

This shallow covered environment also may be suitable for air EM methods as well as both airborne and ground magnetics and VLF.

In the airborne mode, helicopter EM systems incorporating magnetometer, VLF and EM systems, are currently in use in Nevada. The EM systems comprise four frequencies (in the ranges of 500-900, 3500-5000 (2), and 30,000-55,000 Hz), usually in two co-axial and two co-planar coil orientations, mounted in a rigid 7-8 meter bird. Application to gold exploration in Nevada is relatively new, and little data have been released and made available for study and open discussion (see suggested readings).

Calculated resistivities are another product of interest derived from airborne EM surveys, particularly in geologic environments, such as the Great Basin, where massive sulfides are the exception. Interpretation focuses on changes in resistivity indicating different lithologies, contacts, alteration and/or structure. EM profiles and color contour maps of one or more of the calculated apparent resistivities are used in the interpretation process.

As with any EM system the penetration or effective depth of investigation is limited by the frequency used and the resistivity of the near-surface, which is usually described by the skin-depth relationship. The depth of investigation is probably several hundred feet in a typical situation. The usual targets of EM surveys are "good conductors" which produce sharp discrete anomalies,

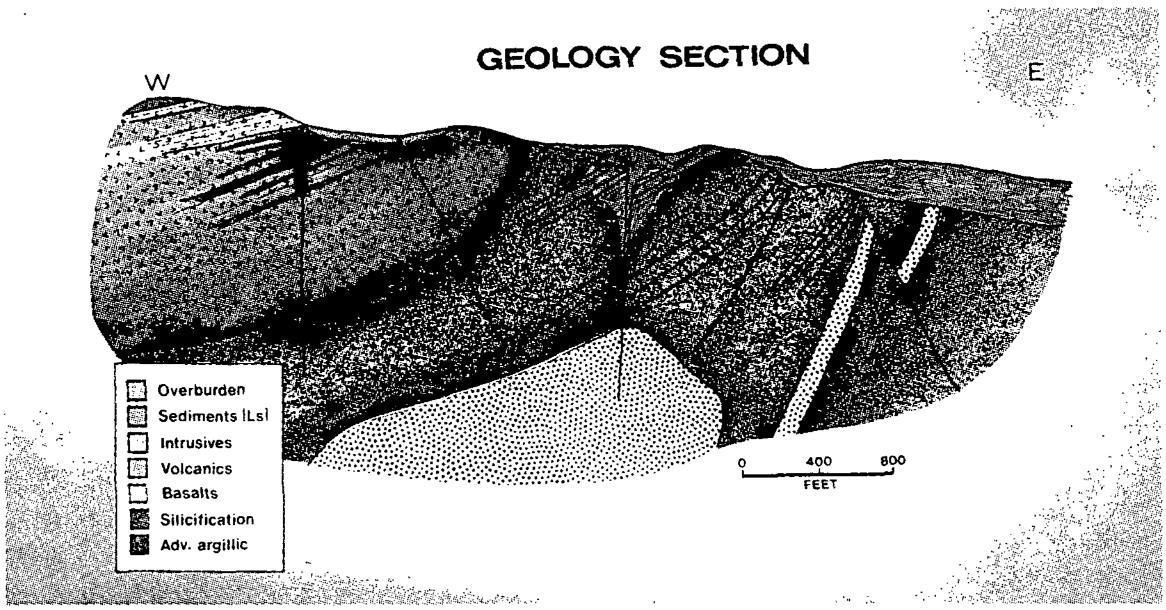

Figure 13. Geology Section

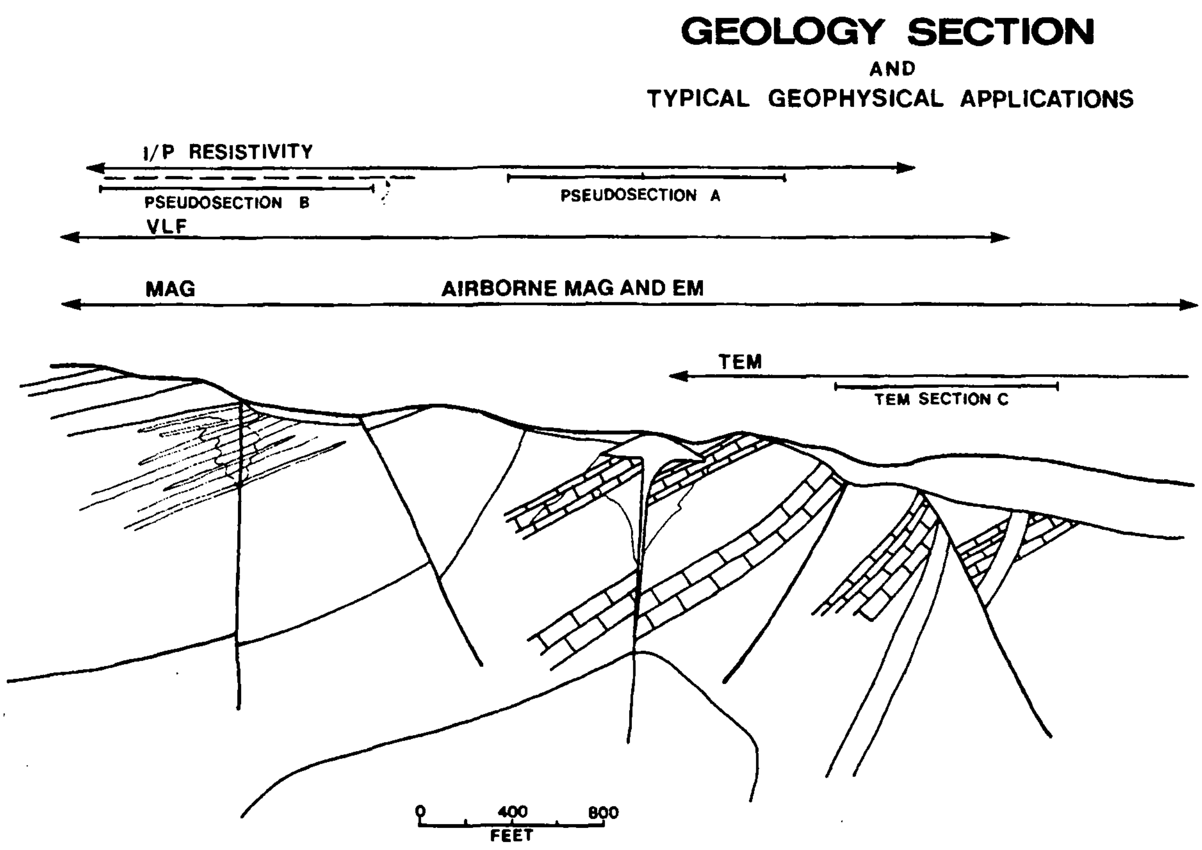

Figure 14. Geology Section and Typical Geophysical Applications

typically massive sulfides or many fault structures.

Induced Polarization and Resistivity

Resistivity techniques differ from EM in that current is introduced into the earth through electrodes in direct contact with the ground. A variety of electrode arrays, current waveforms, and frequencies are used for measurement - the dipole-dipole array using either a time or frequency domain waveform probably being the most common.

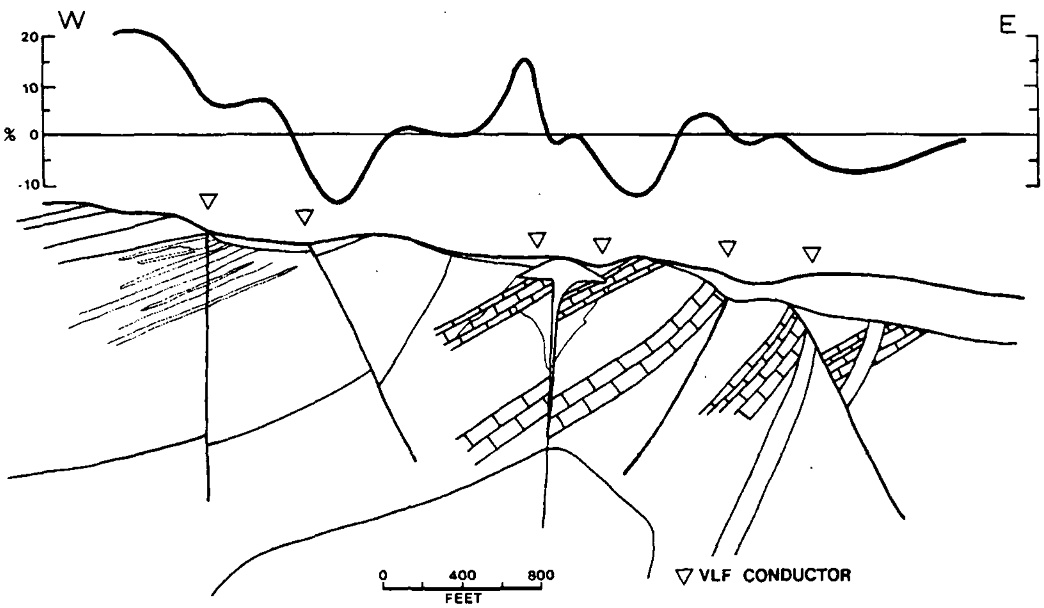

Figure 15. VLF Profile.

Resistivity is primarily a function of rock porosity and water salinity. In an exploration context complex patterns of resistive highs due to silica alteration and lows due to clay alteration and conductive structure are superimposed on alluvial or bedrock resistivities. Interpretation is complicated by the fact that variations in host rock itself due to water porosity and permeability may approach that of many anomalies of exploration interest. Induced polarization or chargeability effects result from the electrical polarization of sulfide minerals, clay minerals in alteration suites, and graphite or graphitic shales.

The next several figures show, in larger scale, two types of alteration, with significantly different physical properties in different host rock environments. A 2-D IP/resistivity model was calculated for each. The first, Figure 16, is a silicified, resistive alteration in sediments; Figure 17 is the IP/resistivity pseudosection. The second, Figures 18 and 19, show a conductive advanced argillic alteration envelope in a host rock of volcanics or tuff sequence, and the calculated IP model.

Seismic

Although not commonly applied, seismic methods have application in mineral exploration, particularly for sedimentary and fault structures at depths where most other methods are severely limited. Refraction seismic has obvious and historic use in depth determinations of placer deposits or alluvium. Shallow high resolution reflection techniques have been applied in certain geologic environments in Nevada to map low angle thrust faults with mixed results. An impedance contrast in

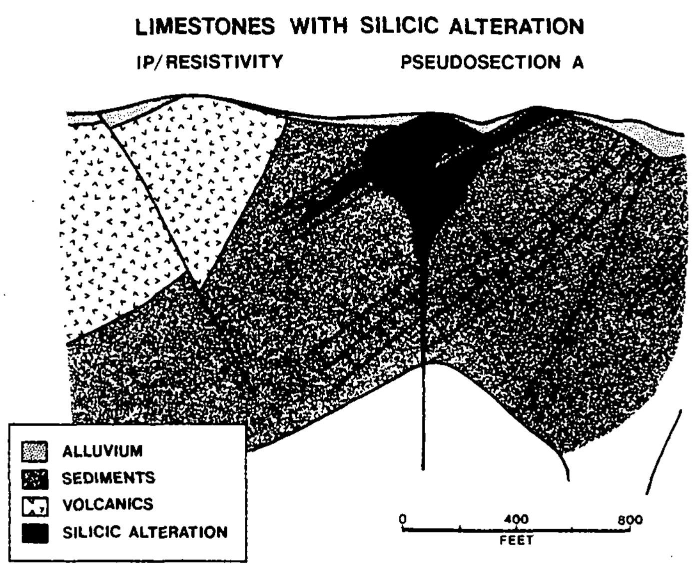

Figure 16. Ip/resistivity model of silicified limestone.

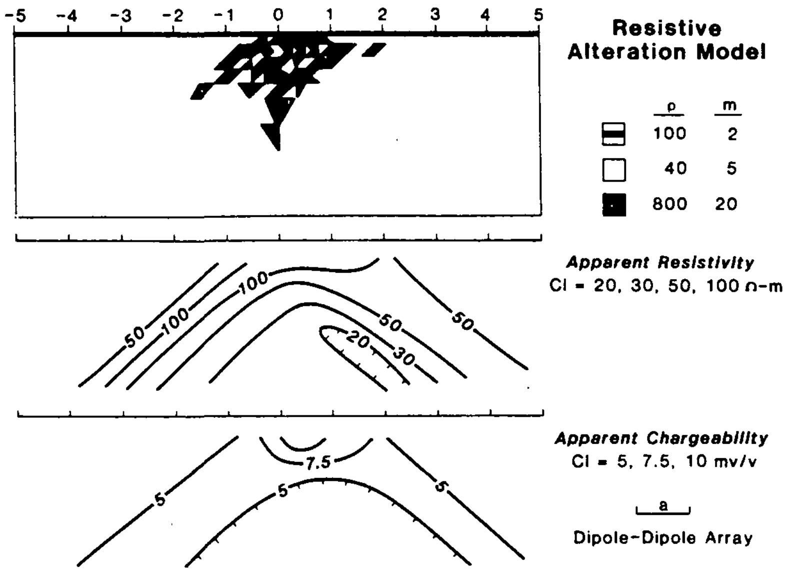

Figure 17. IP/Resistivity Pseudosection A.

zones of hydrothermal alteration and/or mineralization is expected in ore zones, but complex shape, relatively small sizes, steeply dipping contacts, gives reflections and dispersions which are difficult to understand. In areas where application is feasible, interpretation can provide information on structure, bedding angles, and displacement of beds but becomes increasingly difficult with steep dips, multiple faulting (often of small scale relative to depth) and irregular intrusions typical of many mining districts.

Other Methods and Techniques

Other variants of electrical method techniques (e.g. frequency domain EM, large loop TEM systems, resistivity arrays, etc) are feasible and have useful application, but description and comparative advantages and limitations are beyond the scope of this paper. Use of any, or all, requires expertise and knowledge for proper application and interpretation.

Radioactivity has occasionally been used in precious metal prospecting. Using a spectrometer, concentrations of three radionuclides can be inferred from measurement of the radiation directly from potassium and indirectly from the daughter products of thorium and uranium. The geologic application maps the quantity and changes in relative ratios of the "background" response of the three elements (K, Th and U) with lithology and alteration. Potassic metasomatism is of particular interest as it is associated with the alteration assemblages of many different types of gold deposits. Airborne application, in particular, shows interesting mapping potential.

IP/RESISTIVITY PSEUDOSECTION B

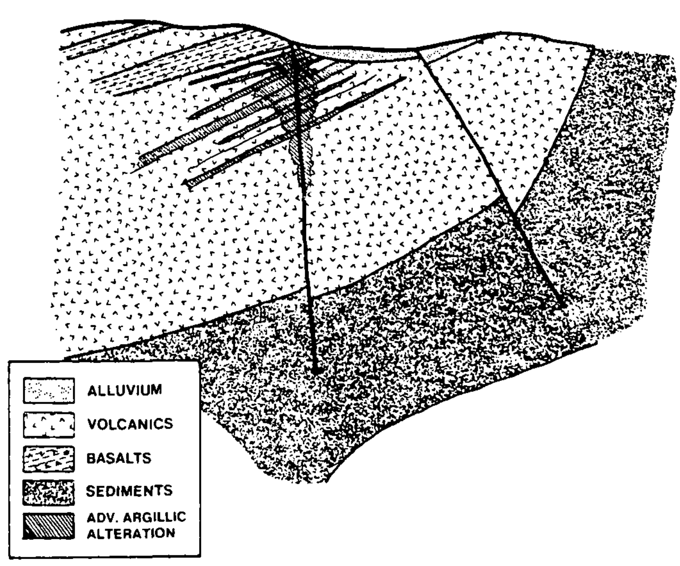

Figure 18. Volcanics with Advanced Argillic Alteration.

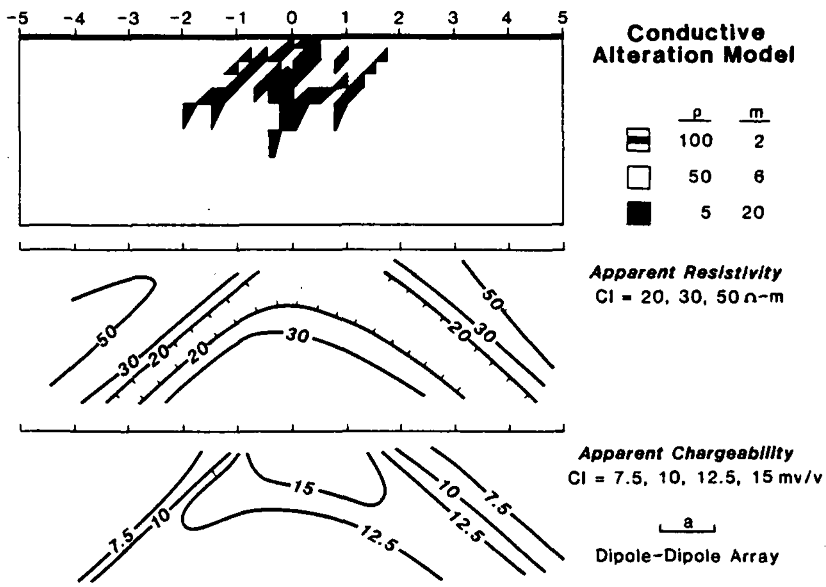

Figure 19. IP/Resistivity Pseudosection B.

Borehole logging techniques utilize the same physical properties, some of which are measured in different ways, e.g. density, porosity and sonic tools. Logging is important for several reasons, including in-situ physical property measurements, exploration at depth adjacent to the hole, and/or engineering studies. Applied to interpretation of surface data or correlation of geologic units where core is not available, in-situ measurement downhole is the best determination of physical properties. Interpretation is a complex process. Costs are relatively high because of the numerous short holes (2-400 feet) typical of mineral prospects and high relative call-out charges.

Survey Design

Some geophysical methods, particularly those of a regional nature (magnetics and gravity), are designed to map the environment and locate those key "district" scale features related to many deposits, namely, favorable lithology, structure and intrusive bodies.

The more detailed methods, particularly the electrical methods, are designed for more specific targets on a smaller "prospect" scale. Selection of method is based in part upon estimates of the size, depth, physical property contrast expected from the alteration and host rock, and the topographic and surface conditions (dry and non-conductive or wet and highly conductive alluvium). Three criteria must be addressed before selection of an optimum and cost effective electrical method; 1) lateral resolution, 2) vertical resolution, and 3) sensitivity of the method to anticipated geologic noise of the area. The depth and size of the target determine the electrode spacing of IP/resistivity or loop size of EM methods. Forward modelling of the assumed parameters is a very useful exercise in planning a survey, but too often is ignored for the more traditional "it's worked before, let's try it again in the same way" approach.

In addition, other factors concerning cost, logistics, timing, and interpretation potential must be considered in survey design.

None of the geophysical methods produce unique solutions, all have inherent limitations in both field application and interpretation.

Relative Costs

Costs and production rates have many variables. In airborne work, survey size (areal extent and line mile totals) is a dominant factor. A detail survey of four square miles can generate up to 65 line miles per square mile (at 100 meter line spacing), so that survey areas are selected with particular care and may not be extensive. Although brief, incomplete, and approximate, some examples of relative cost are listed below for interest and comparison.

	Line Miles	Line Spacing	Cost/mile
regional mag (fixed wing)	1000's	.5 - 2 miles	$12-25
mag (helicopter)	100's	.1 - .5 mile	$ >60
air EM w/ mag	100's	200-500 m (meter)	$ >100

Ground surveys may consist of several lines to extensive grids; surveys are typically in the range of 2 to 10 line miles. Because of limited size, often uncertain ground conditions (steep terrain and ground cover), and contact resistance (IP/resistivity), resulting in unknown production rates, survey costs typically are based upon a daily rate rather than a per mile basis. As target anomalies are shallow, relatively small, and often of low amplitude, close station spacing (25-50 feet) and line spacing (200-600) are desired. Several examples are listed.

Ground mag — 3-5 miles per day; usually with a recording base station magnetometer; integrated VLF system optional extra; 1-2 person crew; usually quoted on a daily rate ($600-800 per day); digital recording and PC data reduction on a daily basis are common.

TEM — 15-25 stations per day depending upon transmitter loop size (200 to 5000 feet), station spacing, and topography; usually quoted on a daily rate for a 3-4 person crew ($1200-1600 per day).

CSAMT — 15-25 stations per day depending upon transmitter length and location, number of lines, station spacing, number of E- and H-field parameters recorded, and natural electrical field noise; 3-4 person crew ($1400-2000 per day).

IP/Resistivity — electrode separation (a-spacing) related to target depth and size, typically separations range from 50 to 1000 feet; line length and number of stations read per day depends upon electrode separation, array, topography, equipment specified, and electrical noise; usually quoted on a daily rate for a 4-5 person crew ($1500-2000 per day)

Summary

Many different geophysical methods have application in precious metal exploration in Nevada. However, application and interpretation potential of certain methods in some geologic environments is not without controversy. Geophysicists differ among themselves on what method is best suited to what geologic environment, on when, or if, to apply certain methods, and whether the cost justifies the application (cost effectiveness).

The proper utilization of geophysics, particularly electrical methods, in gold exploration requires some idea or concept of the geology - a geologic model. Not only is the model itself important in the selection of a method or technique, as well as interpretation, but also some idea of the physical properties of the immediate host rock and of the general area is very useful. A physical property contrast is necessary. The knowledge of physical properties is very important, but, unfortunately, too few studies of this kind are ever made and published. Basically the question must be asked - is the target detectable at the depth indicated with the method and technique selected?

In summary - what geophysical methods do work in gold exploration? On a selective basis, that is with adequate geological input, almost all methods - under restrictions of adequate size, physical property contrast, and depth to source body - have some application in exploration for precious metal deposits. Because of the numerous conditions and limitations, both survey design and interpretation may be complex, and if either is misapplied, the result may be less than satisfactory. Development of an interpretative model is not always straightforward. Because of depth, low contrast, size or other factors, data profiles may appear to be "clean and simple." However, as demonstrated, the nuances of small departures or change in gradient must always be considered in interpretation. Design of survey parameters to optimize detectability, careful field work by qualified and competent operators, followed by reasoned interpretation incorporating available geology, are the keys to the practical and cost effective use of the various methods of geophysics in gold exploration.

Suggested Reading

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