APPLICATIONS OF REGIONAL
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NEW METHODS IN GEOPHYSICS TO VISUALIZE GEOLOGY IN TROPICAL TERRAINS

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ABSTRACT

Mineral exploration in the tropics suffers from difficult geological mapping due to thick vegetation, lack of rock outcrop, and extensive but variable saprolitic weathering. Geophysical methods, either airborne or ground-based, are recognized as a viable exploration method to provide broad coverages of geological information. However, until a few years ago, the interpretation of this data was largely quantitative, involving pattern matching of 2-D images of unprocessed geophysical data. The development of 1-D, 2-D, and 3-D modelling algorithms and the ready availability of powerful low cost computers allow the geophysical interpreter to deal with weathering and topographical effects that previously caused confusing effects. EM data interpretation problems caused by variable sensor height and depth of weathering are accounted for, and useful depth-conductivity sections can be created. In magnetic data, low latitude fields, severe topography, and remanent magnetism hamper the use of reduction to the pole algorithms. Modelling in 3-D using accurate magnetic properties allows for these effects. Interpretation of induced polarization pseudosections in weathered areas is simplified as 2-D inversion sections transform the data into geologically realistic depth sections. Examples of the application of these algorithms are shown. Ground TEM techniques are applied successfully to the Las Cristinas gold project in Venezuela, airborne magnetics to the Porgera gold deposit in Papua New Guinea, and IP/resistivity to the Cerro Crucitas gold prospect in Costa Rica.

GENERAL

New methods of analysis now allow the ready integration of geophysical data with bedrock geology and the variable effects of weathering. The methods are general, but have particular application to exploration in tropical terrains. Three-dimensional physical property models can be built using IP, EM, and magnetic data. When these models are reconciled with the known geology then the geophysical data can be interpreted within a strong geological context that is much more applicable to mineral exploration.

The problems encountered in tropical exploration are well known. The tropics are wet, and highly vegetated with little outcrop in areas of low relief; saprolitic weathering is often extensive and deep but variable, depending on the bedrock to some extent, but more preferentially affected by the presence of sulphides. There may be little saprolite development where there are high rates of erosion, and the depth of oxidation and of sulphides may be very variable depending upon a number of factors. Geological mapping is difficult and the full extent of alteration and mineralization is often not obvious; the extent of the redistribution of ore-forming elements (i.e., depletion and secondary enrichment) can be difficult to determine.

Geophysical methods are complicated by the rugged topography or the deep saprolitic weathering, and by the low magnetic latitudes of the tropics. Magnetic anomalies are quite different from those at higher latitudes and there is a strong interaction with topography which is not intuitive. Reduction to the pole methods are unstable, and can fail completely close to the magnetic equator. They can also fail if the magnetic survey has been collected in a surface draped mode. The alternative, flying a constant barometric altitude survey, leads to a loss of resolution as the survey height becomes large over topographic lows within the survey area. The mineral explorationist usually elects to fly a drape survey, and then struggles with the survey interpretation. Airborne EM surveys face the problem of varying flight heights over rugged terrains and are complicated by deep weathering, particularly in low relief areas. As a result the response is dominated by the weathering profile and the ground clearance of the aircraft system.

There are new solutions to these problems, resulting from the pervasive use of cheap and powerful computers. It is now practical for a

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geophysicist to directly calculate the magnetic or electromagnetic response of complex geometries routinely and easily. This ability is changing survey design and interpretation. With the easy availability of computing power have come a number of new interpretation algorithms. In particular, inversion algorithms allow the routine transformation of geophysical data into equivalent physical property models. These can be directly compared with geology of the weathering profile. Examples are the inversion of IP data into equivalent 2-D IP sections, AEM and EM into conductivity depth sections, and magnetic data into 3-D susceptibility models. These inversion generated models can be rapidly checked and modified using the new forward models that now exist. There are EM models which can consider both galvanic current gathering and induction responses for 3-D models in conductive layered earth models, 2-D and 3-D IP modelling algorithms, and 3-D forward models able to calculate the exact magnetic response of arbitrarily shaped and strongly magnetized bodies.

The deeply weathered terrain of mature tropical environments does not hamper geophysical interpretation as much as might be expected. Conventional experience suggests that the wet soft weathered saprolites provide a conductive blanket which effectively shields the bedrock response. They do not. The constant flow of fresh rainwater has removed almost all the free ions from the weathered saprolite. The electrical resistivity of the saprolitic blanket is surprisingly high, and EM and electrical methods penetrate to bedrock without trouble. In addition, mineralized systems have a distinctive response in the weathering profile; the results from geophysical surveys can be presented in a manner that emphasizes this response. This allows the recognition of a mineralized system that otherwise has a subtle geophysical response in bedrock.

Figure 1 illustrates a typical variation in resistivity which will be reflected in the geophysical response for a mineralized system in a mature saprolitic terrain without significant laterite development. The weathering deepens over the mineralized structure. In bedrock, the background resistivity will fall from a resistive background to some intermediate value due to alteration. In the weathered saprolite close to surface a rise in resistivity is typical—this is ascribed to swelling clays associated with the alteration system and modified by the weathering. The resistivity of the saprolite zone is primarily controlled by the porosity and the conductivity of the pore waters. In the weathered altered zone a relative resistivity high exists, porosity is reduced by the swelling clays and electrical resistivity increases. Below the resistive near-surface oxide zone a sulphide/oxide mixed zone exists at the weathering interface. If the sulphide content within the mineralized system is above background, then the mixed zone will be more acidic than the corresponding part of the weathered section outside the mineralized area. The characteristic resistivity section of a mineralized area will be resistive at surface, dropping to an abnormally conductive value at the mixed zone, and then into an altered bedrock which is more resistive than the weathered section above but less resistive than typical unmineralized bedrock. In the mineralized zone the depth of weathering may be deeper than normal. There may or may not be a massive sulphide or stringer vein system in the bedrock structure. If so, then there will be a corresponding deep response as a part of the geophysical signature. This signature will be modified in an actively eroding terrain. As the rate of erosion increases, the top of this model will be progressively removed. In the unmineralized case the electrical signature is simple. The saprolite forms a relatively uniform blanket of lowered resistivity over the bedrock, and the resistivity values will grade simply from a reduced value in the saprolite to a higher value appropriate for the bedrock.

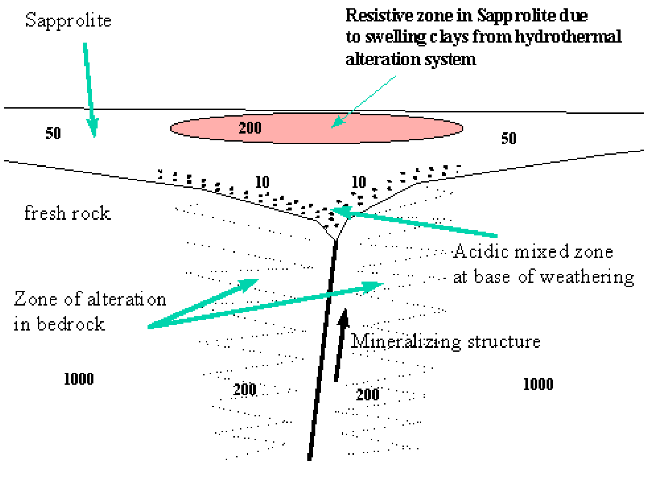

Figure 1: *Typical weathered hydrothermal system in a mature saprolitic terrain with no significant laterite development. Resistivities noted are ohm-metres.*

In the instance where this picture is complicated by a lateritic layer, this evidences itself as a thin highly resistive layer on surface. This lateritic layer may also contain maghemite, and will introduce considerable noise in a ground magnetic survey. However, its effect will be muted in a low level aeromagnetic survey.

EM RESPONSES

It is useful to transform EM data into a conductivity depth section presentation. The response of the weathered saprolite can be fairly well approximated by a layered earth model. Although artifacts of 2-D structures appear in a stitched together 1-D inversion, the depth of weathering can usually be resolved to within 10%. Weathering depressions are obvious, and 2-D effects can be recognized and interpreted individually. The linking in a visual manner of large amounts of EM data to geology is the primary benefit of this approach. The geophysicist is not identifying anomalies, but rather illustrating the data at map scales in a way that weathering depressions, bedrock and overburden resistivities, contacts, and discrete 2-D anomalies can be recognized.

Figure 2 presents GEOTEM data converted to a 1-D equivalent conductivity depth section. An algorithm fitting a descending current filament to the EM field has been used to transform the data to a conductivity depth section (Coggon, 1995). The weathering depression at station 6050 is easily recognized. The depression is interpreted to be associated with a bedrock rock-type change, with the more resistive unit to the right. Also, there is a conductivity high at the base of the weathering station 6100, and this may be due to acid from weathering disseminated sulphides. The highly conductive surface layer is an artifact of the presentation, no estimate of conductivity can be made for very early times, and the surface conductivity is estimated using the trend of conductivities at depth. The increasing resistivity with depth has caused an abnormally low resistivity to be estimated for the surface layer. It would be difficult to interpret the channel traces directly, the resistive part of the weathering manifests itself as a small negative peak in the early time

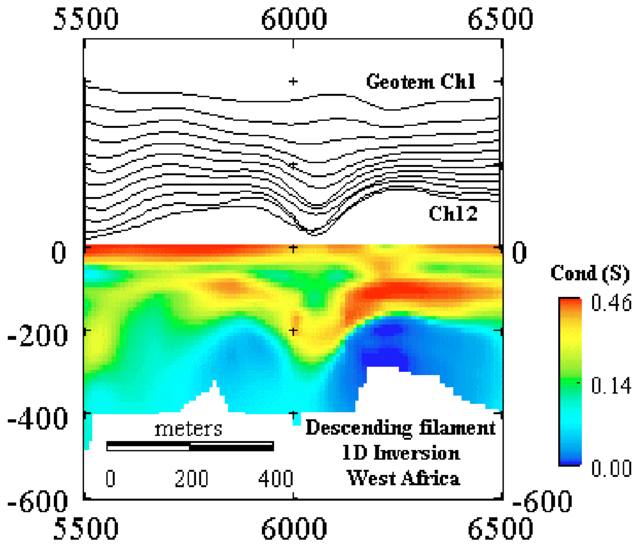

Figure 2: *Conductivity depth section from GEOTEM data using 1-D descending filament algorithm. A bedrock contact and a weathering depression are evident at station 6050. The conductive layer on surface is an artifact caused by extrapolation of early time conductivities to surface.*

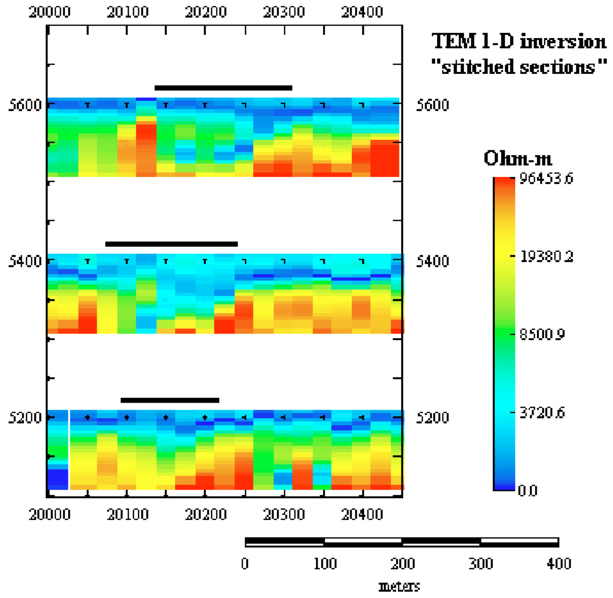

Figure 3: *A 2-D conductivity depth section made by stitching together 1-D inversions. The depth of weathering found by drilling corresponds well with the onset of higher resistivities (>approx. 9000 ohm-m) in the inverted section. A weathering trough due to hydrothermal alteration is marked with a solid bar. Lines 5400 and 5600 show an increase in near-surface resistivities which is attributed to swelling clays and consequent loss of porosity in the altered zone. These data are taken from a TEM sounding data set collected at the Las Cristinas gold project in the Precambrian of Venezuela.*

traces (channels 1 and 2), while the deepening of the weathering interface shows up as a small positive peak in the later channels.

The conductivity sections in Figure 3 illustrate TEM inversions done to estimate the depth of weathering at Las Cristinas in Venezuela. The algorithm finds a smoothly varying layered earth solution which explains the TEM response. A homogenous half space was used as an initial starting model. Only structure necessary to explain the data is introduced into the inverted model. The base of weathering was extrapolated from existing drill hole control. Subsequent drilling indicated an error of about 10% in the depth estimates made from the TEM data. A trough of deeper weathering is marked with a black bar. This trough extends to about 80 m depth on the top two lines. An increase in the resistivity of the mineralized zone within the weathering can be seen at about 30 m depth on these two lines. The resistivities here are higher than those in the generic case of Figure 1. This is ascribed to the high initial resistivities of the bedrock prior to weathering. The very high resistivities shown at depth are probably not real, and are interpreted to be caused in the model by the inversion constraint of smoothness and the lack of sensitivity of EM methods to differences at high values of resistivity.

AEROMAGNETICS

Interpretation difficulties at low magnetic latitudes are caused by the near-horizontal direction of the earth's magnetic field. This causes strong interactions with topography, and a dependency of the anomaly character on the strike of the magnetic body. If a magnetic body lies under the plane of the survey, then the character of the magnetic anomaly will be a negative over the body, with a high to the north and south. If the anomaly is on the south slope of a hill, then there is an additional positive component of the anomaly associated with the source. On the north slope of a hill there will be an additional negative component added to the anomaly. Reduction to the pole algorithms generally assume that a magnetic survey is done on a flat, horizontal plane. The differences in the anomalies introduced by the topography can dramatically influence the results of applying the reduction to the pole algorithm, and can render the results useless.

An experienced interpreter can deal with these problems on a case-by-case basis, but the appearance of magnetic anomalies on a map using total magnetic field is confusing. It is difficult to infer the geometric relationships of the sources intuitively. To overcome this, functions which are not dependent upon the inclination of the magnetic field are used. Two effective data transforms are the analytic function, and the Euler deconvolution. The analytic function is a measure of the maximum gradient; it is independent of the field inclination, and well illustrates the location of contacts and magnetic sources at low magnetic latitudes. The Euler deconvolution algorithm examines each area of the map, and solves a system of equations for each type of source—compact bodies, rod-like, dyke-like, and contacts. If a fit occurs, then the solution is plotted. Large numbers of solutions are plotted, and their distribution can be used to infer the location and depth of geologic features. Maps showing near-surface contact solutions generated by Euler deconvolution can be used as outcrop maps to guide geological mapping where there is little outcrop.

The direct inversion of the magnetic data into a magnetic susceptibility model is a rapid, straightforward, and conceptually simple way of interpreting magnetic data. The interpreter starts with no a priori model and allows the computer algorithm to find a distribution of susceptibilities which explains the observed magnetic field. There are an infinite number of possible solutions, and hence no correct solution in the sense that the solution that was found duplicates the distribution in nature which produced the observed magnetic anomalies. However, the assumptions of simplicity, and smoothly varying distributions of susceptibility generally produce a three-dimensional distribution of magnetic bodies which can be related to geology without trouble. The method is tractable, and boundaries of magnetic bodies and depths to sources are surprisingly accurate. The method is automatic, and takes into account topography in the general case, as data points are quoted in xyz space, and air blocks can be defined in the solution model to constrain the solution. The interpreter needs to be aware that the equivalent source distribution built by this way will be a little fuzzy, and the shape and dip of strongly magnetized bodies will be wrong. However, anomalies from different bodies can be separated, and direct, parameterized forward models can be built to further interpret the data and to calculate the expected magnetic fields exactly for complex geometries.

The interpretation of the magnetic data at Porgera, a gold mine in Papua New Guinea with a resource of about 600 tonnes of gold, illustrates the problems interpreting aeromagnetic data in rugged topography at low magnetic latitudes. Two principal modes of mineralization occur. The first, disseminated mineralization, is associated with the Porgera intrusive complex, which intrudes into a non-magnetic sedimentary sequence. The second style with much higher grades is found in Zone 7, which is a nearly vertical fault-controlled mineralized zone 2–10 m wide which lies along the south flank of the main intrusive bodies, and into which small mineralized intrusive apophyses have been emplaced.

Four separate aeromagnetic surveys have been flown over Porgera. The first was a helicopter drape survey flown using visual flight recovery and a radar altimeter to locate the data. This survey identified the magnetic anomalies due to the intrusive complex, but the data were difficult to interpret in detail as it was difficult to locate the aircraft, and hence the data exactly. Small features in the contoured representation were as likely to be due to mislocation of the aircraft as geology. The second survey was a drape done using visual flight recovery and an inertial guidance system to interpolate the data locations in xyz space. This survey was of good quality, and has been used to produce the reference magnetic survey around the mine area. Next came a regional constant barometric altitude survey to look for other intrusive complexes nearby. This survey detected the intrusive complex, but lacked detail which could be interpreted. Lastly, using present-day differential GPS navigation, and building on the knowledge gained from the second inertial controlled drape survey, a low level closely spaced helicopter magnetic survey with a stinger-mounted sensor was flown to accurately survey the magnetic field in the area of the Porgera intrusive complex.

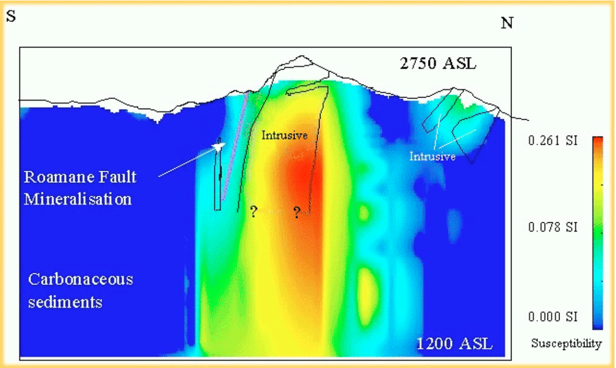

Figure 4: *Magnetic inversion results at Porgera with known geology and Zone 7 overlaid.*

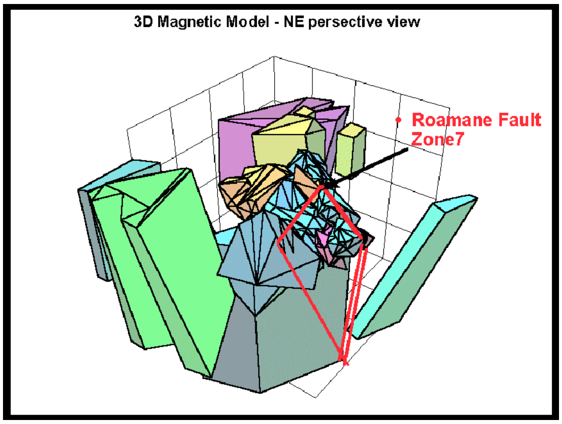

Figure 5: *Faceted model of Porgera intrusive complex. The intrusives are shown as coloured bodies and the non-magnetic sediments occupy the space between them. The tops of the bodies correspond to the topographic surface. The detail in the centre comes from the mine geology model; the less detailed outlying bodies are geophysically inferred. The sediments and air are assigned zero susceptibility.*

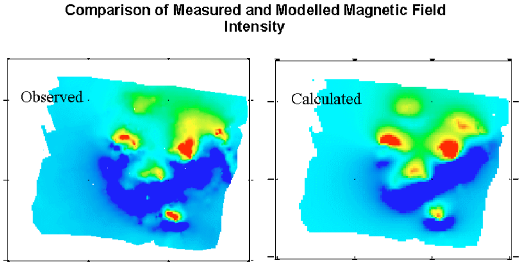

Figure 6: *Observed and computed magnetic anomalies for the Porgera intrusive complex. In order to explain the large dipole it was necessary to include the large dark blue block of intrusive at depth shown in the centre of the model in Figure 5.*

The second survey was interpreted by building a 3-D faceted solid model (Figure 5) and doing a forward computation to match the observed and calculated magnetic fields. This forward calculation was done using an algorithm which exactly calculates the magnetic anomaly taking into account self-demagnetization and remanent magnetic fields (Logan and Angus, 1996). Remanent magnetic fields and susceptibilities were estimated using sample measurements (Schmidt *et al.*, 1996). The known geology within the mine was used to build the detailed models, and outlying bodies were initially modelled as simple 3-D shapes. The magnetic field from the 3-D faceted model using exact measurement positions and average magnetization fields from sample measurements achieved an excellent fit with the observed data. The result is shown in Figure 6 .

The above forward modelling process was later complemented by 3-D magnetic inversion modelling (Li and Oldenburg, 1993) of the more detailed fourth survey. Figure 4 is a north-south section through the Porgera intrusive complex, showing the magnetic susceptibilities from the inversion model, with the known and interpreted geology laid onto it. In areas where little information is known, the inversion results were used to build updated forward models. Both modelling methods complemented each other. In areas of many drill hole intersections exact forward models could be made, whereas in areas where intrusives are buried and no information exists, the inversion model will have more detail. In both cases, drill hole targeting of conceptual mineralization models is greatly aided by the intrusive boundaries and inferred faults derived from these models. In addition, Figure 6 has provided strong evidence that the intrusive complex possesses intrusive roots, or at least has a considerable mass at depth.

INDUCED POLARIZATION

An IP example is drawn from the Cerro Crucitas gold deposit in Costa Rica. Here again, there is strong weathering and a saprolitic weathering profile. The mineralization is associated with silicification in a relatively flat-lying pile of extrusives and pyroclastic sediments. A typical IP pseudo section (Figure 7) shows that mineralization is associated with a surface resistivity anomaly. It is difficult to interpret the most intensely silicified areas, their thickness, or any structures at depth below the near-surface resistive zone using the IP pseudo section alone. The equivalent resistivity section created by inversion has a much more geologic appearance. The bottom of the resistive altered unit is well defined, the effects of topography are accounted for, and the relationship of the gold mineralization in drill holes with the altered silicified unit is quite clear. In the example, a deeper resister interpreted as a silicified feeder structure is not obvious in the pseudo section and is clearly visible in the inverted result. On balance, the inverted result gives the interpreter confidence that the IP data can be used to direct drilling, and to map out the extent and intensity of the silicification.

SUMMARY

The transformation of geophysical data set into an equivalent physical property model makes it much more interpretable. The model can be displayed as an image, or viewed in a visualizer. This methodology adds value to the data, allows the reprocessing of old data to illustrate new features, and increases the usefulness of geophysics in mineral exploration. In tropical terrains particularly, geology is often obscured by weathering and outcrop is scarce. Geophysical surveys allow a geologist to recognize and map features not obvious in surface mapping, and to extend known geology away from drill holes and outcrops. The stratified weathering profile is not a big problem, and alteration systems put their own imprint upon it. If these changes in the weathering profile are understood in a geologic context, then they can be used to advantage. A geophysical interpreter can map alteration systems in the weathered zone, and extrapolate downwards to the unweathered rock at depth. There is no general recipe for the response of a mineralized system; geologist and geophysicist need to co-operate to understand it.

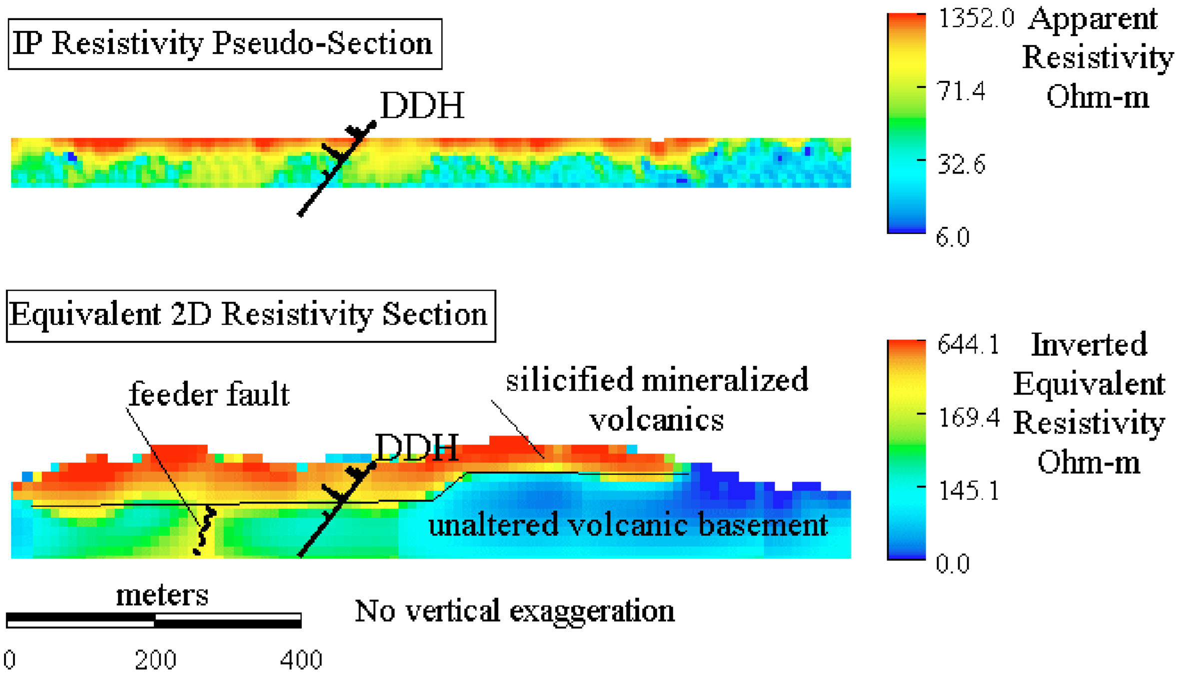

Figure 7: *An IP resistivity pseudo section and an equivalent 2-D resistivity section from Cerro Crucitas, Costa Rica. The 2-D resistivity section is much easier to interpret, and provides confidence that the IP data can be interpreted in a geologic context. The drilling results can be readily linked to the response of the silicified volcanics, and the extent, thickness, and intensity of silicification can be interpreted from the IP data. Histograms on the drill hole trace show gold values in the drill hole.*

Many algorithms exist to interpret a geophysical response. In the past, one used simple models that cast the causative bodies as simple shapes in a neutral background. Computer programs such as PLATE and SPHERE allowed an accurate calculation of EM responses for conducting bodies of simple shapes in highly resistive rocks. Similar programs existed for electrical and magnetic problems, and anomaly responses were described in the terms used to describe these bodies. These algorithms did not work well in conductive environments, or when complex body geometries existed. The display of geophysical data as coloured images allowed the illustration of large amounts of data in computers, and patterns could be recognized that might be difficult to see in profile analysis. However, it was not until computers could be used to transform the data into a display space that is closely related to the physical properties, that a geologic interpretation could be made of large amounts of data in a routine way. The interpretation process has progressed from the analysis of individual simple anomalies, to the computerized display of large amounts of geophysical data in image-processing systems, to the present computerized display of physical properties calculated through inversions. We have returned to the calculation of anomalies through analysis, but are able to do this in a simple way for the complete data set we have acquired. The display of data as images placed the geophysicist in the uncomfortable position of trying to recognize targets through pattern recognition. A careful analysis of a these selected targets was then required to confirm the presence and properties of the targets identified. The present situation is more comfortable. Targets are recognized through a simple, but appropriate analysis which presents the data in ways closely related to physical properties. The targets identified can then be examined and interpreted in detail.

Examples have been given here of 1-D and 2-D and 3-D algorithms used to transform electromagnetic, magnetic, and electrical data into interpretable images. The data are from projects in the tropics, where older data presentation methods had significant problems. In the EM problems, the variable depth of weathering and sensor altitude are the first-order terms which dominate the response. These have been “backed out” by the inversion algorithms, and the image of the weathered rocks turned to the advantage of the interpreter. The weathering thickness and the resistivity of the weathered rocks have been put into a geologic context. In the magnetic example, the exaggerated topographic effect of low magnetic latitudes has been compensated for, and a complex response broken into constituent parts so that individual sources can be analyzed and interpreted separately. In the IP example, the IP response has been presented as an equivalent 2-D section in which faults and contacts and geologic units can be separated easily.

The computational cost of various algorithms that can transform geophysical data into physical property models varies widely. The geophysicist needs to choose one by balancing the quality of fit with geology against the quantity of data to be processed and the time and monies available. Doing this, good interpretations can be produced. These methods have only become practical in the last few years. Their impact on exploration, and the success of geophysical methods in difficult environments will be very large.

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