How to make better use of physical properties in mineral exploration: The exploration site measurement

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In recent years, there has been a growing awareness that a better understanding of physical property information is required in mineral exploration. As a consequence, there has been a strong push to collect more data and to use these data more intelligently. There are a multiplicity of reasons behind this impetus: geophysicists want more information about physical property data to enable better surveys to be planned and better interpretations to come from the data acquired and geologists want physical properties to provide addition information about the geology that might allow them to see variations in rocks that are not easy to see using traditional or more expensive methods (hand specimen examination, thin sections, lithogeochemistry, assays, etc.). If a hole is drilled on a geophysical target, then a physical property measurement of the core or the rocks surrounding the core can confirm if the target was intercepted and provides data that can be used to model the target response.

Some of the impetus is also coming from computer tools that can use the physical property information. For example, the mine planning and GIS tools that are now being used more commonly are able to display physical property data, so people would like to make better use of this capability. The ultimate result should be a better understanding of the significance of physical property data so the information displayed can be interpreted. There is also a more widespread understanding that it is possible to obtain better results from the computer programs that invert geophysical data because the physical property information provides constraints. These inversion programs are now being used more frequently for gravity and magnetic data and this creates a demand for better density, magnetic susceptibility and remnant magnetization data. Physical property information is available in tables published in textbooks and the like, but certain rocks and minerals frequently have properties which span a broad range of values. Having a more precise value in a local area will be a significant advantage. Normally this local value is obtained by measuring the physical properties of samples from the local area. These local samples can be the outcrop, removed from the outcrop, or the core extracted from boreholes. The measurements can be made with sensors on the outcrop or in the boreholes. Alternately, the samples can be removed from the site and measured in a remote laboratory.

With this enhanced impetus, a workshop was held at SEG's 2010 Annual Meeting. The talks discussed the current state-of-the-art in the measurement and use of physical property data.

The first talk, by Desmond Rainsford and Tom Muir of the Ontario Geological Survey (OGS), was about the physical property databases that the OGS has been acquiring over the last few years: a density data base comprising measurements made from rock samples collected in the field and a magnetic susceptibility database built up of multiple measurements made on outcrop. The magnetic susceptibility meters can lose calibration, so meter serial numbers are recorded as part of the measurement protocol, and instruments compared against in-house standards before and after field seasons. These measurements are taken by the field geologists along with a UTM location. The primary purpose of the measurements is to help in geological mapping, an important part of which involves using the aeromagnetic data. In addition to this, it has been observed that in some cases susceptibility measurements can help in the field to distinguish between two rock types that otherwise look similar. An important but occasionally problematic part of the databases is the rock names selected by the geologists. The choice made is sometimes subjective and will depend on the personal biases and experience of the geologist. In the case of the OGS databases, this issue has been addressed by standardizing the number of rock types to a smaller less ambiguous set. Furthermore, the rock type is selected by the mapping geologist who is familiar with the area.

Vince Gerrie from DGI Geosciences then spoke about the advantages and disadvantages of physical properties measurements in boreholes. One of the key advantages is (near) continuous, high-resolution in-situ measurements. The importance of calibration and QA/QC were emphasized. Gerrie feels that the data are being underutilized and proposed that one way of extracting value from the data is to undertake a cluster analysis. These points were illustrated with a case history from the Lalor Lake deposit in Snow Lake.

Don Emerson had prepared some material on physical

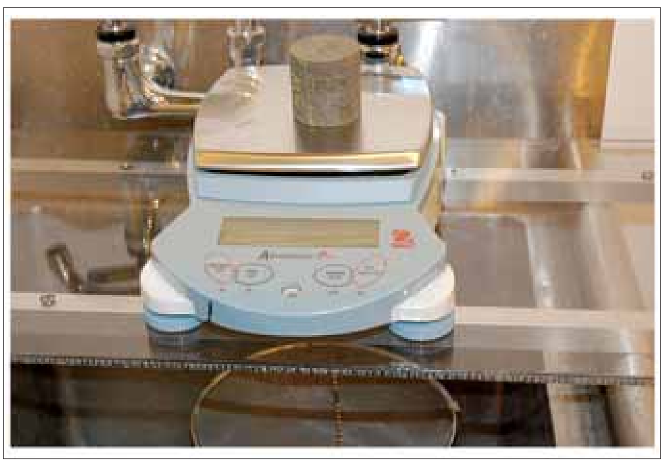

Figure 1. Balance used to measure density. Note that the scale is suspended above a sink.

properties measurements made in the laboratory. He was not able to attend the workshop, so his material was presented by Richard Smith. Emerson also feels that more physical properties measurements can be made and that more use can be made of the data. He argues that sophisticated measurements are not necessary, but that a basic suite of density, susceptibility, galvanic and inductive resistivity, and acoustic P-wave velocity can provide sufficient information to assist in the mineral exploration process. However, it is not sufficient to take the measurements; time is required to analyze the data. In order to extract information, he showed how crossplots of one physical property against another (which is essentially a form of cluster analysis) are useful for distinguishing between rocks. Emerson also emphasized that physical properties are strongly dependent on the mineralogy and the texture of the sample. Another important point he made relates to the question of scale: physical property measurements of a rock type in hand sample, in a borehole, on an outcrop and with a geophysical measurement are all sampling the formation over a different scale length. A similar measurement value should not be expected because the mineralogy and texture can also appear different at different scale. Another issue raised by Emerson was that resistivity (or conductivity) measurements can be strongly dependent on the amount and type of water present in the sample. Ideally, the condition of the sample when measured should be as close as possible to the condition of the rock when it is in the ground. He also emphasized that a single measurement should not be considered definitive as many samples are anisotropic, so the measured property is dependent on the orientation of the sample.

Mark Shore then made a presentation on how physical properties measurements have been used in some of the mineral exploration projects he has worked on. He feels that physical properties measurements can be made with relatively inexpensive test equipment that can be set up on an exploration site. These measurements will not be as precise as laboratory-based analyses, but Shore believes that the data can be used to extract additional understanding from the geophysical and geological work already undertaken. He also stated that some reasonably good data is better than no "perfect" data. He spoke briefly about his experience putting together equipment for measuring the density, magnetic susceptibility, galvanic and inductive resistivity, and time-domain IP effects of samples.

There were then a number of presentations on the use of physical property measurements in exploration programs. Heather Schijns spoke about some work she and some colleagues from the University of Alberta and Finland undertook to assist base metal exploration in Finland. In this case, she argued that the understanding of reflection seismic and vertical seismic profiling results is enhanced by measurements of the seismic velocity taken in the laboratory. Seismic anisotropy was blamed for a deep stratigraphic drill hole missing a target reflector in the Outokumpu area. In this particular case, collection of accurate measurements of S- and P-wave anisotropy proved to be challenging.

The final presentation, by Emmanuel Bongajum and colleagues from the University of Toronto, argued that physical properties can be used to help determine the grade distribution of an ore deposit in three dimensions. In the case of the Nash Creek deposit, it has been noted that there is correlation between density and grade. By using the physical property measurements, building a geostatistical model and using cokriging methods, it is possible to develop a statistically consistent grade estimate. He argues that this technique is better for determining the ore body outline than linearly interpolating between the locations that are above the cutoff grade. The Nash Creek deposit called for more sophisticated data processing because mineralization is contained in a number of different host lithologies with varying physical properties.

The presentations were followed by a discussion period. There is a general feeling that not enough people are taking physical property measurements. If more measurements were being made, then more use might be made of that data. Greater use might lead to a better understanding, positive outcomes, and then more use: a positive reinforcement cycle. The reason why physical properties measurements are not being made is because there are few facilities able to make these measurements. And, even if it is possible to find someone to take the measurements, it is generally expensive. A solution to this might be if there is a commercial laboratory that can provide a service measuring the physical properties of rocks. It was felt that a lab that specialized in physical properties measurements might bring the price down due to economies of scale and encourage more people to send in samples for measurement. Some geophysical contractors had looked at measuring physical properties, but have found that there is not enough business or revenue so the service was provided largely as a favor to clients as part of a larger job. If a physical properties laboratory is to operate commercially, some innovation or paradigm shift in business models is required.

Another issue is that selecting representative samples for sending to a lab is not straightforward—if one or two samples from an outcrop or drill hole are being sent to a lab, then they must be representative of the rock. It is also important to pack and ship the samples in such a way that they will not get destroyed (if fragile) or dried out (if wet); this can be onerous. In addition, geologists do not like their core samples to leave the job site. Borehole logging can overcome some of these issues, as the measurements are made in situ. However, this is not always possible depending on the condition of the hole, the remoteness of the location, and the additional cost of having a logging crew on site and available. When the physical properties measurements are being acquired, the drill crew must be paid a standby rate, which adds to the cost. Finally, there is the potential for a probe to be lost in a drill hole. If the probe lost is an active gamma or neutron source (used for density or chemical composition measurements), then this can potentially incur extremely high costs (replacement or retrieval costs, loss of minable ore, regulatory body intervention).

The issue of scale of measurement raised by Don Emerson was emphasized by Jim Macnae, who said that laboratory or borehole measurements of conductivity rarely relate to the estimates of conductivity from a large-scale electromagnetic

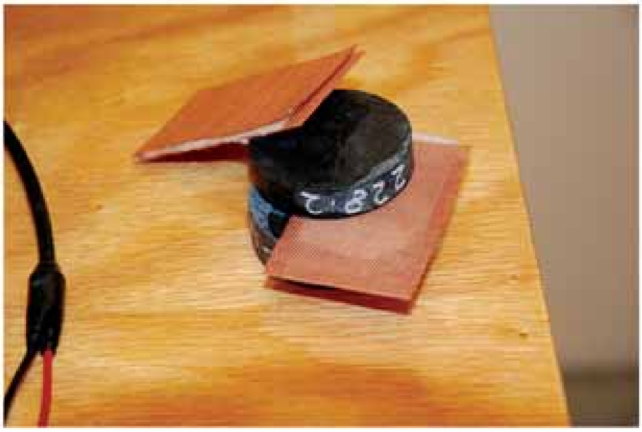

Figure 2. *Copper screen mask used as the electrical contact. Wet white felt is sandwiched between the folded metal screen to ensure an even contact.*

experiment. This is because the conductivity is dependent on the large-scale structures in the rock and has frequency-dependent responses that scale as a power of the linear dimensions of the samples.

Representatives from a number of companies with intense drilling programs spoke briefly about their experiences with setting up a small physical properties measurement facilities on an exploration site. These facilities are able to provide a suite of basic measurements (magnetic susceptibility, density, galvanic resistivity) and to build an extensive data set at a relatively small incremental cost.

There were a number of concrete outcomes from the discussion period. One was that it was felt that, in addition to the case studies at the workshop, more people should be encouraged to talk about case histories when physical properties measurements have added value to exploration programs. Hopefully these successes will lead to more people acquiring and using physical properties data, thus reinforcing the positive cycle. Another way of encouraging people to take physical properties measurement is to give a simple description of how to set up a basic on-site facility to take physical properties measurements. On-site measurements can be done quickly and cost-effectively and the samples never have to leave the site. It was felt that this process would be good for the industry as it would encourage other physical properties measurements (in boreholes and in the laboratory).

Setting up a physical properties laboratory at a field site

The intent of this section is to give some guidance so that mineral exploration companies can set up a number of instruments in an exploration office for measuring physical properties. These instruments could be available to the geologists who are mapping an area and/or logging core. The instruments should be convenient to the work site and the core storage facilities so that the samples would be as close as possible to pristine condition when measured. They would not have dried out or degraded in other ways. The water in the sample would be the in-situ water, not distilled or tap water introduced to wet the sample. The instruments should be easy to purchase, set up and maintain, and easy to use so that the measurements could be taken by a junior geologist or a field assistant with minimal training. In this article, we make a number of suggestions for equipment that might serve this purpose. However, none of the authors feel they have done an exhaustive job finding all the available equipment and selecting the best instruments. Hence, mention of equipment should not be seen as endorsements or recommendations, but simply a suggestion as to one of the possible options. If we have missed out any useful piece of equipment, or if you have had a good experience with some equipment, please feel free to make suggestions or provide reviews of equipment.

Density

It is possible to measure the density by measuring the mass and dividing by the volume of the rock. This is straightforward with a standard weight scale and a means of measuring or calculating the volume. For samples of non-standard shape, the volume is not easy to estimate. One measure of the volume of a sample is the amount of water it displaces when it is immersed. It is also possible to use scales that allow a measurement when the sample is suspended in air and then suspended in water from which it is possible to calculate the density of a sample of any shape. The density (in g/cm^3) is given by the formula: density = (0.9975 × weight in air) / (weight in air – weight in water).

These types of scales require the sample to be suspended in such a way that both sample and holder can be immersed in water. An example scale found on the Internet is sold by mineralab.com. Other examples may be found by searching for the term "specific gravity", a quantity related to the density. Figure 1 shows an Adventurer-Pro scale.

This scale has a resolution of 0.1 g and has a weigh-below hook underneath the top loading platform. Note the chain below the scales in the photograph which goes from the sample platform to a submerged basket. The measurement procedure is as follows: add the chain and submerged basket to the hook underneath the balance; zero the balance; place the dry sample on the top balance platform and measure its weight in air; gently place the sample in the submerged basket; and let the ripples die down and record the sample weight in water.

This procedure takes about a minute per sample. For a sample with a mass of 50 g, simple error propagation and repeat measurements indicate an accuracy of ±0.01 g/cm^3 is readily obtainable. For larger samples, the accuracy is greater. The accuracy of the scales can be calibrated with a large gemmy quartz crystal, available from mineral or gem stores or borrowed from your friendly geologist's office.

Measuring samples that are friable, porous, soluble, or contain a significant volume of liquid is more problematic when the samples must be submersed in water. Depending on the sample, the weight/volume method could be used, or the sample could be sealed in wax or a lightweight shrinkable plastic film prior to submersion. Some paraffin waxes have low melting points and densities conveniently near 1.0 g/cm^3 but this treatment would render the sample unusable for additional measurements.

Magnetic susceptibility

There are a number of instruments that can be used to measure the magnetic susceptibility of outcrop, hand samples, or core. Terraplus offers the KT-10 instrument, which is capable of measuring susceptibility from 10^{-6} to 10 SI units at an operating frequency of 10 kHz. The SM 30, manufactured by ZH Instruments, can be used for outcrop and the SM 100 is a larger unit intended for core samples. Instrumentation GDD manufactures the hand-held MPP-EM2S, which includes a data logger and can be used in a mode that allows data to be acquired continuously, allowing all the samples in one or more core trays to be measured. Bartington Instruments offers the MS2 and MS3 instruments that can be used in either the field or the laboratory. Note that the estimated value of susceptibility can be wrong (e.g., strongly negative) if the sample is highly conductive, as these instruments assume that the conductivity of the sample is small. Systems that operate at a much lower frequencies will have a smaller impact from conductivity, except on conductive samples. The magROCK meter offered by AlphaGeoScience and the GMS-2 susceptibility meter use frequencies of about 750 Hz. The range of susceptibilities in rocks is large, but meters sensitive to the range 0.5×10^{-3} to 200×10^{-3} SI units should be adequate for most purposes.

When using these instruments, expect values to be accurate to within ± 30%. Also, take care to ensure the value is not dependent on the position of the sensors or the orientation of the coil. If the measurement varies, take multiple readings equally spaced in some fashion and take the linear average of the result.

Make sure the instrument does not drift by assigning some nearby and convenient homogenous sample as a calibration standard and ensure that the calibration reading you obtain regularly does not vary significantly. The susceptibility of the standard should be typical for the range of values being measured. It is surprisingly difficult to find well-calibrated reference material for susceptibility standards; a uniform fine-grained igneous rock such as diabase may be a useful ad hoc reference if it has a flat cut surface.

Resistivity

It is possible to measure two types of resistivity, the galvanic and the inductive resistivity. In homogeneous samples, these two values will be the same, but in samples with layered or complex mineralogical textures (grain interconnectivity, etc.) the two values are typically different. The measured value can also vary depending on the orientation of the sample, so resistivity is by definition anisotropic. Note that conductivity is the inverse of resistivity and can be used interchangeably; e.g. 0.1 ohm-m = 10 mho/m = 10 S/m.

Galvanic resistivity. In this case, a sample of known cross-sectional area and length is placed between two electrodes and a potential difference is applied. The current, the area of the sample and the length of the sample are used to derive the resistivity from the measured resistance

$$\text{resistivity} = \text{resistance}^*\text{area/length}.$$

Figure 3. Apparatus (vise with plastic face plates) for clamping the sample (obscured) between the copper mesh electrodes. Another sample is shown on the table. Note that the samples must be sawn with a rock saw to ensure they are flat. There is no need for polishing if the saw cut is clean.

Cylinders such as cut whole or half drill core are suitable, although in the case of anisotropic rocks, resistivity along only a single direction is all that is measured. A rectangular prism can be cut, either from large diameter core or hand samples, and this would permit the measurement of resisitivity in three orthogonal directions.

Note that the common practice of using a household resistance meter will not give a reliable estimate as the current will flow through the sample on the path of least resistance, giving an underestimate of the resistance or an overestimate of the conductivity. As well, the results can be highly dependent on the location of the two resistance probes on the sample due to point contact resistance. The resistance of highly conductive massive sulfide samples will be overestimated due to lead wire resistance in a simple two-wire measurement.

Resistance meters using a four-wire technique (current carrying and voltage measuring wires are separate) in combination with electrodes contacting a relatively large area of a sample of controlled geometry can give reliable results. An example of a commercially available instrument that is specifically designed to measure the resistivity is the SCIP sample core tester manufactured by Instruments GDD. However, alternatives include a high-impedance digital voltmeter coupled with a signal generator or current source, a commercial LCR (induction-capacitance-resistance) meter, or a dedicated current-source meter. Manufacturers of this type of equipment include Agilent, Keithley, Fluke and Instek; there are also others.

Preparing the sample is critical, particularly ensuring that the fluid saturating the sample is as close as possible to the fluid that is in the sample when the rock is in place or in situ. There are a number of approaches commonly used: soaking the sample in deionised water, tap water, or saline water with a salinity that matches the groundwater. The closer the sample can be bought to its original in-situ state, the more useful the measurement will be. Note that removing the sample from its original location disturbs the sample: micro- or macro-frac-

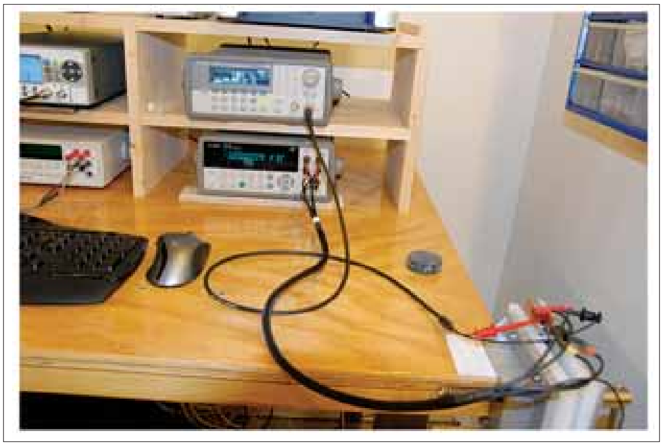

Figure 4. Signal generator and digital multimeter set up to measure the IP effects of a sample. A bipolar pulse with a period of 8 s is imposed on the sample, and voltage read at 30 or 60 samples per second for ten or more stacks.

tures can be introduced by the drilling process, or generated with the sample is broken off an outcrop. It is also possible to open existing zones of weakness when the confining pressure is changed. These fractures can influence the resistivity and this is one argument for taking borehole measurements, as in this case, the rocks are as close as possible to the in-situ state (although the act of drilling still disturbs the environment).

It is also important to ensure that there is good electrical contact between the plates and the sample. Dry rock against dry metal can be problematic, particularly if the surface of the rock is rough, even on a fine scale. One suggestion (Shore, 2010) is to place wet felt in a folded mesh. This has two advantages: there is some "give" to the substrate allowing the wire mesh to conform better to the sample surface, and the contact remains consistently damp during the course of a measurement.

Screens made of noble metals such as platinum or gold are ideal; however, their cost is extremely high. Copper or stainless steel are adequate substitutes if a signal of alternating polarity is used, and the data are processed to remove nonzero baseline values.

An easy way to ensure good contact is to clamp the sample between the copper mesh electrodes. The probes are connected electrically to the screen as shown in Figure 3.

If permanent contacts are required, the ends of a sample could be briefly dipped in a solder bath. However solder does not adhere particularly well to anything but clean metallic substrates. The alternative use of cold-setting silver-filled epoxies has been suggested by Shore.

Inductive resistivity. The MPP-EM2S mentioned above for susceptibility measurements is a simple hand-held instrument also capable of measuring the inductive resistivity. Other hand-held resistivity meters are the GCM-2 resistivity meter manufactured by Fugro. Note that these instruments will give biased resistivity readings if the sample has a significant magnetic susceptibility.

Those interested in building their own instrument for measuring the resistivity inductively are directed to a paper in GEOPHYSICS by Yang and Emerson (1997). The equipment they describe can also measure the magnetic susceptibility. Note that measurements of inductive resistivity are also dependent on fractures, fluid content, etc., as described above for galvanic resistivity. The scaling of frequency responses to sample size is critical and is probably the major limitation of this method.

Induced polarization

Measuring the IP effects essentially involves using an IP system (time or frequency domain) to transmit and receive the signal through a sample between the electrodes used in the galvanic resistivity measurements described above. Note that IP effects can be strongly dependent on the water content, so having the sample in a condition that is as close as possible to the in-situ condition is even more critical than for resistivity measurements.

IP measurements can also be performed using off the shelf equipment, for example a signal generator and a digital multimeter. However, some manipulation of the digital data is required to calculate the chargeability or frequency effect. Simple techniques in use for both electronics and geophysics, such as using measurement bins that are integer multiples of powerline frequency (e.g., 60 Hz, 30 Hz, 6 Hz, or 1, 2 and 10 PLC, respectively) and stacking bipolar pulses permit significantly improved signal to noise ratios. Figure 4 shows a set up capable of measuring the IP effects. The SCIP sample core mentioned above for measuring the galvanic resistivity is also capable of measuring IP effects.

Acoustic velocity and other properties

Some labs measure the acoustic velocity, but this is probably too involved for the simple measurements we are proposing and the cost of the equipment would also be prohibitive.

Thermal conductivity is one physical property that could be measured relatively easily; however, it is not clear what benefit this would provide to an exploration program. Measuring the porosity or fluid permeability is critical in hydrocarbon exploration. The benefits to mineral exploration have not yet been demonstrated.

Archiving the measured data

Shore suggests that for the data to be of future use (mine planning, exploration elsewhere in the camp etc), the methodology should be documented. Also, the measurement should be archived with appropriate metadata, such as the GPS location of the samples, the orientation, distance down a drill hole, a description of the rock type. Ideally, other physical property measurements should be stored in the same place or cross referenced.

Successful use of physical properties in mineral exploration

In a recent presentation at the ASEG annual meeting, Wijn and Core used the density values measured in the drill holes of a well-drilled ore body (Kevitsa) to build a density model for the ore body. Inversion methods were used to determine where the density model was not consistent with the gravity data and then new holes were drilled in untested zones where the density was predicted to be higher.

The authors of this article have used physical properties measurements of the magnetic susceptibility to constrain the upper and lower bounds in 3D inversions. Conductivity measurements can occasionally be used to predict the half-space response where there are no obvious down-hole EM anomalies. Differences from the predicted half-space response and the measured response could be indicative of previously unknown structures.

Conclusion

The equipment and procedures described above are intended to help people to set up simple physical properties measurement facilities at an exploration site (core shack or field exploration office). We hope that the physical properties measurements obtained will have positive exploration outcome and lead to more physical properties data being collected and more use being made of physical properties data.

If anyone has information about other types of simple equipment that could be used, they are encouraged to make this information available, either to the lead authors of this paper, or in the space we intend to make available on the Mining and Geothermal Committee pages of the SEG Web site. Anyone with case histories that illustrate physical properties data being used to advance mineral exploration projects are encouraged to make these examples available as well. TLE

References

Bongajum, E. L., J.-W. Huang, and B. Milkereit, 2010, Integrating petrophysical data to build a 3D-earth model: 80th Annual International Meeting, SEG, Expanded Abstracts, 4423–4427.

Rainsford, D. and T. Muir, 2010, Physical properties—a geological survey perspective: 80th Annual International Meeting, SEG, Expanded Abstracts, 4410–4413.

Schijns, H., D. Schmitt, P. Heikkinen, and I. Kukkonen, 2010, Anisotropy of fractured mica-rich schist from Outokumpu, Finland: VSP measurements, laboratory measurements and theoretical model: 80th Annual International Meeting, SEG, Expanded Abstracts, 4418–4422.

Shore, M., 2010, Physical properties measurements for mineral exploration geophysics: 80th Annual International Meeting, SEG, Expanded Abstracts, 4414–4417.

Wijns, C. and D. Core, 2010, Hunting for massive sulphides between density logs: ASEG Extended Abstract.

Yang, Y. P. and D. W. Emerson, 1997, Electromagnetic conductivities of rock cores: theory and analog results: Geophysics, **62**, no. 6, 1779–1793, doi:10.1190/1.1444278.

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