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Marine self potential exploration*

Graham Heinson
School of Earth Sciences
Flinders University
GPO Box 2100
Adelaide, SA 5001, Australia.
Phone: 08 8201 2212
Facsimile: 08 8201 2676
Email: Graham.Heinson@flinders.edu.au

Antony White
School of Earth Sciences
Flinders University
GPO Box 2100
Adelaide, SA 5001, Australia.
Phone: 08 8201 2359
Facsimile: 08 8201 2676
Email: Antony.White@flinders.edu.au

Steven Constable
Scripps Institution of Oceanography
IGPP-0225
La Jolla
CA, U.S.A. 92093-0225
Phone: +1-619-534-4209
Facsimile: +1-619-534-8090
Email: sconstable@ucsd.edu

Kerry Key
Scripps Institution of Oceanography
IGPP-0225
La Jolla
CA, U.S.A. 92093-0225
Phone: +1-619-534-4209
Facsimile: +1-619-534-8090
Email: kkey@ucsd.edu

ABSTRACT

Recent marine self potential (SP) measurements south of Eyre Peninsula, South Australia and Rose Canyon, San Diego, California have been made. In both cases, a series of horizontal electrode dipoles were towed close to the seafloor in water depths of up to 100 m to measure the electric potential gradients generated by mineralisation beneath the seafloor. A proton-precession magnetometer was also towed at the surface in the Eyre Peninsula experiment. Marine SP measurements show significantly lower noise levels than land measurements, due to the uniform marine environment and low contact resistance of the electrodes, so that anomalies of less than a few tens of microvolts per metre can be detected. The major source of noise is from ocean swell and waves, which may be minimised by coherent stacking of signals, and by band-pass filtering. South of Eyre Peninsula SP electric field anomalies of 100 μV/m and width 2 km were observed in a number of traverses perpendicular to the trend of an onshore mylonite zone. Little correlation exists between the SP and magnetic data, suggesting that the SP sources are probably due to non-ferrous minerals such as graphite, and/or from the electrokinetic effect of groundwater flow through the fracture zone.

Keywords: Self potential, marine geophysics, redox potentials, electrokinetic effects.

INTRODUCTION

Self Potentials are naturally occurring electric voltages that may result from three different physical processes. Electrokinetic potentials arise when a fluid flows in porous media as a consequence of pore pressure gradient, while regions with temperature gradients may give rise to thermoelectric potentials. Diffusion potentials, which are of greatest significance in geophysical exploration, occur across boundaries with differing geochemical compositions. Although the detailed electrochemistry is poorly understood (Sato and Mooney, 1960; Burr, 1986), SP anomalies over mineralised bodies can be of the order of several hundred millivolts, and with gradient electric fields of up to 1 μV/m.

There are some advantages in making SP measurements in seawater, particularly because of significantly lower noise levels compared to equivalent land observations (Corwin, 1975). Contact resistance of seawater with electrodes is typically less than 1 Ohm, orders of magnitude smaller than that on land, and seawater temperature and salinity are stable over the time scale of a typical experiment. Additionally, meteorological and hydrogeological factors, which are a major source of noise on land, will be minimal in the ocean. Marine SP surveys may be conducted more rapidly than on land and are able to produce continuous profiling across an anomaly. However, the number of marine SP surveys performed to date is limited. Corwin (1975) reported that a 300 mV SP anomaly was measured by a simple horizontal dipole towed behind a ship in shallow water off north-eastern USA. More recently, Thompson et al. (1997) report on the use of marine SP to locate petroleum seepages.

This paper presents initial results from two recent marine SP experiments across Rose Canyon, San Diego, USA in October 1997, and south of Eyre Peninsula, Australia in April 1998. The objective of the first experiment was to quantify the ambient noise levels for a towed series of electrodes close to the seafloor. The second experiment was designed to investigate the marine extensions of onshore mineralisation, and compare measured SP signals with magnetic data along the same cruise tracks. A particular target was a mylonite zone which bisects the southern end of Eyre Peninsula in a north-south orientation, and which contains economic quantities of graphite. Offshore aeromagnetic measurements show a marine extension of many of the magnetic lineaments associated with the dominant structural trends on land.

INSTRUMENTATION

Figure 1 shows the SP instrument configuration used in the Eyre Peninsula experiment. A series of pairs of electrodes were towed behind the ship, and digital data are both telemetered back to an on-board logging system and are recorded in a towed logger. Electrodes were made of a non-polarising Ag-AgCl composition, to form horizontal dipoles, which vary in length from 3 to 12 m. The minimum gradient measurement recorded was 0.3 μV/m with a sample rate of 25 Hz. Note that rather than measure absolute potentials, the electric dipoles determine the potential gradient, or in other words, the electric field.

The position of the towed instrument relative to the ship was determined in two ways. Firstly, a pressure sensor provided a direct measurement of the depth of the tow below the sea-surface with a resolution of 1 m (and consequently the height above the seafloor if we know the water depth from the ship's bottom sounder). Secondly,

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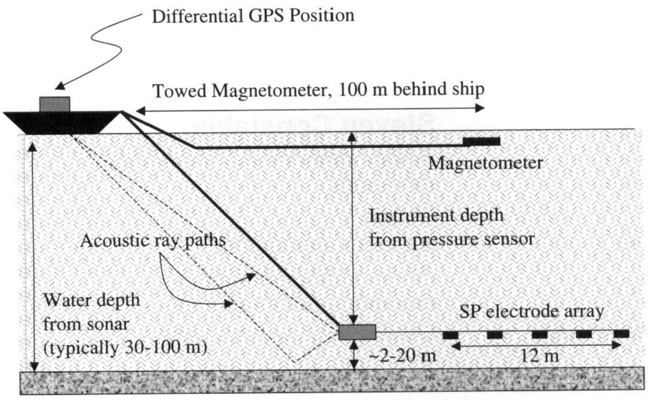

Figure 1. A schematic view of the SP and magnetic tow instruments used in the Eyre Peninsula experiment, April 1998.

using the acoustic transponder attached to the towing fish, the height above the seafloor was monitored by measuring the difference in travel times between the direct path and the return path which included a reflection from the seabed. The acoustic system was primarily used to avoid collision with small rocky outcrops at the seabed. The ship's position was logged using differential GPS. In principal, it should be possible to locate the towed instrument's horizontal position to within 20 m by this method. For a detailed survey, moored seabed transducers could be used to triangulate the position more accurately.

A proton-precession magnetometer with a sensitivity of 0.1 nT was also streamed out behind the ship to a distance of 100 m. Magnetic measurements were made with a sample interval of about 3 s. The ship's speed was a constant 3 knots, which is equivalent to 1.5 m/s. At this rate, the spatial sampling interval of magnetic field was about 4.5 m and the SP electric field was 6 cm. Clearly, the electric field is over-sampled, but it allows a complete characterisation of the noise spectra for realistic geological targets. During each tow, the SP instrument was about 20 m or less above the seabed in continental shelf seas of depth 100 m. In shallower waters (less than 50 m), it was possible to get within a few metres. Once the cable was winched out, it was important not to vary the towing depth to avoid noise from vertical movement of the tow.

Over the course of a week at sea on the ORV Franklin, approximately 90 hours of tow data were collected, which equates to approximately 500 km of cruise track. Thirteen separate survey lines were obtained south of Eyre Peninsula, which intersected the probable offshore extension of major electrical conductivity anomalies (Kusi et al., 1998) and a mylonite shear zone. Three additional survey lines were obtained in the Spencer Gulf over large marine magnetic anomalies.

NOISE ANALYSIS

A towed array of electrodes may record both temporal and spatial variations of electric field, from induced and static sources. Static sources of SP were the principal targets of the Eyre Peninsula experiment, and are therefore not classified as a noise source. There are three distinct sources of temporal signals: (a) induction from external magnetic field variations; (b) motional induction from ocean currents, tides, swell and waves; and (c) drift of each electrode's offset-voltage with respect to the seawater potential. Figure 2 shows noise spectra from Eyre Peninsula and San Diego data in terms of frequency and spatial wavelength, based on a constant tow rate of 3 knots (1.5 m/s).

Induced electric fields in the ocean from external plane-wave magnetic field sources are of least significance in an

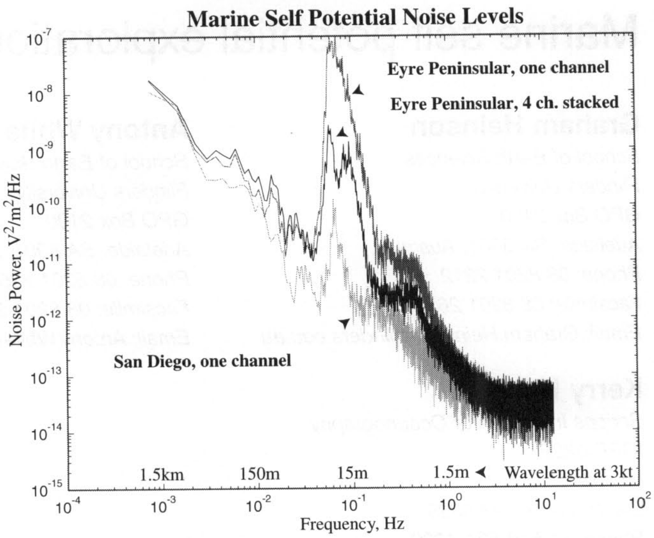

Figure 2. Noise spectra for SP electric field data collected during the offshore San Diego and Eyre Peninsula experiments. In both surveys, the towed SP instrument was approximately the same height above the seabed on the continental shelf. Original data were sampled at 25 Hz. Approximate wavelengths are shown assuming a speed of 3 knots (1.5 m/s).

SP survey at mid-latitudes. From seafloor magnetotelluric experiments it is found that typical electric field amplitudes are less than 20 μV/m during large magnetic storms, and generally less than 2 μV/m at other times (Filloux, 1987). Time-varying ionospheric fields were recorded at fixed remote sites (on the seafloor and on land) by both a magnetometer and electrometer, and such time-varying fields could be subtracted from the towed data if necessary. However, a preliminary inspection indicated no major magnetic storm activity during the period of the tows and we have therefore made no corrections at this stage.

At frequencies less than 3×10^{-4} Hz (periods longer than 1 hour), water currents can produce a significant electric field. The Lorentz term $\mathbf{E}_h = \mathbf{v} \times \mathbf{B}_z$ defines the size of horizontal electric field $\mathbf{E}_h$, where $\mathbf{v}$ is the horizontal component of water velocity, $\mathbf{B}_z$ the vertical component of the Earth's magnetic field, and the 'x' term denotes the cross-product. Note that the resulting electric field is orthogonal to the water current orientation. Thus, a 1 knot current (0.5 m/s) in a vertical field of 50,000 nT will produce a horizontal electric field of 25 μV/m. This is the maximum electric field for the case in which the current is orthogonal to the direction of tow. While currents of this magnitude are not uncommon on the continental shelf, they will be relatively constant over the time frame of each tow cycle, and therefore introduce only an offset into the measured SP signal. Tides in the ocean (mainly the M_2 tide with period 12.4 hours, and its harmonics) will produce similar amplitudes of electric fields over long wavelengths, and are probably of no concern.

The largest signal in Figure 2 is from the ocean swell and wave noise, at frequencies of 0.06 - 0.1 Hz (10 - 16 s period). It is particularly strong in the Eyre Peninsula data, where Southern Ocean weather systems generate an almost constant ocean swell of amplitude 2 - 5 m. Sinusoidally varying electric fields with amplitudes of over 50 μV/m result. The San Diego data show a similar peak, but is about 100 times smaller in electric field amplitudes, reflecting the much calmer sea-state conditions. Unfortunately, the frequency bandwidth of the swell corresponds to wavelengths of 15 - 30 m, which may be important in mapping small-scale SP features. Swell signals result primarily from motional induction, rather than movement of the towed instrument. Although the pressure gauge indicated some changes in depth associated with swell, the movement was generally less than 2 m in total, and induced signals were observed even when the tow was at constant depth.

As the swell and wave noise has a relatively narrow bandwidth, it can be filtered from the data. One method is to simply stack the electric fields measured from different pairs of sensors. As the swell signal has a finite-wavelength of about 300 m, adjacent pairs of electrodes will measure a different phase. Swell signals will consequently not stack in-phase and so the swell noise is reduced, as shown in Figure 2.

The final source of variability is due to electrode drift (Filloux, 1987). Each electrode has a characteristic reference potential with respect to seawater, which changes gradually with time due to impurities in the seawater and aging of the electrode. Consequently, the potential difference between any pair of electrodes is not zero or constant, but drifts over time-scales of hours to days. Such drift is relatively monotonic and smooth, and can be removed by subtracting a low-order polynomial or any other simple function.

A MARINE SELF POTENTIAL ANOMALY

Figures 3 and 4 shows respectively the location of one tow line, and corresponding SP electric and magnetic field data collected over 12 hours during the Eyre Peninsula experiment. At 3 knots, this represents 65 km of cruise track. The direction of tow was initially 90° for 4 hours, then 180° for 3 hours, followed by 270° for 5 hours. The ship track passed within 2 km of the southernmost tip of Eyre Peninsula, and crossed several north-south trending aeromagnetic anomalies.

Magnetic data have a uniform baseline of 59000 nT subtracted, but are otherwise unprocessed. The SP electric field data from a single pair of electrodes separated 3 m have been averaged to 1 s samples, then filtered using a 21-point robust median filter to remove the swell signal. An increase in the SP electric field over the entire tow is probably due to electrode drift. The principal features in the SP electric and magnetic fields are repeatable on a number of survey lines along the same cruise track and on parallel cruise lines.

Although data processing is still at an early stage, there are several features to note. Firstly, a large SP electric field anomaly of 100 μV/m occurs about 150 minutes after the start of the tow (approximately 13.8 km along the cruise track) on the northern line. This anomaly has negative and positive peaks, which can be associated with the edges of the anomalous region below the seabed. The width of this anomaly, from peak to trough, is about 2 km. Smaller and broader SP anomalies exist at later times along the tow. Magnetic anomalies are of the order of 1000 nT, and are much shorter wavelength than the SP anomalies.

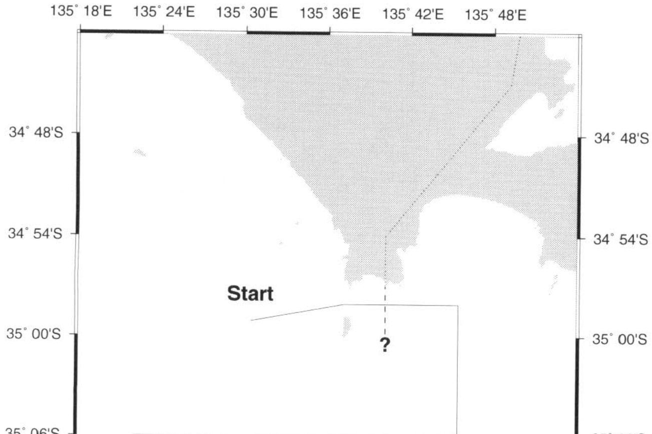

Figure 3. Location of one set of SP electric and magnetic field tows during the Eyre Peninsula experiment. The total length of the tow is approximately 65 km. The dashed line shows the mylonite zone with a possible offshore extension.

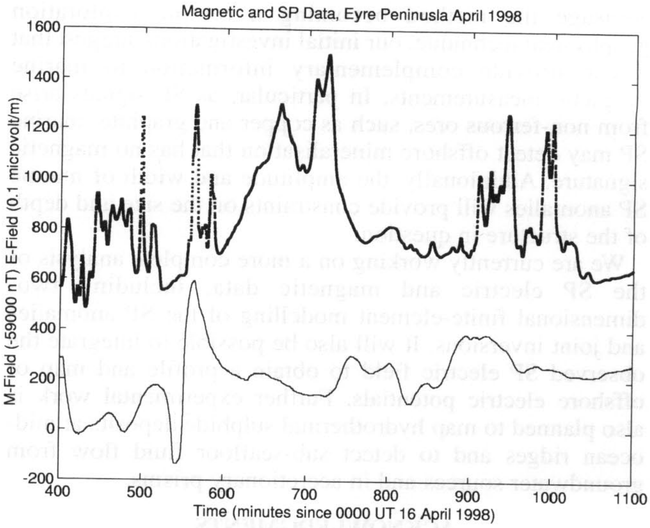

Figure 4. SP electric fields (lower trace) and magnetic fields (upper trace) for the tow line shown in Figure 3. Note that the magnetic field data are raw values with 59,000 nT subtracted, and the SP electric field data have been filtered to reduce swell-induced signal using a 21-point robust median filter.

DISCUSSION

Little correlation exists between the SP electric and magnetic fields, which suggests that mineralisation with high magnetic susceptibility does not produce an SP source in the marine environment. A probable source of the SP anomaly is due to graphite along the mylonite zone which trends north-south through the eastern margin of Eyre Peninsula. Graphite has been observed to produce SP anomalies of amplitude 0.8 V (Sato and Mooney, 1960), but the electrochemical mechanism to produce a marine SP anomaly is not clear. Corwin (1975) has suggested that it is due to redox reactions through the top few metres of sediment, which has been confirmed experimentally (Thompson et al., 1997). However, the SP anomalies in Figure 4 have very long wavelengths (> 2 km), suggesting that the source of the potential is considerably deeper than the sediment layer. We are currently developing finite-element models of possible potential sources and electrical conductivity distributions that are compatible with the observations.

An alternative hypothesis for the SP signal source is due to fluid flow through a fracture. Fluid flow produces an electric potential through the electrokinetic effect. Heinson and Segawa (1997) show that offshore fluid venting may produce a measurable electric field, particularly if the electrokinetic potentials for the basement rocks are large. Geochemical analysis of radon and radium isotopes along the mylonite zone along eastern Eyre Peninsula indicates the possibility of deep-water circulation through the mylonite zone (Sweetapple and Veeh, 1988). The mylonite zone may consequently be a conduit for offshore groundwater flow into the Southern Ocean.

CONCLUSION

Marine SP signals arising from sub-seafloor mineralisation can be detected using relatively simple instrumentation towed behind a ship. Although we do not envisage the method becoming a routine exploration geophysical technique, our initial investigations suggest that it can provide complementary information to marine magnetic measurements. In particular, as SP signals arise from non-ferrous ores, such as copper and graphite, marine SP may detect offshore mineralisation that has no magnetic signature. Additionally, the amplitude and width of marine SP anomalies will provide constraints on the size and depth of the structure in question.

We are currently working on a more complete analysis of the SP electric and magnetic data, including two-dimensional finite-element modelling of the SP anomalies and joint inversions. It will also be possible to integrate the observed SP electric field to obtain a profile and map of offshore electric potentials. Further experimental work is also planned to map hydrothermal sulphide deposits at mid-ocean ridges and to detect sub-seafloor fluid flow from groundwater sources and in accretionary prisms.

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