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The Marine Magnetic Gradiometer - A Tool for the Seismic Interpreter

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Marine magnetic gradiometer — a tool for the seismic interpreter

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The marine magnetometer has been used since the early '50s as an ancillary tool on vessels conducting regional and local seismic surveys. Emphasis on marine magnetic data by academia has led to major discoveries about the structure of the earth's crust, such as the association of shallow, crustal magnetic anomalies to seafloor spreading and long-wavelength anomalies to deep crustal origin. The same enthusiasm has not occurred in industry primarily because greater emphasis has been placed on multichannel seismic reflection data.

Magnetic data have been seriously limited by the problem of short-term time variations in the earth's magnetic field. These variations give rise to spurious magnetic anomalies that can be misinterpreted as geologic structures. One conventional method of estimating temporal variations for marine surveys has been the use of stationary magnetometers. Where there are nearby onshore magnetic base stations, it is sometimes possible to remove temporal variations from marine magnetic data. However, phase and amplitude variations in the temporal changes in the earth's magnetic field can be large at distances on the order of tens of kilometers. At polar magnetic latitudes, variations are more severe than at low magnetic latitudes.

At low latitudes the gradiometer can reduce the smaller temporal variations. In the Gulf of Mexico, lower strength of the earth's magnetic field induces lower amplitude magnetic anomalies in geologic features of interest. Greater care must be taken to resolve these lower amplitude geologic anomalies from temporal anomalies.

The advent of the marine gradiometer, in the late '60s, and the recent development of data-reduction methods have provided means to reduce spurious time variations in the magnetic field. An interpreter can incorporate the corrected magnetic data with COP seismic reflection data to provide better interpretation of the geologic structures.

Excerpts from the results of a 1984 US Geological Survey geophysical investigation in the Ross Sea (Figure I) illustrate how marine magnetic gradiometer data can effectively give better magnetic information about structures present in the CDP data. In frontier areas as the Antarctic, as well as in highly studied regions, combining both gradiometer and CDP data gives the seismic interpreter a better understanding of probable geologic structures and rock types than can be obtained by COP data alone.

Method. The marine magnetic gradiometer system uses two total-field sensors that are towed on a single cable and are separated by 150 m. The forward sensor is as far as 600 m behind the vessel to minimize the effects of the ship's magnetic field. The difference between simultaneously measured field values at the two sensors is essentially free of the effects of time variations in the earth's magnetic field because the time variations occur simultaneously and with similar magnitude at both sensors. By dividing this difference by the distance between sensors, an

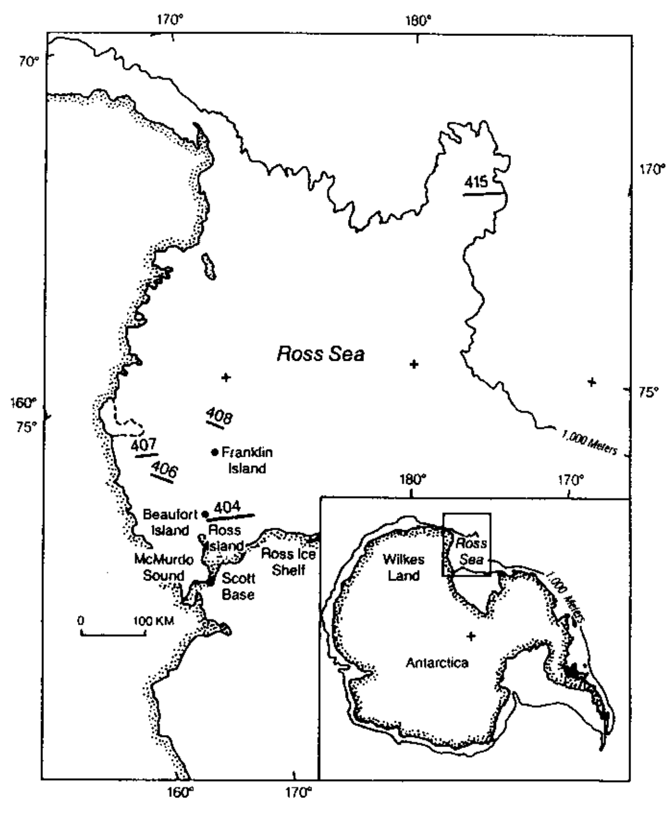


Figure 1. Ross Sea survey area from 1984 USGS investigation.

approximation of the magnetic gradient is obtained.

The gradient of the magnetic field between the sensors should be able to be used to determine the corrected (time-variation-free) total-field anomalies by numerical integration of the gradient along the ship's track. This simple procedure, however, generally gives unsatisfactory results because small measurement and instrumental errors from the sensors are highly amplified in the occurrence of false anomalies caused by the sensors varying in alignment with each other and with the ship's magnetic field.

In the mid-80s, R.O. Hansen developed an alternative approach using a time-variation suppression technique. In this method, the long-wavelength components are approximated as due entirely to geology. In effect, a trade-off is made in which very long-period time variations are incompletely suppressed, while long-wavelength errors in the reconstruction are minimized. In '87, Hansen and J.R. Childs applied this approach to correct the magnetic gradiometer data from the Antarctic. These data illustrate the significant effect of temporal magnetic variations on geologic interpretations.

Survey. During February 1984, the USGS conducted marine geologic and geophysical investigations of the Wilkes Land and Ross Sea sectors of the Antarctic continental margin. Magnetic gradiometer and multichannel seismic reflection data as well as gravity data were recorded during most of the survey.

The magnetic gradiometer data were measured with two sensors towed 230 m and 380 m behind the vessel. Tow depths of the sensors ranged from about 25 m for the slave (forward) sensor to 42 m for the master (rear) sensor. Measurements of the magnetic field were made every 6 s (15 m). For the Ross Sea survey, land-based magnetic measurements were recorded at Scott Base, McMurdo Sound, and were provided by the New Zealand Department of Scientific and Industrial Research.

The multichannel seismic data were recorded using a 24 channel, 2400 m hydrophone streamer. A 1300 in^3 array of five airguns was fired at 50 m intervals to provide 24-fold coverage. The seismic sections are band-pass filtered and stacked with far-offset weighting to reduce seafloor multiples.

Benefits. Marine magnetic-gradiometer data can be used to remove temporal variations from the magnetic data collected at high magnetic latitudes. After data processing, the resulting corrected magnetic anomalies are significantly different from those "observed" anomalies initially recorded aboard ship. The geologic interpretation based on the magnetic data also differs. An examination of the magnetic data before and after removal of the time variations reveals how these corrected anomalies can help to better understand the events observed in the CDP seismic reflection data.

Examples. The following examples illustrate the advantages of gradiometer data in the interpretation of data from the USGS Ross Sea survey (Figures 2-6 and Table 1). The multichannel seismic reflection profiles and their corresponding observed and corrected magnetic anomalies are shown. The observed magnetic data are the average value of the two sensors, and the corrected data were derived using Hansen's time-variation suppression technique. The Scott Base magnetogram (when available) and the "computed" time variation reconstructed solely from the gradiometer data are shown for comparison.

Figure 2 is a magnetic profile with both real and spurious anomalies from line 415 of the Ross Sea survey. The observed magnetic data indicate that several large amplitude (80-150 gamma) anomalies with similar wavelengths (4-5 km) occur in the central part of the line. These anomalies suggest that the entire region is underlain by shallow, highly magnetic rocks at about equal depth. This is a reasonable assumption because Cenozoic volcanic rocks are found in nearby onshore areas.

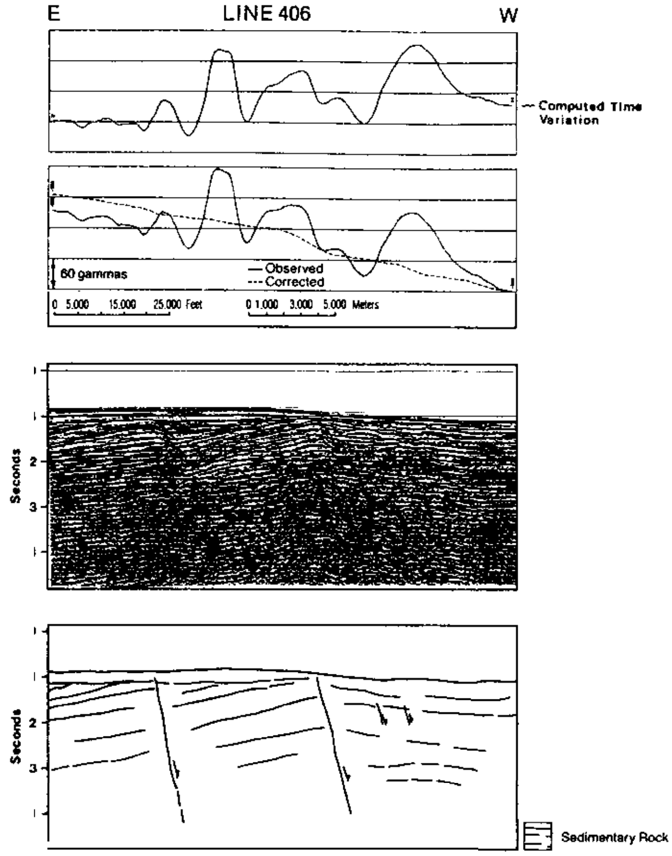


Figure 3. Temporal variations in magnetic and seismic data from line 406 of the survey.

A simple interpretation of the seismic section shows a central bathymetric rise underlain by disrupted reflectors and bounded on the left by a 15 km wide basement graben. The seismic data alone cannot rule out the presence of shallow magnetic rocks in the layered sedimentary section, as suggested by the observed magnetic data. Yet, once the magnetic time variations are removed, only a central magnetic anomaly, having steep gradients coincident with the bathymetric rise and disrupted zone, remains. The corrected magnetic profile implies that shallow magnetic rocks do not occur extensively in the seismic section except perhaps where basement is shallow east of the basement graben. This corrected magnetic information allows the interpreter to more confidently exclude the possibility of shallow intrusive or volcanic rocks in the seismic section. Quantitative analysis on the corrected magnetic data could provide more accurate estimation of depths to magnetic sources.

Another example of how temporal variations in the magnetic data can lead to an inaccurate interpretation of the magnetic data, and associated CDP seismic data, is illustrated in Figure 3. The observed magnetic data have four 70-120 gamma anomalies with wavelengths of 3-7 km. Significantly, the observed anomalies occur over large, tilted fault blocks that lie within a rift zone at the edge of a major basement graben. A reasonable interpretation of the observed magnetic data would attribute the four large magnetic anomalies to geologic features such as faulted sills, intrusives, or volcanic rocks associated with the tilted structures observed in the CDP seismic data. Once the magnetic temporal variations are removed, the interpretation is quite different. Any likelihood of shallow magnetic sources disappears. The four large magnetic anomalies are solely temporal variations. The long-wavelength gradient in the corrected magnetic data suggests that deep magnetic sources exist. These may be related to postulated basement faulting at 10-12 km depth. The long-wavelength gradient in the

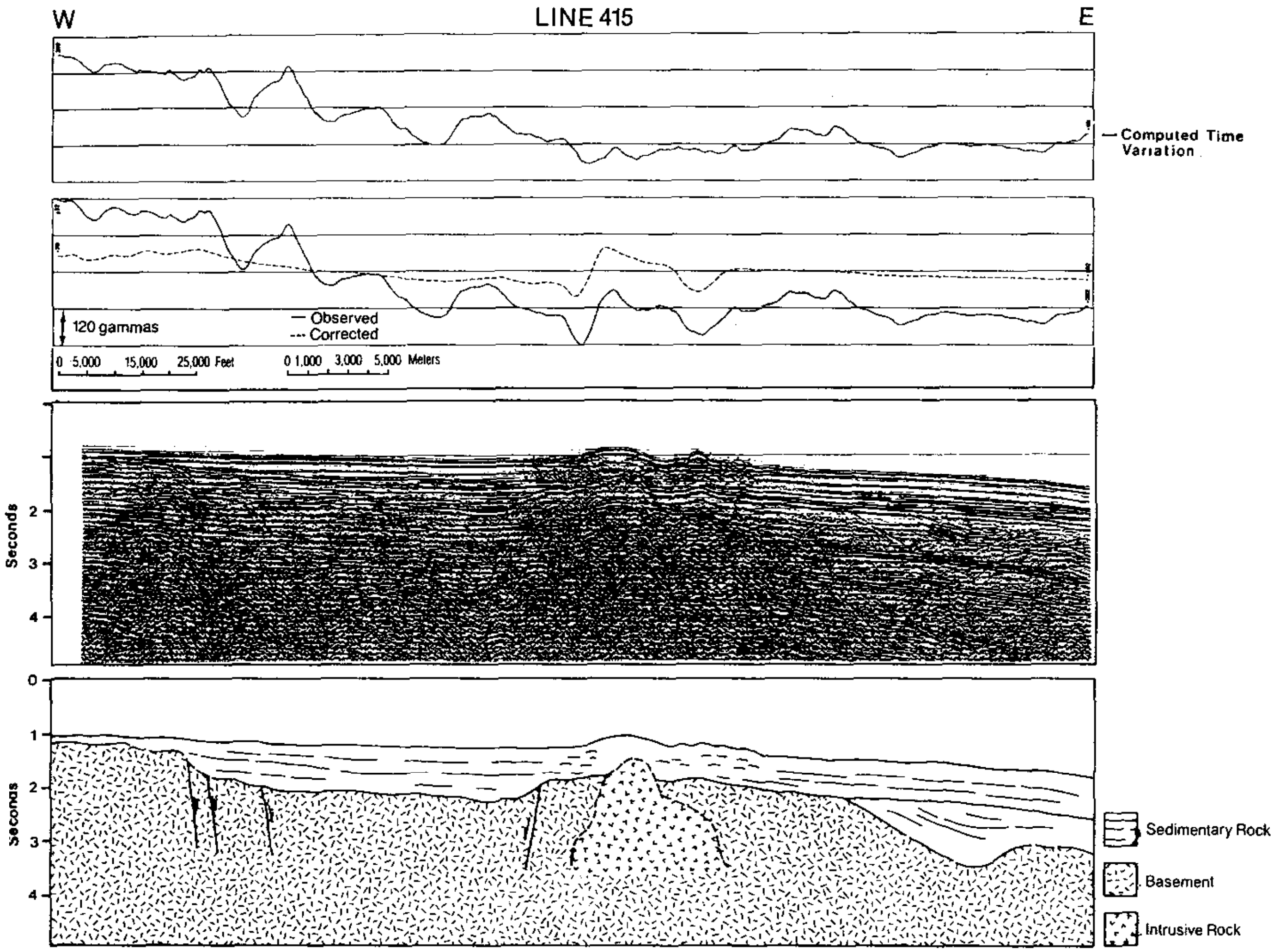


Figure 2. Magnetic profile with real and spurious anomalies from line 415 of the survey.

Table 1: Uses of magnetic gradiometer data in magnetic and geologic interpretations

	OBSERVED DATA		CORRECTED DATA	
	Observation	Interpretation	Observation	Interpretation
	I. Discrimination between magnetic anomalies due to geologic bodies and to temporal variations			
Fig. 2.	Several large magnetic anomalies in center of profile	Several magnetic bodies or structures at shallow depth	One large magnetic anomaly in center of profile	One magnetic body coincident with antiformal structure in CDP data
Fig. 3.	Four large magnetic anomalies	Magnetic bodies associated with structures in CDP data	No large anomalies present	Shallow seismic structures nonmagnetic
Fig. 4.	Isolated magnetic anomaly	Intrusive magnetic body	Same as observed data	Same as observed data
Fig. 6.	Several small symmetric anomalies	Shallow isolated magnetic bodies	Single 'step' anomaly with small gradient	Magnetic body at 2 km depth, possibly associated with fault zones
	II. Resolution of the true shape of magnetic anomalies and underlying geologic bodies			
Fig. 5.	Two large magnetic anomalies flanked by zones of small anomalies	Broad magnetic bodies (intrusives?) with flanking shallow magnetic sources (volcanics?)	Two large anomalies minor small anomalies (on left)	Two magnetic bodies (narrower and minor associated sources)
	Ill. Determination of correct location of magnetic anomalies and underlying geologic bodies			
Fig. 5.	Magnetic gradient	Deep magnetic body or contact	Same as observed except shifted 5 km	Same as observed except shifted 5 km

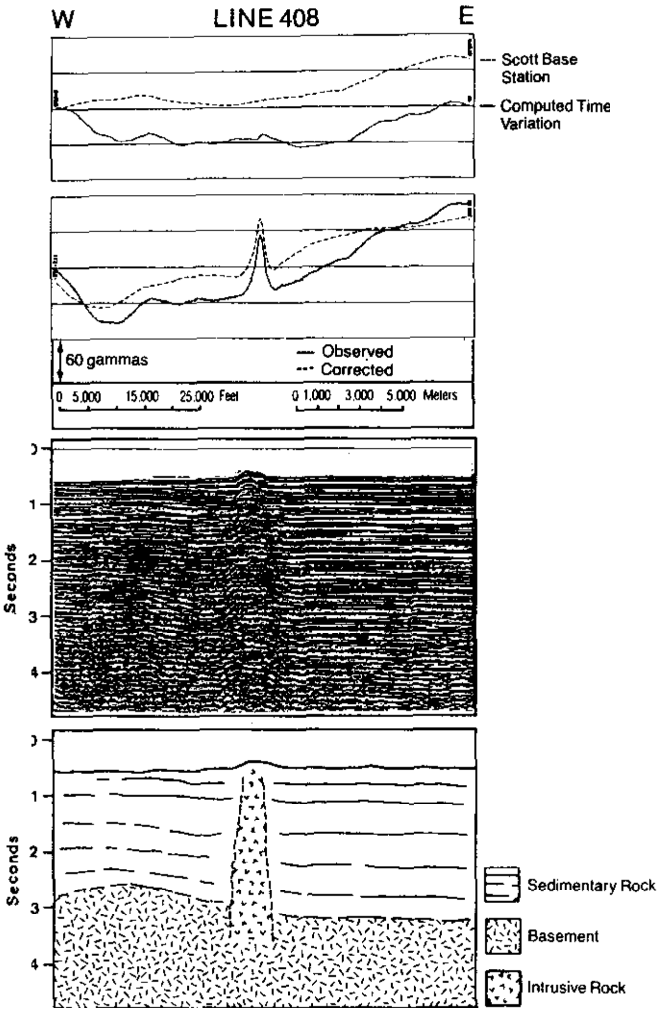


Figure 4. Isolated magnetic anomaly appears in both observed and corrected magnetic data from line **408** of the survey.

marine data is also observed in aeromagnetic data over the same area. This similarity suggests the existence of deeply buried structures, nearly impossible to resolve in multichannel seismic data, which can be located with the marine gradiometer.

Even though gradiometer data can be used to remove spurious temporal anomalies from the observed data, the question might be raised as to whether the gradiometer technique can accurately reproduce an anomaly that is unequivocally caused by a buried magnetic body. Figure 4 shows an isolated magnetic anomaly appearing in both the observed and corrected magnetic data in an otherwise smooth and nearly flat magnetic field. The magnetic anomaly occurs over an isolated bathymetric knoll and subsurface (intrusive?) structure in the CDP seismic data. The same interpretation would have been made with a single-sensor magnetometer without the benefit of the gradiometer. The gradiometer unequivocally demonstrates that coincidental time variations are not responsible for the magnetic anomaly. The gradiometer processing accurately reproduces the geologically caused magnetic anomaly and confirms that the disrupted antiformal reflections are likely due to an igneous intrusive or volcanics. These isolated structures are probably late-Cenozoic volcanic features and are common in the region (e.g., nearby Franklin Island).

A second advantage to using gradiometer data in high magnetic latitudes is the ability to resolve the shape of a true-spatial anomaly coincident with time variations. This is important if the interpreter wishes to determine the shape of the underlying magnetic source body for correlation with reflections in the seismic data. For the Antarctic survey, Figure 5 illustrates the most dramatic differences between the shapes of observed and corrected magnetic anomalies where real geologic source bodies are present. In the central part of the profile, the observed data show two large (200-300 gamma) magnetic anomalies flanked on both sides by 5-15 km zones of smaller (25-75 gamma) anomalies. When the time variations are removed, the small anomalies disappear, and, more importantly, a large portion of the two central anomalies changes dramatically. In fact, at point A, the corrected magnetic data differ from the observed magnetic data by about 150 gammas.

The difference between the observed data and the reconstructed data is so large that Hansen and Childs tested the validity of the anomaly reconstruction process for this site. They compared the time variations in the Scott Base magnetograms from Ross Island (100 km away) with the computed time variations from the gradiometer data and found an excellent correlation (top of Figure 5). Even with the minor phase shifts in the magnetic time variations between Scott Base and the ship, the onset of the large 250 gamma magnetic storm, which dramatically altered the anomaly shapes, is readily apparent. Hence, Hansen and Childs concluded that the large difference in anomalies is real.

In Figure 5, the interpreted geometry of source bodies responsible for the magnetic anomalies would be significantly different based on the observed or the corrected anomaly profiles. The seismic profile shows a well-layered sedimentary section to the east that is abruptly truncated by a zone of disrupted reflections. The disrupted zone lies between two volcanic islands (Ross Island and Beaufort Island, Figure 1) and consequently the zone is thought to be volcanics and subvolcanic intrusions. A preliminary interpretation based on the observed magnetic profile would indicate a broad intrusive zone bordered by shallow volcanic rocks within the layered sedimentary section. However, an interpretation based on the corrected magnetic anomalies suggests that the intrusive zone is narrower and that only two significant magnetic bodies are present at shallow depth. Model studies also suggest that only two isolated intrusive bodies are present. The important point, illustrated in Figure 5, is that before magnetic data can be used to assist with the interpretation of the CDP data, temporal variations of all amplitudes must be eliminated. Once this is done, quantitative analysis of the corrected data can aid the seismic interpreter in deciding whether the area of incoherent reflections is caused by geologic bodies that are also defined by the magnetic data.

A third benefit from the use of gradiometer data is that the locations of even subtle magnetic anomalies can be determined, once the time variations have been removed. An example of this is shown in Figure 5 at points B and C. Here the location of a small-amplitude magnetic gradient is shifted 5 km from B on the observed profile to C on the corrected profile. Because of the small amplitudes of both gradients, the source body causing the gradient is likely to lie deep within the sedimentary section or within the basement. The 5 km shift to the east from the initial anomaly location implies a similar shift in the location of the source body. The shifted location is near the structural edge of the Victoria Land basin and may be related to basin faulting. The determination of correct anomaly location can thus have an important role in geologic interpretation of the CDP seismic data.

A final example, Figure 6, shows how gradiometer data is used in uncovering small-amplitude magnetic anomalies that have been masked by the temporal variations. In this example, the magnetic temporal variations are not large (10-30 gamma), but they mask the anomaly caused by geologic sources. In Figure 6, the observed magnetic data show two 30 gamma anomalies with wavelengths and amplitudes that imply shallow magnetic sources without any obvious seismic expression. Once the temporal variations are removed, a different anomaly pattern emerges. A single low-amplitude gradient replaces the two small symmetric anomalies. The seismic profile shows a dipping sequence of reflectors that is down-faulted in the center of the figure. The sedimentary section here is believed to be 8-10 km thick. The down faulting is associated with the development of a major basement graben and ac-

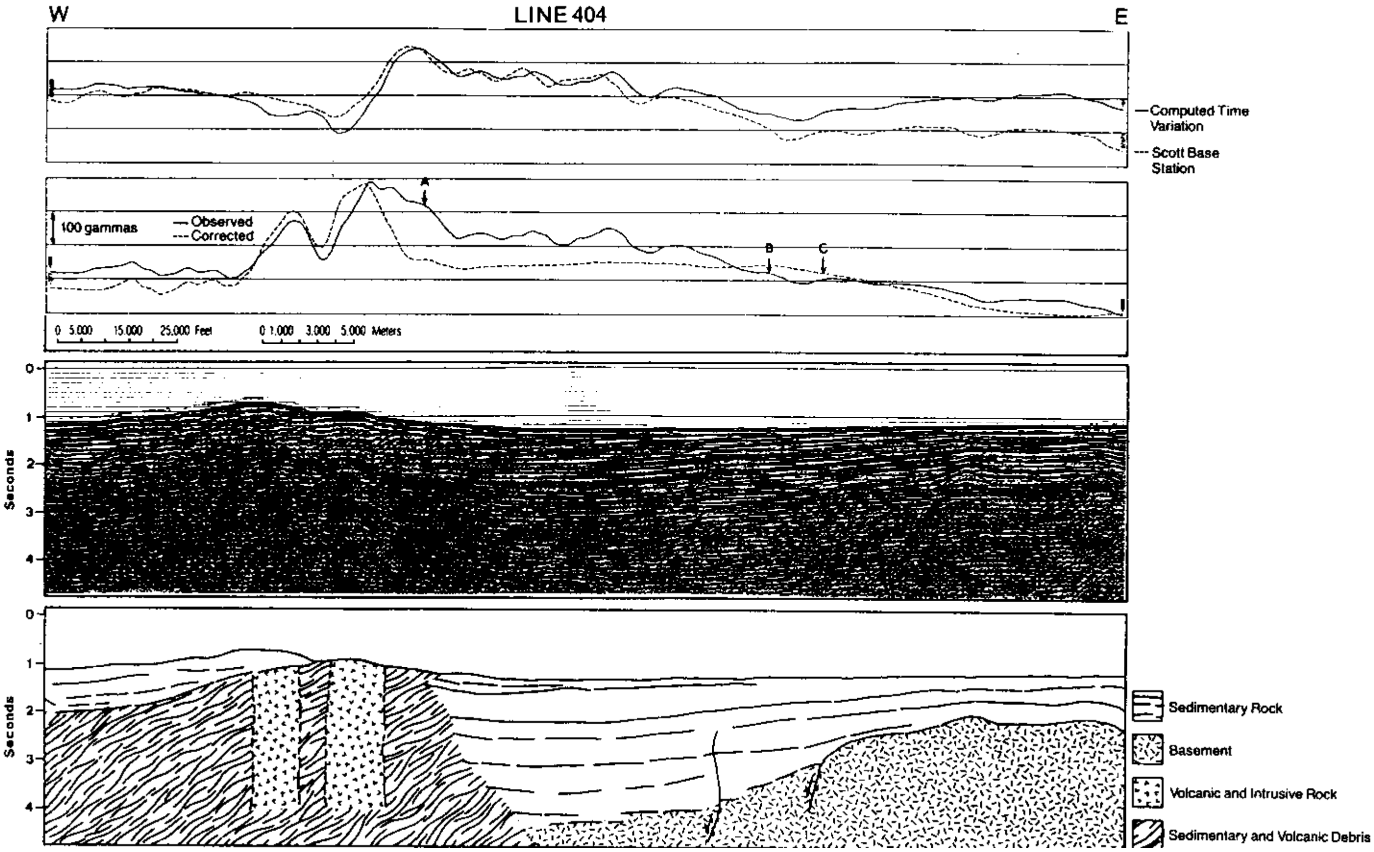


Figure 5. Dramatic differences in shapes of observed and corrected magnetic anomalies occur once the time variations are removed from line 404 of the survey.

tive rift zone. A quantitative depth-to-source analysis of the corrected magnetic data gives a dominant magnetic-source depth of about 2 km. This depth is within the upper part of the layered sedimentary section. The location of the corrected anomaly over the major graben faults suggests that the magnetic anomaly may be associated with magnetic materials along the faults. The magnetic source does not lie near the seafloor, as might be concluded from examination of the observed data. The change in the magnetic interpretation from shallow to deep sources is significant and further illustrates the importance of removing even small-amplitude temporal variations from magnetic data prior to interpretation in conjunction with CDP data. Again the ability to perform quantitative analysis on the corrected data can be a valuable asset to the seismic interpreter in understanding the possible types of rocks and structures at depth.

Conclusions. We have shown examples of magnetic gradiometer data recorded in high magnetic latitudes of the Antarctic to illustrate the dramatic changes that can occur in magnetic anomalies once the temporal variations are removed from the observed data. Removal of these temporal variations can lead to significantly different interpretations of the magnetic or geologic source bodies that give rise to the magnetic anomalies. Although we have concentrated on examples that have large-amplitude temporal variations, we have also shown that similar differences in the interpretations are likely to arise in areas where temporal variations are small.

In the Antarctic, the removal of temporal variations with the gradiometer data has successfully allowed:

- Discrimination between magnetic anomalies caused by temporal variations and those due to buried magnetic source bodies (geologic features).

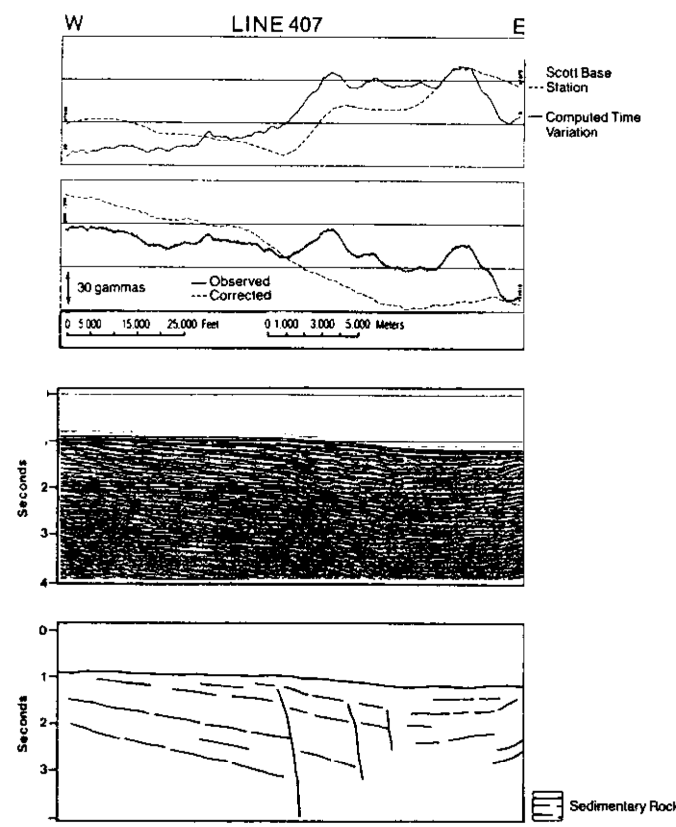


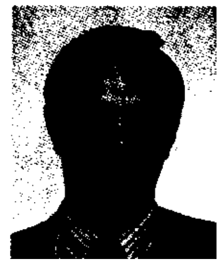
Figure 6. Gradiometer data uncover small-amplitude magnetic anomalies masked by temporal variations in line 407 of the survey.

- Resolution of the shape of magnetic anomalies and the underlying source bodies.
- Determination of the proper location of magnetic anomalies and the underlying source bodies.

Properly recorded and processed, magnetic data can play an important part in petroleum exploration, because these data provide information on the locations, magnetic properties, and geometries of underlying rock bodies. This information, when combined with seismic and gravity data, limits the possible geologic interpretations. The importance of removing temporal variations from magnetic data is clear from the examples we have shown, especially to accurately delineate the magnetic bodies (intrusives, volcanics, basement rocks, etc.) that may also be visible as reflection horizons in CDP seismic reflection data.

Once temporal variations have been removed from marine magnetic data, they can aid the seismic interpreter in the geologic interpretation of CDP seismic reflection data. Magnetic gradiometer data provide an accurate way in which these temporal variations can be removed. Hence, magnetic gradiometer data should be included in all marine seismic surveys to optimize the application of magnetic interpretive methods to the geologic interpretation.

Suggestions for further reading. Background on magnetic surveys, particularly the problems caused by short-term time variations in the earth's magnetic field, may be found in *An overview of the external magnetic field with regard to magnetic surveys* by R.D. Regan and P. Rodriguez (*Geophysical Surveys* 1981). Another background source is *An evaluation of the marine magnetic gradiometer by* D.C. Eggers and D.T. Thompson (GEOPHYSICS 1984). Relevant articles by R.O. Hansen are *Two approaches to total field reconstruction from gradiometer data* (*SEG Expanded Abstracts* 1984), *Reconstruction of time-variation-free total fields from marine gradiometer data* (EG&G Geometrics *Technical Report 29* 1985), and (with J.R. Childs) *The Antarctic continental margin magnetic gradiometer data suppression of time variations.* The Hansen-Childs article is found in the 1987 book, *The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea,* edited by A.K. Cooper and F.J. Davey. It was published as Volume 5B of the Circum-Pacific Council for Energy and Mineral Resources Earth Science Series. This publication contains several other articles which present many of the data and interpretations cited in this paper. Aeromagnetic data of the same area is presented in *Interpretation of an aeromagnetic survey of the Western Ross Sea Continental Shelf, Antarctica* by H.J. Duerbaum and J.C. Behrendt (EOS 1986). L



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MARINE MAGNETIC GRADIOMETER SOFTWARE

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