Identification of Shapes and Trends of Volcanic Bodies in the Western Ross Sea, Antarctica, by Correlation of Magnetic Profiles, Magnetic Maps and Seismic Profiles

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By
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Abstract

On the western edge of Antarctica a rift basin has been forming since the Jurassic Period. This is a complex area with several types of faulting as well as magmatic intrusions. The data collected thus far has shown the Victoria Land Basin to contain four spreading centers that have thinned the crust and allowed magmatic traces to surface. The purpose of this study is to determine whether the volcanics caused the rifting or if the rifting provided a pathway for the magma to work its way up to the surface. This theory will be tested by examining the shape and pattern the magmatic centers represent.
Introduction

The following study of the Western Ross Sea is the examination of a small area that is linked to a much larger area of study. The purpose of this study is to document the neotectonic faults and the volcanic bodies contained within western Ross Sea and more specifically the Terror Rift structure. The objectives of this study are twofold: (1.) In past interpretations of marine seismic data in western Ross Sea, where seismic profiles exhibited disturbed areas (i.e. No continuous, planar seismic reflectors), it can also be the result of disruption of sedimentary strata within fault zones. Magnetic data will be used to identify the position of volcanic bodies (expected to have magnetic signatures) and the positions of these will be matched with the seismic profiles are A) volcanic bodies or B) fault zones [or possibly C) fault zones used as pathways by volcanic bodies] (2.) In past interpretations of magnetic maps of the western Ross Sea constructed from airborne magnetic data, linear anomaly patterns have been interpreted as 'rift fabric' (Behrendt et al, 1996) associated with Cenozoic volcanic rocks. No detailed study has been conducted to determine geometry of the inferred volcanic bodies that could produce such a 'fabric.' By comparing marine magnetic profiles, magnetic anomalies mapped from airborne magnetic data, and seismic reflection profiles, can test the hypothesis that linear 'rift fabric' visible on magnetic anomaly maps of the Ross Sea is formed by Cenozoic volcanic bodies. Analysis of these data sets together will provide better constraints on the 3D shape and orientation of Cenozoic volcanic bodies.
Geologic Setting of western Ross Sea

East and West Antarctica are called so because of their position respective to the Greenwich Meridian (0° longitude). The Ross Sea forms the boundary between the craton of East Antarctica and the younger orogenic belt of the west (Davey and Brancolini, 1995). On the west side of the Ross Sea is the Transantarctic mountain chain and coinciding with that mountain belt is the rift shoulder of the west Antarctic Rift system that stretches for over 4000 km. This shoulder is block faulted and backtilted to the west and reaches elevations of over 4000 m (Davey and Brancolini, 1995).

Since the 1970s at least three distinct Proterozoic terranes have been identified and comprise the majority of the northern Victoria Land Basin. These terranes are believed to have been accreted in the early Paleozoic along NW-SE striking fault systems. The distinctions do become blurred between the terranes due to the appearance of the Beacon Supergroup, a Jurassic basaltic plateau and dolerites intruded around 180Ma in the Bowers and Wilson terranes. These supergroups do not manifest themselves in the Robertson Bay terrane, the northeastern most terrane. This non-appearance could be due to several factors; 1.) Original non-deposition or 2.) Complete erosion of Permo-Jurassic rocks due to greater uplift of the block.

The two faults that separate the terranes are the Leap Year fault and the Lanterman fault. The Leap Year fault separates the Robertson Bay terrane from the Bowers terrane and is identified by the Millen schist along the NE wall. The Lanterman fault separates the Bowers terrane from the Wilson terrane and is characterized by the highly deformed units found along the major counterclockwise bends.
The Wilson terrane includes large granite batholiths intruded into the Proterozoic and Lower Cambrian (age uncertain) metamorphics. The granite is the Cambro-Ordovician Granite Harbor granitic series. The Bowers terrane is a narrow belt, striking NW-SE, and is distinctive by volcanic rocks and marine volcanoclastic sediments metamorphosed at low grade. In the Robertson Bay terrane slightly metamorphosed continental shelf sediments are intruded by Devonian-Carboniferous granitoids.

The tectonic activity in the Ross Sea region can be characterized by three distinct sets of faults; NW-SE, N-S, and NE-SW (See figure 3). They are named based on their average azimuth, but variances occur from location to location. During the first extensional event the NW-SE right later, strike-slip faults dissected the offshore N-S extensional faults. Where the intersections take place there is usually a high or a volcanic center. The eastern area of the VLB (Victoria Land Basin) is characterized by block faulting produced by the NE-SW normal faults. These normal faults do not propagate past any of the NW-SE regional faults.

The NW-SE fault system has been described as seven major faults that have been mapped by continuous deformation from NW Victoria Land to the central high in the Ross Sea (Salvini et al, 1997). The deformation described is a gradual folding with some minor faulting which supports a strike-slip motion. Upon closer inspection and interpretation of the seismic profiles along the Aviator fault, one of the seven aforementioned, one can see two distinct episodes of deformation. There is extensional deformation that occurred post-RSU6. RSU6 is a large angular unconformity. This extension occurred at redefined locals that were already affected by a tectonic movement and were reactivated with an extensional component.
The N-S trending faults are common and widespread over the Ross Sea area. These faults are characterized by normal faulting that has been reactivated post RSU6. The N-S trend, usually seen more exactly as NNE-SSW, has been mapped southwestward to Ross Island. The unique thing about these faults is that they change frequency and dimensions as one will move across the area. In the South the faults are represented as a few larger faults, which have produced the Cenozoic depocenters. In the North most of the faults are smaller and more frequent.

The NE fault system is confined to the coastal region of the Northern Victoria Land, South of the Lanterman fault. Block faulting had tilting have characterized this fault system which has offset Jurassic rocks. In some areas the Cenozoic age lava flows of the McMurdo volcanics truncate the fault traces.

Tectonically, Antarctica is one of the most unusual regions of the globe. Approximately 95% (LeMasurier, 1990) of the perimeter is divergent plate boundaries. This coupled with the numerous rift basins within the continent make Antarctica a constantly expanding continent. These spreading centers allow the highly diverse felsic and hydroclastic rocks to be erupted to the surface. The hydroclastic rocks are mainly a product of millions of years of Ice caps and glaciers covering a large portion of the continent and contributing water to the rocks below. The dominant structure of the larger volcanoes on Antarctica is either basaltic shield volcanoes or shield-like volcanoes of felsic or intermediate composition (LeMasurier, 1990).

The overall setting at the western Ross Sea starts just east of the Transantarctic mountains where a 4-5 km high rift shoulder escarpment rises up to meet the mountains. This escarpment, the highest in the world, is the western edge of this asymmetric rift
system. If one moves away from the coast, the area magnetic surveys reveal extensive late Cenozoic magnetic anomalies located on the Ross Sea shelf. The extensive distribution of the exposed late Cenozoic alkaline volcanic rocks and their ocean island basalt chemistry were cited as evidence for a mantle plume head (Behrendt, 1996). The McMurdo volcanic group is a general term describing any Cenozoic volcanics contained in the area of the Ross Sea or Ross Ice Shelf. This group represents one of the most extensive alkali volcanic fields anywhere. The McMurdo group is the first terrestrial geologic record since the Ferrar Supergroup tholeiites were erupted in the Jurassic period. These volcanics have been dated as far back as 35 Ma or further using core samples and 25-19.8 Ma taking surface samples. The McMurdo Group has been subdivided into three separate providences based on spatial distribution and tectonic setting. The three providences are the Hallett, Melbourne, and Erebus providences.

The Erebus volcanic providence includes Ross Island and the surrounding areas. The main volcano on Ross Island is Mt. Erebus, hence the name and location of the providence. The unique formation of the magmatic centers is of particular interest. There are two separate centers, one around Mt. Erebus and the second around Mt. Discovery. The most intriguing part is the spatial distributions of the volcanic centers surrounding them are situated at 120° to each other. This distinct pattern may indicate several larger mantle plumes or hot spots (See figure 4).

The oldest center of the Erebus volcanic providence is located over, and around Mt. Morning. Gandalf Ridge (18.7-15.5 Ma), Riviera Ridge (15.2-13.0 Ma), and Mason Spur (13.5-12.4 Ma) seem to follow a trend of older ridges. These ridges seem to have been overlain by the younger (<2 Ma) rocks of Mt. Morning. At about 11 Ma a major
petrologic change to a basanite/phonolite association developed with eruptions at the eastern tip of Minna Bluff (11.9 Ma) and the northern end of Black Island (10.9 Ma). Volcanic activity then appears to have migrated northwestward to central Minna Bluff (8.3-7.3 Ma) and Mt. Discovery (5.3-4.4 Ma) (Kyle, 1990). Further to the north, Ross Island was progressively built up from the perimeter in. The odd shape of the island, with its three distinct points, is caused by the three volcanic centers out on the wings, 120° from each other. The oldest is Mt. Bird (4-3 Ma), followed by Mt. Terror to the northeast (2.6 Ma). To the south is Hut Point Peninsula (1.8-4 Ma), finally the center of the island was build up with the appearance of Mt. Erebus (<1 Ma).

The mineralogy of the volcanic providences has been used to distinguish the evolution of the petrologic suits. There is a wide variety of distinctive minerals within the volcanics. Large anorthoclase phenocrysts are found on Mt. Erebus as well as clinopyroxene accompanied by olivine, spinels, apatite, plagioclase, and kaersutite found in the basic and ultrabasic rocks. The felsic rocks usually contain feldspar ranging from oligoclase to sanidine. The most abundant feldspar is anorthoclase. Alkali amphibolites and micas are uncommon.

Structural Interpretation of western Ross Sea

After interpreting the seismic lines there are seven acoustically distinct units that can be identified covering three large, sediment filled basins. From the surface down the units are given the distinctions of units V1-V7 (See figure 5).

V1
Unit V1 is a flat lying sedimentary unit that extends from the sea floor to a depth of 1.2 km, which correlates to a subsurface time of 1 sec. to reach the bottom of the unit with the seismic sounding equipment. V1 unconformably overlies the sediments directly below it. At times this unconformity rises up to just below the sea floor, making the identification of the boundary difficult. Unit V1 also shows signs of glacial processes manifested in irregular depositional and erosional features. Near Ross Island this unit is shown to be onlapping volcanic structures.

**V2**

Unit V2 is a thin unit ranging in depth from 1.3 km to 200 m with fluctuations occurring frequently due to depositional conditions (Cooper et al, 1987). This unit is a well-layered one, bounded on both sides by unconformities. Late Oligocene – Middle Miocene is the age.

**V3**

The highly reflective rocks of unit V3 have a reflection velocity of 2.7-3.3 km/sec (Cooper et al, 1987) the reflection velocity increases as one moves further down from the surface of this unit, suggesting a uniform depositional pattern. This unit becomes thicker and looses some continuity as it moves closer to the Discovery Graben. The rocks have been estimated at late Oligocene and older in age.

**V4**

Unit V4 is very similar to unit V3, the only differences are the increased velocity as well as the degree of distortion near the Discovery Graben. On the western end of the unit V4 has been eroded away and has become a significant marker for an angular
unconformity. On the east end, near the Coulman high, the top of V4 onlaps with the top the basement surface. The age is Paleogene or older.

**V5**

Only recently being discovered, scientists thought this unit to be part of the basement rocks because of the high reflective velocity (4.9-5.4 km/sec). Layering was later found and V5 is now considered a steeply dipping unit that is the base of an angular unconformity on the western edge of the Victoria Land Basin (VLB). V5 may be as thick as 7-8 km near Discovery Graben, but thins out in both directions. The age of V5 is estimated at Mesozoic – Paleogene.

**V6**

Unit V6 is the unit responsible for most of the deformation at shallow depths. This unit is most likely extrusive rock containing volcanic debris, it is by no means a continuous unit, although it is seen several places at the sea floor. Magnetic have shown V6 to be highly magnetic.

**V7**

Unit V7 is the true basement rock of the region. At times the boundary between V6 and V7 becomes very indistinct. The major difference is the broken and fractured surface of V7 slowing down the reflectiveness. Most of the unit is more than 5 km below the sea floor. All rock types and ages are merely estimations at this time.

The Victoria Land Basin is classified and broken down into four north-south trending structural zones as well as one other zone that overlaps them. Simply labeled zones 1-4 moving from west to east, each has its own characteristics. Zone 1 features horsts, grabens, intrusives, and large offset normal faults near the western edge. Zone 2
contains the graben and arch systems of the Terror Rift. The normal faults of the eastern flank represent zone 3. Zone 4 is made up of the grabens and half grabens of the Coulman high. Zone 5 is the intrusive volcanic body zone, normally restricted to the southern half of the basin.

**Terror Rift**

This late rift structure within the VLB contains two major components. On the western edge of the Terror Rift is the Discovery Graben, directly to the east of that is the Lee Arch. The **Discovery Graben** is a structural depression defined by a series of high angle normal faults that for the most part, dip toward the axis. Several of the faults may be extensions of much larger faults that extend well into the basement rocks and represent very large offsets. Most of the areas is lacking recent seismicity associated with active movement along the faults. The **Lee Arch** is a structural high area that is represented by the upheaval of units V1-V5. These five sedimentary units are being thrust upwards due to the pressure of unit V6 as well as the upfaulting associated with the basement rocks (V7). As has been characteristic of all volcanics of the region the arch manifests itself much more prominently in the southern part of the VLB and dies out [or becomes buried] towards the north.

**Structural Evolution of the VLB (See figure 6)**

Prior to the Middle and Late Jurassic time the VLB was a relatively flat fluvial basin where Beacon strata were deposited. During the Jurassic the area was uplifted and deformed slightly. Also at the same time the rocks were being intruded by sills and local
volcanics polling near the center of a graben in formation. Extension and the resulting downfaulting and recession of the VLB probably occurred during the Early to Middle Cretaceous period. Unit V5 was possible deposited during the Late Cretaceous-Paleogene. Also possibly around this time was the rifting between Australia, New Zealand, Tasmania, and Antarctica; opening a path for sediment to travel to the VLB. The late stage rifting begins with the reintroduction of volcanism to the south of the basin. Also the Transantarctic Mountains were being built at this time. This phase is still continuing to develop even today and includes the uplift, intrusion and cutting of unconformities. The Terror Rift zone along with the Coulman high was also formed during this late stage.

**Interpretations of the Magenetics in the Ross Sea**

Approximately 100, 1-10 km wide, roughly circular anomalies were interpreted as Cenozoic volcanism. These anomalies varying in amplitude from 100-100 nT (nano Teslas) followed a rough linear pattern interpreted as rift fabric. Several of these volcanic centers are also crossed by seismic lines revealing that they do indeed reveal themselves amongst the sediment of the sea floor. On the aeromagnetic maps (figure 11) there is a distinct break of three sections. There is a highly magnetic northern area. The central area has negligible anomalies, and the southern section has a strong Correlation to that of the north. There are two possibilities for this lessening of magnetic feedback in the central area. 1.) The presence of an increased thickness of sediment or 2.) More highly magnetic material being compiled in the northern and southern sections. These
two highly magnetic regions are most probably from the same source and are equivalent to the Erebus volcanic providence from Ross Island.

**Magnetic Surveying**

A magnetic anomaly is a disruption of the earth's overall magnetic field caused by a body of rock usually containing iron. The object will give off its own magnetic field where the unseen magnetic lines loop from one pole to the other. When these lines encounter the surface there is a specific vector (angle and magnitude) that can be measured. Through simple vector addition on can find if the field at a specific point works with or against the field of the earth. If it works with the earth it is classified as a positive anomaly, while if it takes away from the value of the earth's field it is considered a negative anomaly.

Not all rocks have a magnetic field that surrounds them; most rocks containing iron, magnetite, hematite, goethite, or pyrrhotite give off a magnetic field. Iron is the most common of the minerals listed above. This is partially the reason why volcanic rocks usually have a magnetic signature; they are usually high in iron content. The other reason for volcanics giving off magnetic values is that during the time when the magma cools over a relatively short period of time, it solidifies as a uniform body allowing the iron atoms to align themselves with the dominant magnetic field, usually the earth. This alignment will give the magmatic body a stronger dipole. Once the body has solidified the magnetic direction is also set in place. Therefore volcanic bodies are great indicatators of past pole reversals of the earth's field.
Aeromagnetic surveys are relatively simple procedures. They are able to scan a large, possibly remote, area in a short amount of time with minimal equipment. A magnetometer is attached to an airplane, either by a boom or a towed line and the plane is flown along a regular pattern at a set height and distance from each line. The lines are flown perpendicular to the survey lines to correlate with the points of intersection, and check for errors.

Shipborne surveys are basically the same concept as the airborne surveys, whereas a magnetometer is towed behind the ship, as to reduce an affects the ship may have on the readings, and the ship passes over a similar back and forth pattern and records the measurements.

**Methods**

The Data that I was given was over 700 pages of shot points. They were originally in the following form:

Day-of-year:hr:min:sec.000/year/lat_(S/N)/degrees_lat/min_lat.xxxx/
lon_(E/W)/degrees_lon/min_lon.xxxx/mag_total_field/mag_anom

The initial task was for me to import the data into an Excel file, eliminate the data that was not needed for ArcGIS and modify the latitude and longitude values. I changed all of the south and west points to negative and the north and east values to positive. Also, ArcGIS does not recognize lat/long values in degrees and minutes so I converted all of
the minutes to decimal degrees by dividing the minutes and seconds by 60. The final modified spreadsheet looked like:

Lat_degrees/long_degrees/magnetic value/anomaly value

This file was then saved as a .csv (comma delineated) file for it to be imported into ArcGIS I was able to select the specific lines that would serve my purpose of mapping the western Ross Sea and the rift basins within it. There were only 3 magnetic lines out of 31 that were in the vicinity of being able to help me. I took these three line and color coded them according to their magnetic value. I used an equal bin separation with 4 breaks and a yellow (low) to red (high) color scheme.

In addition to the magnetic data there were also several other files that were used as background and supplemental data. First there were the seismic lines which were also in an Excel format and were converted to .csv files as well. The bathymetry file shows the depth of the Ross Sea over a wide area, this map is displayed as both a contour map and as a contour shaded map. I also used a map of the land; this gave a perspective with the Transantarctic Mountains. A coast line was also added as well as a topographic map. These two maps were especially important and had to be laid down in ArcGIS first because they were in the TAMERA format. With these layers in place i could add the seismic and magnetic data and have it adjust to fit the coordinate system.
Conclusions

With the information available to me, I was not able to draw any conclusions about the magnetic data. It turns out that there was one ship line through the western Ross Sea. This ship track, although down the middle of the VLB seems to avoid any major volcanic anomalies identified on the seismic profiles (see figure 10). Based on the shaded anomaly maps from Behrendt et al, 1996 the magnetic trends do seem to follow a similar trend as the rift basins that they overlap. From this information I would have to say that the fault zones were used as pathways for volcanic bodies; with only one non-distinct line the description of any shape is difficult and most likely not accurate at all. With a more systematic approach to the shipborne magnetics much information can be learned.
References


Also the maps and data provide to me by Dr. Terry Wilson.
Table I

| Geological Age | M | Cretaceous | L | E | L | E | M | L | E | L | E | M | L | I |
|----------------|---|------------|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ma             | 120| 100 | 80 | 60 | 40 | 20 | 0 |   |   |   |   |   |   |   |   |

Figure 3. Cenozoic tectonic map of the Ross Sea region.
Figure 10. Proposed tectonic model for the evolution of the Ross Sea region in the last 32 Ma (post-RSU6). The Ross Sea Region has been affected by reactivation of regional right-lateral, strike-slip faults. Post-RSU6 extensional faulting with N-S trend and reactivations are interpreted here as either transfer or accommodating faults between adjacent NW-SE, regional, strike-slip faults. Volcanic activity concentrates along N-S fault alignments in a belt between Victoria Land and the Ross Sea. Central volcanoes lie at intersections of these alignments with the regional, strike-slip faults.
Fig. A.III.4. Generalized tectonic map of Erebus volcanic province, compiled from Warren [1969], Cooper et al. [1987], Wright-Grassham [1987], and Kyle (unpublished observations, 1987).
Table 1—Characteristics of acoustic units V1 to V7 in the Victoria Land basin, Antarctica.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Thickness (km)</th>
<th>Velocity$^1$ (km/s)</th>
<th>Age$^2$</th>
<th>Description$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>&lt;1.2</td>
<td>1.7–2.3</td>
<td>E.-M. Miocene to Present</td>
<td>Glacial marine sedimentary</td>
</tr>
<tr>
<td>V2</td>
<td>0.2–1.3</td>
<td>2.1–2.9</td>
<td>Late Oligocene to E.-M. Miocene</td>
<td>Glacial marine sedimentary</td>
</tr>
<tr>
<td>V3</td>
<td>0.3–2.5</td>
<td>2.7–4.1</td>
<td>Paleogene to late Oligocene</td>
<td>Marine? sedimentary</td>
</tr>
<tr>
<td>V4</td>
<td>&lt;1</td>
<td>4.0–4.9</td>
<td>Paleogene and/or older</td>
<td>Marine? sedimentary</td>
</tr>
<tr>
<td>V5$^3$</td>
<td>&lt;8</td>
<td>4.5–5.6</td>
<td>Cretaceous to early Paleogene</td>
<td>Marine? sedimentary</td>
</tr>
<tr>
<td>V6$^4$</td>
<td>&lt;8?</td>
<td>—</td>
<td>Paleogene to Holocene</td>
<td>Volcanic rocks (M,H)</td>
</tr>
<tr>
<td></td>
<td>&lt;7?</td>
<td>—</td>
<td>Jurassic to Paleogene</td>
<td>Volcanic rocks (F)</td>
</tr>
<tr>
<td>V7$^5$</td>
<td>&lt;3?</td>
<td>5.0–6.2</td>
<td>E. Paleozoic to Jurassic</td>
<td>Variable - includes A, BE,BO,F,G,K,R, and W$^6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.5–7.4</td>
<td>Precambrian to E. Paleozoic</td>
<td></td>
</tr>
</tbody>
</table>

$^1$ Refraction velocities from Cooper, Davey, and Cochrane (this volume).
$^2$ Age and lithology are inferred from: (1) drillholes DSDP 273 and MSSTS-1 for units V1 and V2 and (2) regional geology for units V2 through V7.
$^3$ Unit V5 may, in places, contain Devonian to Jurassic Beacon Supergroup and Ferrar Group dolerite sills.
$^4$ The younger volcanics are found beneath the Lee arch and along the edge of the VLB. The older volcanics occur beneath the Discovery graben.
$^5$ Beneath the VLB, the upper part of unit V7 may be BE and F, which overlies plutonic and metamorphic rocks (A, G, K, or W); beneath the northern and possibly central Coulman high, unit V7 may be composed of metasedimentary and volcanic rocks (BO and R).
$^6$ A, Admiralty Intrusives; BE, Beacon Supergroup; BO, Bowers Supergroup; F, Ferrar Group; G, Granite Harbour Intrusives; H, Hallett volcanic rocks; K, Koettlitz Supergroup; M, McMurdo volcanic rocks; R, Robertson Bay Group; W, Wilson Supergroup.
Figure 26—Interpretive models for the evolution of the VLB based on MCS seismic data (Fig. 7). A. Central VLB (MCS 407). B. Southern VLB (MCS 403/404). Two rifting periods are postulated: early phase during which the asymmetric graben underlying the basin formed (possibly upper Mesozoic time) and a late phase (extended from Paleogene to the present) during which the Terror rift and other young fault and intrusive structures developed. Most basin-filling may have occurred during an intermediate phase during Cretaceous and into Paleogene time. TAM is Transantarctic Mountains.
Figure 3—A. Bathymetric map of the Victoria Land basin (VLB) region (from Davey and Cooper, this volume) showing location of USGS ship tracklines. B. Shotpoint map for multichannel seismic-reflection profiles.
Figure 18—MCS lines across the eastern edge of the Discovery graben (western edge of Lee arch) showing large normal faults that dip toward the highly intruded Lee arch. A. Line 414A. B. Line 407B. Irregular seafloor relief occurs above the arch where magnetic data suggest magmatic intrusives. See Figures 3B and 15 for location.
Fig. A.12.1. Map of western Ross Sea. Short-wavelength magnetic anomalies along S.P. Lee ship track over the western Ross Sea continental shelf. Numbered track lines also have 24-fold seismic reflection data. Anomalies a–h are caused by submarine volcanoes and subvolcanic intrusions throughout the Victoria Land basin. Anomaly d (about 1400 nT) is at the 0- to 750-nT scale. MCS, multichannel seismic line.