Flat-topped mounds in western Ross Sea: Carbonate mounds or subglacial volcanic features?

L. Lawver[1], J. Lee[2], Y. Kim[2], and F. Davey[3]

[1]*University of Texas at Austin, Institute for Geophysics, Jackson School of Geoscience, 10100 Burnet Road, R2200, Austin, Texas 78758, USA*

[2]*Korea Polar Research Institute (KOPRI), Unit of New Antarctic Station, Get-pearl Tower, 12 Gaetbeol-ro, Yeonsoo-Gu, Incheon, 406-840, Korea*

[3]*GNS Science, P.O. Box 30368, Lower Hutt, 5040, New Zealand*

ABSTRACT

Detailed multibeam bathymetry data in the western Ross Sea, Antarctica, delineate a field of unusual flat-topped seafloor mounds located ~50 km west of Franklin Island and an arcuate zone of pockmarks to the northwest and west of Franklin Island. Sixteen mounds occur in an area about 30 km square at a depth of ~500 m, within the Terror Rift, the active extensional part of the Victoria Land Basin. The mounds tend to be circular in the east and linear in the west, with their steepest slope to the southeast, and shallowest slope to the northwest, consistent with erosion by northwest ice-sheet movement. The largest mound is ~4 km across and 100 m high. Five similar features were delineated to the south and east of Franklin Island at depths of 400–650 m. Seismic, gravity, and magnetic data indicate that the mounds are largely low-density, nonmagnetic bodies overlying a largely nondisrupted sedimentary section, but some mounds have an associated small (~50 nT), short-wavelength, normal or reversed magnetic anomaly, indicating a magnetic core to the mounds. Their proximity to inferred subsurface gas hydrates suggests they may be carbonate banks, but they also occur close to volcanic centers including Franklin Island. Our preferred interpretation is that they are of volcanic origin, erupted during a geomagnetic reversal and under a grounded ice sheet forming hyaloclastite edifices, previously unknown under the Ross Sea. The pockmarks range from 200 m to 500 m in diameter.

INTRODUCTION

The southern part of the western Ross Sea (Fig. 1) coincides with a major rift basin, the Victoria Land Basin, which contains sediments up to 14 km thick and documents an extension-rifting history that may extend back as far as the Cretaceous (Davey et al., 1983; Cooper et al., 1987). The major extension of the basin probably occurred only since the late Eocene (~38 Ma; De Santis et al., 2001; Davey et al., 2006). The most recent extensional deformation has focused on the central part of the basin (Lee Arch and Discovery Graben of the Terror Rift, Cooper et al., 1987) where major faulting and volcanism still occur (Cooper et al., 1987; Hall et al., 2007). Extensive volcanism continues along the axis of the Victoria Land Basin, from Ross Island to Mount Melbourne (Fig. 1), where recent subice volcanism has occurred at Shield Nunatak (Wörner and Viereck, 1987). Franklin Island, a recently active volcanic center (Armstrong, 1978; Rilling et al., 2009), lies along a volcanic ridge under the eastern part of Victoria Land Basin that is imaged on aeromagnetic data (Chiappini et al., 1999). Numerous, additional small, young volcanic centers lie in this region. Lawver et al. (2007) documented a group of low, flat-topped mounds in a restricted region of the Lee Arch to the west of Franklin Island. They speculated that they may be caused by subglacial eruptions, similar to those that occur in Iceland, and give rise to low-density and magnetized hyloclastite rocks, because the magnetic anomalies are subdued over the features. The mound field lies at an offset (accommodation zone) in the Terror Rift (Salvini et al., 1997).

Detailed analyses of multichannel seismic data across the region west of the mounds by Geletti and Busetti (2011) have delineated bottom simulating reflectors (BSRs) and sub-BSRs that they infer are caused by gas hydrates. They document a mound over a fault that they suggest is caused by the fault releasing pressure on the gas hydrates, allowing free gas to form and rise up the fault zone to form a mud volcano at the surface. They also identify a pockmark close to the mounds cluster and overlying their BSR region. Lawver et al. (2007) report the presence of an extensive field of pockmarks lying to the east and northeast of the mounds and extending from the Lee Arch to Franklin Island at depths of 450–500 m (Fig. 1). The presence of natural gas in the subsurface has been associated with roughly circular depressions in the seafloor—pockmarks—where natural gas has apparently escaped (King and Maclean, 1970; Hovland, 1981; Hovland and Judd, 1988), and these have been found in many regions globally (e.g., Judd and Hovland, 2007; Pilcher and Argent, 2007). These pockmarks are inferred to result from the expulsion of sub-seafloor gas occurrences associated with the phase change from hydrate to free gas, and support the existence of extensive gas in the sedimentary section, as found on the Ross Shelf by Deep Sea Drilling Leg 28 (McIver, 1972). These results suggest an alternate interpretation for the mounds—that they are carbonate mounds (Lawver et al., 2008), similar to those seen in the Porcupine Bight off northwest Europe (Shannon et al., 2007).

New multibeam bathymetry, gravity, and geomagnetic data over the mound and pockmark fields have been integrated with existing geophysical data to define their characteristics and extent in more detail and examine their cause. We present gravity and magnetic models of some of the mounds, indicating the low density and some localized magnetization of the mounds.

METHODS

The new data were recorded across part of the southern part of mound field and to the south and east of Franklin Island by *RVIB Araon* using a Kongsberg Simrad EM122 multibeam echo-
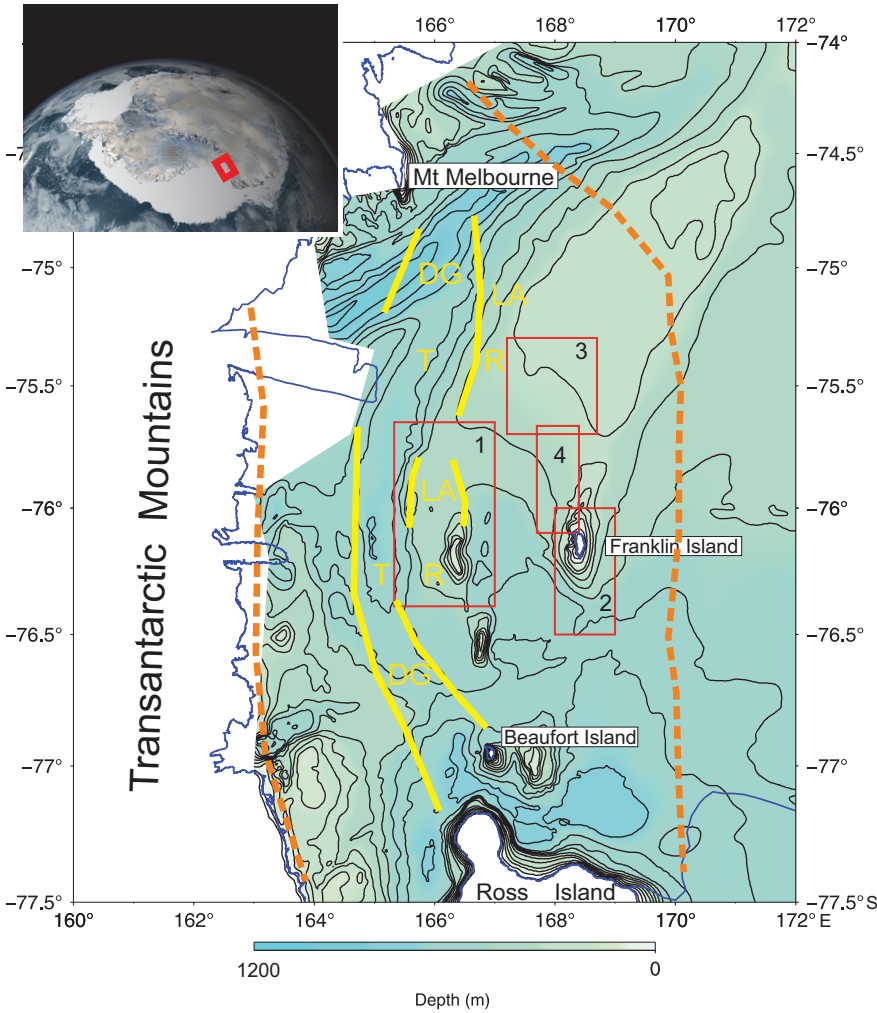
Figure 1. Western Ross Sea region (red box on inset National Aeronautics and Space Administration image of Antarctica). Bathymetry, 100-m intervals after Davey (2004), masked at western limit of marine data. Thick orange-dashed lines show extent of the Victoria Land Basin. Thick, solid yellow lines show location of the Terror Rift (T R) comprising the Discovery Graben (DG) and Lee Arch (LA) (Cooper et al., 1987). Red-outlined boxes denote: 1—mounds region (Fig. 2); 2—Franklin Island region mounds (Fig. 4); 3—northern pockmark region (Fig. 5B); and 4—southern pockmark region (Fig. 5A).
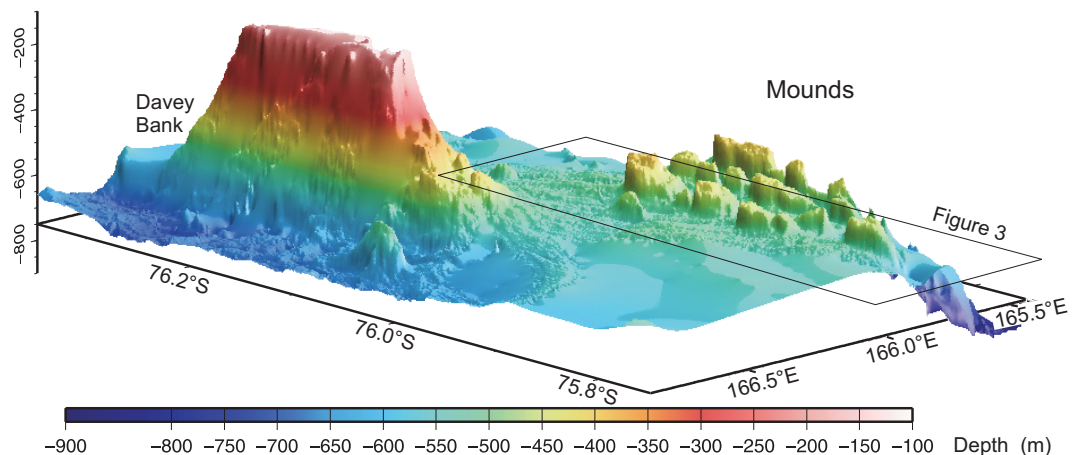
sounder in February 2011. Seawater velocity-depth profiles were recorded at three stations using an Applied Microsystems SV Plus V2 sound-velocity probe lowered to the seafloor. A Micro-g LaCoste Air-Sea System II gravity meter system was used for gravity recordings with base ties at Lyttleton, New Zealand, at the start and the end of survey. Instrument drift was low (0.5 mGal over 30 days), and an accuracy of 1 mGal is estimated in good sea conditions. A Bartington Instruments Ltd. Mag-03M three-component fluxgate magnetometer was installed on the ship's mast for three-component magnetic data. These magnetic data were processed using the methods of Korenaga (1995), but only a limited data set was recovered. The multibeam data were integrated with existing multibeam data recorded by *RVIB Nathanial B. Palmer* (NBP9602, NBP9702, NBP0301, NBP0302, NBP0401, and NBP0701 data obtained via GeoMapApp) (Figs. 2–5). The new potential field data and those from NBP0401 have been used for modeling.

DATA: MOUNDS

The new data extend the area of the field of unusual flat-topped seafloor mounds located west of Franklin Island by ~6 km to the southwest. An additional nine mounds have been delineated. The total field lies ~20 km northwest of a major volcanic ridge (Fig. 2, Davey Bank) and covers an area about 30 km square at a depth of ~500 m (Fig. 3). The largest mound is ~4 km across and 100 m high (Fig. 3). The mounds are generally circular in the east and linear in the west (Fig. 3), have a northerly trend to their distribution, and are probably fault controlled. The southeast flanks of the mounds have the steepest slope, with the shallowest slope to the northwest, consistent with emplacement of relatively unconsolidated deposits under a north-

Figure 2. Three-dimensional view of western mounds and Davey Bank from the northeast. Location is red-outlined box 1 in Figure 1. The extent of Figure 3 is shown by the thin black line. Vertical exaggeration ~35:1.

west-moving ice sheet or possibly by northwest-trending seafloor currents. Schopka et al. (2006) derive a similar conclusion for Helgafell, a subglacial volcano in Iceland. Similar mounds also occur 25 km south (four mounds) and 5 km east (one mound) of Franklin Island (Fig. 4) at depths of 650 m and 500 m, respectively. In this region, the largest mound is ~2.5 km across and 60 m high (Fig. 4). The steepest slope is again to the southeast, the shallowest slope to the northwest. Their alignment is generally north-south.

The coverage of gravity and magnetic data are limited to relatively widely spaced profiles, and as the ship tracks often only passed over the flanks of the mounds (Fig. 3), profiles across selected mounds were used for modeling. Both gravity and magnetic anomalies are very small in general (~1 mGal and ~10 nT, respectively), but gravity anomalies of up to ~2 mGal are associated with the mounds. Marine gravity data are often affected by ship movements or bad sea conditions, and are subject to strong low pass filtering. Therefore, over the mounds the anomalies are too small and smoothed to be of value for detailed modeling, although the total anomaly may give a good estimate of the bulk density of the mounds. Magnetic data show both very small anomalies indicating nonmagnetic bodies forming most of the mounds, and distinct but small-amplitude (~50–100 nT), short-wavelength, normal or reversed magnetic anomalies over four of the mounds (A, B, C, and D), suggesting a magnetic core or cap to the mounds (Fig. 6). ModelVision™ software was used to compute simple 2.5D or disk-shaped gravity and magnetic models. Although the bathymetry data are detailed, the gravity data are strongly filtered and sparse, and the magnetic field data are sparse with their significant, but small, anomalies falling within the limits of the mounds. Therefore, 3D modeling was not used. The models (Fig. 6) indicate that the mounds are largely low density (2.2–2.6 mg/m³). The magnetic anomalies (mounds A–D) can be fitted by magnetic cores to the mounds with magnetizations between 2.5 and 4 Am⁻¹, at the lower end for basaltic volcanic cores, or by thin (~10 m) bodies at the top or base of the central part of the mounds with magnetizations of ~12 Am⁻¹, more typical for basalt. The model in Fig. 6C (disk cap) also includes a magnetization of 0.6 Am⁻¹ for the whole of mound C as a typical figure for hyaloclastite (e.g., Dietze et al., 2011), but it has little effect on the model fitting. The disk-cap model (subaerial flows) is very similar to one where the magnetized body is a similar thin disk at the base of the mound (pillow lavas), e.g., Figure 6B, because the bodies are thin (~10 m) and at depths of ~500 m. An alternate thin disk model is a combination of the two (with each
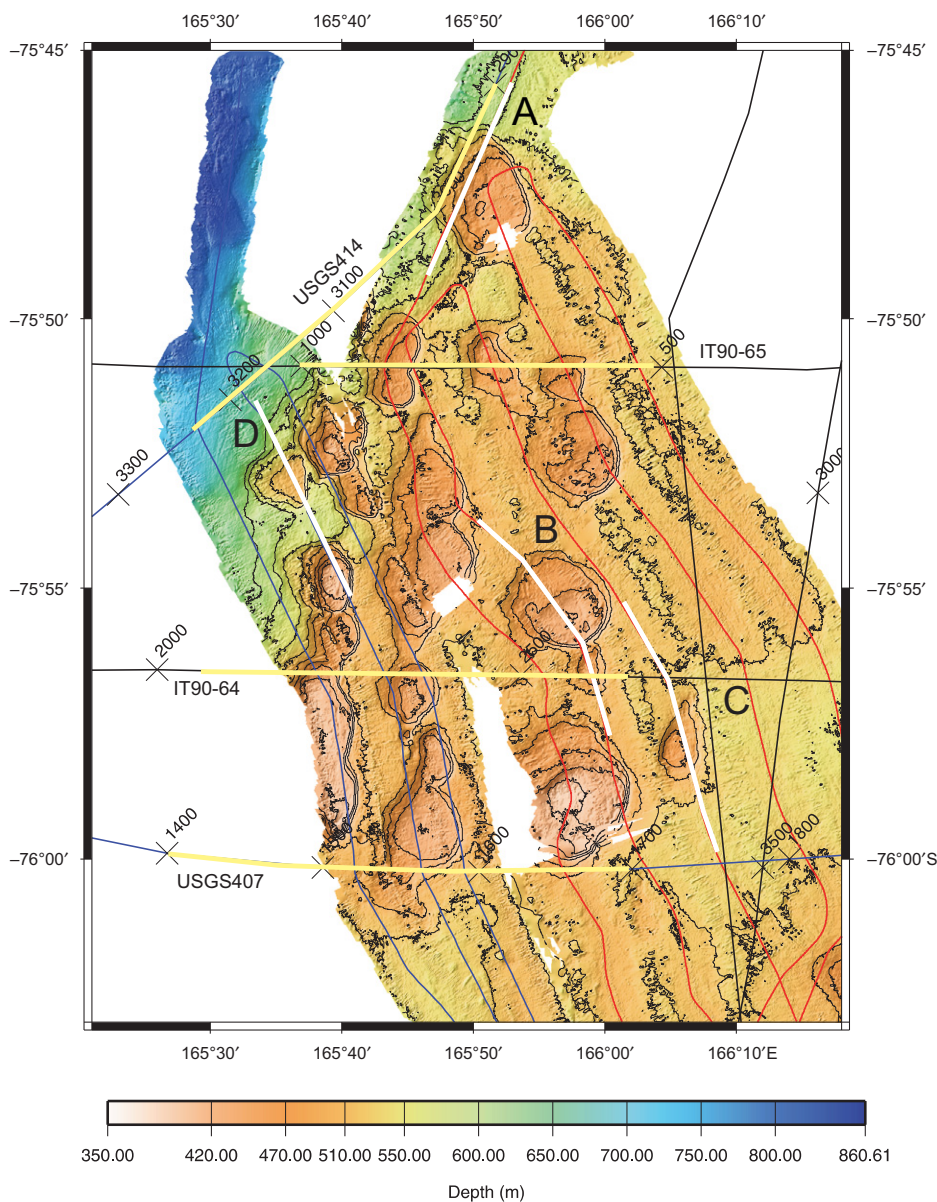
layer approximately half the thickness). It is not possible to differentiate between these models.

Although no new seismic data were recorded, existing data (Cooper et al., 1987, lines USGS407 and 414; Brancolini et al., 1995, lines IT90-64 and 65) cross the mounds field (Fig. 7). No high-resolution data are available. Little structure can be seen within a mound, although they often overlie a largely flat-lying sedimentary section (Fig. 7) with faulting with large offsets in places. An estimate of the seismic velocity for the mounds was derived from velocity "pull-up" in the underly-

ing sediments, using the reprocessed seismic data of Geletti and Busetti (2011). In most cases, velocity pull-up is difficult to measure due to the deformation by faulting. Two examples—SP 900 on line IT65 and SP2600 on line IT64—have mound height of 0.08 s two-way traveltime (twt) and 0.06 s twt, and velocity pull-up of 0.02 s twt and 0.03 s twt, respectively. Assuming an original flat-lying subsurface reflector and a seawater velocity of 1.5 km/s, seismic velocities for the mounds of 1.7 ± 0.1 km/s and 2.0 km/s ± 0.2 km/s were obtained.

Figure 3. Bathymetry of western mounds; contours 25-m intervals. Tracks: blue—*ARAON*, red—*NBP0401*. Seismic profiles (Fig. 7) are shown in light yellow and annotated with line number and shot points. Four mounds with short wavelength magnetic anomalies are labeled A–D. The location of gravity and magnetic model profiles (Fig. 6) across these mounds are shown as white lines.
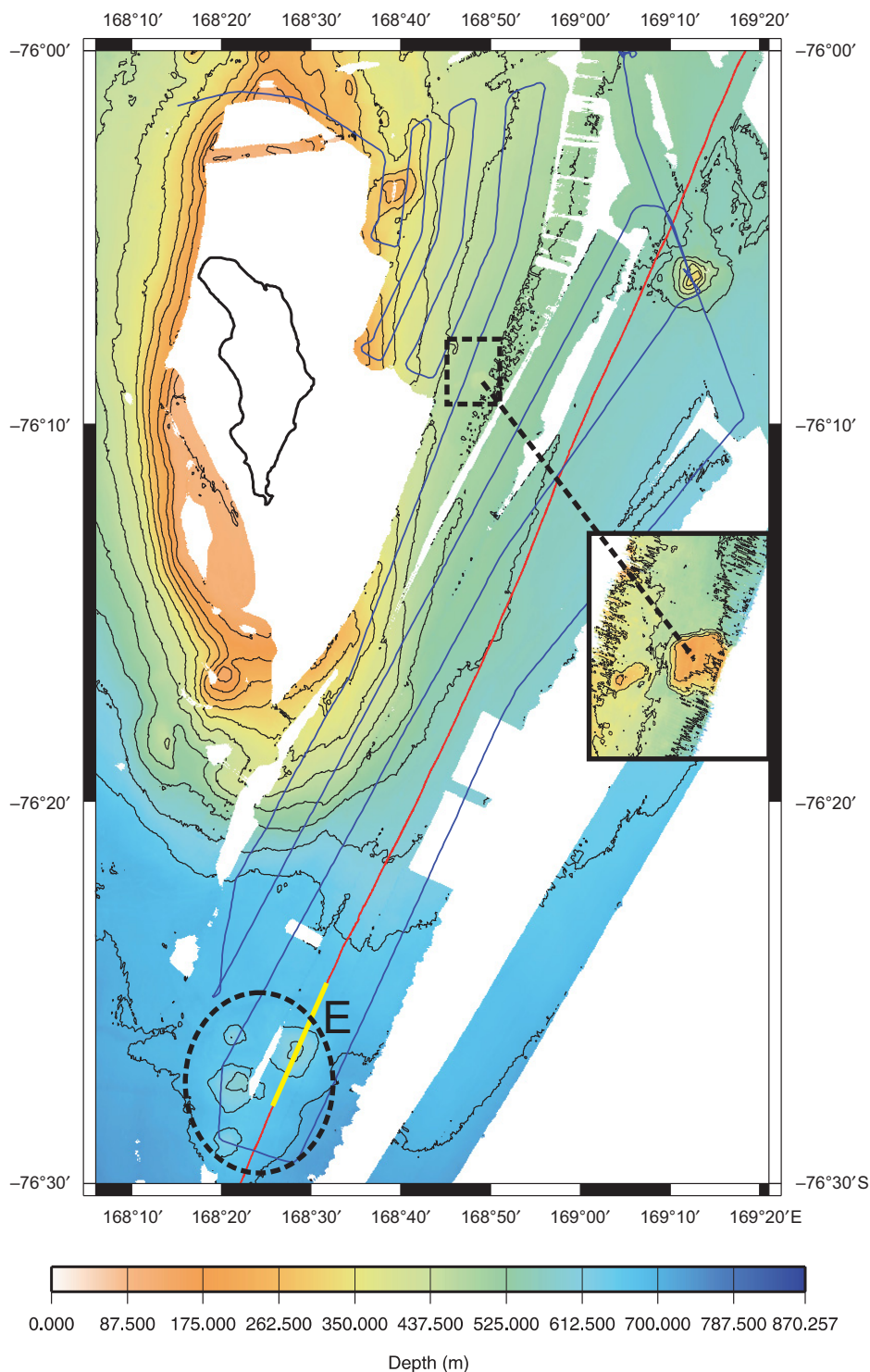
Figure 4. Bathymetry of southern mounds; contours 50-m intervals. Location is red-outlined box 2 in Figure 1. Tracks: blue—*ARAON*, red—*NBP9602*. Location of the main group of southern mounds is delineated by the black-dashed oval. Location of the gravity and magnetic profile (Fig. 6) across mound E is shown by the yellow line. Inset: small bank east of Franklin Island delineated by black-dashed line in main figure—contours 10-m intervals (420–500 m).

DATA: POCKMARKS

The pockmarks occur in two restricted fields to the west and north of Franklin Island (Fig. 5), extending across a band ~10 km wide for ~40 km northwest from Franklin Island. The pockmarks are roughly circular, average ~200–500 m in diameter, and are up to 30 m deep (Lawver et al., 2007). They are found concentrated at depths between 430 and 475 m, with a seafloor gradient on the order of 10 m per km or a nearly flat seafloor. The depth range of the pockmarks increases to the south to ~550–400 m before they disappear as the bottom morphology steepens along the western margin of Franklin Island. To the north of the detailed survey area, a smaller pockmark field was detected at ~75°35′S (Fig. 5B) with additional elongate, crosscutting depressions of similar depth extent. The latter have an elongate form similar to ones commonly found toward the continental shelf edge and are thought to be iceberg furrows (Anderson, 1999; Davey and Jacobs, 2007) or were caused by other ice erosion processes.

DISCUSSION

The flat-topped mounds form a distinct field of 15 mounds covering an area of ~30 km square along the Lee Arch, a fault-controlled, uplifted ridge forming the eastern part of the active deforming Terror Rift in the center of the Victoria Land Basin. They are circular in the east and more linear in the west where they trend approximately north-south, subparallel to the underlying faulting (Cooper et al., 1987; Brancolini et al., 1995; Hall et al., 2007, Fig. 3). The mounds are characterized by a low density and often lack any magnetic anomaly. Distinct, small magnetic anomalies occur over four of the mounds. Seismic-velocity pull-ups of underlying reflections (Fig. 7) indicate low seismic-velocity rocks (<2.5 km/s) forming the mounds, consistent with the limited gravity modeling. Two possible causes of the mounds are (1) carbonate banks such as occur in the Porcupine Seabight and flanks of the Rockall Trough (O'Reilly et al., 2003; Shannon et al., 2007) or (2) small volcanic edifices as occur elsewhere in western Ross Sea such as on the Franklin Island volcanic ridge to the east (Rilling et al., 2009) or onshore such as Shield Nunatak (Wörner and Viereck, 1987).

Carbonate edifices develop from the accumulation of shell banks as a result of seafloor currents, from the development of coral banks or occur as bioherms, ancient organic reefs of mound-like form built by a variety of marine invertebrates and often associated with seafloor vents. The Porcupine Trough and Rockall Basin
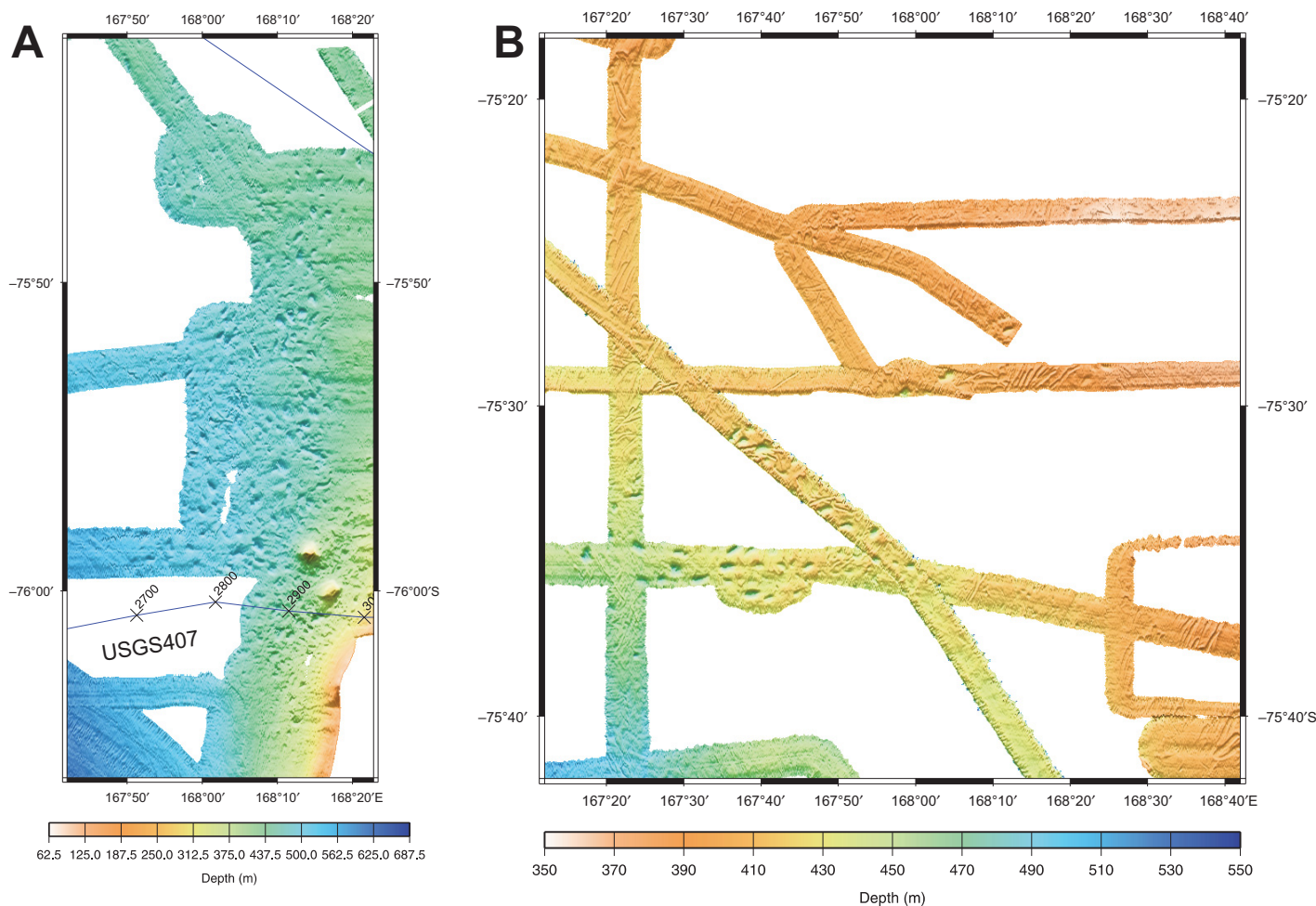
Figure 5. (A) Pockmarks and ice furrows west of Franklin Island. Location is red-outlined box 4 in Figure 1. Seismic line USGS407 (Fig. 7E) track marked with shot points annotated. (B) Pockmarks and ice furrows northwest of Franklin Island. Location is red-outlined box 3 in Figure 1.

provide good examples of carbonate banks (O'Reilly et al., 2003; Shannon et al., 2007) that occur as clusters of seafloor mounds or buried or partially buried features along the margin of the hydrocarbon containing Rockall and Porcupine basins at depths of 500–900 m. Individual mounds are more than 100 m high and up to a few kilometers in diameter, similar to the Ross Sea mounds. Their location is compatible with the possibility of fluid flow from underlying strata toward the surface (Shannon et al., 2007). The location and morphology of the Ross Sea flat-topped mounds, their low density, low seismic velocity, and their proximity to inferred subsurface gas hydrates and associated faulting and mud volcanoes (Geletti and Busetti, 2011) suggest they may be carbonate banks. However, recent drilling studies (Kano et al., 2010) found no evidence of enhanced hydrocarbon concentrations associated with carbonate mounds. Furthermore, we have been unable to find any

reports on distinct localized magnetic signatures occurring with carbonate mounds, and a higher seismic velocity than we derive may be expected for some carbonates. Magnetic susceptibility from carbonate mound cores are generally very low, with the maximum values (up to

70×10^{-5}, Kano et al., 2010; Pirlet et al., 2011) occurring in thin sedimentary layers within the mound. These would not give the distinct anomalies observed.

The main mound field lies along a major volcanic and structural trend within the Victoria

Figure 6 (*on following page*). **(A–F) Gravity and magnetic models across mounds A–D (Fig. 3), mound E (Fig. 4). Mound names are shown in white on the models. Gravity data in upper panel, magnetic data in central panel, and depth model in lower panel (upper interface is bathymetry). Solid line with crosses—observed data; plain solid line—computed anomaly; dashed line in (A) is assumed magnetic regional field. Two-and-a-half–dimensional models were used (strike length 1.5–2.0 km depending on size of mound) except for the magnetic models in Figures 6B and 6C, where a disk model was used for the magnetic base in Figure 6B and the cap in Figure 6C. Similar fits are obtained with a core through a mound or a disk at the top or base of the mound. Green body—mound; blue body—inferred magnetic cap (lava flow) or base (pillow lavas). Mm and Dm are the magnetization and density of the mound; Mc and Dc are the magnetization and density of the magnetic core (cap, core, or base). Magnetizations and densities are in Am^{-1} and $kg/m^3 \times 10^3$.**
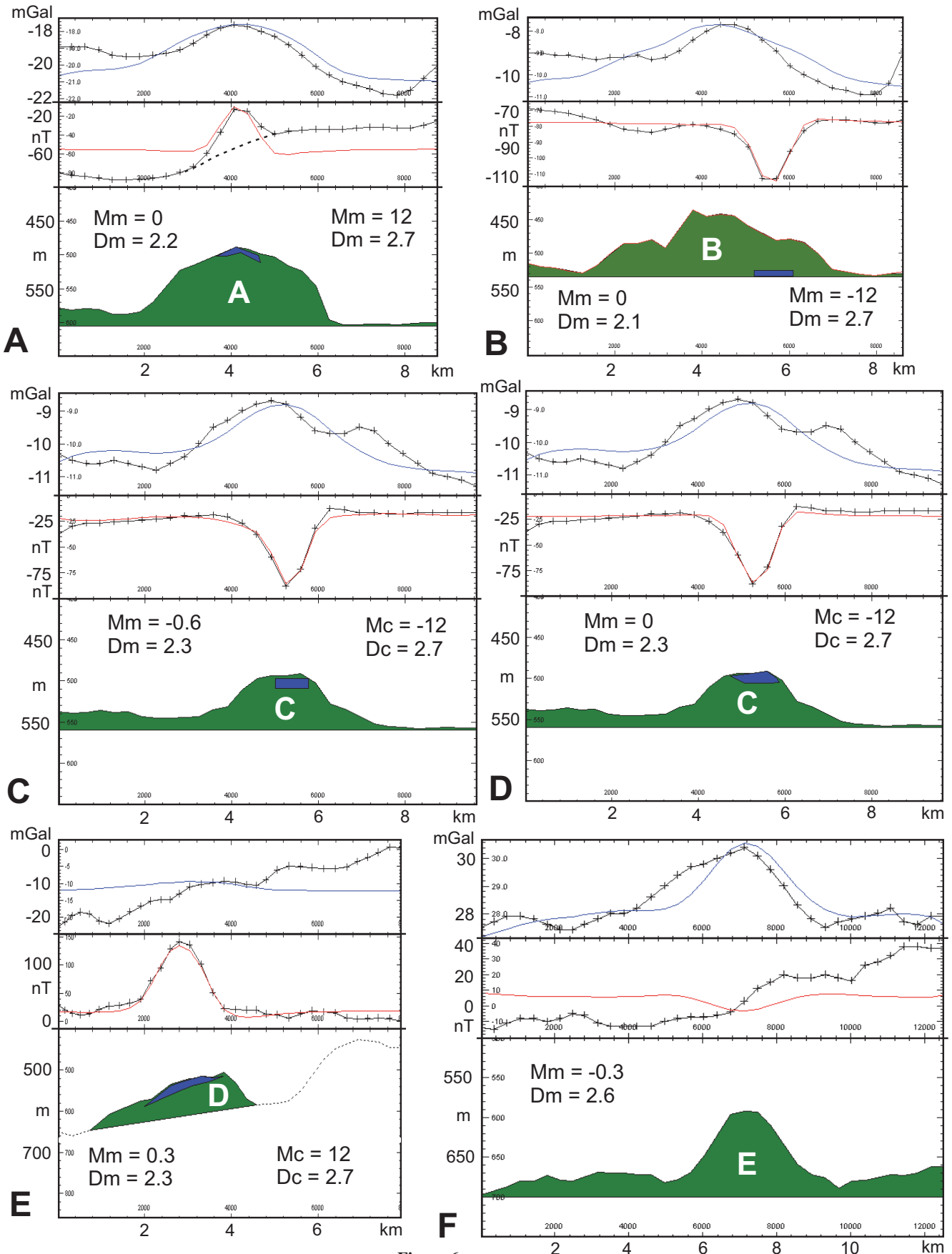
Figure 6.

Figure 7. (A–D) Seismic profiles across the western mounds (m), located by green lines in Figure 3. Profile IT90-64 (sp 2520) crosses the southern part of mound B. (E) Seismic profile across the pockmarks (p m) off Franklin Island and located on Figure 5A. Seismic data after Brancolini et al. (1995), Cooper et al. (1987), and the Scientific Committee on Antarctic Research Seismic Data Library System.
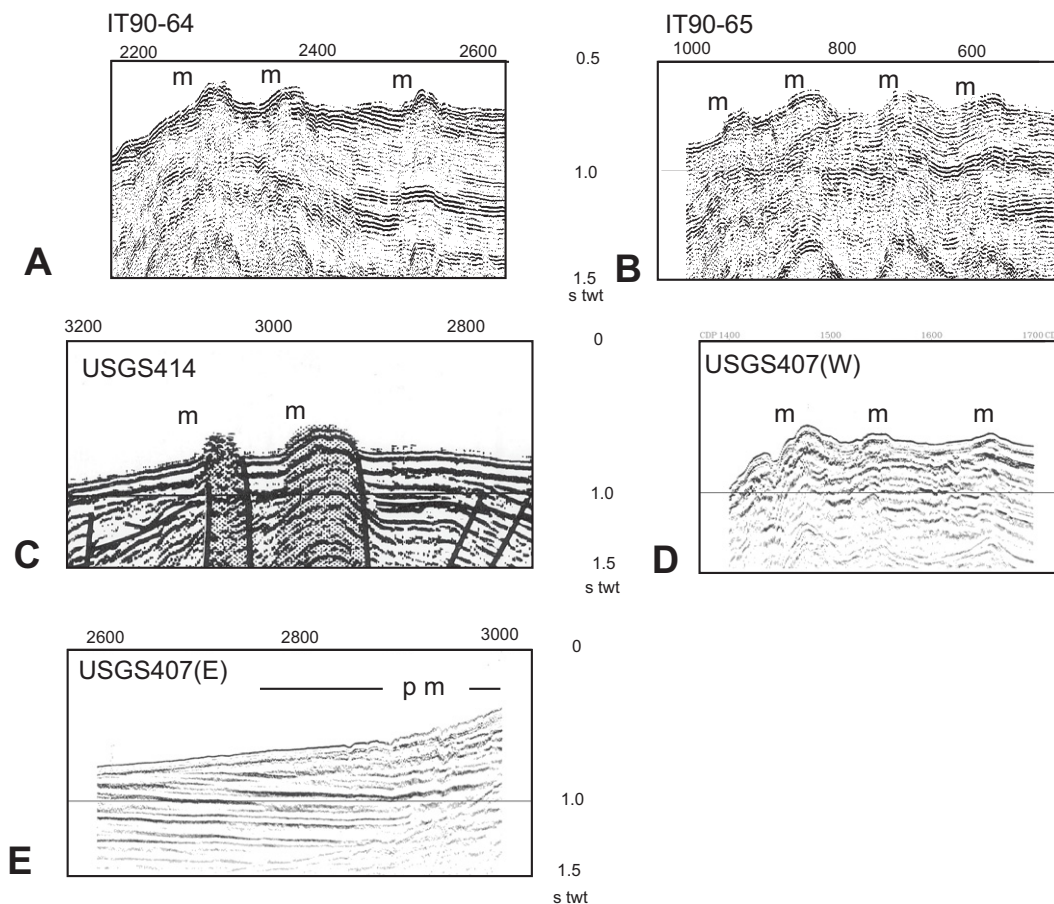
Land Basin, the Terror Rift (Cooper et al., 1987), from Ross Island to the south, to Mount Melbourne on Terra Nova Bay to the north (Fig. 1). Flat-topped mounds with similar characteristics also occur farther east, close to and southwards along the volcanic Franklin Island ridge (Fig. 4), suggesting an association with volcanism. The small, but distinct, short-wavelength magnetic anomaly modeled above, indicating both normal and reversed magnetization, suggest that they are partially of volcanic origin. The low-density, mainly low-magnetization of the rocks forming the mounds would suggest that they could have been erupted under a grounded ice sheet as hyaloclastite edifices similar to Iceland (Jones, 1969; Schopka et al., 2006; Dietze et al., 2011), as has been proposed by Lawver et al. (2007) on the basis of morphology. Jones (1969) identifies four stages to the development of a subice hyaloclastic mound: (1) basal layer of pillow lavas erupted under high confining pressure; (2) an overlying layer where the pressure of the water and ice is reduced, allowing explosive fragmentation and a tephra and/or hyaloclastic cone to develop; (3) if the eruption continues and melts through the ice, effusive subaerial activity may produce a lava cap; and (4) the

lava cap can grow in size and build a hyaloclastic delta or foreset breccia. Where a lava cap is produced, it protects the underlying hyaloclastite to form a tuya with a particular form of steep sides and flat top formed by the protective lava cap. A good example in the region is Shield Nunatak, a small (300 m high, ~2 km diameter) subglacially erupted parasitic cone on the south flank of the active Mount Melbourne that consists mainly of hyaloclastic and clastics overlain by thin subaerial lavas and other volcanics (Wörner and Viereck, 1987); however, no pillow lavas occur at its base. This subice process was well documented by Gudmundsson et al. (1997), who observed the evolution of a subice volcano that penetrated the overlying ice but where the subaerial exposed section was restricted to ~300 m in diameter as ice flowed toward the hole. The short-wavelength magnetic anomaly models over some of the mounds are consistent with a lava cap, a base pile of pillow lavas, or a combination of the two. The bulk of the mounds would be formed of hyaloclastites, which can have very low densities ($1.8–2.4 \times 10^3$ kg/m³) and magnetizations (Le Masurier, 2002; Schopka et al., 2006; Caratori Tontini et al., 2010).

The short-wavelength magnetic anomalies document a restricted extent to the magnetic rocks on some mounds and their modeling by a thin cap or base layer with magnetizations appropriate for basalts would fit well with a tuya origin, and is the critical factor supporting the volcanic model. Although hyaloclastites can form under ice as thick as 500–750 m (Gudmundsson et al., 1997), the volcanic edifice needs to break through the ice cover to form a cap of lava flows. There is a distinct lack of constraints to unequivocally define when and how volcanism occurred. The persistence of a mound of relatively unconsolidated volcanogenic rocks on the seafloor indicates a young age because multiple grounded ice-sheet movements across the continental shelf during the Pleistocene would tend to erode the features. During a major ice-sheet advance toward the continental margin, when sea level would have been lower by ~150 m, the top of the mounds would have still been at 300 m bsl and under a significant thickness of ice. This suggests that the model of a pillow-lava base layer is appropriate because there is no evidence of significant vertical tectonics over the past 1 Ma in the region. The normal and reversed magnetization

suggests the mounds may have been emplaced around one of the last geomagnetic reversals (0.78 Ma or 1.81 Ma), consistent with ages of the younger small volcanic edifices on the Franklin Island ridge (Rilling et al., 2009) and in the Mount Melbourne volcanic field to the northwest (Wörner and Viereck, 1987). In view of the magnetic anomaly data, we prefer the model of eruption of hyaloclastic edifices under an expanded West Antarctic ice sheet ~800 ka ago. If our interpretation is correct, the volcanic mounds were formed under quite different conditions to other small volcanic centers found on the Ross Sea shelf. The volcanic centers reported by Rilling et al. (2009) near Franklin Island and those off Cape Adare in northwestern Ross Sea (Panter and Castillo, 2007) are conical basaltic edifices on the seafloor, with associated magnetic anomalies up to 300 nT. The mounds lie at a similar depth, and Wörner and Viereck (1987) note that, although fragmentation in volatile-rich basalts can occur at greater depths, massive hyaloclastic deposits are largely formed at water depths less than 300 m. However, Gudmundsson et al. (1997) observe that hyaloclastites can form under up to 700 m of ice and this indicates that the mounds could have formed under a grounded ice sheet. This interpretation would restrict their age of formation to the time when grounded ice sheets traveled toward the continental shelf edge. The concentration of mounds in a small region appears to be associated with tectonic movements at the offset (accommodation zone) and change in trend of the Terror Rift (Salvini et al., 1997) that allowed magma to rise along the high-angle, normal faulting occurring there (Hall et al., 2007). This occurred during an ice-sheet advance when grounded ice lay over the region up to 700 m thick (Denton and Hughes, 2000), a thickness similar to the ice thickness just inboard of the grounding line of the present West Antarctic ice sheet (Drewry, 1983).

Pockmarks have often been interpreted to indicate the release of subsurface gas (e.g., King and Maclean, 1970) associated with the presence of hydrates (e.g., Judd and Hovland, 2007). Geletti and Busetti (2011) indicate the presence of subsurface gas (gas hydrates) in the western Victoria Land Basin, which, if extending farther east, may provide a source for pockmarks off Franklin Island, although their study area lies well to the west of them. The spatial relationship of the mounds and underlying gas hydrates to the pockmarks is also unclear because the pockmarks lie along the western margin of the Franklin Island volcanic ridge, several tens of kilometers from the mounds. Seismic data across the pockmarks show a flat-lying sedimentary sequence that progressively crops out at the seafloor as water depth

increases (Fig. 7E, profile USGS407). The close association with the Franklin Island ridge suggests that heat from the volcanism has enhanced thermogenic processes and gas propagated along sedimentary layers until they outcrop at the seafloor. The western limit of the pockmark field may be constrained by water depth and pressure. We consider that the linear and sinuous depressions of similar depths and widths in the region have a different origin and result from seafloor erosion by glacial processes as documented by Anderson (1999) and Davey and Jacobs (2007).

CONCLUSIONS

Multibeam bathymetry data have delineated a field of unusual flat-topped seafloor mounds located ~50 km west of Franklin Island in the western Ross Sea. The total field covers an area about 30 km square and lies at a depth of ~500 m. The mounds lie over the Lee Arch, the more recently active rifting part of the Victoria Land Basin, where the arch and associated faulting undergoes a westward offset from north to south that has been interpreted as an accommodation zone by Salvini et al. (1997). The mounds have a northerly trend and tend to be circular in the east and linear in the west. The mounds are up to 4 km in diameter and 100 m high, but some appear to be coalesced features. The mounds have a steepest slope to the southeast, and shallowest slope to the northwest, consistent with formation within a northwest-moving ice sheet or erosion by northwest ice sheet movement. Four similar features were delineated ~25 km to the south of Franklin Island at a depth of 650 m, and one 5 km east of Franklin Island at a depth of ~400 m. Seismic, gravity, and magnetic data indicate that the mounds are largely low-density, nonmagnetic bodies overlying a largely nondisrupted sedimentary section. Some mounds, however, have an associated small (~50–100 nT), short-wavelength, normal or reversed magnetic anomaly, suggesting a magnetic core or cap to the mounds. Their morphology and proximity to inferred subsurface gas hydrates and associated mud volcanoes and pockmarks also suggest they may partially be carbonate banks, although because they occur close to a major volcanic bank and similar mounds are found along the volcanic Franklin Island ridge, carbonate bank formation may not be involved. The short-wavelength magnetic anomalies guide our preferred interpretation that they are of volcanic origin, erupted under a grounded ice sheet forming hyaloclastite edifices often with a thin basaltic layer at base or top, and are the result of an unusual occurrence of volcanicity, a geomagnetic reversal, and major ice-sheet advance at the same time.

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