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Irina Borissova, Millard F. Coffin, Philippe Charvis, Stéphane Operto

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Structure and development of a microcontinent: Elan Bank in the southern Indian Ocean

Irina Borissova
Geoscience Australia, GPO Box 378, Canberra, ACT 2601, Australia (Irina.Borissova@ga.gov.au)

Millard F. Coffin
Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, 4412 Spicewood Springs Road, Building 600, Austin, Texas 78759-8500, USA

Now at Ocean Research Institute, University of Tokyo, 1-15-1 Minamidai, Nakano-ku, Tokyo 164-8639, Japan (mcoffin@ori.u-tokyo.ac.jp)

Philippe Charvis
UMR Géosciences Azur, Institut de Recherche pour le Développement, Observatoire Océanologique de Villefranche, B.P.48, 2 Quai de la Darse, 06235 Villefranche-sur-mer, Cédex, France (charvis@obs-vlfr.fr)

Stéphane Operto
UMR Géosciences Azur, Centre National de la Recherche Scientifique, Observatoire Océanologique de Villefranche, B.P.48, 2 Quai de la Darse, 06235 Villefranche-sur-mer, Cédex, France (operto@obs-vlfr.fr)

[1] Microcontinents appear to commonly form on young continental margins close to hot spots, but difficulties in understanding their geology and evolution have inhibited assessment of their global distribution and significance. Thick volcanic accumulations in areas affected by hot spot magmatism only complicate the issue. Elan Bank, a large western salient of the Kerguelen Plateau, is a microcontinent that originally lay between India and Antarctica in Gondwana. Recent regional plate tectonic reconstructions suggest that during Gondwana breakup, Elan Bank and India initially separated from Antarctica, and Elan Bank became isolated in the Southern Ocean via a ridge jump to the north between Elan Bank and India. In Albian time (~108 Ma), voluminous magmatism attributed to the Kerguelen hot spot overprinted and radically altered the original microcontinent and its surroundings. Recent ODP investigations, deep seismic reflection data, and a wide-angle seismic line on Elan Bank allow us to gain the first insight into the feature's integrated crustal structure and geological evolution and the adjacent continent-ocean transition zone. Our analysis shows that Elan Bank's crust is at least 16 km thick. The upper igneous crust consists of a 2–3 km thick layer with seismic velocities ranging from 4.4 to 5.9 km/s that can be interpreted as the result of accumulation of lava flows originating from the Kerguelen hot spot. Seismic velocities at the base of the crust are as low as 6.6 km/s, which is consistent with a fragment of thinned continental crust ~14 km thick. A high velocity body, located at depths of 5 to 10 km, could be interpreted as plutonic rocks emplaced during the major regional magmatic episode. On the basis of deep seismic reflection data, we interpret extensional structures beneath the volcanic flows. In Albian time, when the area was affected by the Kerguelen hot spot, volcaniclastic material and lava flows accumulated in faulted grabens and basins both on the bank and within the continent-ocean transition zone to the south, creating the appearance of flat, unstructured basement. The seismic structure and inferred composition of Elan Bank revealed by this study contribute to our understanding of microcontinent formation as well as provide a template for identifying microcontinents in accreted terranes and mountain belts.

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1. Introduction

[2] Microcontinents are found in every major ocean basin [e.g., *Nur and Ben-Avraham*, 1982], where they preserve histories of continental fragmentation and provide insight into unravelling convergent margin, continental suture, and accretionary mountain belt geology. Recent geological and geochemical evidence arising from Ocean Drilling Program (ODP) Leg 183 Site 1137 has revealed that Elan Bank in the Southern Ocean is a microcontinent [*Coffin et al.*, 2000; *Frey et al.*, 2000; *Nicolaysen et al.*, 2001; *Weis et al.*, 2001; *Frey et al.*, 2003]. Elan Bank is located in the central-eastern Enderby Basin about 900 km north of the Antarctic margin, and encompasses ~140,000 km^2 of seafloor between 1000 and 3500 m water depth (Figure 1). It extends west from the central Kerguelen Plateau and is asymmetric in shape, with a steep slope facing south and a fairly gentle slope facing north.

[3] Continental breakup between India and Antarctica, and Early Cretaceous seafloor spreading in the Enderby Basin has not been well understood due to a lack of well-defined marine magnetic anomalies and fracture zones [*Coffin et al.*, 2002; *Kent et al.*, 2002; *Gaina et al.*, 2003]. Recently proposed magnetic anomalies in the Enderby basin [*Gaina et al.*, 2003] suggest that India and Antarctica broke up in Early Cretaceous time (Hauterivian, ~130 Ma; timescale of *Gradstein et al.* [1994], used throughout), about 10 million years prior to the onset of massive magmatism associated with the Kerguelen hot spot. At the time of breakup, Elan Bank belonged to the Indian plate [*Kent et al.*, 2002; *Gaina et al.*, 2003], but a ridge jump after M2 time (~124 Ma) transferred it to the Antarctic plate (Figure 2).

[4] In this paper we describe, for the first time, the structure and development of the Elan Bank microcontinent, on the basis of seismic and drilling results, in the context of the early opening of the Indian Ocean and Kerguelen flood volcanism.

2. Data and Methods

[5] Both wide-angle seismic and multichannel seismic reflection (MCS) data were acquired over Elan Bank in the 1990s. A wide-angle line (Figure 3) was acquired during M/V *Marion Dufresne* cruise 66 in 1991 [*Operto and Charvis*, 1996]. The seismic source was an untuned array of eight, 16 liter airguns fired every 100 s (180 m). The receivers consisted of five three-component digital ocean bottom seismometers (OBS) [*Nakamura et al.*, 1987] evenly spaced along the 140 km long shooting line (Figure 3). A detailed description of data acquisition is provided in *Operto and Charvis* [1996]. The wide-angle data were processed using a zero-phase Butterworth band-pass filter between 5 and 15 Hz. Predictive spectral deconvolution was applied afterward to improve picking of secondary arrivals.

[6] MCS lines (Figures 1 and 3), including one coincident with the wide-angle line, were acquired aboard R/V *Rig Seismic* survey 179 in 1997 [*Borissova et al.*, 2002]. The seismic source was a tuned array of either 20 (lines 4, 5, 6, and 7) or 10 (lines 2, 3) sleeve guns totalling 49.2 or 24.6 l,

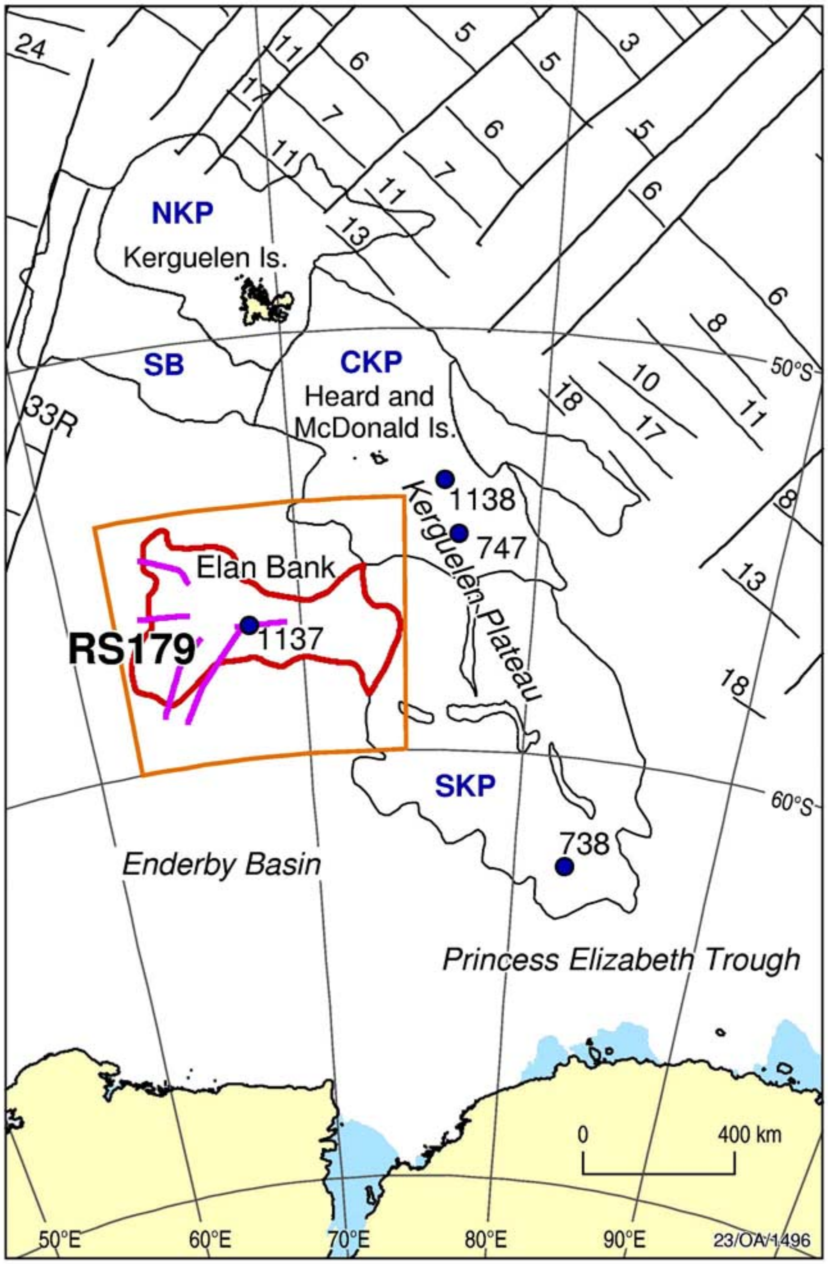

Figure 1. Location of Elan Bank (delineated in red) in the Indian Ocean, including MCS coverage (RS179, pink lines) and ODP Site 1137. Magnetic lineations after *Cande et al.* [1989]. SB, Skiff Bank; NKP, Northern Kerguelen Plateau; CKP, Central Kerguelen Plateau; SKP, Southern Kerguelen Plateau. The study area (Figure 3) is outlined in orange. Blue areas off Antarctic coast indicate permanent ice.

respectively, fired every ~20 s. The receiver was a 3000 m, 240 channel digital streamer, and the record length is 14–16 s. The MCS data were processed through FX migration.

[7] Information on the stratigraphy of Elan Bank is derived from ODP Site 1137, which is located on a basement high in the central part of the bank. The coincident wide-angle and MCS profile (Line 6) transects the drill site (Figure 3).

[8] The hole penetrated igneous basement consisting mainly of brecciated and massive basalts dated at 107.7 Ma [*Duncan*, 2002]. Basement is overlain by Campanian glauconitic sandy packstone, and nannofossil pelagic oozes of Late

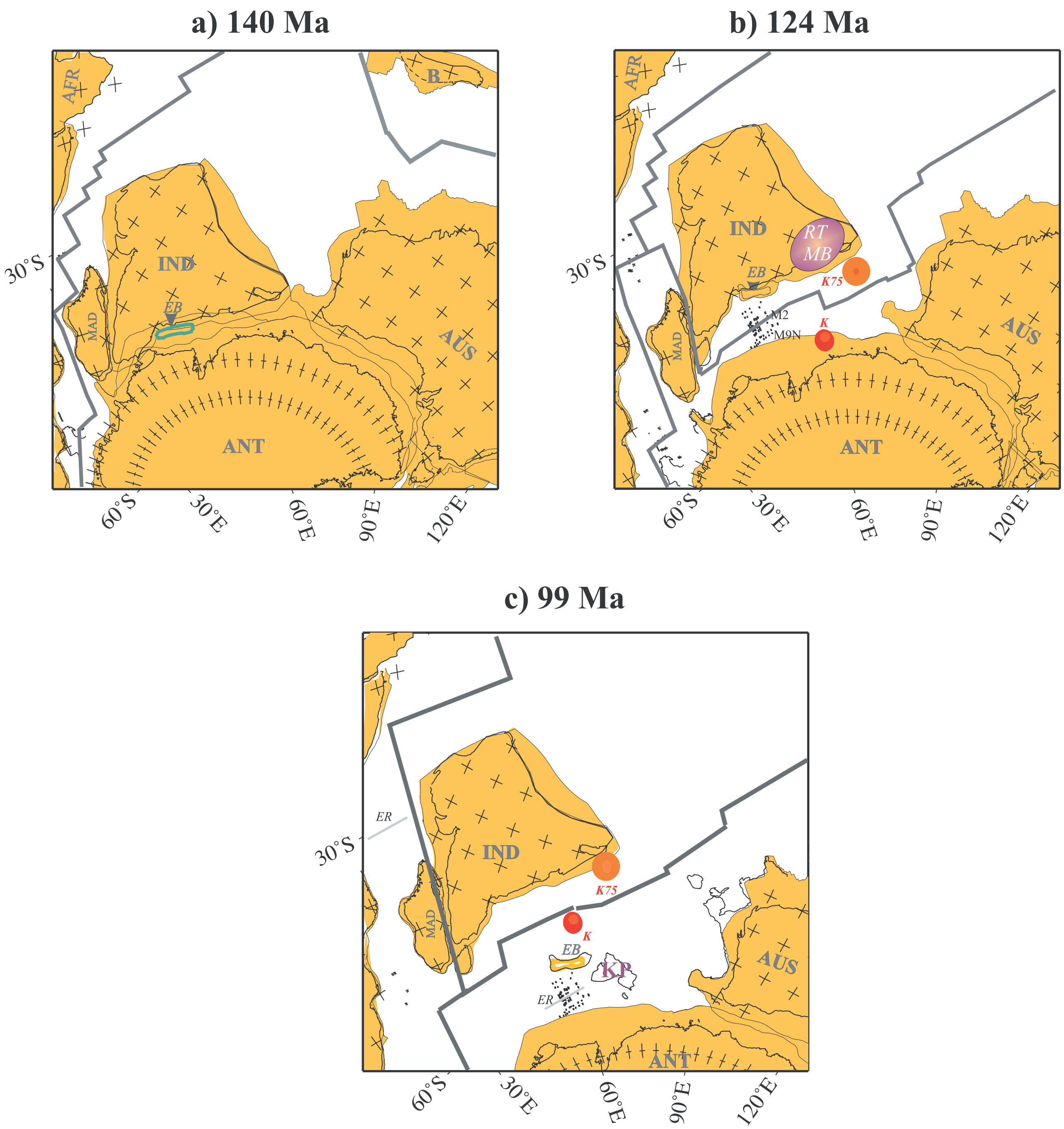

Figure 2. Plate reconstructions of the southern Indian Ocean region after *Gaina et al.* [2003]. AFR, Africa; ANT, Antarctica; AUS, Australia; B, Burma; EB, Elan Bank; KP, Kerguelen Plateau; MAD, Madagascar; RT/MB, Rajmahal Traps and Mahanadi Basin; K, Kerguelen hot spot; K75, Kerguelen hot spot position at 75 Ma; ER, extinct spreading ridge; black dots indicate magnetic anomaly picks, with M9N (~130 Ma) and M2 (~124 Ma) labeled.

Eocene to Pleistocene age (Figure 4). Volcaniclastic conglomerate recovered within the upper part of the basement complex (Figure 4) contains clasts of garnet-biotite gneiss [*Nicolaysen et al.*, 2001]. The conglomerate is interpreted to have a local source, and to have been deposited in a braided river environment [*Coffin et al.*, 2000; *Frey et al.*, 2000]. Dates of zircons and monazites in individual clasts range from 534 to 2547 Ma, whereas biotite grains yield ages of ~550 Ma

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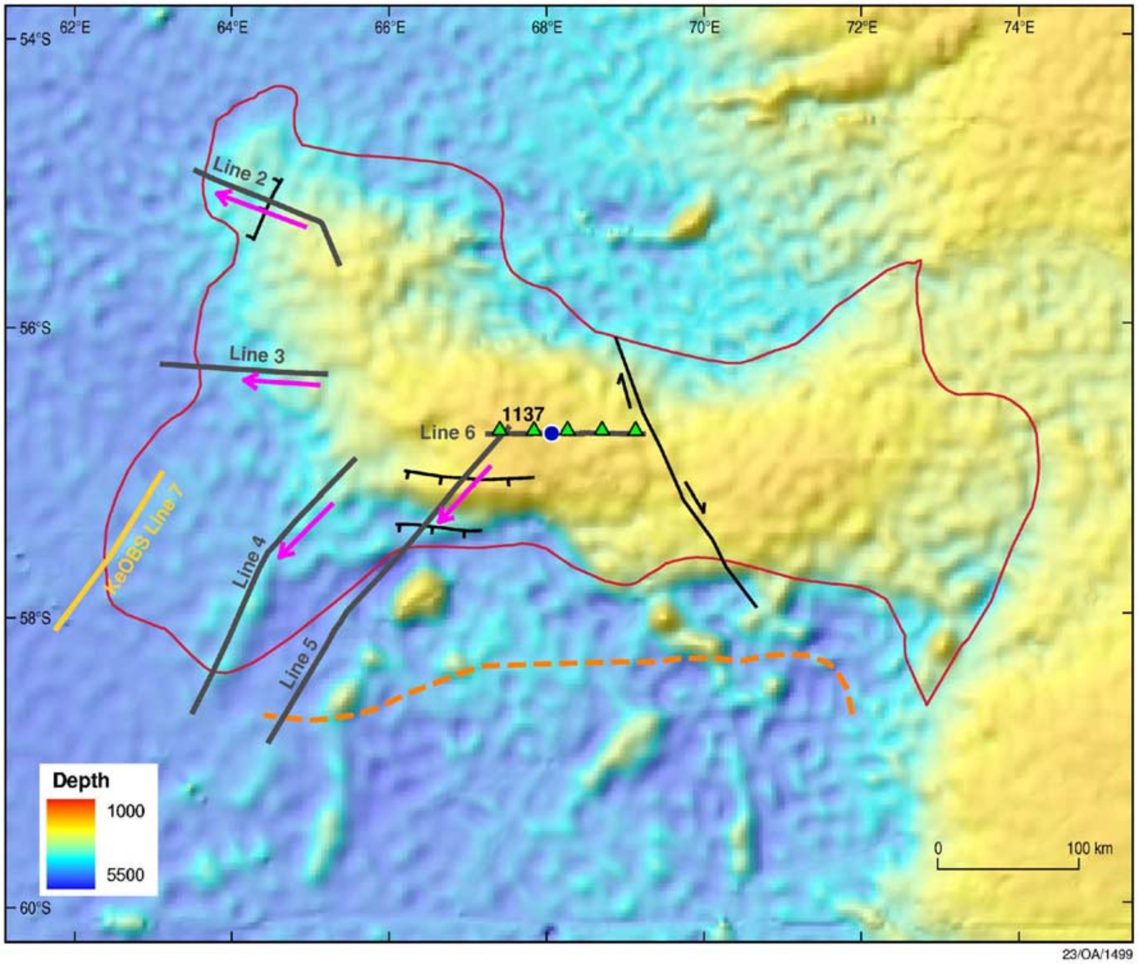


Figure 3. Predicted bathymetry [*Smith et al.*, 1997] of Elan Bank showing distribution of seaward dipping reflection complexes (SDRs, pink arrows), major faults, and possible southern limit of continent-ocean transitional zone mapped from the seismic data (dashed orange line). Also shown Geoscience Australia survey lines (GA survey 179), ODP Site 1137, OBS stations (green triangles), and KeOBS Line 7 (yellow line [*Charvis and Operto*, 1999]).

[*Nicolaysen et al.*, 2001]. The predominantly Cambrian dates are similar to the age of gneissic terranes in northeastern India, southwestern Australia, and East Antarctica [*Nicolaysen et al.*, 2001].

3. Wide-Angle Seismic Results

[9] Wide-angle seismic sections recorded along Line 6 (Figure 3) exhibit clear arrivals up to offsets of 120 km (Figure 5). The crustal velocity model is based on simultaneous inversion of travel times of seismic arrivals interpreted from all five record sections [*Zelt and Smith*, 1992]. For the sedimentary layer, we calculated a velocity of 2.10 km/s from OBS 1 and 2 arrivals (P1, Table 1 and Figure 5). As we observed no other refracted arrivals from the sediment layer, we used 2.10 km/s as a constant velocity for the sediment along the profile. Phase P2 (Table 1 and Figure 5) appears clearly on all record sections with an apparent velocity of ~5 km/s. We assume that this phase is refracted in the upper igneous crust, where velocities vary from 4.4–4.9 km/s at the top to 5.2–5.9 at the base. A clear reflection underlies this 3 km thick layer on OBS record sections 1 and 2 (Pr2, Figure 5).

[10] We interpret Phase P3 (Table 1 and Figure 5) as a refracted arrival from the lower crust. Inversion of travel times produces strong lateral velocity variations in this layer. From 0–70 km and 120–140 km, seismic velocities range from 6.0 at the top to 6.7 km/s at the base of the layer, whereas

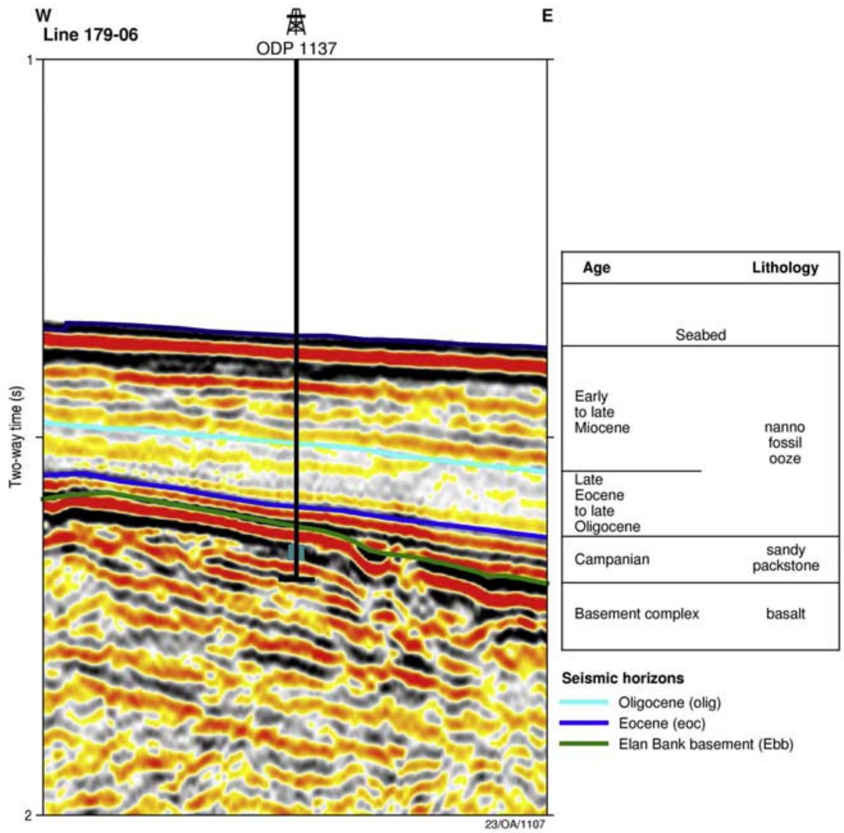
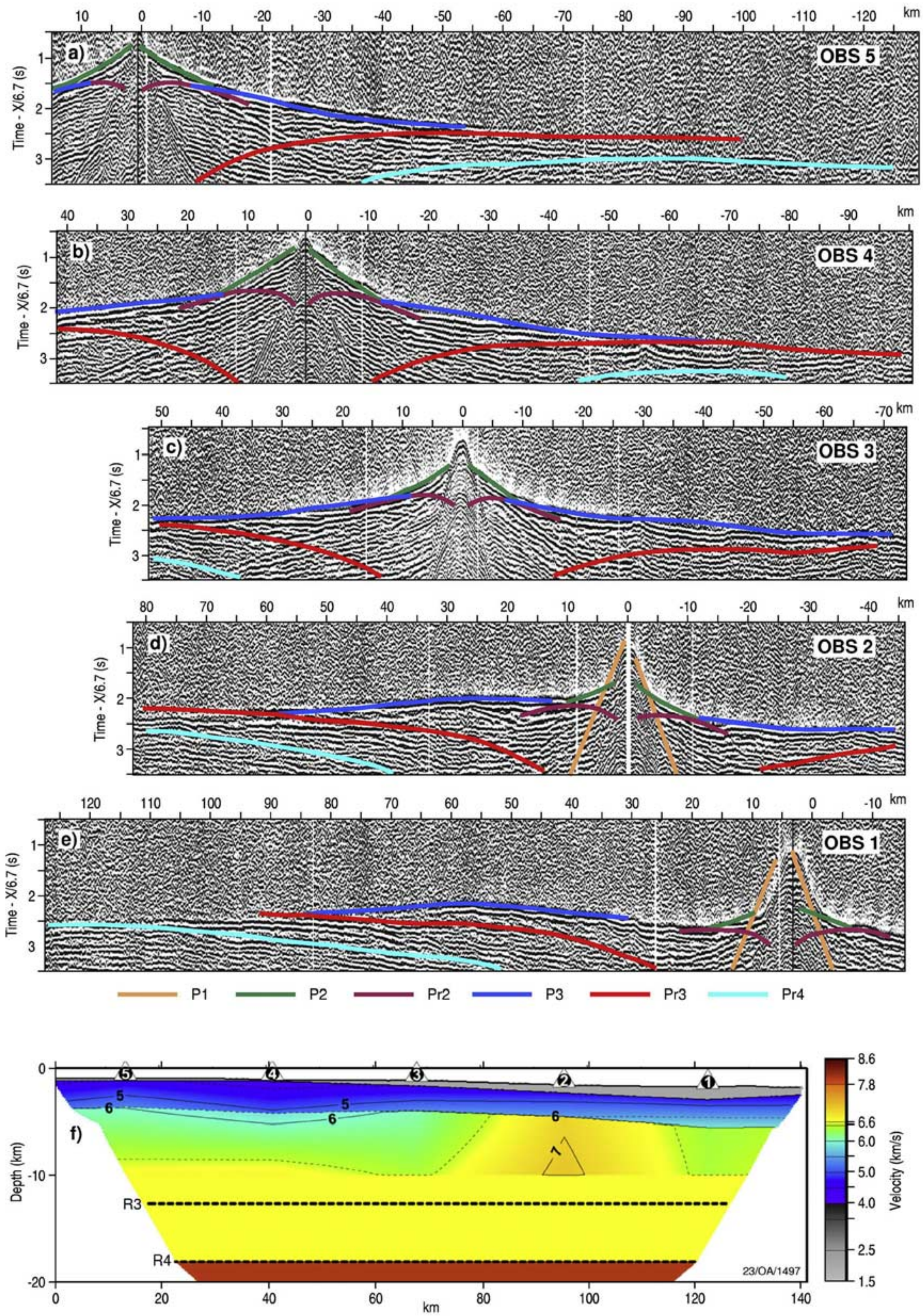


Figure 4. Detail of MCS data at ODP Site 1137 and correlation with seismic horizons mapped on Survey 179 lines (Figures 7 and 8). Location of the unit containing volcaniclastic conglomerates is shown by a blue segment.

from 70–120 km, seismic velocities reach 6.9 km/s at the top of the layer. This high velocity body is required to achieve the fit of P3 phases from record sections 1 to 3 (Figures 5c–5e), but its geometry is only poorly constrained on account of the 25–km spacing between instruments. We observe at least two major wide-angle reflections on most record sections at offsets >40 km (Pr3 and Pr4, Figure 5). At large offsets, post-critical reflections tend to be linear, with a slope consistent with an apparent velocity of <6.7 km/s. We tested various values, ranging from 6.1 to 7.2 km/s, for the velocity of the lower crust. We calculated the depth to the deep reflections for each velocity value, keeping the uppermost part of the model constant (Figure 6). The best fit is achieved for velocities of 6.1 to 6.7 km/s at the base of the crust (~0.1 s of RMS misfit), but the quantity of data used, for which a ray was successfully traced, decreases sharply for velocities <6.6 km/s. As explained by *Zelt and Smith* [1992], a final model must be rejected if it is not possible to trace rays to most observation points as it will not account for some of the observed seismic phases. This test supports a seismic velocity between 6.6 and 6.7 km/s at the base of the crust. In the best fitting velocity model, the two reflections labeled R3 and R4 are at 12.5 and 18 km depth, respectively, employing a con-

Figure 5. (opposite) (a–e) OBS record sections along line 6 (see Figure 3 for location). Travel times calculated in the best-fitting model for different phases are shown for comparison. (f) Best-fitting velocity model along line 6 from 2-D inversion of travel times. Velocities are color-coded and the velocity contour interval is 0.5 km/s; (g) Comparison of seismic velocities determined in the lower crust beneath Elan Bank (Elan B., this study), the northern Kerguelen Plateau (NKP [*Charvis et al.*, 1995]), the Southern Kerguelen Plateau (SKP [*Operto and Charvis*, 1995, 1996]) together with the average velocities versus depth for continental crust (C.C. [*Christensen and Mooney*, 1995]).


a)
OBS 5
b)
OBS 4
c)
OBS 3
d)
OBS 2
e)
OBS 1
Time - X/6.7 (s)
km
P1
P2
Pr2
P3
Pr3
Pr4
f)
Depth (km)
R3
R4
23/OA/1497
Velocity (km/s)
km

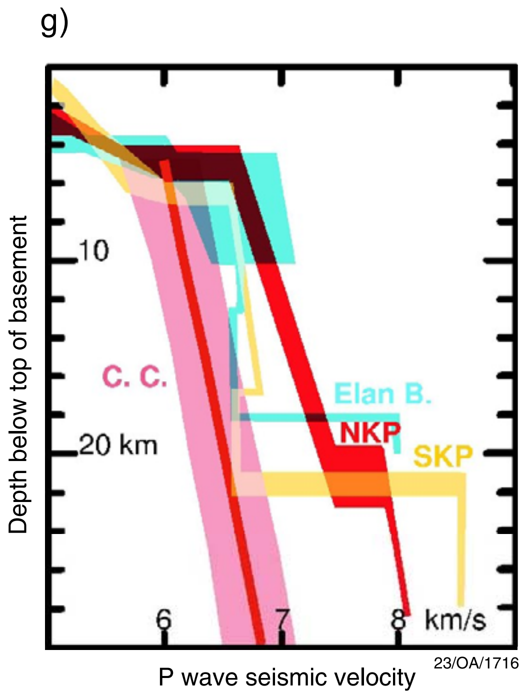


Figure 5. (continued)

stant velocity of 6.65 km/s in the lowermost crust. Reflector R4 is likely to be the Moho, despite the fact that we observe no refraction arrivals from the upper mantle.

[11] The 3 km thick upper igneous crust of Elan Bank, and of the nearby Enderby Basin [*Charvis and Operto*, 1999] closely resembles that of the Southern, Central, and Northern Kerguelen Plateau, where it is up to 6 km thick [*Charvis et al.*, 1995; *Schaming and Rotstein*, 1990; *Operto and Charvis*, 1995, 1996] (Figure 5g). This ubiquitous layer has been drilled, and consists of originally subaerial basaltic lava flows [e.g., *Coffin et al.*, 2000; *Frey et al.*, 2000].

[12] The 14 km thick lower crust, with velocities as low as 6.6 km/s at ~18 km depth, is not consistent with oceanic plateaus for which lower crust is characterized by high velocity material [e.g., *Coffin and Eldholm*, 1994]. Velocities in the lower crust reach 7.2–7.4 km/s beneath the Northern Kerguelen Plateau [*Charvis et al.*, 1995] and in the Enderby Basin [*Charvis and Operto*, 1999]. In contrast, a similar crustal structure, with a low-velocity lower crust (6.7 km/s), in the Raggatt Basin (Southern Kerguelen Plateau) has been interpreted as thinned lower continental crust [*Operto and Charvis*, 1995, 1996]. Comparison of average velocities versus depth in lower continental crust [*Christensen and Mooney*, 1995] with velocities modeled in the lower crust beneath Elan Bank and the Raggatt Basin as well clearly support a continental origin for the lower crust of both features (Figure 5g). The high velocity body beneath OBS 2 may be related to the emplacement of the volcanic carapace of Elan Bank. Transiting magmas partially crystallized during ascent, leaving high-density plutonic bodies within the crust. We propose that the high-velocity anomaly inferred from wide-angle data denotes high-density bodies associated with the extensive magmatism affecting the area.

4. Multichannel Seismic Reflection Results

[13] The five MCS lines (Figures 1, 3, and 7) show sedimentary cover of <1 s two-way time (twt) on Elan Bank. Seismic sequences extrapolated from ODP Site 1137 include a Tertiary to Pleistocene succession 0.5–0.8 s twt thick with medium amplitude, generally continuous reflections, and a Cretaceous sequence 0.1 s twt thick characterized by continuous bright reflections. The most promi-

Table 1. Seismic Phases Used for 2-D Inversion of Travel Times

Phases	P1	P2	Pr2	P3	Pr3	Pr4
Description	refracted in sedimentary cover	refracted in upper igneous crust	reflected from base of upper igneous crust	refracted in lower igneous crust	reflected from deep crust	reflected from base of crust (?)
Data used	22	165	165	360	228	228
RMS misfit	0.030	0.048	0.048	0.054	0.103	0.103
X^2	0.369	0.806	0.806	0.604	0.811	0.811

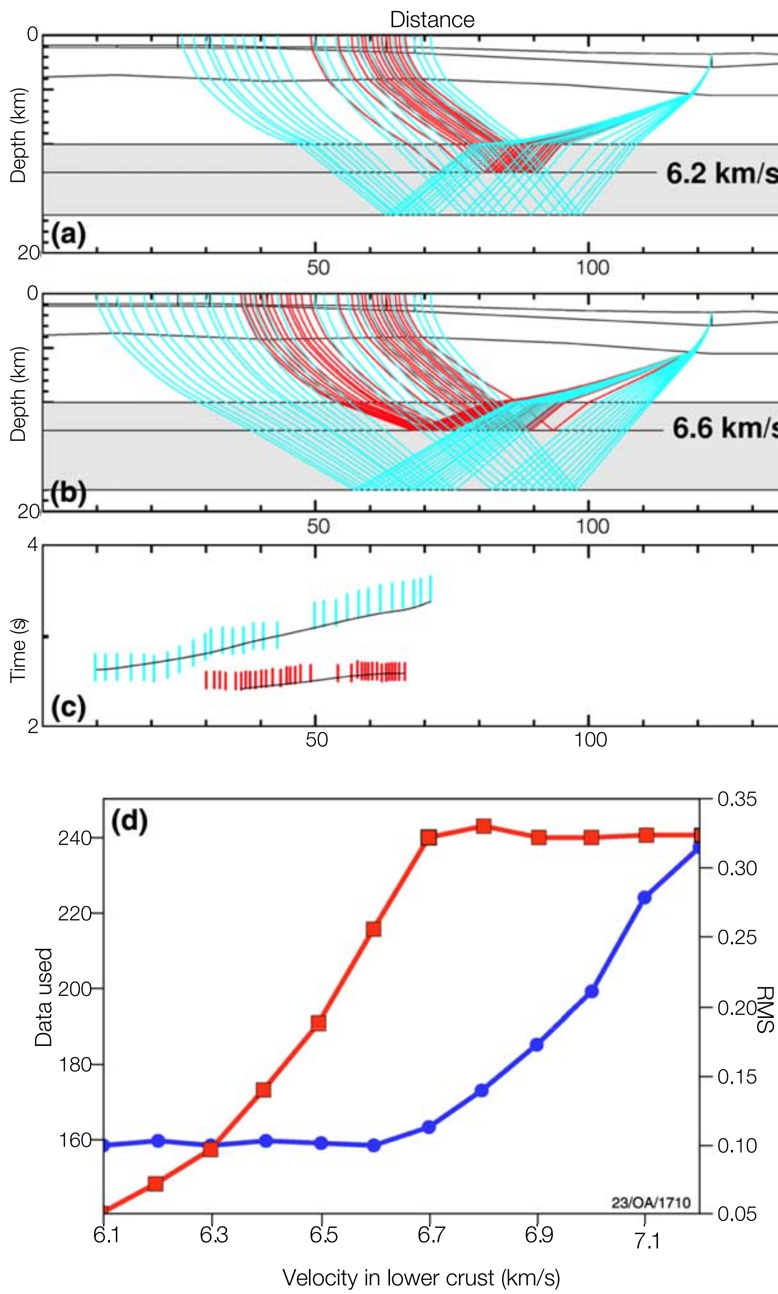


Figure 6. (a–c) Rays traced for seismic phases Pr3 (red) and Pr4 (blue) in models with lower crustal velocities of 6.2 (Figure 6a) and 6.6 (Figure 6b) km/s. Rays cannot be traced at large offset to match observed travel times for a seismic velocity of 6.2 km/s. (d) RMS misfits of travel times for seismic phases Pr3 and Pr4 calculated for different lower crustal velocities. RMS misfits increase rapidly for velocities higher than 6.7 km/s, but velocities lower than 6.6 km/s do not match all of the observed travel times. Vertical bars represent observed travel times, digitized from record sections, ± errors used in the inversion [*Zelt and Smith*, 1992]. Black line is travel time computed in the final model.

nent unconformity marking the boundary between sediment and basement is Campanian [*Coffin et al.*, 2000]. On the crest of Elan Bank, this unconformity is commonly angular, suggesting wave base erosion (Figure 7). Acoustic basement of Elan Bank displays a complex seismic character. It contains many dipping reflections (Figures 3 and 8a), non-reflective buildups, and faulted intrabasement reflections similar to those mapped on volcanic passive margins [e.g., *Planke et al.*, 2000] and the Kerguelen Plateau

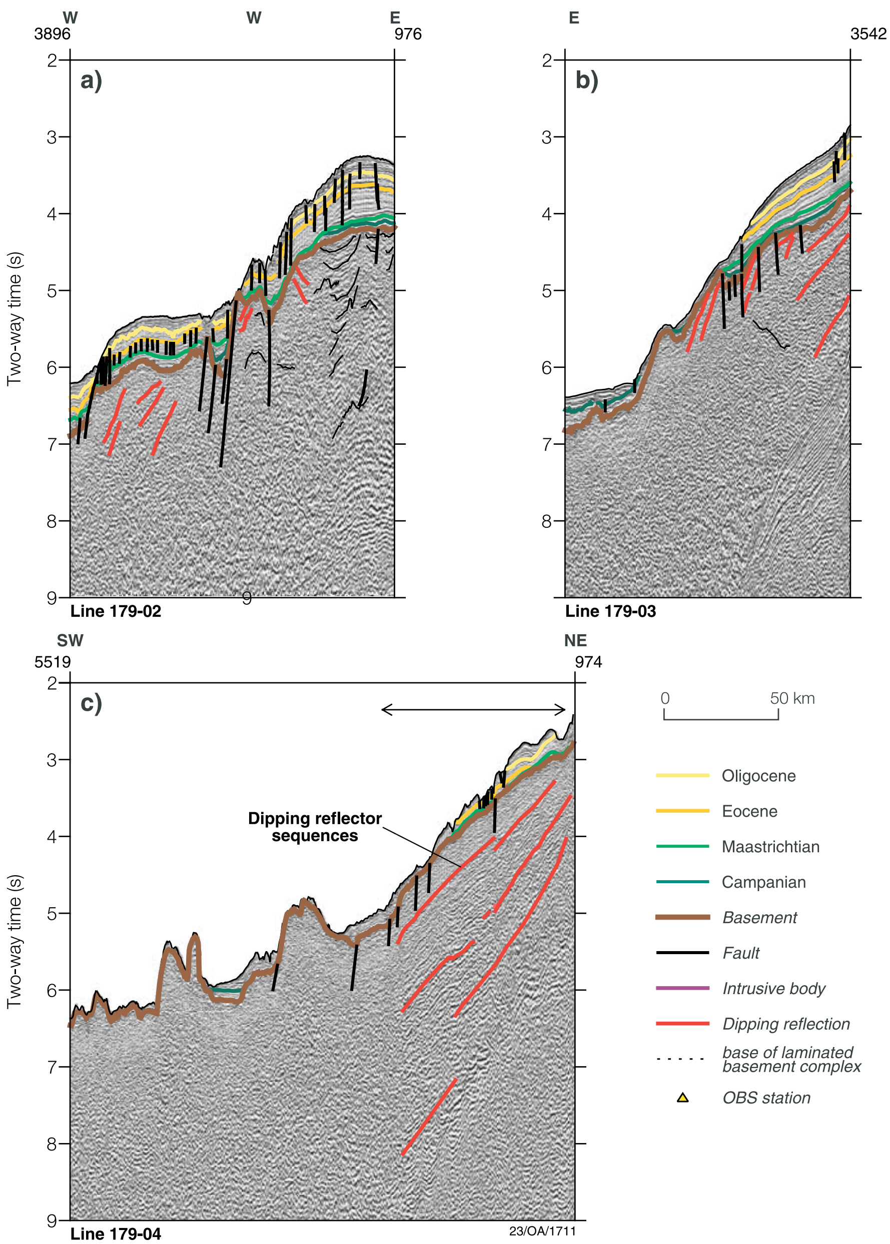


Figure 7. (a–e) Interpreted seismic lines from Elan Bank. Arrows correspond to expanded sections shown in Figure 8a–8c.

[e.g., *Schaming and Rotstein*, 1990]. In these cases, intrabasement dipping reflections have been confirmed by drilling to be massive subaerial lava flows. On Elan Bank the dipping reflections terminate in places against a surface (Figure 7; Lines 179-03, 179-04) that could correspond to a large fault dipping toward the crest of Elan Bank or pre-existing basement. At the base of the slope, lava flows extend at least 50 km southward, as indicated by a clear flow edge on Line 179-05 (Figure 8b). A smooth surface and bright reflection at the top of such a succession usually indicates marine rather than subaerial emplacement [*Eldholm et al.*, 1995].

[14] South of the continental crust of Elan Bank we observe a possible continent-ocean transition zone (Figure 3). On Line 179-05, a strong reflection (possible lava flows) at ~7.0 s twt overlies crust containing many parallel reflections (Figure 8b).

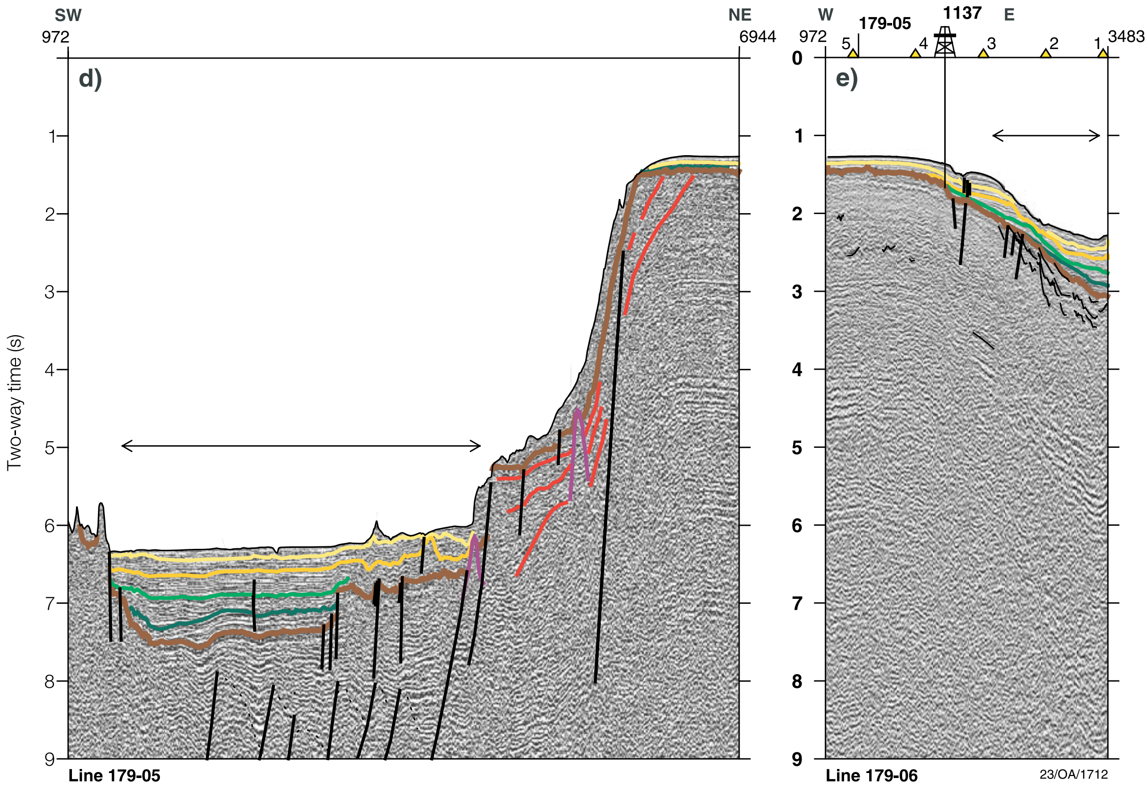


Figure 7. (continued)

Poorly imaged, faulted basement appears to lie 1 to 1.5 s below these lava flows. This reflective and layered crust could represent a continental-ocean transition zone underlain by highly extended continental crust with sedimentary sequences capped by basalt flows, or alternating volcaniclastics and basalts. Alternatively, it may represent complexly structured oceanic crust formed during initial stages of the breakup and affected by volcanic activity on Elan Bank's margin. The outermost boundary of this zone coincides with a basement high (Figure 7d).

[15] An interpreted OBS line extending off the southwestern edge of the Elan Bank into the Enderby Basin (Figure 3) [*Charvis and Operto*, 1999] showed a 14 km igneous crust beneath the distal edge of the bank thinning to 10 km in the Enderby basin. The crust consists of two layers: an upper one with velocities ranging from 5.0 to 6.5 km/s, and a lower one with velocities gradually increasing from 6.7 km/s at the top of the layer to 7.32 at its base. This unusually thick crust with higher than average velocities in layer 3 has been interpreted as oceanic crust formed near a hot spot [*Charvis and Operto*, 1999]. The thickness of layer 2 on this line varies considerably (1.5 to 3.7 km), suggesting variations in volcanics accumulated along Elan Bank's margins.

[16] If layered crust on Line 179-05 corresponds to volcanic complexes, then layer 2 thicknesses on this line range from 3 to 5 km. Satellite-derived and shipboard gravity data, however, show the presence of a major negative free-air anomaly south of Elan Bank. This combination indicates the presence of high-density material at shallow levels and may correspond to a thinner crust than that of the adjacent Enderby Basin as described by *Charvis and Operto* [1999].

[17] Bathymetry and gravity data from Elan Bank suggest that ENE-WSW and NW-SE trending faults as well as volcanic flows off of the margin have determined its shape (Figure 3). Seismic data indicate ENE-WSW trending normal faults, whereas NW-SE trending faults appear to displace large basement blocks and probably acted as transform

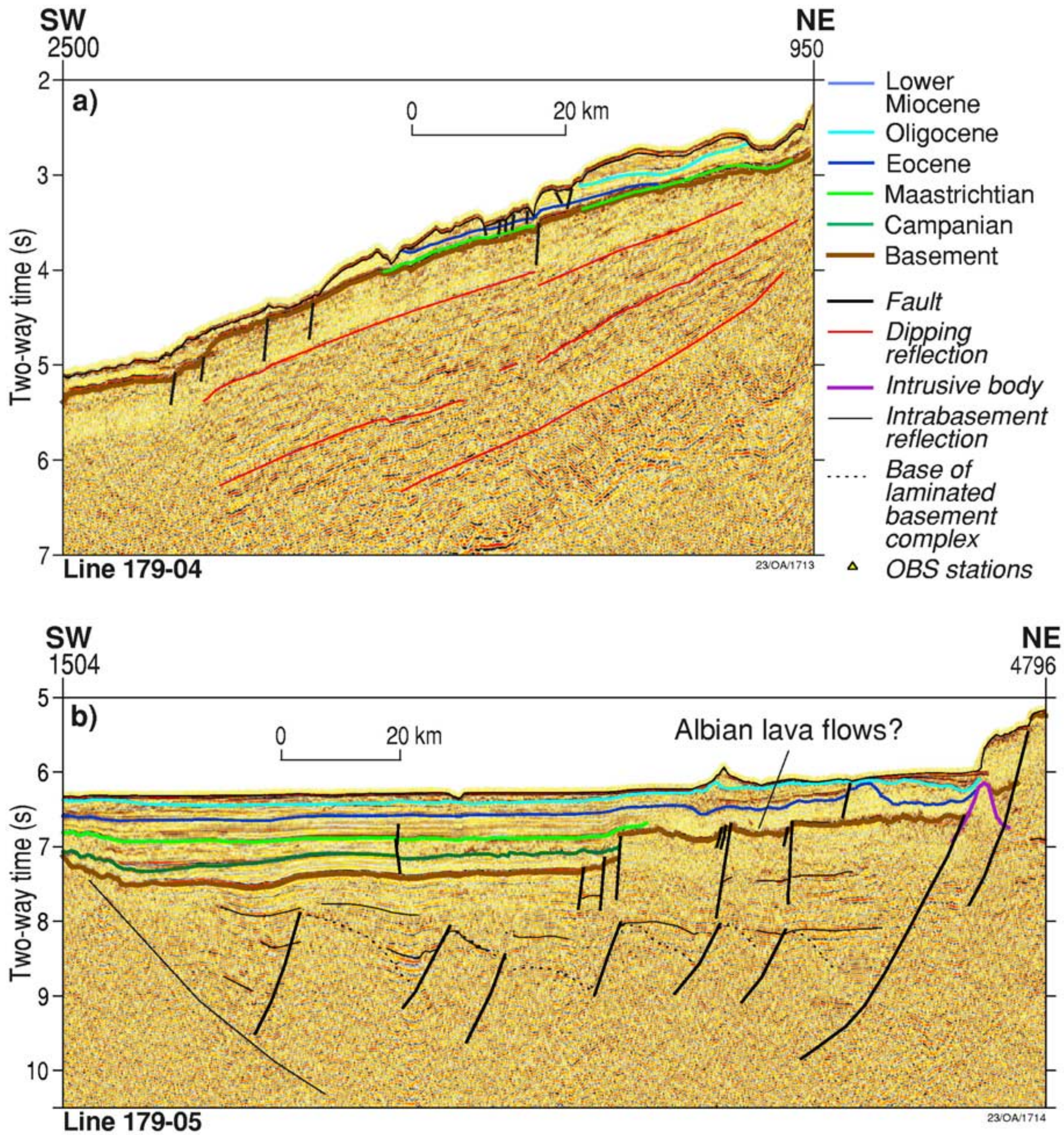


Figure 8. (a) Example of dipping reflections within basement of Elan Bank (Line 179-04). (b) Transitional zone south of Elan Bank (Line 179-05). (c) basin in the central part of Elan Bank capped by Aptian (∼108 Ma) lava flows (Line 179-06).

faults at the time of the breakup. A strike-slip fault (Figure 3) corresponds to a basement low that separates the western and eastern parts of Elan Bank (Figures 3 and 7e). A seismic line across this low (Figure 8c) shows tilted blocks including possible syn-rift sequences of unknown age beneath the uppermost volcanic sequence. The total thickness of sediment, including volcaniclastics, in this trough reaches at least 2 km (2 s twt). This trough could be a pull-apart feature that formed along a transform fault. The trough formed and accumulated sediment prior to the final phase of volcanism on Elan Bank.

[18] MCS lines on the crest of Elan Bank show a strong erosional, commonly angular unconformity separating sediment and acoustic basement (Figures 7d–7e) [*Borissova et al.*, 2002]. At Site

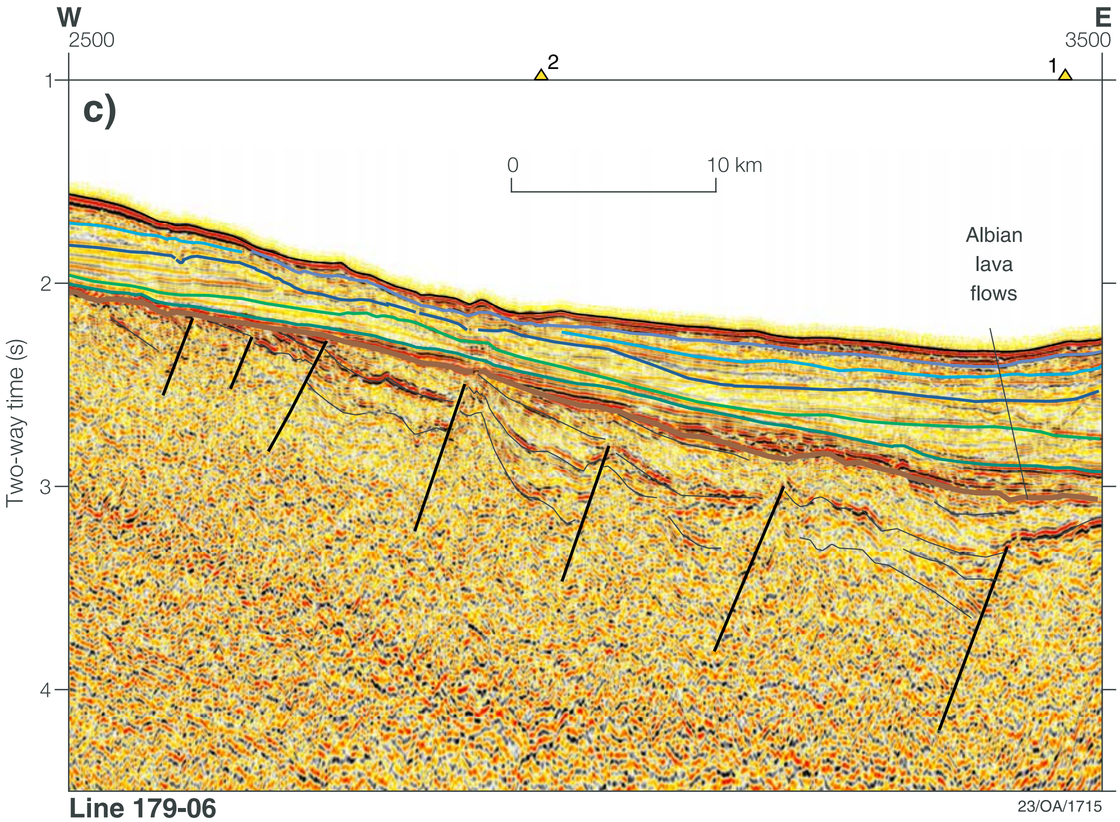


Figure 8. (continued)

1137, the age of basal sediment is Late Campanian (74–75 Ma [*Coffin et al.*, 2000]). The absence of older Cretaceous sediment on shallow parts of Elan Bank suggests that it remained above sea level at least until Maastrichtian time, when most of the southern and central Kerguelen Plateau had subsided beneath sea level. The persistent relatively high elevation of Elan Bank is probably due to buoyancy of its continental root. Even at present it is higher than most of the adjacent Kerguelen Plateau, excluding currently volcanically active areas. This, in turn, suggests that in considering the entire Kerguelen Plateau, Elan Bank probably contains the largest proportion of continental crust.

5. Concluding Discussion

[19] Elan Bank is a microcontinent modified by volcanic and probably plutonic rocks. Early Cretaceous breakup between India/Elan Bank and Antarctica resulted in formation of the southern margin of Elan Bank. Breakup between India/Elan Bank and Antarctica occurred at about chron M9N (~130 Ma [*Gaina et al.*, 2003]). A zone of deep faulted crust buried beneath later volcanic accumulations could represent either highly extended continental crust, or transitional crust formed during the early stages of breakup between Elan Bank and Antarctica. It is not clear whether breakup between Elan Bank and Antarctica was accompanied by any significant volcanism. Recent MCS data from the Enderby Land margin and Princess Elizabeth Trough (Figure 1), which likely represent segments of Antarctic margin conjugate to Elan Bank, shows well-developed seaward dipping reflections only in close proximity to the Southern Kerguelen Plateau (H. M. Stagg, personal communication, 2003). The remainder of the Enderby Land margin, including that directly south of Elan Bank, does not display characteristics of a rifted volcanic margin.

[20] Spreading in the Enderby Basin apparently ceased in Barremian time (~124 Ma [*Gaina et al.*, 2003]); however it is not clear when Elan Bank

was transferred to Antarctic plate. It could have coincided with initiation of hot spot-related volcanism in the area. Volcanism associated with the Kerguelen hot spot is believed to have commenced on the Southern Kerguelen plateau in Aptian time (~119 Ma [*Coffin et al.*, 2002; *Duncan et al.*, 2002]). Massive volcanism on Elan Bank initiated by interaction with the Kerguelen hot spot has masked the continent-ocean transition zone to the south. Grabens and basins both on Elan Bank and in the continent-ocean transition zone accumulated volcaniclastic material and lava flows, creating the appearance of flat unstructured basement and masking the original faulted basement. Alternatively, Elan Bank could have been transferred to the Antarctic plate as late as ~109 Ma (Aptian), which is the sole date for basalts on Elan Bank [*Coffin et al.*, 2002; *Duncan*, 2002]. Much of Elan Bank remained above sea level into Maastrichtian time, and likely experienced significant erosion.

[21] Elan Bank is the only region of the Kerguelen Plateau from which continental rocks have been recovered, yet other portions of the plateau display different geophysical and geological signatures of continental components. On the southern plateau, a 4–6 km thick transition zone at the base of the crust characterized by relatively low velocities of 6.7–6.9 km/s (Figure 5g) and it has been proposed to be a fragment of continental crust [*Operto and Charvis*, 1995, 1996]. On the southernmost plateau, basalt from Site 738 (Figure 1) is interpreted "to have inherited its isotopic signature from old lithospheric mantle underlying the East Antarctica and southwestern Australia continental margins, rather than from the Kerguelen hot spot" [*Alibert*, 1991], and *Mahoney et al.* [1995] suggested that at Site 738, continental lithosphere was incorporated into the Kerguelen hot spot at "relatively shallow levels". Geochemical evidence for continental crust is also evident in basaltic lavas from Sites 747 (Figure 1; central Kerguelen Plateau) and 1142 (Broken Ridge) [*Frey et al.*, 2003].

[22] Elsewhere in the eastern Indian Ocean, recent GA MCS data from the West Australian margin suggest that several marginal plateaus (Naturaliste, Wallaby, Quokka and Joey Rises) along this volcanic rifted margin are failed microcontinents. Originally these plateaus were described as oceanic features formed during excessive volcanism associated with hot spot activity [*Coleman et al.*, 1982; *Storey et al.*, 1992]. However, deep MCS data reveal complex extensional structures beneath the volcanics, including possible pre-breakup sequences [*Borissova*, 2002; *Sayers et al.*, 2003; *Stagg et al.*, 2003]. Magnetic anomalies surrounding these continental fragments are difficult to interpret. Rift jumps and rift propagation episodes have been suggested in some areas to explain their complex pattern [*Mihut and Müller*, 1998].

[23] *Müller et al.* [2001] noted that microcontinents commonly form on young continental margins proximal to large igneous provinces, and proposed that ridge jumps or propagation eventually leading to microcontinent formation are driven by thermal anomalies associated with a hot spot. Elan Bank's development as a microcontinent, forming in a young ocean basin close to a major hot spot, seems to fit this hypothesis. In Early Cretaceous time, Elan Bank was moving southeast relative to the Kerguelen hot spot (Figure 2) [*Coffin et al.*, 2002; *Kent et al.*, 2002; *Gaina et al.*, 2003], and this may have contributed to the ridge jump that separated Elan Bank and India. Elan Bank is an example of a microcontinent formed on or near a volcanic rifted margin, which has been later incorporated into a major oceanic plateau. Thick volcanic sequences masking continental nature of Elan Bank are a common characteristic of other continental fragments isolated during breakup on volcanic margins. The ~140,000 km^2 by ~16 km thick dimensions of the Elan Bank microcontinent, including flood volcanism on its upper crust, provide a template for identifying and understanding possible continental fragments along convergent margins and in orogenic belts. Dispersal and accretion of continental fragments in association with both plate tectonics and hot spot activity [e.g., *Müller et al.*, 2001; *Gaina et al.*, 2003] has likely been a significant process for much of Earth history.

[24] In general, the role of microcontinents has been underestimated and understudied in plate kinematic analyses of continental rifting and breakup. During breakup, relatively large continental fragments such as Elan Bank can become isolated within oceanic

lithosphere either proximal or distal to their original parents or conjugates. Along volcanic rifted margins in particular, such microcontinents may be much more common than our current state of knowledge would suggest. Our understanding of continental margin development, including resource potential, will advance through investigating breakup processes that include continental fragmentation and microcontinent isolation.

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