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Eocene initiation of Ross Sea dextral faulting and implications for East Antarctic neotectonics

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Abstract: The Ross Sea region of the East Antarctic plate provides evidence for intraplate tectonic activity in Cenozoic times. Still unresolved are the cause, timing and kinematics of this intraplate tectonism. By integrating and discussing the different (kinematic and temporal) signals of Cenozoic tectonism, intraplate dextral shearing is recognized as the main tectonic regime controlling the structural architecture of the Ross Sea region from the Mid-Eocene (*c*. 40–50 Ma) onward. We speculate that propagation and persistence of this tectonic regime through time constitutes a feasible seismogenetic framework to explain past and current tectonism in the Ross Sea region.

The Mesozoic–Cenozoic tectonic evolution of the Ross Sea region (namely Victoria Land and the Ross Sea; Figs 1 and 2) is dominated by the separation of the Antarctic continent from Australia and greater New Zealand and the development of the Ross Sea embayment (e.g. Stock & Cande 2002, and references therein). These events led to the development of two roughly orthogonal passive margins in the Southern Ocean and the Ross Sea, bounding the East Antarctic craton to the north and to the east, respectively (e.g. Lawver & Gahagan 1994; Sutherland 1999; Mukasa & Dalziel 2000; Stock & Cande 2002) (Fig. 1).

The post-break-up Cenozoic separation history is particularly complex and includes the transfer of continental blocks originally belonging to the Antarctic plate (Tasmania and South Tasmania Rise) to the Australia plate, through a diffuse transform boundary active until about Oligocene time (Stock & Cande 2002, and references therein).

The occurrence of Cenozoic intraplate deformation in the Southern Ocean and the Ross Sea regions has been recently proposed to reconcile global plate tectonics based on plate closure calculations (Cande *et al*. 2000) and models of global plate motions in the Pacific region (Steinberger *et al*. 2004). In particular, Steinberger *et al*. (2004) advocated a pre-Mid-Eocene, major intraplate dextral motion at the northeastern edge of the East Antarctic plate, whereas Cande *et al*. (2000) reconstructed a Cenozoic (from 43 to 26 Ma) rigid rotation between East and West Antarctica during the opening of the Adare Trough in the northwestern Ross Sea (Fig. 2). An increasing body of evidence, based on different datasets, attests that Cenozoic dextral intraplate shearing has affected both the Ross Sea and the Southern Ocean shoulders along NW–SE dextral fault systems, striking oblique to both passive margins, which can be traced from one margin to the other across the intervening continental lithosphere of Victoria Land (Salvini *et al*. 1997; Rossetti *et al*. 2003; Fig. 2). This tectonic regime is interpreted as responsible for the post 32 Ma transition from orthogonal to oblique rifting in the western Ross Sea (Salvini *et al*. 1997), and for magma production and emplacement of the Cenozoic McMurdo Magmatic Province along the western Ross Sea shoulder (Salvini *et al*. 1997; Rocchi *et al*. 2002). Additional supporting evidence for recent tectonic activity in the region comes from the occurrence of a low but significant level of seismic activity at the northeastern edge of the East Antarctica plate (Reading 2002; Fig. 1). In north Victoria Land, earthquakes seem to be localized along the Cenozoic, NW–SE-striking intraplate dextral fault systems or along strands emanating from them (Fig. 2). Furthermore, fossil seismic activity is recorded along the western Ross Sea shoulder, as indicated by the occurrence of pseudotachylyte-bearing fault cores distributed along the western margin of the Ross Sea (Fig. 2). The discovery of pseudotachylyte-bearing fault rocks is of particular significance as it offers the possibility of directly sampling the products of dynamic ruptures produced during coseismic faulting at near-focal depths along exhumed fault zones (Sibson 1975). The recent dating at *c*. 34 Ma of the fault-zone hosted pseudotachylyte veins exposed at the tip of the NW–SE-striking, right-lateral Priestley Fault (Di Vincenzo *et al*. 2004; Fig. 2) opens new perspectives for the reconstruction of the tectonic and geodynamic evolution of the region, as the concomitant occurrence of pseudotachylytes and modern earthquakes along the same strike-slip fault systems may be diagnostic of long-lived fault activity in the Ross Sea region extending back into the Cenozoic.

The characteristics described above define the Ross Sea region as a key area for assessment of the history of intraplate faulting in the East Antarctic plate and, consequently, the tectonic regime(s) responsible for the past and present seismic activity. Still unresolved is the cause of Antarctic seismic intraplate activity in terms of plate tectonics, as plate closure calculations for magnetic anomalies younger than 26 Ma do not require any

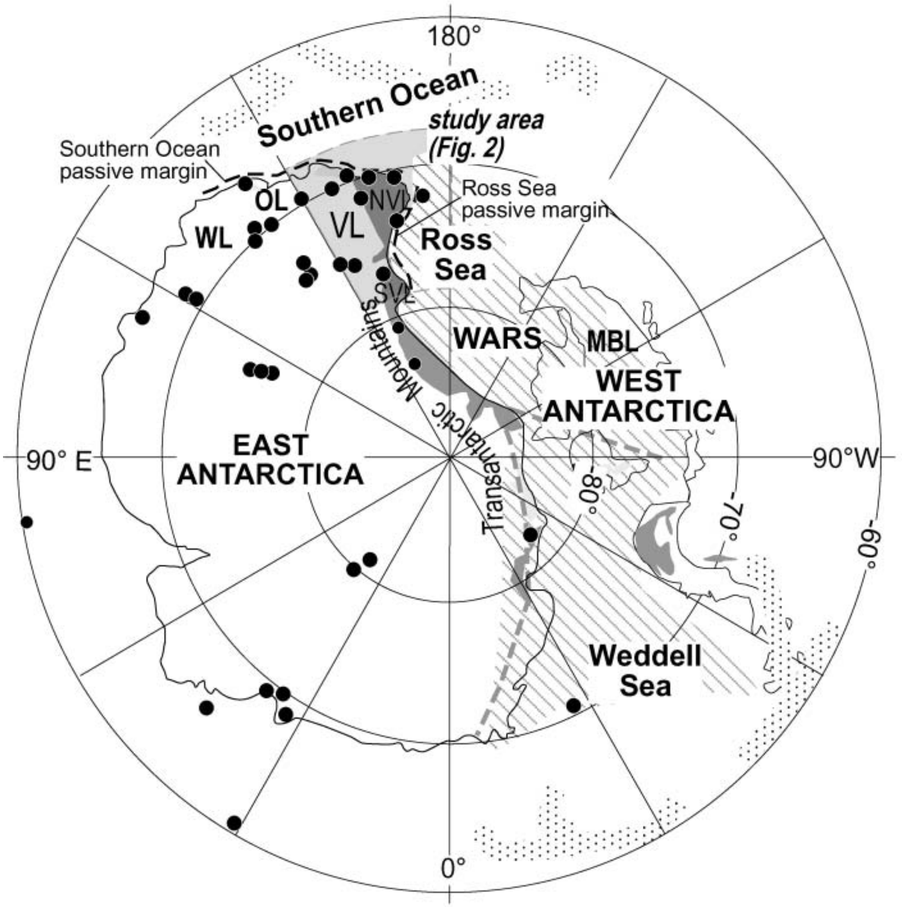

Fig. 1. The Antarctic continent and the West Antarctic Rift (WARS) system (modified after Tessensohn & Wörner 1991; Wilson 1999). The distribution of seismic activity (●) within the Antarctic plate is also indicated (after Reading 2002). MBL, Marie Byrd Land; NVL, North Victoria Land; OL, Oates Land; SVL, South Victoria Land; VL, Victoria Land; WL, Wilkes Land.

intra-Antarctic motions (e.g. Stock & Cande 2002) and the lithospheric stresses have been tentatively interpreted as the effect of competing tectonic forces and ice loading–unloading cycles (Reading 2002).

In this paper, after revisiting the available apatite fission-track (AFT) thermochronological ages from Victoria Land, we present results from a pilot study where kinematic and temporal data from the tip of the NW–SE-striking Priestley Fault are integrated with results obtained from the interpretation of a reprocessed offshore multichannel seismic reflection profile acquired across the southern termination of the Priestley Fault itself (IT90AR-61B; see Fig. 2 for location). Our purpose is twofold: (1) to provide an updated tectonic framework of the Ross Sea region, suitable for incorporation into refined plate tectonic reconstructions of the Australia–Antarctica–Pacific plate motions; (2) to provide support to the hypothesis that dextral intraplate faulting has been responsible for the distribution and origin of seismic activity in this region of the Antarctic plate, in a time span running from at least the Mid-Eocene to the present. Our results indicate that well after the onset of rifting between Antarctica and Australia, the near-perpendicular passive margins in the Southern Ocean and Ross Sea were tectonically connected and interacted during the late Cenozoic.

The Cenozoic tectonic architecture of the Ross Sea region

The Neoproterozoic to Early Palaeozoic basement rocks exposed in the Ross Sea region were exhumed since the Cretaceous, with a major phase of denudation starting in Cenozoic times, at *c.* 40–50 Ma (e.g. Fitzgerald 1992, 2002; Lisker 2002). This Cenozoic age coincides with a major tectonic change in the Ross Sea region, as attested by the opening of the Adare Trough (Cande *et al.* 2000), the onset of the Cenozoic McMurdo igneous activity (Rocchi *et al.* 2002), and the activation of dextral intraplate faulting (Salvini *et al.* 1997; Rossetti *et al.* 2003). The Cenozoic tectonic architecture in the Ross Sea region consists of NW–SE-striking right-lateral strike-slip to transpressional fault systems in Victoria Land, which are abutted by north–south-striking right-lateral transtensional basin boundary faults in the Ross Sea and onshore along the entire western Ross Sea margin (Wilson 1995; Salvini *et al.* 1997; Hamilton *et al.* 2001; Storti *et al.* 2001) (Fig. 2). The western boundary of the continental sector at the northeastern edge of Antarctica affected by important NW–SE-striking intraplate right-lateral strike-slip faulting can be traced approximately from the USARP Mountains area in the north to the David Glacier in the south (Fig. 2).

The Eocene–Oligocene fault history

The Cenozoic age of the dextral fault network in the Ross Sea region has been mainly established from interpretation of offshore reflection seismic profiles (e.g. Salvini *et al.* 1997; Hamilton *et al.* 2001). The recent availability of AFT thermochronological data along both the Ross Sea and the Southern Ocean margins (see Fitzgerald (2002) and Lisker (2002) for a review) and the discovery of pseudotachylyte-bearing fault cores

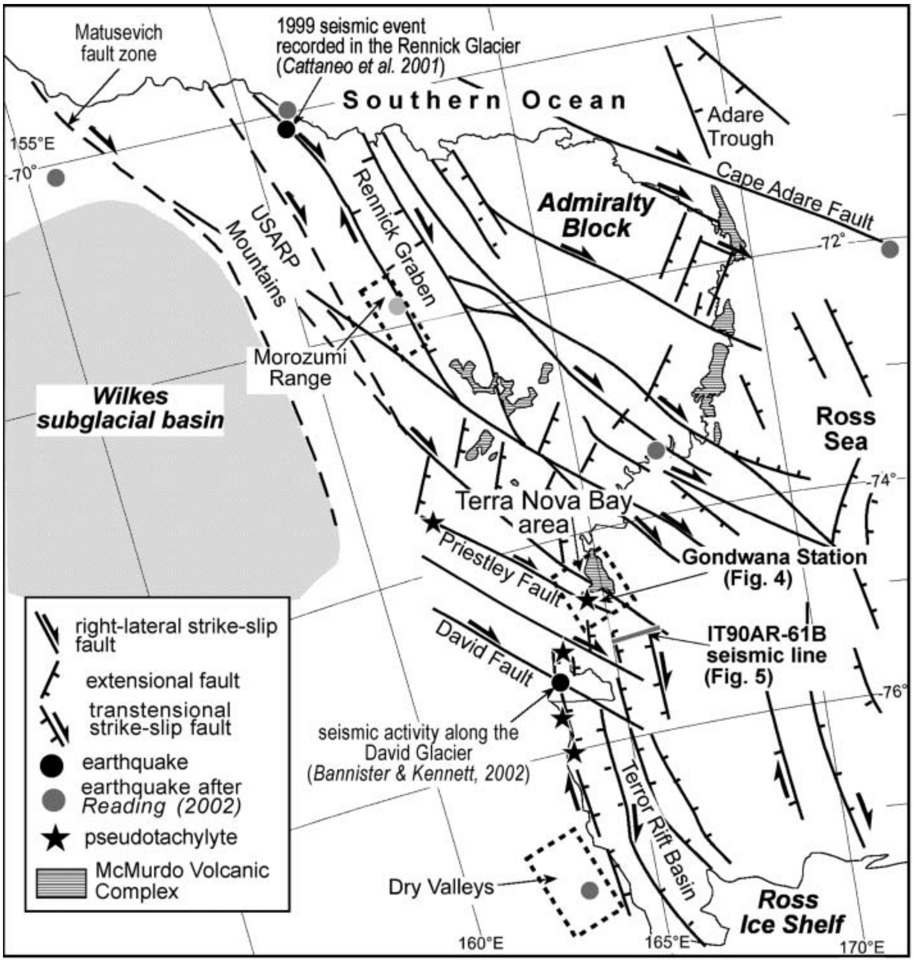

Fig. 2. Simplified tectonic map of the Ross Sea region, with the major Cenozoic fault systems (modified and readapted after GANOVEX Team 1987; Salvini *et al*. 1997; Cande *et al*. 2000; Ferraccioli *et al*. 2001; Kleinschmidt & Läufer 2003; Rossetti *et al*. 2003) and the recent earthquake distribution indicated (see text for further details on the data sources).

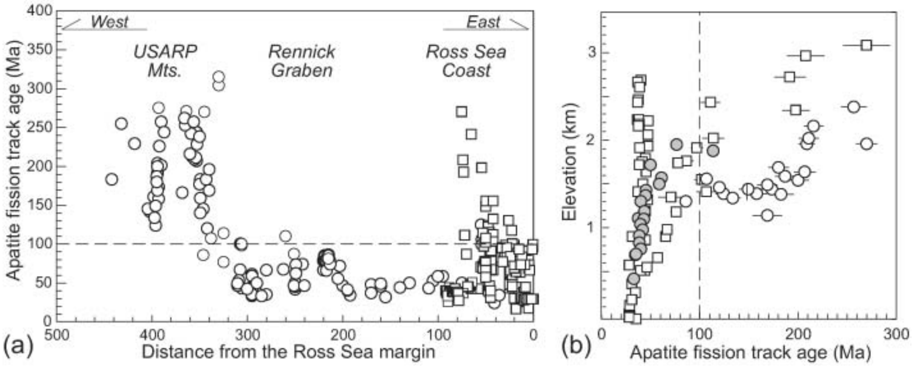

Fig. 3. (**a**) Trend of AFT ages with respect to their distance from the western Ross Sea coast along the Southern Ocean passive margin (○), and across the Transantarctic Mountains front from the Terra Nova Bay area to the Dry Valleys region (Ross Sea passive margin; □). The AFT ages abruptly increase west of the Rennick Graben (*c*. 300 km from the Ross Sea margin). A few older ages from the Transantarctic Mountains are an artefact of the high sample elevations. (**b**) Plot showing the relationship of AFT ages ($\pm 2\sigma$) v. elevation for vertical sample profiles from the USARP Mountains (○), the Morozumi Range (●), and the Dry Valleys–Terra Nova Bay area (□) (modified from Lisker 2002). It should be noted that within the last area the vast majority of AFT ages are younger than 100 Ma. Only a few samples from an altitude of >2 km have older ages. In contrast, samples from the USARP Mountains, west of the Rennick Graben, have generally older AFT ages. (Refer to Fig. 1 for sample location.) AFT data sources: Gleadow *et al*. (1984), Gleadow & Fitzgerald (1987), Fitzgerald & Gleadow (1988), Fitzgerald (1992), Balestrieri *et al*. (1994, 1997), Lisker (2002), Rossetti *et al*. (2003), and unpublished data.

along the western Ross Sea provides the opportunity to place new onshore kinematic and time constraints on the activity of this fault network.

AFT thermochronology

For normal geothermal gradients, the low-temperature conditions for fission-track retention in apatite (partial annealing

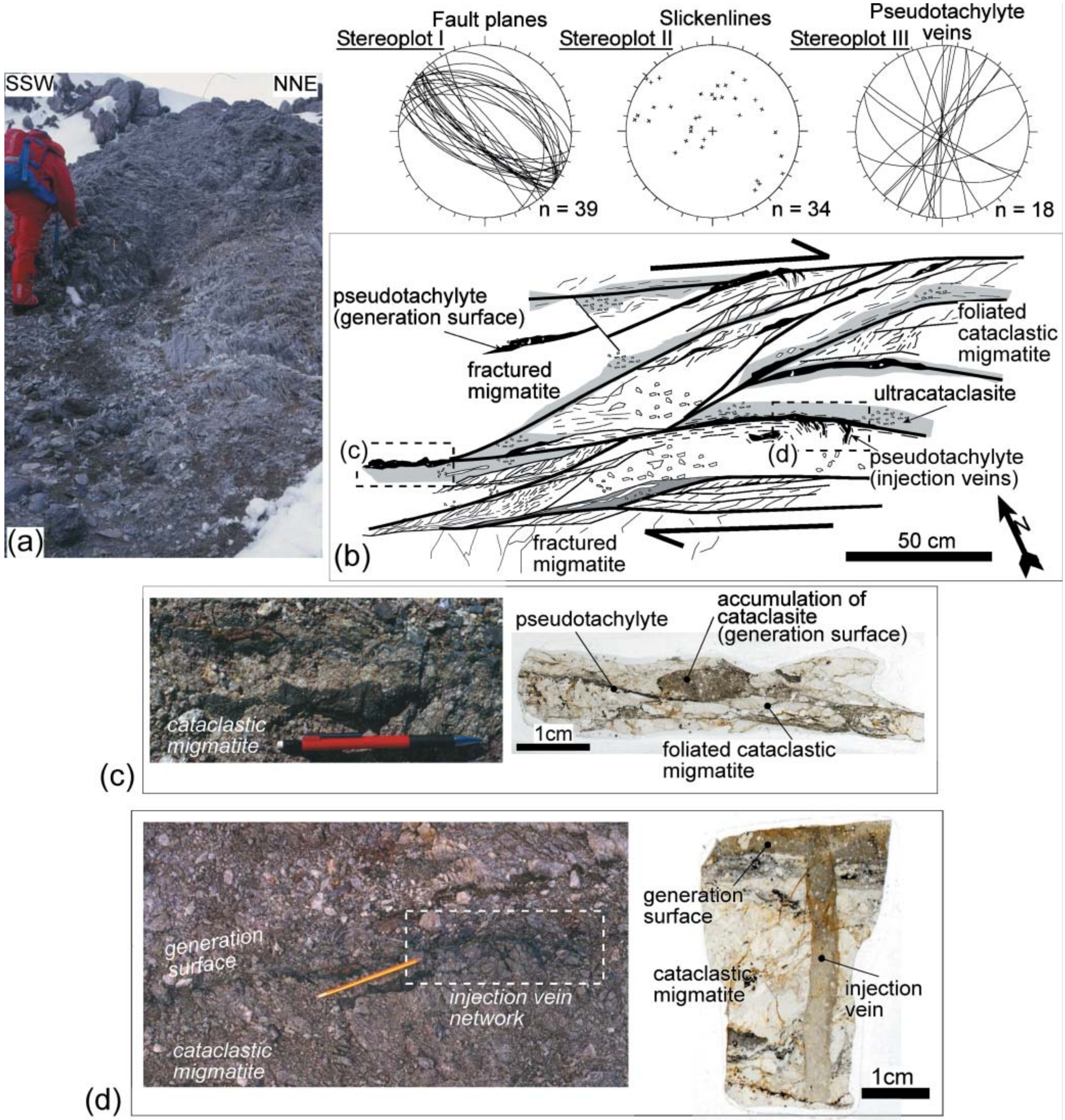

Fig. 4. Structural features of the fault core of the NW–SE-striking Priestley Fault at Gondwana Station (see Fig. 2 for location). The stereoplots (equal area projection, lower hemisphere) represent the collected structural data. (**a**) Cohesive cataclasite from the fault core domain, where the pseudotachylyte veins occur. The cataclastic rocks have a fragmental appearance and show numerous mesoscopic faults and diffuse veining. (**b**) Field sketch in plan view illustrating structural relations between the NW–SE-striking cataclastic zones and the pseudotachylyte veins. Most of the pseudotachylyte veins occur along the most prominent shear surfaces (bold lines), where ultracataclasites also occur. In the fault core, the S–C fabric in foliated cataclasites is consistent with distributed dextral shearing. (**c**) Left: dark subparallel generation zones. Right: rock slab showing the sharp boundary between cataclastic migmatite and pseudotachylytes. (**d**) Left: pseudotachylyte injection veins departing from a generation surface. Right: rock slab showing the same relations at the centimetre scale. The progressive decrease in fragment size and of fragment-to-matrix abundance ratio when moving from the generation surface to the injection vein pseudotachylyte should be noted.

zone between 60° and 120 °C, with a mean effective closure temperature constrained at 110 ± 10 °C; Green & Duddy 1989), makes AFT thermochronology an efficient tool to establish the age of the late-stage deformation history affecting the upper 3–4 km of the crust, where brittle deformation predominates.

The pattern arising from over 300 sets of AFT data from north Victoria Land is characterized by a distinctive trend of increasing ages from the Ross Sea coast towards the East Antarctic Craton (Fig. 3a). In particular, the age pattern and the regional distribution of the track lengths indicate a markedly different cooling history for the tectonic blocks of northern Victoria Land, with a rather sudden transition west of the Rennick Graben region (Fig. 3a). Virtually all AFT sample ages from westernmost northern Victoria Land and Oates Land (Fig. 3a), as well as from the adjacent George V Land (Lisker & Olesch 2003) and Terre Adélie (Arné *et al*. 1993), are generally older than Cretaceous (between *c*. 300 and *c*. 100 Ma), showing an age pattern similar to that of the pre-Gondwana break-up conjugate margin of southeastern Australia (Lisker 2002, and references therein). In contrast, the vast majority of samples from the western shoulder of the Rennick Graben and the Admiralty Block have AFT ages younger than 100 Ma. Only a few older ages were obtained from the morphologically highest samples of the Transantarctic Mountains, representing a break in slope of vertical sample profiles (Fig. 3b).

Offsets in age–elevation slopes, indicating the onset of cooling–denudation stages, were recognized at various localities at *c*. 80 and at *c*. 50–40 Ma (e.g. Balestrieri *et al*. 1994; Lisker 2002). A comparison of the vertical AFT profiles indicates that the stage commencing at *c*. 40–50 Ma was the episode with the highest amount of denudation, as well as the only episode consistently recorded in northern Victoria Land (Fig. 3). The amount of denudation during the Cenozoic varies considerably throughout the Admiralty Block, and does not strictly correlate with the topographic elevation (or the amount of Cenozoic uplift), or with the distance to the Ross Sea margin (Fig. 3). Accordingly, the Cenozoic AFT age pattern does not fit into a classical passive continental margin configuration, where distinctive regional patterns of AFT data with younger ages at the coast monotonically increasing towards the continental interior are expected (e.g. Gallagher & Brown 1997). In particular, such a tendency is not exhibited across the Southern Ocean passive margin of northern Victoria Land, where the denudational response induced by activation and propagation of Cenozoic, partitioned strike-slip faulting at *c*. 40–50 Ma is documented by opening of the Rennick Graben (Rossetti *et al*. 2003).

Pseudotachylyte vein occurrence and age

Pseudotachylytes have been found along the western coast of the Ross Sea, along both NW–SE- and north–south-striking fault systems (Fig. 2). Typically, pseudotachylytes occur within zones of cataclastic deformation and are marked by dark, fine-grained, and locally foliated steeply dipping cataclasites, up to several metres thick. The fault rocks exposed at the tip of the Priestley Fault (Fig. 2) were selected as a key site to decipher the

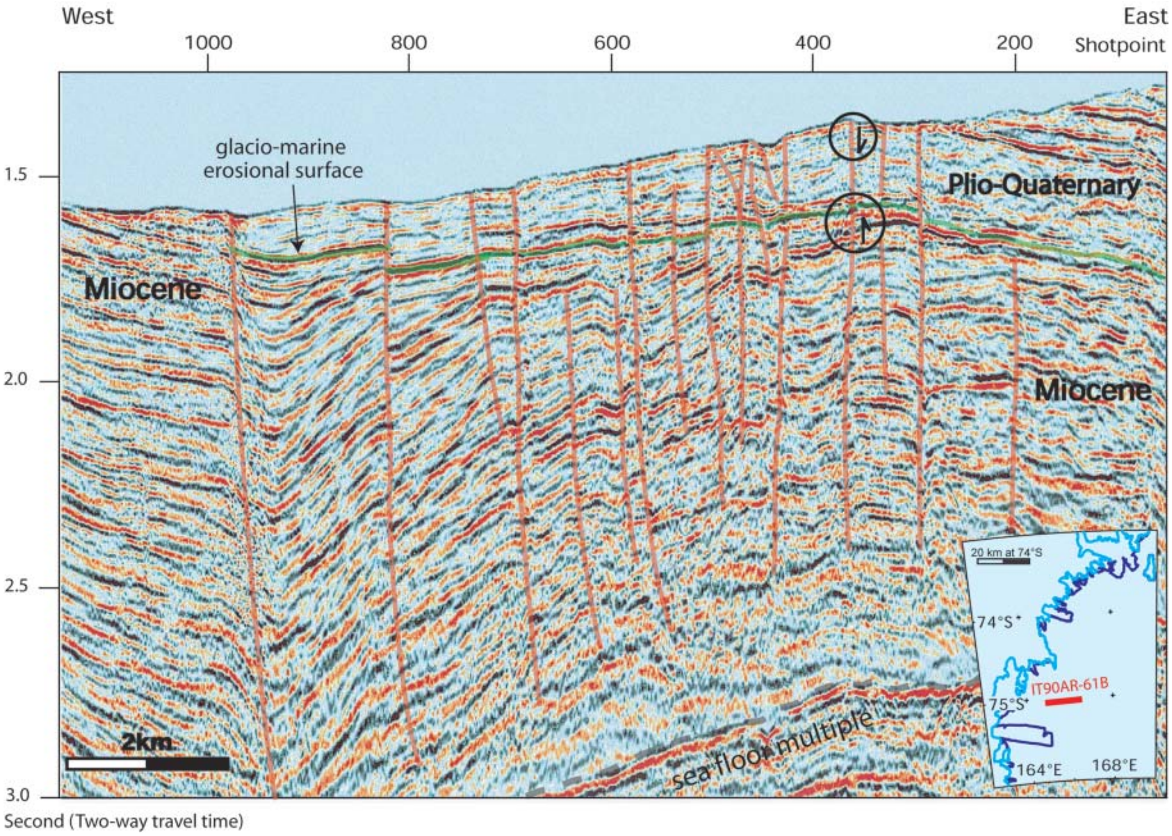

Fig. 5. Interpretation of the offshore IT90AR-61B multichannel seismic profile across the northern termination of the Terror Rift, at the southern tip of the Priestly Fault. The tectonic activity resulted in intense faulting affecting the Miocene sediments and, partially, the Pliocene–Quaternary glacial marine deposits. The main faults have been active in recent times and have produced sea-floor morphologies that are still preserved despite the area being subjected to intense glacial erosion. Arrows in the circles (top right) indicate zones with apparent opposite direction of displacement along the same fault strand. Seismic profile collected by the Osservatorio di Geofisica Sperimentale (now Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) in 1990.

kinematics and timing of fossil coseismic faulting in north Victoria Land.

The studied pseudotachylyte-bearing fault zone occurs within Early Palaeozoic migmatite rocks, exposed close to the German Gondwana Station on the Ross Sea coast (Fig. 2). The fault trace consists of a broad (at least 50 m thick), NW–SE-striking cataclastic damage zone, consisting of high-angle anastomosing fault strands, preferentially dipping to the SW (Stereoplot I in Fig. 4). The direction and sense of shear on these fault surfaces was deduced from the orientation of corrugation, striations and grooves, and the arrangement of secondary Riedel shears (e.g. Petit 1987). Strike- and dip-slip slickenlines typically coexist on the fault surfaces (Stereoplots I and II in Fig. 4), with mutual overprinting relations. Kinematic indicators within the fault zone, mostly provided by the Riedel shears (lunate structures and extensional cracks), consistently record dominantly dextral strike slip to oblique reverse slip.

The fault core is several metres thick and contains cohesive foliated cataclasites, where the primary metamorphic structures of the host rock are completely obliterated (Fig. 4a). The fault core is also characterized by a higher degree of rock alteration and veining. Fine-grained ultracataclasites and pseudotachylyte veins occur in the central portion of the core and are typically bounded by foliated cataclasites. The orientation of the cataclastic foliation, subsidiary faults and extension cracks is consistent with distributed right-lateral shear (Fig. 4b). Pseudotachylytes consist of black to dark green aphanitic zones a few millimetres to 5–6 cm wide, and occur both as generation surfaces along the strike of the cataclastic zones and as injection veins roughly orthogonal to them (Fig. 4c and d, and Stereoplot III in Fig. 4). Details of petrological analysis, the dating procedure and interpretation of $^{40}Ar/^{39}Ar$ laserprobe analyses have been provided by Di Vincenzo *et al*. (2004). In summary, *in situ* laserprobe analyses on selected samples yielded concordant ages at *c*. 34 Ma for an injection vein, interpreted to date a major episode of coseismic faulting during dextral shearing at the Eocene–Oligocene boundary.

The post-Miocene to present fault history

The present-day intraplate stress field in Antarctica is largely unknown because of the scarcity of earthquakes with magnitudes yielding reliable focal mechanism solutions and localization problems (Reading 2002). Information on the intraplate stress field are consequently mostly derived from borehole data on Neogene–Quaternary cores samples drilled in the Cape Roberts area, where the fracture pattern documents a stress regime that is compatible with regional late Cenozoic dextral transtension along the Transantarctic Mountains front (e.g. Wilson & Paulsen 2000).

There is limited evidence for neotectonic activity in the region, mostly derived from faulting that affects the McMurdo volcanic products (e.g. Lanzafame & Villari 1991; Storti *et al*. 2001) and geomorphological features (e.g. Jones 1997). Furthermore, analysis of young volcanic cone alignments in south Victoria Land documents that magmatism emplacement occurred under a non-isotropic regional stress field (Paulsen & Wilson 2003). Nevertheless, seismic activity in the Ross Sea region has been recorded along the trace of the Cape Adare (Behrendt *et al*. 1996), Lanterman (Cattaneo *et al*. 2001) and David (Bannister & Kennett 2002) dextral fault systems of Salvini *et al*. (1997), all of which are argued to have had earlier Cenozoic activity (Fig. 2).

The IT90AR-61B multichannel seismic reflection profile

Interpretation of the multichannel seismic reflection profile IT90AR-61B (see Fig. 2 for location) provides important constraints on the recent tectonic activity in the adjacent offshore region of the Priestley Fault (Fig. 5). The profile intersects the prominent Cenozoic north–south-striking Terror Rift basin, a deep tectonic depression developed at the southern tip of the Priestley Fault to accommodate its residual dextral shear (Storti *et al*. 2001). The most significant feature is the occurrence of numerous fault strands post-dating the major Miocene glaciomarine erosional surface and also affecting the Pliocene–Quaternary sediments. Some of the faults are responsible for the sea-floor morphology, causing formation of small (about 15–20 m high) escarpments, mounds *c*. 1–2 km long, and sags of several hundred metre width. The majority of these fault strands are steeply dipping, and the vertical separation across the fault-bounded contacts attests to dominant extensional fault throw. Each fault strand shows up to 100 m of vertical offset in the buried sedimentary sequence. The steep and depth-convergent fault arrays as well as the presence of reverse throws along the same fault surface (see top right side of Fig. 5) also suggest the occurrence of deformation partitioning with a significant horizontal component of slip in addition to the dominant extensional one. This is a common feature all along the western part of the Ross Sea shoulder, which is dominated by north–south transtensional shearing (Salvini *et al*. 1997; Hamilton *et al*. 2001).

Tectonic synthesis: towards a model for the neotectonic evolution of the Ross Sea region

The integration of the information derived from structural data, AFT thermochronology (*c*. 40–50 Ma) and the $^{40}Ar/^{39}Ar$ dating of pseudotachylytes along the Priestley Fault (*c*. 34 Ma) supports the activity of dextral wrench faulting across Victoria Land at least since the Eocene–Oligocene boundary. This age overlaps with the timing of the rifting processes affecting the Ross Sea and resulting in the opening of the Adare Trough in the interval 43–26 Ma (Cande *et al*. 2000; Fig. 2). Nevertheless, the AFT age pattern in north Victoria Land (Fig. 3) does not conform to a regional denudational response of the Transantarctic Mountains acting as a rift-shoulder, as the denudation phase commencing at *c*. 40–50 Ma was systematically recorded far west in the continent interior and intimately linked with the activity of the NW–SE-striking dextral fault systems. Accordingly, the episode indicated at *c*. 40–50 Ma by the AFT ages can be tentatively interpreted as the denudational response to localized extension and uplift triggered by the activation and propagation of Cenozoic, partitioned strike-slip faulting within the continental crust of north Victoria Land from *c*. 40–50 Ma onward (Rossetti *et al*. 2003). The slip history is attested by fossil earthquake ruptures occurring in concomitance with the onset of the McMurdo magmatism along the western margin of the Ross Sea at about 48 Ma (Tonarini *et al*. 1997; Rocchi *et al*. 2002). This suggests that strike-slip deformations played an important role in controlling the development of the Cenozoic volcanic margin in Victoria Land. Continuing magmatic activity may in turn have enhanced the seismic activity in a feedback mechanism, by analogy to that proposed for the East Greenland volcanic rifted margin (Karson *et al*. 1998).

The presence of modern earthquakes along the NW–SE-striking fault networks and the offshore seismic evidence for neotectonic activity at the southern tip of the Priestley Fault support the Quaternary activity of the same strike-slip-related fault network. This suggests a long-lasting faulting regime, active at least from the Early Oligocene until the present in the Ross Sea region. If we assume that earthquake nucleation started in the early phases of dextral wrench faulting as documented along the Southern Ocean coast (i.e. at *c*. 40–50 Ma) and continued up to modern times, this implies that fossil and modern seismicity at the northeastern edge of East Antarctica may relate to the activation, propagation and linkage of major intraplate dextral fault systems from the Mid-Eocene onward. The kinematic scenario for the neotectonic evolution of the Ross Sea region is thus consistent with the progressive SE-directed extrusion of the continental lithosphere of north Victoria Land operated by dextral wrench faulting. Further support for this hypothesis derives from preliminary global positioning system (GPS) data showing the SE motion of the Terra Nova Bay permanent station (Negusini *et al*. 2005).

The proposal of active tectonism in the Ross Sea region made in this paper may contrast with plate closure calculations for magnetic anomalies in the Southern Ocean rifting zone, which do not necessitate significant intra-Antarctica motion younger than 26 Ma (Cande *et al*. 2000; Stock & Cande 2002). On the other hand, the strike-slip motion described in this paper may well fall within the confidence interval of magnetic anomaly data. Furthermore, in the proposed model of southeastward extrusion of north Victoria Land, accommodation and compensation of the continental dextral displacement occurs in the previously rifted offshore region within the north–south-trending transtensional belt of the western Ross Sea margin (see also Storti *et al*. 2001; Rossetti *et al*. 2003; Fig. 2). This is confirmed by the rift history reconstructed for the southwestern Ross Sea area, where a late Early Oligocene rift reorganization occurred, and a Miocene to recent continuum of deformation has been reconstructed (Wilson *et al*. 2003). We thus propose (at least from the Early Oligocene to the present) tectonic connection between the rifting processes occurring in the Southern Ocean and the Ross Sea neotectonics induced by the propagation of the dextral faulting through the continental crust of Victoria Land.

The tectonic scenario discussed above may also provide further constraints for the geodynamic reconstructions of the plate tectonic regime in the Pacific–Antarctic region during the Cenozoic. Our reconstruction, in particular, suggests that there are consistent kinematic and temporal relationships documenting changes in the tectonic regime of the northeastern edge of the East Antarctic plate, including the onset of diffuse intraplate dextral wrench faulting, that were roughly coeval with the Mid-Eocene major reorganization of spreading in the Pacific basin (e.g. Müller *et al*. 2000; Veevers 2000). We present here a reappraisal of the relevance of intraplate dextral shearing in controlling the post 40 Ma tectonic architecture of the Ross Sea region to indirectly contribute to a new generation of plate motion reconstructions among the Antarctic, Australian and Pacific plates.

Conclusions

The following key issues can be extracted from this study and should be carefully considered in any future tectonic model: (1) dextral wrench faulting dominates intraplate deformation at the northeastern edge of East Antarctica; (2) intraplate dextral wrench faulting commenced in the Mid-Eocene; (3) propagation of distributed and partitioned dextral shear in the continental crust of northern Victoria Land is indicated by a long-lasting seismogenetic fault network that is possibly responsible for the neotectonic activity in the Ross Sea region.

The complex picture of neotectonic activity in the area cannot be explained within a simple and rather uniform passive margin framework and/or by ice cap dynamics alone. Instead, it fits the framework of a diffuse intraplate dextral wrench-faulting scenario, where the western Ross Sea margin has to be regarded as a continental sheared margin.

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