Intraplate strike-slip tectonics as an alternative to mantle plume activity for the Cenozoic rift magmatism in the Ross Sea region, Antarctica

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Abstract: The West Antarctic Rift System is one of the largest areas of crustal extension in the world. Current interpretations on its driving mechanisms mostly rely on the occurrence of one or more mantle plumes, active during the Cenozoic or the Mesozoic. Recent studies of structural-chronological relationships between emplacement of plutons, dyke swarms, and volcanic edifices since middle Eocene in northern Victoria Land imply that magma emplacement is guided by strike-slip fault systems that dissect the western rift shoulder in Victoria Land. These studies led to a critical re-examination of the arguments used to support plume models. In Victoria Land, the linear geometry of the uplift and the relative chronology of uplift and extension are inconsistent with the traditional concepts of lithospheric evolution above a mantle plume. The geochemical signature of the mafic rocks is equivocal, because both OIB and HIMU features cannot be exclusively interpreted in terms of plume activity. From a thermal point of view, magma production rates are low compared with the core part of plume-related provinces. Additionally, the hot mantle below the West Antarctic Rift System is not documented as deep as expected for mantle plumes and the shape of thermal anomaly is related to lithospheric geometry, being linear rather than having circular symmetry. The lack of any decisive evidence for plume activity is contrasted by evidence that large-scale tectonic features guide magma emplacement: the Cenozoic fault systems reactivated inherited Palaeozoic tectonic discontinuities and their activity is dynamically linked to the Southern Ocean Fracture Zones. As an alternative to both active, plume-driven rifting and passive rifting, we propose that lithospheric strike-slip deformation could have promoted transtension-related decompression melting of a subplate mantle already decompressed and veined during the late Cretaceous amagmatic extensional rift phase. Magma ascent and emplacement occurred along the main strike-slip fault systems and along the transtensional fault arrays departing from the master faults.

Thinning of the lithosphere and rifting have long been considered in terms of the end-members model of active versus passive rifting: namely, the forces leading to rift formation may be related to hot mantle upwelling from significant depth or may be driven by plate dynamics processes. Recent multidisciplinary studies carried out on the West Antarctic Rift System (WARS) shed light on the relative role of different processes on rift evolution. The WARS is one of the largest areas of crustal stretching in the world, being similar in size to the East African Rift System and to the Basin and Range extensional province of the western USA (e.g. Tessensohn & Wörner 1991). The WARS is marked by a topographic trough 750 to 1000 km wide and 3000 km long (LeMasurier & Rex 1991), running from the base of the Antarctic Peninsula in the Weddell Sea, to the Ross Sea Embayment-northern Victoria Land (Fig. 1). Both flanks of the rift system have been affected by late Oligocene-Miocene to Recent volcanic activity (LeMasurier & Thomson 1990). Investigations of the volcanism in Marie Byrd Land led to the proposal of a genetic link between the WARS and an active plume centred below Marie Byrd Land. The evidence cited in favour of this hypothesis includes: (1) the geochemical similarity between the basalts from WARS and basalts associated with

From: STORTI, F., HOLDSWORTH, R. E. & SALVINI, F. (eds) *Intraplate Strike-Slip Deformation Belts.* Geological Society, London, Special Publications, **210**, 145–158, 0305-8719/03/$15

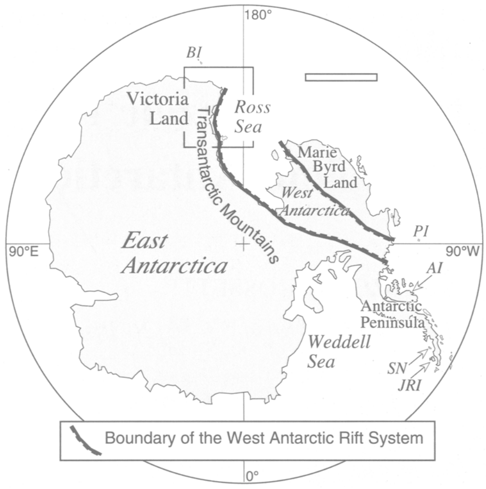

Fig. 1. Location map of the WARS. The box represents the area enlarged in Fig. 2, i.e. the northeastern portion of the Ross Embayment. Abbreviations: BI: Balleny Islands; PI: Peter I Øy; AI: Alexander Island; SN: Seal Nunatak; JRI: James Ross Island.

long-lived hot-spot tracks (Hole & LeMasurier 1994); (2) the presence in Marie Byrd Land of horst-graben sub-ice topography producing a large uplifted dome (LeMasurier & Landis 1996); (3) the modest Cenozoic extension in the WARS, insufficient to generate the observed amount of magmatism; (4) the lack of significant plate tectonic events coeval to rifting and volcanism in West Antarctica (Hole & LeMasurier 1994); (5) the high heat flow in the Ross Sea area (Blackman *et al.* 1987; Storey *et al.* 1999). This model has been progressively extended to different part of the rift system, mainly based on the geochemical features of magmas, leading to the hypothesis of rifting linked to two plumes active below Marie Byrd Land and Mt Erebus, respectively (Storey *et al.* 1999).

Recent geological-geophysical investigations in the Ross Sea region (namely Victoria Land and the Ross Sea) highlighted a complex Cenozoic geodynamic scenario, dominated by intraplate right-lateral strike-slip tectonics which induced a significant oblique component in the rifting process (Salvini *et al.* 1997). This, coupled with the spatial, structural, and chronological distribution of plutons and dyke swarms recently found on the western Ross Sea shoulder (e.g. Tonarini *et al.* 1997; Rossetti *et al.* 2000; Rocchi *et al.* 2002) casts doubts on the plume scenario and may support a transtension-related source for the Cenozoic magmatism in the Ross Sea region.

In this paper we review the major structural, magmatic, and chronological features of the WARS in the Ross Sea region and compare them with the main characteristics expected for a mantle plume dominated tectonomagmatic scenario. Such a critical comparison led us to propose an alternative to both plume-related and passive rifting scenarios, with the genesis and emplacement of Cenozoic magmas triggered by deep-reaching intraplate strike-slip to transtensional tectonic discontinuities.

The West Antarctic Rift System: an overview

The WARS is geometrically asymmetric. The eastern flank in Marie Byrd Land is characterized by a basin-and-range topography, with about 3 km of uplift in the central part (LeMasurier & Rex 1989). The opposite flank in northern Victoria Land (NVL) is constituted by the Transantarctic Mountains, which includes the exhumed roots of the early Palaeozoic Ross orogenic belt (Stump 1995 and references therein) with NW–SE to NNW–SSE-striking crustal discontinuities (Gibson & Wright 1985; Salvini *et al.* 1997; Finn *et al.* 1999) that were reactivated during the Cenozoic. The Ross Orogen was eroded to produce a flat-lying erosional surface Devonian to Triassic in age, known as the Kukri peneplain. Rifting affected NVL and East Antarctica in the middle Jurassic, causing the generation of the Ferrar Large Igneous Province (Storey & Alabaster 1991; Elliot 1999). During the late Cretaceous, the Antarctic plate reached the southern polar position and has not moved appreciably since then. At that time, widespread denudation occurred in NVL (Stump & Fitzgerald 1992; Balestrieri *et al.* 1994; Fitzgerald & Stump 1997) and the Transantarctic Mountains started to rise, related to a major phase of amagmatic rifting in the Ross Embayment (e.g. Tessensohn & Wörner 1991). Crustal thinning led to the formation of four main N–S elongated basins in the Ross Sea (Victoria Land Basin, Northern Basin, Central Trough, and Eastern Basin) separated by basement highs (Cooper *et al.* 1991).

The middle Eocene was characterized by a major change in the geodynamic scenario of the WARS, marked by the inception of intraplate right-lateral strike-slip faulting that caused the change from orthogonal to oblique rifting along the western shoulder (Salvini *et al.* 1997). A major phase of renewed uplift and denudation affected the Transantarctic Mountains (Fitzgerald & Stump 1997) and deeply sourced magmatic activity started in Victoria Land and western Ross Sea (Tonarini *et al.* 1997), continuing until the Recent on both flanks of the rift.

Magnitude of extension in the WARS

The amount of extension in the WARS is uncertain. The maximum late Cretaceous to Recent displacement between East and West Antarctica has been estimated by Fitzgerald *et al.* (1986) as 255–350 km, while Trey *et al.* (1999) proposed 480–500 km, and DiVenere *et al.* (1994) suggested about 1000 km. For the Cenozoic magnitude of extension, a very low value (<50 km) is proposed by Lawver & Gahagan (1994), while a higher value is regarded as possible by Kamp & Fitzgerald (1987). Cande *et al.* (2000) suggested that 180 km of separation in the Western Ross Embayment occurred in Eocene-Oligocene times.

Cenozoic tectonics of the Ross Sea region: a review

Recent geological-geophysical data on Cenozoic faulting in the Ross Sea region strongly impact on the previous interpretations that assign only a negligible role of Eocene to Recent deformations in the structural architecture of the whole area (Salvini *et al.* 1997; Salvini & Storti 1999; Storti *et al.* 2001; Rossetti *et al.* 2002). The new Cenozoic tectonic fabric identified from the multidisciplinary integration of offshore and onshore data has a complex 3D distribution of fault geometry and kinematics (Fig. 2). Well-developed NW–SE-striking

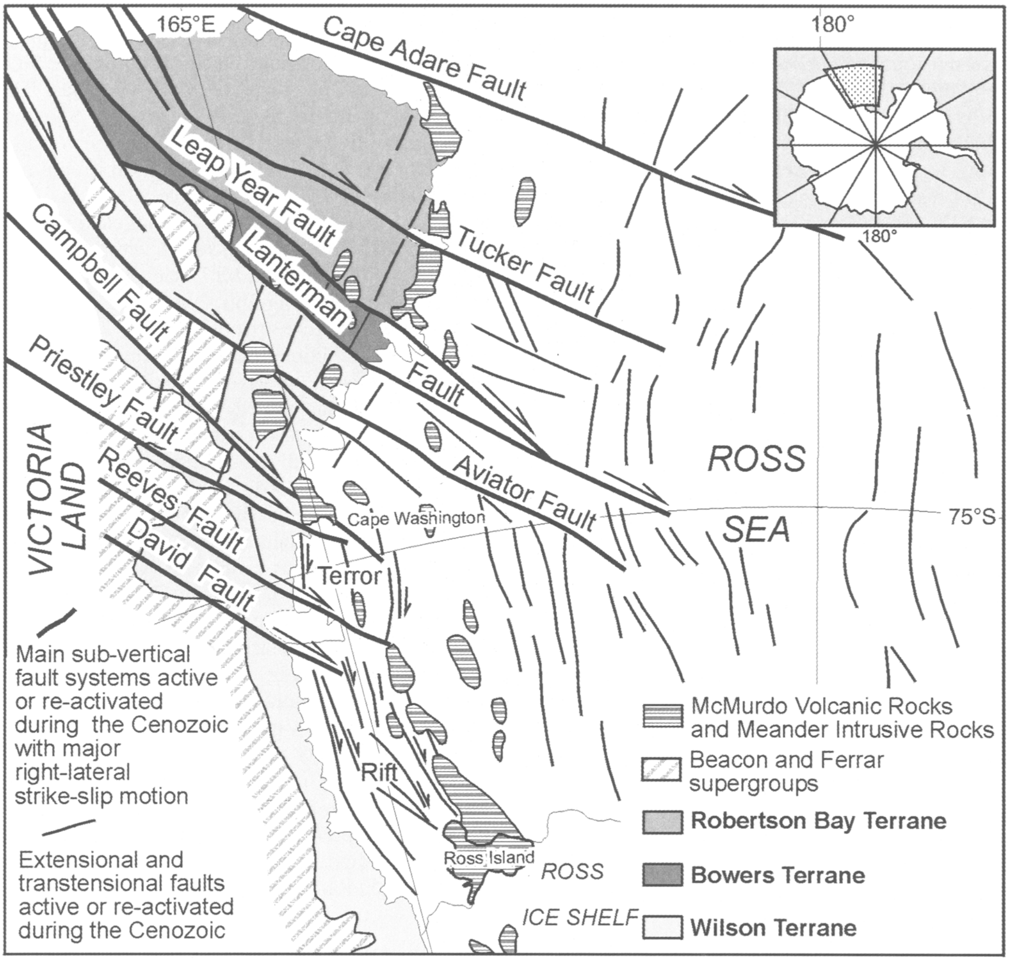

Fig. 2. Tectonic map of Cenozoic fault patterns in the Ross Sea region (Victoria Land and Ross Sea), redrawn after Salvini *et al.* (1997) and Salvini & Storti (1999). The area reported in Fig. 3 is the central-northern portion of coastal Victoria Land.

right-lateral strike-slip fault systems occur in NVL and in the northern sector of the Ross Sea. They include the strike-slip brittle reactivation of two major terrane boundary faults, i.e. the Lanterman Fault and the Leap Year Fault. Detailed field work along the Lanterman Fault (Rossetti *et al.* 2002) and the Priestley Fault (Storti *et al.* 2001) documented very complex internal structural architectures, which are typical of intraplate fault systems, characterized by strike-slip to transpressional conditions along the master fault segments. Approaching their southeastern terminations, the NW–SE strike-slip fault systems are abutted by the N–S-striking basin boundary fault systems of the western Ross Sea (Fig. 2). Interpretation of reflection seismic profiles across these basins basically showed a two-stage evolution: (1) early extensional deformations (Cooper *et al.* 1991) overprinted by (2) transtensional deformations with local positive inversion phenomena (Salvini *et al.* 1997, 1998). Transtensional conditions have also been described along the western shoulder of the Ross Sea (Wilson 1995; Rossetti *et al.* 2000). In this frame, the horizontal slip component along the N–S-striking faults in the western Ross Sea is related to the transfer of the residual right-lateral strike-slip shear from the NW–SE-striking fault systems into the basins (Salvini *et al.* 1997; Storti *et al.* 2001).

The availability of a good offshore stratigraphic record in the seismic profiles provides age constraints on the age of faulting in the Ross Sea region (Cooper *et al.* 1991; Brancolini *et al.* 1997). Early extensional deformations in the basins, which were preserved by younger reactivation, are systematically sutured by the RS-U6 unconformity, a major break-up unconformity in the Ross Sea. Transtensionally reactivated former extensional faults and the offshore portion of the NW–SE right-lateral strike-slip faults cut across RS-U6 and, in many cases, have a bathymetric expression suggesting very recent activity. The passage from extensional to transtensional regime in WARS evolution is chronologically documented by dating the RS-U6 unconformity. This age is still a matter of debate and has been tentatively constrained at about 30 or 42 Ma by Busetti (1994).

Cenozoic magmatism in the Ross Sea region: a review

Geology and geochemistry of igneous rocks

Plutons and dyke swarms of the Meander Intrusive Group (Tonarini *et al.* 1997), along with volcanoes of the McMurdo Volcanic Group (LeMasurier 1990), are exposed in the coastal region of Victoria Land, i.e. the western rift shoulder, and cover a time span of almost 50 Ma, from middle Eocene to the present. The plutons crop out in a 200-km-long section of the western rift shoulder, on the Ross Sea coast of NVL between Campbell Fault and Leap Year Fault, and are usually associated with strong positive magnetic anomalies (Müller *et al.* 1991). The largest intrusions cover individually about 70–80 km^2 (Fig. 3). All the intrusions have isotropic internal fabric, and the overall map shape in some cases is weakly elongated trending around N140E. These intrusive masses are made up of gabbroic and syenitic portions, sometimes interlayered, sometimes mingled together (Rocchi *et al.* 2001). Gabbros are mainly *ol-hy* normative and mildly alkaline, while syenites are generally *Q*-normative, sometimes peralkaline. The dykes occur over a 400×50 km area as widespread swarms cutting either the Palaeozoic basement or the Cenozoic igneous complexes. Most hypabyssal rocks are basic (basanites, tephrites, alkali-basalts) to intermediate in composition, partly bridging the SiO_2 gap found for the intrusive rocks (Fig. 4a). The dyke association is alkaline to strongly alkaline, and is generally ne-normative. Among the volcanic features, large active volcanoes (e.g. Mt Erebus and Mt Melbourne), small active edifices (Mt Rittmann), and rather young monogenetic scoria cones coexist with older volcanoes, either well preserved (e.g. Mt Overlord, Mt Discovery), or largely dissected (Mt Morning and some large edifices in the Daniell and Adare peninsulas).

The overall compositional spectrum of the Meander Intrusive Group overlaps that of the geographically overlapping Melbourne Volcanic Province, that however also contains scarce phonolites (Fig. 4a). The overall distribution of incompatible elements is dominated by high ratios of Nb and Ta relative to LILE and Y-HREE (Fig. 4b), as typical of oceanic island basalts (OIB; Sun & McDonough 1989). The ubiquitous prominent K and Pb negative anomalies are noticeable. Intrusive rocks, dykes, and younger volcanic rocks display comparable trace element distribution, including marked K and Pb troughs (Fig. 4b). The $^{87}Sr/^{86}Sr(t)$ ratios for fresh, crustally uncontaminated samples from plutons and dykes vary from 0.70299 to 0.70372 and $^{143}Nd/^{144}Nd(t)$ is between 0.512839 and 0.512941. Sr–Nd isotope compositions of young lavas range across the same interval, although data for dykes and plutons cluster towards slightly more enriched compositions with respect to younger lavas (Fig. 5; Rocchi *et al.* 2002).

Geochronology of igneous rocks

Chronological data are available for igneous rocks from NVL north of the Priestley Fault (Fig. 6; (Müller *et al.* 1991; Tonarini *et al.* 1997; Armi-

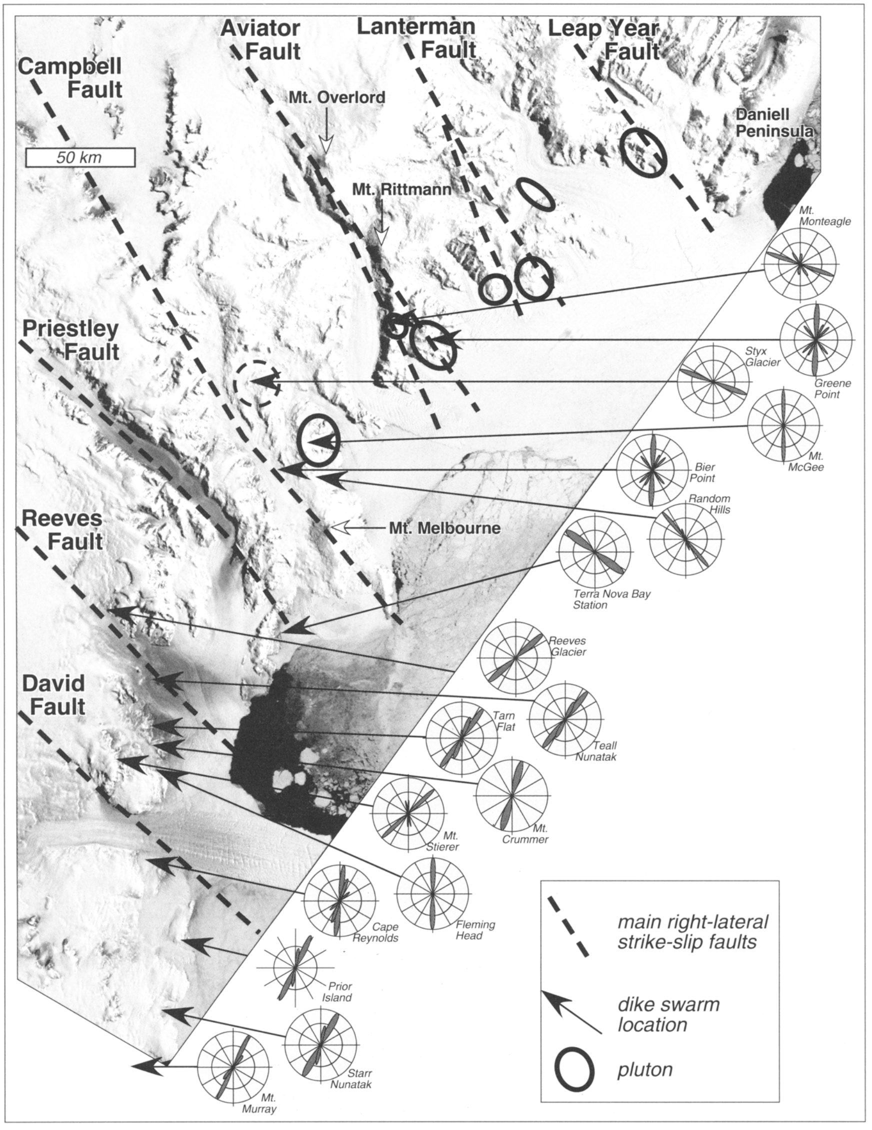

Fig. 3. Satellite image of central-northern portion of coastal Victoria Land, reporting: (1) outcrop contours of the Cenozoic plutons, (2) location of the main dyke swarms (arrow points), and (3) rose diagrams for the dyke swarms. Base image is a Landsat satellite image mosaic in Lambert conformal conic projection, courtesy of Lucchitta *et al.* (1987). The number of measured dykes is 220.

enti & Baroni 1999; Rocchi *et al.* 2002). The gabbro-syenite plutons have ages between 48 and 23 Ma, and the dykes cover the time span 47–35 Ma, representing the earliest record of regionally extensive Cenozoic rift-related igneous activity in Antarctica. The dykes cutting the Cenozoic plutons are generally a few million years younger than the host intrusion, and no significant age difference can be detected between these dykes and those cutting the Palaeozoic basement. The age ranges for NNW–SSE dykes and the N–S dykes (see below) are indistinguishable within analytical errors. In the area between Campbell Fault and Aviator Fault, the igneous activity (plutons and dyke swarms) is restricted to the time interval 48–35 Ma, whereas between Aviator Fault and Leap Year Fault the magmatism ranges from 31 to 18 Ma in age.

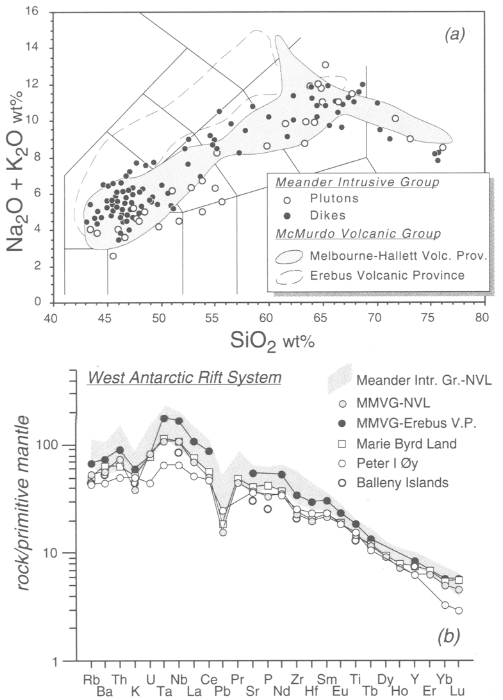

Fig. 4. (**a**) TAS diagrams (Le Bas *et al.* 1986) for the studied plutonic-subvolcanic association. Volcanic products from the Melbourne and Hallett Volcanic Provinces (LeMasurier & Thomson 1990; Armienti *et al.* 1991) and the Erebus Volcanic Province (LeMasurier & Thomson 1990; Kyle *et al.* 1992) are reported for comparison. (**b**) Primitive mantle normalized (McDonough & Sun 1995) multielement spidergrams of averages of volcanic provinces linked to the WARS. Shaded field represents the variability of the middle-late Eocene dykes from northern Victoria Land. Averages are calculated from mafic rocks with MgO>5wt%. Sources of data: MIG-NVL: mafic dykes from Rocchi *et al.* (2002); MMVG-NVL: lavas from the Melbourne and Hallett Volcanic Provinces (Wörner *et al.* 1989; Rocholl *et al.* 1995); MMVG-EVP: Erebus Volcanic Province (Kyle *et al.* 1992); MBL: Marie Byrd Land (Hole & LeMasurier 1994; Hart *et al.* 1997); Peter I Øy (Prestvik *et al.* 1990; Hart *et al.* 1995); Balleny Islands (Green 1992).

Relations between faulting and dyke injection

The orientation of dykes along the western shoulder of the Ross Sea is almost bimodal in the area north of the Reeves Glacier and is unimodal in the southern sector (Fig. 3). In the northern sector, dykes strike NW–SE and almost N–S, i.e. parallel to the major right-lateral strike-slip fault systems and to the basin boundary faults, respectively. At Terra Nova Bay Station, dyke arrangement in left-stepping en echelon tension gash arrays with a

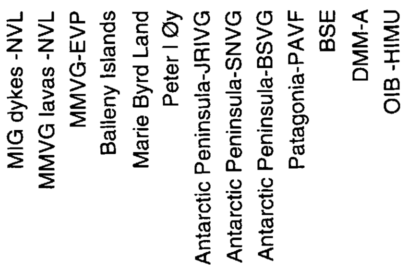

Fig. 5. Multiple plot summarizing the isotopic variations of mafic products across the WARS, the adjoining, contemporaneously active volcanic provinces, and the main OIB reservoirs. The arrow in the middle diagram points to the high $^{143}Nd/^{144}Nd$ ratio for DMM-A. Source of data: MIG-NVL: mafic dykes from Rocchi *et al.* 2002; MMVG-NVL: lavas from the Melbourne and Hallett Volcanic Provinces (Wörner *et al.* 1989; Rocholl *et al.* 1995); MMVG-EVP: Erebus Volcanic Province (Kyle *et al.* 1992); MBL: Marie Byrd Land (Hole & LeMasurier 1994; Hart *et al.* 1997); Peter I Øy (Prestvik *et al.* 1990; Hart *et al.* 1995); Balleny Islands (Hart 1988; Green 1992); JRIVG: James Ross Island Volcanic Group (Antarctic Peninsula; Hole *et al.* 1995; Lawver *et al.* 1995); SNVG: Seal Nunataks Volcanic Group (Antarctic Peninsula; Hole 1990; Hole *et al.* 1993); BSVG: Bellingshausen Sea (i.e. Alexander Island) Volcanic Group (Antarctic Peninsula; Hole 1988; Hole *et al.* 1993);

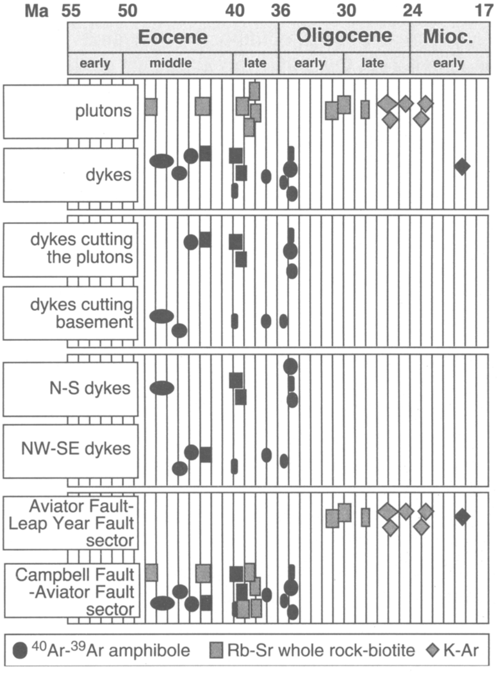

Fig. 6. Age data of igneous activity in Victoria Land north of Campbell Fault. ^{40}Ar–^{39}Ar ages after Rocchi *et al.* (2002); Rb-Sr ages after Tonarini *et al.* (1997), K-Ar ages after Müller *et al.* (1991). Acquisition of geochronological data for dykes from south of Campbell Fault is in progress.

NW–SE envelope trend (Fig. 7a), supports their emplacement in a NW–SE right-lateral strike-slip shear zone which constitutes a splay fault of the Priestley Fault (Storti *et al.* 2001). In the southern sector, dykes are arranged in left-stepping arrays at an angle of about 30° to the N–S transtensional master faults and in places show tension-gash-like relationships with these faults (Fig. 7b), indicating syntectonic dyke emplacement in a dextral regime (Rossetti *et al.* 2000).

This field evidence indicates that dyke emplacement and geometry were initiated and driven by the ongoing tectonics. In the northern sector, both the NW–SE right-lateral strike-slip fault systems and the basin boundary faults along the Ross Sea shoulder induced magma emplacement. In the southern sector, the emplacement of dykes was linked to the activity of transtensional faults. The

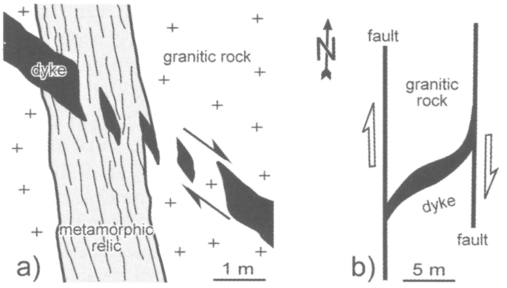

Fig. 7. Outcrop-scale relations between right-lateral strike-slip faulting and dyke injection. (**a**) Left-stepping en echelon tension gash arrays of basaltic dykes at Terra Nova Bay Station after Storti *et al.* (2001). (**b**) Cartoon showing the tension gash geometry of dykes at Starr Nunatak (after Rossetti *et al.* 2000). For locations, see Fig. 3.

genetic relationships between tectonic and magmatic activities constrain the age of onshore faulting, which had to be active since Eocene times, at least north of Priestley Fault (Fig. 6).

Discussion: a role for a mantle plume on WARS development?

Evidence from the regional tectonic framework

Typical features of a mantle plume dominated tectonic scenario are the development of a low-amplitude, broad-wavelength uplifted region with a roughly circular symmetry and an almost radial pattern of extensional fault systems (Olsen 1995), particularly for the Antarctic plate, which has been almost stationary since Cretaceous time. The present-day tectonic and morphological architecture of Marie Byrd Land has been interpreted as fitting these features (LeMasurier & Landis 1996). Conversely, Victoria Land is characterized by an elevated linear rift shoulder (the Transantarctic Mountains) developed by N–S extensional to transtensional faulting and transverse faulting (e.g. Cooper *et al.* 1991; Behrendt *et al.* 1996; Wilson 1999; Rossetti *et al.* 2000) that, in the northern sector, abut NW–SE-striking intraplate right-lateral fault systems (Salvini *et al.* 1997) with no evidence for either doming or radial structures.

The relative chronology of uplift and extension also counters the traditional concepts of lithospheric evolution above a mantle plume. The main extension episode occurred in the late Cretaceous (e.g. Lawver & Gahagan 1994), while the main uplift episode occurred during the Eocene (Stump & Fitzgerald 1992; Fitzgerald & Stump 1997). A thermal source for the uplift of the Transantarctic Mountains has been suggested (Smith &

PAVF: Pali Aike Volcanic Field (southern Patagonia; D'Orazio *et al.* 2000). BSE (Bulk Silicate Earth), DMM-A (Depleted MORB Mantle-type A), and OIB-HIMU (Ocean Island Basalts with high $^{238}U/^{204}Pb$ ratio; Zindler & Hart 1986).

Drewry 1984; Berg *et al.* 1989; Stern & Ten Brink 1989), but alternative mechanisms have been proposed such as isostatic uplift of the hanging wall of a major fault cutting the lithosphere (Stern *et al.* 1992) or uplift linked to a shallow-dipping detachment fault in an asymmetric passive rift setting (Fitzgerald *et al.* 1986; Fitzgerald & Baldwin 1997). Finally, the activity of a plume carrying higher-than-normal mantle temperatures is difficult to reconcile with the prolonged subsidence of Ross Sea basins during Cretaceous and Cenozoic time.

Evidence from geochemical data

The plutons and dyke swarms of NVL (Meander Intrusive Group) display the typical OIB geochemical features. The geochemical characteristics of the whole igneous association show restricted variations over 50 myr and across the whole area (Rocchi *et al.* 2002). Additionally, a close similarity is observed with the neighbouring Cenozoic magmatic provinces of the Antarctic plate and with magmatic provinces from oceanic and continental setting classically defining the HIMU affinity, i.e. characterized by $^{206}Pb/^{204}Pb$ in excess of 20.5 (Fig. 5; Hofmann 1997). These geochemical features represent one of the classical arguments used to infer the activity of a deep mantle plume for many volcanic provinces in both oceanic and continental settings, based on the ambiguous relation between OIB–HIMU chemistry (a chemical reservoir) and mantle plume (a physical entity). On this ground, the wide diffusion of Cenozoic volcanism with similar geochemical affinity throughout Antarctica, Southern Ocean islands, Tasmania, New Zealand, and Campbell Plateau led Hart *et al.* (1997) to hypothesize the origin of magmas from a fossil plume head source, which impacted the Gondwana lithosphere before break-up in this area, i.e. before the late Cretaceous. The moment of plume impingement is controversial and could be related to either the middle Jurassic emplacement of the Ferrar Large Igneous Province (LIP) or the mid-late Cretaceous break-up of New Zealand from West Antarctica (Weaver *et al.* 1994). However, the occurrence of Ferrar basalts exclusively along the Transantarctic Mountains coupled with their absence in Marie Byrd Land and the other sites of Cenozoic OIB magmatism is evidence against a role for widespread sublithospheric mass contribution to the source of Cenozoic magmatism by a Jurassic plume. On the other hand, the idea of a late Cretaceous plume activity in West Antarctica is overruled by the lack of Cretaceous magmatism across the whole Victoria Land coupled with evidence for subsidence instead of buoyant uplift (LeMasurier & Landis 1996). Actually, the geochemically grounded claim for a fossil plume head source is set up to satisfy the need for a shallow, weak, enriched layer, common to wide areas below the Southern Ocean and the adjoining continents. One of the most used isotopic issue to claim for mantle plumes is the high $^{206}Pb/^{204}Pb$ ratio, thought to be derived from deep mantle plumes that entrained slab material recycled into the deep mantle over a long time period (10^9 years). However, Halliday *et al.* (1995) showed that such a high $^{206}Pb/^{204}Pb$ ratio can be also attained by the magma source at rather shallow depth, in shorter time interval (10^8 years, provided the source has a rather high U/Pb ratio) and proposed a model for U/Pb fractionation close to mid-ocean ridges and later sampling of such high U/Pb source by oceanic islands magmatism. It is worth noting that Cenozoic mafic dykes and lavas from NVL have an average U/Pb ratio of 0.44 ± 0.11 and 0.66 ± 0.17. This implies a high U/Pb ratio in the magma source, which therefore has been able to produce high $^{206}Pb/^{204}Pb$ ratios in a time span of the order of 10^8 years. Therefore, we propose a model (see further on) in which the source enrichment occurred in the late Cretaceous some tens of million years before the magmatism.

Evidence from the thermal and magmatic regional framework

Two classical pieces of evidence for the activity of mantle plumes are the preservation of hot-spot tracks and the high volume of magmas produced. In the WARS, chronological-areal progression of magmatism is lacking and the volume of magmas produced is low. However, these facts cannot be unequivocally used to counter the plume hypothesis owing to the very low mobility of the Antarctic plate since the late Cretaceous and the peculiar 'stationary' setting of the Antarctic plate, almost completely encircled by mid-ocean ridges (Hole & LeMasurier 1994).

The presence of seismically slow (hot) mantle in the WARS has been imaged from surface wave tomography (Danesi & Morelli 2000, 2001). The depth to which hot mantle extends cannot be safely modelled below 200 km, not deep enough to support or discard the occurrence of an active plume. Nevertheless, it is worth noting the slow mantle does not have a circular symmetry, as expected for a plume: the group velocity maps of Rayleigh waves (Danesi & Morelli 2000) show minimum values arranged on a line corresponding to the belt of transformation of the ridge between the Antarctic and Australian plates (Fig. 8). This indicates that shallow hot mantle is related to a linear geodynamic feature >4000 km long, such as the belt of Southern Ocean fracture zones. These large-scale tectonic lineaments cross the continental litho-

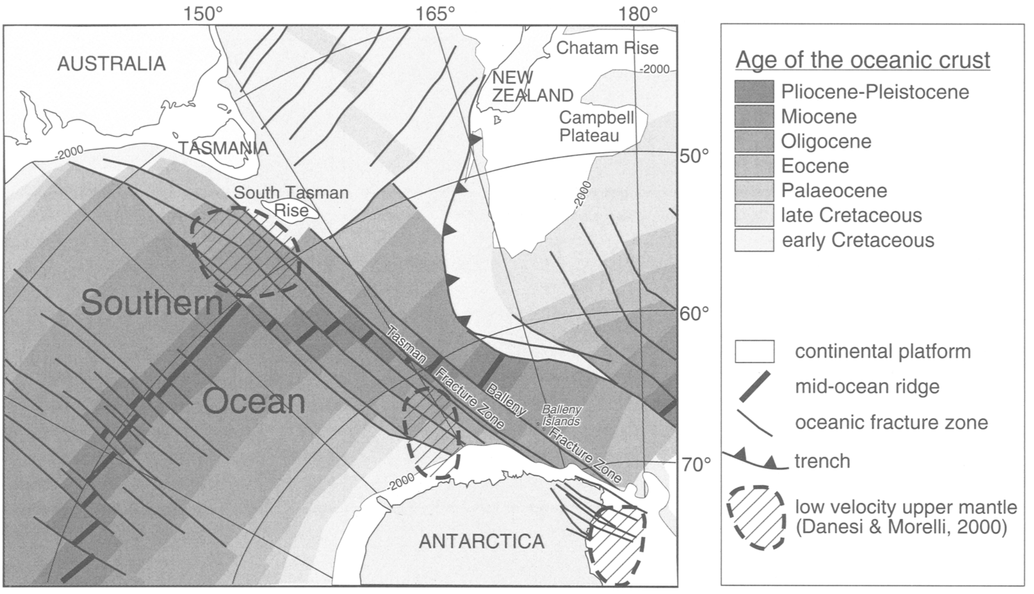

Fig. 8. Southern Ocean Fracture Zones. Redrawn after Salvini *et al.* (1997), with mantle low-velocity anomalies after Danesi & Morelli (2000).

sphere through NVL to the Ross Embayment (Salvini *et al.* 1997) and could be responsible for the transtensional Cenozoic rifting phase with a rise of mantle geotherms to generate melt in the mantle and strike-slip to transtensional tectonic activity controlling the emplacement of magmas within the crust or at the surface.

Intraplate strike-slip faulting: an alternative geodynamic scenario for magma genesis and emplacement

The equivocal geochemical data, coupled with the lack of diagnostic tectonomagmatic and geomorphic evidence, do not support the activity of a mantle plume as the driving mechanism for the generation and emplacement of Cenozoic magmas in NVL. On the other hand, spatial and temporal links between the Cenozoic strike-slip tectonic regime and the igneous activity support intraplate right-lateral shear as an effective and alternative geodynamic scenario for magma emplacement. According to Salvini *et al.* (1997) the magmatic activity is focused in a belt along the western shoulder of the Ross Sea owing to the rheological zoning of the brittle crust induced by the eastward shallowing of the Moho moving from the Transantarctic Mountains to the Eastern Basin in the Ross Sea (Cooper *et al.* 1991): crustal thickness below the western Ross Sea shoulder would be appropriate for the fracturing/permeability conditions required for magma ascent. Additionally, this belt corresponds at depth to a topographic gradient at the base of the lithosphere, that could enhance convection-driven melting (Anderson 1995).

The recent data reviewed in this paper on (1) the structural architecture of some of the intraplate right-lateral fault systems and their relations with dyke emplacement, (2) the attitude and chemical composition of Cenozoic dykes along a significant segment of the western shoulder of the Ross Sea, and (3) the geochronological constraints support the strike-slip-related model for magma emplacement. The space-time distribution of plutons and dykes in NVL (Fig. 9), suggest that igneous activity has been active in different crustal sectors and/or along different boundary faults in different times. The boundaries between these sectors are the major right-lateral fault systems identified by Salvini *et al.* (1997). In particular, the crustal sector affected by Cenozoic pluton emplacement is bounded to the north by the Leap Year Fault and to the south by the Campbell Fault (Fig. 9a). The three adjacent sectors with different dyke geometries and frequency are bounded, from the north to the south, by the Leap Year Fault, the Aviator Fault, and the Priestley Fault, respectively (Fig. 9b); the two adjacent sectors characterized by different timing of magma emplacement are bounded by the Leap Year Fault, the Aviator Fault, and the Priestley Fault, respectively (Fig. 9c).

During the last 50 myr NVL has been affected

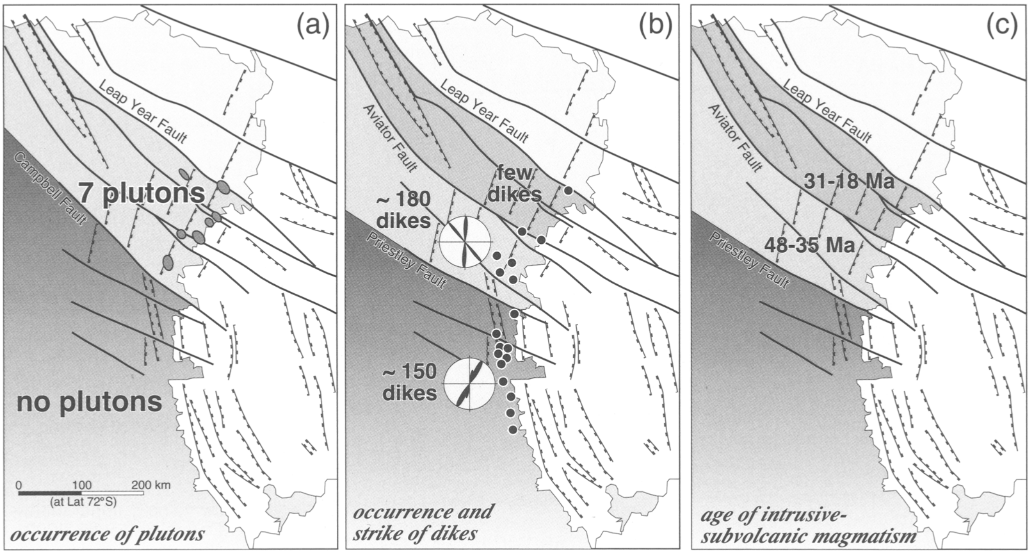

Fig. 9. Space-time distribution of Cenozoic plutonic and subvolcanic igneous products in northern Victoria Land.

by lithospheric shear processes which divided the area into sectors characterized by different tectonomagmatic history. Such a compartmentalization may relate to the crustal fabric inherited from the previous tectonic history of the region, namely the early Palaeozoic Ross Orogeny and the late Cretaceous Ross Sea initial opening. Different slip rates along the major intraplate right-lateral fault systems may have induced a temporal zoning to magma genesis and emplacement.

A general model for the tectonomagmatic history of the western Ross Embayment

The alternative context proposed for magma genesis and emplacement on the western shoulder of the WARS leads to a model for the Mesozoic-Cenozoic tectonomagmatic history of the western Ross Embayment (Fig. 10). During the late Cretaceous, an early rift phase occurred with orthogonal extension that stretched the crust and the underlying strong lithospheric mantle. Lithospheric attenuation probably led to the production of very small degree partial melts. These were not sufficient to give way to surface magmatism (amagmatic rift phase), but were essential in distributing fertile, enriched, low-melting point veins/domains in a wide zone of the Antarctic plate mantle. At the middle Eocene, the increase of differential velocity along the Southern Ocean Fracture Zones reactivated the Palaeozoic tectonic discontinuities in northern Victoria Land as intraplate dextral strike-slip fault systems. The activity of these lithospheric deformation belts promoted local decompression melting of the enriched mantle domains created during the late Cretaceous and isotopically matured since then (Fig. 11). The magma rose and was emplaced along the main NW–SE discontinuities and along the N–S transtensional faults arrays departing from the master NW–SE systems (Fig. 10). This model relates the driving forces of events such as uplift, active faulting, magmatism, and seismicity to the dynamics of the Antarctic plate rather than to deep-source forces such as mantle plumes.

Conclusions

The occurrence of Cenozoic magmatism in the Ross Embayment has long been related to the presence of a mantle plume, associated with the origin and development of the whole West Antarctic Rift System. The plume hypothesis was proposed on the basis of geochemical constraints and morphological evidence in Marie Byrd Land. Our review of the tectonomagmatic framework along the western shoulder of the Ross Sea casts doubt on the mantle plume-related source for magma generation and ascent and favours intraplate right-lateral strike-slip faulting as an alternative mechanism for magma genesis and emplacement. In particular, the tight link between tectonic activity and magma emplacement suggests that the inherited lithospheric fabric of northern Victoria Land led to the tectonomagmatic compartmentalization of the whole lithosphere, with the boundaries between the

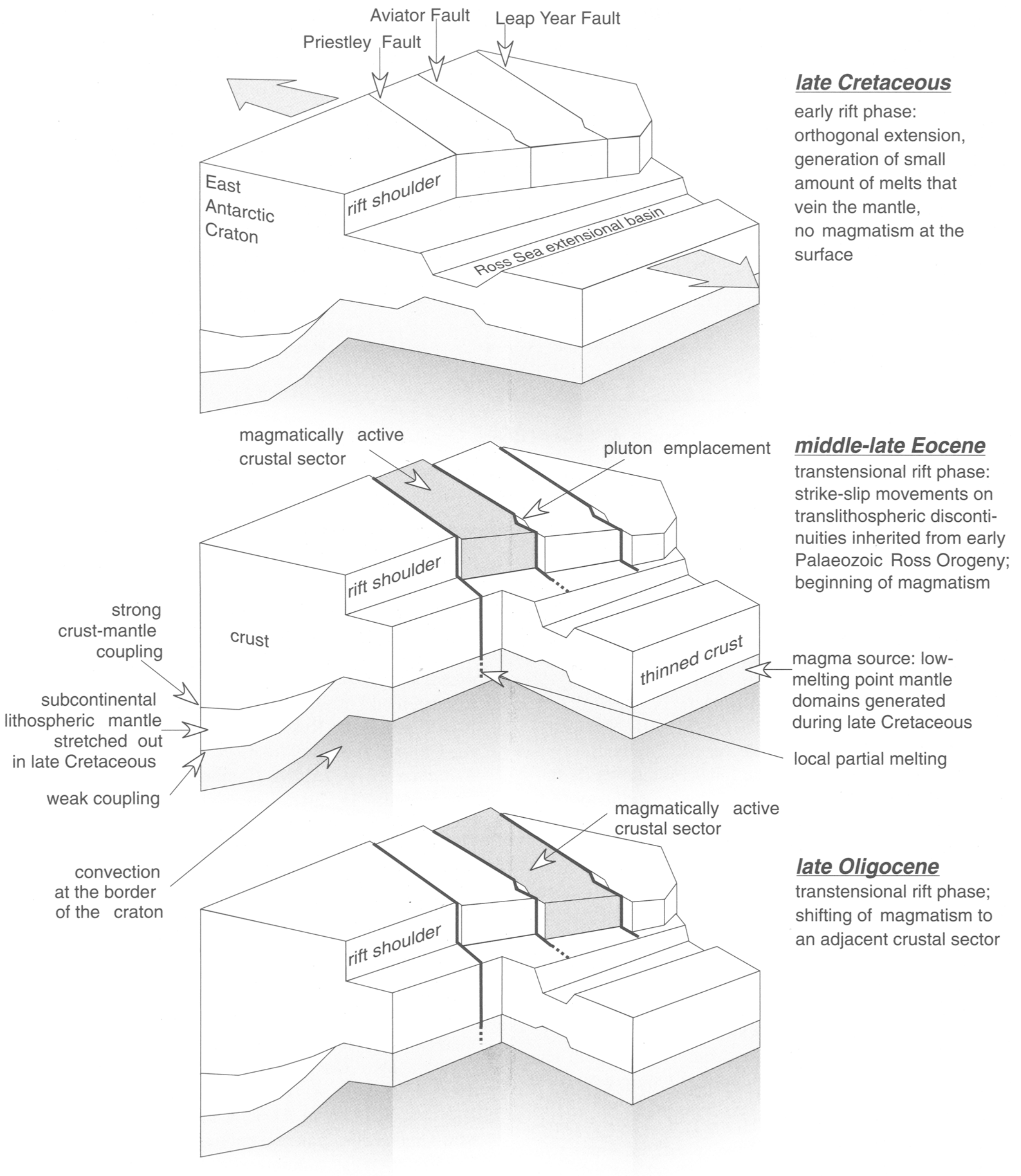

Fig. 10. General model for the Meso-Cenozoic tectonomagmatic history of the western Ross Embayment.

sectors playing an active role in both melt generation and emplacement.

We are grateful to P. Armienti, M. D'Orazio, F. Mazzarini, and F. Salvini for the stimulating discussions on the geology of the Ross Sea region. Thanks are due to B. Murphy and C. Macpherson for the constructive and stimulating review that helped us to improve and clarify the paper. The whole work is part of the Italian Antarctic Research Program (PNRA).

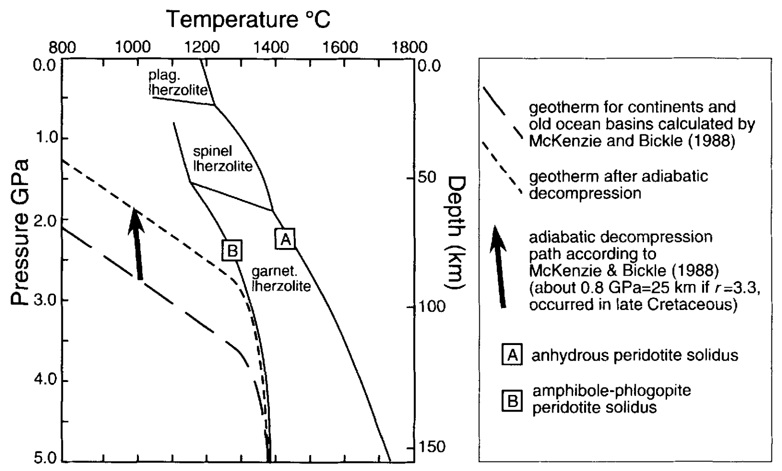

Fig. 11. P-T diagram, modified after Smith & Lewis (1999). Geotherms and adiabatic decompression paths after McKenzie & Bickle (1988).

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