The Antarctic Rift: Plume vs. Plate Dynamics

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Introduction

Thinning of the lithosphere in major continental rift systems is commonly considered in terms of the end-members models of active versus passive rifting, and a genetic connection is commonly acknowledged between lithospheric extension, magmatism and mantle plume activity.

The West Antarctic Rift System (WARS) (Figure 1) in one of the major active continental rifts on Earth, with late Oligocene to Recent volcanic activity [1]. Geophysical investigations and studies of volcanism led to the proposal of a genetic link between the WARS and an active plume centered below Marie Byrd Land [2]. The evidence cited in favour of this hypothesis includes:

1. geochemical similarity between the basalts from the WARS and basalts associated with long-lived hot-spot tracks [3];
2. the presence in Marie Byrd Land of horst-graben sub-ice topography producing a large uplifted dome [4];
3. modest Cenozoic extension in the WARS, insufficient to generate the observed amount of magmatism;
4. the lack of significant plate tectonic events coeval with rifting and volcanism in West Antarctica [3]; and
5. high heat flow in the Ross Sea area [5].

This model has been progressively extended to the whole 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 [5].

Recent geological-geophysical investigations in the Ross Sea region (namely Victoria Land and the Ross Sea) highlighted complex Cenozoic geodynamics dominated by intraplate, right-lateral strike-slip tectonics inducing a significant oblique component in the rifting process [6]. This, and the spatial, structural, and chronological distribution of plutons and dyke swarms recently found on the western Ross Sea shoulder (*e.g.*, [7-10]), casts doubts on the plume scenario and may support a transtension-related source for the Cenozoic magmatism of the Ross Sea region.

In this webpage, the geochemical, chronological and structural evidence is critically compared with the main features expected for a plume-powered system, and a model is proposed that is an alternative to both plume-driven and purely passive rifting.

Tectonics, magmatism and geochemistry

1. Hot-spot tracks

- No time progression of volcanic activity exists in the WARS.
- This could be related to the peculiar setting of the Antarctic plate, which has been stationary since the late Cretaceous, and almost completely encircled by mid-ocean ridges [3].

» NO definitive proof either in favour or against plume occurrence in the WARS.

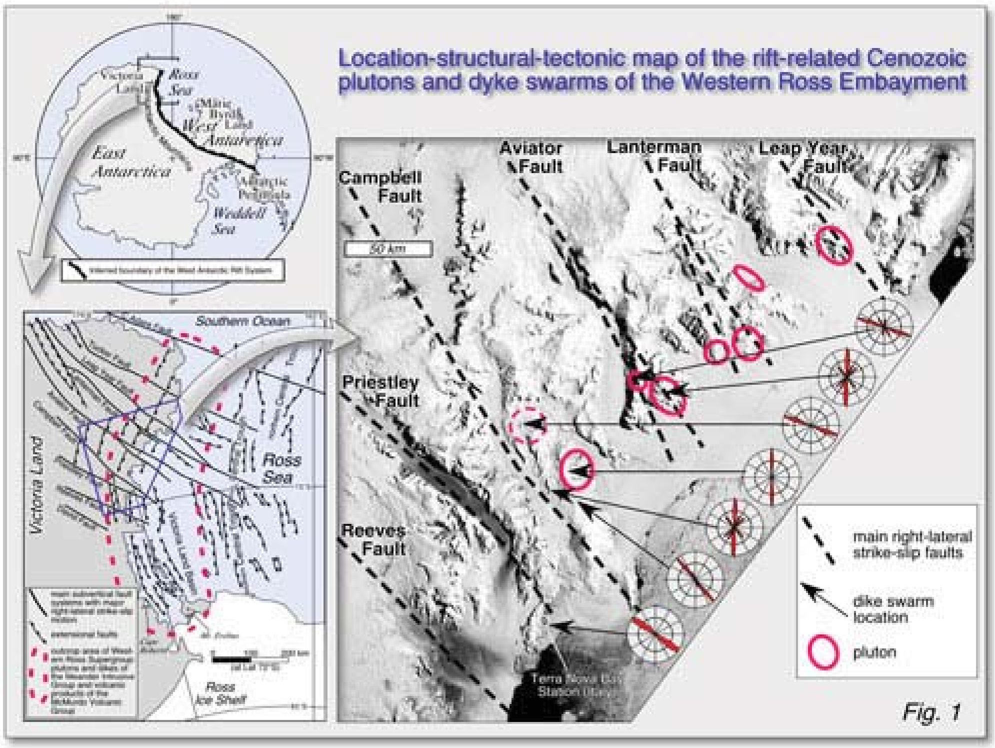

Figure 1: Location map. Click on map to enlarge.

2. Doming? Trend and and shape of surface uplift

- Overall domal uplift in Marie Bird Land.
- No doming on the western coast of the Ross Sea. Cenozoic uplift is linear, leading to the formation of the Transantarctic Mountains, dissected by transverse fault systems in northern Victoria Land.

» Lack of the circular symmetry typically associated with mantle plumes.

3. Uplift-extension: relative timing

- Prolonged subsidence and basin formation in the Ross Sea during the Cretaceous and Cenozoic.
- The main extensional episode occurred in the late Cretaceous [11], while the main denudation-uplift event began in the middle Eocene.

» The activity of a plume with higher-than-normal mantle potential temperature is difficult to reconcile with (1) Cretaceous and Cenozoic subsidence, and (2) uplift following extension rather than preceding it.

4. Extension-magmatism: relative timing

- The main extensional episode occurred in the late Cretaceous.
- Magmatism started in the middle Eocene.

» The magmatism started 30 Myr later than the main extension.

5. Cenozoic lithospheric extension

- The amount of Cenozoic extension is still matter of debate [12, 13].

» The model proposed here does not require Cenozoic extension.

6. Volume of magmatism

- Aeromagnetic data have been interpreted as evidence for a large volume of volcanic products (10^6 km^3) concealed beneath the ice sheet [14].
- This volume, when the long duration of igneous activity is taken into account (almost 50 Myr), gives low average magma production rates.

» The magma production rate is much lower than that expected in a mantle plume-dominated scenario [15].

7. Magma chemistry

- Trace elements and Sr-Nd-Pb isotopes indicate OIB-HIMU chemistry (Figure 2).
- Primitive lavas have low He isotope ratios (R/Ra=6-7) [16]. In the standard helium-isotope model, these values are lower than those expected for magmas from mantle plumes rising from the lower mantle. Recent criticism on He systematics [17] has questioned the primary validity of the standard model for He, and this should be borne in mind when considering these data (see also Helium fundamentals webpage).

» Focal point: a mantle plume is a physical entity, not a geochemical reservoir. Therefore plume occurrence (including both active and fossil) cannot be inferred from geochemistry alone.

- A residual potassic (hydrous) phase in the source [8] implies a magma source temperature lower than invoked for mantle plumes [18]. Mantle domains rich in hydrous phases are sufficient to explain “hot-spot-like” basalt geochemistry without the need for anomalously high mantle temperatures [19].
- The geochemical features of magmatism did not vary over 50 Myr [8].
- The geochemical features of magmatism show little variability across the whole rift and beyond (*i.e.* across the whole Antarctic plate) [8].
- It is worth noting that HIMU igneous provinces straddling the continent-ocean boundary (*e.g.*, the Cameroon Line) share the geochemical features of continental rifts and oceanic islands.

» Low source temperature, the same source all across the Antarctic plate and beyond, and the same source for 50 Myr: is there a fossil plume head below the WARS?

- The geochemically-based claim for a fossil plume head source, is invoked to satisfy the need for a shallow, weak, enriched layer (the perisphere? [20]), common to large areas beneath the Southern Ocean and the adjoining continents. One of the most commonly cited isotopic arguments in support of mantle plumes is the high $^{206}Pb/^{204}Pb$ ratio, proposed to result from deep mantle plumes that entrained slab material subducted into the deep mantle over a long time period (10^9 years). However, such a high $^{206}Pb/^{204}Pb$ ratio can also be attained in the magma source at shallow depth, in a shorter period of time (10^8 years, provided the source has a rather high U/Pb ratio [21]). The Cenozoic mafic dykes and lavas from northern Victoria Land have average U/Pb ratio of 0.44±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 over a time span of the order of 10^8 years.

» In the model proposed here, source enrichment occurred in the late Cretaceous, some tens of million years before the commencement of magmatism. It is not related to mantle plume activity, but to a geologic process for which there is evidence – lithospheric extension.

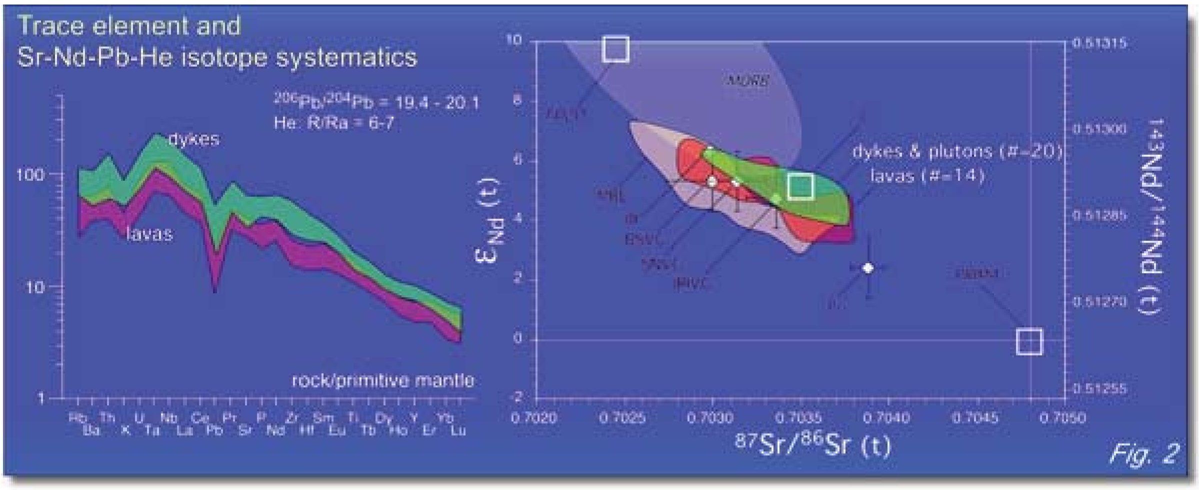

Figure 2: Trace element and Sr-Nd-Pb-He isotope systematics. Abbreviations: MBL: Neogene lavas from Marie Byrd Land; PI: Peter Island; BI: Balleny Islands; JRIVG, SNVG, BSVG: volcanic groups of the Antarctic Peninsula. Details on data sources are given in [8]. Click on figure to enlarge.

Relative timing of events

8. Space-time distribution of igneous activity

- In addition to the lack of hot spot tracks, no radial patterns of igneous activity are found.
- Rather, magmatism was activated sequentially in adjacent crustal sectors.
- The dyke swarms have NNW or NS strikes, pointing to a geometric link with intraplate NNW strike-slip fault systems [8].
- NNW and NS dykes are coeval [8].

- Pseudotachylyte generation is coeval with dyke emplacement [22].

» Magma emplacement and regional tectonic activity share the same geometry and timing.

Geometry and timing of igneous activity vs. plate dynamics

- Tight geometric link between dextral strike-slip systems in northern Victoria Land and Southern Ocean Fracture Zones ([6], Figure 3)
- Beginning of magmatism is coeval with global plate reorganization [23, 24] and increase in differential movements of Southern Ocean Fracture Zones (43-47 Ma) [25, 26].

» The tectonic framework to which emplacement of magmas is linked, is related to plate-scale tectonic processes. Also the beginning of magmatism coincides with a process that could trigger differential movements along the strike-slip fault systems, i.e differential movements on oceanic fracture zones, as shown by the Cenozoic age of pseudotachylytes generated on a NNW fault system in Victoria Land, which is a Paleozoic fault reactivated by the oceanic fracture zones [6, 8, 22]. Hence, the igneous activity appears to be governed by plate dynamics, i.e. from above, and not from below [27].

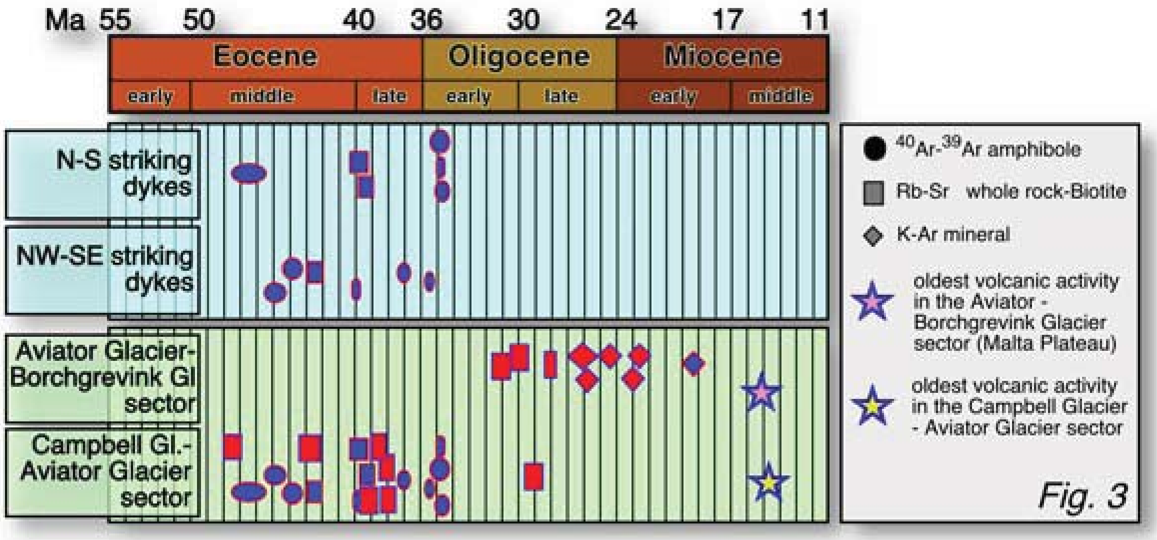

Figure 3: The chronology of Cenozoic magmatism in northern Victoria Land.

Temperature

Hot mantle? Mantle tomography

- The depth to which seismic tomography can reliably image in the Antarctic region is 200 km, which is not deep enough to confirm or disprove the presence of an active deep mantle plume.
- Slower (hotter?) mantle does not show circular symmetry, but is rather linear. In the continental part of the Antarctic Plate it is clearly bounded by the cold East Antarctic Craton, and in the oceanic part of both the Antarctic and Australian plates it overlaps with the belt of ridge transformation (*i.e.,* the zone around 150°E where the closely spaced oceanic fracture zones displace the Australia-

Antarctica ridge by ~ 1,300 km, from 50°S to ~ 62°S) (Figure 4) [28].

» Shallow, hot mantle is related to a linear geodynamic feature > 4,000 km long, that extends from Tasmania to the Ross Sea.

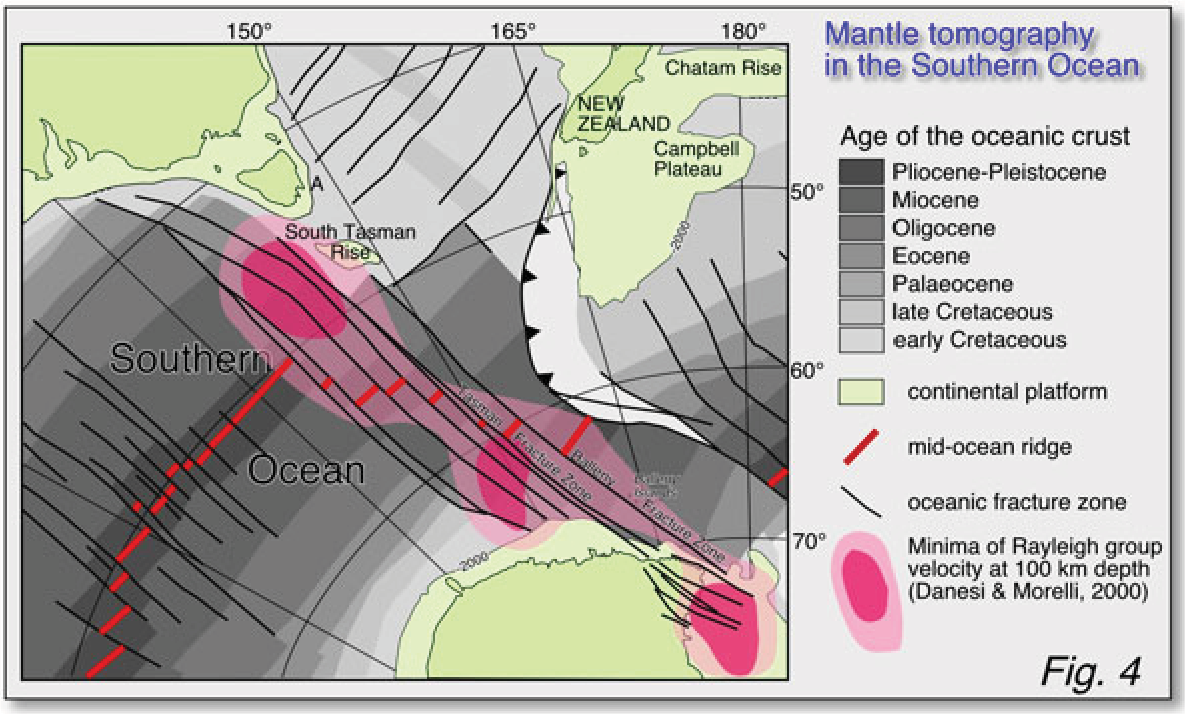

Figure 4: Plate tectonic setting and mantle tomography in the Southern Ocean.

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

- *Late Cretaceous*: an early rift phase occurred with orthogonal extension that stretched the crust and the underlying strong lithospheric mantle (Figure 4, [10]). Lithospheric thinning probably led to the production of very small degree partial melts. These were not sufficient to give way to surface magmatism *(i.e.* rifting was amagmatic), but distributed fertile, enriched, low-melting point veins/domains widely throughout the Antarctic plate mantle.

- *Middle Eocene*: the increase of differential velocity along the Southern Ocean Fracture Zones reactivated the Paleozoic 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 (Figure 4). 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 (Figure 1).

- This model (Figure 5) 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. It is therefore potentially testable, *e.g.*, by:

    1. checking the distribution of magmatism vs. strike-slip fault systems in the still poorly known areas onshore, such as central Victoria Land (where fault systems are almost lacking) and northernmost Victoria Land (where the faults are widely spaced: Figure 1);

2. determining the age of pseudotachylytes in other areas, to control further their contemporaneity with magma emplacement;
3. using the growing seismic data set to determine mantle velocity anomalies deeper than 200 km;
4. using aeromagnetic data to define better the shapes of partly buried intrusions and link them to a tectonic framework;
5. investigating the origin of felsic magmas (differentiation vs. unmixing [9]) to constrain the original volume of mafic melt and developing models for the structure of the upper crust.

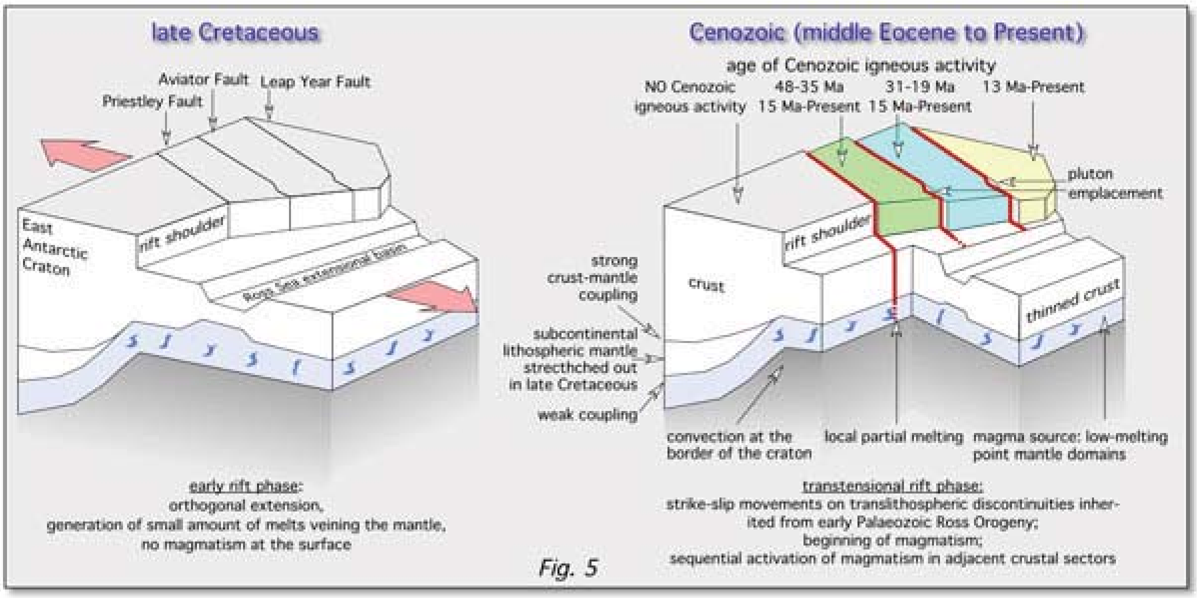

Figure 5: Model for Cretaceous and Cenozoic tectonic development of the Antarctic rift. Click on figure to enlarge.

References

1. LeMasurier W.E., Thomson J.W., eds. 1990. Volcanoes of the Antarctic Plate and Southern Oceans. *Antarctic Research Series*., **48**. American Geophysical Union, 487.
2. Behrendt J.C., LeMasurier W.E., Cooper A.K., Tessensohn F., Tréhu A., Damaske D., 1991. Geophysical studies of the West Antarctic Rift System. *Tectonics*. **10**(6): 1257-1273.
3. Hole M.J., LeMasurier W.E., 1994. Tectonic controls on the geochemical composition of Cenozoic, mafic alkaline volcanic rocks from West Antarctica. *Contributions to Mineralogy and Petrology*. **117**: 187-202.
4. LeMasurier W.E., Landis C.A., 1996. Mantle-plume activity recorded by low relief erosion surfaces in West Antarctica and New Zealand. *Geological Society of America Bulletin*. **108**: 1450-1466.
5. Storey B., Leat P.T., Weaver S.D., Pankhurst R.J., Bradshaw J.D., Kelley S., 1999. Mantle plumes and Antarctica-New Zealand rifting: evidence from mid-Cretaceous mafic dykes. *Journal of the Geological Society, London*. **156**: 659-671.

6. Salvini F., Brancolini G., Busetti M., Storti F., Mazzarini F., Coren F., 1997. Cenozoic geodynamics of the Ross Sea region, Antarctica: Crustal extension, intraplate strike-slip faulting, and tectonic inheritance. *Journal of Geophysical Research*. **102**(B11): 24,669-24,696.

7. Tonarini S., Rocchi S., Armienti P., Innocenti F., 1997. Constraints on timing of Ross Sea rifting inferred from Cainozoic intrusions from northern Victoria Land, Antarctica, in *The Antarctic Region: Geological Evolution and Processes*, C.A. Ricci, Editor: Siena. 511-521.

8. Rocchi S., Armienti P., D'Orazio M., Tonarini S., Wijbrans J., Di Vincenzo G., 2002. Cenozoic magmatism in the western Ross Embayment: role of mantle plume vs. plate dynamics in the development of the West Antarctic Rift System. *Journal of Geophysical Research*. **107**(B9): 2195, 10.129/2001JB000515.

9. Rocchi S., Fioretti A.M., Cavazzini G., 2002. Petrography, geochemistry and geochronology of the Cenozoic Cape Crossfire, Cape King and No Ridge igneous complexes (northern Victoria Land, Antarctica), in *Antarctica at the close of a millennium*. Proceedings of the 8th International Symposium on Antarctic Earth Sciences, Wellington 1999, Royal Society of New Zealand Bulletin, J.A. Gamble, D.N.B. Skinner, and S. Henrys, Editors: Wellington, New Zealand. 215-225.

10. Rocchi S., Storti F., Di Vincenzo G., Rossetti F., 2003. Intraplate strike-slip tectonics as alternative to mantle plume activity for the Cenozoic rift magmatism in the Ross Sea region, Antarctica, in *Intraplate strike-slip deformation belts*, F. Storti, R.E. Holdsworth, and S. F., Editors. Geological Society Special Publication. 158-171.

11. Fitzgerald P.G., Stump E., 1997. Cretaceous and Cenozoic episodic denudation of the Transantarctic Mountains, Antarctica: new constraints from apatite fission track thermochronology in the Scott Glacier region. *Journal of Geophysical Research*. **102** (B4): 7747-7765.

12. Cande S.C., Stock J.M., Müller R.D., Ishihara T., 2000. Cenozoic motion between East and West Antarctica. *Nature*. **404**: 145-150.

13. Lawver L.A., Gahagan L.M., 1994. Constraints on timing of extension in the Ross Sea region. *Terra Antartica*. **1**: 545-552.

14. Behrendt J.C., Saltus R., Damaske D., McCafferty A., Finn C.A., Blankenship D., Bell R.E., 1996. Patterns of late Cenozoic volcanic and tectonic activity in the West Antarctic rift system revealed by aeromagnetic surveys. *Tectonics*. **15**(2): 660-676.

15. Finn C., Bell R.E., Blankenship D.D., Behrendt J.C., 2001. The relation of crustal structure, warm mantle, and ice sheets to Cenozoic volcanism in West Antarctica. in *Antarctic Neotectonics*, Siena, Italy, 11-15 July 2001.

16. Nardini I., Armienti P., Rocchi S., Tonarini S., Harrison D., 2003. Cenozoic Volcanism in the Western Ross Embayment: any evidence for a mantle plume from isotope systematics? in *9th International Symposium on Antarctic Earth Sciences*, Potsdam (Germany), 8-12 September 2003.

17. Meibom A., Anderson D.L., Sleep N.H., Frei R., Chamberlain C.P., Hren M.T., Wooden J.L., 2003. Are high ^{3}He/^{4}He ratios in oceanic basalts an indicator of deep-mantle plume components? *Earth and Planetary Science Letters*. **208**: 197-204.

18. Smith A.D., Lewis C., 1999. The planet beyond the plume hypothesis. *Earth Science Reviews*. **48**: 135-182.

19. Bonatti E., 1990. Not so hot “hot spots” in the oceanic mantle. *Science*. **250**: 107-111.

20. Anderson D.L., 1995. Lithosphere, Asthenosphere, and Perisphere. *Reviews of Geophysics*. **33**(1): 125-149.

21. Halliday A.N., Lee D.-C., Tommasini S., Davies G.R., Paslick C.R., Fitton J.D., James D.E., 1995. Incompatible trace elements in OIB and MORB and source enrichment in the sub-oceanic mantle. *Earth and Planetary Science Letters*. **133**: 379-395.

22. Rossetti F., Di Vincenzo G., Läufer A., Lisker F., Rocchi S., Storti F., 2003. Cenozoic right-lateral strike-slip faulting in North Victoria Land: and integrated structural, AFT and ^{40}Ar-^{39}Ar study. in *9th International Symposium on Antarctic Earth Sciences - Antarctic Contribution to Global Earth Science*. Potsdam (Germany).

23. Lithgow-Bertelloni C., Richards M.A., 1998. The dynamics of Cenozoic and Mesozoic plate motions. *Reviews of Geophysics*. **36**: 27-78.

24. Veevers J.J., 2000. Change of tectono-stratigraphic regime in the Australian plate during the 99 Ma (mid-Cretaceous) and 43 Ma (mid-Eocene) swerves of the Pacific. *Geology*. **28**: 47-50.

25. Cande S.C., Mutter J.C., 1982. A revised identification of the oldest sea-floor spreading anomalies between Autralia and Antarctica. *Earth and Planetary Science Letters*. **58**: 151-160.

26. Richards M.A., Lithgow-Bertelloni C., 1996. Plate motion changes, the Hawaii-Emperor bend, and the apparent success and failure of geodynamic models. *Earth and Planetary Science Letters*. **137**: 19-27.

27. Anderson D.L., 2001. Top-down tectonics? *Science*. **293**: 2016-2018.

28. Danesi S., Morelli A., 2000. Group velocity of Rayleigh waves in the Antarctic region. *Physics of the Earth and Planetary Interiors*. **122**: 55-66.

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