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Cenozoic tectonic lineaments of the Terra Nova Bay region, Ross Embayment, Antarctica

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Abstract

The Cenozoic tectonic framework of the Terra Nova Bay region is dominated by NW–SE-trending dextral strike–slip faults that represent the onshore expression of dextral transform shear along the Tasman Fracture Zone and Balleny Fracture Zone in the Southern Ocean. These intraplate faults reactivated inherited, Paleozoic crustal discontinuities established during the Ross Orogeny. Cenozoic, N–S to NNE–SSW transtensional faults developed in the crustal blocks in between the strike–slip faults as a kinematic consequence of the transcurrent motion. These transtensional faults provided a suitable mechanism to accomplish for dextral horizontal throw along the NW–SE strike–slip faults. The complex, strike–slip-induced kinematics controlled the location and the emplacement mechanisms of Cenozoic basic magma in the coastal sector of the Terra Nova Bay region. Sequential restoration of the present-day fault pattern in the Terra Nova Bay region, allowed reconstruction of the geologic framework of the area prior to onset of the strike–slip activity (from 105 Ma to 32 Ma), and also before the opening of the Ross Sea (earlier than 105 Ma). The pre-extensional framework was dominated by a vast, flay-lying plateau, mainly made up by the Jurassic Ferrar Supergroup rocks. Crustal thinning occurred due to movement on NNE–SSW- to NE–SW-trending extensional faults, and the inherited, through-going Paleozoic NW–SE regional-scale discontinuities were reactivated as transfer faults. Main extensional faults in the western side of the Ross Sea dip to the NE, and segmented this region into a series of blocks with minor tilting. Strike–slip tectonics characterises Late Cenozoic time, and is responsible for N–S extensional, rather symmetrical faulting along transfer zones in between major NW–SE transcurrent faults. Intersections between these two trends eased deep magma rise and the development of long-lasting, central volcanoes. The morphological effects of the last tectonic event were the development of NW–SE and N–S depressions and the rapid growth of volcanic edifices, that influenced both location and orientation of the main glaciers in northern Victoria Land and are responsible for their characteristic zig-zagging.

Keywords: Antartica; tectonic evolution; Cenozoic; Ross Sea region; lineaments; fracture zones

1. Introduction

In these last years a multidisciplinary geological–geophysical research project on the Cenozoic tectonic evolution of the Ross Sea region, Antarctica, has been carried out by our research group. Tectonic analysis of the offshore seismic reflection profiles available in the ANTOSTRAT Project (1995) framework (e.g., Brancolini and Salvini, 1994) has been coupled with tectonic analysis of the Mesozoic–Cenozoic fault pattern onshore

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(e.g., Salvini and Storti, 1994), to produce a general tectonic map of the whole Ross Sea region (Brancolini et al., 1997). Overprinting relationships among different fault systems, offshore and onshore age constraints, geometric and kinematic analysis of the cross-sectional fault patterns, together with plate tectonic reconstructions, have been used to set up a Mesozoic–Cenozoic evolutionary model of the Ross Sea region (Salvini et al., 1997a).

In this paper we illustrate the tectonic framework of the Terra Nova Bay region, namely the area bordered by the Mesa Range to the north, by the Drygalski Ice Tongue to the south, by the Polar Plateau to the west and by the western Ross Sea to the east (Figs. 1 and 2). Particular emphasis is given to the description of the Cenozoic fault pattern and to the sequential restoration of the fault arrays to infer the overall tectonic pattern of the Terra Nova

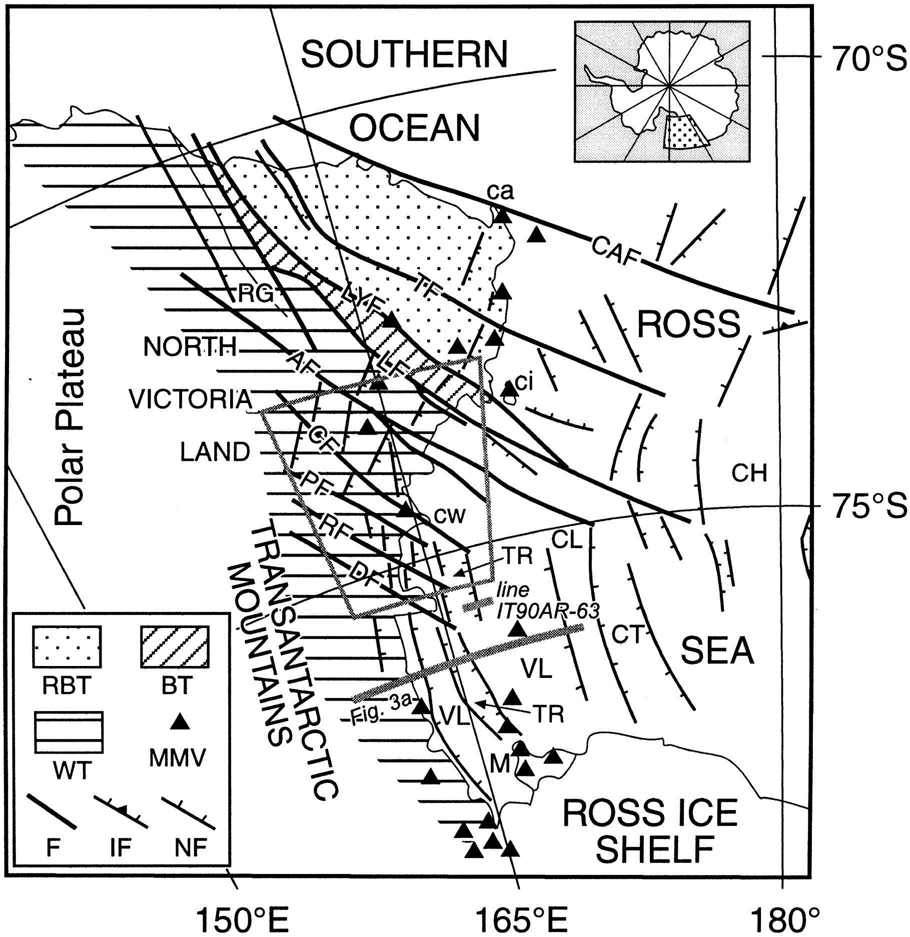


Fig. 1. Tectonic sketch map of Victoria Land and the Ross Sea. The main NW–SE fault systems are clearly visible and affect the whole region. Most of these faults represent reactivated, inherited Early Paleozoic discontinuities formed during the terrane accretion of the Ross Orogen. The main extensional grain is also outlined and shows an arcuate shape roughly parallel to the coastline. N–S tectonics relate to the interactions between adjacent NW–SE faults. Cenozoic volcanic rocks crop out along a belt that follows the coastal trend. The gray box indicates location of Fig. 2. Locations of the cross section and seismic line in Fig. 3 are also indicated. RBT, Robertson Bay Terrane; BT, Bowers Terrane; WT, Wilson Terrane; F, right-lateral strike–slip faults; IF, inverted extensional faults; NF, extensional faults, barbs on the downthrown block; MMV, main outcrops of Cenozoic McMurdo Volcanic rocks; CAF, Cape Adare Fault, TF, Tucker Fault; LYF, Leap Year Fault; LF, Lanterman Fault; RG, Rennick Graben; AF, Aviator Fault; CF, Campbell Fault; PF, Priestley Fault; RF, Reeves Fault, DF, David Fault; CH, Central High; CL, Coulman High; CT, Central Trough; VL, Victoria Land Basin, TR, Terror Rift; M, McMurdo Sound; ca, Cape Adare; ci, Coulman Island; cw, Cape Washington.

Bay region during the major evolutionary stages of the Ross Sea opening and consequent uplift of the Transantarctic Mountains.

2. Geological overview of northern Victoria Land

Three major terranes have been recognized in northern Victoria Land (Fig. 1). From NE to SW they are the Robertson Bay Terrane, the Bowers Terrane and the Wilson Terrane (Kleinschmidt and Tessensohn, 1987; Bradshaw, 1989; Carmignani et al., 1989; Laird, 1989). The Leap Year Fault (Findlay and Field, 1983) separates the Robertson Bay Terrane from the Bowers Terrane, and the Lanterman Fault (Dow and Neall, 1974; Gibson, 1985) separates the Bowers Terrane from the Wilson Terrane. Terrane matching is commonly ascribed to the Early Paleozoic Ross Orogeny, when new crustal material was accreted by transpression to the East Antarctic Craton (Findlay and Field, 1983; Weaver et al., 1984; Bradshaw et al. 1985). However, geodynamic considerations on the contrasting stratigraphy and on the different structural levels of the rocks outcropping respectively to the north and to the south of the Leap Year Fault suggest that the final matching of the Robertson Bay Terrane and the Wilson–Bowers terranes lithospheric block might have been achieved in Mesozoic times (Salvini and Storti, 1994).

Large batholiths of the Cambro-Ordovician Granite Harbour Intrusives (Gunn and Warren, 1962) characterize the Wilson Terrane. They intruded into low- to high-grade metamorphic rocks of uncertain age but generally ascribed to the Proterozoic and to the Lower Cambrian (Kleinschmidt and Tessensohn, 1987). The Bowers Terrane (Cambrian–Ordovician) is a narrow NW–SE-elongated belt made up by low-grade metavolcanic and metasedimentary rocks (Weaver et al., 1984). Cambrian–Early Ordovician terrigenous continental shelf sediments of low metamorphic grade (Burrett and Findlay, 1984) are widely exposed in the Robertson Bay Terrane. They are intruded by Devonian–Carboniferous granitoids of the Admiralty Intrusives (Vetter and Tessensohn 1987).

The Paleozoic rocks of the Wilson Terrane–Bowers Terrane assembly have been deeply eroded up to peneplanation (sub-Beacon Peneplain). The sub-Beacon Peneplain (Gunn and Warren, 1962) is one of the most outstanding morphological and geological features of the Transantarctic Mountains. It consists of the envelopment of partially overlapping regional erosional surfaces, progressively younging from the south (Devonian) to the north (Triassic) (Barrett et al., 1972). Shallow-water continental and marine sediments (Beacon Supergroup) were unconformably deposited above the sub-Beacon Peneplain (Wolfe and Barrett, 1995 and references therein). The Beacon Supergroup is in turn overlain and intruded by the Jurassic sequence of the Ferrar Supergroup, consisting of thick and areally extensive basaltic lava flows (Kirkpatrick Basalt; Grindley, 1963) and dolerite sills (Ferrar Dolerite). No outcrops of the Beacon and the Ferrar supergroups have been found north of the Leap Year Fault, in the Robertson Bay Terrane. Widespread volcanic activity affected the coastal sector of the Victoria Land and the western Ross Sea (McMurdo Volcanic rocks; Harrington, 1958) during the Cenozoic time.

3. Cenozoic tectonic pattern

The pre-Mesozoic basement in the Terra Nova Bay region mainly consists of granitoids (both Granite Harbour Intrusives and Admiralty Intrusives) and metamorphic rocks and has been left undifferentiated in the sketch map of Fig. 2. An abrupt decrease of the outcropping granitoids belonging to the Granite Harbour Intrusives occurs to the north of the Wilson Terrane–Bowers Terrane boundary.

The tectonic fabric of the cristalline basement originated during the Ross Orogeny in early Paleozoic times (about 500–480 Ma). Structural trends defined by a steeply dipping metamorphic foliation, highly strained shear zones and fold axial trends, are mainly NW–SE (Gibson, 1987; Kleinschmidt and Tessensohn, 1987; Carmignani et al., 1989). The spatial distribution of different metamorphic facies in the crystalline basement of the Terra Nova Bay region (GANOVEX Team, 1987; Carmignani et al., 1989; Giudice et al., 1991) supports the presence of NW–SE-trending Paleozoic crustal discontinuities. Glaciers presently occupy the major NW–SE structural lineaments.

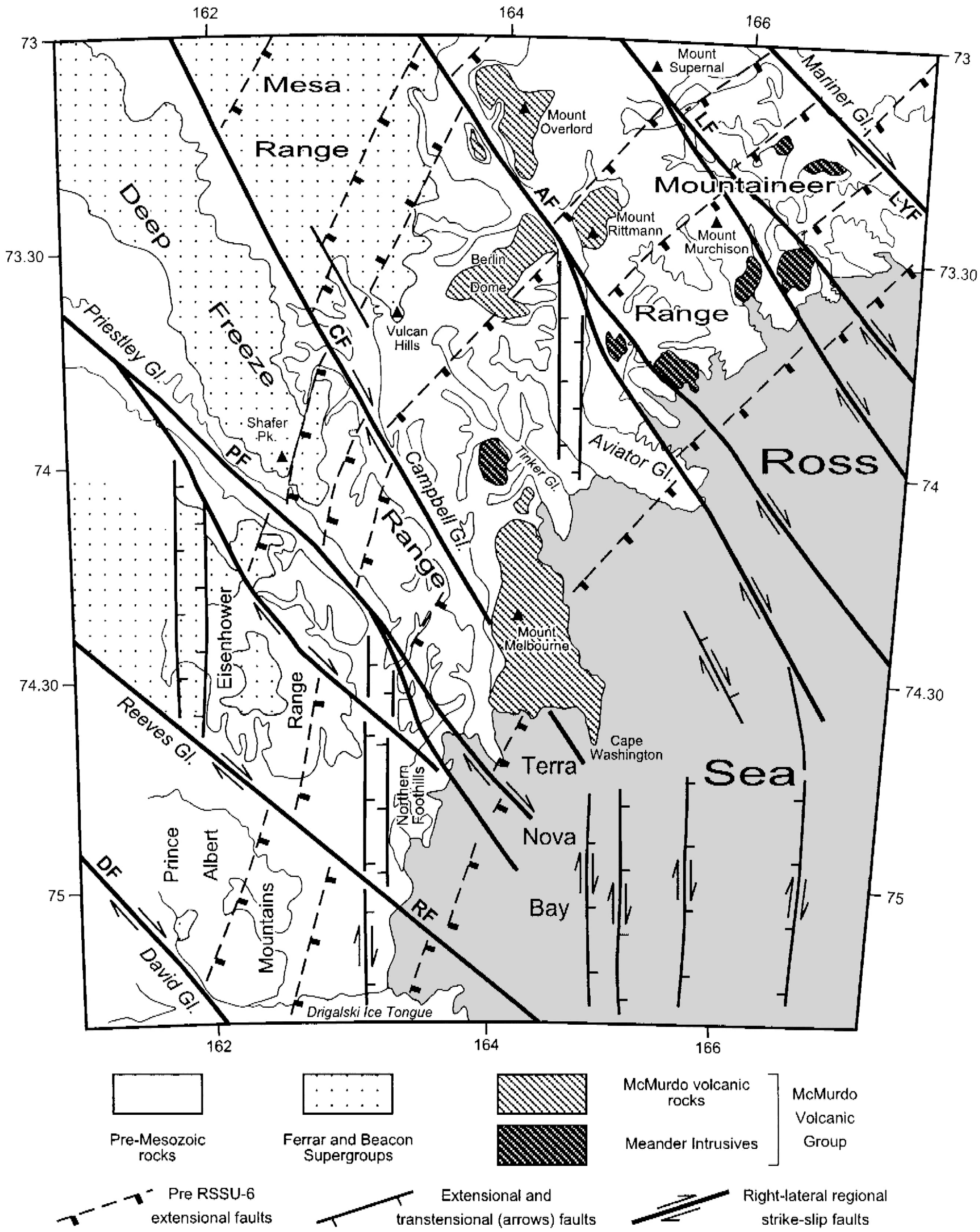


Fig. 2. Present-day tectonic map of the Terra Nova Bay region. See Fig. 1 for location. Three main sets of fault systems contribute to the present-day tectonic setting. The NW–SE fault systems are the dominant ones and their activity relates to the last, right-lateral, transtensional event. Neither NE–SW and N–S extensional or transtensional faulting ever cut across the NW–SE faults, suggesting their relative younger activity. The cross relationships of NW–SE faults with N–S faulting, their kinematic compatibility, and interactions with Cenozoic magmatism suggest that both systems were active during the Late Cenozoic tectonic event. Main volcanic edifices locate along NW–SE faults, at their intersection with N–S tectonic depressions. Glacier flows are deeply affected by the presence of NW–SE and N–S discontinuities and follows the two trends with a characteristic zig-zag pattern.

By the end of the Paleozoic–Early Mesozoic times the Ross Orogen was isostatically compensated and thermally re-equilibrated as testified by the development of the sub-Beacon peneplain. Yet the Wilson Terrane–Bowers Terrane lithospheric block preserved a series of NW–SE-trending mechanical anisotropies along localized belts that will have influenced the pattern of the later Mesozoic and Cenozoic tectonics (Fig. 2).

Large outcrops of the Jurassic Ferrar Supergroup overlie the Permian–Triassic sediments of the Beacon Supergroup (unified as Mesozoic rocks in Fig. 2) and are widely exposed in the northwestern sector of the region, in the Mesa Range, northern Deep Freeze Range and in the Eisenhower Range (Fig. 2). Only a small outcrop of Jurassic rocks occurs southward, in the Prince Albert Mountains. No outcrops of the Beacon and Ferrar rocks have been preserved eastward, along the Ross Sea shoulder, where tectonically enhanced erosion caused faster removal of a greater amount of material (e.g., Van der Beck et al., 1994).

Cenozoic volcanic rocks crop out in the coastal sector of the Terra Nova Bay region (Fig. 2). Effusive rocks are clustered close to the two major central volcanoes: Mt. Melbourne and Mt. Overlord. Two other effusive centres are present south of Mt. Overlord (Mt. Rittmann and Berlin Dome). North of the Campbell Glacier, Cenozoic intrusive rocks (Meander Intrusives) are exposed in the coastal region (e.g., Tonarini et al., 1997).

The Cenozoic pattern of onshore and offshore faults in the Victoria Land is shown in Fig. 1. The dominant set of fault systems trends NW–SE and major glacier streams lie roughly parallel to that trend. Seven major NW–SE fault systems constitute the main tectonic grain of the northern Victoria Land (Fig. 2). Both positive and negative flower structures have been discovered along their path, and suggest a right-lateral, strike–slip sense of motion of these faults (Salvini et al., 1997b).

Each of these fault systems consists of an envelope of coalescent right-lateral strike–slip faults that define a discrete regional-scale deformation zone. Deformation intensity along the shear zones varies abruptly both along and across strike. Polished fault surfaces and slickensides generally border elongate zones of fault breccia, fault gouge, cataclasite, ultracataclasite and, locally, pseudotachylyte (Rossetti and Storti, 1998). Dyke swarms originated along the fault zones and in the borderland zones in between them. Cenozoic dykes with strike–slip slickensides intruded along main fault planes with contradictory temporal relationships between dikes and faults. This suggests that magma rise was triggered by the regional NW–SE right-lateral strike–slip fault zones during the Cenozoic.

N–S tectonic depressions are common features in between adjacent faults. Field investigations have confirmed their tectonic origin and their relationship with the strike–slip tectonics and with the Cenozoic magmatism (Rossetti and Storti, 1998). The N–S depressions have been interpreted as extensional or transtensional structures associated to the general Cenozoic, right-lateral shear affecting the region.

The main glaciers of northern Victoria Land developed along the main path of the regional, NW–SE faults (Fig. 2). In the coastal region, linked to the change in crustal thickness and rheology towards the Ross Sea (Salvini et al., 1997a,b), some of the NW–SE faults branch in correspondence with Cenozoic intrusions of the Meander Intrusives or central volcanoes of the McMurdo Volcanic rocks, and of N–S tectonic depressions. In the regional, right-lateral tectonic picture, the junctions between NW–SE faults and N–S extensional depressions produce the most favourable conditions for persistent, deep magma rise: this explains the development of large volcanoes and intrusions in northern Victoria Land (Salvini et al., 1997a,b). This variation in the tectonic style is recorded in the path of some of the main glaciers, that abruptly deviate into the N–S depressions in correspondence with the main Cenozoic volcanoes or intrusions.

NE–SW to NNE–SSW faults are common in the Terra Nova Bay region (in the following referred as the NE–SW fault system). They border the western shoulder of the Ross Sea (Fig. 2) and relate to the Transantarctic Mountains uplift. Faults roughly trend parallel to the coastline (Fig. 1), and rotate N–S to NNW–SSE to the South, in front of the Victoria Land Basin. Their strike and apparent throw have been obtained by photogeological mapping and quantitative map analysis of the outcrop patterns of the Ferrar Supergroup in the Deep Freeze Range (Giudice et al., 1991) and in the Mesa Range (Petri

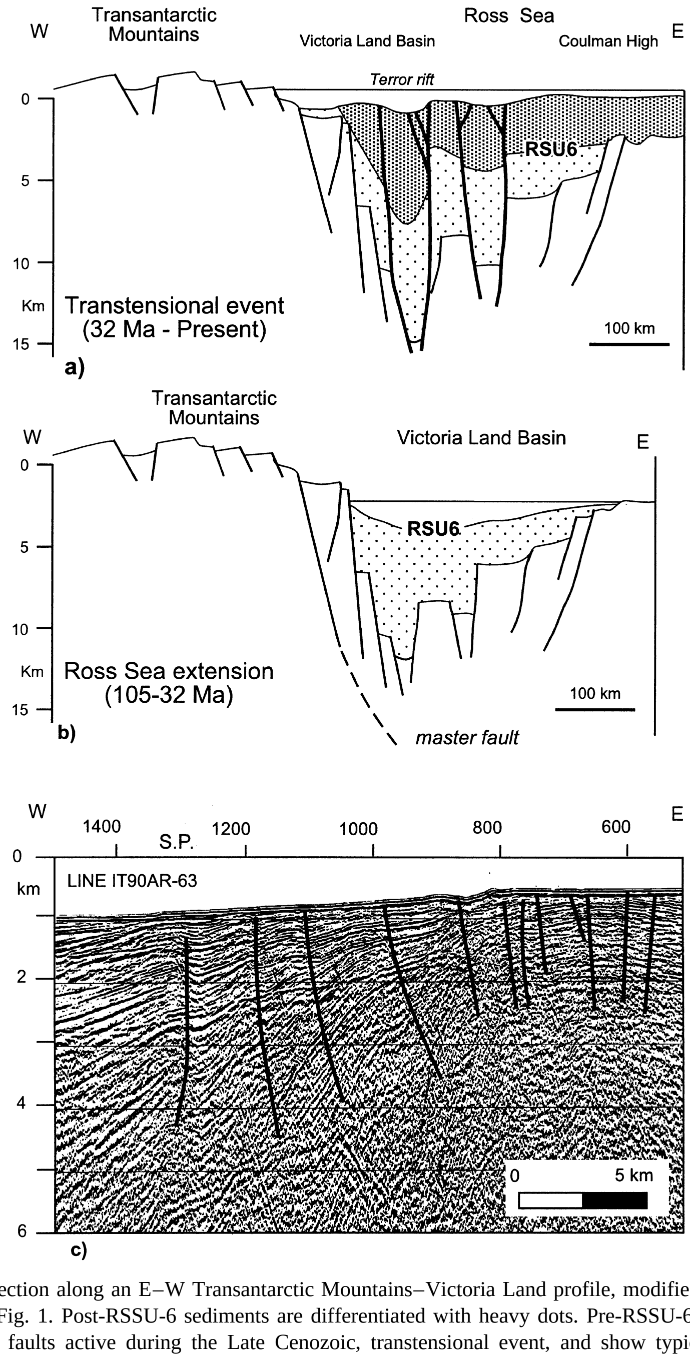


Fig. 3. (a) Geological cross section along an E–W Transantarctic Mountains–Victoria Land profile, modified from Behrendt et al. (1991). Location of the profile is in Fig. 1. Post-RSSU-6 sediments are differentiated with heavy dots. Pre-RSSU-6 sediments are shown in light dots. Heavier lines represent faults active during the Late Cenozoic, transtensional event, and show typical flower structures near the surface. Note the general symmetry of Late Cenozoic tectonic depressions. (b) Restored geological cross section of Fig. 3a in Early Cenozoic times. The asymmetric shape of the the Victoria Land Basin is well evident, and suggests a half graben geometry with the listric master faults in the western side and dipping eastward. (c) Interpreted seismic section IT90AR-63 showing a tectonic flower structure along the eastern margin of the Terror Rift. Location is in Fig. 1 (after Salvini et al., 1998).

et al., 1997). Observed and calculated apparent displacements show a general downthrow of fault blocks toward SE and ESE (Salvini and Storti, 1994). Northward of the Aviator Glacier, southward of the Reeves Glacier and in the coastal region, faults have been located by morphotectonic analysis and satellite imagery interpretation. An important feature of the NE–SW-trending fault system is its systematic segmentation against the through going NW–SE regional fault zones.

The third fault system set in the Terra Nova Bay Region trends N–S (Fig. 2) and has been already introduced. Offshore, N–S faults constitute the northern end of the Terror Rift in the Victoria Land Basin (Fig. 3a,c). These faults have not been imaged in the seismic profiles north of Cape Washington. Positive flower structures along the N–S faults, especially the easternmost ones, testifies for the occurrence of positive local inversion into an overall transtensional framework (Salvini et al., 1998). In particular, Fig. 3c shows an example of flower structures along the eastern slope of the Terror Rift Basin, with either normal or reverse stratigraphic separations along near-vertical fault planes. The already mentioned morphological evidences support the presence of N–S-trending faults onshore, in particular in correspondence of the abrupt clockwise turns of the Aviator, Campbell, and Priestley Glaciers.

Merging onshore and offshore data has provided the possibility to constrain the age of the fault systems in the whole Ross Sea region (Brancolini et al., 1997). In the Terra Nova Bay area, the offshore segments of the Aviator Fault and of the Lanterman Fault in many cases cut across most of the sedimentary succession and, in places, these faults have morphological expression on the seafloor. NW–SE strike–slip faulting postdates the unconformity RSSU-6 offshore, whose age has been inferred to be around 32 Ma (Busetti, 1994). This means that the activity of the NW–SE regional strike–slip belts is younger than the Oligocene and has continued to recent times, possibly up to the present. The same age constraints (i.e., they cut the RSSU-6) have been found for the N–S faults east of Terra Nova Bay and can be reasonably assumed also for the onshore N–S trending faults.

The NE-trending fault system was active over a much wider time span. The Jurassic rocks belonging to the Ferrar Supergroup are affected by NE–SW faulting. East of the Vulcan Hills (Berlin Dome) a clearly developed fault escarpment is overprinted by lava flows belonging to the McMurdo Volcanic Group (Salvini and Storti, 1994). Absolute dating of the nearest McMurdo lava flows gave an age of 12.6 Ma (Armienti et al., 1991), providing a minimum age for fault movement. Age determinations and cross-cutting relationships (Fig. 2) suggest that the NE–SW fault system may be generally older than the N–S fault systems. The NE–SW fault trend is parallel to the boundary between the continental crust of Victoria Land and the thinned Ross Sea one, and this may well indicate that this fault system developed during the Ross Sea opening over the last 105 Ma. Locally, offshore NE–SW faults show inversions that cut post-RSSU-6 sediments. These reactivations refer to the onset of the NW–SE right-lateral strike–slip tectonics, for they are both compatible with its kinematics and age (Salvini et al., 1997a).

4. Tectonic evolution

Three major stages have been identified in the Mesozoic–Cenozoic evolution of the Ross Sea region (Salvini et al., 1997a): (1) 105–55 Ma extension; (2) 55–32 Ma renewed extension; (3) 32 Ma to Present right-lateral strike–slip tectonics and transtension. The absolute ages assigned to the main stages are interpretative, based on the offshore age information from the western Ross Sea. The lack of good age constraints onshore does not allow us to detail the timing of the fault activity in Victoria Land more closely. Differentiation between the first and the second evolutionary stages is mainly based on apatite fission track dating of onshore materials (e.g., Fitzgerald, 1992), regional-scale inferences linked to magmatic activity (e.g., Tessensohn and Worner, 1991) and plate tectonic reconstructions for the SW Pacific Ocean (e.g., Lawver and Gahagan, 1994). Uncertainties in the absolute dating of the RSSU-6 unconformity in the seismic lines offshore (Busetti, 1994) do not allow closer estimation of the onset age (32–0 Ma) for strike–slip tectonics in the Ross Sea region. Other considerations are the diachronous onset of deformation at the regional scale and the

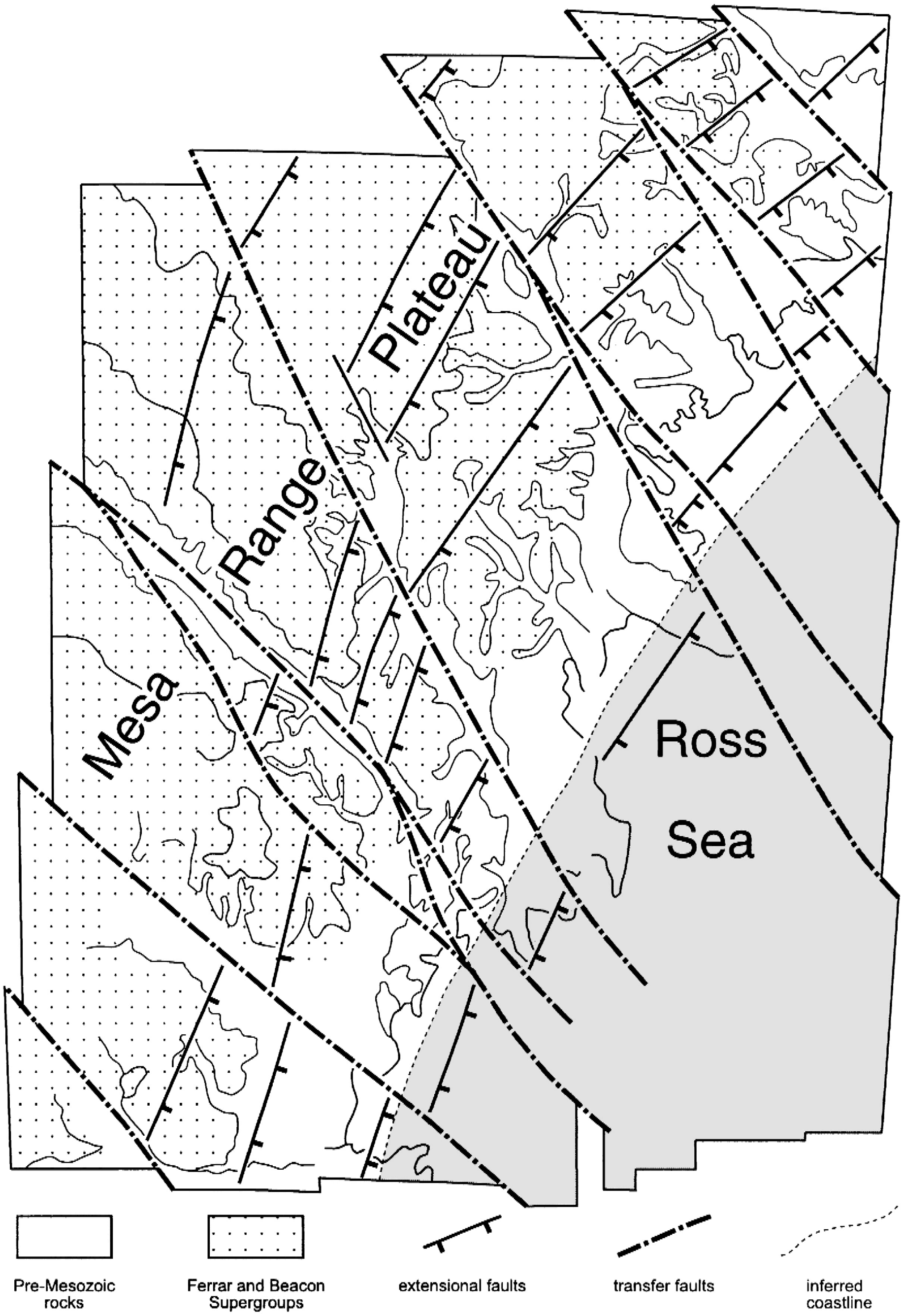


Fig. 4. Tectonic setting of the Terra Nova Bay region restored at 32 Ma. The NE–SW to NE–SSE extensional fault system relates to the Ross Sea embayment and the associated uplift of the Transantarctic Mountains. Restoration of right-lateral, strike–slip offsets shows the arcuate trend of this fault system. The coastline has been inferred by the present-day distribution of pre RSSU-6 sediments in seismic profiles in the Victoria Land Basin.

possible reactivation of the pre-existing faults during the younger tectonic events.

The sequential restoration of the tectonic pattern in the Terra Nova Bay region has allowed us to

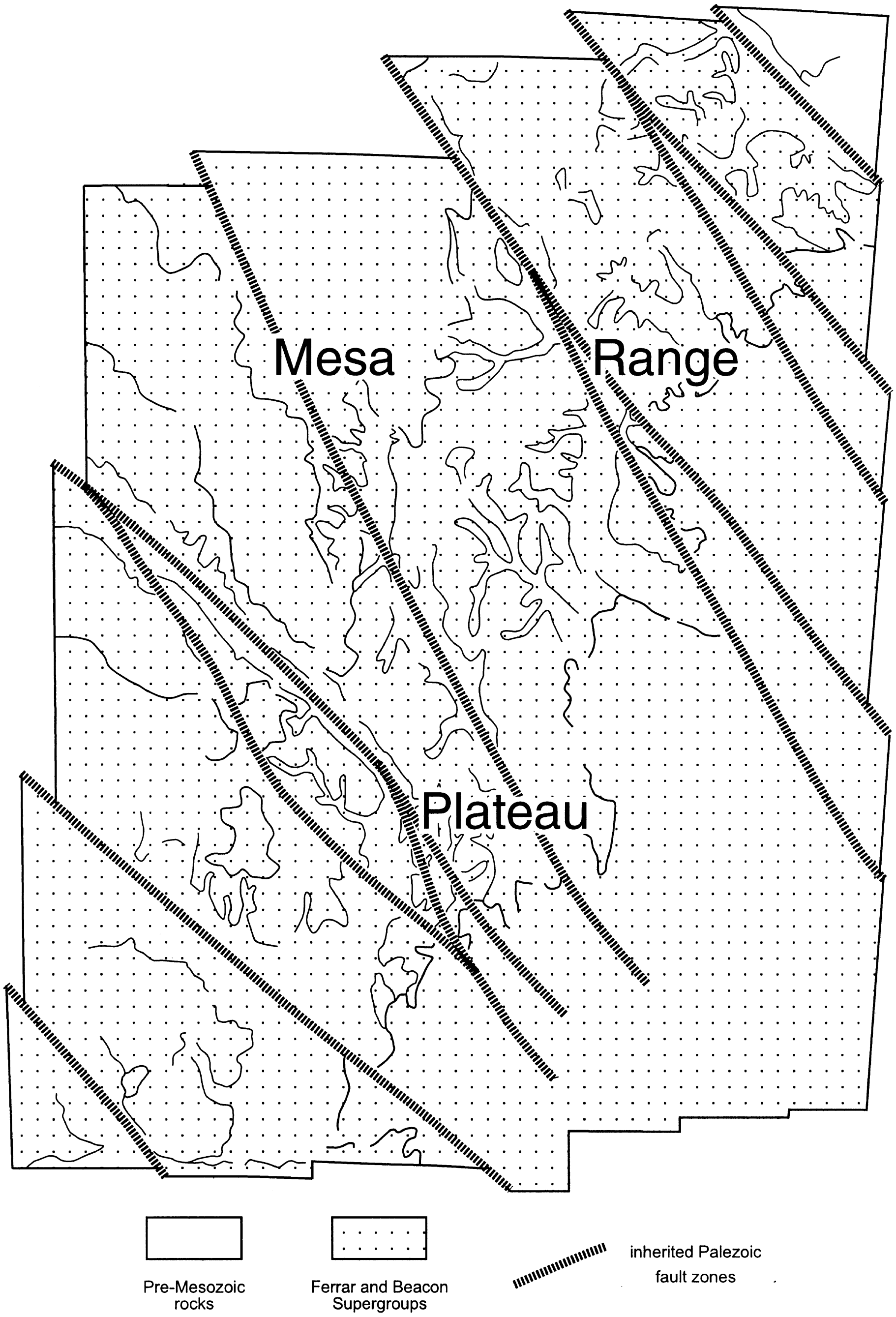


Fig. 5. Tectonic setting of the Terra Nova Bay region restored at 105 Ma. This is the most speculative reconstruction. Almost all the fault systems have been removed. The Mesa Range Plateau relates to the sub-Beacon peneplain and is the dominant landscape. Peneplain relics found in the seismic record offshore testifies its original extension in the present-day Ross Sea.

reconstruct the fault pattern initially produced by the two extensional events. The deformation attributable to each separate event is poorly distinguishable, due to the lack of tight age constraints onshore. The main difference resides in the tectonic style. The older event is characterized by E- to SE-dipping extensional faults with a general eastward down-throw and subordered anthitetic faults (Petri et al., 1997) in a half graben geometry. The younger one is associated to the regional strike–slip tectonics and does not have a defined polarity, that is, extensional faulting is rather symmetrical and creates N–S- to NNW–SSE-elongated, tectonic depressions. The development of the Terror Rift within the Victoria Land Basin represents the best example of the interaction between the two tectonic episodes (Fig. 3a–c). The older Victoria Land Basin shows a steep western shoulder and a gentle, eastern slope. The younger Terror Rift depression and the adjacent one, have symmetrical steep slopes, locally associated to inversion tectonics due to the strike–slip component.

The displacement due to the younger event in the Terra Nova Bay region has been inferred by restoring the pattern of the older faults into a homogeneous, arcuate shape that it is assumed to have bordered the Late Cretaceous Ross Sea. The resulting tectonic pattern is illustrated in Fig. 4. As a passive marker, also the present-day coastline has been restored. A speculative geological landscape prior to the Ross Sea opening has been obtained by interpretatively restoring the extension of the first event faults as proposed by Petri et al. (1997) and is shown in Fig. 5.

5. Pre-Ross Sea opening (pre. 105 Ma)

Total restoration of the Mesozoic–Cenozoic fault patterns produces a reconstruction of the pre-extensional tectonic setting of the Terra Nova Bay region (Fig. 5). The NW–SE trending crustal discontinuities remain because they are inherited elements from the early Paleozoic Ross Orogeny. The Jurassic and Triassic rocks of the Ferrar and Beacon supergroups crop out in most of the region at 105 Ma, and form an extensive, flat-lying plateau (Mesa Range Plateau) that predates the development of the Transantarctic Mountains. The occurrence of these volcanic and sedimentary rocks has not been assumed in the Robertson Bay Terrane (right-hand corner in Fig. 5), where evidence of their original deposition is not preserved.

6. Ross Sea extension and Transantarctic Mountains uplifting (105–32 Ma)

Starting at about 95–105 Ma (Veevers, 1984) extension affected the Ross Sea area and most crustal thinning occurred before 85 Ma (Lawver and Gahagan, 1994). This produced the Ross Embayment and started the uplift of the Transantarctic Mountains, with associated block-faulting in the Terra Nova Bay region (Salvini and Storti, 1994). The faulting frame in Fig. 4 represents the tectonic pattern due to this older, extensional event.

Partial restoration of the Cenozoic tectonic framework in the Terra Nova Bay region by unravelling the post 32 Ma deformation and magmatic activity provides insight on the pre RSSU-6 fault pattern (Fig. 4). NW–SE-trending right-lateral strike–slip faulting was not active but the major fault zones persisted as inherited crustal discontinuities. In northern Victoria Land, N–S extensional or transtensional faults did not occur, given their kinematic link with the successive, strike–slip tectonics. Most of the magmatic rocks belonging to the McMurdo Volcanic Group are younger than 32 Ma, apart from few ''precursory'' dykes (Tonarini et al., 1997). A reasonable inference is the widening of the Ferrar and Beacon rocks in the Mesa Range, Eisenhower Range, and Mountaineer Range, as well as south of the Reeves Glacier (Mesa Range Plateau). The Mesa Range Plateau constituted one of the main sectors of the Early Cenozoic Transantarctic Mountains.

The pre 32 Ma tectonic pattern of the Terra Nova Bay region is characterized by the NE–SW to NNE–SSW extensional faults all along the western shoulder of the Ross Sea. As already described, in southern Victoria Land the NE–SW fault system rotates and becomes roughly N–S, being responsible for the initial development of the Victoria Land Basin. Here, the tectonic style of the pre-32 Ma extension can be inferred by restoring the displacement of the last event in a seismic derived profile (Fig. 3a–c). Fig. 3b reveals the original, asymmetric development of the Victoria Land Basin in a half graben geometry with an eastern dipping master fault.

Attempts to correlate extensional faults across the NW–SE regional fault zones have failed for the lack of correlation criteria and for the strongly different fault patterns across these inherited crustal discontinuities. This proves that inherited NW–SE faults re-acted as transfer zones during the extensional deformation (Fig. 2).

Apart from the general attribution of the NE–SW fault system to the pre 32 Ma tectonics, no absolute age constraints are at present available to relate this extensional tectonics to the second (32 to 55 Ma) or to the first (55 to 105 Ma) evolutionary stages of the Ross Sea opening. The presence of well-preserved fault escarpments in the Vulcan Hills area and in the Deep Freeze Range favours the reactivating of many NE–SW-trending faults during the second evolutionary stage, where a strong increase of the uplift of the Transantarctic Mountains occurred in the last 55 Ma (e.g., Fitzgerald, 1992). Moreover, the major pre RSSU-6 extensional basins in the Ross Sea trend roughly N–S (Cooper et al., 1987), and this suggests an E–W extensional direction during the Ross Sea opening. Given the low azimuthal difference between the two extensional fault systems (N–S and NE–SW to NNE–SSW), part of the NE–SW-trending faults may well have originated earlier than 55 Ma and possibly reactivated during the renewed uplift of the Ross Sea shoulder, i.e., the Transantarctic Mountains, after 55 Ma.

7. Transtensional tectonics (32 Ma to Present)

The 32 Ma to Present (post RSSU-6) right-lateral strike–slip tectonics along the NW–SE-trending regional fault zones and the coeval right-lateral transtension along the N–S-trending faults can be linked in a comprehensive kinematics where N–S faulting is triggered by the NW–SE strike–slip motion (Salvini et al., 1997a,b). To the south of Cape Washington, the general strike–slip trend merges with the extensional tectonics of the former event, and rotates into NNW–SSE-trending transtensional faults parallel to the coast. Evidence of this strike–slip regime have been discovered further south, in the Dry Valleys region (Wilson, 1995; Jones, 1996). In the Terra Nova Bay region, E–W extension is kinematically compatible with NW–SE right-lateral strike–slip faulting being generated by the dynamic stresses induced in the borderland zones of the strike–slip faults (e.g., Harding, 1985).

The opening of the N–S-trending Terror Rift within the pre RSSU-6 Victoria Land Basin in the Ross Sea provides the best example of the kinematic link between NW–SE and N–S faulting (Fig. 6). The section in Fig. 3a illustrates the differences in style between the last, transtensional event and the previous, extensional ones. The former events are characterized by an asymmetrical extension (Fig. 3b) characterized by horizontal extension much greater than the vertical component. The tectonic depressions formed during the last event have symmetrical shapes (Fig. 3a) and a vertical offset comparable or slightly greater than the horizontal component.

The northern end of the Terror Rift lies in the area north of Terra Nova Bay and east of Cape Washington. The Priestley Fault and the Campbell Fault converge in the same area. The lack of evidence for their offshore continuation eastward of the Terror Rift and the occurrence of a right-lateral strike–slip component along the basin-controlling faults in the Terror Rift (Salvini et al, 1997b) suggest the existence of a kinematic link between the opening of this deep trough and the motion along the Priestley and Campbell faults. Also the southern branch of the Aviator Fault is likely to end close to the eastern boundary fault of the Terror Rift (Fig. 2). This may imply that even part of the right-lateral strike–slip displacement along the Aviator Fault has been accomplished by N–S transtension in the Terror Rift (Fig. 6).

Accordingly, we can generalize this kinematic interpretation to N–S faulting along the southern part of the Aviator Glacier and of the Priestley Glacier, in the Eisenhower Range, and in the Evans Nevé. In all these cases transtensional opening of N–S tectonic troughs may provide a mechanism to accomplish for the progressive compensation of displacement along the regional NW–SE right-lateral strike–slip belts.

The influence of the NW–SE right-lateral strike–slip faulting on the post RSSU-6 geological setting of the Terra Nova Bay region is also testified by the spatial association of the Cenozoic intrusions and dyke swarms. Cenozoic intrusions are exposed in the

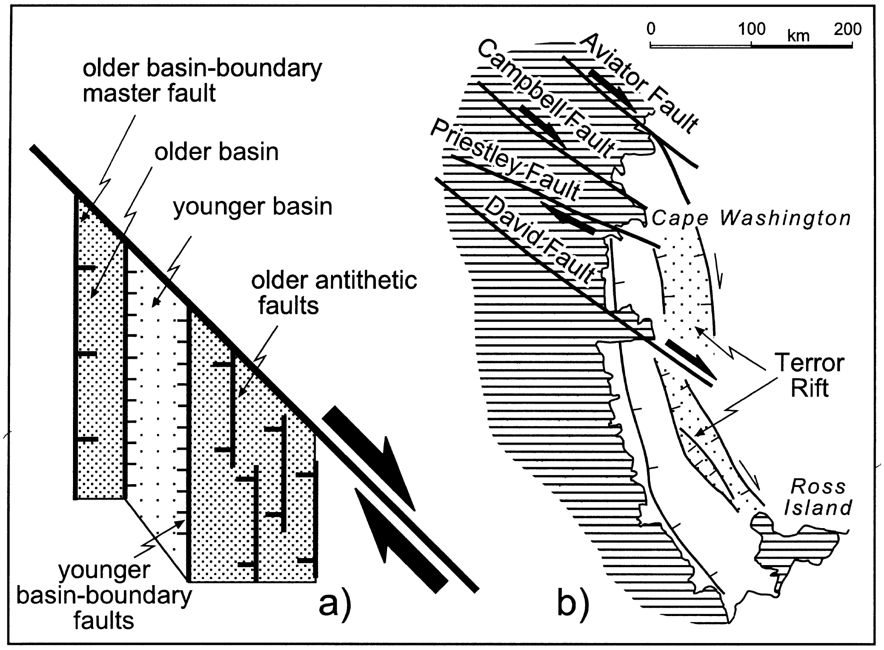
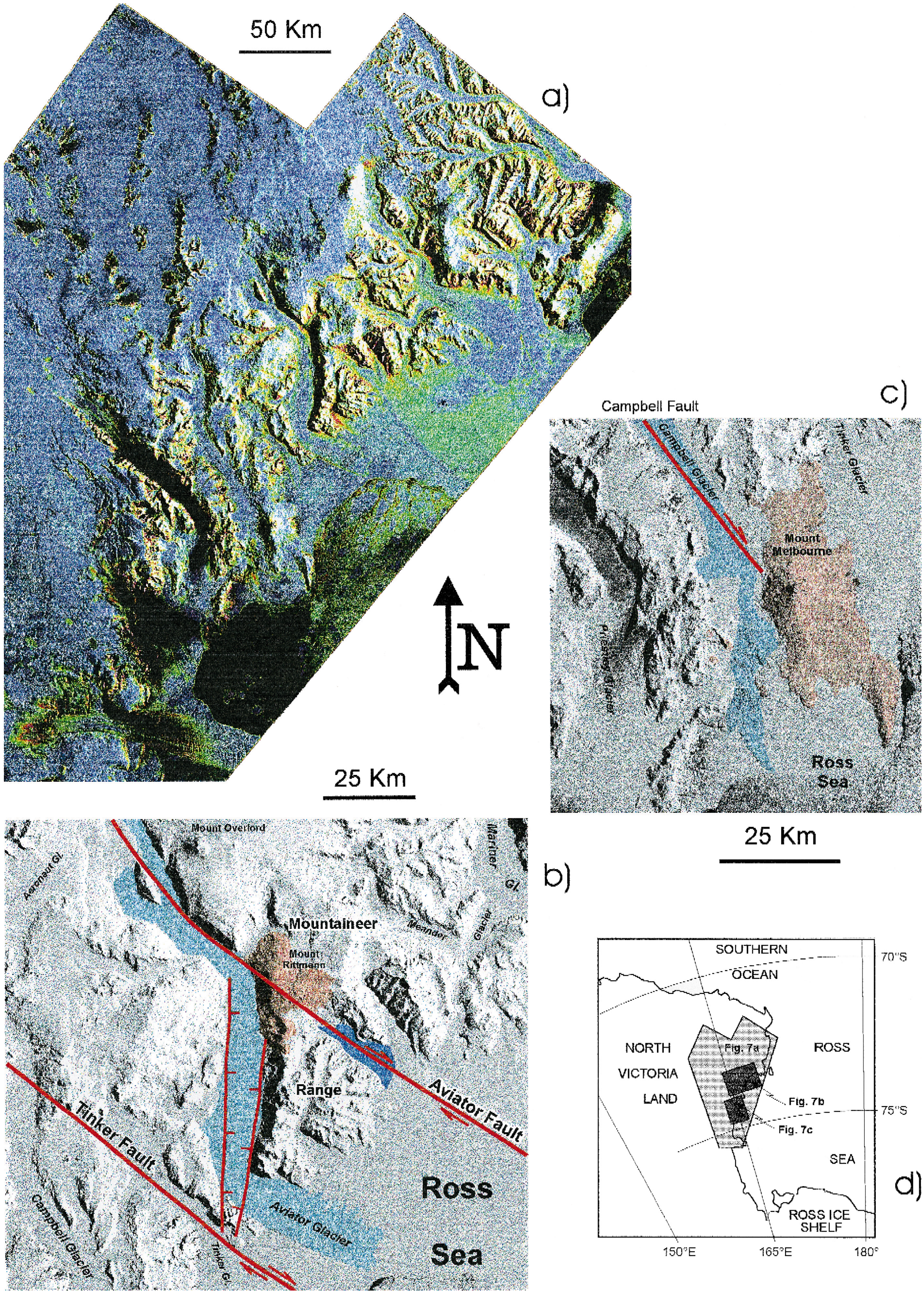


Fig. 6. Basin reactivation mechanism for the Cenozoic opening of the Terror Rift. (a) Conceptual model; (b) relations among right-lateral strike–slip motions along the Aviator Fault, the Campbell Fault, the Priestley Fault, and the David Fault, and the opening of the Terror Rift.

coastal region northeast of the Campbell Fault. At present, no outcrops of Meander Intrusives rocks have been discovered to the southwest of this regional strike–slip belt (Fig. 2). Cenozoic mafic dyke swarms and their genetic relationships with the strike–slip and transtensional faulting are well exposed southward of the Reeves Fault (Rossetti and Storti, 1997, umpublished data). Only a limited number of McMurdo dykes crop out north of the Reeves Fault, in the Northern Foothills–southern Deep Freeze Range area.

Finally, we can speculate on the present-day position of the coastline to infer possible evidences of Cenozoic tectonics in the Terra Nova Bay region. In

Fig. 7. (a) False color enhanced mosaic of Landsat MSS Band 7 images of the coastal region of the northern Victoria Land. The zig-zag patterns of the main glaciers are visible. Color code refers to spatial frequency analysis, where warm colors (red) refer to higher contrasted zones, while cold colors (blue) represent homogeneous areas. Reddish colors evidentiate rock outcrops or crevassed areas. Heavily crevassed glaciers are black, as in the Priestley Glacier in the center-left of the image. Open Sea is again represented by black color. The Aviator Glacier locates in the center of the image and shows a NW–SE to N–S zig-zagging. The Drygalski Ice Tongue is visible in the bottom. The Campbell Glacier locates immediately NE of the Priestley Glacier, and shows in yellow-green colors a crevassed area in its final flow, just SW of the Mt. Melbourne Volcano. Location of the mosaic is in Fig. 7d. Original mosaic courtesy of the CNR — Laboratorio di Telerilevamento Polare, Rome, Italy. (b) Annotated portion of the image of Fig. 7a, showing the Aviator Glacier region. Light blue represents the present-day Aviator Glacier flow. Light red represents the Mt. Rittmann Pleistocene volcano (0.7 Ma). The abnormally large but short glacier occupying the valley at the SE of the volcano is represented in blue, and has been interpreted as the relic of the paleo-Aviator flow. Late Cenozoic faulting is shown with red lines. (c) Annotated portion of the image of Fig. 7a, showing the lower Campbell Glacier area. The glacier flow is represented in light blue colors. Light red colors indicate the Mt. Melbourne quiescent volcano. The N–S deviation of the Campbell Glacier flow has been interpreted as caused by the settlement of the volcanic edifice in Plio–Pleistocene times. It provoked the reduction in width of the low Campbell Glacier flow along a N–S new path. This trend is tectonically related, as it is clearly visible in the shape of the volcanics. The reduction in width of the Campbell caused a change in the dynamics of its flow with the generation of a crevassed area SE of the main volcanic edifice that is represented by green-yellow colors in Fig. 7a (along the coast, between the Aviator and the Priestley Glaciers). (d) Location of images in Fig. 7a–c.



50 Km
a)
N
25 Km
Mount Overlord
Aeronaut Gl.
Mariner Gl.
Mountaineer
Meander Glacier
Mount Rittmann
Range
Aviator Fault
Tinker Fault
Campbell Glacier
Aviator Glacier
Tinker Gl.
Ross
Sea
b)
c)
Campbell Fault
Campbell Glacier
Tinker Glacier
Mount Melbourne
Priestley Glacier
Ross
Sea
25 Km
SOUTHERN
OCEAN
70°S
NORTH
VICTORIA
LAND
Fig. 7a
ROSS
Fig. 7b
75°S
Fig. 7c
SEA
d)
ROSS ICE
SHELF
150°E
165°E
180°

the northern sector, from the Mariner Glacier to the Tinker Glacier, the coastline trends roughly NE–SW; southward of the Campbell Glacier it trends NNE–SSW. The change in orientation occurs in correspondence of the Campbell Fault, where the Mt. Melbourne volcano developed (Fig. 2). The continuity of the coastline ends south of the Reeves Fault (Fig. 2), where at least part of the abrupt westward shift may relate to the right-lateral displacement of this fault.

8. Influences of Late Cenozoic tectonics on glacier evolution

The Landsat-MSS satellite image of Fig. 7a represents the east coastal region of the northern Victoria Land. The main glaciers are visible and show their zig-zagging trend. Their regional paths follow a NW–SE trend with poor relationships to the coast line. In the coastal zone some of the main glacier paths have an abrupt bend and assume a N–S flow direction.

In the Terra Nova Bay region, the close dependence of glacier flow directions on the location and trend of Cenozoic faults is well illustrated by the Aviator Glacier, whose upper stream follows the NW–SE trace of the Aviator Fault and then, in the coastal region, it deviates into a N–S path just in front of the Mt. Rittmann volcano (Fig. 7b). Traces of the older Aviator Glacier valley are still possibly visible in the image SE to the volcano and are represented by a short ice tongue with overdimensioned width and lacking of its charge area. The two NW–SE sectors, respectively to the NW and to the SE of Mt. Rittmann align very well and have similar widths. The younger, N–S flow is very well defined and straight, and this strongly suggests that the Aviator Glacier flow was there trapped into a partly pre-existing topographic depression related to the E–W extension associated to the strike–slip tectonics. Similar structures have been observed offshore in the Victoria Land Basin (e.g., Fig. 3).

A similar N–S bend in proximity of the coast characterizes the Campbell Glacier, whose flow path bends from SE to S just in front of the Mt. Melbourne volcano (Fig. 7c). The development of the Mt. Melbourne volcano appears thus to have influenced the flow path of the Campbell Glacier, and the N–S trend of the Mt. Melbourne Volcano structure may testify for the presence of N–S faulting similar to the Aviator Glacier tectonics. Moreover, Mt. Melbourne lava flows likely floored the Campbell Glacier valley, presently causing ice accumulation immediately to the north, and the steepening and narrowing of the coastal sector of the Campbell Glacier, where a strongly crevassed area has been developing behind the ice tongue.

To sum up, Late Cenozoic tectonics in Victoria Land has influenced the evolution of glacial processes in three ways: (a) NW–SE strike–slip faults generated more easy erodible, elongated weaker belts that localized glacier flow; (b) tectonically related central volcanoes located along the NW–SE strike–slip fault zones close to their interception with the N–S tectonic depressions, and volcanoes development should have been a major obstruction to the flow path of the glaciers; (c) N–S tectonic depressions in the coastal sector of northern Victoria Land produced topographic lows that trapped the deviated glacier flows.

9. Conclusions

The Cenozoic tectonic pattern of the Terra Nova Bay region resulted from the overprinting of a pre-existing extensional framework by intraplate right-lateral strike–slip shear along NW–SE-trending regional fault zones, in their turn inherited from events of the Ross Orogeny. This caused reactivation of pre-existing NNE–SSW-trending, possibly Mesozoic and/or Early Cenozoic extensional faults as transtensional ones, and development of new N–S-trending extensional and transtensional faults.

The Cenozoic strike–slip geodynamics strongly influenced location and emplacement mechanisms of the McMurdo Volcanic rocks, constraining both the position and trend of dikes, and location of central volcanoes. This tectonic event developed on an already developed and active glacial morphology, and influenced the main glacier flows, originally developed along inherited, rheologically weaker, NW–SE belts.

Sequential restoration of fault displacements accomplished during sequentially older deformations has allowed reconstruction of the Early Cenozoic, and the Late Jurassic tectonic configurations of the Terra Nova Bay region. The former was characterized by extensional faulting along the Ross Sea shoulder and reactivation of NW–SE inherited crustal discontinuities as transfer faults. The latter was characterized by a virtually undeformed basaltic plateau (Mesa Range plateau) predating rifting between Antarctica and Australia and the opening of the Ross Sea.

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