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Asymmetric extension associated with uplift and subsidence in the Transantarctic Mountains and Ross Embayment

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Apatite fission track data combined with regional geological observations indicate that the uplift of the Transantarctic Mountains has been coeval with thinning and subsidence of the crust beneath the Ross Embayment In the Dry Valleys region of south Victoria Land, the mountains have been uplifted about 5 km since the early Cenozoic at an average rate of about 100 m/Ma During uplift, the crust remained at constant thickness or was slightly thickened by magmatic underplating In contrast, the crust beneath the Ross Embayment has been extended and consequently thinned beginning in the Late Cretaceous but mainly during Cenozoic times We suggest here that the uplift of the Transantarctic Mountains and the subsidence of the Ross Embayment are a result of passive rifting governed by a fundamental structural asymmetry defined by a shallow crustal penetrative detachment zone that dips westward beneath the Transantarctic Mountain Front The localization and asymmetry of this detachment and its unusually deep level expression are attributed to a profound crustal anisotropy inherited from an early Palaeozoic collision along the present site of the mountain range

1. Introduction

The mechanism of uplift of the Transantarctic Mountains (TAM) remains enigmatic despite discussion about their formation since the early days of Antarctic exploration [1]. The mountains have a simple stratigraphy comprising a Precambrian and early Palaeozoic basement unconformably overlain by sub-horizontal sediments of the Devonian to Triassic Beacon Supergroup Both the basement and its cover are intruded by the Jurassic Ferrar Dolerite [2] The crust beneath the mountains has been estimated to be of only moderate thickness [3] and unlike most other major Cenozoic mountain ranges of the world, uplift was not accompanied by thrusting, folding or andesitic volcanism Rather, uplift has been exclusively by vertical crustal movement with gentle tilting of fault blocks This movement has coincided with rift-related alkaline volcanism active from the Late Cenozoic along or just offshore of the eastern side of the TAM This side of the mountains, which borders the Ross Embayment, is step-faulted down towards the coast and has been called the Transantarctic Mountain Front The TAM Front is bounded to the east by a zone of anomalously thin crust beneath the Ross Embayment, which has been the site of accumulation of thick sedimentary sequences since the early Tertiary or possibly as early as the late Mesozoic [4] The mountain front marks an abrupt change in crustal thickness that has long been considered to represent the boundary between East and West Antarctica [3]

Lithospheric stretching models [5] have been used to explain the formation of sedimentary basins that accompany crustal thinning, subsidence and rifting in the development of passive continental margins These models are axially symmetrical however, and fail to answer a number of points regarding basin margin uplift and general basin topography (e.g [6]) In contrast, recent models for the development of the Basin and Range–Colorado Plateau region of North America emphasize the importance of structural asymmetry

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and the role of detachment faulting during continental extension [7–9] These ideas have more recently been extended to explain the development of rifted continental margins [6] Here we propose a model for the evolution of the TAM–Ross Embayment region which is similar to, and to a large extent derived from these recent models for the extensional tectonics of the Basin and Range Province

While there is a general consensus that the formation of the TAM–Ross Embayment system has involved continental extension, there have been no previous attempts to explain the seemingly contrasting evolution of the TAM and the Ross Embayment, or the coincidence of the mountain range over almost all its length with an early Palaeozoic foldbelt (the Ross Orogen) Smith and Drewry [10] attribute the rise of the TAM to the delayed effects of the overriding by east Antarctica of anomalously hot asthenosphere formed under west Antarctica in the late Cretaceous The resulting heat flow increase would cause phase changes in the uppermost continental mantle, in turn causing uplift Although a novel idea, this model is difficult to test by direct observations and does not address the asymmetrical development of the mountain range, nor its relationship to the Ross Embayment and the Palaeozoic foldbelt

In this paper we look at fission track data and review regional geological evidence which suggest that the uplift of the TAM was coeval with most of the thinning and subsidence of the crust beneath the Ross Embayment, and with alkaline volcanism along and just offshore of the TAM Front These lines of evidence support the notion that both terrains developed in an extensional regime during the Cenozoic We propose that the extension was governed by a fundamental asymmetry in the crustal structure defined by a crustal penetrative detachment zone that dips westward beneath the TAM Front The localization and asymmetry of this detachment zone is attributed to pre-existing anisotropies in the lithospheric structure of the Ross orogen This interpretation has important implications for future work in that it provides the first specific and testable model for the evolution of the TAM–Ross Embayment system

2. Geology and history of the Transantarctic Mountains

The TAM form a major transcontinental range that varies from 100 to 200 km in width and has elevations up to 4500 m (Fig 1) Despite the high elevations, the crust beneath the mountains, as determined from gravity modelling is only 40–45 km thick [3,11,12], and is similar to the crustal thickness of the adjacent low-lying topographically depressed areas of the East Antarctic craton [3,11,13] This contrasts with the Ross Embayment, a region of thinned continental crust [3] extending about 800 km between the TAM and Marie Byrd Land, where the crustal thickness is between 21 and 30 km [11–13], with the thinnest crust measured by seismic refraction in McMurdo Sound (Fig 2) [14] In comparison with the abrupt 10 km change in crustal thickness on the western side of the Ross Embayment, crustal thickness increases gradually from the Ross Embayment to 35 km under Marie Byrd Land [3,15]

Throughout their length in the Ross Sea sector (Fig 1), the TAM expose Precambrian/Cambrian metasedimentary and metavolcanic rocks, and syntectonic to post-tectonic granites The bulk of the granitoids form the Ordovician Granite Harbour Intrusive Suite, which were intruded during a time of convergence (the Ross Orogeny) [16] above a westward dipping subduction zone [17,18] that lay along the length of the present TAM and also parallel to the line of the Beardmore Orogen of late Precambrian age [16] This metamorphic and granitic basement was eroded in the Silurian and early Devonian to form the Kukri Peneplain, which is overlain by about 2 5 km of almost totally undeformed mid-Palaeozoic to early Mesozoic shallow marine and fluvial sediments of the Beacon Supergroup [2] Beacon sedimentation ended in the mid-Jurassic and was followed by the extensive intrusion of tholeiitic magma as sills and dykes (Ferrar Dolerite) and their extrusion as lavas (Kirkpatrick Basalt) [2] Beacon strata and dolerite sills usually parallel the Kukri Peneplain, which allows the peneplain to be used as a reference surface for determining post-Jurassic tectonic movement Palaeogeographic reconstructions of the Beacon depositional basins [2] indicate that the TAM Front had no physiographic expression from the Devonian to the Triassic, and restriction

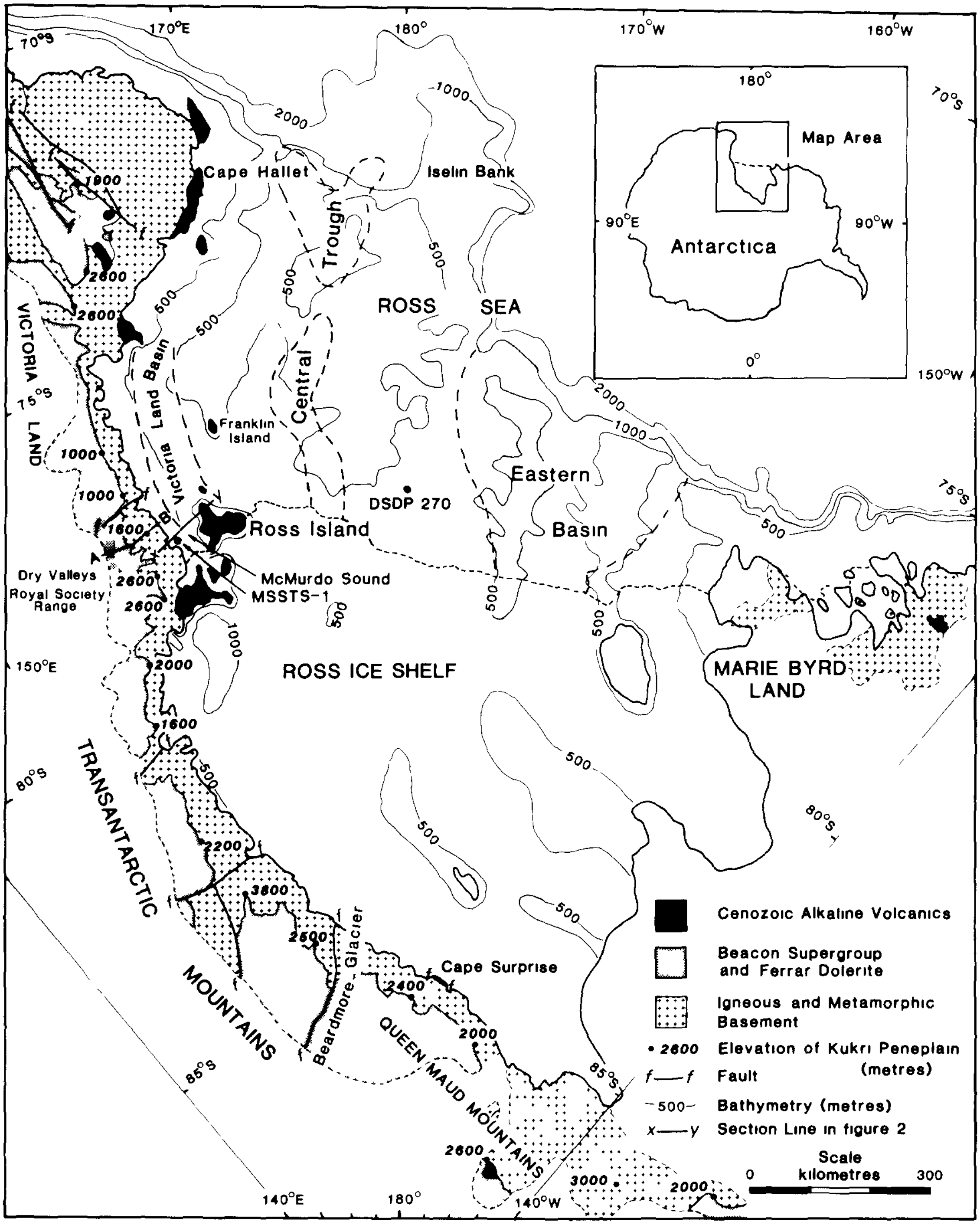

Fig 1 Index map of the TAM–Ross Embayment showing onshore geology [50], localities mentioned in the text, bathymetry [38,50,51] and sedimentary basins of the Ross Sea [4,21] Position of the Kukri Peneplain was obtained from [50] and the elevations from the appropriate U S G S 1 250,000 Topographic Maps

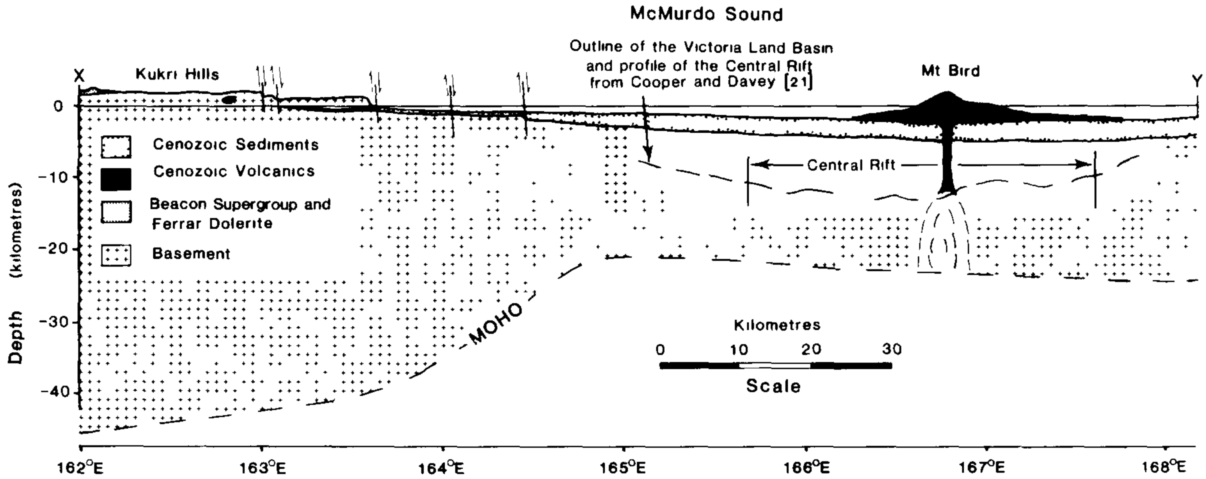

Fig 2 Crustal cross section through McMurdo Sound on a line X-Y as marked in Fig 1, showing the abrupt change in crustal thickness across the Transantarctic Mountain Front as modelled from gravity data and one reversed seismic refraction profile [14,47], sediment thickness and position of faults within McMurdo Sound [52] and the projected outline of the Victoria Land Basin from Line 407 in [21]

of the Beacon Supergroup to broad elongate basins centred on the present site of the TAM suggests an average to slightly reduced crustal thickness at the time of deposition [2] In view of the present-day similarity in crustal thickness beneath the TAM and the adjacent craton, it is possible that the crust beneath the TAM has thickened slightly since Beacon deposition The timing of crustal thickening will be discussed later

The mid-Jurassic magmatism was followed by a gap of 160 million years in the on-land geological record in the Ross Sea sector, the next recorded event being the eruption of alkaline lavas of the McMurdo Volcanic Group along the TAM Front These began at least 19 Ma ago [19] and continue to the present Volcanic products older than 30 Ma have been recorded in an offshore drillhole [20], and are also suspected in deeper seismic sequences offshore [21] Alkaline volcanism is concentrated in certain areas along the mountain front (Fig 1) and extends up to 150 km offshore (e g Franklin Island and in the Victoria Land Basin [21]) The chemistry of the lavas is typical of other continental rift-related volcanoes such as those in the East African rift and implies crustal extension over this period [22]

Recent extensional tectonism in the Ross Embayment is supported by unusually high heat flows in the Victoria Land Basin (83–126 mW m^{-2} [23]) and in the Ross Island–Dry Valleys area (67–80 mW m^{-2} [24]) These values are considered to be too high and regionally extensive to be caused by the McMurdo Volcanics alone, suggesting unusually high conductive heat transfer through anomalously thin lithosphere such as occurs in other modern continental extensional orogens, such as the Basin and Range Province [24] Unusually high temperatures at shallow levels in the mantle beneath the TAM Front are indicated by the breakdown of phologite to leucite + glass + fosteritic olivine + feldspar as well as high temperature breakdown reactions in spinel seen in xenoliths from the alkaline volcanics from Foster Crater (J A Gamble, personal communication) This further supports the notion that the continental lithosphere is anomalously thin beneath the mountain front

3. Structure and uplift history of the Transantarctic Mountains

The pattern of uplift across the TAM is best known in south Victoria Land near McMurdo Sound (Fig 1), where the axis of maximum uplift lies some 30 km west (inland) of the coast East of the axis, the amount of uplift decreases rapidly through the step-faulted zone of the mountain front (Fig 3) West of the axis the amount of

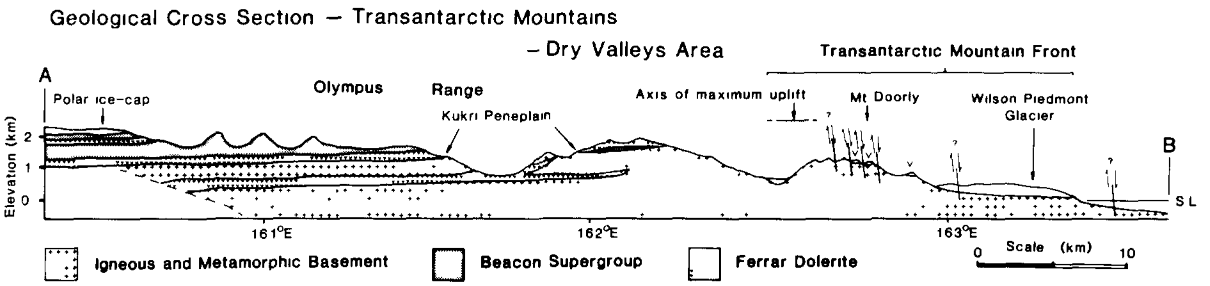

Fig 3 Geological cross section of the TAM through the Dry Valleys region on a line as marked *A-B* in Fig 1, including Mt Doorly showing the step faulted nature of the Transantarctic Mountain Front Faults marked with a question mark indicate that the exact position of that fault is not known Note the gently westerly dip of the Kukri Peneplain and Beacon Supergroup strata, eventually resulting in their disappearance under the polar ice-cap Modified after McKelvey and Webb [53]

uplift decreases steadily, as seen from the gentle westerly dip of the Kukri Peneplain The mountains themselves do not diminish in elevation however, because the preserved thickness of Beacon strata increases towards the polar plateau, disappearing beneath ice 80–200 km inland of the coast at elevations close to 2 km This simple structure is evident along most of the length of the mountains, although in places, for example, the Miller Range in the Beardmore Clacier region and west of the Rennick Glacier in north Victoria Land, basement rocks have been uplifted on the edge of the polar plateau

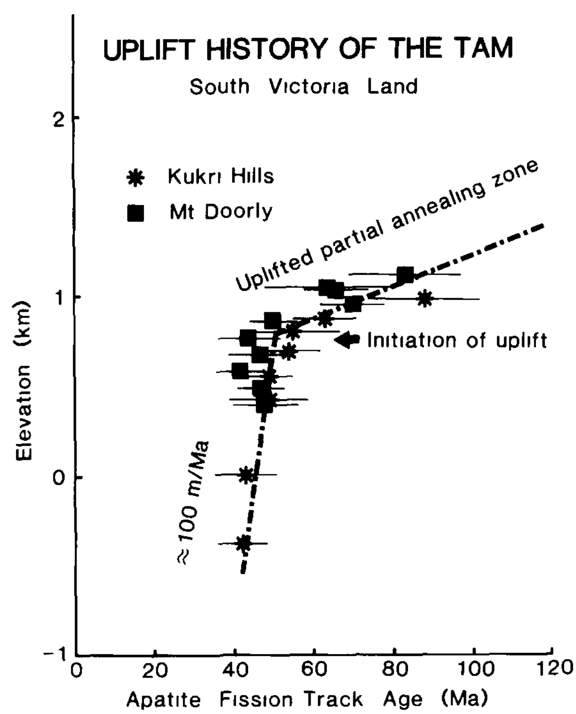

Fig 4 Apatite fission track age versus elevation graph for two sampling profiles in south Victoria Land [26,27] Errors on ages are plotted as two standard deviations The upper part of the profile represents an uplifted partial annealing zone The "break in slope" of the graph at about 50 Ma represents the start of uplift of the TAM in this area and the gradient of the lower slope represents the average uplift rate The data from the two separate profiles plot almost perfectly together indicating that they lie in similar positions within the Transantarctic Mountain Front

Apatite fission track analysis on basement rocks from the Dry Valleys of south Victoria Land has provided the only quantitative approach so far for estimating the timing and rate of uplift of the TAM [25–27] The apatite fission track ages show a strong correlation with elevation (Fig 4) and the shape of the age-elevation profile indicates a two-stage uplift history for the TAM The older part of the profile has a shallower gradient, whilst the younger part of the age-elevation profile for ages less than about 50 Ma, has a much steeper gradient The slope for the older part of the profile is about 15 m/Ma and was previously interpreted as a very slow pre-Eocene uplift rate [25] However, this is now regarded as an artifact of the pre-uplift thermal profile (an uplifted fossil "partial annealing zone"), formed during a period of relative thermal and tectonic stability established after cooling that followed the Jurassic thermal event associated with the intrusion of Ferrar Dolerite [26,27] The pronounced "break in slope" in the apatite fission track age-elevation profile at 50 Ma marks the base of the uplifted partial annealing zone, and therefore dates the start of uplift of the TAM

The stratigraphic thickness above the base of the uplifted partial annealing zone (the "break in slope") has been estimated [27] from the known thickness of granite, Beacon Supergroup strata and Jurassic dolerite plus basalt [28,29], at about 4 5–5 km, and provides a minimum value for the thickness prior to uplift The base of the uplifted annealing zone has an elevation of about 800 m at Mt Doorly [27] and from the eastern end of the Kukri Hills [26]. By summing these and subtracting the elevation of the land surface following the extrusion of the Jurassic basalts, which although poorly constrained has been estimated at around 500 m [27], we obtain a range of 4 8–5 3 km for a minimum uplift of this axis since the Jurassic If uplift did not begin until 50 Ma, as the age-elevation curve indicates, then the average uplift rate since that time is about 100 ± 5 m/Ma It is important to realise that this is an average rate and may well conceal periods of faster and slower uplift, or even subsidence An alternative method of estimating the amount of uplift assumes a thermal gradient of 30°C/km prior to uplift, based on the present-day gradient in the DVDP-6 drill-hole in the Dry Valleys [24] Using this thermal gradient, the depth to the base of the partial annealing zone lies at about 4 km (a temperature of close to 130°C [30]) giving some 4 8 km of uplift, again assuming that the surface elevation prior to uplift was 500 m and that the mean annual surface temperature close to 0°C

4. Structure and subsidence history of the Ross Embayment

The Ross Embayment, comprising the Ross Sea and Ross Ice Shelf (Fig 1) has a continental shelf, on average 500 m deep, divided by broad north-south to northeast-southwest trending ridges into three distinct sedimentary basins, the Eastern Basin, the Central Trough and the Victoria Land Basin [4] Seismic reflection profiles [21,31,32] show the basinal strata to be largely undeformed with occasional normal faulting Major normal faults also mark the western margin of the Embayment and the km have been reported from Cape Surprise [33], and at Mt Doorly a series of step faults records a total displacement of about 1 km [27]

The structure of the Victoria Land Basin, which lies adjacent to the Transantarctic Mountains, is particularly important It consists of a 14 km thick sequence of sub-horizontal strata offset by many small normal faults, some of which displace the sea floor and show a progressive increase in displacement with depth [21] This syn-depositional faulting has created a central rift that coincides with a bathymetric trough, along which lie volcanic centres [21], one of which (Mt Erebus on Ross Island) is still active Similar volcanic rocks also crop out at places on the western margin of the basin and the eastern flank of the Transantarctic Mountains These features all indicate that sedimentation and volcanism occurred in an extensional tectonic regime throughout the history of the basin The Central Trough and Eastern Basin are both shallower (maximum of 7 km of strata) and simpler in structure than the Victoria Land Basin, they both lack a central rift and any volcanic centres [4,32], but nevertheless also appear to have formed in an extensional tectonic regime

The early history of subsidence of the Ross Embayment can only be established from seismic reflection data as no deep drilling has yet been attempted Initial subsidence, however, must post-date the Triassic Beacon strata that were deposited in a trough bounded by highlands west of the present Transantarctic Mountains [2] The oldest strata dated directly were cored by MSSTS-1 on the margin of the Victoria Land Basin, and are of Late Oligocene age (30 Ma) [20] The 226 m cored by MSSTS-1 is thought to have penetrated only Units 1 and 2 of the five sedimentary units in the basin revealed in seismic traces, representing only 2 km of the 14 km of sediment postulated to be present in the central rift [34] At present the age of older strata is necessarily conjectural, and the lowest stratified unit could be Beacon Supergroup and Ferrar Group rocks However, reworked microfossils from the MSSTS-1 core do give a guide Late Cretaceous and Early Cenozoic foraminifera [35] and palynomorphs [36] indicate the strata of this age may be exposed somewhere on the western margin of the Victoria Land Basin Erosion along this margin north of McMurdo Sound has exposed the oldest sedimentary formation of the basin (sedimentary unit 5) upturned against the TAM Front [34], which could, if exposed to the south, have been the source of the oldest reworked material We conclude therefore that subsidence in the Victoria Land Basin probably began in the Late Cretaceous/Early Cenozoic, that the greatest amount of subsidence occurred during the Cenozoic, and that subsidence and sedimentation has continued to the present day. The western margin of the basin at MSSTS-1 experienced steady subsidence through the Late Oligocene and Miocene followed by more rapid subsidence and then 1 km of uplift in the Pliocene [20], but this cannot be taken to represent the basin as a whole.

The Central Trough is the least well known of the three basins, but in the central part more than 2200 m of pre-Late Oligocene sediments are considered to occur beneath 3800 m of younger sediments [32]. The Eastern Basin and the Central Trough are separated by a basement high, the northward extension of which forms the Iselin Bank. Multichannel seismic reflection data across the Iselin Bank show the incision of basement by two north-south trending graben covered by a thin sedimentary section [31].

Drilling close to the margin of the Eastern Basin also provides a chronology for basin subsidence. The western margin, at DSDP site 270, was above sea level for millions of years, long enough for a well developed palaeosol to form on the basement gneiss [37]. It subsided below sea level in the Late Oligocene to depths of several hundred metres and was uplifted and eroded in the Pliocene [38]. Net subsidence over the 26 Ma period of sedimentation was about 1 km. In the central part of the basin equivalent strata (late Oligocene and Miocene) are about 3.7 km thick and are underlain by an older sequence more than 2200 m thick [32]. Like MSSTS-1, DSDP-270 also contains reworked Late Cretaceous foraminifera [35], suggesting that the deepest sedimentary succession here, like that of the Victoria Land Basin, is of this age as well. A Late Cretaceous age for the oldest rift-related strata in the Ross Sea is also consistent with the oldest strata in the Great South Basin of New Zealand [39], now 3000 km, but then only 500 km, to the north [39].

In summary, the floor of the Ross Embayment has sunk at least 10 km adjacent to the TAM, and 6 or 7 km in basins farther east. Reworked microfossils and seismic stratigraphy suggests that most subsidence in the Victoria Land Basin took place in the Late Cretaceous/Early Cenozoic, but in the Eastern Basin most sediment, and presumably most subsidence, post-date the Late Oligocene. An extensional tectonic regime has persisted throughout sedimentation, and in the western part of the Ross Embayment this sedime alkaline volcanism. Extensive disruption of the sequences by growth faults above the anomalously thin crust in the Victoria Land Basin [21] also suggests that subsidence there was coeval with crustal thinning.

5. Model for extensional asymmetry in the TAM-Ross Embayment

Continental extension has traditionally been regarded as an axially symmetrical process involving pure-shear thinning of the ductile lithosphere and listric normal faulting of the brittle lithosphere. While such extension models, especially those involving depth-dependent extension, have successfully accounted for subsidence histories of extensional terrains such as rifted continental margins, they cannot account for the asymmetry on a regional scale of a number of modern extensional orogens, such as the classic Basin and Range–Colorado Plateau system. Moreover, axially symmetrical models involving depth-dependent extension are often geometrically unacceptable because they generally do not permit the construction of balanced cross-sections (i.e. mass is not conserved). The significance of large-scale structural asymmetry during the evolution of the Basin and Range Province, first suggested by Wernicke [7], has recently been highlighted by publication of a number of studies [6,8,40,41]. The governing structures during the evolution of the Basin and Range extensional orogen are low-angle normal shear zones or detachment faults which show regionally consistent movement sense.

The chronology of uplift of the TAM and subsidence of the Ross Embayment discussed in the previous sections suggests that the uplift of the TAM is intimately associated with thinning and subsidence of the Ross Embayment; both terrains are related to the TAM extensional orogen that has developed since the Late Cretaceous/Early Cenozoic. The pronounced asymmetry of this orogen is highlighted by the contrasts in the evolution of the two terrains. The TAM have undergone about 5 km of uplift in the last 50 Ma, whereas the Ross Embayment has undergone equally dramatic subsidence with the formation of basins, 6 km or more thick since the Late Cretaceous/Early Cenozoic Moreover, while the crust beneath the TAM has remained of constant thickness, or more probably been slightly thickened since deposition of the Beacon Supergroup, the continental basement beneath the Ross Embayment had been thinned Using a one-layer extensional model we can estimate crustal thinning in the Ross Embayment by assuming it had a crustal thickness of 35–40 km prior to rifting (similar to that in East Antarctica) and comparing this with the present-day average crustal thickness of 25–30 km over the width of the Embayment (800 km) The total crustal extension determined in this way is about 25–30%, or close to 200 km In the Victoria Land Basin actual extension may be as much as 50%, with possibly as much as 70% beneath the central rift

Theoretical models for the evolution of extensional terrains show that the first-order changes in surface elevation reflect the relative changes in thickness between the crust and subcrustal lithosphere [5,42,43] Where extensional strain is equally partitioned between the crust and subcrustal lithosphere, subsidence and basin development results [5] Subsidence is greatly enhanced if extensional strain is greater in the crust Preferential partition of strain into the subcrustal lithosphere results in minimal subsidence and may, in the case where little or no strain is accommodated in the crust, result in uplift The contrasting uplift and subsidence histories across the TAM Front may therefore be viewed as a consequence of a regional variation in the depth at which extensional strain has been accommodated, with extension partitioned largely into the crust beneath the Ross Embayment and into the subcrustal lithosphere beneath the TAM

We can use the Kukri Peneplain as a reference surface for a first-order approximation of the amount of uplift that an area has undergone, even though there must have been slight variations in the original elevations of this erosion surface along the length of the TAM corresponding to localized Devonian basins [2] In this way, it can be seen from Fig 1 that the Dry Valleys–Royal Society Range region (an area of greater peneplain elevation than to the north or south) is coincident with a concentration of Cenozoic volcanics It is possible therefore that uplift induced by extensional strain may be locally enhanced by the influence of magmatic additions underplating the base of the crust Magmatism during the Jurassic may also have contributed to magmatic accretion and hence crustal thickening In terms of volume and distribution, the Jurassic igneous event was of greater significance than the Cenozoic event, but a rift system evidently did not form during the Jurassic [44], and the apparent lagk of any great thickness of sediments older than Cenozoic in the Ross Embayment indicate that little or no significant extension took place before this time It is, however, difficult to aportion the amount of underplating caused by the Jurassic versus the Cenozoic events Our observations here are a first-order look at what is a complex problem Nevertheless it is likely that some of the inferred crustal thickening beneath the TAM (since the time of Beacon deposition) has occurred during uplift of the mountains The correlation of volcanism in the Dry Valleys–Royal Society Range region with greater uplift does provide circumstantial evidence for magmatic underplating during the Cenozoic compared to the immediate north or south of this area It should be noted, however, that in other areas of high Kukri Peneplain elevation relative to surrounding regions, for example just north of the Beardmore Glacier (Fig 1), Cenozoic volcanism is notably lacking Nevertheless, the above model can account for the magnitude, timing and rate of uplift of the TAM compared to subsidence of basins within the Ross Embayment In addition, we note that gravity models for the structure of the Ross Embayment [34] are consistent with the model proposed here for the TAM–Ross Embayment system

The inferred regional variation in the depth of strain accommodation across the TAM Front precludes an axially symmetrical model for the Ross Embayment–TAM extensional orogen Rather, it suggests that at least within the upper lithosphere, strain has been localised along a detachment or shear zone which dips westward from the Ross Embayment and penetrates the Moho below the western boundary of the TAM Front (Fig 5) It is this shallow dipping detachment zone which allows for the translation in the depth of extensional strain accommodation from the crustal levels in the Ross Embayment to subcrustal levels beneath the TAM Front While independent evidence for

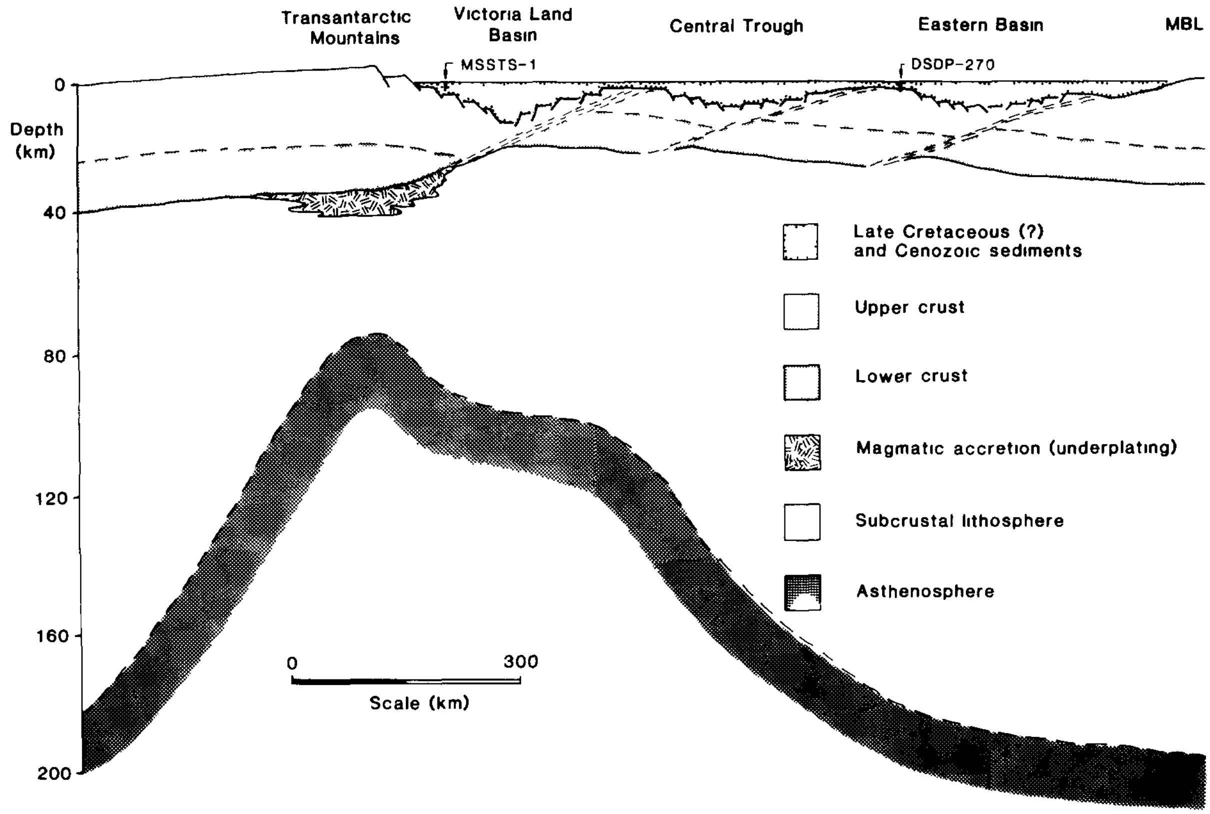

Fig 5 Conceptual model of asymmetric extension in the TAM–Ross Embayment showing the inferred detachment zone beneath the TAM and possible detachments beneath the Ross Embayment The position of the asthenosphere–subcrustal lithosphere boundary is estimated using the approach of Turcotte [42] to calculate uplift and subsidence as a function of relative thinning of crust versus subcrustal lithosphere Strain in the subcrustal lithosphere is modelled as ductile pure-shear flow Initial lithospheric thickness is assumed to be 300 km [54] Positions of MSSTS-1 and DSDP-270 drillholes are diagrammatic *MBL* = Marie Byrd Land

the existence of such a structure is not available, we note that the inferred position and asymmetry of this structure parallels the structural grain and asymmetry in the metamorphic basement of the TAM-imparted during early Palaeozoic subduction

While regional shear zones often follow pre-existing structural grain or lines of inherited weakness [7,45], major faults do not always reactivate old thrusts and in some extensional belts the sense of asymmetry is opposite to these old planes of weakness (e g [46]) However, the sense of asymmetry in the TAM–Ross Embayment is the same as the postulated detachment zone and therefore this extensional orogen could be due to reactivation of a fundamental lithospheric weakness generated during early Palaeozoic convergence The coincidence of a Palaeozoic foldbelt with an extensional regime over 3000 km strongly supports a passive rather than an active mechanism [42] for Cenozoic extensional tectonism in the TAM The confinement of the Ferrar magmatism to a linear zone along the site of the TAM has also been suggested to be a result of reactivation of pre-existing zones of weakness the Beardmore and Ross orogenic belts [44] Indeed, the inferred west dipping asymmetry of the regional detachment structure and parallel nature of the structural grain of the Cenozoic, Mesozoic, Palaeozoic and Precambrian tectonic events is rather too similar to be mere coincidence

While the existence of a single, shallow west-dipping, crustal penetrative detachment zone may account for the asymmetry in the western Ross Embayment and TAM, it seems unlikely that such a structure could accommodate the estimated 200 km of extension across the Ross Embayment without complete separation of the continental crust. The dip of the detachment zone can be either inferred from the angle of the Moho beneath the mountain front obtained from gravity models [47] as 20–30°, or be calculated by assuming it runs from the base of the crust under the TAM to near the top of the basement high between the Victoria Land Basin and Central Trough, in which case an angle of about 10° is obtained. We note that detachments modelled for the Basin and Range Province have shallow regional initial dips of 10–30° [8]. These detachment or shear zones tend to shallow or steepen due to a number of factors [8] but usually do not follow regional sub-horizontal boundaries due to changing rheological properties between different crustal layers. The idea of being able to apply a regional dip to a detachment or shear zone and that this shear surface can penetrate rheological boundaries has been confirmed [45].

These regional angles of dip of the detachment, together with the 10 km reduction in crustal thickness suggests that the detachment fault here is unlikely to accommodate much more than 50–100 km of extension. The possibility of similar detachments, perhaps not as major, in the central and eastern Ross Embayment is, however, suggested by the geometry of the basement in this region. Profound geometric similarity to the Basin and Range Province [8,40] may be observed with meridional trending sedimentary basins separated by relatively narrow highs exposing metamorphic basement. Indeed, it is conceivable that these basement highs are analogous to the Cordilleran Core complexes in the Basin and Range Province which are exposed between shallow dipping detachment zones [8,9,48]. Furthermore, crustal thinning due to low-angle detachment faulting may have resulted in widespread tectonic unroofing within the Ross Embayment, the presence of calc-silicate gneiss drilled at DSDP-270 [37], being consistent with this model.

6. Conclusion

The development of the TAM and the Ross Embayment has been shown to be broadly contemporaneous. Fission track dating studies show that there has been about 5 km of uplift in the TAM since the Early Cenozoic. Less well constrained is the timing of the subsidence of basins within the Ross Embayment. The sedimentary sequences there, although not well dated, indicate that subsidence may have begun in the late Cretaceous, with major sediment accumulation since the early Cenozoic. The model proposed here to explain the contemporaneous but contrasting histories of these two terrains is based on recent studies of continental extension zones, in particular within the Basin and Range Province. It further emphasizes the importance of asymmetry in the interpretation of continental extension.

We invoke regional variation in depth of extensional strain to account for the contrasting uplift-subsidence of the TAM–Ross Embayment system and suggest that the fundamental controlling structure for the development of this extensional orogen is a shallow westerly dipping detachment fault zone which has allowed translation of extensional strain from crustal levels in the Ross Embayment to subcrustal levels beneath the TAM. The proposed detachment fault is most likely coincident with an old plane of weakness due to early Palaeozoic subduction, and implies passive rather than active rifting. Extension, of the order of 200 km across the Ross Embayment is suggested, but cannot be accommodated on the one detachment fault beneath the TAM Front, so it is suggested that other detachment faults exist under the Basin and Range style morphology in the rest of the Ross Embayment to the east of the Victoria Land Basin (Fig. 5). These detachment faults should overlap through any given vertical line to allow for the possibility that strain is accomodated entirely within the detachment zone and that the crustal "lozenges" (Fig. 5) that lie between the detachment zones are essentially strain free.

Hinz and Block [32] show that any deformation in the Central Trough and Eastern Basin of the Ross Sea must predate the Late Oligocene, as sediments thought to be that age and younger are undeformed. The Victoria Land Basin is, however, an active tectonic basin, and multichannel seismic data from here suggest two periods of rifting tentatively dated as late Mesozoic and then Paleogene(?) to recent [34]. Sea-floor magnetic studies [49] suggest that relative displacement between East and West Antarctica took place sometime from the Late Cretaceous to Late Eocene but that the timing and amount of displacement is uncertain What is clear both from the geophysical and geological evidence summarised here, is that from the Late Cretaceous/Early Cenozoic the Ross Embayment has been the site of extension and basin formation, the TAM has been the locus of uplift and that these two events are related

While the model presented here for the evolution of the TAM–Ross Embayment system is largely conceptual, it does have important consequences for the direction of future research in the region allowing for the refinement of input parameters as well as a test of the basic idea The stratigraphy and age of the sediments of the Ross Sea basins, especially the Victoria Land Basin, and a seismic refraction study to accurately determine the crustal thickness beneath the TAM would greatly add to our knowledge of the geological evolution of this part of Antarctica

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