ELSEVIER

Geomorphology 28 (1999) 181–200

GEOMORPHOLOGY

Landscape development in the Royal Society Range, southern Victoria Land, Antarctica: stability since the mid-Miocene

David E. Sugden [a,*], Michael A. Summerfield [a], George H. Denton [b], Thomas I. Wilch [c], William C. McIntosh [c], David R. Marchant [d], Robert H. Rutford [e]

[a] *Department of Geography, University of Edinburgh, Edinburgh EH8 9XP, UK*
[b] *Department of Geological Sciences and Institute of Quaternary Studies, University of Maine, Orono, ME, USA*
[c] *Department of Geoscience, New Mexico Institute of Mining and Technology, Socorro, NM, USA*
[d] *Department of Earth Sciences, Boston University, Boston, MA 02215, USA*
[e] *Geosciences Program, University of Texas, Dallas, TX, USA*

Received 1 January 1998; received in revised form 16 October 1998; accepted 31 October 1998

Abstract

Post-rifting landscape development in the Royal Society Range, a rift-flank block in the southern Victoria Land sector of the Transantarctic Mountains, has been reconstructed through a combination of morphological mapping and geochronological data. Creation of the Royal Society Range rift flank ~55 Ma BP was associated with extension in the Ross Sea Basin and some surface uplift of the Royal Society Range probably occurred at this time. Extrapolation of fission-track data for other sectors of the Transantarctic Mountains, coupled with a reconstruction of pre-rift stratigraphy, indicates that a seaward-thickening wedge of crustal section up to ~6 km at the coast has been removed since rifting. Much of this crustal stripping probably occurred in the early Cenozoic, and cosmogenic isotope data together with $^{40}Ar/^{39}Ar$-dated volcanic cones and surficial ashes demonstrate that denudation over much of the Royal Society Range has been insignificant since the mid-Miocene. This denudation probably occurred primarily through fluvial processes, and the generally limited impact of subsequent glacial action has led to the preservation of elements of the pre-glacial fluvial landscape. The present elevation of a sub-aerially erupted lava flow constrains maximum surface uplift in the Royal Society Range over the past 7.8 Ma to less than 67 m, assuming present sea level as a datum. Similarities between the denudational and surface uplift histories of the Royal Society Range and the adjacent Dry Valleys area show that the latter has not experienced an unusual tectonic and glacial history, as has been previously suggested. Our analysis strongly supports the notion of a stable East Antarctic Ice Sheet and minimal landscape modification in the Royal Society Range since at least the mid-Miocene. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: landscape development; Royal Society Range; mid-Miocene

---

[*] Corresponding author. Tel.: +44-131-650-1000; Fax: +44-131-650-2524; E-mail: office@geo.ed.ac.uk

PII: S0169-555X(98)00108-1

1. Introduction

The Royal Society Range is a 70-km broad rift-flank block facing the Ross Sea Basin in southern Victoria Land, Antarctica (Fig. 1). As with other sectors of the > 3000 km-long Transantarctic Mountains, the Royal Society Range represents part of the upwarped margin of an extensive landsurface that rises gradually from the interior of Antarctica and eventually emerges from beneath the East Antarctic Ice Sheet. The highest terrain of the Royal Society Range, at over 4000 m, lies only 45 km inland of the Ross Sea shoreline, and the precipitous seaward drop in elevation along this coastal zone is marked by a spectacular rift-margin escarpment.

There has been a lack of previous geomorphological research on the Royal Society Range aimed at an overview of landscape evolution, although the history of long-term landscape development in this area is important for a number of reasons. First, the relief of the Royal Society Range is amongst the highest of any passive continental margin, being matched only by some of the other sectors of the Transantarctic Mountains. It is an extreme example of a high-elevation rifted margin (Gilchrist and Summerfield, 1990, 1994) and it provides a valuable basis for comparison with other passive margins around the world. Second, the apparently extremely slow rates of landscape change throughout much of the late Cenozoic in this arid, polar environment constitute a denudational regime starkly different from that of rifted margin settings elsewhere.

Third, an understanding of landscape development in the Royal Society Range is an important element of the current debate about the stability of the East Antarctic Ice Sheet (Miller and Mabin, 1998). The argument that the ice sheet is dynamic and largely disintegrated as recently as ~ 3 Ma ago is crucially dependent on the age of the glaciogenic Sirius Group deposits that are found at high altitudes at many locations throughout the Transantarctic Mountains. If, as has been suggested, these deposits are of Pliocene age then the dynamic ice sheet hypothesis is plausible, but if they are significantly older then this model is fatally undermined. One of the key Sirius Group sites is located on Table Mountain on the inboard slope of the Royal Society Range, and the age and morphological setting of this deposit is highly significant in the wider context of the landscape chronology of the area (Fig. 2).

Finally, it is important to determine the history of landscape development in the Royal Society Range in order that it can be compared with the chronology of landscape evolution in other structural units of the Transantarctic Mountains. We have already made the case for the antiquity of various landscape elements in the Dry Valleys area, and have shown that these have experienced minimal modification over the past ~ 15 Ma (Denton et al., 1993; Marchant et al., 1993; Sugden et al., 1995). A key implication of this research is that in the Dry Valleys region the Sirius Group deposits must be at least as old as mid-Miocene. However, others have argued that the Dry Valleys have had a unique tectonic and denudational history (van der Wateren and Hindmarsh, 1995; Hindmarsh et al., 1998). In such a case comparison with the structural block forming the Royal Society Range is especially valuable both because it lies immediately adjacent to the Dry Valleys block and because its present mean elevation is significantly higher.

Here we combine geomorphological mapping and landscape interpretation with geochronological data and an assessment of tectonic models to propose a history of post-rifting landscape development for the Royal Society Range. Our aim is to set landscape evolution in this area in the broader context of the long-term landscape development in the south Victoria Land sector of the Transantarctic Mountains.

2. Current debates

Uncertainties about the glacial and landscape history of the Royal Society Range, and the Transantarctic Mountains in general, can be resolved into four specific, but related, issues: (1) the timing and magnitude of surface uplift and the resulting changes in topography through time; (2) the spatial and temporal pattern of post-rifting denudation; (3) the relative importance of different surface processes responsible for the form of the present landscape; and (4) the tectonic mechanisms that have operated during, and since, the rifting event that initially created the Transantarctic Mountains.

The major uncertainty about the development of topography concerns the timing of surface uplift

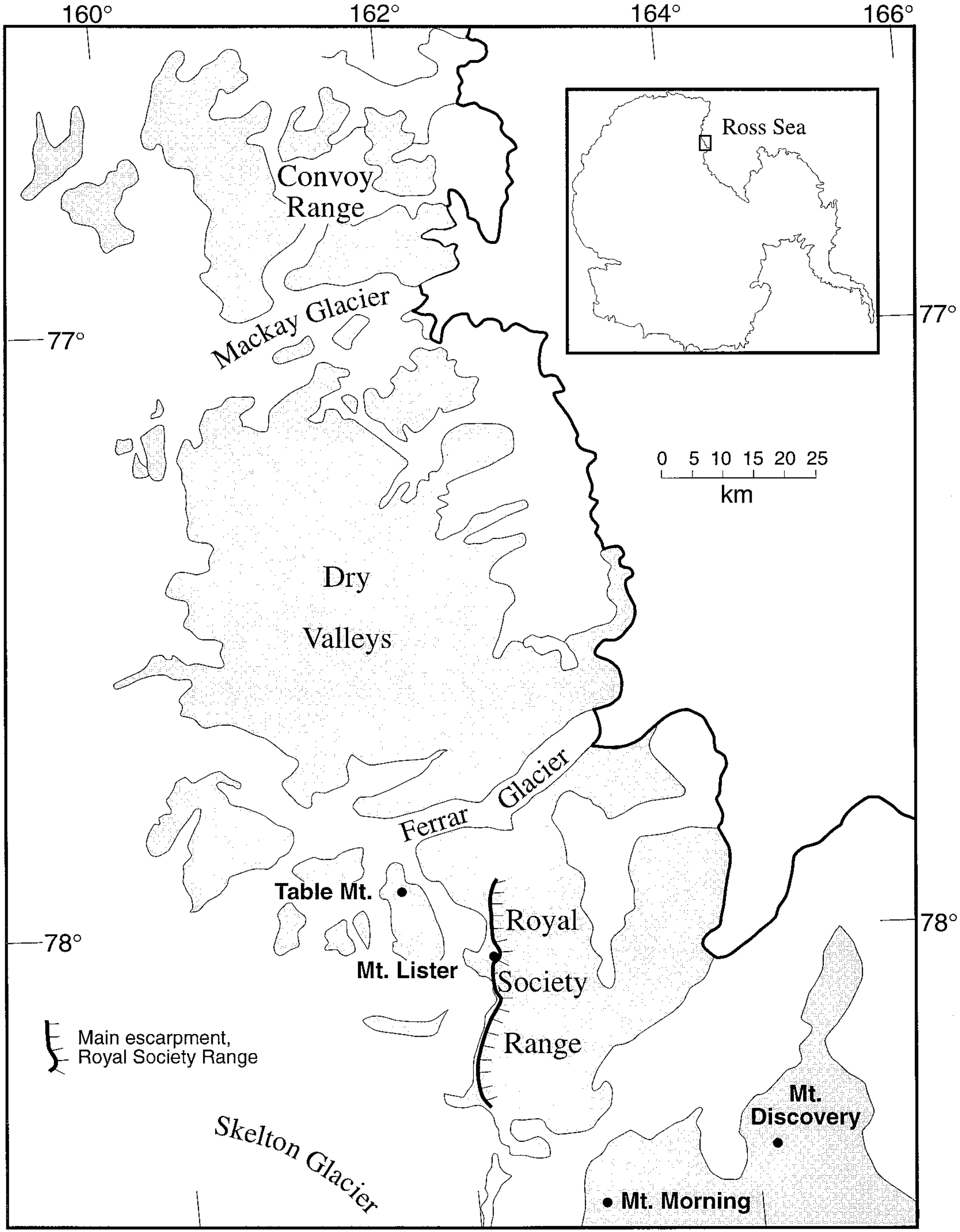

Fig. 1. Location map showing the Royal Society Range, Dry Valleys and Convoy Range blocks of the Transantarctic Mountains and the bounding Skelton, Ferrar and Mackay outlet glaciers.

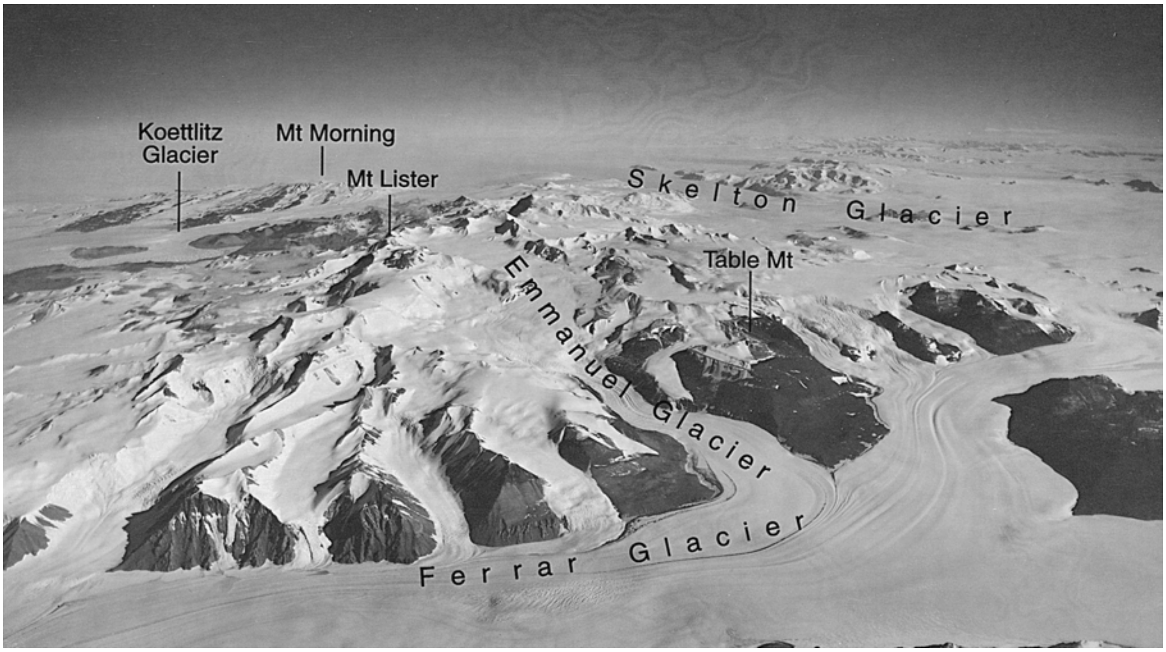

Fig. 2. The Royal Society Range viewed from the north. Mt. Lister is 4025 m in altitude. Table Mountain carries Sirius Group deposits. US Navy photograph, TMA 2303.

during, and following, the episode of crustal extension and rifting that created the Ross Sea Basin and the rift-flank forming the Transantarctic Mountains. Although some surface uplift was probably associated with rifting ~55 Ma ago, it has also been suggested that significant surface uplift of at least 1300 m has occurred at least locally during the past 2.5–3 Ma, such as in the Beardmore Glacier area of the central Transantarctic Mountains (Webb et al., 1987; McKelvey et al., 1991). A range of evidence has been interpreted as supporting the idea of surface uplift at a rate of ~1 km Ma^{-1} since the early or middle Pliocene, including the 'youthful' morphology and high relief of the Transantarctic Mountains, and the presence of Holocene fault scarps on offshore reflection profiles and normal faults, interpreted as late Pliocene or younger, displacing moraines by as much as 300 m (Behrendt and Cooper, 1991, 1994). In contrast to this view, isotopic dating of sub-aerially erupted volcanic rocks has demonstrated that in the Dry Valleys sector, at least, Pliocene–Quaternary surface uplift has been minimal (Wilch et al., 1993).

A second point of disagreement is the denudational history of the Transantarctic Mountains. One implication of rapid Pliocene–Quaternary surface uplift and a Pliocene age for the Sirius Group would be that dissection of individual fault blocks which led to the isolation of these now high-altitude glacial deposits would also have occurred during the past ~3 Ma. However, abundant morphological and geochronological evidence from the Dry Valleys area indicates slow rates of denudation for much of the landscape extending back to the mid-Miocene (Summerfield et al., 1999).

The debate over the relative importance of glacial and fluvial processes in the creation of the landscape of the Transantarctic Mountains has extended throughout most of the present century. An early view, presented by Taylor (1922), was that the landscape is essentially glacial in origin and that the different erosional levels observed can be explained by different glacial episodes. Such an argument has been applied to the Dry Valleys area where valley benches have been attributed to past glaciations and high-level valley heads to the action of cirque glaciers

(Bull et al., 1962; Nichols, 1971; Selby and Wilson, 1971; Calkin, 1974). The alternative view is that the landscape was originally fluvial in origin and has subsequently been modified by glaciers. In northern Victoria Land, for instance, Priestley (1909) interpreted valley-side facets as representing the glacial straightening of formerly sinuous fluvial valleys. Recently, it has been argued that the original dissection of the Dry Valleys block was by fluvial action and that, in spite of modification to varying degrees by subsequent glacial action, many fluvial landforms are still preserved today, including dendritic valley patterns, graded valley confluences, sinuous valleys and valley benches (Sugden et al., 1995).

A range of tectonic models has been proposed to account for the macroscale topography of the Transantarctic Mountains and their surface uplift history, but no consensus as to the dominant processes involved has emerged (Kerr et al., in press). Proposed mechanisms include the effects of isostatic unloading and crustal flexure related to ice loading and glacial erosion (Wellman and Tingey, 1981; Drewry, 1983; McGinnis et al., 1985; Tingey, 1985), phase changes in the deep crust (Smith and Drewry, 1984), asymmetric extension (Fitzgerald et al., 1986), flexural uplift of the footwall of a half-graben basin supplemented by thermal uplift, denudational unloading and the Vening Meinesz uplift effect (Stern and ten Brink, 1989), thermal uplift (ten Brink et al., 1993), flexural uplift as a result of lithospheric necking (van der Beek et al., 1994) and the flexural isostatic response to differential denudation (Kerr and Gilchrist, 1996). Clearly, such mechanisms, and the timing and amount of uplift that they imply, must be compatible with palaeoelevation data, the sequence of landscape development and the associated denudational histories derived from geochronological data.

3. Field setting

The Royal Society Range is the highest of the sequence of tilted rift-flank blocks which constitute the southern Victoria Land sector of the Transantarctic Mountains. Elevations reach up to 4025 m (Mt. Lister), and the altitude along the rim of the block is consistently above ∼3000 m. The dramatic fronting escarpment is 1600–2000 m high and rises above the depression occupied by the Blue Glacier basin (Fig. 3). Blue Glacier itself is separated from the coast by lower terrain, around 900 m high, which is breached by the glacier in the north (Fig. 4). In places this

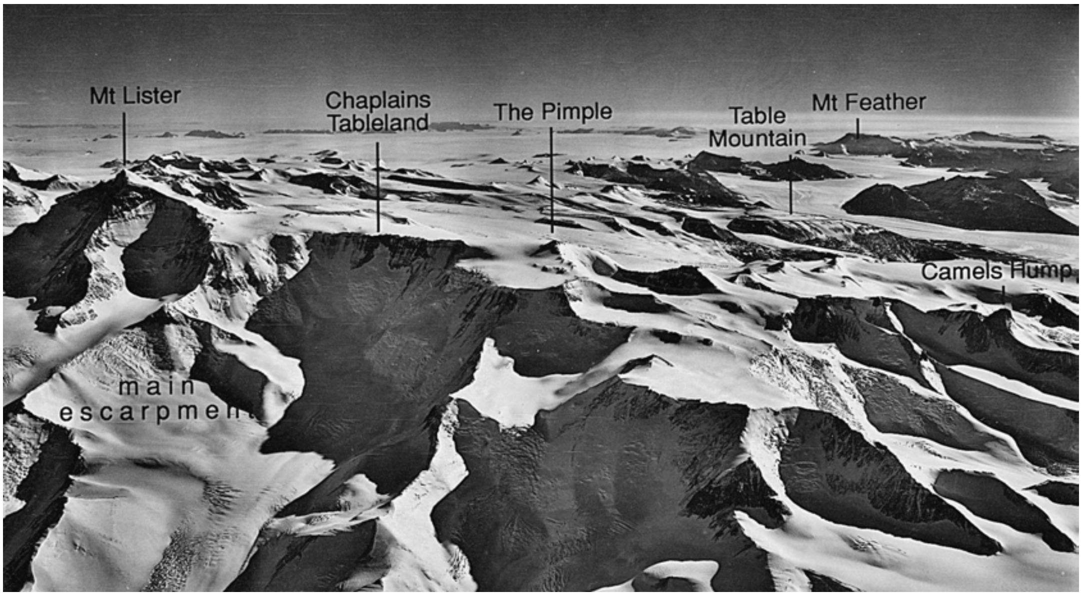

Fig. 3. The Royal Range looking inland, showing the main escarpment and tilted tableland. Inselbergs stand proud above the plateau surfaces. US Navy photograph VX 6, F.31, TMA 040.


KEY:
Summit surface
Erosion surface
Valley bench
Coastal piedmont
Coastal piedmont (ice covered)
Cliff top
Cliff top (degraded)
Cliff (probably glacial)
Ridge crest bounded by rectilinear slope
Major rectilinear slope
Areal scour (heavy)
Areal scour (light)
Glacial lineation
Major meltwater channel
Residual peak
Volcanic cone
Tor
Spotheight (m)
Contour (m)
Glacier streamline
N
0 5 10 15 20 25 30 (km)
BOWERS PIEDMONT GLACIER
HOBBS GLACIER
JOYCE GLACIER
BLUE GLACIER
FERRAR GLACIER
TAYLOR GLACIER
EMMANUEL GLACIER
WALCOTT GLACIER
RADIAN GLACIER
SKELTON GLACIER
KOETTLITZ GLACIER
ROYAL SOCIETY RANGE
TRANSECT
Garwood Valley
Marshall Valley
Miers Valley
Walcott Bay
Williams Peak
Chaplains Tableland
Mt. Lister
The Pimple
Camels Hump
Cathedral Rocks
Kukri Hills
Table Mt.
The Spire
Mt. Rücker
Mt. Huggins
Mt. Kempe
Mt. Dromedary
Beacon Valley
Arena Valley
Mt Feather 3011
(17Ma)
(11.98 Ma)
(11.34 - 12.43 Ma)
(12.1 Ma)
(7.79 Ma)
(1.55 Ma)
(6Ma)
(1300m)
(2000m)
(2200m)
1097
1180
1487
1340
1182
1090
1280
1574
1690
1130
990
554
2596
3215
4025
3650
3816
3733
3004
2273
1969
1880
2230
2005
2400
3460
2260
2420
2345
2841
2450
1750
1450
2120
1530
1000
2000

lower terrain is separated from the coast of McMurdo Sound in the southern Ross Sea by a gently sloping surface. The Royal Society Range is bounded to the north by the Ferrar Glacier; the surface of this outlet glacier falls steadily seaward from an altitude of 1900 m, 90 km inland to near sea level at its floating snout. There is approximately 2800 m of relief between the glacier surface and the highest point on the adjacent rim of the rift flank at The Pimple (3215 m). Tributaries of the Ferrar Glacier drain ice from the northern periphery of the Royal Society Range. The southern boundary of the Royal Society Range is demarcated in the east by the tributaries of glaciers flowing eastwards into Koettlitz Glacier and thence into McMurdo Sound, and in the west by tributaries feeding Skelton Glacier which flows southwards to join the Ross Ice Shelf.

Exposed bedrock in the Royal Society Range comprises a Precambrian igneous and meta-igneous basement complex unconformably overlain by Devonian-to-Triassic-age sandstones, siltstones and conglomerates of the Beacon Supergroup which dip gently westward away from the Ross Sea coast. The unconformity at the base of the Beacon Supergroup sedimentary sequence is known as the Kukri erosion surface, and it affords a key reference for documenting subsequent differential uplift in southern Victoria Land. Basement crops out up to elevations of $\sim$2600 m on the escarpment front, with granite forming the prominent peak of Camels Hump (2273 m) 8 km south of the Ferrar Glacier. Inland of the escarpment, the gently inclined Kukri erosion surface is exposed on the sides of larger valleys. Ferrar dolerites (Jurassic) have intruded both the basement and overlying sedimentary sequence forming thick sills. Small outcrops of late Cenozoic alkaline volcanics and associated intrusions also occur throughout the area, and in the south two large volcanoes—Mt. Morning (2723 m) and Mt. Discovery (2681 m)—form the southern flank of the Koettlitz Glacier basin. The former was constructed $\sim$19 Ma ago and the latter around 5 Ma BP (Kyle, 1990).

The precipitous flank of the Royal Society Range and adjacent blocks of southern Victoria Land along McMurdo Sound has long been regarded as constituting a downfaulted margin (Ferrar, 1907; Taylor, 1913; Wright and Priestley, 1922), although Fitzgerald (1992) noted that these north–south trending longitudinal faults appear to be offset by subsidiary east–west trending transfer faults. Recent detailed mapping by Wilson (1995) has shown that the longitudinal fault arrays in the southern Victoria Land sector are in fact orientated obliquely to the line of the escarpment front and offshore rift basins, implying that the regional rift boundary is not controlled by continuous rift border faults. Major east–west trending transverse faults orientated approximately normal to the escarpment front are thought to demarcate the northern and southern boundaries of the Royal Society Range block. To the north the Ferrar fault runs along the trough formed by the Ferrar Glacier, although its precise location is uncertain. To the south the boundary may be marked by a major transfer fault up, or near, the Skelton Glacier which coincides with the inflection point in McMurdo Sound of the trend of the Transantarctic Mountains (Fitzgerald, 1992). A lineation identified on Landsat imagery running WNW–ENE just north of Skelton Glacier and through the Koettlitz Glacier may represent this major structure (Lucchita et al., 1987; Fitzgerald, 1992).

The present climate of the Royal Society Range is polar hyperarid. Specific meteorological data are lacking, but through extrapolation from the Dry Valleys area immediately to the north (Schwerdtfeger, 1984; Fortuin and Oerlemans, 1990; Marchant and Denton, 1996) we infer that mean annual temperatures are probably about -17 to -20°C at low elevations near the coast, with mid-summer temperatures exceeding $+5$°C. In this coastal zone geomorphic processes requiring meltwater, such as gelifluction, debris flows and (limited) stream flow are possible. Temperatures decline inland with increasing elevation, and liquid water is effectively absent above an altitude of $\sim$1000–1500 m. If one assumes a lapse rate of 10°C km^{-1}, mean annual temperatures would be less than -40°C in the highest parts of the Royal Society Range. Mean annual

Fig. 4. Geomorphological map compiled from fieldwork, supplemented by air photographs. The transect line shows the location of the cross-section in Fig. 8.

snow precipitation probably reaches a maximum of 100 mm at the coast and relative humidity declines inland, especially in areas most exposed to the strong katabatic winds that blow from the Polar Plateau. Although some biotic activity is present at low elevations near the coast, at altitudes above ~2000 m even cryptoendolithic microorganisms are unable to survive (Friedmann et al., 1994).

4. Landscape morphology and relative chronology

In order to characterize the key landscape components and place them in a relative temporal sequence, we carried out an extensive programme of field observation and geomorphological mapping. A geomorphological map at a scale of 1:250 000 was constructed (Fig. 4) using Landsat Thematic Mapper imagery (Fig. 5), aerial photography and observations from numerous helicopter forays, with additional ground mapping in 20 key areas carried out over two summer field seasons. As it was not feasible to undertake helicopter landings at high altitudes, mapping of the summits between Mt. Lister and Mt. Kempe and over much of the area inland of this ridge crest was based on remote sensing interpretation without ground truth.

The principles of the method used in landform identification and classification, together with a discussion of their limitations, have been reported elsewhere (Denton et al., 1993; Sugden et al., 1995). The primary classification is based on morphology and involves the identification of landforms such as erosion surfaces, ridge crests, cliffs and rectilinear slopes. A second level of categorization is based on inferred genesis and identifies distinctive glacial and volcanic landforms.

4.1. Erosion surfaces, escarpments and valleys

The dominant landform on the backslope of the Royal Society Range escarpment is a suite of high-level erosion surfaces that gradually decline in elevation inland (Fig. 3). The highest surface, Chaplains Tableland, forms the northern flank of Mt. Lister and has an altitude of around 3000 m. Another extensive surface, which occurs at an elevation of 1800–2200 m on both flanks of Emmanuel Glacier, extends westwards beneath neighbouring glaciers and includes Table Mountain and its associated Sirius Group deposits (Fig. 3). Associated with these surfaces are prominent peaks, of which The Pimple, rising above Chaplains Tableland, is a notable example featuring on early maps of the region drawn by Taylor (1922). There are many other pyramidal peaks rising several hundred metres above the 1800–2200 m surface. A much lower erosion surface, which in places rises gradually inland over distances of > 3 km, extends northwards along the coast from Garwood Valley, where it is buried beneath Bowers Piedmont Glacier.

The major rift-flank escarpment is dissected by glacier-filled valleys up to 15 km long. Extensive rectilinear slopes bound such valleys and have gradients of up to 36° over a vertical range of up to 1600 m. Smaller escarpments comprising rectilinear slopes bound the axial 3000 m surface on its inland flank. There are also escarpments delimiting the blocks of higher terrain near the coast. For example, there is a 600–900 m escarpment bounding Williams Peak on its inland flank which in places rises from a sharp break of slope marking the surrounding lowland. A similar escarpment occurs on the boundary of the coastal lowland.

Major valleys radiate from the crest of the Royal Society Range. The pattern is well displayed in Figs. 5 and 6, which show the main valleys (and glaciers) and divides. On the inland backslope the valleys run into the basins of the Ferrar and Skelton glaciers, but along the coast the Walcott, Miers, Marshall, Garwood and Hobbs valleys drain directly towards the Ross Sea. These valleys exhibit a number of significant features. First, they form a dendritic pattern with tributaries in any one basin joining sequentially and merging downstream to create a single trunk valley. Second, the valley pattern is integrated with the main divides; the sole exception of a breached divide is near The Spire where a valley runs southwards across the main divide into the Skelton Basin. Third, many of the valley glaciers, for example those flowing towards Ferrar Glacier, are flanked by rectilinear slopes bearing a thin mantle of rock debris that extends to the bounding divides at angles of 30–36°. Fourth, some valleys have convexo–concave slopes, especially at lower altitudes. Examples occur on the valley benches flanking Ferrar Glacier and inland of

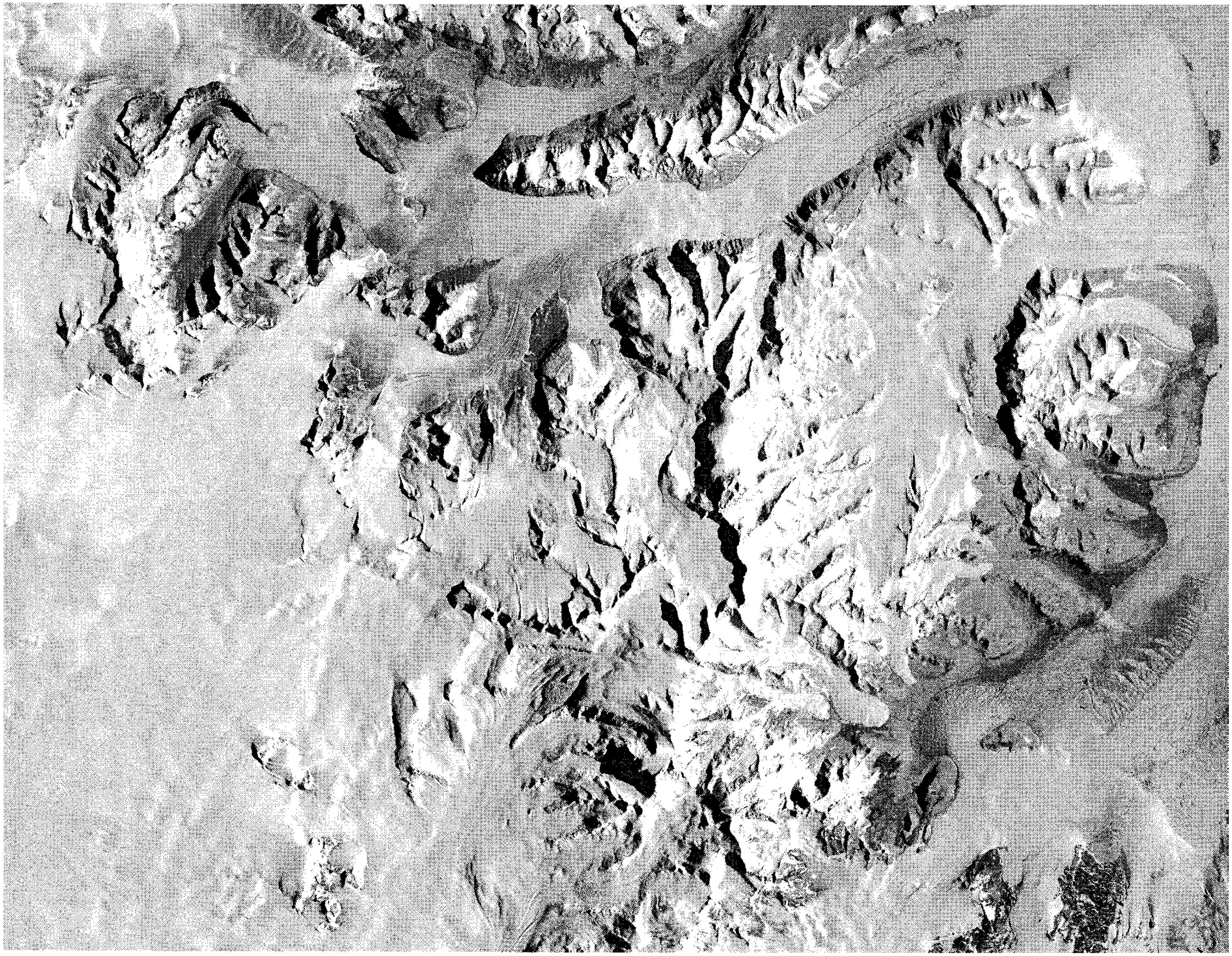

Fig. 5. Landsat TM image of the Royal Society Range covering approximately the same area as in the geomorphological map in Fig. 4.

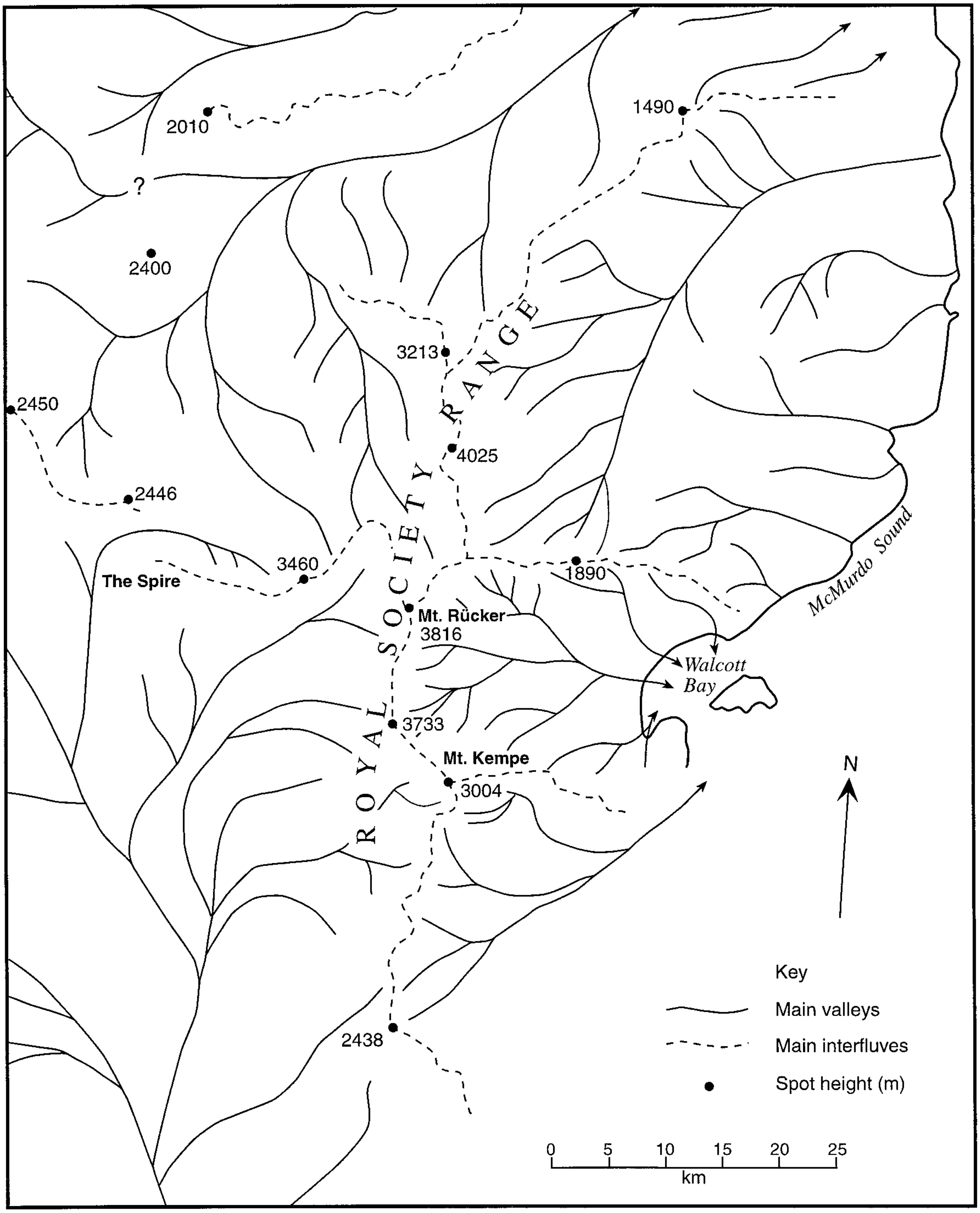

Fig. 6. The valleys and main divides of the Royal Society Range. Many of the valleys are filled by glaciers and in these cases the centreline of the valley has been assumed to lie beneath the middle of the glacier.

Williams Peak. Finally, the valleys are cut below present sea level in their lower reaches, the mouth of Ferrar Valley, for example, being 165 m below sea level.

4.2. Glacial landforms

Large areas near the coast have experienced areal scouring and consist of series of shallow rock basins and irregular, convex hills with a relief of tens of metres (Figs. 4 and 7). There is little regolith and underlying rock structures are clearly visible. There are about 20 streamlined rock hummocks on the divide south of the mouth of Miers Valley. They are hundreds of metres long, have smooth convex sides with an amplitude of 5–10 m, and their long axes are orientated southwest–northeast. Channels cut in bedrock cross saddles over much of the region subject to areal scouring in the vicinity of Garwood, Marshall and Miers valleys. Individual channels, commonly about 20 m deep, are sinuous in planform, and a few contain large potholes. The overall pattern of these channel systems is anastomosing, and in some cases long profiles are convex with an amplitude of tens of metres. One channel system crossing from Marshall Valley to Joyce Glacier is over 2 km long, and some channels cut across spurs over 900 m high. The form and location of these channels suggests an origin by subglacial meltwater flow.

Areal scouring exhibits distinct vertical and horizontal zonation. Its highest occurrence is in the south of the main axis of the Royal Society Range near Mt. Kempe, Mt. Huggins and Mt. Rücker. Here spurs extending towards the coast are scoured to altitudes of ~2100 m, but the upper limit of scouring falls away to the north. In the coastal zone areal scouring affects spurs up to altitudes of about 1200 m, including the divide between Garwood and Marshall valleys, as well as the coastal and inland flanks of the higher areas of coastal terrain. Areal scouring extends up to elevations of ~1200 m on the uplands on the southern flank of Ferrar Valley seaward of the main escarpment. The interior of the relatively high Williams Peak area is devoid of areal scouring and instead exhibits smooth, regolith-covered convex slopes, including, in one location, an upstanding bedrock tor. The upper limit of areal scouring on

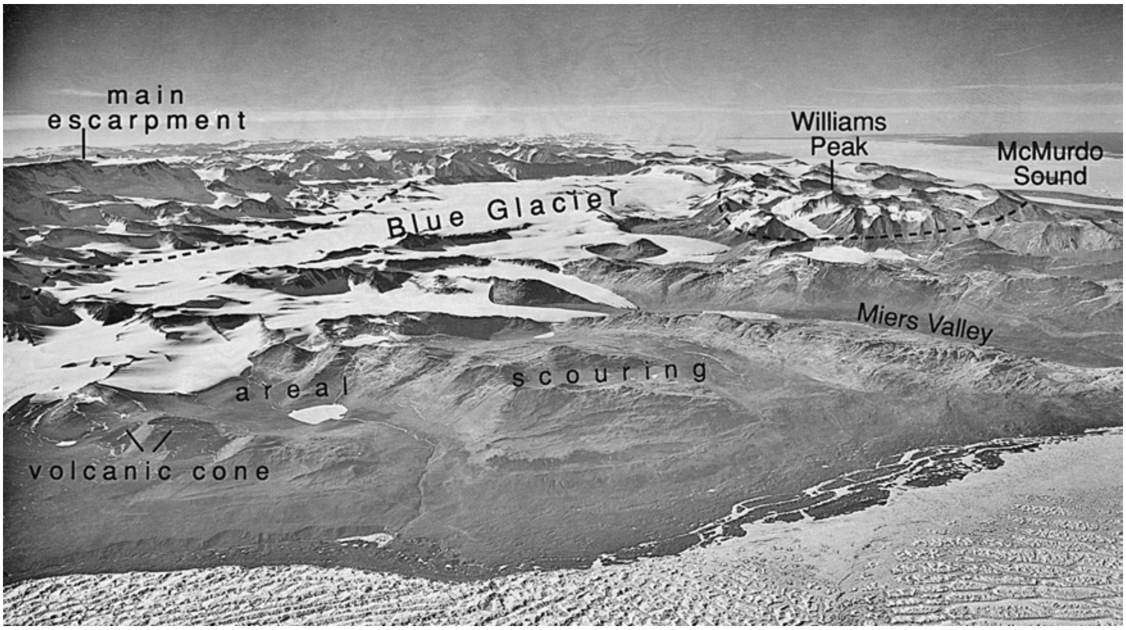

Fig. 7. Photograph of the area between the main Royal Society escarpment and the coast, viewed from the south. Blue Glacier occupies a depression between the escarpment foot and coastal mountain massifs. Approximate limits of areal scouring by overriding ice are indicated, together with the site of volcanic cones dated at 11.3–12.4 Ma. US Navy photograph, VX 6, F31, TMA 00210.

surrounding spurs lies between 1100 and 1200 m, and Williams Peak itself is significant as an area of unmodified terrain amidst a landscape of extensive areal scouring (Fig. 7). We interpret the pattern of areal scouring, streamlined hills and divide-crossing meltwater channels as indicative of the former presence of ice flowing parallel to the coast in a north-easterly direction.

There are many areas where outlet, valley and cirque glaciers are bounded by precipitous slopes and cliffs with a mean gradient > 45°. An excellent example is provided by Cathedral Rocks on the southern side of Ferrar Glacier where the valley side marks the northern termination of the axis of the Royal Society Range (Fig. 4). Valley-side slopes become less precipitous both up and down glacier. Other examples are common on the sides and heads of valleys on the coastal flanks of the rift front and the dissected backslope, and degraded cliff tops mark the sides of valleys such as Garwood Valley near the coast.

It is generally acknowledged that such cliffs mark the sides of glacial troughs and tributary cirques which are either being formed at present, or were eroded by glacial action in the past. However, as Priestley (1922) recognized, not all steep slopes have been created by glacial erosion, so it is worth highlighting some significant morphological relationships. Many cliffed cirque and trough walls have been cut into rectilinear slopes. Clear examples of cirques incised into rectilinear slopes forming part of the main escarpment are to be found near Mt. Huggins and on the escarpment in the Williams Peak area overlooking Blue Glacier, while the cliffs overlooking the lower part of Emmanuel Glacier clearly truncate rectilinear slopes.

5. Geochronological constraints on denudational history and landscape development

Valuable constraints on the denudational history and topographic evolution of the Royal Society Range are provided by radiometric dating of volcanic rocks and in situ-produced cosmogenic isotope analysis. Lavas forming small volcanic cones tens to hundreds of metres across have been erupted on to areally scoured landsurfaces in the south of the Royal Society Range. $^{40}Ar/^{39}Ar$ dating of these features has revealed ages spanning the Pliocene and late Miocene. Cones on an 800-m high areally scoured plateau immediately north of Walcott Bay have yielded ages of 12.43 ± 0.22, 11.98 ± 0.40 and 11.34 ± 0.66 Ma. A cone on the ice-scoured valley slope overlooking Walcott glacier has an age of 12.1 ± 1.2 Ma, while a lava flow at the mouth of Walcott Valley has been dated at 7.79 ± 0.44 Ma BP. The relationships of these volcanic features to the underlying glacial topography, together with the lack of any downstream fan of volcanic erratics, suggest that their formation post-dates the glaciation that eroded the areally scoured landscape.

Survival of these minor volcanic features to the present without significant modification is important in that it indicates very low rates of denudation for at least the past ~ 12 Ma, a conclusion already established from the preservation of surficial ash deposits in the neighbouring Dry Valleys (Denton et al., 1993). The lack of liquid water under the present climate clearly slows down weathering and subdues rates of landscape change, and the implication is that similar conditions have persisted since at least the late Miocene. As these volcanic sites are close to the coast and at relatively low elevations, we would expect them to have been subject to *relatively* high rates of denudation for this polar environment. This implies even lower rates of denudation inland at higher altitude where the climate is colder, precipitation and relative humidity are lower, and liquid water is effectively absent.

Confirmation of these extremely low inland rates of denudation over the past few million years is provided by measurements of concentrations of in situ-produced cosmogenic nuclides on the inland flank of the Royal Society Range at Table Mountain (~ 2000 m elevation) associated with Sirius Group deposits. Cosmogenic ^{10}Be concentrations in quartz indicate maximum denudation rates of 0.7 m Ma^{-1} for granite boulders and 0–0.05 m Ma^{-1} for silicified sandstone bedrock surfaces (Ivy-Ochs et al., 1995). Similarly, low denudation rates are also indicated at this site by minimum ‘exposure ages’ derived from cosmogenic ^{21}Ne concentrations in quartz and ^{21}Ne and ^{3}He concentrations in pyroxene from dolerite (Bruno et al., 1997). These rates of denudation of < 1 m Ma^{-1} are similar to those recorded by cosmogenic isotope data in the Dry Valleys block and elsewhere in the Transantarctic Mountains (Summerfield et al., 1999, in press).

Inferring changes in topography through time is much more difficult than reconstructing the record of denudation, because it requires the preservation of features that can be related to a specific palaeodatum. In the Royal Society Range, however, the 7.8-Ma-old sub-aerially erupted lava flow at the mouth of Walcott Valley constrains maximum net surface uplift since this time to 67 m. The location of this site is especially valuable because it lies in the coastal zone and therefore close to the longitudinal fault structures across which earlier crustal movements have been concentrated, and only 20 km east of the >3000 m high axis of the Royal Society Range. It could be argued that since the site is seaward of the main summits, it would not have experienced any significant Pliocene–Quaternary surface uplift that may have affected the escarpment. But any such recent differential movement would be clearly evident in the landscape as major fault scarps in view of the very slow rates of landform modification evident since the late Miocene. Only minor fault scarps have been recorded (Jones, 1996). This lack of any significant change in topography since the late Miocene is mirrored by data from Taylor Valley in the Dry Valleys area where the present elevations of ^{40}Ar/^{39}Ar-dated, subaerially erupted lavas show that there has been less than 300 m of surface uplift over the past 2.57 Ma (Wilch et al., 1993).

6. Discussion

6.1. Interpretation of denudational history and landscape evolution

Valuable insights into long-term (10^7–10^8 years) denudation can be garnered from apatite fission-track thermochronology (Brown et al., 1994). Although no published apatite fission-track analysis data are currently available for the Royal Society Range, it is useful to consider the denudational history revealed by data for a number of other sectors of the Transantarctic Mountains. In the immediately adjacent Dry Valleys area, extending north from the Ferrar Glacier to Granite Harbour, there is clear evidence of a period of accelerated denudation rates initiated in the early Cenozoic (50–55 Ma BP), with a less certain phase of Cretaceous denudation being identified inland (Gleadow and Fitzgerald, 1987; Fitzgerald, 1992). The amount of denudation since the early Cenozoic is at a maximum of ~ 5 km in the vicinity of the rift-flank axis and Ross Sea coastal zone, and declines inland to the west. This gives a maximum mean denudation rate for the past ~ 50 Ma of ~ 100 m Ma^{-1}, although thermal modelling of fission-track age and track length data indicates that crustal cooling (denudation) rates were higher (~ 200 m Ma^{-1}) for a period of about 10–15 Ma after the initiation of this phase of accelerated denudation. This early Cenozoic phase of denudation is also recorded in northern Victoria Land (where the initial phase of accelerated denudation appears to have occurred at a rate of 200–400 m Ma^{-1}) and in the central Transantarctic Mountains (Fitzgerald and Gleadow, 1988; Stump and Fitzgerald, 1992; Fitzgerald, 1994). Significant Cretaceous denudation is also evident in these areas, with an additional late Cretaceous phase of accelerated denudation being identified in the Scott Glacier area of the central Transantarctic Mountains in the late Cretaceous ($\sim$ 85 Ma BP) (Stump and Fitzgerald, 1992).

The regional extent of the phase of crustal cooling (denudation) throughout the Transantarctic Mountains initiated ~ 55 Ma BP implies that the Royal Society Range block would also have experienced this event. The present pattern of bedrock outcrop certainly indicates the removal of a wedge of crustal section in the Royal Society Range since the early Cenozoic comparable to that in the neighbouring Dry Valleys area and other sectors of the Transantarctic Mountains. Beacon Supergroup strata and associated dolerite sills are widespread on the inland flank of the mountain crest and absent in the coastal zone. This suggests that they have been stripped by erosion near the coast, a conclusion first drawn by Wright and Priestley (1922). Calculations of depths of crustal section removed derived from fission-track thermochronology, together with an extrapolated original thickness of Beacon Supergroup sedimentary rocks and dolerite sills, have been used in the Dry Valleys region to estimate spatial variations in denudation (Gleadow and Fitzgerald, 1987; Sugden et al., 1995). In the Royal Society Range approximately 3.1 km of

Beacon Supergroup strata and dolerite intrusions overlie the Kukri erosion surface. This is a minimum estimate for the original thickness as it does not take into account the Kirkpatrick Basalts that may have topped the stratigraphic sequence. In the Allan Hills, 150 km north-northwest of the Royal Society Range, an estimated thickness of 500 m of these Jurassic basalts remains (Ballance and Watters, 1971). The fact that the basalts occur throughout much of the Transantarctic Mountains and were once part of a continental flood basalt province implies that they are remnants of a thicker and much more extensive basalt pile and may have covered the Royal Society block.

Near The Pimple on the axis of the Royal Society Range the exhumed Kukri erosion surface is at an altitude of $\sim$2600 m (Fig. 8). Assuming 3.1 km of formerly overlying crustal section, and allowing for the altitude of adjacent peaks, there has been a minimum of about 1.7 km of denudation from the highest summits of the Royal Society Range. The same assumptions yield a minimum estimate of $\sim$2.4 km of crustal section removed from the Table Mountain area, and at least 5.7 km denuded from the coastal zone. Given the present westward slope of the Kukri erosion surface at around 2–3°, it is possible to extrapolate inland from exposures of basement in the Kukri Hills and at Cavendish Rocks along the middle of Taylor Valley to estimate a loss of about 0.6 km of section from above the summit of Mt. Feather, 100 km from the coast. This is the same depth of denudation estimated for Mt. Fleming, a similarly positioned peak in the Dry Valleys block to the north (Sugden et al., 1995). The implication of these estimates, even given uncertainties in the assumptions on which they are based, is that a seaward-thickening wedge of crust has been denuded from the Royal Society Range since rifting $\sim$55 Ma ago.

There are several lines of evidence indicating that post-rift denudation had effectively ended by the mid-Miocene. The volcanic cone ages of $\sim$12 Ma demonstrate minimal modification of the low-altitude ice-moulded landscape near the coast since the mid-Miocene. Preservation of the 7.8-Ma-old basalt flow in the bottom of Walcott Valley is further confirmation of minimal denudation over the past few million years. Such evidence from the dating of volcanic deposits is corroborated by the cosmogenic isotope data indicating extremely low rates of denudation (< 1 m Ma^{-1}) on the higher level surfaces and demonstrating at least a Miocene age for the Sirius Group deposits of Table Mountain. The argument for minimal denudation in the Royal Society Range since the mid-Miocene is further supported by comparison with the morphology of Mt. Morning, a 2723-m high volcano on the southeast flank of Koettlitz Glacier with trachyandesite flows K–Ar dated to 18.7 Ma BP (Armstrong, 1978). Its original uniform slopes are only lightly fretted by a radial set of shallow, narrow valleys (Fig. 9). This provides a stark contrast to the deeply incised valleys character-

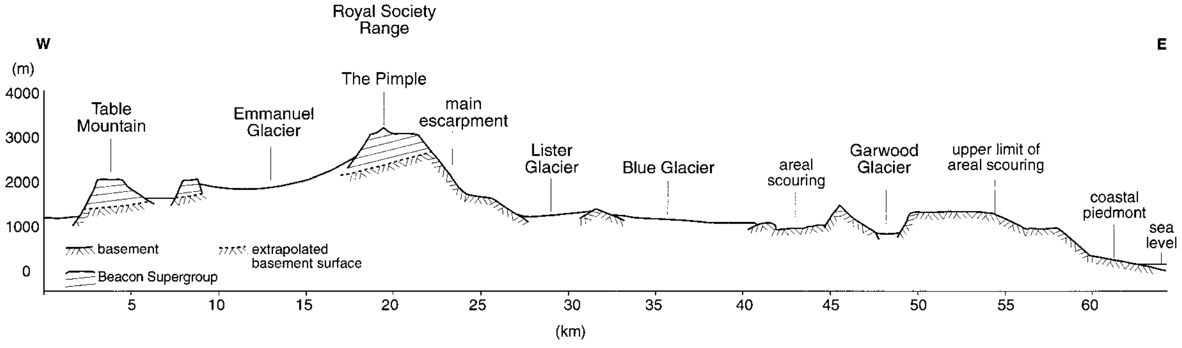

Fig. 8. Cross-section from the coast across the Royal Society range showing the main features of the topography and the basement surface falling inland from 2600 m at the front of the main escarpment. For location of cross-section see Fig. 4.

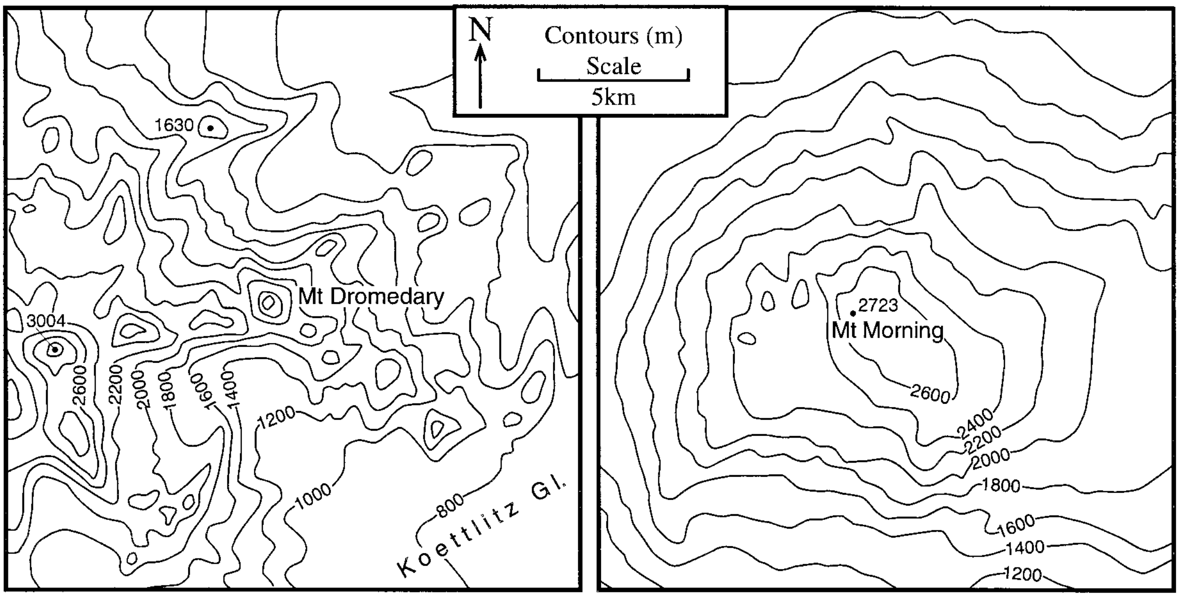

Fig. 9. The contrast between the lightly dissected surface of the mid-Miocene volcano of Mt. Morning and the heavily dissected area around Mount Dromedary, the latter comprising the nearest mountain of comparable altitude in the Royal Society Range. Contours from USGS 1:250 000 map.

istic of parts of the Royal Society Range at a similar altitude.

Geochronological data for the Dry Valleys area mirror this picture of extremely slow post-mid-Miocene denudation rates and demonstrate that the denudational record of these two rift-flank blocks has been similar. In addition, the present elevations above sea level of Pliocene and Miocene sub-aerially erupted volcanic deposits confirm that there has been minimal surface uplift in both the Dry Valleys and Royal Society Range blocks during the past few million years.

6.2. Relative role of fluvial and glacial processes

Although modified markedly by glacial processes in places, the landscape of the Royal Society Range still bears the hallmarks of its fluvial origin. One argument for this interpretation is the dendritic valley pattern radiating from the axis of the rift flank. The nature of this pattern and the consistency of the angle at which tributaries join trunk valleys are all features that characterize river networks and that are difficult to explain by glacial action alone. Likewise, there are landforms indicative of mass movement and fluvial processes rather than glacial erosion, such as escarpments fringing erosion surfaces; examples are found in the coastal zone, on the inland flank of the Williams Peak area. In addition, the backslope of the Royal Society Range is dotted with pyramidal and conic peaks which rise abruptly from surrounding erosion surfaces. Such forms are present in fluvially eroded landscapes and there is no obvious mechanism by which they could be created by glacial action.

The pattern of landscape modification by ice observed in the Royal Society Range points to selective glacial erosion. This is especially evident in the Williams Peak area where at high altitudes there are rounded, regolith-covered slopes rather than evidence of glacial erosion in the form of areal scouring; by contrast, areal scouring is widespread at lower elevations. Such a landscape association is well-known in formerly glaciated regions in the northern hemisphere where areal scouring is attributed to erosion by overriding warm-based ice and the preservation of pre-glacial landforms is taken to indicate ineffective erosion by cold-based ice (Sugden, 1978).

Upstanding terrain modifies the temperature regime of the overlying ice through a reduction in ice thickness and divergence of ice flow with the effect that an ice cover can locally protect a landscape from erosion (Glasser, 1995). In such areas the continuity of surrounding spurs and valleys indicates that areal scouring results in only a few tens of metres of denudation. This interpretation of glacial landscape development is supported by research on the classic landscape of areal scouring on the Fennoscandian Shield which is now known to have experienced limited glacial erosion (Lidmar-Bergström, 1997). The implication is that areal scouring of the coastal periphery of the Royal Society Range is unlikely to have resulted in significant denudation, and that some parts of the landscape could have been protected from erosion and retained their pre-glacial fluvial form. This interpretation is further supported in the Royal Society Range by the truncation of rectilinear slopes by glacial cliffs, a landform association that is most readily explained by the glacial modification of a pre-existing landform.

Most glacial erosion is likely to be associated with glacial troughs, and there is evidence that the ice at the bottom of the main outlet glaciers in southern Victoria Land is at the pressure melting point and therefore capable of erosion. For instance, debris entrainment and regelation is apparent at the snout of Taylor Glacier (Robinson, 1984) and meltwater deposits are present in cores recovered from the front of Ferrar Glacier (Barrett and Hambrey, 1992). The most remarkable evidence comes from images taken from submersibles of the grounding line of Mackay Glacier which reveal meltwater and freshly eroded rock debris (Powell et al., 1996).

It appears that these large outlet glaciers are capable of eroding troughs under present-day conditions, and are thus likely to have been eroding them for millions of years. But the efficacy of erosion is probably very much less in the case of small glaciers which are cold based. For instance, there are only small moraines in front of Meserve Glacier which flows down the southern side of Wright Valley in the Dry Valleys area, although these represent the total glacially transported load over the past 3.7 Ma (Hall et al., 1993). Another example is provided by Radian Glacier on the front of the Royal Society Range; here a volcanic cone dated at 1.55 ± 0.3 Ma BP is located only tens of metres from the lateral margin of the glacier and yet there is no sign of valley deepening or significant slope modification since it was constructed. The most graphic evidence for the lack of erosion being accomplished by local glaciers draining the precipitous seaward flank of the Royal Society Range rift flank is provided by submarine images of the snout of Blue Glacier at the Ross Sea coast which show no meltwater discharge from beneath the ice, and little, or no, basal ice debris (Powell, 1994).

On the basis of this evidence, both from the Royal Society Range and other localities in southern Victoria Land, we conclude that a fluvial signature remains in the landscape, not only in the overall valley pattern, but also in individual landforms and slope elements. Significant glacial erosion under present conditions is restricted to major outlet glaciers, but the much greater extent of warm-based ice in the past is indicated by the widespread nature of areal scouring at lower altitudes. Although warm-based ice would also have been present in a much greater proportion of troughs under such conditions, the degree of preservation of fluvial forms implies that even this phase of more active glacial erosion played a rather limited role in denudation and landscape development. This further suggests that much of the post-rift denudation involved in removing the wedge of crustal section across the Royal Society Range occurred under a fluvial regime prior to the onset of glaciation.

6.3. Tectonics and post-rifting landscape development

The three periods of accelerated denudation and crustal cooling in the early Cretaceous, late Cretaceous and beginning in the early Cenozoic identified in the Transantarctic Mountains through apatite fission-track thermochronology are coeval with periods of major plate reorganisation in the southwest Pacific (Stump and Fitzgerald, 1992). These involved the initial rifting of Australia from Antarctica, separation of Australia, New Zealand and Antarctica, and finally, an increased rate of spreading between Antarctica and Australia. This temporal coincidence strongly suggests a causal link between these tectonic events and the observed periods of accelerated denudation, but it is not possible to assume that denudation was necessarily a direct result of surface uplift. Although an intimate temporal and causal link between uplift and denudation (crustal cooling) has been almost universally assumed in thermochronological studies, denudation rates are controlled by local relief rather than absolute elevation above sea level (Ahnert, 1970; Summerfield and Hulton, 1994).

The most prominent episode of accelerated denudation recorded in the Transantarctic Mountains is that beginning in the early Cenozoic and it is highly probable that this event also affected the Royal Society Range. Crustal extension and subsidence in the Victoria Land Basin would have produced a fall in regional base level and this alone would have been capable of initiating an episode of rapid denudation if the adjoining rift flank already stood at a significant elevation above sea level. Previous calculations of elevation changes in the Dry Valleys area associated with the early Cenozoic rifting event have assumed an initial elevation of ∼ 500 m on the basis that the Jurassic Kirkpatrick Basalt in the Allan Hills was erupted onto an alluvial flood plain (Gleadow and Fitzgerald, 1987). Such estimates are, however, only illustrative, as there are no marine or shoreline deposits capable of providing an early Cenozoic sea level palaeodatum in the Transantarctic Mountains. Continental facies diagnostic of low-energy depositional environments do not provide useful information on elevation as they can develop at any location with low local relief, irrespective of altitude (Summerfield and Brown, 1998).

Given the prolonged episode of terrestrial deposition represented by the Beacon Supergroup sediments and the likely original extent and thickness of the Kirkpatrick Basalt pile topping this sequence and Ferrar dolerites intruding it, much of the Transantarctic Mountains, including the Royal Society Range, may have already been standing at a significant elevation above sea level at the time of rifting. Elsewhere, underplating associated with continental flood basalt provinces, for example in the Karoo magmatic event in southeast Africa, has been invoked to explain ‘permanent’ surface uplift (Cox, 1993) and this process may also have operated in association with the ∼ 176 Ma BP flood basalt event that extended over more than 1200 km of the Transantarctic Mountains (Heimann et al., 1994).

The pre-rift elevation resulting from any such underplating is not constrained, and a range of other processes related to the early Cenozoic rifting event have certainly contributed to the uplift of the Royal Society Range. Thermally driven isostatic compensation may have promoted some uplift, but untenable amounts of mantle thinning are required for this to have been a significant mechanism (van der Beek et al., 1994). Strong isostatic anomalies over the Ross Sea indicate that the whole rift flank system is in a state of upward flexure, indicating that mechanical uplift has been important (van der Beek et al., 1994). According to the analysis by van der Beek et al. (1994), the model that best fits the present topography involves necking in the lower crust (30 km depth) coupled with asymmetric extension (with lithospheric extension concentrated under the Transantarctic Mountains). This model is similar to that suggested previously by Fitzgerald et al. (1986). In addition to these effects directly related to the tectonic processes of rifting, flexural isostatic rebound in response to differential denudation across the Royal Society Range will also have generated some surface uplift immediately inboard of the main escarpment (Kerr and Gilchrist, 1996). Quantification of this effect is difficult, as it depends on poorly constrained variables such as the flexural rigidity of the lithosphere and the temporal and spatial variations in denudation rates. The short wavelength and high amplitude of the topography of the Royal Society Range, however, does not require an unrealistically low flexural rigidity in the unrifted lithosphere inland of the faulted rift-flank, given a large differential in denudation rate across the rift-flank escarpment. Some denudational unloading and consequential isostatic uplift of divides would also have been promoted by the glacial deepening of valleys, although this effect would have been less in the Royal Society Range than the Dry Valleys area due to the lack of major transverse glacial valleys.

Behrendt and Cooper (1991) have suggested that the 2 km difference in elevation between the highest parts of the Dry Valleys area and the Royal Society Range indicates that there has been significant differential surface uplift between these two adjacent blocks. However, a similar tectonic and surface uplift history for both blocks is indicated by the limited vertical offset between them of Ferrar sills and the Kukri erosion surface at the base of the Beacon Supergroup sequence. Offsetting of these features on either side of the transfer fault lying beneath the Ferrar Glacier (Fitzgerald, 1992) close to the axis of the Royal Society Range (Cathedral Rocks area) indicates relative downfaulting of the Dry Valleys block in the Kukri Hills area to the north by only about 300 m (P.G. Fitzgerald, personal communication). Although this represents a net relative displacement since the intrusion of the Ferrar sills in the Jurassic, the amount of displacement is modest and not easy to reconcile with significant recent differential movement between these adjacent rift-flank blocks. Consequently, the present high elevation of the Royal Society Range in comparison with the Dry Valleys block may not be primarily due to tectonics. Rather, it is likely that the Royal Society Range contains a high crest largely because it has experienced less erosion of its Beacon Supergroup sedimentary cover, probably as a result of its location along a persistent drainage divide near the coast (Fig. 6). As in other rifted margin settings, there is evidence of neotectonic activity in the Royal Society Range block—late Quaternary faulting has been identified in the Garwood and Hidden valleys, for instance (Jones, 1996)—but the wide range of evidence cited here demonstrates that this does not necessarily imply any sustained episode of tectonic uplift extending over the late Cenozoic and capable of producing significant changes in topography.

7. Conclusions

Our interpretation of landscape development in the Royal Society Range in combination with geochronological data leads to the following conclusions with respect to current debates concerning the glacial and landscape history.

(1) The amount of surface uplift associated with the rifting event ~55 Ma ago is poorly constrained, although significant relief probably existed at the time of rifting. There has been minimal surface uplift since at least the late Miocene.

(2) A seaward-thickening wedge of crustal section of about 1 km inland and ~6 km at the coast has been removed since rifting ~55 Ma BP. Most of this denudation was accomplished by the mid-Miocene.

(3) Denudation since the mid-Miocene has been confined to relatively minor modification of the landscape by glacial action except under specific conditions such as continuing incision of troughs by warm-based ice. Limited glacial modification of the landscape as a whole has allowed the preservation of elements of the pre-glacial fluvial landscape.

(4) No single tectonic mechanism appears capable of accounting for the gross morphology and surface uplift history of the Royal Society Range, but asymmetric lithospheric necking and differential denudational unloading are likely to have been significant processes. Significant pre-rift elevation, possibly related to underplating associated with the 176 Ma BP flood basalt event, may have been important in promoting the phase of accelerated denudation associated with rifting ~55 Ma ago, as recorded by fission-track thermochronology.

(5) In terms of the current debate about the history of the East Antarctic Ice Sheet, our interpretation of landscape development in the Royal Society Range strongly supports the stability hypothesis and a pre-mid-Miocene age for the glaciogenic Sirius Group deposits. Furthermore, we find no significant differences between the Cenozoic surface uplift and denudational history of the Royal Society Range and that established earlier for the Dry Valleys area.

Acknowledgements

This research was supported by the UK Natural Environment Research Council (grant no. GR3/9128) and by the Division of Polar Programs of the US National Science Foundation. We are grateful to Paul Fitzgerald for comments on the tectonic history of the Royal Society Range.

References

Ahnert, F., 1970. Functional relationships between denudation, relief, and uplift in large mid-latitude drainage basins. Am. J. Sci. 268, 243–263.

Armstrong, R.L., 1978. K–Ar dating: Late Cenozoic McMurdo

Volcanic Group and Dry valley glacial history, Victoria Land, Antarctica. New Zealand J. Geol. Geophys. 6, 685–698.

Ballance, P.F., Watters, W.A., 1971. The Mawson diamictite and the Carapace sandstone formations of the Ferrar group at Allan Hills and Carapace Nunatak, Victoria Land, Antarctica. New Zealand J. Geol. Geophys. 14, 512–527.

Barrett, P.J., Hambrey, M.J., 1992. Plio-Pleistocene sedimentation in Ferrar Fiord, Antarctica. Sedimentology 39, 109–123.

Behrendt, J.C., Cooper, A.K., 1991. Evidence of rapid Cenozoic uplift of the shoulder escarpment of the Cenozoic West Antarctic drift system and a speculation on climate forcing. Geology 19, 315–319.

Behrendt, J.C., Cooper, A.K., 1994. Minimal Pliocene–Pleistocene uplift of the dry valleys sector of the Transantarctic Mountains: a key parameter in ice-sheet reconstructions: comment. Geology 22, 668–669.

Brown, R.W., Summerfield, M.A., Gleadow, A.J.W., 1994. Apatite fission track analysis: its potential for the estimation of denudation rates and implications for models of long-term landscape development. In: Kirkby, M.J., (Ed.), Process Models and Theoretical Geomorphology. Wiley, Chichester, pp. 23–53.

Bruno, L.A., Baur, H., Graf, T., Schlüchter, C., Signer, P., Wieler, R., 1997. Dating of Sirius Group tillites in the Antarctic Dry Valleys with cosmogenic ^{3}He and ^{21}Ne. Earth Planet. Sci. Lett. 17, 37–54.

Bull, C.B.B., McKelvey, B.C., Webb, P.-N., 1962. Quaternary glaciations in southern Victoria Land, Antarctica. J. Glaciol. 4, 63–78.

Calkin, P.E., 1974. Processes in the ice-free valleys of southern Victoria Land, Antarctica. In: Fahey, R.D., Thompson, R.D., (Eds.), Research in Polar and Alpine Geomorphology. Department of Geography, University of Guelph, Ontario, Canada, pp. 167–186.

Cox, K.G., 1993. Continental magmatic underplating. Philos. Trans. R. Soc. London, Ser. A 342, 155–166.

Denton, G.H., Sugden, D.E., Marchant, D.R., Hall, B.L., Wilch, T.I., 1993. East Antarctic Ice Sheet sensitivity and Pliocene climatic change from a Dry Valleys perspective. Geogr. Annlr. Stockholm 75A, 155–204.

Drewry, D.J., (Ed.), 1983. Antarctica: Glaciological and Geophysical Folio. Cambridge Univ. Press, Cambridge.

Ferrar, H.T., 1907. Report on the field geology of the region explored during the ‘Discovery’ Antarctic Expedition, 1901–04, in Geology, National Antarctic Expedition, 1901–04. Natural History 1, 1–100.

Fitzgerald, P.G., 1992. The Transantarctic Mountains of southern Victoria Land: the application of fission track analysis to a rift shoulder uplift. Tectonics 11, 634–662.

Fitzgerald, P.G., 1994. Thermochronologic constraints on post-Paleozoic tectonic evolution of the central Transantarctic Mountains, Antarctica. Tectonics 13, 818–836.

Fitzgerald, P.G., Gleadow, A.J.W., 1988. Fission-track geochronology, tectonics and structure of the Transantarctic Mountains in northern Victoria Land, Antarctica. Chem. Geol. (Isotope Geosci. Sect.) 73, 169–198.

Fitzgerald, P.G., Sandiford, M., Barrett, P.J., Gleadow, A.J.W., 1986. Asymmetric extension associated with uplift and subsidence in the Transantarctic Mountains and Ross Embayment. Earth Planet. Sci. Lett. 81, 67–78.

Fortuin, J.P.F., Oerlemans, J., 1990. Paramaterization of the annual surface temperature and mass balance of Antarctica. Ann. Glaciol. 14, 78–84.

Friedmann, E.I., Druk, A.Y., McKay, C.P., 1994. Limits of life and microbial extinction in the antarctic desert. Antarctic J. Rev. 29, 176–179.

Gilchrist, A.R., Summerfield, M.A., 1990. Differential denudation and flexural isostasy in formation of rifted-margin upwarps. Nature 346, 739–742.

Gilchrist, A.R., Summerfield, M.A., 1994. Tectonic models of passive margin evolution and their implications for theories of long-term landscape development. In: Kirkby, M.J., (Eds.), Process Models and Theoretical Geomorphology. Wiley, New York, pp. 55–84.

Glasser, N.F., 1995. Modelling the effect of topography on ice sheet erosion, Scotland. Geogr. Annlr. 77A, 211–215.

Gleadow, A.J.W., Fitzgerald, P.G., 1987. Uplift history and structure of the Transantarctic Mountains and new evidence from fission track dating of basement apatites in the Dry Valleys area, southern Victoria Land. Earth Planet. Sci. Lett. 82, 1–14.

Hall, B.L., Denton, G.H., Lux, D.R., Bockheim, J.G., 1993. Late Tertiary palaeoclimate and ice-sheet dynamics inferred from surficial deposits in Wright Valley. Geogr. Annlr. Stockholm 75A, 239–267.

Heimann, A., Fleming, T.H., Elliot, D.H., Foland, K.A., 1994. A short interval of Jurassic continental flood basalt volcanism in Antarctica as demonstrated by ^{40}Ar/^{39}Ar geochronology. Earth Planet. Sci. Lett. 121, 19–41.

Hindmarsh, R.C.A., van der Wateren, F.M., Verbers, A.L.L.M., 1998. Sublimation of ice through sediment in Beacon Valley. East Antarctica. Geogr. Annlr. Stockholm 80A, 209–219.

Ivy-Ochs, S., Schlüchter, C., Kubik, R.W., Dittrich-Hannen, B., Beer, J., 1995. Minimum 10^{Be} exposure ages of early Pliocene for the Table Mountain plateau and the Sirius Group at Mount Fleming, Dry Valleys, Antarctica. Geology 23, 1007–1010.

Jones, S., 1996. Late Quaternary faulting and neotectonics, South Victoria Land, Antarctica. Geol. Soc. London 153, 645–652.

Kerr, A.R., Gilchrist, A.R., 1996. Glaciation, erosion and the evolution of the Transantarctic Mountains. Antarctica. Ann. Glaciol. 23, 303–308.

Kerr, A.R., Sugden, D.E., Summerfield, M.A., in press. Linking tectonic and landscape development in a passive margin setting: the Transantarctic Mountains. In: Summerfield, M.A., (Ed.), Geomorphology and Global Tectonics. Wiley, Chichester.

Kyle, P.R., 1990. Erebus Volcanic Province. In: Le Mesurier, W.E., Thomson, J.W., (Eds.), Volcanoes of the Antarctic Plate and Southern Oceans. Ant. Res. Ser. Amer. Geophys. Union, WA, 48, 81–133.

Lidmar-Bergström, K., 1997. Long-term perspective on glacial erosion. Earth Surf. Processes Landforms 22, 297–306.

Lucchita, B.K., Bowell, J.A., Edwards, K.L., Eliason, E.M., Ferguson, H.M., 1987. Multispectral landsat images of Antarctica. US Geol. Surv. Bull. 1696.

Marchant, D.R., Denton, G.H., 1996. Miocene and Pliocene paleoclimate of the Dry Valleys region, Southern Victoria land: a geomorphological approach. Mar. Micropaleontol. 27, 253–271.

Marchant, D.R., Denton, G.H., Swisher, C.C. III, 1993. Miocene–Pliocene–Pleistocene glacial history of Arena Valley, Quartermain Mountains, Antarctica. Geogr. Annlr. 74A, 269–302.

McGinnis, L.D., Bowen, R.H., Erickson, J.M., Allred, B.J., Kreamer, J.L., 1985. East–West Antarctic boundary in McMurdo Sound. Tectonophysics 114, 341–356.

McKelvey, B.C., Webb, P-N., Harwood, D.M., Mabin, M.C.G., 1991. The Dominion Range Sirius Group—a record of late Pliocene–early Pleistocene Beardmore Glacier. In: Thomson, M.R.A., Crame, J.A., Thomson, J.W., (Eds.), Geological Evolution of Antarctica. C.U.P., Cambridge, pp. 675–682.

Miller, M.F., Mabin, M.C.G., 1998. Antarctic Neogene Landscapes—in the refrigerator or in the deep freeze? GSA Today 8 (4), 1–3.

Nichols, R.L., 1971. Glacial geology of the Wright Valley, McMurdo Sound. In: Quam, L.O., (Ed.), Research in the Antarctic. Am. Assoc. Advancement Science, Washington, DC, pp. 293–340.

Powell, R.D., 1994. Processes and facies of glacier grounding-line systems with inferences on lithofacies architecture and seismic stratigraphy. Terra Antartica 1, 433–434.

Powell, R.D., Dawber, M., McInnes, J.N., 1996. Observations of the grounding-line area at a floating glacier terminus. Ann. Glaciol. 22, 217–223.

Priestley, R.E., 1909. Scientific results of the western journey. In: Shackleton, E.H. (Ed.), The Heart of the Antarctic, Vol. 2. Heineman, pp. 315–333.

Priestley, R.E., 1922. Physiography, Robertson Bay and Terra Nova regions, Report of the British Antarctic Expedition (Terra Nova), 1910–1913. Harrison, London, 87 pp.

Robinson, P.L., 1984. Ice dynamics and thermal regime of Taylor Glacier, south Victoria Land, Antarctica. J. Glaciol. 30, 133–160.

Schwerdtfeger, W., 1984. Weather and Climate of the Antarctic. Elsevier, Amsterdam.

Selby, M.J., Wilson, A.T., 1971. Possible Tertiary age for some Antarctic cirques. Nature 229, 623–624.

Smith, A.G., Drewry, D.J., 1984. Delayed phase change due to hot aesthenosphere causes Transantarctic uplift. Nature 309, 536–538.

Stern, T.A., ten Brink, U.S., 1989. Flexural uplift of the Transantarctic Mountains. J. Geophys. Res. 94, 10315–10330.

Stump, E., Fitzgerald, P.G., 1992. Episodic uplift of the Transantarctic Mountains. Geology 20, 161–164.

Sugden, D.E., 1978. Glacial erosion by the Laurentide ice sheet. J. Glaciol. 20, 367–391.

Sugden, D.E., Denton, G.H., Marchant, D.R., 1995. Landscape evolution of the Dry Valleys, Transantarctic Mountains: tectonic implications. J. Geophys. Res. 100, 9949–9967.

Summerfield, M.A., Brown, R.W., 1998. Geomorphic factors in the interpretation of fission-track data. In: Van den Haute, P., De Corte F., (Eds.), Advances in Fission-Track Geochronology. Kluwer, Dordrecht, The Netherlands, pp. 269–283.

Summerfield, M.A., Hulton, N.J., 1994. Natural controls of fluvial denudation rates in major world drainage basins. J. Geophys. Res. 99, 13871–13883.

Summerfield, M.A., Stuart, F.M., Cockburn, H.A.P., Sugden, D.E., Denton, G.H., Dunai, T., Marchant, D.R., 1999. Long-term rates of denudation in the Dry Valleys, Transantarctic Mountains, southern Victoria Land, Antarctica based on in-situ-produced cosmogenic ^{21}Ne. Geomorphology 27, 113–129.

Summerfield, M.A., Sugden, D.E., Denton, G.H., Marchant, D.R., Cockburn, H.A.P., Stuart F.M., in press. Cosmogenic isotope data support previous evidence of extremely low rates of denudation in the Dry Valleys region, southern Victoria Land, Antarctica. Geol. Soc. Spec. Publ.

Taylor, G., 1913. A résumé of the physiography and glacial geology of Victoria Land, Antarctica. Scott's Last Expedition, Vol. 2. Smith, Elder, London, pp. 416–429.

Taylor, G., 1922. The physiography of the McMurdo Sound and Granite Harbour region, British Antarctic (Terra Nova) Expedition, 1910–1913. Harrison, London, 246 pp.

ten Brink, U.S., Bannister, S., Beaudoin, B.C., Stern, T.A., 1993. Geophysical investigations of the tectonic boundary between East and West Antarctica. Science 261, 45–50.

Tingey, R.J., 1985. Uplift in Antarctica. Z. Geomorphol. Suppl. 54, 85–99.

van der Beek, P., Cloetingh, S., Andriessen, P., 1994. Mechanisms of extensional basin formation and vertical motions at rift flanks: constraints from tectonic modelling and fission-track thermochronology. Earth Planet. Sci. Lett. 121, 417–433.

van der Wateren, F.M., Hindmarsh, R., 1995. East Antarctic Ice Sheet: stabilists strike again. Nature 376, 389–391.

Webb, P.-N., McKelvey, B.C., Harwood, D.M., Mabin, M.C.G., Mercer, J.H., 1987. Sirius Formation of the Beardmore Glacier Region. Antarctic J. US 22, 8–13.

Wellman, P., Tingey, R.J., 1981. Glaciation, erosion and uplift over part of East Antarctica. Nature 291, 142–144.

Wilch, R.I., Denton, G.H., Lux, D.R., McIntosh, W.C., 1993. Limited Pliocene glacier extent and surface uplift in Middle Taylor Valley, Antarctica. Geogr. Annlr. 75A, 331–351.

Wilson, T.J., 1995. Cenozoic transtension along the Transantarctic Mountains–West Antarctic rift boundary, southern Victoria Land, Antarctica. Tectonics 14, 531–545.

Wright, C.S., Priestley, R.E., 1922. Glaciology, British (Terra Nova) Antarctic Expedition, 1910–1913. Harrison, London, 581 pp.