Episodic uplift of the Transantarctic Mountains

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ABSTRACT

An apatite fission-track age profile from the Scott Glacier region provides evidence of uplift and denudation of the Transantarctic Mountains in the Early and Late Cretaceous. Samples for fission-track analysis were collected over a vertical range of ~2 km from the Mt. Griffith massif. Apatite ages from the upper 700 m of Mt. Griffith vary little with elevation, indicative of rapid cooling accompanying Early Cretaceous uplift and denudation. Ages from the northeast buttress of Mt. Griffith (the Fission Wall) define a steep gradient and are indicative of rapid cooling accompanying Late Cretaceous uplift and denudation. The two parts of the profile are separated by a fault. Subsequent uplift and denudation of the Mt. Griffith massif in the Cenozoic were required to elevate the massif (and the apatite age profile) to its present position. This younger uplift was most likely initiated in the early Cenozoic, penecontemporaneously with well-documented early Cenozoic uplift in the Victoria Land region of the Transantarctic Mountains. These three periods of uplift coincide with periods of major plate reorganization in the southwest Pacific region: (1) initial rifting of Australia from Antarctica and impingement of the Pacific-Phoenix ridge with the subduction zone marginal to New Zealand in the Early Cretaceous, (2) separation of Australia, New Zealand, and Antarctica in the Late Cretaceous, and (3) cessation of spreading in the Tasman Sea ~10 m.y. prior to accelerated spreading between Australia and Antarctica in the early Cenozoic.

INTRODUCTION

The Transantarctic Mountains are a major intracontinental range that spans virtually the whole of Antarctica (Fig. 1), extending for 3500 km, reaching elevations >4000 m, and defining the boundary between East and West Antarctica. The mountains are believed to have been uplifted in an intraplate setting as a major rift-shoulder structure (Fitzgerald et al., 1986; Stern and ten Brink, 1989). On their seaward flank (West Antarctic side), the Transantarctic Mountains have a steep and spectacular escarpment (Fig. 2) that in places is defined by down-to-the-coast, steeply dipping normal faults. Along this flank there is also a transition from 40–45-km-thick crust underneath the mountains to seaward areas of thinned (~17–25 km) continental crust (e.g., Bentley, 1983; Cooper et al., 1987). On their landward flank (East Antarctic side), the mountains dip gently under the East Antarctic ice sheet. The timing of the uplift of the Transantarctic Mountains is important because it relates to the separation of East and West Antarctica and, in the larger tectonic framework, the breakup of Gondwana.

Prior to the application of fission-track dating, the uplift of the Transantarctic Mountains was known only to be post-Jurassic and pre–late Tertiary, on the basis of bedrock geologic relations. Previous fission-track studies in both northern and southern Victoria Land indicated initiation of uplift and denudation of the Transantarctic Mountains at ~55 Ma (Gleadow and Fitzgerald, 1987; Fitzgerald and Gleadow, 1988). In this paper we present the results of a 2-km vertical sampling profile from the Mt. Griffith–Fission Wall massif (lat 85°50′S, long 155°30′W), the results of which provide the first evidence for both Early and Late Cretaceous uplift events in the Transantarctic Mountains.

The Transantarctic Mountains are composed of a Late Proterozoic to early Paleozoic orogenic belt (Ross orogen), unconformably overlain by Devonian to Triassic sedimentary rocks (Beacon Supergroup) and Jurassic flows and sills of basaltic composition (Ferrar Group) (Craddock, 1982). In the Scott Glacier area, the most pervasive rocks are the Cambrian-Ordovician Granite Harbour Intrusives. These rocks compose the lower slopes of the Mt. Griffith massif and grade upward into a dacite porphyry of similar age (Wyatt Formation), which probably represents an extrusive phase of the batholith (Stump et al., 1986). A 70-m-thick dolerite sill (presumably Jurassic in age) intrudes Mt. Griffith at an elevation of 2800 m.

SAMPLING STRATEGY AND METHODS

Sampling strategy was that used in other parts of the Transantarctic Mountains (e.g., Gleadow and Fitzgerald, 1987); samples were collected at regular vertical intervals (~100 m) over the maximum vertical relief in order to reveal information covering the greatest possible time period. Samples were collected from the summit of Mt. Griffith (3190 m) down to the base of the Fission Wall (1296 m). The sampling profile was collected in two segments: (1) down the north face and the northwest ridge of Mt. Griffith to an elevation of 2500 m and (2) down the steep northeast buttress of the Mt. Griffith massif (the Fission Wall), ~2 km east-northeast of Mt. Griffith.

Interpretation of fission-track data follows the approach of Fitzgerald and Gleadow (1990), based on principles in Gleadow et al. (1986) and Green et al. (1986, 1989). Interpretation has been aided by use of forward modeling of fission-track parameters based on the preferred equation of Laslett et al. (1987). The external detector method and zeta calibration

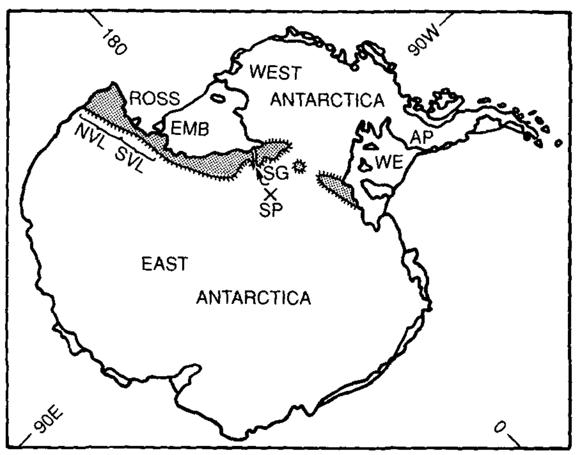

Figure 1. Location map for Antarctica. AP—Antarctic Peninsula, NVL—northern Victoria Land, SVL—southern Victoria Land, ROSS EMB—Ross Embayment, SG—Scott Glacier, SP—South Pole, WE—Weddell Embayment, patterned area—Transantarctic Mountains.

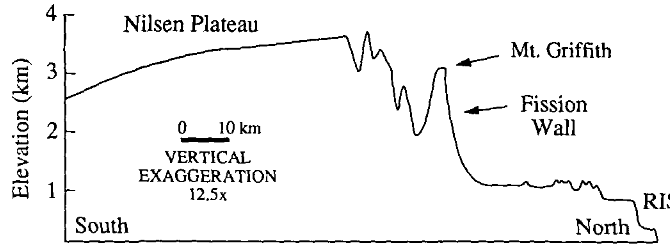

Figure 2. Topographic profile across Transantarctic Mountains along west side of Scott Glacier. RIS—Ross Ice Shelf.

Additional material for this article, GSA Supplementary Data 9208, is available on request from the GSA Documents Secretary (see footnote 1).

approach were used (Hurford and Green, 1983). Ages were calculated using zeta values of 322 ±4.2 (Fitzgerald) and 323 ±6.2 (Stump) for dosimeter glass SRM612. Apatite age is reduced during annealing mainly as the result of the reduction in the length of fission tracks, and this length reduction is dominantly dependent on the maximum temperature a track has experienced throughout its existence. Above ~110 °C, annealing is essentially instantaneous over geologic time ($>10^7$ yr), whereas below ~60 °C, tracks will anneal very slowly. Partial annealing of tracks occurs at successively faster rates from ~60 to 110 °C in the partial annealing zone for long periods of heating. Tracks are produced continuously throughout time, and therefore the relative proportions of long and short tracks give information about the time-temperature path that a sample has folllowed.

INTERPRETATION OF DATA

Apatite ages vary from 119 ±9 to 62 ±6 Ma (Table 1[1]) and generally increase with increasing elevation. Ages from the northeast ridge of Mt. Griffith and the northwest buttress (Fission Wall) are on separate but almost parallel trends (Fig. 3) and do not appear to form one continuous profile. Mean track lengths vary little down the profile. All apatite ages are younger than Jurassic magmatism (~180 Ma; Kyle et al., 1981), and it is likely that apatite ages were reset to zero at that time. We interpret the apatite age profile in the following way:

1. *Early Cretaceous uplift and denudation.* Ages from the summit of Mt. Griffith down to an elevation of 2500 m on the northeast ridge—a decrease of more than 700 m—do not vary significantly. Ages have a weighted mean of 112 ±2 Ma. Mean track lengths average 13.3 μm with standard deviations of between 1.3 and 1.9 μm. The steep slope of this part of the profile indicates that these samples were cooled rapidly. However, the track-length distributions indicate that they did not quickly transit the partial annealing zone. Samples on this part of the profile were cooled from temperatures of >110 °C to not less than 60 °C at ~115 Ma. Further cooling ceased until these samples were uplifted in the Late Cretaceous.

2. *Late Cretaceous uplift and denudation.* All ages from the Fission Wall profile are significantly younger than those from Mt. Griffith. The upper 12 samples from the Fission Wall (weighted mean age of 81 ±2 Ma) define a steep gradient of ~300 ±150 m/m.y., interpreted as evidence for rapid cooling brought about as a result of uplift and denudation in the Late Cretaceous. However, in a situation akin to the samples from Mt. Griffith, track-length distributions (average mean length = 13.2 μm with standard deviations of 1.7 to 2.3 μm) indicate that these samples also resided for a significant period of time in the partial annealing zone. These samples were uplifted from the zone of total annealing (temperatures of >110 °C) to the zone of partial annealing (60–110 °C) in the Late Cretaceous where they resided until further cooled (uplifted) as a result of early (?) Cenozoic uplift.

3. *Fault between Mt. Griffith and the Fission Wall.* We consider it unlikely that the trend from Mt. Griffith and the Fission Wall was once linearly continuous and has since been offset by faulting. However, we do believe that there is a fault between the Mt. Griffith profile and the Fission Wall profile. The track-length data require that samples from both Mt. Griffith and the Fission Wall resided for a significant period of time in the partial annealing zone, which would not be possible if uplift and denudation were continuous from Early through Late Cretaceous at such a rapid rate. Following Early Cretaceous uplift, an apatite partial annealing zone developed as tracks in samples lying at successively higher temperatures annealed at successively faster rates. However, the form of a partial annealing zone that would have developed over the ~30 m.y. (from ~115 to 85 Ma) is not seen in the profile between Mt. Griffith and the Fission Wall. We believe that a fault (down to the southwest, the Mt. Griffith side) has removed this uplifted partial annealing zone. The summit of Mt. Griffith and the top of the Fission Wall are only 2 km apart, but a well-defined saddle between the two marks the likely position of the fault.

4. *Early(?) Cenozoic uplift.* The 62 ±2 Ma age for the lowermost sample of the Fission Wall, plus a systematic decrease in mean track length for the bottom seven samples, suggests that the lower part of the profile represents the upper part of an uplifted partial annealing zone that developed following Late Cretaceous uplift. The Mt. Griffith–Fission Wall profile must have been uplifted since 62 Ma in order for the profile to be revealed here. We believe that this subsequent uplift of the Transantarctic Mountains in this region most likely occurred in the early Cenozoic, penecontemporaneously with the uplift recorded in Victoria Land (Fig. 4).

[1]Table 1, Fission Track Analytical Results, Mt. Griffith–Fission Wall Massif, GSA Supplementary Data 9208, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

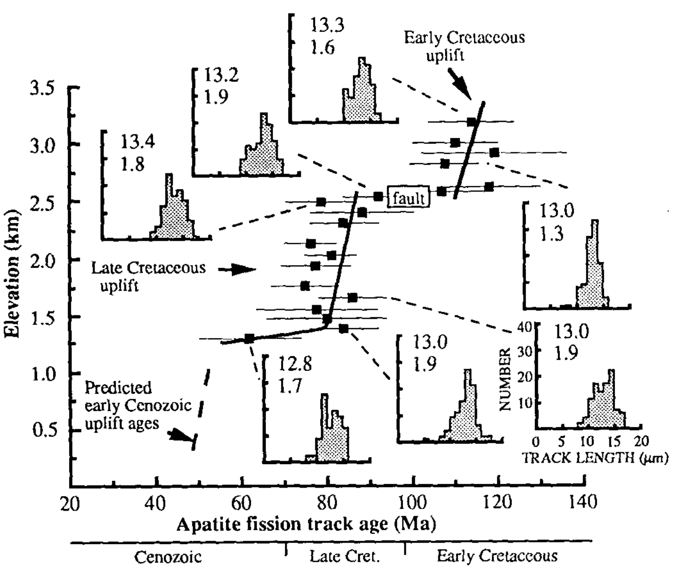

Figure 3. Apatite fission-track age vs. sample elevation for Mt. Griffith–Fission Wall profile. Errors bars are two standard deviations. Track-length distributions (mean and standard deviations in micrometres) are shown for some representative samples.

REGIONAL TECTONICS

Data from the Mt. Griffith–Fission Wall apatite age profile indicate periods of uplift and denudation of the Transantarctic Mountains, in Early Cretaceous, Late Cretaceous, and Cenozoic times. Fission-track data from the Transantarctic Mountains in Victoria Land indicate that uplift was initiated in the early Cenozoic (~55 Ma) (Gleadow and Fitzgerald, 1987; Fitzgerald and Gleadow, 1988). Fission-track data demonstrate no Cretaceous uplift in southern Victoria Land, although there may have been a period of Cretaceous tectonism in northern Victoria Land (Elliot and Foland, 1986; Schmierer and Burmester, 1986). Evidence from in situ *Nothofagus* fragments in the Sirius Formation near the head of the Beardmore Glacier (McKelvey et al., 1991), plus a variety of other observations (as summarized in Behrendt and Cooper, 1991; and Fitzgerald, 1992) suggest that the Transantarctic Mountains also underwent uplift in the Pliocene-Pleistocene. There appear to have been at least four episodes of uplift of the Transantarctic Mountains since the start of the Cretaceous. Whereas the Cenozoic episodes apparently affected the mountains throughout the Ross Embayment sector, the Cretaceous episodes were not so extensive.

The early Cenozoic uplift of the Transantarctic area in Victoria Land has been related to extension and crustal thinning of the Ross Embayment, especially the formation of the Victoria Land basin, adjacent to the Transantarctic Mountains in the Ross Sea (Fitzgerald et al., 1986). Seismic profiling shows that the Ross Embayment contains three basins filled with up to 8 km of deformed sediment unconformably blanketed by ~6 km of younger sediment. Timing of rifting events within the Ross Embayment remains poorly determined. Paleomagnetic data from Marie Byrd Land

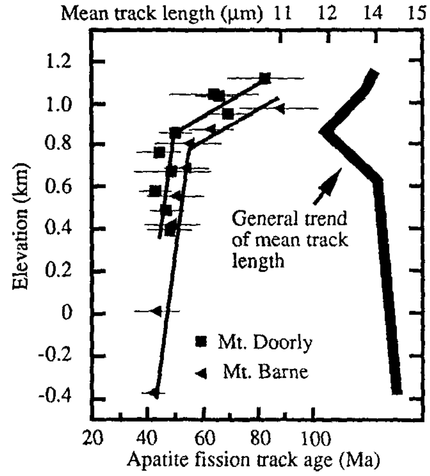

Figure 4. Apatite fission-track age profile for southern Victoria Land (modified from Fitzgerald et al., 1986).

indicate that it may have moved 200–500 km away from East Antarctica, with a possible dextral rotation of 10°–45° since the Early Cretaceous (Grindley and Oliver, 1983). Estimates of the amount of crustal thinning in the Ross Embayment between Marie Byrd Land and East Antarctica range from 25%–30% (Fitzgerald et al., 1986) to 40%–50% (Lawver and Scotese, 1987). Cooper et al. (1987, 1991) inferred early and late periods of rifting in the Ross Embayment, the younger sediments being deposited during the Cenozoic, and they suggested that older deformed sediments were deposited in the late Mesozoic. The oldest strata cored to date in the Ross Embayment are early Oligocene (Barrett et al., 1991). Although the early (suggested Cretaceous) graben development in the Ross Embayment was extensive, it apparently was not matched by a contiguous uplift throughout the Transantarctic Mountains; in particular, fission-track evidence indicates no uplift and denudation at this time in southern Victoria Land.

Within the broad regional context, the Cretaceous was a time of continental breakup in this sector of Gondwana (Fig. 5). Separation of Australia from Antarctica, Australia from New Zealand, and New Zealand from Antarctica all commenced at approximately the same time. Anomalies 33 (77 Ma) or 34 (84 Ma) have been identified along each of the boundaries (Weissel et al., 1977; Cande and Mutter, 1982). Cande and Mutter (1982) extrapolated from A34 along the boundaries of Australia and Antarctica, across a broad magnetic quiet zone adjacent to both continents, suggesting breakup along this margin between 90 and 110 Ma. Very slow separation of Australia and Antarctica (half rate of 4.5 mm/yr) ensued until A20 (43 Ma), at which time the spreading rate increased. It seems likely that generation of oceanic crust between Australia and Antarctica predated slightly the separation of the Campbell Plateau and Marie Byrd Land (Bradshaw, 1989). Until 105 ±5 Ma, New Zealand had an active subducting margin, while marine sedimentation was occurring in extensional basins marginal to southeastern Australia (Bradshaw, 1989; Davidson et al., 1984), synchronous with those in the Ross Embayment (Cooper et al., 1991). Impingement of the Pacific-Phoenix ridge with the subduction zone at ~100 Ma marked a halt to compressive tectonics in New Zealand (Bradshaw, 1989). The Early Cretaceous uplift of the Transantarctic Mountains in the Scott Glacier area occurred during this time of continental breakup.

Given the lack of evidence for Cretaceous uplift in southern Victoria Land and considering the position of Scott Glacier at the end of the Ross Embayment, tectonic events in the area of the Weddell Embayment may be more related to Early Cretaceous uplift of the Scott Glacier area of the Transantarctic Mountains. Paleomagnetic and isotopic data suggest rotations and translations of the Ellsworth-Whitmore Mountains block, Thurston Island block, and Antarctic Peninsula block during the Late Jurassic and Early Cretaceous, until about 110 Ma when these blocks apparently became fixed to East Antarctica (Grunow et al., 1991). Opening of the southern Weddell Sea may have started as early as 165 Ma (LaBrecque and Barker, 1981); ocean crust was certainly being formed by 135 Ma (Martin and Hartnady, 1986; Grunow et al., 1991). Apatite fission-track data from the Ellsworth Mountains indicate more than 4 km of unroofing in the Early Cretaceous between 141 and 117 Ma (Fitzgerald and Stump, 1991). The Early Cretaceous uplift in the Scott Glacier area may be an expression of either or both the final differential movements around the Weddell Embayment and crustal extension within the Ross Embayment.

After 100 Ma, the Pacific-Phoenix spreading center propagated between New Zealand and Antarctica, eventually joining the spreading center between Australia and Antarctica and continuing into the Tasman Sea (Lawver et al., 1991). Separation of the continental fragments at about 80 Ma (anomalies A33 and A34) coincided with the second episode of uplift in the Scott Glacier area.

Spreading in the Tasman Sea ceased at 55 Ma (Weissel and Hayes, 1977), whereas an increased spreading rate between Australia and Antarctica commenced about 43 Ma (Cande and Mutter, 1982). Between these two dates is a period of considerable reorganization of plate motions (Lawver et al., 1991; Cooper et al., 1991) in the southwest Pacific marked by a 40° counterclockwise rotation in the direction of spreading between Antarctica and the Campbell Plateau (Stock and Molnar, 1987). This period also appears to be a time of rapid uplift in the Transantarctic Mountains. Forward modeling of apatite fission-track data from southern Victoria Land (Fitzgerald, 1987) requires an initially rapid period of uplift and denudation of the mountains in the early Cenozoic (~55–45 Ma) in order to generate track-length distributions comparable to those obtained

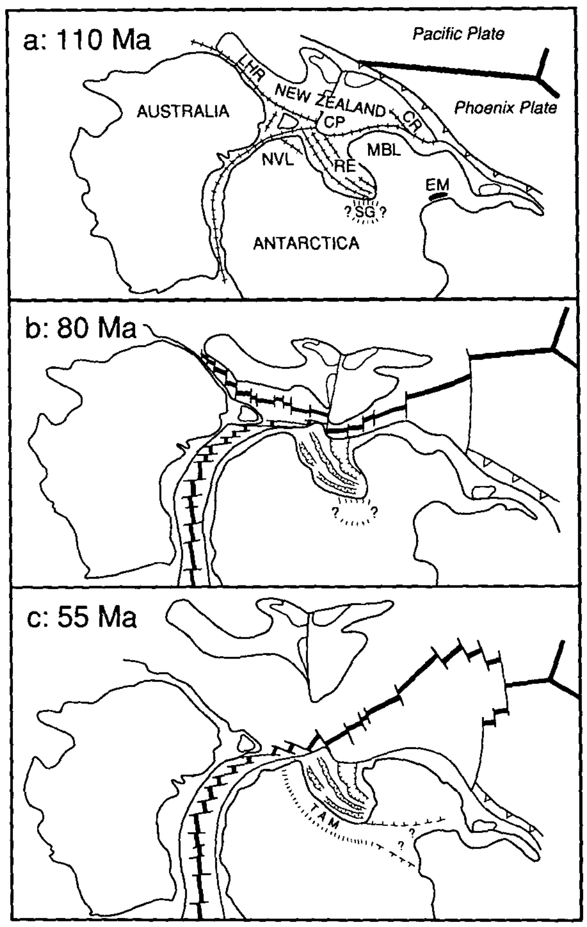

Figure 5. Paleogeographic reconstructions of Early Cretaceous (110 Ma), Late Cretaceous (80 Ma), and early Cenozoic (55 Ma). CP—Campbell Plateau, CR—Chatham Rise, EM—Ellsworth Mountains, LHR—Lord Howe Rise, MBL—Marie Byrd Land, NVL—northern Victoria Land, RE—Ross Embayment, SG—Scott Glacier, TAM—Transantarctic Mountains. Adapted from Barker (1982), Kamp (1986), Weissel et al. (1977), and Grunow et al. (1991).

beneath the break in slope (Fig. 4). It is possible that spreading may have preferentially propagated south into the Ross Embayment upon cessation of spreading in the Tasman Sea (55 Ma), manifesting itself in the form of crustal extension and uplift of the Transantarctic Mountains until the increase in spreading rate between Australia and Antarctica (43 Ma). Each of the three episodes of uplift in the Transantarctic Mountains indicated by apatite fission-track analysis marks an important change in the plate-tectonic regime in this sector of Gondwana.

CONCLUSIONS

Two periods of uplift and denudation (Early and Late Cretaceous) in the Scott Glacier area of the Transantarctic Mountains are indicated by apatite fission-track analysis. Combined fission-track evidence for uplift of other parts of the mountains in the early Cenozoic, and other evidence for uplift during the Pliocene-Pleistocene, suggests at least four episodes of uplift in the Transantarctic Mountains since the Early Cretaceous. Each of the three older episodes coincide with major plate-tectonic changes in the region.

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