EARLY CRETACEOUS UPLIFT OF THE SOUTHERN SENTINEL RANGE, ELLSWORTH MOUNTAINS, WEST ANTARCTICA

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Abstract: Apatite fission track analysis of a 4.2 km vertical profile of samples collected from the western flank of the southern Sentinel Range indicates unroofing (uplift and erosion) in excess of 4 km between ~140 and 117 Ma following the initial separation of East and West Gondwana and accompanying the opening of the Weddell Sea. A single apatite age (169 ± 17 Ma) from the Heritage Range indicates less uplift there during the Early Cretaceous, but suggests that Early Cretaceous uplift was initiated between ~145 and ~169 Ma. The amount of uplift and denudation in the southern Sentinel Range since the Early Cretaceous is unlikely to have been more than 3 km and was probably much less. At least 1.8 km of relief has persisted there since the Early Cretaceous.

Key words: Ellsworth Mountains, Sentinel Range, uplift, fission track

Introduction

In contrast to East Antarctica, a stable remnant of the Gondwana supercontinent, West Antarctica is composed of at least five crustal blocks, separated from each other by deep sub-ice basins and troughs that may represent areas of rifting and extension, and possibly floored by either oceanic crust (Masolov *et al.*, 1981; Jankowski and Drewry, 1981) or attenuated continental crust. This collage of blocks has undergone relative movements during and after the breakup of Gondwana in the middle Mesozoic. West Antarctica is separated from East Antarctica along the Transantarctic Mountains Front, and the Ross and Weddell Embayments. The late Mesozoic and Cenozoic evolution of West Antarctica, and its relationship to East Antarctica is one of the fundamental tectonic problems still outstanding in Gondwana geology.

The Ellsworth - Whitmore Mountains block (EWM) is sandwiched between East Antarctica and the other West Antarctic crustal blocks (Fig. 1). The dominant physiographic features of the EWM are the Ellsworth Mountains. These include Vinson Massif (4897 m), the highest point on the continent, and one of a series of lofty peaks that define the north-south trending spine of the Sentinel Range. Relief on the spectacular western flank of the Sentinel Range is in excess of 4 km (Fig. 2). From this topographic maximum the mountains descend to 2 km below sea-level beneath the Rutford Ice Stream lying to the east (Drewry, 1983).

The dramatic relief of the Sentinel Range and the presence of late Cenozoic volcanic activity in West Antarctica has suggested to previous workers that at least the latest phase of uplift of the Ellsworth Mountains has been relatively recent, most likely in the late Cenozoic, and most likely associated with extension between different crustal blocks at about this time (e.g. Garrett *et al.*, 1987; Dalziel *et al.*, 1987). Behrendt and Cooper (1991) suggested that the Ellsworth Mountains form part of a rift shoulder uplift associated with the Transantarctic Mountains and the West Antarctic rift system formed during the late Cenozoic.

The objective of this study was to apply fission track

analysis towards the resolution of the uplift history of the Ellsworth Mountains. Samples were collected from the western flank of the Sentinel Range, notably from Vinson Massif. Unfortunately, logistic problems severely restricted the full extent of sampling and precluded any work in the Heritage Range. The results presented herein provide the first constraints on the timing of uplift of the Ellsworth Mountains.

Geology of the Ellsworth Mountains

The Ellsworth Mountains consist of an apparently conformable sequence of Cambrian through Permian sedimentary rocks which lack the conspicuous mid-Paleozoic unconformity (Kukri Peneplain) that has been mapped in the Transantarctic Mountains (TAM) from the Ohio Range to northern Victoria Land (Fig. 1). The structural trend of the Ellsworth Mountains is perpendicular to that of the TAM, an observation that led Schopf (1969) to suggest that the Ellsworth Mountains had rotated to their present location from a position near Coats Land, a scenario that is still fundamental in understanding the tectonic evolution of West Antarctica (e.g. Grunow *et al.*, 1991).

The stratigraphy of the Ellsworth Mountains is summarized in Fig. 2. All samples for this study were collected from the 2600–3400 m thick Devonian Crashsite Group, which is composed almost entirely of very well-cemented mediumto coarse-grained quartzite with abundant cross bedding and ripple marks. This group forms the spine of the Sentinel Range and is also found in the Heritage Range. The Ellsworth Mountains were deformed during the Gondwanide Orogeny, a pervasive folding event that produced asymmetric, tight to isoclinal folds. This event probably took place as a single event in the Triassic (Craddock, 1972; Storey *et al.*, 1987), although some possible Paleozoic movements have been suggested (Yoshida, 1983).

Rocks of the Ellsworth Mountains show increasing metamorphism with depth of section, from laumontite grade in the Polarstar Formation (Castle and Craddock, 1975) to pumpellyite-actinolite and lower greenschist grade in the

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Fig. 1. Map of West Antarctica and part of East Antarctica showing boundaries of crustal blocks and main subglacial basins, modified from Storey *et al.* (1988a). AP = Antarctic Peninsula; BST = Bentley Subglacial Trench; BSB = Byrd Subglacial Basin; EWM = Ellsworth-Whitmore Mountains block; HN = Haag Nunataks; MBL = Marie Byrd Land; TI = Thurston Island; RIS = Rutford Ice Stream. Position of cross-sections in Fig. 2 are marked A-A' and B-B'.

Heritage Group (Bauer, 1983). The exposure of successively younger bedrock units to the east, together with the steep western margins and more gradual easterly slopes of the Sentinel and Heritage Range, suggest that the Ellsworth Mountains are an easterly tilted block (Fig. 2).

Fission Track Analysis, Sampling Strategy and Analytical Methods

Apatite fission-track analysis has been routinely applied to thermo-tectonic problems (e.g. Green, 1986; Fitzgerald and Gleadow, 1988) since Wagner and Reimer (1972) observed that apatite ages increase with increasing elevation. Better understanding of annealing (Green *et al.*, 1986; Laslett *et al.*, 1987) and the use of confined track length measurements (e.g. Gleadow *et al.*, 1986a, b) has permitted development of forward modelling programs (Duddy *et al.*, 1988; Green *et al.*, 1989). These programs allow a better interpretation of apatite fission track data.

The increase of apatite age with increasing elevation is explained as the consequence of an idealized column of rock moving up through an idealized critical track retention tion. The effective closure temperature, equivalent to the stage when approximately half the tracks become stable, varies with cooling rate (Wagner and Reimer, 1972; Dobson, 1973; Haack, 1977; Wagner et al., 1977). For cooling rates of 0.1-100°C/m.y. over geological time (periods of 10–100 m.y.) the effective closure temperature is $\sim 100 \pm$ 20°C (Naeser and Faul, 1969; Calk and Naeser, 1973; Harrison et al., 1979). However, it is now known that fission tracks anneal at all temperatures and that only the rate of annealing varies with temperature (Green et al., 1986). Apatite annealing studies in deep drill holes (e.g. Naeser, 1981; Gleadow and Duddy, 1981) and in laboratories (e.g. Green et al., 1986: Laslett et al., 1987) show that apatite age decreases with increasing temperature, forming a distinctive profile until a zero age is reached at a temperature of ~110° to ~130°C. The depth of zero apatite age will depend on the geothermal gradient, the duration of heating and the chemical composition of the apatites (Green et al., 1986). At temperatures near the base of the partial annealing zone (PAZ) the rate of annealing is almost instantaneous, but at surface

isotherm (or closure temperature) during uplift and denuda-



Fig. 2. Stratigraphic column and topographic cross sections (vertical exaggeration $6.5 \times$) through Vinson Massif in the Sentinel Range (A-A'), and Springer Peak in the Heritage Range (B-B'). Geology for the construction of cross-sections is from Craddock *et al.* (1986). RIS = Rutford Ice Stream.

temperatures it is very slow. Track length distributions will also vary with temperature and will form distinctive patterns depending on the temperature at which these samples have resided (Gleadow *et al.*, 1986a, b). Track length distributions with means $\geq ~14 \ \mu m$ and small standard deviations ($\leq ~1.5 \ \mu m$) are indicative of rapid cooling. Distributions with means of 12–13 $\ \mu m$ and larger standard deviations $(\geq 1.5 \ \mu m)$ are indicative of more complex thermal histories with considerable track annealing. Annealing may render apatite ages meaningless in terms of dating geological events but is the characteristic of apatite fission track analysis that allows resolution of the thermal (and hence the tectonic) history of areas, especially by examination of the variation of age and track length over a vertical profile (e.g. Fitzgerald and Gleadow, 1990). Apatites from the Crashsite Group quartzite have a composition similar to that of Durango apatite, a widely used age standard (Hurford and Green, 1983) that retains fission tracks at temperatures $\leq 110^{\circ}$ C for cooling rates of 0.1° to 10°C/m.y. over geologic time (~10⁷ years) (Green *et al.*, 1986).

26 samples were collected on the Vinson Massif profile, the upper three from the Mt. Liptak Formation, the remainder from the Howard Nunataks Formation. An additional 5 samples from Bowers Corner extend the profile to lower elevations. We also analyzed one sample collected by Gerald Webers (Macalester College, Minnesota) from the Springer Peak Formation at ~1200 m on Springer Peak in the Heritage Range. Dr. Webers kindly provided this sample prior to our field work so that we could determine the quantities of apatite present and gauge the sample size necessary for this study. All samples yielded sufficient apatite for analysis, the rounded to subrounded grain shapes reflecting the sedimentary origin of the apatites.

Apatites were separated from crushed samples using conventional magnetic and heavy liquid techniques. Apatite grains were mounted in epoxy resin on glass slides, ground and polished to reveal an internal surface and then etched in 5N HNO₃ for 20 seconds at room temperature to reveal fossil fission tracks. Ages were determined using the external detector method, an automated Autoscan[™] stage, and low-uranium muscovite as the external detector to record induced tracks during irradiation. Samples were irradiated in the graphite reflector region of the V-43 position (Cd for Au ratio of 280) at the Georgia Institute of Technology Nuclear Reactor. Thermal neutron fluences were monitored in a muscovite detector adjacent to discs of the NBS standard reference glass SRM612. When possible, 20 grains were counted in each age determination. Counting was done at magnifications of $1250\times$ under dry objectives using a Nikon Optiphot microscope, and only those grains that displayed sharp polishing scratches were counted. Ages were calculated using the zeta calibration method of Hurford and Green (1983) and Green (1985), and errors were calculated by the conventional method (Green, 1981). Zeta calibrations for glass SRM612 were determined empirically by counting age standards, hence the reported fission-track ages are independent of uncertainties in the ²³⁸U fission decay constant and the need for explicit thermal neutron dosimetry (Hurford and Green, 1982).

Track lengths were measured using horizontal confined fossil tracks (Lal *et al.*, 1969; Laslett *et al.*, 1984) in grains whose polished surfaces were approximately parallel to the c-axis. A track was taken as horizontal if it remained in focus along its length or had an uniform bright reflection under reflected light. Measurements were made under dry objectives using a projection tube and digitizing tablet attached to a microcomputer. Ideally, 100 track length measurements are made per sample, except when track numbers are insufficient.

Results

Apatite ages range from 146 ± 9 Ma near the top of the Vinson Massif to 117 ± 5 Ma for the lowermost sample (Table 1; Fig. 3). Mean track lengths vary from a maximum of 14.3 µm for several samples in the upper part of the profile to 13.4 µm near the base of the profile. Length distributions have a weighted mean of 13.9 µm, but appear to vary systematically with elevation (Fig. 4). Lengths from samples in the upper parts of the profile are generally longer than those from the lower parts of the profile, except for the



Fig. 3. Variation of apatite fission-track age $(\pm 2\sigma)$ with elevation for the Vinson Massif - Bowers Corner profile; also shown are representative track length distributions (mean and standard deviation in microns).

Sample number	Elevation (m)	Number of grains	Standard track density (x10 ⁶ cm ⁻²)	Fossil track density (x10 ⁶ cm ⁻²)	Induced track density (x10 ⁶ cm ⁻²)	Correlation coefficient	Chi square probability (%)	Age $(\pm 1\sigma)$ (Ma)	Uranium (ppm)	Mean Track Length (µm)	Standard Deviation (µm)
			K								
Vinson Massif -	western flank										
HBD	4887	20	1.81	1.345	2.754	0.985	50	141 ± 6	15	13.6 ± 0.16	1.62
HBE	4650	8	1.58	3.134	5.387	0.994	99	146 ± 9	34	(100)	
			(7379)	(448)	(770)						
HAT	4014	20	1.48 (9397)	2.654 (1143)	4.506 (1941)	0.948	6	139 ± 6	30	14.3 ± 0.10 (100)	0.96
HAX	3418	20	1.53	1.902	3.418	0.994	25	136 ± 5	22	14.2 ± 0.10	0.98
	5110		(9692)	(1548)	(2782)			100 - 0		(100)	01/0
НАУ	3254	18	1.78	1.074	2.220	0.988	91	137 ± 7	12	14.1 ± 0.13	1.31
			(8366)	(730)	(1509)		-			(100)	
HAZ	. 3100	20	1.53	2.287	3.960	0.987	70	141 ± 6	26	14.3 ± 0.10	1.02
НАР	2501	20	(9692)	(1251)	(2100)	0.007	60	121 . 5	25	(109)	1.22
	2501	20	1.70 (8366)	(1388)	(2980)	0.992	08	131 ± 5	25	14.1 ± 0.12 (100)	1.23
HAQ	2401	20	1 73	1 152	2 491	0.978	83	128 + 6	14	136 ± 0.15	1 46
	2401	20	(8366)	(738)	(1595)	0.970	05	120 2 0	14	(100)	1.40
HAR	2261	20	1.77	1.362	2.860	0.982	69	134 ± 6	16	13.7 ± 0.12	1.20
			(8366)	(899)	(1888)					(100)	
HAF	2098	20	1.77	1.695	3.858	0.971	61	124 ± 6	22	13.8 ± 0.12	1.18
			(11200)	(771)	(1755)					(100)	
HAG	1905	15	`1.77´	ì.92Ó	4.129	0.993	17	131 ± 6	23	13.6 ± 0.13	1.34
			(11200)	(816)	(1755)					(100)	
HAI	1670	20	`1.77 ´	1.257	2.838	0.983	57	125 ± 7	16	13.9 ± 0.14	1.42
			(11200)	(568)	(1282)					(100)	
HAK	1492	20	1.75	1.226	2.931	0.978	. 3	117 ± 5	17 .	13.8 ± 0.14	1.38
			(8366)	(890)	(2128)			*124 ± 9		(101)	
Bowers Corner										. ,	
HBR	887	20	1.80	1.381	3.190	0.978	7	124 ± 6	18	13.9 ± 0.16	1.60
			(5762)	(866)	(2000)					(101)	
HBS	785	20	1.79	1.410	3.141	0.940	4	128 ± 5	17	13.4 ± 0.12	1.23
			(5762)	(1133)	(2524)			*127 ± 6		(100)	
HBT	690	20	1.79	1.687	4.120	0.973	20	117 ± 5	23	13.7 ± 0.15	1.54
			(5762)	(1012)	(2471)					(100)	
Heritage Range			. ,							• •	
Springer Peak	~1,200	13	1.41	1.342	1.868	0.887	<1	161 ± 10	13	13.3 ± 0.25	1.71
-			(4338)	(479)	(667)			*169 ± 17		(46)	

Table 1. Fission track analytical results - southern Sentinel Range apatites.

Brackets show number of tracks counted (densities) or measured (length). Standard and induced track densities were measured on mica external detectors (g=0.5), and fossil track densities on internal mineral surfaces. Ages were calculated using $\zeta=322 \pm 4$ for dosimeter glass SRM612 (Hurford and Green, 1983). * Mean age, used where pooled data fail χ^2 test at 5%.



Fig. 4. Mean track length and standard deviation versus elevation for the Vinson Massif - Bowers Corner profile.

summit sample which lies off this general trend with a mean length of 13.6 μ m. Standard deviations average 1.3 μ m, and also follow this apparent trend, although it should be noted that the standard deviations only vary from 1.0 to 1.6 μ m. The sample from Springer Peak has an older apatite age, 169 \pm 17 Ma, a shorter mean length, 13.3 μ m, and a larger standard deviation, 1.7 μ m, than any of the samples from the Vinson Massif - Bowers Corner profile.

Discussion and Interpretation

The data from the Vinson Massif - Bowers Corner profile indicate >4 km of denudation in response to uplift in the Early Cretaceous from ~140 to ~120 Ma. The track length data adds some subtlety to this interpretation. Mean lengths \geq 14.0 µm for ages between ~130 and ~140 Ma (between 2500 m and 4000 m) indicate that these samples cooled rapidly. For the uppermost sample (HBD, 4887 m), and samples below ~2400 m (<~130 Ma), mean lengths are slightly shorter and the standard deviations are slightly larger, indicating that these samples have undergone a minor amount of annealing. The simplest interpretation of the profile (Fig. 3) is of an average unroofing rate of ~200 m/ m.y. between ~140 and ~120 Ma, but with more rapid cooling (and hence unroofing) between ~140 and ~130 Ma. The mean track length of 13.6 µm for the top sample HBD lies off the apparent trend of increasing mean length with elevation, and reflects a greater degree of annealing than the other samples above 2500 m. This sample reflects either; [1] a transition from a slower period of unroofing (where more time has been spend at temperatures where annealing is greatest) to more rapid unroofing between ~140 and ~120 Ma, or [2] an abrupt change from a period of relative thermal and tectonic stability to more rapid unroofing between ~140 and ~120 Ma (i.e. this sample resided in the lower part of a PAZ and has since been uplifted to its present position).

The sample from Springer Peak has undergone more annealing than any of the samples on the Vinson Massif -Bowers Corner profile. The Heritage Range is lower and does not have a dramatic mountain front like the western flank of the Sentinel Range (Fig. 2). The age of 169 ± 17 Ma indicates that there was significantly less Early Cretaceous unroofing in the Heritage Range than the Sentinel Range, although it is not possible to estimate how much less, as we do not know the slope of the apatite age profile above ~140 Ma. With its greater amount of annealing, we may speculate that the sample from Springer Peak represents part of an uplifted PAZ and that somewhere between the ages of ~169 and ~140 Ma there is a dramatic transition in the slope of the apatite age profile (Fig. 5). Given the decreased mean length for the uppermost sample from the Vinson Massif, it is possible that this transition, or "break in slope" is close to 140 Ma, although it should be noted that this is speculative. If a break in slope in the apatite age profile, indicating the initiation of uplift, is between ~140 and ~169 Ma, then it will be found in the Heritage Range where strata containing ages >140 Ma have not been eroded away.

For a normal crustal geothermal gradient $(25^{\circ}C/km)$, the top of a PAZ (~60°C) would be at a depth of 2.4 km below the surface (Fig. 6). The lowermost samples from Bowers Corner do not display evidence of prolonged residence at temperatures>60°C. Following Early Cretaceous unroofing these samples are therefore unlikely to have resided at depths much in excess of 2.4 km. As the relief between the uppermost and lowermost samples on this profile is 4.2 km, there must have been ≥ 1.8 km of relief in the Sentinel Range following Early Cretaceous uplift and denudation.

If we assume that the base levels of Early Cretaceous valleys were at sea-level and if the lowermost sample from Bowers Corner (HBT, 690 m) lay close to the top of the post-Early Cretaceous PAZ (2.4 km below sea-level), then the amount of uplift since the Early Cretaceous is \sim 3.1 km or less. If the paleogeothermal gradient was steeper (e.g. 30°C/km) then the amount of unroofing since the Early Cretaceous would be less (\sim 2.7 km) because the depth to the top of the PAZ would be less (2 km). Alternatively, if the paleogeothermal gradient was shallower, then the amount of unroofing would be greater. In addition, if the base levels of Early Cretaceous valleys were at a higher elevation than sealevel, then the amount of uplift since then would also have been less.

The timing and exact amount of additional uplift since the Early Cretaceous is unconstrained from the available fission track data. Whether this additional uplift was in response to a gradual isostatic adjustment due to continuing erosion and unroofing, or whether it came as a single event or rapid pulses since the Early Cretaceous is not discernible from this data. However, a minimum of 1.8 km of relief has remained in the Sentinel Range since the Early Cretaceous, most likely a direct consequence of the resistance to erosion of the very well-cemented quartzites of the Crashsite Group. The western flank of the Sentinel Range is composed almost exclusively of quartzite and very little debris or talus is seen at the base of 2500 m near-vertical faces, a testimony to the resistance of the rock.

Constraints can be placed on the amount of strata eroded off the top of Vinson Massif since the Early Cretaceous. The track length distribution of sample HAT (4014 m) indicates rapid cooling, whereas that of the uppermost sample, HBD (4887 m) is indicative of some partial annealing. HAT must have resided at temperatures >110°C (i.e. the temperature at the base of the PAZ) prior to uplift. Assuming a



Fig. 5. Apatite fission track age versus elevation for all data. Track length distribution for the sample from Springer Peak (with mean length and standard deviation in microns). Diagram illustrates the presence of the possible "break in slope" indicative of an uplifted PAZ at the top of the Vinson Massif - Bowers Corner profile. The sample from Springer Peak is shown elevated to a position within the suggested uplifted PAZ, reflecting the lesser amount of uplift within the Heritage Range.



Fig. 6. Uplift model for the southern Sentinel Range. T is the top, and B, the bottom of the Vinson Massif - Bowers Corner vertical profile. The model is drawn assuming a 25° C/km geothermal gradient, hence depths to the top of the PAZ (~60°C) and to the base of the PAZ (~110°C) are 2.4 km and 4.4 km, respectively. (A) Pre-Early Cretaceous uplift and denudation: profile resides at temperatures above ~110°C, although the uppermost sample (HBE) may actually reside within the PAZ. (B) By ~117 Ma the entire profile (T-B) has risen through the PAZ with the lowermost sample showing minimal annealing. This places B at a maximum depth of 2.4 km from the ground surface. Assuming sea level at valley bottoms, and T at ground surface at the mountain top indicates a minimum relief of 1.8 km. Erosion is likely to have denuded considerable rock since ~117 Ma to bring T to the surface, and therefore relief at ~117 Ma was probably considerably greater than 1.8 km. (C) Present day: Top of profile (T) at elevation of 4887 m. Its minimum elevation of 1.8 km at ~117 Ma implies maximum uplift of 3 km since that time.

paleogeothermal gradient of 25° C/km, this translates to a depth of >4.4 km. HAT was collected 900 m below the summit suggesting at least 3.5 km of strata has been eroded off the summit of the Vinson Massif since the Early Cretaceous. Stratigraphically there is 2.9-3.4 km of section above the Howard Nunataks Formation (Craddock *et al.*, 1986). However, stratigraphic level throughout the Ellsworth Mountains is in this case a very poor indicator of the relative amount of uplift in the Early Cretaceous because the sequence was deformed in the Triassic (Fig. 2). For example, the sample from ~1200 m from the Heritage Range type locality of the Springer Peak Formation yielded an age of 169 ± 17 Ma, an older age than those from the stratigraphically higher units at the Vinson Massif.

The total amount of uplift and denudation in each range can be crudely estimated using metamorphic grade, and the stratigraphic level presently exposed. The rocks of the Heritage Group have recrystallized under pumpellyiteactinolite to greenschist facies conditions (Bauer, 1983) indicating that these rocks have spent considerable time at temperatures of at least 300°C. The laumontite (zeolite) grade of the Polarstar Formation (Castle and Craddock, 1975) indicates temperatures near 200°C. Residence at these temperatures for periods of 10⁷ years is sufficient to completely erase any pre-existing fission tracks; thus all fission tracks in the Ellsworth Mountain samples are postdepositional and reflect the thermal history of the sample since it has been buried to its maximum depth.

In a normal continental geotherm (~25°C/km), the Polarstar Formation (laumontite facies), the uppermost unit exposed, would have been buried to depths of ~8 km, and the Heritage Group (pumpellyite-actinolite to greenschist facies) to depths of ~12 km. The western flank of the southern Sentinel Range has been uplifted and denuded a minimum of 4.2 km in the Early Cretaceous and a maximum of 3 km since that time, therefore it is likely that the amount of uplift and denudation in this area prior to the Early Cretaceous is minimal. The Heritage Range, on the other hand, may have had considerable uplift and denudation prior to ~169 Ma. Using similar elevation of near sea-level in the Early Cretaceous and a mean annual temperature of 0°C at that time, the depth to the base of the PAZ prior to uplift and denudation is \sim 4.4 km. The current elevation of the sample (1200 m), plus the fact that this sample has undergone considerable annealing, therefore suggests that the amount of post-169 Ma uplift and denudation is not more than 5.6 km. Consideration of metamorphic grade gives a rough estimate of 12 km of total uplift and denudation since peak metamorphic conditions were reached, suggesting that a considerable amount of uplift and denudation may have occurred in the Heritage Range prior to ~169 Ma.

Estimates of pre-Early Cretaceous uplift will, however remain necessarily speculative as they reply on a number of assumptions: [1] The geothermal gradient has never exceeded 25°C/km since the deposition of the sediments, which is uncertain given that the Ellsworth Mountains have undergone a period of compressive deformation (Gondwanide Orogeny) as well as being adjacent to extensional terrains, on its eastern flank (Weddell Sea), and on its western flank (Transantarctic rift system) at some time during the Cenozoic. [2] The thickness of the sedimentary package in the Ellsworth is relatively uniform in thickness throughout the Ellsworth Mountains, even after compressive deformation.

Tectonic Implications

The Early Cretaceous uplift and unroofing of the Sentinel Range followed the initial breakup of Gondwana and coincided with the opening of the Weddell Sea. The initial breakup of Gondwana is marked by rift-related bimodal magmatism (Ferrar Dolerite, Kirkpatrick Basalt, and Falla Formation) along the Transantarctic Mountains (Schmidt and Rowley, 1986) and peraluminous granites within West Antarctica (Storey et al., 1988b) at ~180 to 175 Ma. Marine magnetic anomalies in the Somali Basin (Rabinowitz et al., 1983; Martin and Hartnady, 1986) indicate that East Gondwana (Antarctica-India-Australia) and West Gondwana (South America-Africa) became separated at ~155-150 Ma; the initial opening of the Weddell Sea occurred at ~160 Ma, based on the identification of anomaly M29 in the southern Weddell Sea (LaBrecque and Barker, 1981), Gondwana breakup was accompanied by subduction along its Pacific margin, and tectonic compression is recorded by folding of the Late Jurassic Latady Formation in the southern Antarctic Peninsula (AP), before emplacement of the Lassiter Coast Intrusive Suite between 113 and 100 Ma (Kellogg and Rowley, 1989).

Grunow et al. (1991) conclude from their paleomagnetic data that the EWM rotated 90° counterclockwise with respect to East Antarctica between ~230 (Gondwanide Orogenv) and ~175 Ma based on paleomagnetic data. Additional paleomagnetic data from the AP, Thurston Island block (TI), and EWM imply that between the Middle Jurassic and Early Cretaceous, these three blocks and West Gondwana moved as a single entity, without rotation (Grunow et al., 1987; Longshaw and Griffiths, 1983). The opening of the South Atlantic at ~130 Ma changed the two plate rifting system between East and West Gondwana, to a three plate system (Lawver et al., 1991), and according to Grunow et al. (1991) caused the EWM to become attached to AP-TI to form the microcontinent Weddellia. Paleomagnetic data require a ~30° clockwise rotation of Weddellia with respect to East Antarctica between ~125 and ~100 Ma (Grunow et al., 1991) producing ~750 km of sinistral shear between the EWM and East Antarctica. By ~110 Ma Weddellia appears to have been in its present day position with respect to East Antarctica. Uplift and unroofing of the southern Sentinel Range, uplift in the Scott Glacier area of the Transantarctic Mountains (Stump and Fitzgerald, 1992), and extension in the Ross Embayment between Marie Byrd Land and East Antarctica (Cooper et al., 1991) all occurred in the Early Cretaceous and may have been interrelated.

If the appearance of the Ellsworth Mountains as an easterly tilted block is a manifestation of deformation in the Triassic, it may be impossible to tell from topography alone which side is a rift flank. Conceptually, if the uplift of the Ellsworth Mountains is related to rifting and opening of the Weddell Sea, then their eastern flank should be the rift shoulder. On the other hand, if the western flank of the mountains is related to Cenozoic movement along a rift shoulder that forms a large curve along the TAM - Whitmore

Mountains - Ellsworth Mountains (Behrendt and Cooper, 1991), then it should resemble a rift shoulder. The west flank of the Sentinel Range does resemble a rift shoulder, but the data presented herein show that most of the uplift of the Ellsworth Mountains occurred in the Early Cretaceous, at the time of the opening of the Weddell Sea. It is almost certain that differential erosion across the breath of the Sentinel Range produced the present topography, with the hard, erosion-resistant strata of the Crashsite Group being preferentially preserved while other units were eroded. On the other hand, if uplift was uniform across the breath of the Sentinel Range, then there must have been a much more extensive stratigraphic section than the one presently preserved, as the uppermost units are exposed at lower elevations in the northeast. In the Heritage Range, the single apatite age implies much less uplift after ~169 Ma, yet deeper stratigraphic levels are exposed. One scenario which may explain the observed distribution of strata and apatite fission track ages is:

[1] folding of the sedimentary package in the Triassic produced a thickened section of Crashsite Group quartzite on the western flank of the mountains.

[2] uplift of the mountains as a rift shoulder in the Early Cretaceous accompanied the opening of the Weddell Sea.

[3] renewed uplift has occurred at some time since the Early Cretaceous, but was dominant in the Sentinel Range (\leq 3 km). This later period of uplift, plus differential erosion would accentuate the western flank of the mountains.

It should be appreciated that the final point with respect to the Heritage Range is necessarily speculative as it is based in part on one rather poorly constrained age. The uplift and denudation history of the Ellsworth Mountains prior to the Early Cretaceous is not well constrained by the fission track data. For example, in the Heritage Range, the exposure of deeper stratigraphic levels with older apatite ages, compared to the present high elevation exposures of shallower stratigraphic levels with younger apatite ages in the Sentinel Range, imply that a significant amount of uplift and denudation may have occurred prior to ~169 Ma. Such inferences about the amount of uplift and denudation prior to the Early Cretaceous are necessarily speculative as they are based upon assumptions about the metamorphic grade of the rock, the sedimentary package being of fairly uniform thickness, and that the geothermal gradient throughout time has remained relatively constant.

Conclusions

The fission track data presented above provide evidence for more than 4 km of unroofing on the western flank of the Sentinel Range in the Ellsworth Mountains between ~145 and ~117 Ma. The data suggest, but do not constrain, the time when uplift started in the Early Cretaceous, which may have been only a few million years prior to 145 Ma, nor does it provide evidence of the pre-169 Ma uplift-denudation history of the range. A single sample from Springer Peak indicates much less unroofing there after ~169 Ma, but suggests that evidence for the initiation of Early Cretaceous uplift will be found in the Heritage Range. Significant uplift and unroofing of the Sentinel Range thus followed initial breakup of West and East Gondwana and accompanied the opening of the Weddell Sea. It may also have been synchronous with, and possibly even related to, compressive deformation in the southern Antarctic Peninsula (Kellogg and Rowley, 1989). Post Early Cretaceous uplift in the southern Sentinel Range is unlikely to have been much more than 3 km, and could have been considerably less. At least 1.8 km of relief has persisted in the southern Sentinel Range since the Early Cretaceous.

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