Early Cretaceous Uplift in the Ellsworth Mountains of West Antarctica

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Apatite fission-track analysis of samples covering a 4.2-kilometer vertical section from the western flank of Vinson Massif, Antarctica's highest mountain, indicates that the Ellsworth Mountains were uplifted by 4 kilometers or more during the Early Cretaceous following the initial separation of East and West Gondwana and accompanying the opening of the Weddell Sea. Relief of at least 1.8 kilometers has persisted in the Ellsworth Mountains since the Early Cretaceous, and a maximum of 3 kilometers of uplift has occurred since that time.

OUR UNDERSTANDING OF THE HISTORY of Antarctica during the breakup of Gondwana is based on data from paleomagnetism, sea-floor magnetic anomalies, aeromagnetics, bedrock geology, and topography [for example, (*1–3*)]. West Antarctica plays a key role in the understanding of the breakup of Gondwana because of the possibility that there was a plate boundary between East and West Antarctica during the Mesozoic and Cenozoic (*2*). West Antarctica is made up of a collage of at least five crustal blocks (Fig. 1), four of which have distinct Phanerozoic histories (*1, 2, 4*), whereas the fifth, Haag Nunataks, contains Precambrian rocks. The boundaries between these blocks in most places are defined by deep subice basins and troughs (*5*) that are believed to mark zones of rifting that may be floored by oceanic crust (*6*). In comparison, East Antarctica appears to be a stable remnant of Gondwana, separated from West Antarctica by the Transantarctic Mountain front and the Ross and Weddell embayments (*1*). Located between the Transantarctic Mountains (TAM) and the other crustal blocks of the West Antarctica collage, and containing the Ellsworth Mountains (EM) with their disparate structural trend and exceptional elevation, the Ellsworth-Whitmore Mountains block (EWM) is perhaps the keystone to understanding the geologic evolution of West Antarctica during the breakup of Gondwana.

The EM are the dominant physiographic feature of the EWM. Vinson Massif (4897 m) forms part of the spine of the Sentinel Range in the EM and has relief of ~4 km on its western flank. The northeastern flank of the EM dips into the 2-km-deep trough of the Rutford Ice Stream. The EM consist mostly of a thick, folded succession of Cambrian to Permian sedimentary rocks that have been correlated with the Paleozoic cover sequence of the TAM and the Cape fold belt of southern Africa, although they lack the conspicuous middle Paleozoic unconformity seen in the TAM from the Ohio Range to northern Victoria Land. The structural trend of the EM is perpendicular to the structural trend of the TAM. The rocks in the EM increase in metamorphic grade with depth, from laumontite grade in the uppermost unit, the Permian Polarstar Formation, to pumpellyite-actinolite grade and lower greenschist facies in the lower units of the Cambrian Heritage Group (7). The spine of the Sentinel Range is composed entirely of well-cemented orthoquartzite of the Devonian Crashsite Group (*8*). Both the Sentinel and Heritage Ranges are topographically higher on their western flanks than to the east, and in both ranges stratigraphically lower rocks are exposed to the west. These observations suggest that the present-day EM can be envisaged as a block tilted down to the east.

Apatite fission-track analysis is routinely used in the resolution of uplift and denudation histories of mountain ranges [for example, (*9*)]. The temperature zone of track retention in apatite will vary depending on cooling rate and composition of the apatite. Apatites analyzed from the Crashsite quartzite have a composition similar to Durango apatite, a widely used standard in which tracks are retained at temperatures ≤110°C for cooling rates of 0.1° to 10°C per million years over geologic time (*10*). For these cooling rates, at temperatures greater than ~110°C tracks will effectively anneal instantaneously, whereas at lower temperatures (<60°C) tracks will anneal slowly. Partial annealing of tracks (track length reduction) occurs successively faster from ~60° to 110°C in the partial annealing zone (PAZ). 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 followed (*11*).

Apatite ages on samples of the Crashsite Group, collected on the west flank of Vinson Massif and at Bowers Corner (vertical relief of ~4.2 km), range from 141 ± 5 Ma (±1σ; Ma, million years ago) at the top of the massif to 117 ± 5 Ma for the lowermost sample (Fig. 2). Ages increase systematically with increasing elevation and define a slope of ~200 m per million years. This slope is interpreted as an unroofing rate, brought about by denudation in response to uplift. Track length distributions have a weighted mean of 13.9 μm, and an average standard deviation of 1.35 μm; these values indicate that the samples cooled rapidly and did not reside for substantial periods of time in the

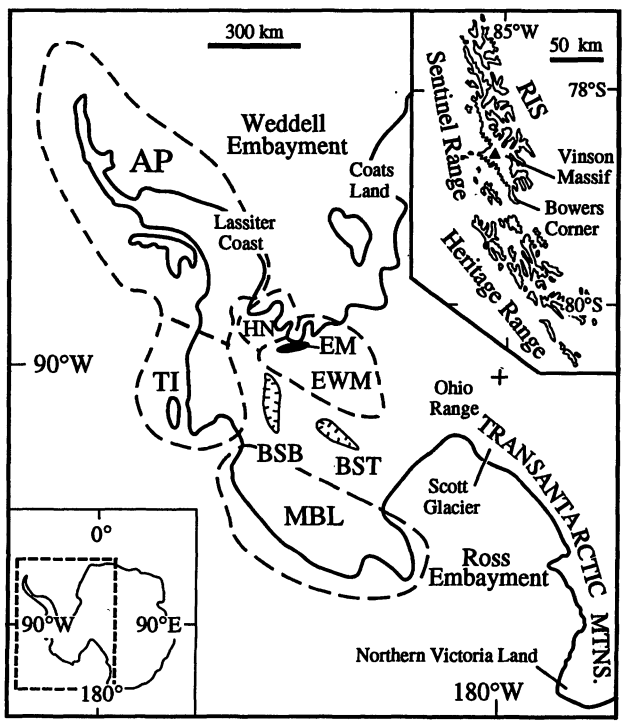

Fig. 1. Map of West Antarctica and part of East Antarctica showing boundaries of crustal blocks and main subglacial basins, modified from (*4*). AP, Antarctic Peninsula; BST, Bentley Subglacial Trench; BSB, Byrd Subglacial Basin; EWM, Ellsworth-Whitmore Mountains; HN, Haag Nunataks; MBL, Marie Byrd Land; TI, Thurston Island; RIS, Rutford Ice Stream.

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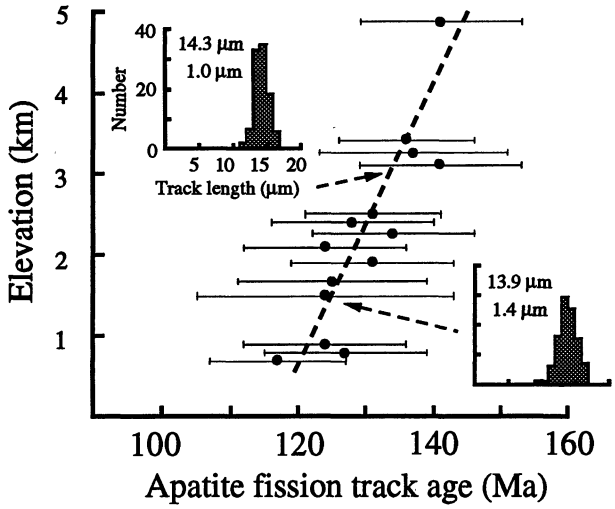

Fig. 2. Variation of apatite fission-track age (±2σ) with elevation; also shown are representative track length distributions (mean and standard deviation in microns). Ages were determined using the external detector method and zeta calibration, and errors were determined by conventional analysis (*22*).

PAZ. The data indicate that significant uplift and denudation occurred in the Early Cretaceous, at least 4 km over ~20 million years. For a normal upper-crustal geotherm (25°C per kilometer), the top of the PAZ would be at a depth of 2.4 km below the surface. Because the lowermost samples from this study show no evidence of prolonged residence within the PAZ, and because there is ~4.2 km of relief between the top and bottom samples of the profile, there must have been at least 1.8 km of relief in the EM after Early Cretaceous uplift. If the base levels of Early Cretaceous valleys were at sea level, and if the lowest sample (present elevation of 690 m) lay just above the top of the PAZ (2.4 km below sea level), then the maximum possible uplift of the EM since the Early Cretaceous is ~3 km, although it could be considerably less. If baselevels of Early Cretaceous valleys were above sea level or the Early Cretaceous geotherm was higher, uplift in the EM since that time would be less than 3 km. Whether the additional uplift of the EM since the Early Cretaceous was a gradual isostatic response to continuing slow denudation or whether it came in a rapid pulse at some later time is not distinguishable from the fission-track data. A minimum of 1.8 km of relief has remained in the EM since the Early Cretaceous. The resistance of the Crashsite Group to erosion must be the primary reason for the persistence of this topography.

The timing and kinematics of microplate movement during the breakup of Gondwana, and in particular those of West Antarctica, remain poorly constrained. Initiation of rifting within West Antarctica and along the TAM is suggested at ~180 to 175 Ma by the presence of bimodal volcanism in the TAM and peraluminous granites in the EWM (*12*). East and West Gondwana (Antarctica-India-Australia and South America–Africa, respectively) became separated at ~155 to 150 Ma, as indicated by marine anomalies in the Somali Basin (*13*). Initial generation of ocean crust in the southern Weddell Sea may have occurred earlier on the basis of the tentative identification of marine magnetic anomaly M29 (160 Ma) there (*14*). During early separation, West Antarctica is thought to have been attached to West Gondwana, and dextral strike-slip faulting is thought to have occurred between East and West Antarctica (*12*). Throughout the period of Gondwana breakup subduction was active along the Pacific margin of the supercontinent (*15*). During this period in the southern Antarctica Peninsula (AP), folding of the Late Jurassic Latady Formation occurred before intrusion of the Lassiter Coast Intrusive Suite (113 to 100 Ma) (*15*).

On the basis of lithological and structural observations, Schopf (*16*) suggested that the EM moved to their present location from a position adjacent to Coats Land. Paleomagnetic data from Cambrian rocks in the EM support this interpretation, but neither the timing nor sense of rotation is certain (*17*). Grunow *et al.* (*18*), on the basis of paleomagnetic data, suggested that the EWM rotated 90° counterclockwise between ~230 and ~175 Ma before intrusion of middle Jurassic peraluminous granites and after the Permo-Triassic Gondwanide Orogeny. Further paleomagnetic data from the AP, Thurston Island, and EWM imply that between Middle Jurassic and Early Cretaceous these three blocks and West Gondwana moved as a single entity without significant rotation, but from Early to mid-Cretaceous (~125 to 100 Ma), clockwise rotation of these three blocks by 30° with respect to East Antarctica caused ~750 km of sinistral shear (*18, 19*). By ~110 Ma, the EWM were in their present-day position with respect to East Antarctica (*18*). Early Cretaceous uplift of the EM may be related to Early Cretaceous uplift of the TAM in the Scott Glacier area (*20*), possibly linked to extension in the Ross Embayment between East Antarctica and Marie Byrd Land at this time.

Our fission-track data do not indicate the time of the initiation of uplift and denudation of the EM, but they do constrain it to have been before 141 Ma and show that more than 4 km of unroofing occurred during the subsequent 20 million years. Significant uplift and denudation of the EM thus followed the initial separation of East and West Gondwana and perhaps was synchronous with compressive deformation in the southern AP (*15*). Various authors have suggested that an episode of rifting or block faulting during the Late Cenozoic may have been responsible for the present relief of the EM and the TAM [for example (*4, 5, 21*)]. Our data do not distinguish whether post–Early Cretaceous uplift and denudation of the EM occurred gradually or in a pulse, but they do constrain the amount of uplift to have been a maximum of 3 km, and possibly considerably less; thus a significant part of the EM was extant before the late Cenozoic.

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A Dominant Negative Form of Transcription Activator mTFE3 Created by Differential Splicing

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Transcription factor E3 (mTFE3) is a murine transcription activator that binds to the intronic enhancer of the immunoglobulin heavy chain gene. A naturally occurring splice product of mTFE3 messenger RNA (mRNA) lacked 105 nucleotides that encode an activation domain; both absolute and relative amounts of long and truncated mRNAs varied in different tissues. Cells were cotransfected with complementary DNAs that encoded the two mRNA forms in amounts that corresponded to the amounts of each mRNA found in different cells. Small changes in substoichiometric amounts of the truncated form of mRNA effected trans-dominant negative modulation of mTFE3 activity. These findings identify a function for differential splicing in the regulation of transcription factor activity.

THE TRANSCRIPTIONAL ACTIVATOR TFE3 (*1*) is one of several structurally related proteins that bind to multiple functionally important sites that include the μE3 or C2 site in the immunoglobulin heavy chain (IgH) enhancer (*1–5*), the C2 site in the IgH V_{H1} (variable) promoter (*4, 5*), the KE3 site in the immunoglobulin κ intronic enhancer (*4, 5*), and the upstream-stimulating factor (USF) binding site in the adenovirus major late promoter (*1, 2, 5*). Studies have identified a transcriptional activation domain near the NH_2-terminus of the human TFE3 protein (*1*). We describe differential splicing of mTFE3 RNA that yields a long form and a truncated form that lacks part of the transcriptional activation domain. Small changes in substoichiometric amounts of the truncated isoform effect down-modulation of the transcriptional activity of mTFE3.

We first isolated an mTFE3 cDNA by screening a λ gt11 expression library with a probe that contained the IgH enhancer μE3 binding site; subsequent overlapping cDNA clones were isolated by DNA hybridization (*5*). Sequence analysis of the cDNAs revealed that we had isolated clones that encoded two isoforms of mTFE3 (Fig. 1A), the murine homolog of human TFE3 (*1*). The mTFE3-S (short) mRNA encodes a polypeptide of 291 amino acids, whereas the mTFE3-L (long) mRNA encodes a polypeptide of 326 amino acids, assuming that the first in-frame methionine is the initiating methionine. Comparison of the human sequence and the murine long-form sequence revealed that the two proteins are nearly identical from the initiator methionine to just COOH-terminal to the leucine zipper (LZ).

Both isoforms contain a basic (B) region, a helix-loop-helix (HLH) region, and an LZ, all of which are important for sequence-specific DNA binding or subunit interactions (*2, 5–8*). We confirmed the ability of mTFE3 to bind DNA and to form multimers by an electrophoretic mobility shift assay (EMSA). A truncated form of mTFE3-S (MTFE3-S-STU), missing the COOH-terminal 120 amino acids but retaining the B-HLH-LZ region, and MTFE3-L were synthesized in vitro. We subjected reticulocyte lysate extracts to an EMSA using an IgH enhancer fragment that contained the μE3 site as a probe. Lysates programmed with either mTFE3-L or mTFE3-S-STU RNA showed DNA-protein complexes that had mobilities consistent with the sizes of the two proteins and that were not present in unprogrammed lysate (Fig. 2, lanes 1, 2, and 4). Lysate programmed with both mTFE3-L and mTFE3-S-STU showed a complex of intermediate mobility (Fig. 2, lane 3). We conclude that both mTFE3-L and mTFE3-S can bind the IgH μE3 site with similar affinity and that mTFE3-L and mTFE3-S can form heteromultimers that also bind the μE3 site with an affinity similar to that of homomultimers.

Fusion of a heterologous DNA-binding domain (GAL4) to regions of TFE3 allowed the identification of a 126–amino acid transcriptional activation domain (*1*). This region contains a stretch of amino acids with a net negative charge that could form an amphipathic helix (underlined in Fig. 1B), which could be a transcriptional acti-

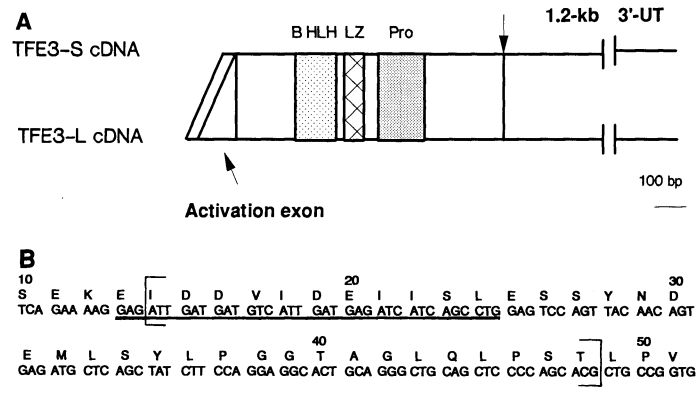

Fig. 1. Structure of mTFE3. (**A**) Schematic representation of mTFE3 cDNAs. Both reading frames terminate at the downward vertical arrow as indicated and contain 1.2 kb of 3′ untranslated sequence (UT). The two cDNAs are identical except for the activation exon. (**B**) Sequence of the NH_2-terminus of mTFE3-L. The numbers above the amino acids mark their positions relative to the initiating methionine. The sequence of the activation exon is bracketed. The underlined sequence represents the putative amphiphatic helix (*1*). Abbreviations for the amino acid residues are as follows: A, Ala; C, Cys; D, Asp; E, Glu; F, Phe; G, Gly; H, His; I, Ile; K, Lys; L, Leu; M, Met; N, Asn; P, Pro; Q, Gln; R, Arg; S, Ser; T, Thr; V, Val; W, Trp; and Y, Tyr.

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