A plateau collapse model for the formation of the West Antarctic rift system / Transantarctic Mountains

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Summary A recent model (Bialas et al., 2007) proposes that the Transantarctic Mountains (TAM) are the remnant edge of a collapsed plateau. In this model, the West Antarctic rift system/TAM region was a plateau (the "West Antarctic Plateau") with thicker than normal crust before undergoing a topographic reversal. Plateau collapse was due to continental extension and concomitant denudation beginning in the Jurassic when widespread tholeiitic magmatism marked initial rifting between East and West Antarctica. This was followed by the major period of West Antarctic extension in the Cretaceous and then more localized extension in the western Ross Embayment in the Paleogene and Neogene. The West Antarctic plateau formed inboard of subduction zone that existed along the Pacific margin of Gondwana throughout the Paleozoic until the late Mesozoic. The remnant plateau edge, now supported by slightly thickened crust, represent the ancestral TAM that remained following plateau collapse.

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Introduction

The Transantarctic Mountains (TAM) bisect the Antarctic continent, separating the two contrasting geological provinces of East and West Antarctica (Dalziel, 1992) and forming the western flank of the West Antarctic rift system (WARS) (Figure 1). The TAM stretch for >3000 km, reach elevations >4000 m and are capped by undeformed strata of the Devonian-Triassic Beacon Supergroup. Low-temperature thermochronology has been applied along the TAM to constrain the denudation history and by inference, the uplift and formation of the mountains. Episodes of denudation are recorded in the Jurassic (Fitzgerald and Baldwin, 2007), the early Cretaceous, late Cretaceous, the Eocene and Oligocene (e.g., Fitzgerald, 2002 and references therein). Denudation along the TAM in the Cretaceous is typically 1-2 km. The majority of denudation has occurred since the early Eocene, being constrained as ca. 4-9 km at the mountain front, decreasing inland. These periods of denudation have been correlated to regional tectonic events, except the onset of the major phase of denudation beginning in the early Eocene, which has always been problematic (Fitzgerald, 2002). Thermochronology is used to constrain the thermal history of a region, with the recorded cooling history related to denudation, which in the TAM is erosional not tectonic. However, erosion is largely associated with the formation of relief, a change in base-level, that can be created by either mountain uplift or subsidence due to extension.

The WARS is a broad region of extended continental lithosphere, ca. 750-1000 km wide, lying dominantly below sea-level. Sedimentary basins (Northern Basin, Victoria Land Basin, Central Trough and the Eastern Basin) are only delineated well in the Ross Sea and generally trend parallel to the TAM (e.g., Davey and Brancolini, 1995). Extension within the WARS was initiated in the Jurassic (ca. 180 Ma) during the initial stages of breakup of Gondwana, as marked by voluminous tholeiitic magmatism found along the TAM (e.g., Elliot and Fleming, 2004). The main phase of distributed extension within the WARS was during the Cretaceous (e.g., Lawver and Gahagan, 1994). Extension during the Cenozoic was more localized, being isolated to the basins adjacent to the TAM (e.g., Hamilton et al., 2001; Davey et al., 2006).

The TAM are the longest intracontinental rift flank mountains in the world and there are many models for their formation. These models include those that invoke mainly thermal processes (e.g., Smith and Drewry, 1984), a combination of mechanical and thermal processes related primarily to extension in the adjacent WARS (e.g., Fitzgerald et al., 1986; ten Brink et al., 1997) or the mechanical effects of extension of thick lithosphere (van der Beek et al., 1994; Busetti et al., 1999). One of the major failures of all these models is that they typically do not attempt to explain the multiple phases of denudation that are separated by periods of relative tectonic and thermal quiescence. Nor do they attempt to explain the disparity between wide rifting in the Cretaceous that may require hot, thin lithosphere (e.g., Buck, 1991) whereas rift-flank uplift of the TAM may require cold-thick lithosphere. Two new models or ideas do address these concerns. Huerta and Harry (2007) use dynamic finite element modeling to explore possible conditions (especially those of the pre-rift thermal state of the lithosphere) responsible for the two-stage evolution of the WARS. Their models, using constant regional extension rates, predict diffuse rifting in the WARS followed by focused rifting near the East-West Antarctic boundary without requiring a change in tectonic regime (e.g., plate motion change) provided upper mantle temperatures are initially 730 ± 50°C. Bialas et al. (2007) propose a plateau collapse model and use numerical modeling to test the idea that the WARS/TAM was a high elevation plateau (West Antarctic plateau) with thicker than normal crust before the onset of continental extension. With extension the WARS underwent a topographic reversal, but leaving the TAM as the remnant edge of the former plateau. In essence, Bialas et al. (2007) are modeling the Cretaceous portion of the extensional history of the WARS. Their results indicate that elevation of the remnant plateau edge is related to initial upper mantle temperatures, with an initial moho temperature of 675-850°C required to retain the plateau edge, but still generate wide rifting in the middle of the former plateau. In general, the Huerta and Harry (2007) model and the Bialas et al. (2007) plateau collapse model agree well on the conditions required for the earlier diffuse extension, with later extension being focused on the edges. In this paper we briefly examine some geological evidence that supports the plateau collapse model.

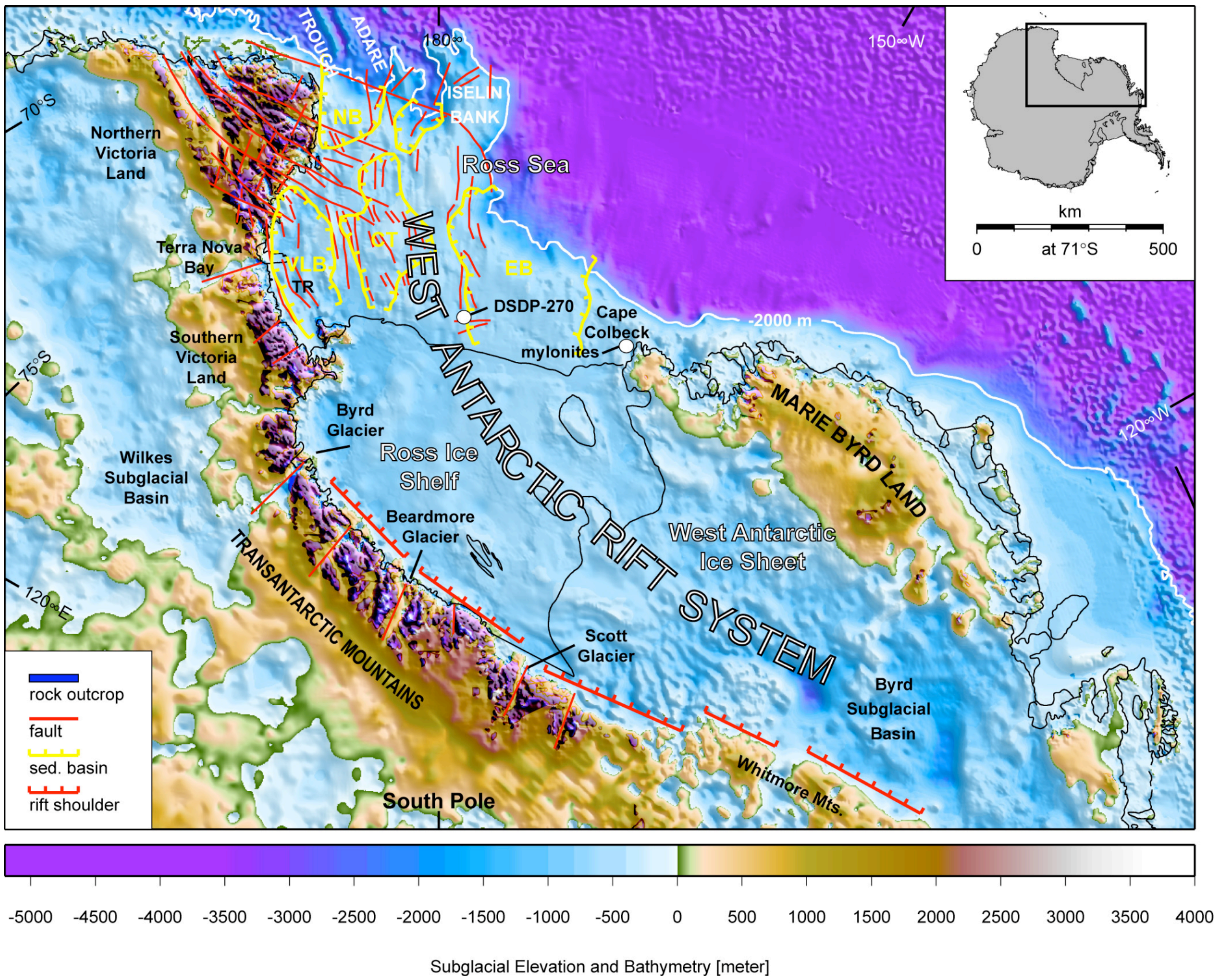

Figure 1. Topographic and bathymetric map of part of the Transantarctic Mountains and West Antarctic rift system. The WARS is the region defined by the Ross Sea, Ross Ice Shelf, and the West Antarctic Ice Sheet. The Ross Embayment = Ross Sea + Ross Ice Shelf. The Ross Sea is characterized by elevated heat flow and a series of asymmetric basins separated by basement highs. The WARS tectonic history is usually taken to be the same as the Ross Sea. CT = Central Trough; EB = Eastern Basin; NB = Northern Basin; TR = Terror Rift; VLB = Victoria Land Basin. Image created using data from the BEDMAP compilation [2000].

Discussion

The TAM has been the location of multiple orogenic episodes, including Rodinia assembly followed by Rodinia break-up that led to the formation of a rifted passive margin along the paleo-Pacific margin of Australia and East Antarctica at least up until the late Neoproterozoic (e.g., Goodge et al., 2004b). The margin changed to an active continental arc ca. 530 Ma until ca. 480 Ma (Ross Orogeny in Antarctica, Delamarian Orogeny in Australia), resulting in deformation, calc-alkaline magmatism and crustal thickening. In Australia, rollback from ca. 508-460 Ma formed a back-arc basin (Foster et al., 2005), although this apparently did not occur in Antarctica. The along-strike Australian equivalent to the region that is now the extended portion of the Ross Embayment is the Lachlan Fold Belt (LFB). This fold belt records an extremely complex record of deposition, shortening, accretion and magmatism from the Cambrian into the Carboniferous (e.g., Foster and Gray, 2000). In Antarctica, the Robertson Bay Group of northern Victoria Land is equivalent to the western subprovince of the LFB and the Swanson Formation of Marie Byrd Land to the eastern subprovince (Summerfield, 1991; Sutherland, 1999; Foster and Gray, 2000). Outboard of the Antarctic fold belt-equivalent and along the paleo-Pacific margin of Gondwana, in what is now Marie Byrd Land, a continental arc was active from at least 320 Ma to ca. 110 Ma (Mukasa and Dalziel, 2000). By analogy with the LFB, it was during the Late Ordovician to the Carboniferous that the West Antarctic Plateau, a region of thickened continental crust, was initially formed, but was maintained and likely enhanced as subduction continued along the paleo-pacific margin of Antarctica until the late Mesozoic.

In the TAM following the Ross Orogeny there was ca. 15-20 km of erosion (Capponi et al., 1990) at denudation rates of up to ca. 0.5 km/my (Goodge et al., 2004a) to eventually form the Kukri erosion surface. Following a period of non-deposition, strata of the Beacon Supergoup, initially marine, glacial, then non-marine, were deposited from Devonian to Triassic (e.g., Barrett, 1991; Isbell, 1999). While paleocurrents in the lower units indicate that relief on the erosion surface controlled deposition patterns, at least in the central TAM (Isbell, 1999), as deposition continued paleocurrents indicate that Beacon basins were elongate parallel to the current TAM with high topography either side, and thus a topographic reversal has occurred since the end of the Triassic (Barrett, 1981).

The initial break-up of Gondwana is recorded in Antarctica by voluminous Jurassic Ferrar tholeiitic magmatism, preserved as thick sills and lava flows along the TAM and is also associated with rifting (and hence subsidence) within the WARS (e.g., Elliot, 1992). In the TAM, this voluminous magmatism in the Jurassic likely resulted in crustal thickening. At ~105 Ma, subduction of the Pacific-Phoenix spreading center along the Pacific margin off Marie Byrd switched the tectonic regime and ~20 m.y. of extensional tectonics followed in New Zealand (e.g., formation of the Paparoa core complex (Tulloch and Kimbrough, 1989)), in Marie Byrd Land (e.g., exhumation of the Fosdick Mountains metamorphic complex from mid-crustal levels (Richard et al., 1994)) and in the Ross Embayment (e.g., wide rifting (Cooper et al., 1991); detachment faulting at DSDP site 270 (Fitzgerald and Baldwin, 1997) and detachment faulting and formation of mylonites in the eastern Ross Sea at Cape Colbeck (Siddoway et al., 2004)). Wide rifting in the Ross Embayment likely ceased when New Zealand and the Campbell Plateau were rifted away from Antarctica ca. 83-79 Ma (Stock and Cande, 2002).

The Bialas et al. (2007) numerical model for plateau collapse does not generate a remnant plateau edge that has the present elevation (ca. 4 km) of much of the peaks of the TAM. Rather the elevation of the post-wide rifting (late Cretaceous) remnant plateau-edge (proto-TAM) was likely in the ca. 2 km range and has since been accentuated by the isostatic response along the front of the range due to erosion, especially wet-based glacial erosion after 34 Ma that has enhanced peak heights by up to 50% (~2 km) (Stern et al., 2005).

The strength of this plateau collapse model for the WARS/TAM is that is supported by regional geological information and it appears to solve a number of geological or geophysical discrepancies in previous models. The concept of plateau collapse is also testable in the geological record and provides a basis for further study. In addition, the plateau collapse model is not mutually exclusive with respect to any other model that seeks to explain the Cenozoic development of the TAM to high elevations by other means, for example the thermal effects of hot West Antarctic mantle lithosphere.

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