Structure and Kinematics of the Central Transantarctic Mountains: Constraints from Structural Geology and Geomorphology near Cape Surprise

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Received 7 February 2000; accepted in revised form 24 April 2001

Abstract - The transition zone between the Transantarctic Mountains (TAM) and the West Antarctic rift system is defined as the Transantarctic Mountain Front (TMF). In the vicinity of Cape Surprise (84°30'S) near the Shackleton Glacier in the central TAM, two fault sets have been mapped. Mesoscopic faults and geomorphic trends indicate that one set of normal faults within the TMF is generally dip-slip in nature and strikes parallel to the mountain range. The second fault set is oriented approximately perpendicular to this. Kinematic analysis of lineated fault surfaces reveals an extension axis oriented 020°-040°, orthogonal to the trend of the central TAM. However, asymmetric drainage patterns and a small number of lineated fault surfaces support a kinematic model of Cenozoic dextral transtension in the TMF. While age constraints on these two episodes of deformation are poor, it is likely that dextral transtension followed orthogonal extension, as suggested from other regions of the TAM. Apparent orthogonal extension in the TMF is thus consistent with early Cenozoic rift-flank uplift driven by isostatic forces. A middle to late Cenozoic period of transtension could be contemporaneous with strike-slip faulting in the Ross Sea, and could also indicate less strain partitioning between the rift system and the TMF after the uplift rate decreased.

INTRODUCTION

Mountain ranges and sedimentary basins are some of the primary, large-scale geologic effects of tectonic processes. In Antarctica, the Transantarctic Mountains (TAM) define the uplifted flank of the intracontinental West Antarctic rift system (WARS), as indicated by their topography, architecture, and outcrop pattern (Fig. 1A; Fitzgerald et al., 1986; Stern & ten Brink, 1989). The Transantarctic Mountains Front (TMF) (Barrett, 1979) is the onland zone of evident and inferred normal faults that accommodated rift-flank uplift. Although significantly lowered by erosion (e.g., Gleadow & Fitzgerald, 1987), the high elevations (~4000 m) that are common along the crest of the TAM (e.g., Fig. 2) are the result of rock uplift, predominantly in the Cenozoic, that has occurred within and adjacent to the TMF.

The high elevations and long length (~3500 km) of the TAM places it amongst the largest non-contractional mountain ranges in the world. How a range of such dimensions formed is of fundamental importance to the understanding of continental tectonics in general and Antarctic tectonics in particular. Several mechanisms for the main Cenozoic uplift of this rift margin have been proposed. These include simple shear linking different lithospheric levels under the Ross Embayment and TAM with strain partitioning accommodated on low-angle detachment faults (Fitzgerald et al., 1986). Although this model as an explanation for Cenozoic uplift is now regarded as unlikely, Cretaceous extension in the WARS was probably accommodated, at least in part, along low-angle detachment faults and this mechanism may be responsible for the episodes of Cretaceous exhumation recorded in the TAM (Fitzgerald and Baldwin, 1997; Fitzgerald, 2001). Another proposed model for the Cenozoic uplift of the TAM invokes isostatic uplift as a result of the Vening-Meinesz effect due to crustally penetrative normal faulting along the margin of strong East Antarctic lithosphere, lateral heating of the thick East Antarctic lithosphere by the hotter lower lithosphere of the attenuated WARS, and erosion (Stern & ten Brink, 1989; Bott & Stern, 1992, ten Brink et al., 1997). More recently, models that invoke plastic necking (Chéry et al., 1992) and deep lithospheric necking aided by strong erosion-induced isostatic rebound (van der Beek et al., 1994; Busetti et al, 1999) have been suggested. Recent geophysical work has, however, revealed that there is no significant basin in the WARS adjacent to the central TAM off-shore the Robb-Lowery Glaciers, as there is off-shore of Victoria Land. This suggests a lack of mechanical coupling between the rift system and the presumed isostatic response of the mountain range (ten Brink et al., 1993). Combined with data showing that the main phase of TAM uplift was not coeval with the main period of extension in the WARS (e.g. Fitzgerald & Baldwin, 1997; Fitzgerald, 2001) plus evidence for Cenozoic transtension in the TMF (e.g. Wilson, 1995), the origin of the mountain range remains an outstanding tectonic problem.

A mechanistic understanding of the tectonic history of the TAM is by default linked to an understanding of the kinematics of its mountain front, as well as to its degree of coupling with the rift system. Constraints on the kinematic histories of the TMF and WARS are therefore critical. To date, the Cenozoic kinematics of the TMF has only been
described at a few locations. Mapping and kinematic analyses have suggested a significant component of strike-slip deformation across the TMF in Victoria Land, where normal faults strike obliquely to the range’s trend (Findlay & Field, 1983; Fitzgerald, 1992; Wilson 1992; Stackebrandt, 1994). These observations and mesoscale brittle fault kinematic analyses from southern Victoria Land suggest that the TMF is dextrally transtensional (Wilson, 1995), probably in response to transtension and strike-slip faulting in the greater WARS (Grindley & Olliver, 1983; Lawver & Gahagan, 1991; DiVenere et al., 1994; Salvini et al., 1997). Whether such strain is present...
along the entire range and whether it was contemporaneous with uplift has implications for the mechanism(s) of uplift. Wilson (1995), for example, pointed out that flexural uplift of the TAM due to mechanical unloading would not be likely if the TMF were dominantly transtensional.

In this paper we describe the general structural geology of the mountain front in the vicinity of Cape Surprise. An analysis of large-scale geomorphic trends over a broad region is shown to elucidate the regional fracture pattern. We present results of fault kinematic analyses and quantitative descriptions of drainage basin asymmetry and from those we interpret the kinematic history of this portion of the TAM.

**GEOLOGIC AND TECTONIC SETTINGS**

The TAM mark the edge of the East Antarctic craton, a fundamental lithospheric boundary since the Proterozoic. The region’s history of repeated mountain building and basin subsidence, as well as evidence for Cenozoic transtension along the rift margin of the TAM, suggests that the TMF marks the zone of lithospheric weakness and pre-existing anisotropies (e.g. Fitzgerald et al., 1986; Wilson, 1995).

The basement in the Cape Surprise region (Fig. 1B) is composed primarily of late Proterozoic to Cambrian metamorphic rocks of the Ross Supergroup (McGregor, 1965; Wade & Cathey, 1986) and Cambrian-Ordovician granitoids of the Queen Maud Batholith (Borg, 1983). During the Cambrian-Ordovician Ross orogeny (Stump, 1995), volcanic and marine sedimentary rocks of the Ross Supergroup were metamorphosed and deformed and also intruded by granitoids (McGregor, 1965; Stump, 1981). Exhumation of the basement following the Ross orogeny produced the low-relief Kukri Erosion Surface, unconformably overlain in the Shackleton Glacier region (La Prade, 1969), reflecting the mountain range’s overall tilt-block or flexure architecture (e.g. Gleadow & Fitzgerald, 1987; Fitzgerald & Gleadow, 1988).

In sharp contrast, Beacon sediments and Ferrar sills at Cape Surprise occur at an elevation of ~200 m with dips ranging from 30°NE to 35°SW (Barrett, 1965; La Prade, 1969). The presence of these units so near the coast makes this location unique within the TAM. These strata and sills have been down-thrown 3.1-5.2 km into their present position across one or more approximately NE-dipping normal faults (Barrett, 1965; Miller et al., 1996). The inferred range-parallel fault immediately south of Cape Surprise, which was suspected of accommodating most or all throw, was named the North Boundary fault by La Prade (1969). A number of approximately NE-striking faults were also mapped by Barrett (1965) at Cape Surprise, however the only other normal faults mapped in the TAM did not begin until the early Cenozoic (Gleadow & Stump, 1997). At least in some sectors of the TAM, Cenozoic uplift appears related to coeval extension localized along the western side of the rift system (e.g. Cooper et al., 1991).

In the Prince Olav Mountains, the Kukri Erosion Surface is exposed ~2620 m above sea level (Mt. Munson), dipping gently (~5°) SSW (Barrett, 1965; La Prade, 1969). Farther inland, towards the south, the Kukri Erosion Surface and overlying units become subhorizontal (La Prade, 1969), eventually disappearing beneath the ice cap. Significant rock uplift, but approaching 10 km in some places, have occurred along the inland margin of the TMF (e.g. Gleadow & Fitzgerald, 1987; Fitzgerald & Gleadow, 1988). Since about 55 Ma, ~5 km of rock uplift, but approaching 10 km in some places, have occurred along the inland margin of the TMF (e.g. Gleadow & Fitzgerald, 1987; Fitzgerald & Gleadow, 1988). The amount of rock uplift decreases inland of the TMF, reflecting the mountain range’s overall tilt-block or flexure architecture (e.g. Gleadow & Fitzgerald, 1987; Fitzgerald & Stump, 1997). The majority of these units so near the coast makes this location unique within the TAM. These strata and sills have been down-thrown 3.1-5.2 km into their present position across one or more approximately NE-dipping normal faults (Barrett, 1965; Miller et al., 1996). The inferred range-parallel fault immediately south of Cape Surprise, which was suspected of accommodating most or all throw, was named the North Boundary fault by La Prade (1969). A number of approximately NE-striking faults were also mapped by Barrett (1965) at Cape Surprise, however the only other normal faults mapped in the TAM did not begin until the early Cenozoic (Gleadow & Stump, 1997; Schäfer et al., 1998). Significant rock uplift began in a roughly NE-SW to E-W direction (Paulsen et al., 1999). For example, the Spillway fault, at the mouth of

**STRUCTURAL GEOLOGY**

STRUCTURES

Field work consisted of mapping the smaller-scale structures within the general architecture previously framed by Barrett (1965) and La Prade (1969). In addition, the authors mapped south of Cape Surprise where basement rocks crop out (Fig. 3). Structures are herein simply categorized into those associated with the Ross orogeny (D1), those that predate or are contemporaneous with the Ferrar Dolerite (D2), and those that postdate the Ferrar Dolerite (D3).

D1 structures include folds, metamorphic foliation, reverse faults, and boudinage in the plutonic and metasedimentary basement (McGregor, 1965; Stump, 1981; Paulsen et al., 1999). Structures indicate contraction in a roughly NE-SW to E-W direction (Paulsen et al., 1999). For example, the Spillway fault, at the mouth of
the Liv Glacier, strikes ~315° and foliation measured near Cape Surprise strikes approximately N-S and dips steeply west.

D2 structures include tholeiitic Ferrar sills and dikes. Fracture and/or fault zones with halos of mineralogic alteration, hereafter simply called alteration zones, are in some places spatially associated with these intrusions. Elsewhere the alteration zones are found alone.

Sills found within the basement south of Cape Surprise on Garden Spur appear oriented parallel to the Kukri Erosion Surface and Beacon bedding: a 80 m-thick dolerite sill (154°/30°SW) intruded into basement granites below spot-height 700 is approximately parallel to the SE-dipping Beacon strata across the glacier at Cape Surprise. A single Ferrar dike was found on Mt. Munson striking 107°. This dike is surrounded by a 5 m-wide yellow to red zone of intense mineralogical alteration. This alteration is likely hydrothermal and related to Jurassic Ferrar magmatism, similar to alteration zones in southern Victoria Land basement granites (Craw & Findlay, 1984). Many alteration zones were found close to Cape Surprise. These alteration zones (n = 14) include a dominant set that strikes 111° and a secondary set that strikes 035° (Fig. 4A). Some of the large alteration zones of the primary set near the Cape, which were over 50 m long, dip approximately 50°N (Fig. 3).

We have adopted the statistical method outlined by Bull & Brandon (1998, p. 67) of discriminating significant peaks in a histogram for our analysis of oriented, circular data (e.g. Fig. 4A). This consists of defining the expected distribution of data if they were selected randomly from a uniform parent population with no preferred orientations. This uniform parent distribution is shown graphically as a thick black circle on the rose diagram. The expected limits of variation due to random sampling of this population are expressed as the relative standard error. Two standard errors are depicted as a gray circular envelope around the uniform distribution. Peaks in the sample data that extend beyond this envelope are considered to have significantly greater probabilities than that of a uniform distribution at the ~95% confidence level. Both the dominant and secondary set of alteration zones are, thus,
considered significant.

Following Jurassic magmatism, D3 deformation tilted the sills and sedimentary beds into their present attitudes (Figs. 4B & 4C) and faults cross-cut these sills (Fig. 3). The mean strike of Beacon strata at Cape Surprise is 131°, but can be separated into two discrete dip domains with mean attitudes of 134°/32°S and 123°/22°N (n = 25). This differential tilting was accommodated by scissor-slip faulting. D3 faults, both large and small (Fig. 4D), are divisible into two sets. The dominant set strikes 123° (n = 21) with dips ranging from 37° to 61°NE whereas the secondary set strikes ~041° (n = 6) with dips from 13° to 82° to both the SE and NW. Calculated against all sampled faults, the dominant set is a statistically significant cluster at the 95% confidence level following the criteria of Jowett & Robin (1988) whereas the number of faults in the secondary set is too small to determine significance. In a general geometric sense, these faults have attitudes similar to those of range-bounding normal faults and transfer faults in other rift margins (e.g. Gibbs, 1984; McClay & Khalil, 1998).

The NW-striking set of D3 faults, which includes the North Boundary fault, was responsible for the large magnitude offset across the TMF associated with uplift of the mountain range. An exposed example is the normal fault that marks the contact between Beacon sediments and the basement at Cape Surprise, previously mapped as the Sukri Erosion Surface (Barrett, 1965; La Prade, 1969), just southwest of Facet Peak (informal name, 84°31.2’S, 174°26.8’W). Granite in the footwall is juxtaposed against the Fairchild Formation (J. Isbell, personal communication, 1995) in the hangingwall. This fault is oriented 125°/60°NE, has steeply raking (70°-80°E) slickenlines on the footwall surface, ~20 m-wide crush zone of poorly calcite-cemented breccia in the hangingwall, and truncates bedding with an attitude of 160°/40° NE.

The NE-striking set of D3 faults is exemplified by two faults mapped by Barrett (1965) west of Facet Peak. Smaller examples were also found southeast of Facet Peak (Fig. 3), of which one has a counterclockwise sense of scissor or rotational slip around a horizontal axis—the same sense as determined on another, larger fault by Barrett (1965). Across other small NE-striking fault zones, Beacon strata are slightly drag-folded in a way implying a component of dextral slip. These faults are surrounded by halos of alteration up to ~10 m-wide. Given this evidence, these faults are either older than Cenozoic and are part of the D3 deformation episode, or the alteration zones were reactivated as faults in the Cenozoic. Even though their exact origin is not well constrained, these faults’ reactivated nature is a characteristic of most faults that strike at high angles to rift trends, such as transfer faults (e.g. Davison, 1994).

The best evidence for N- to NE-striking faulting in the basement south of Cape Surprise, with a similar sense of slip, is in the variation in the dip of the Ferrar sill on spot-height 700 (30°SW) and spot-height 950 (~5°SW). In contrast to the structure of the coastal area, no significantly vertical offsets of the Sukri Erosion Surface along the Prince Olav escarpment were observed, indicating that these small, approximately NE-striking faults, as observed at Cape Surprise, do not extend that far inland.

KINEMATIC ANALYSIS OF FAULTS

Kinematic analysis of fault slip yields information about progressive strain (Marrett & Allmendinger, 1990). Slip measurements comprised the orientations of basement fault planes and the trends and plunges of striae on these planes. Slip magnitudes were generally not determined due to ice, snow, or scree cover, and a lack of identifiable offset markers. We assume scale invariance of kinematics
on visible small faults in ridge outcrops and invisible large faults covered by valley glaciers (following Wilson, 1995). That is, the faults we analyzed should reflect regional kinematics. We derived kinematic solutions using the software Fault Kinematics 3.5 (Allmendinger et al., 1993) in order to maintain consistency with previous workers in the TAM (Wilson, 1995). The graphical method of Marrett & Allmendinger (1990) solves for the axes of incremental extension ($S_1$) and shortening ($S_3$) based on the fault plane attitude, the lineation’s plunge and trend, and the sense of fault slip for individual faults. Following the Monte Carlo approach of Jowett & Robin (1988), these axes cluster into statistically significant sets. A Bingham distribution of incremental strain axes (Fisher et al., 1987) was assumed only to objectively estimate their mean. If the individual incremental strain axes represent a plausibly discrete set, for example one that approximates a Bingham distribution, then their mean orientation is a tenable approximation of the bulk incremental strain axis of that set. It should be noted that these axes, individual and mean, do not necessarily coincide with the finite strain axes and the magnitudes of these axes are not known.

Because of the lack of identifiable markers in the granite, the slip senses on most faults were inferred from mineral steps in slip-fiber lineations (Davis & Reynolds, 1996). These showed a consistent normal sense of slip where present. For purposes of the kinematic analysis here, those lineated fault surfaces with ambiguous slip senses were considered to be normal, consistent with the majority of faults measured within the TMF (e.g. Wilson, 1995). The $S_1$ axes ($n = 24$) document a NNE-SSW trend with a mean trend and plunge of 206°/4° (Fig. 5A) in a significant cluster at the 95% confidence level (Jowett & Robin, 1988). This compares closely to the kinematic solution for fault planes with unambiguous slip-fiber lineations ($n = 11$), for which the mean trend and plunge of $S_1$ axes is 201°/12°.

If every fault plane-slickenline pair formed synchronously, then the kinematic solution would be tenable, but because some fault planes host multiple sets of lineations this solution is not. The polykinematic faults each have two kinematic solutions and two derivable mean $S_1$ axes (Fig. 5B), trending NNE and NW. A plot of moment tensor eigenvectors of a Bingham axial distribution of $S_1$ axes (Fig. 5C) calculated for NE-trending set ($n = 21$) yields the mean principal strain axes: $S_1 = 200°/5°$, $S_2 = 291°/1°$, and $S_3 = 036°/85°$, statistically indistinguishable from the results in figure 5A. The remaining NW-trending set ($n = 3$) of extension axes produce eigenvectors with mean trends and plunges as follows: $S_1 = 281°/66°$, $S_2 = 012°/13°$, and $S_3 = 167°/76°$. Given the lack of clear cross-cutting relationships, the relative ages of the NW- and NNE-trending $S_1$ axis sets are unknown.

The fault kinematic data presented above are, of course, for faults with unknown, but probably small, amounts of displacement. It is possible that they record slightly different extension directions than faults with greater displacement. A sufficient number of large faults would, of course, better characterize the kinematics of the area. Our data set includes only one unarguably large fault: that which juxtaposes granite and Fairchild Formation on the southern flank of Facet Peak (Figs. 3 & 4). Considering the thickness of missing strata (Barrett, 1965; La Prade, 1969), separation on the fault must be at least 320 m. This normal fault and the slickenlines measured on it yield an incremental extension direction that trends 042°-049°. Although this value is ~20°-30° off of the mean extension axis calculated for all of the faults, we note that it is consistent with extension that is very close to orthogonal with the coastline and mountain range. With no proper knowledge about how to weight the value of this incremental extension axis against those of the rest of the faults, it is probably safe to conclude that the true mean extension axis in the Cape Surprise area trends 020°-040°.
GEOMORPHOLOGY

GEOMORPHIC TREND ANALYSIS

Geomorphic trend analysis was used to determine whether landforms have a preferred orientation. Preferred trends not parallel to the regional surface gradient are most likely to reflect underlying structure (Morisawa, 1963; Scheidegger, 1983). Geomorphic trend analysis complements regional lineament mapping in the central TAM (Paulsen & Wilson, 1998), providing less information on where large structural features are but more statistical characterization of the structural sets within that region.

Following previous studies in glaciated and non-glaciated terrain (e.g. Scheidegger, 1983; Ai et al., 1982; Eyles et al., 1997) we analyzed the glacial network, digitized from 1:250 000-scale United States Geological Survey (USGS) Antarctic series topographic maps. The center-lines of glaciers composing the drainage network were transformed into dashed lines with segments of lengths equivalent to 750 m on the ground. Each segment was separated by a gap equivalent to 250 m on the ground so that image analysis software (namely, NIH Image) could discriminate and measure the azimuths of the individual line segments. These azimuths were measured with respect to a local standard meridian (174°W), because at such high latitudes the meridians are significantly non-parallel at regional scales. The Liv and Shackleton Glaciers were excluded because of the bias their self-evident trends would introduce. The region was divided into four subregions, each lying either within basement or Palaeozoic-Mesozoic cover, west or east of the Shackleton Glacier.

Preferred landform orientations were recognized as those that are more common than random orientations, which is considered here the scatter (±2 standard errors) about the uniform distribution of azimuthal orientations (Bull & Brandon, 1998). Preferred landform orientations theoretically correlate to an underlying structural fabric (Scheidegger, 1983), which finds some support in comparisons with mesoscale structures in the Cape Surprise area (Fig. 6). A WNW trend, parallel to the coastline and significant at the 95% confidence level is present in most southern sub-regions. Northern sub-regions in the basement all have strong N to NNE trends and weaker WNW trends.

DRAINAGE BASIN ASYMMETRY

Based on field observations, drainage networks in the TAM near Cape Surprise appear asymmetric (Miller et al., 1996). For example, tributary glaciers are often present to the SE of the NNE-trending trunk glaciers (Fig. 7). (The distinction between trunk and tributary glaciers is somewhat arbitrary. Here, we principally distinguish them based on their mapped width, length, and geometry: trunk glaciers are often wider, longer, and more linear than their tributaries. For purposes of objectivity in our analysis, we present a topological distinction below.) As a corollary to the above observation of confluences, spurs that diverge off of NNE-trending ridges more often point to the NW than the SE (Figs. 2 & 7). Miller et al. (1996) attributed...
this pattern to possible down-to-the-northwest block tilting. In a more general way, asymmetry in drainage basin geometry is commonly thought to indicate neotectonic block tilting in fluvial landscapes (e.g. Hare & Gardner, 1985; Cox, 1994; Keller & Pinter, 1996). Evidence for Cenozoic pediplanation in the Cape Surprise area (Miller et al., in press) and elsewhere in the TAM (Sugden et al., 1995), which is indicative of a subaerial, nonglacial environment of formation, is grounds for us to assume the glacial drainage networks near Cape Surprise occupy formerly fluvial networks.

To determine whether the basins in the Cape Surprise area are asymmetric, we used the technique of Cox (1994). The cross-sectional symmetry or asymmetry of a drainage basin is quantified using the transverse topographic symmetry factor \( T \), which is defined as

\[
T = \frac{D_a}{D_d}
\]  

(1)

\( D_a \) is the distance from the mid-line of the basin to the mid-line of the trunk glacier (measured perpendicular to the

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**Fig. 7** (A) Map of asymmetric drainage in the TMF, between the Shackleton and Liv Glaciers. North is towards the top. Drainages are numbered as follows: (1) Massam Glacier, (2) lower Barrett Glacier, (3) unnamed glacier in the Gabbro Hills, (4) lower Gough Glacier, (5) Le Couteur Glacier, (6) Morris Glacier, and (7) unnamed glacier northeast of Mt. Daniel. Note the NW-pointing ridgelines in basins 1, 2, 5, 6, & 7. Shaded-relief base maps are the “Shackleton Glacier” and “Liv Glacier” from the 1:250,000-scale Antarctic series by the United States Geological Survey. (B) Analytical results of the topographic symmetry factor \( T \), a normalized measure of drainage asymmetry, are presented in a polar scattergram. The magnitudes of the analytical data are shown graphically as the distances from the center of the circle, where \( T = 0 \) at the center and \( T = 1 \) at the edge. The azimuth is measured clockwise from the top of the circle. A square marks the mean \( T \) value of the entire dataset. (C) Schematic model illustrating the relationship between asymmetrical stream patterns and active or relatively recent block-tilting, for instance associated with normal faulting. If applicable to the TMF between Shackleton and Liv Glaciers, this would be analogous to a view towards the north or northeast.

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**Fig. 8** A diagram of a drainage basin showing the measurements used in calculating the topographic symmetry factor \( T \). \( D_a \) is the distance from the basin mid-line to the trunk stream and \( D_d \) is the distance from the basin mid-line to the basin divide.
basin mid-line) and \( D_j \) is the distance from the basin mid-line to the basin divide (see Fig. 8). In this glacialized terrain, we arbitrarily designate the longest, widest glacier the trunk glacier. All glaciers of first order, topologically analogous to Strahler’s (1952) first order streams, were excluded or considered tributaries of the trunk glacier. As \( D_j \) and \( D_j \) are vectors, measured perpendicular to the trunk glacier, \( T \) is a vector of normalized length that represents the mean azimuth and intensity of basin asymmetry. For example, the measured cross-section of the basin is symmetric if \( T = 0 \). Its asymmetry is a maximum where \( T = 1 \) (i.e. the trunk stream flows directly adjacent to one of the basin’s divides).

\[ T \] was measured for 7 drainage basins, or coastal portions of basins, covering 1460 km\(^2\) (Fig. 7A). Areas of basins measured were those that do not directly drain the frontal escarpment of the Prince Olav Mountains. This was done in order to prevent any bias in the shape of the valley network that might result directly from scarp retreat. The basins’ boundaries and the trunk glaciers were extracted from 1:250 000-scale USGS topographic maps of the region. Seventy-seven measurements of \( T \) were made at a frequency of one measurement per 2 km along each trunk glacier (Fig. 7B). For the 7 measured basins, mean \( T \) has a magnitude of 0.22 and an azimuth of 293°, which indicates that the basins tend to be centered around NNE-directed trunk glaciers and portions of the basins ESE of the these trunk glaciers tend to be larger than those on the WNW sides.

To test whether the measured samples of \( T \) are statistically significant, the Rayleigh test of significance for two-dimensional vector data was used to determine the probability (\( p \)) that a combination of random vectors would produce a mean \( T \) that was greater in magnitude (Curray, 1956). This probability is defined as

\[ p = e^{-\frac{L^2}{2n}} \]

where \( e \) = base of the natural logarithm, \( L \) = mean magnitude of \( T \) in percent, and \( n \) = number of basin segments measured. For our data, \( p \) = 0.024, indicating that the measured values of \( T \) connotes an asymmetry significant to the 95% confidence level.

The phenomenon of drainage basin asymmetry has been studied in landscapes occupied by stream networks. In these, basin asymmetry has been interpreted as indicating that processes external to the fluvial system (e.g. lithologic structure, tectonics, and climate) dominate over internal processes (Cox, 1994). Internal processes include fluvial dynamics. Being more stochastic, these processes tend to produce basin planforms that are more symmetrical (Morisawa, 1963). Whereas climate and prevailing winds can produce asymmetric valleys (Wilson, 1968), structure and tectonics are thought to influence the asymmetry of drainage networks and basins. Asymmetry may reflect dipping planes of variable resistance to weathering and erosion (e.g. joints, strata, or sills) or neotectonic tilting of the landsurface (e.g. Hare & Gardner, 1985; Cox, 1994; Keller & Pinter, 1996). Both result in differential rates of headward fluvial erosion.

Although the measure of basin asymmetry as a tectonic indicator has not been applied before to glaciated regions, we suggest that asymmetric drainage in the Cape Surprise region: (1) predates glaciation, (2) is fluvial in origin, and (3) resulted from tectonic tilting down to the NW. A case for the importance of fluvial erosion in the landscape development of the TAM, and the persistence of such landforms to this day, has been made, for example, by Sugden et al. (1995).

The exact origin of the asymmetry in the Cape Surprise region, however, and therefore the age of deformation remain open to interpretation. Two possible hypotheses emerge. Hypothesis (1): The deformation could have been contemporaneous with development of the extant landscape in the TMF, in which case the asymmetric pattern likely developed in direct response to down-to-the-WNW tilting due to range parallel transtension (Fig. 7C). Small displacement normal faulting and the formation of half graben in a range-front, low relief pediplain, postulated by Miller et al. (in press), might be responsible. The existence of this pediplain, its present position only several hundred meters above sea level, and the fact that it is not evidently faulted by range-parallel faults, suggests that fluvial processes contributed to landscape development in the Cape Surprise area after most rift-flank uplift had occurred.

Hypothesis (2): The existing drainage network pattern in granite could be a feature inherited from antecedent streams that evolved an asymmetry in once-overlying Beacon strata that had some component of NW dip. Although it is difficult to falsify either hypothesis, and thus better constrain the age of the drainage network, both invoke fault blocks with similar kinematics.

**DISCUSSION**

The dominant existing structural kinematic model for the Transantarctic Mountains presents the TMF as a zone of normal faulting with a significant component of dextral translation (Findlay & Field, 1983; Lanzafame & Villari, 1991; Fitzgerald, 1992; Wilson, 1995; Fitzgerald & Stump, 1997). This characterization, which has been gleaned from the obliquity of Cenozoic fault strikes to the mountain front and, in a few locales, the oblique rakes of fault slip lineations, has been assigned by some to the TMF for the entire period of Cenozoic uplift (e.g. Wilson, 1995). Indeed, oblique fault slip on NNE- to NE-striking faults in southern Victoria Land during the late Quaternary may indicate that dextral transtension continues to this day (Jones, 1996). These lines of evidence for oblique extension in the TMF agree with evidence for dextral transtension and strike-slip faulting in the development of the Ross Embayment after the Jurassic (Grindley & Oliver, 1983; Schmidt & Rowley, 1986; Lawyer & Gahagan, 1991; Storey, 1991; DiVenere et al., 1994; Sutherland, 1995; Salvini et al., 1997), lending support to the inference that the TMF is in coupled transtension with the West Antarctic rift system. Based on the simplest assumption of homogeneous strain within the rift system, one would predict a larger strike-slip component to transtension in
the central TAM than that observed in southern Victoria Land (Fig. 9).

As pointed out by Wilson (1995), evidence for transtension implies that mechanical unloading is not likely to be an effective mechanism for uplift of the TAM. However, certain geodynamic models of this uplift favor lithospheric heat transfer from the rift as the primary cause for isostatic uplift of the rift flank (Stern & ten Brink, 1989). Still, the existing transtensional model holds that such kinematics existed pretty much the length of the TMF during the major phase of uplift, that strike-slip faulting along the range front may have even initiated the uplift (ten Brink et al., 1997).

In contrast to this interpretation, recent seismic studies suggest that dextral strike-slip faulting and transtension in the Ross Sea does not predate ~30 Ma (Salvini et al., 1997). Prior to this, extension in the Ross Sea was approximately east-west, or roughly orthogonal to the TAM in Victoria Land (Salvini et al., 1997).

Thus, two models for the general kinematics of the Cenozoic WARS and TMF exist against which to compare our data. Model (1): Regional transtension has occurred in the TMF since the inception of uplift in the early Cenozoic. Model (2): The kinematic history of the TMF can be divided into two phases, in order to generally conform to the Cenozoic history of the WARS. In model (2), orthogonal extension or dextral transtension with a relatively small oblique component occurred from the initiation of the main phase of uplift of the TAM until ~30 Ma, followed by transtension with a much larger oblique, or wrench, component.

Whereas the strikes of the faults and trends of the extension axes are oblique to the trend of the range front in southern Victoria Land, the dominant post-Jurassic (D3, probably Cenozoic) structures in the Shackleton Glacier region tend to parallel the trend of the TAM and the most
significant extension direction is orthogonal to the range front. This implies a deformation regime that differs from that in southern Victoria Land in two ways. Firstly, the most significant direction of maximum mean incremental extension at Cape Surprise does not indicate transtension. Secondly, this axis of extension is not parallel to that in southern Victoria Land. These are in notable contrast with any TMF kinematics thus far predicted from Cenozoic strain within the Ross Sea (e.g. Salvini et al., 1997) or from plate motions (Sutherland, 1995).

Despite these significant differences, the second set of fault lineations and the asymmetric drainage patterns in the Cape Surprise region indicate the likelihood of a discrete episode of deformation characterized by a maximum extension axis subparallel to the trend of the TAM. Although the constraints on the timing of this deformation episode are not well established, the kinematics of this deformation is consistent with existing models for dextral transtension in the TMF. In general, the kinematic pattern at Cape Surprise may be similar to patterns of dominantly dip-slip normal faulting elsewhere in the TAM followed by more oblique slip (Wilson, 1992; 1995). As such, transtensional deformation in the TMF, especially with an extension axis oriented at as low an angle as appears in the Cape Surprise region, is not expected to be contemporaneous with the large magnitude of range uplift observed. Although the data do not preclude the potential of a large strike-slip fault initiating uplift along the range front in the early Cenozoic (ten Brink et al., 1997), they are not consistent with a model describing the entire TMF as transtensional throughout the Cenozoic.

Inconsistent extension axes measured in the TMF at different locations along the TAM principally argue against range-wide uniform and steady transtension during the Cenozoic. More importantly, they appear to question the presence of transtension everywhere along the TAM during the early phases of uplift. Although the ages of different faulting episodes need to be better constrained at Cape Surprise and elsewhere along the TAM, we propose two end-member explanations for the kinematics seen in our study area.

1. Following the onset of significant rift-flank uplift in the early Cenozoic and prior to ~30 Ma, extension in the TMF near Cape Surprise was nearly orthogonal to the trend of the range. Any transtension in the TMF coincided with strike-slip faulting within the WARS and was initiated at ~30 Ma, well after the onset of rift-flank uplift.

2. The two episodes of deformation in the TMF near Cape Surprise both occurred during transtension in the WARS. Strain partitioning (Teyssier et al., 1997) could explain the occurrence of dominantly range-parallel normal faults and orthogonal extension in the TAM. In such a scenario, the wrench component of transtension could be taken up by a strike-slip fault (or faults), most likely below the Ross Ice Shelf in the WARS. The kinematics of the WARS would, therefore, be more effectively partitioned from kinematics in the TMF during the major phase of rift-flank uplift in the early Cenozoic. Locally, the differential stresses attributed to isostatic response or thermal buoyancy, for example (Stern and ten Brink, 1989; van der Beek et al., 1994; Buseti et al., 1999), and responsible for rift-flank uplift overwhelmed any strike-slip component to faulting that was acting in the greater rift system, outboard of the TMF. Thus, apparent early Cenozoic extension directions in different regions of the TAM are possibly more a reflection of pre-existing large-scale structures than any far-field, plate tectonic stress field. In this scenario, an increased component of approximately range-parallel extension was the result of increased strain coupling with the WARS as the rate of rift-flank uplift subsided. Some of this deformation was accommodated by both NW- and NE-striking faults in the Cape Surprise area.

Although it is not possible to delineate between the two scenarios with the data we have collected from the Cape Surprise region, considering other structural data sets within the TMF and in the WARS, the bulk of the evidence would appear, at this stage, to favor the first scenario. That is, following the onset of significant rift-flank uplift in the early Cenozoic, extension in the TMF near Cape Surprise was nearly orthogonal to the trend of the range. At about 30 Ma, the stress regime in the TMF changed to include a significant dextral strike-slip component, coincident with strike-slip faulting within the WARS. In this case, the asymmetric drainage basins in the Cape Surprise area were most likely formed following 30 Ma, as a result of down-to-the-northwest block faulting during dextral transtension.

**CONCLUSIONS**

Fault kinematic, geomorphic trend, and drainage basin asymmetry analyses from the Cape Surprise region have led to a number of conclusions regarding the structure and kinematics of the TMF in the central TAM:

1. The architecture of the front of the range, which locally trends NW, is composed of NW-striking normal faults and NNE-NE-striking normal or transfer faults. South of the TMF’s inland margin (i.e. the axis of maximum uplift) the NE-striking set is not evident except possibly beneath the Shackleton Glacier. This is a different pattern to that documented in southern Victoria Land where range-front faults strike obliquely to the trend of the TAM.

2. Faults in the Cape Surprise region record at least two separate extension directions. The primary, statistically significant mean incremental extension axis is approximately perpendicular to the trend of the range, or 020°-040°. The highly raking slip lineations, the likelihood of fault reactivation, and the extension direction are consistent with the hypothesis that uplift of the TAM was driven by isostasy rather than a mechanical result of regional extension or transtension. A poorly defined secondary set of incremental extension axes trending roughly parallel to the range is differentiated from the primary set on polykinematic faults.
3. The planform asymmetry of drainage basins along the TMF could be the result of block-tilting down towards the northwest. This is consistent with the fault kinematic evidence for an extension axis with a significant component approximately parallel to the range. Although we present no data constraining the age of this deformation episode, it is congruent with evidence for middle to late Cenozoic dextral strike-slip faulting and transtension in the WARS (Salvini et al., 1997). This transtensional history of displacement in the TMF may only be relatively recent, following isostatic uplift and after perhaps the majority of mountain building ceased or since strike-slip faulting offshore increased. Inconsistencies between the kinematics of the greater rift system and that within the TAM are also possibly the result of strain partitioning, which would have been most pronounced during early Cenozoic rift-flank uplift.

ACKNOWLEDGEMENTS - Funding for this work was provided by a NSF grants OPP 93-16720 and 96-15294 and the University of Arizona. Antarctic Support Associates, Helicopters New Zealand, Ken Borek Air, and U.S. Navy Squadron VXE-6 provided essential support in the field. Graeme Dingle is graciously acknowledged for incomparable field assistance. Thoughtful reviews by Francesco Salvini, David Sugden, and Terry Wilson improved the paper’s clarity.

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