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Lithosphere folds in the Eurekan orogen, Arctic Canada?

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ABSTRACT

Cornwall and Princess Margaret arches are major regional uplifts in the Tertiary Eurekan orogen of the northeastern Canadian Arctic Islands and have influenced the development of adjacent synorogenic sedimentary basins. The arches are subparallel structures, about 200 km apart, and gravity and seismic-refraction data indicate that they are underlain at depth by crust-mantle upwarps. They may have developed as a result of crustal-scale folding during Eocene compression. Finite-element models for a layered quartz-diorite-olivine lithosphere rheology suggest that the horizontal stresses required are about 75 to 200 MPa. The strength of the continental lithosphere in the Eurekan orogen is affected by the existence of a thick succession of Paleozoic and younger sedimentary rocks in the crust and by the occurrence of a major igneous (thermal) event in the area 20–30 m.y. prior to the main phase of deformation.

INTRODUCTION

The Eurekan orogeny is largely responsible for the fragmentation and inversion of Carboniferous-Paleogene sedimentary basins and their foundations in the Cambrian-Devonian Franklinian mobile belt (Fig. 1; Thorsteinsson and Tozer, 1970; Balkwill, 1978, 1983a; Ricketts, 1987a; De Paor et al., 1989). The Eureka Sound Group, consisting of more than 4000 m of middle Campanian to about middle Eocene strata (Miall, 1986; Ricketts, 1986), provides the stratigraphic record of the transition from the latest stages of thermal subsidence in the Sverdrup basin (initiated in the Carboniferous-Permian; Balkwill, 1978; Stephenson et al., 1987) to the infilling of synorogenic (e.g., intermontane) basins superposed on the earlier stratigraphic foundations (Miall, 1985; Ricketts, 1987a, 1989). Until the middle Eocene, sediments of the Eureka Sound Group filled a regionally subsiding basin that was centered near west-central Axel Heiberg Island, coinciding approximately with the main Sverdrup basin depocenter.

Eurekan compressional deformation climaxed during the middle Eocene (Ricketts, 1987a). Two kinds of structural elements that evolved during Eurekan tectonism are major arches and uplifts, hundreds of kilometres in length, and high-angle reverse faults, or thrusts

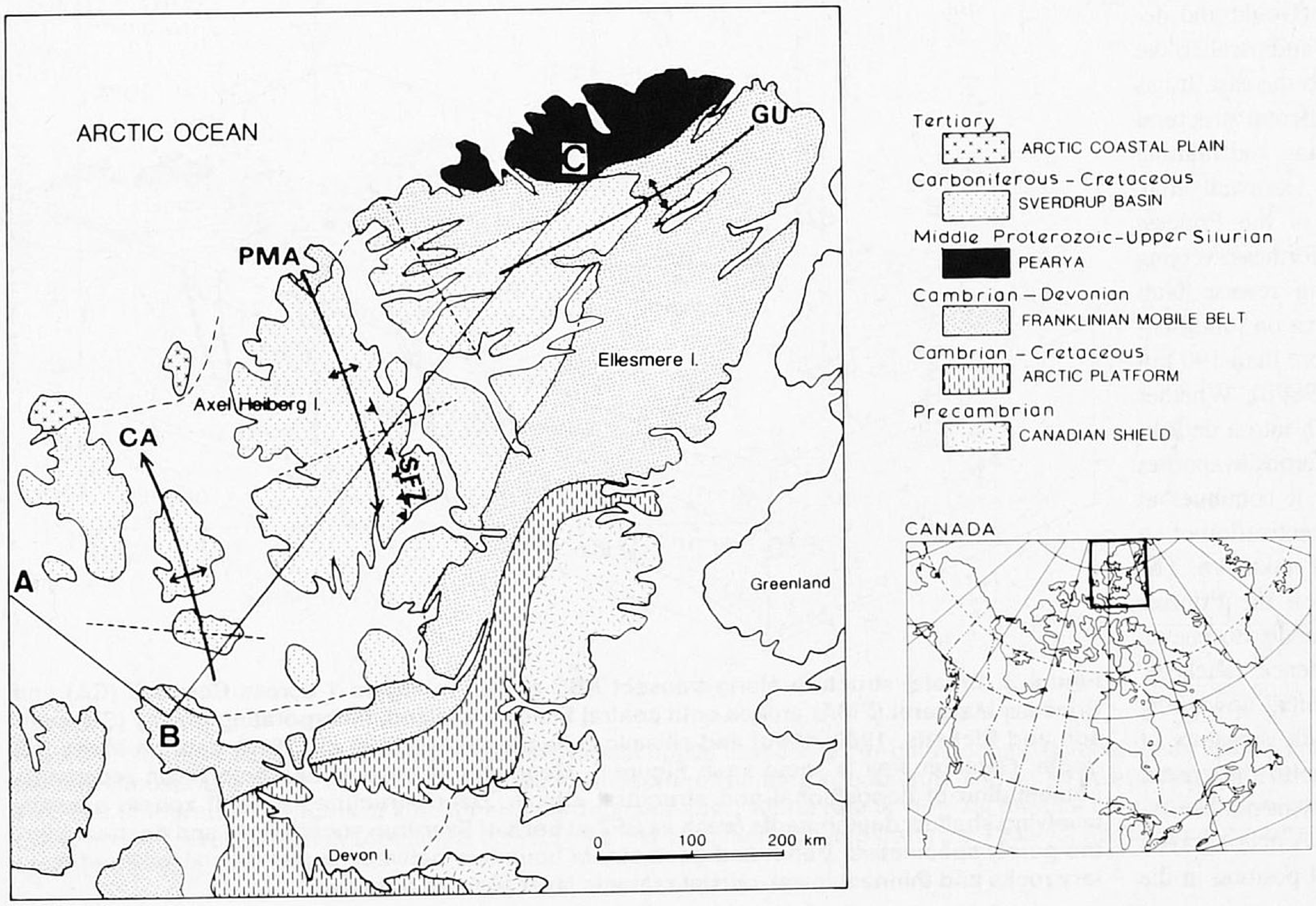

Figure 1. Regional tectono-stratigraphic elements of northeastern Canadian Arctic Islands (after Trettin, 1987), showing location of Cornwall arch (CA), Princess Margaret arch (PMA), Stolz fault zone (SFZ), and Grantland uplift (GU); dashed lines are gravity profiles interpreted by Stephenson and Ricketts (1990); line ABC is crustal transect shown in Figure 4.

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(Fig. 1). The locations of both structure types possibly have been controlled by the presence of Paleozoic or older structures (e.g., Balkwill, 1983a, 1983b; Trettin, 1987). The nature of these structures at depth and their relations to the coeval evolution of intermontane sedimentary basins are enigmatic. What is known of the geophysical signatures of the Eurekan arches, and of the timing of arch and basin development, is consistent with a model of a rheologically layered lithosphere folding in response to Eurekan compression.

CRUSTAL STRUCTURE OF MAJOR EUREKAN STRUCTURAL ELEMENTS

The Cornwall arch (Balkwill, 1974) is a simple, moderately asymmetric, northwest-plunging anticline that has ~4–5 km of structural relief (Balkwill, 1983a). The timing of uplift is between late Maastrichtian and early Eocene (Balkwill, 1978; McIntyre and Ricketts, 1989). The present-day topography of the Cornwall arch (about +100 m, coinciding with the arch axis) is in phase with a positive Bouguer anomaly (about 70 mgal; dotted line in Fig. 2). This relation is opposed to what is expected from simple isostatic considerations. Stephenson and Ricketts (1989, 1990) have modeled the supracrustal geologic contribution to the observed gravity anomaly, on the basis of the cross section of Balkwill (1983a); they concluded that a basement and/or mantle uplift, of similar amplitude and conformable with the supracrustal anticline, must underlie the Cornwall arch. The existence of a 4–5-km-high mantle upwarp below the arch is also supported by the deep seismic-refraction data of Forsyth et al. (1979).

The Princess Margaret arch (Gould and de-Mille, 1964), plunges southeast and parallels the Cornwall arch about 200 km to the east. It has similar structural relief but a different structural style, with more complex folding and faulting than that encountered on the Cornwall arch. The most prominent feature of the Princess Margaret arch is the east- to northeast-verging Stolz thrust, a steeply dipping reverse fault whose trace parallels the arch axis on southeastern Axel Heiberg Island for more than 100 km (van Berkel, 1986; Ricketts, 1987b). Whether the Stolz thrust flattens at depth into a detachment, for example, in Carboniferous evaporites (Ricketts, 1987b), or whether it continues at depth and coincides with the reactivation of an older fault (Balkwill, 1983b) is unknown. The major period of deformation on the Princess Margaret arch is known to be middle Eocene on the basis of stratigraphic evidence (Ricketts, 1987a), but it is possible that initial upwarping began slightly earlier. The gravity signature of the Princess Margaret arch, due to the greater near-surface geologic complexity, is not as simple as that of the Cornwall arch. A major gravity high corresponds to a structural position in the hanging wall of the Stolz thrust zone (Stephenson and Ricketts, 1989), superimposed on an antithetic isostatic pattern (Fig. 2, dash-dotted line), such as that of the Cornwall arch. Stephenson and Ricketts (1989, 1990), in view of constraints afforded by the local geology of the Stolz thrust zone (e.g., Ricketts, 1987b; van Berkel, 1986), showed that a mantle uplift, with structural relief similar to that of the Princess Margaret arch, is not inconsistent with the observed regional gravity profile. The available deep seismic-refraction data of Forsyth et al. (1979) are too sparse to completely resolve the crustal structure underlying the Princess Margaret arch, but they further suggest the presence of a mantle upwarp. About 80–90 km along strike to the north, below the polar continental shelf, a basement and mantle upwarp contiguous with the Princess Margaret arch can also be seen in more recent seismic-refraction velocity models (Forsyth et al., 1989).

The crustal structure of northern Ellesmere Island, aligned with the structurally complex Grantland uplift (Fig. 1; cf. Trettin et al., 1972; Maurel, 1989) and nearer the zone of maximum Eurekan compression, is unknown. Gravity and seismic data are unavailable for most of this region. Along a gravity profile on northwesternmost Ellesmere Island (Fig. 2, dashed line), however, a typical isostatic compensation relation is suggested, the topographic uplift coinciding with a regional Bouguer anomaly low. This relation implies that Eurekan crustal shortening in this area was accompanied by crustal thickening.

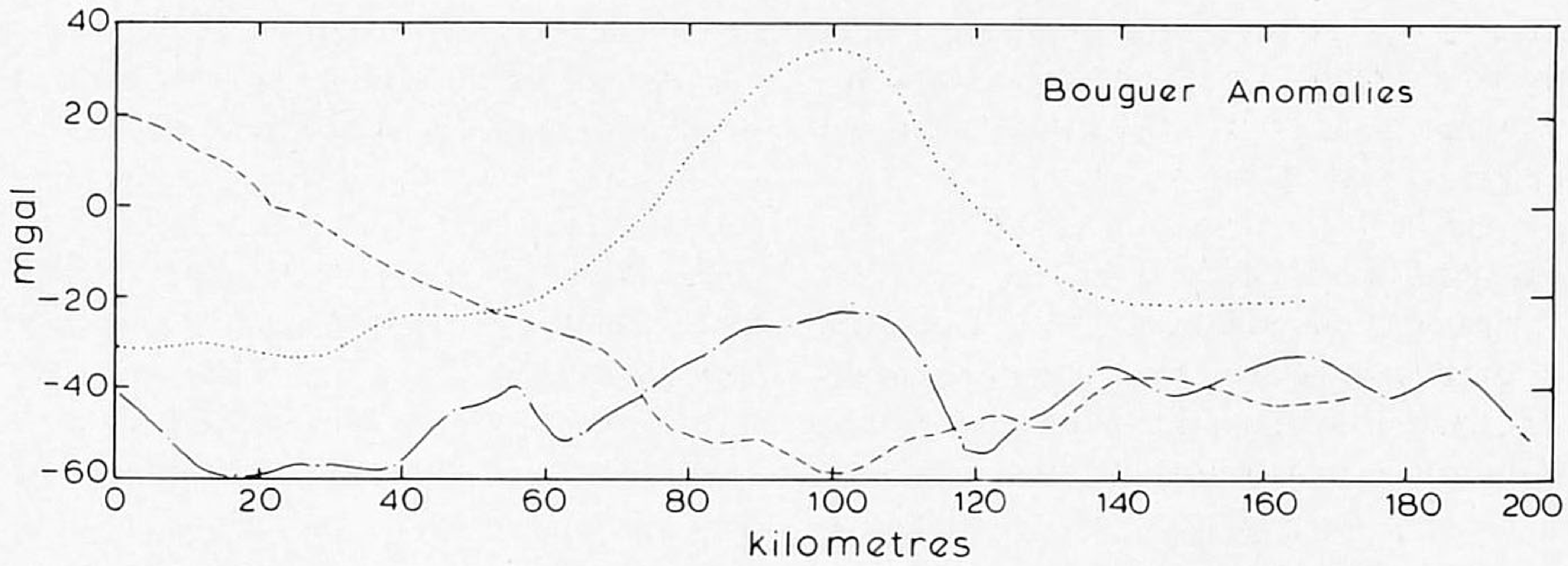

Figure 2. Mildly smoothed (Stephenson and Ricketts, 1989) Bouguer anomalies along profiles shown in Figure 1, across traces (aligned at distance = 100 km) of Cornwall arch (dotted line), Princess Margaret arch (dash-dot line), and southwestern extrapolation of Grantland uplift (dashed line). Gravity signature of Cornwall arch is enhanced by basic intrusive rocks exposed at surface in core of arch.

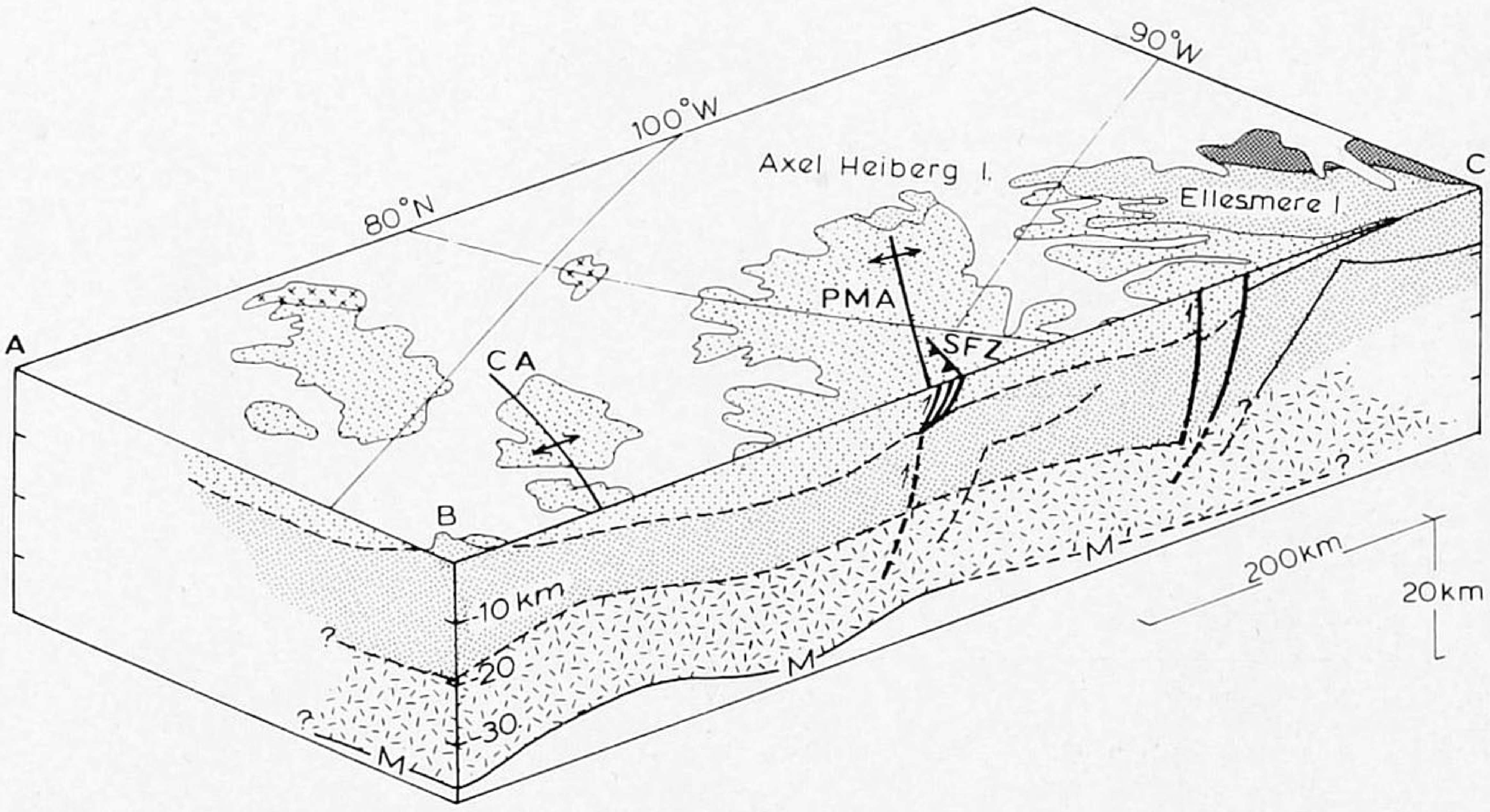

Figure 3. Crustal structure along transect ABC shown in Figure 1 across Cornwall (CA) and Princess Margaret (PMA) arches onto central Ellesmere Island, incorporating gravity (Stephenson and Ricketts, 1989, 1990) and seismic-refraction (Forsyth et al., 1979) data on Moho (M) depth. Geologic key is same as in Figure 1. Geometry of base of Sverdrup basin represents combination of depositional and structural effects. Deep structures of fault zones, possibly involving shallow detachments (such as SFZ at base of Sverdrup succession) and deeper faults, are purely speculative. Depth and geometry of boundary between upper-crustal metasedimentary rocks and thinned, lower-crustal cratonic layer are also unknown.

Figure 3 illustrates a possible crustal architecture associated with major Eurekan positive structural features, based on geologic evidence and gravity and seismic-refraction studies. Unlike the Grantland uplift, the Cornwall arch is not isostatically compensated and is associated with an anticompensation crustal geometry. The Princess Margaret arch and its related Eurekan structures are between those of northern Ellesmere Island and the Cornwall arch and have large-scale crustal and isostatic characteristics that are interpreted to be transitional. The change in apparent isostatic signatures and crustal foundations among these large-scale features corresponds to increasing distance from the zone of maximum Eurekan compression.

DYNAMICS OF EUREKAN ARCHES

The undulating crustal structure illustrated in Figure 3 is interpreted to be the result of crustal folding during the Eocene that accommodated Eurekan compression. The brittle-ductile failure on the eastward flank of the Princess Margaret arch may be transitional to more profound failure and resulting internal crustal detachment and thickening beneath the Grantland uplift. That the Cornwall and Princess Margaret arches originated as crustal folds has been investigated by using finite-element models of a rheologically stratified lithosphere in the presence of increasing in-plane (compressional) stresses below a sedimentary basin. The models take into account the effects of a major igneous event affecting the area during the Cretaceous (Embry and Osadetz, 1988) that culminated about 20–30 m.y. before the hypothesized folding. This thermal event was dominated by the intrusion of dikes and sills trending in a direction subparallel to the strike of the arches. It appears to have been responsible for renewed subsidence in the Sverdrup basin (Stephenson et al., 1987) and later accommodation of Eureka Sound Group sediments (Ricketts, 1989), the depocenter of which was between the subsequently developed arches.

The calculations assume a three-layer rheological model of the continental lithosphere (quartz-diorite-olivine corresponding to upper crust–lower crust–mantle), based on extrapolation of rock-mechanics data (Goetze and Evans, 1979; Brace and Kohlstedt, 1980); the derived lithosphere strength curves are shown in Figure 4. The geotherms used in calculating these strength curves are those, at the depicted times, of a conductively cooling, 120-km-thick lithosphere initially thinned by about one-half (but could correspond to those generated at other times following an appropriate amount of lithosphere thinning).

Results shown in Figure 4 (differential bulge uplift) are the flexural uplifts peripheral to the sedimentary basin in the presence of horizontal loads vs. those developed without horizontal loads. Finite amplification of the peripheral uplifts occurs for horizontal loads that are less than the integrated strength of the lithosphere. When this strength is exceeded, the numerical model predicts instantaneous, infinitely large amplitude buckling. The physical interpretation of this result is vertical displacements of several kilometres occurring in a manner analogous to large-scale flexural-slip folding of the lithosphere, shear-strain being concentrated within the weak layers and the finite amplitude of folding being controlled by the strong layers (e.g., Ramsay, 1967). Figure 4 shows that this should occur for in-plane stresses of ca. 75–200 MPa (0.75–2 kbar; the horizontal load divided by the lithosphere thickness) for ages up to 60 m.y. after the one-half thinning event (or immediately after about 10%–15% thinning of the lithosphere). Buckling stresses of these magnitudes may therefore lead to finite-amplitude folding of the continental lithosphere in geologic settings such as the Eurekan orogen.

The phenomenon of lithosphere folding has been documented in the Bay of Bengal by Weissel et al. (1980) and others (cf. Stein et al., 1989) on the basis of seismic and potential-field data. Finite-element calculations using an oceanic-lithosphere rheological model suggest much

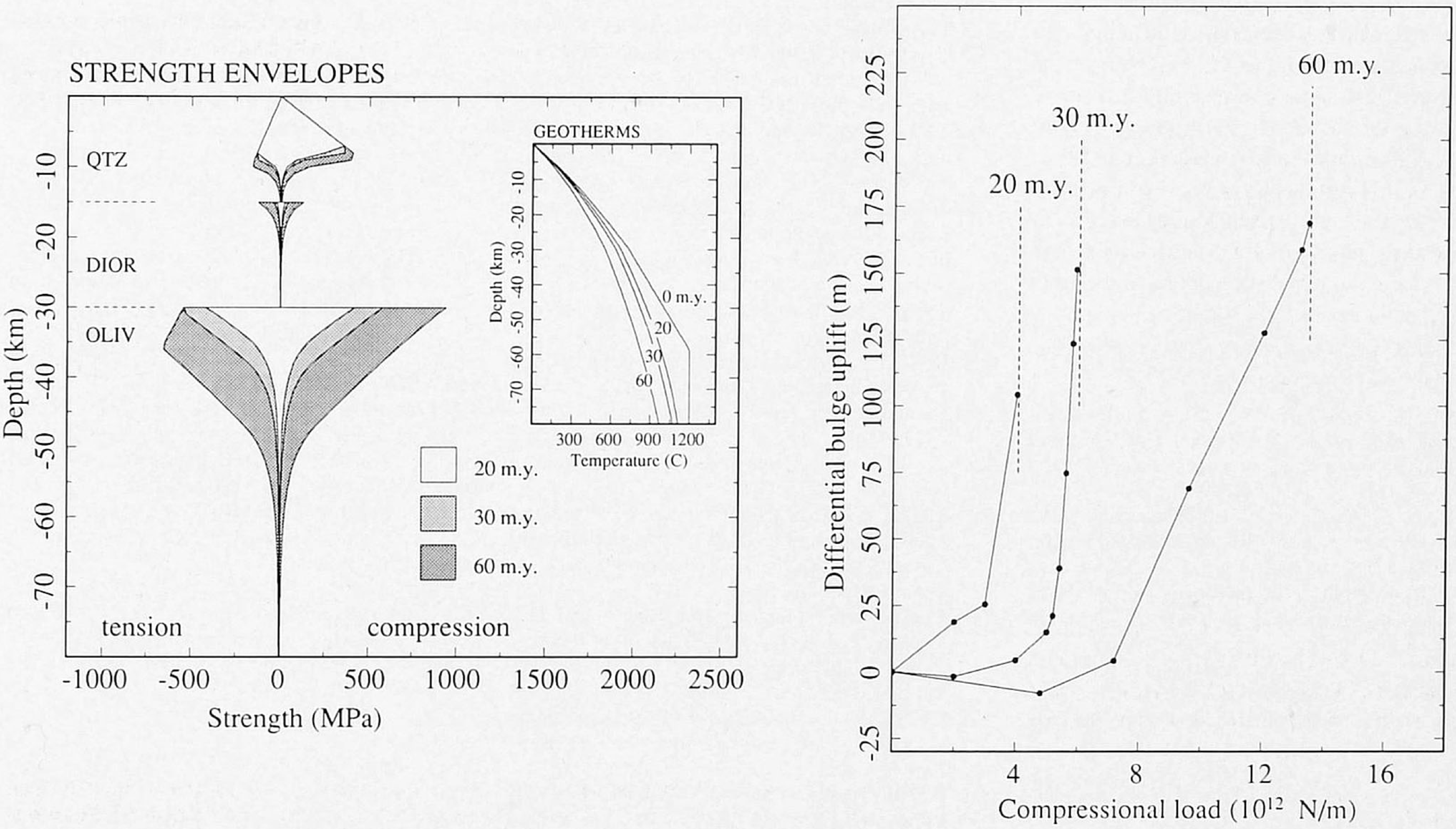

Figure 4. Strength envelopes and finite-element model uplifts induced by in-plane compressional loads (10^{12} N/m) for quartz-diorite-olivine layered lithosphere at 20, 30, and 60 m.y. after lithosphere thinning (geotherms shown in inset). Vertical dashed lines indicate buckling stresses (integrated strengths of lithosphere) for depicted ages. Strain rate is 10^{-15}/s; thermal conductivities in crust and mantle are 2.5 and 3.1 W·m^{-1}·K^{-1}; crustal heat production is 0.5–1.5 × 10^{-6} W·m^{-3}; melting temperature is 1200 °C. Rheological parameters are those of Brace and Kohlstedt (1980).

higher buckling stresses of ca. 500–700 MPa (5–7 kbar) there, similar to the levels deemed necessary from analytical deformation models (McAdoo and Sandwell, 1985; Zuber, 1987) and similar to ambient stress levels calculated for the Indian plate from plate-boundary forces (Cloetingh and Wortel, 1986). In comparison, the calculated continental-lithosphere buckling-stress magnitudes are not exceptionally large.

CONCLUSIONS

Seismic-refraction and gravity data indicate that flexures incorporating the crust-mantle boundary probably underlie the Cornwall and Princess Margaret arches, which were uplifted ~4–5 km during the Eocene culmination of the Eurekan orogeny. These flexures may be the result of a common phase of crustal-scale folding, with a wavelength of ~200 km, developed in response to intraplate compressional stresses loading a rheologically stratified lithosphere. Thinned and heated, layered lithosphere should buckle in the presence of in-plane compressional stresses of less than 200 MPa, much less than those required to fold the oceanic lithosphere. The buckling strength of the continental lithosphere beneath the Cornwall and Princess Margaret arches has been reduced by a combination of the possible coincidence of preexisting structures, the presence of sedimentary basin depocenters between the subsequently developed flanking arches, the presence of older clastic sedimentary sequences (including the Franklinian geosyncline) in the crust beneath the Sverdrup and younger basins, and a history of Cretaceous thermal rejuvenation and igneous intrusion. Toward the zone of maximum Eurekan compression, from the eastern flank of the Princess Margaret arch, crustal folding has led to progressively more profound large-scale failure and consequent crustal detachment and probable thickening beneath the Grantland uplift.

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