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N86-31148

THERMAL CONTROL OF THE STYLE OF EXTENSIONAL TECTONICS; Paul Morgan, Department of Geosciences, Purdue University, West Lafayette, IN 47907, USA.

Crustal extension is accommodated by a wide range of structural styles ranging from high-angle normal faults to low-angle detachments. In some areas different structural styles are superposed by multiple extension events, and in other areas different structural styles are juxtaposed along strike in the same extension event. As shown below with examples from the Rio Grande rift and the Red Sea-Gulf of Aden rift system, high strains and low-angle faulting are commonly spatially and temporally associated with hot and probably thin lithosphere as indicated by major coeval magmatic activity. Theoretical studies of strength profiles in the lithosphere suggest that there may effectively be a critical range for the geotherm above which low-angle faulting and crustal decollement may be favored over high-angle faulting.

At least two phases of Cenozoic extension have been identified in the Rio Grande rift (1). Early phase extension began in mid-Oligocene (about 30 Ma) and may have continued to the Early Miocene (about 18 Ma). This phase of extension is characterized by local high-strain extension events (locally 50-100%, regionally 30-50%), low-angle faulting and the development of broad, relatively shallow basins. Extension events were not synchronous during early phase extension and were often temporally and spatially associated with major magmatism. Late phase extension occurred primarily in the Late Miocene (10 to 5 Ma) with minor extension continuing to the present. It is characterized by apparently synchronous, high-angle faulting giving large vertical strains with relatively minor lateral strain (5-20%) which produced the modern Rio Grande rift morphology. Late phase graben or half- graben basins cut, and often obscure early phase broad basins. A similar two-phase extension history has been reported for other areas of the Basin and Range province (2).

Evidence has recently been presented for the Red Sea-Gulf of Aden rift system to suggest that rotation of the Arabian peninsula away from north-east Africa has been accommodated synchronously by mechanisms ranging from sea-floor spreading in the central portion of the Red Sea to diffuse extension in the Afar triangle (3). Courtillot (3) has described this mechanism as the propagation of two rifts from the the Red Sea and the Gulf of Aden into the Afar region, the eventual interconnection of which will effect the complete separation of southern Arabia from the African continent. Of interest to the present study is the change in extensional style along strike in the Red Sea-Gulf of Aden rift system from continental separation to diffuse extension for the same total extensional strain. The diffuse extension is spatially associated with extensive volcanism (4).

Experimental rock mechanics data can be used to estimate lithospheric strength profiles for lithosphere of different compositional and thermal structures (5). These profiles show an approximately linear increase in brittle strength with depth in the lithosphere which is truncated by an approximately exponential decrease in ductile strength at the brittle- ductile transition. The depth of this transition depends primarily upon composition, temperature and strain rate, and compositional layering can result in "layers" of strength within the lithosphere, the most prevalent of which are a layer of upper crustal strength and a layer of uppermost mantle strength. The most fundamental result of studies of lithospheric strength profiles is that the lithosphere is significantly weaker in regions where the geotherm is elevated, resulting in shallow brittle-ductile transition(s), and to a lesser extent where the crust is thick, resulting in the replacement of ductilely strong mantle layers with relatively ductilely weak crustal layers at equivalent depths and temperatures. This results suggests that the geotherm and/or crustal thickness may be important factors in the localization of extensional strain. The second important result of these studies is the prediction that the relative importance of the crustal and mantle strength layers may change as the geotherm changes: for low heat flow (stable areas) most of the strength in the lithosphere is in the uppermost mantle; at intermediate heat flow values the uppermost mantle and crustal strengths become similar; for high heat flow, negligible mantle strength is predicted, with all the strength residing in the uppermost crust.

Uncertainties in the extrapolation of laboratory rock mechanics data to lithospheric conditions limit the quantitative use of the lithospheric strength profiles calculated from these data. However, qualitative mechanisms can be proposed which are consistent with the calculated strength profiles and the tectonic observations in the Rio Grande rift and Red Sea-Gulf of Aden rift system. Major magmatic activity leading up to early phase extension in the Rio Grande rift indicates very high heat flow from which a strength profile with only strength in the uppermost crust is predicted. During this extension event the lithosphere was dominated by its ductile properties with shallow decollement at a shallow brittle-ductile transition resulting in low-angle faulting in a thin upper crustal brittle layer. A reduction in magmatism prior to late phase extension suggests lower heat flow, from which a strength profile with some uppermost mantle strength is predicted. Increased lithospheric strength may be one factor in producing smaller lateral strain during this event, but it is also possible that the layer of mantle strength prevented shallow crustal decollement resulting in high-angle planar or large-radius listric normal faults (1).

For the Red Sea-Gulf of Aden system variation in the volumes of volcanics along the strike of the rift system suggest variations in heat flow and the geotherm along strike. Abundant volcanics consistent with high heat flow in the Afar region suggests mechanical conditions similar to early phase extension in the Rio Grande rift, with a relatively ductile lithosphere resulting in diffuse extension. Distributed dike intrusion has made an important contribution to this diffuse extension (9). In the central portion of the Red Sea and the Gulf of Aden smaller volumes of volcanics consistent with lower heat flow suggest mechanical conditions similar to late phase Rio Grande rift extension, favoring high-angle faulting. As vertical strain is constrained by buoyancy considerations, however, continued extension on high-angle faults is limited, and can only be accommodated by dike intrusion, probably initially localized by the high-angle faults. To accommodate a high total strain in the lower heat flow areas an early transition from crustal extension to organized sea-floor spreading is predicted.

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