Thermochronometric constraints on tectonic and geomorphic evolution of the northern and central Saudi Arabian Red Sea Rift Margin

Daniel F. Stockli[1], Eugene Szymanski[1], Peter Johnson[2], Fayek H. Kattan[2], Khalid Kadi[2], Abdullah Al Shamari[2], Gomaa Omar[3], and Stephanie Brichau[1]

[1]Dept. of Geology, University of Kansas, Lawrence, Kansas 66045, United States, [2]Saudi Geological Survey, Jeddah, 21514, Kingdom of Saudi Arabia, [3]Dept. of Earth and Environmental Science, University of Pennsylvania, Philadelphia, Pennsylvania 19104, United States

The Tertiary Red Sea-Gulf of Suez rift system is one of the best-exposed examples of a continental rift (Figure 1) and a prime example of active continental break-up [e.g., *Cochran, 1983*; *Bosworth et al., 2005*]. Though much progress has been made in understanding the plate tectonic framework and modern strain field of the Red Sea [see *Reilinger et al., 2006*, this newsletter], limited knowledge of how extensional strain is spatially and temporally distributed along the continental margins has made it difficult to adequately evaluate and test models for the dynamic evolution of this rift system. Traditionally, the timing of growth and exhumation of rift flanks is determined by identifying erosional products within the basin fill. In the Red Sea, however, most of the pre-, syn-, and post- rift sedimentary rocks are either deeply buried within the rift, have been uplifted and eroded away, or are poorly dated due to the scarcity of datable synrift Tertiary volcanic rocks, hampering attempts to adequately reconstruct the rifting history along the entire margin of the Red Sea. Although the Egyptian and Yemeni margin of the Red Sea has been studied in some detail [e.g., *Omar et al., 1987*, *1989*; *Menzies et al., 1997*], little is known about the timing of Tertiary rifting of the Saudi Arabian margin. In this unprecedented collaborative project with the Saudi Geological Survey, we have been undertaking a comprehensive low-temperature thermochronometric investigation integrated with structural and geomorphic studies to determine the timing, origin, and geometry of extensional faulting and rift flank exhumation along the central and northern Red Sea margin in Saudi Arabia (Figure 1). The primary aim of this thermochronometric study is to systematically resolve the timing and spatial resolution of extensional faulting and post-rift erosion along the Saudi Red Sea margin and to distinguish between different models proposed for the geodynamic evolution of the Red Sea rift system.

Tectonic and Geological Evolution of the Central and Northern Red Sea

The Saudi Arabian Red Sea coastal margin has experienced a complex geological, tectonic, and geomorphic history. The margin is lithologically underlain by an assemblage of Neoproterozoic granitic gneisses, metasedimentary and volcanic rocks, ophiolites, and voluminous syn- to post-kinematic granitic intrusions and felsic to mafic Pan-African dikes. Basement fabrics are dominated by NW-trending foliations in the basement and WNW- to NW-trending basement shear zones of the late Pan-African Najd fault system. The Neoproterozoic assemblage is regionally unconformably overlain by a flat-lying Paleozoic sedimentary sequence. The overall picture of the Red Sea prior to rifting is that of a low relief, low elevation continental to marine realm. Subsequent uplift and exhumation related to the opening of the Red Sea has caused erosion of much of the pre-rift stratigraphy.

Volcanism began throughout the Red Sea at ~32-30 Ma and appears to largely predate earliest rift sedimentation. Rapid extension did not start until early Miocene times and is constrained by the oldest definite synrift strata in the northern Red Sea and Gulf of Suez at ~22 Ma [see summary in *Bosworth et al., 2005*]. This timing for the onset of Red Sea rifting is supported by apatite fission track and (U-Th)/He data from the Gulf of Suez region recording rapid rift flank exhumation at 21-23 Ma [*Omar et al., 1989*; *Stockli and Bosworth, unpubl.*]. Along the southern Saudi Arabian margin, however, *Bohannon and others* [1989] reported an onset of rapid extension that is distinctly older (23-28 Ma), possibly suggesting a diachronous onset of rifting along strike. *Menzies and others* [1997], on the other hand, obtained apatite fission track ages from the Yemen portion of the Red Sea margin that indicate rapid cooling occurred <25 Ma, post-dating the main period of basaltic volcanism (32-29 Ma). Basaltic volcanism on the Saudi Arabian margin has continued from the Late Oligocene throughout the entire development of the Red Sea and is characterized by large flood basalt provinces known as Harrats. The eruptive centers of the older flows follow a N30°W trend parallel to the Red Sea, while younger fields are oriented more northerly (N20°W - N10°E) [*Coleman et al., 1983*; see *Nyblade et al., this newsletter*]. Tertiary dikes, flows, and intrusions on the Saudi coastal plain bracket the age of rifting. Along the central Red Sea coast near Jeddah, the earliest synrift volcanic rocks range from >27 Ma to ~20 Ma [*Pallister, 1987]*. The emplacement of NW-trending dikes at 24-18 Ma has been interpreted to represent a change in style of magmatism indicative of a dramatic increase in the extension rate [e.g., *Pallister, 1987*].

Geomorphic Evolution of the Saudi Arabian Margin

The Saudi Arabian Red Sea margin can be subdivided into two distinctly different geomorphic domains: (1) From about 21°N to the southern tip of Yemen, the

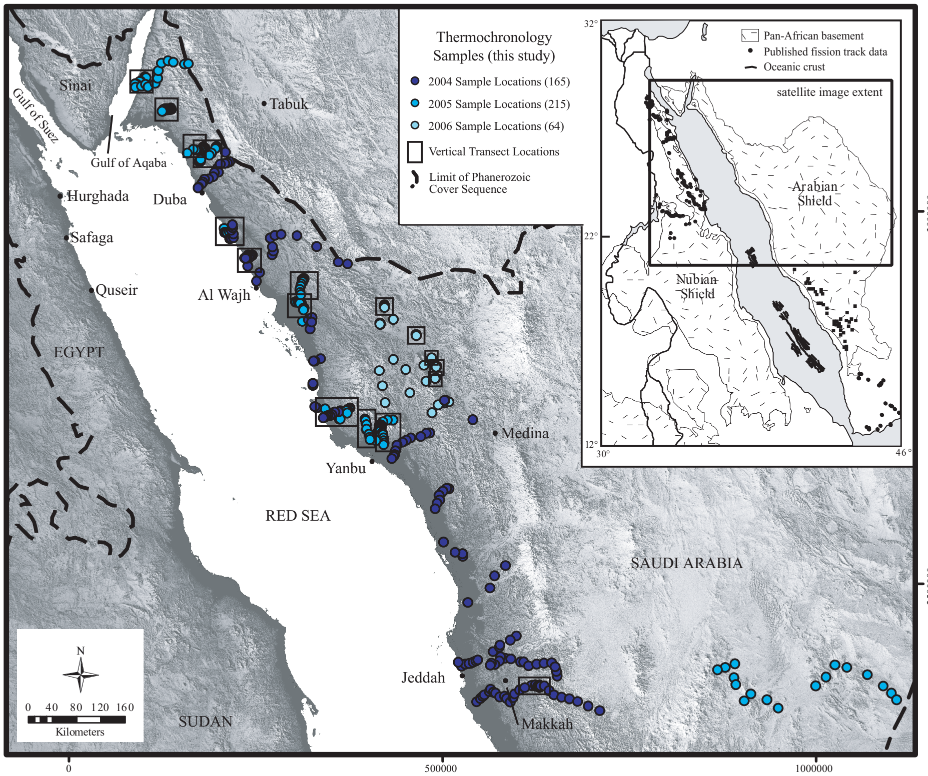

Figure 1. Shaded digital relief map of the central and northern Red Sea showing locations of low-temperature thermochronometric samples and vertical sampling transects collected from the Saudi Arabian Red Sea margin for this collaborative study. Inset map outlines Neoproterozoic basement exposures of the Arabian and Nubian Shields and published thermochronometric sample locations.

Saudi Red Sea margin is dominated by an impressive continuous ~2-3 km high erosional escarpment. The escarpment is the result of erosional rift flank retreat and appears to be independent of any structures in the underlying Precambrian. In central western Saudi Arabia, this upper surface is a mature erosion surface that extends east from the lip of the escarpment and bevels late Cretaceous-middle Eocene sedimentary rocks. East of Makkah (Mecca) this surface is partially overlain by Oligo-Miocene Harrat flood basalts and is likely late Cretaceous in age. (2) North of Makkah the Red Sea escarpment is discontinuous and less elevated and is interrupted by paleovalleys that descend from elevations of 1000-1500 m to the coastal plain. These paleovalleys post-date rifting and are infilled by ~5-10 Ma flood basalt that spilled from their eruptive centers east of the escarpment. We are currently carrying out detailed ^{40}Ar/^{39}Ar and magnetite (U-Th)/He dating of geologically significant basalts sequences.

The central Saudi Arabian Red Sea margin comprises erosional surfaces in addition to the prominent pre-Tertiary erosional surface dominating southern Saudi Arabia and Yemen. A very distinctive surface is well developed between the modern coastal plain and the main rift flank escarpment. It stretches for >500 km and dips gently seaward ranging from 300-100 m in elevation. A small escarpment (50-75 m high) separates this surface from the modern coastal plain, which is often rimmed by uplifted middle Miocene carbonate reefs. This surface likely represents a major wave-cut platform associated with the middle Miocene tectonic reorganization in the Red Sea coeval with the development of the Gulf of Aqaba transform. New apatite (U-Th)/He data from the area between Yanbu and Umm Lujj support a middle to late Miocene age for this erosional surface. North of Al Wajh, additional coastal uplift related to tectonism along the Aqaba transform system is expressed by spectacular coastal cliffs that appear to increase in height from south to north. New apatite (U-Th)/He data from the area between Dhuba (Duba) and the Gulf of Aqaba exhibit significant post-Miocene cooling and exhumation increasing in magnitude from south to north.

Low-Temperature Thermochronometry

Over the past three years, our collaborative efforts have focused on a comprehensive thermochronometric study of exhumed crystalline basement along the central and northern Saudi Arabia Red Sea rift margin, stretching from the costal escarpment south of Makkah/Jeddah to the northern Gulf of Aqaba (Figure 1). Apatite and zircon (U-Th)/He and apatite fission track analysis directly date the timing of onset of extension and also quantify the pre- and post-rift erosional denudation of the rift flanks. A critical aspect of constraining the evolution of rifting and rift flank exhumation is acquiring chronological constraints on faulting, rift segmentation, and rift localization. The answers to these questions have far-reaching implications for the understanding of rifting dynamics and the interplay between extensional faulting and subsidence during syn-rift sedimentation. In addition, integration of detailed thermochronometric data with detailed structural and kinematic analysis is necessary to interpret the temporal constraints in their proper tectonic framework [e.g., *Stockli et al., 2005*].

We have collected more than 400 thermochronometric samples to resolve the timing of extensional faulting and to differentiate between different episodes of cooling and exhumation affecting the Saudi Arabian Red Sea margin. Our sampling strategy can be summarized by two major approaches:

(1) Following the strategy described by *Stockli et al*. [2005], a series of detailed vertical transects were collected across the exhumed crustal blocks and topographic escarpments along the Saudi Red Sea margin to constrain the timing and spatial distribution of extensional

faulting and evolution of rift segmentation and localization, as well as rift flank exhumation (Figure 1). The detailed vertical transects, spanning up to 3000 m in elevation between Jeddah and the Gulf of Aqaba, allow for detailed reconstruction of the Mesozoic to late Cenozoic thermal history. In addition, vertical transects were collected in the footwall of the inland Hamd-Jizl halfgraben north of Medina to elucidate the temporal relationship between distributed inland extension and normal faulting within the main Red Sea basin.

(2) Horizontal traverses were collected across the entire rift margin from the modern coastal plain to the edge of the exposed Neoproterozoic Arabian Shield (Figure 1). These thermochronometric traverses range from ~100 km in length in northern Saudi Arabia (Gulf of Aqaba and Dhuba) and ~200 km (Al Wadj and Yanbu) to ~600 km (Jeddah/Makkah). These long-baseline traverses were designed to investigate the width of exhumation related to rifting and crustal attenuation and to constrain how far extensional faulting encroaches into the rift margins beyond the border fault systems, such as in the Hamd-Jizl basins north of Medina (Figure 1). Knowledge of the temporal and spatial distribution of crustal attenuation and the timing of flexural amplification and exhumation of the entire width of the rift flank is critical for evaluating the role of processes such as active versus passive asthenospheric upwelling, secondary convection, and flexural unloading of the crust, as well as the distribution of sub-crustal lithospheric extension relative to crustal thinning.

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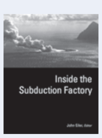

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