6-1991

Reply [to “Comment on ‘Topographic and Volcanic Asymmetry Around the Red Sea: Constraints on Rift Models’”]

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Scholar Commons Citation
Dixon, Timothy H.; Ivins, Erik R.; and Franklin, Brenda J., "Reply [to “Comment on ‘Topographic and Volcanic Asymmetry Around the Red Sea: Constraints on Rift Models’”]" (1991). *School of Geosciences Faculty and Staff Publications*. 506.
https://scholarcommons.usf.edu/geo_facpub/506

TECTONICS, VOL. 10, NO. 3, PAGES 653-656, JUNE 1991

REPLY

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We thank Camp and Roobol [this issue] for their comment and interest in our paper on asymmetric features in the vicinity of the Red Sea [Dixon et al., 1989]. Camp and Roobol question our interpretation of the volcanic age data in Saudi Arabia, though they apparently agree with other aspects of our model. We feel the age data do not indicate any significant "hot spot"-like trends in an east-west sense, perpendicular to the main trend of the Red Sea. Camp and Roobol feel that the age data indicate a younging trend to the east, which would not accord with the predictions of our model.

There are several important points which Camp and Roobol fail to recognize or choose to ignore. First, voluminous mafic igneous rocks are in fact present west of the Saudi Arabian volcanic fields and are significantly younger than the mean age of the Saudi Arabian volcanics, namely the post-5 Ma seafloor basalts and gabbros in the Red Sea axial trough. This first-order trend in the ages of mantle-derived mafic rocks supports our model; in our opinion, second-order variability in ages of continental lavas is much less significant. We address this second order variability below. The critical underlying assumption in our model which Camp and Roobol do not directly challenge is that young mafic rocks in Saudi Arabia and those in the Red Sea axial trough are related manifestations of a common mantle phenomenon. Of course, it is possible that the two settings have experienced separate, unrelated mantle upwelling events, but in view of the similarity in timing and spatial proximity, we think this very unlikely. Note that geochemical differences between the continental basalts, which tend to be alkalic, and mainly tholeitic axial trough basalts are readily explained via mechanisms such as assimilation of continental crust, varying depths of magmatic reservoirs, different degrees of partial melting during the early phases of mantle activity, and diverse fractionation histories. Camp and Roobol point out that several volcanic suites appear locally related to different tectonic trends. However, the genetic significance of these associations is not clear. They may only reflect near-surface control on eruption mechanism and thus are not relevant to the deeper-seated processes of interest here.

The second important point concerns the statistical significance of trends (or lack thereof) in the age data. This is best considered by looking at actual data on volcanic ages, rather than the more subjective approach used by Camp and Roobol (e.g., Figure 1 of Camp and Roobol [this issue]) which obscures the true variability in the data. Our original assessment of volcanic age trends was based on all age data published after 1970 meeting standards for quality laid out in Dixon et al.[1989]. Camp and Roobol base much of their argument for east younging age trends on a large amount of unpublished data. They concede that K-Ar ages are subject to large uncertainties, but they are not clear on the criteria used in their age compilation map. In order to investigate this in more detail and to assess the validity of Camp and Roobol's claim that ages young to the east, we recompiled the available data which met criteria given in our original paper, including data for plutonic rocks. Figure 1

Paper number 91TC00056.
0278-7407/91/91TC-00056$02.00

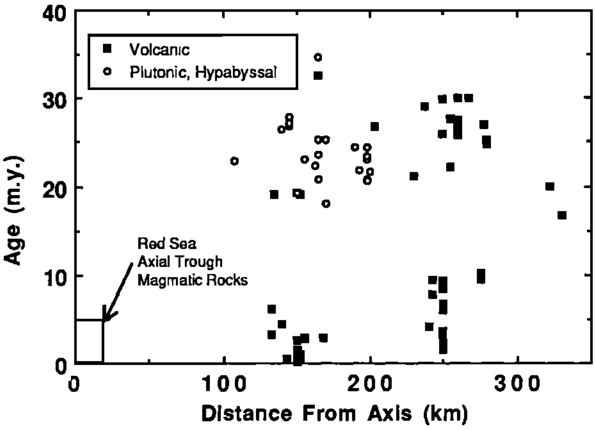

Fig. 1. Age of volcanic, plutonic and hypabyssal rocks less than 35 Ma in Saudi Arabia and Yemen as a function of distance from the Red Sea axial trough. Only data with uncertainties less than 10%, or less than 1.0 m.y. for samples less than 10 Ma, are used. If given in the source publication, we also precluded data with $^{40}Ar_{radiogenic}/^{40}Ar_{total}$ <10%. Sources are Brown et al. [1984], Capaldi et al. [1983], Coleman et al. [1984], Pallister [1987], and Camp and Roobol [1989].

plots these data on an ENE-WSW trend, perpendicular to the long axis of the Red Sea, projecting data from 16°N to 28°N latitude onto the transect. Note that the plutonic data, generally located 120-180 km from the Red Sea axial trough (Figure 1), tend to cluster near the coastal areas, reflecting flank uplift associated with Red Sea rifting and subsequent incision and exposure of these rocks. We suspect that similar age plutonic rocks underlie the Saudi Arabian crust to the east but are not exposed in these nonuplifted areas. It is clear that there are no statistically significant younging trends in these data, unless of course one considers the post-5 Ma seafloor rocks, in which case the data support our model. Since magmatism associated with young oceanic crust is far more extensive than the small-volume "harrats" of similar age [Camp and Roobol, 1989], this is probably the important aspect. However, even if one ignores the seafloor contribution, the data do not support Camp and Roobol's model. A straight-line fit slopes to the west if only the volcanic continental data are used, and slopes east if both volcanic and plutonic continental data are considered, but in neither case does the slope deviate significantly from zero even at the 1σ level.

We agree completely with Camp and Roobol that the oldest dated mafic material in Saudi Arabia related to Red Sea rifting is approximately 30 Ma and that younger, post-13.8 Ma lavas are more common. However, for purposes of evaluating our model, we must focus on the earliest indications of mantle upwelling rather than emphasizing relative volumes of exposed igneous rocks as a function of age. Available data may be biased toward younger ages, since initial mantle activity is more likely to result in intrusive bodies in the lower and middle crust which are not exposed.

To assess the significance of the apparent absence of an age trend, we must consider carefully the likelihood of generating observable age-distance trends in volcanism in this geological setting, assuming slow movement of the overlying plate as described in our model. As we mentioned in our original paper, Epp [1984] presented several models explaining why simple age-distance trends might not develop for a hot spot in oceanic lithosphere, including lateral channelling of magmas and continued volcanism after passage over a hot spot. It is also instructive to consider the contrasts between the Red Sea/Saudi Arabia region and a hot spot chain with a well-developed age trend, the Hawaiian-Emperor chain, where Pacific lithosphere moves across a strong, long-lived hot spot at a rate of about 9 cm/yr, generating the 3500 km Hawaiian volcanic chain in just over 40 m.y.

There are three important differences between the Hawaiian-Emperor chain and the Red Sea example, differences we believe make it extremely unlikely that a similar, well-developed trend in ages could be generated in Saudi Arabia. First, the strength and spatial definition of mantle upwelling in the Red Sea region between 30 and 10 Ma is simply not comparable to the Hawaiian hot spot. The history of rifting and volcanism suggests that upwelling first initiated weakly around 30 Ma over a fairly broad region and did not become strong or localized until after 10 Ma when the Red Sea began to extend actively and form oceanic crust. Second, the Afro-Arabian plate motion rate in a hot spot reference frame is almost an order of magnitude slower than Pacific motion. Thus the distance over which we might see a younging trend develop is considerably smaller, presumably contributing to the observed overlap in ages (Figure 1). Some appreciation of scale can be seen in Figure 6 of our original paper where we plot volcanic ages for a large region that includes Afar and the Ethiopian Rift. Inspection of this figure suggests that volcanism in Saudi Arabia actually is restricted to a zone fairly close to the Red Sea; the region over which we might observe a trend in ages is less than 300 km wide (Figure 1). Third, continental crust is a strong impediment to passage of mantle-derived mafic melts, unless that crust is actively extending [Hildreth, 1981], complicating any inferences concerning trends in mantle activity based solely on observed volcanism. We feel these three differences between the Red Sea and better documented hot spot trends in the Pacific make it quite likely that one or more of Epp's models applies, precluding development of simple age-distance trends in the Saudi Arabian crust during the relevant time period.

It is important to recognize that our model does not require large scale migration of overlying crust with respect to upwelling mantle; a relatively small (several hundred kilometers) realignment is consistent with both the model and the observations. We speculated in our original paper that one criterion for a "successful" (i.e., ocean-forming) rift was the proximal location of the initial locus of upwelling mantle relative to a crustal weak zone that controlled rift location. In this model, interaction between upwelling mantle and the crustal weak zone facilitates rapid thermal weakening of the lithosphere, enhancing the rifting process (see Figure 10 of Dixon et al. [1989]). This interaction can take place only if the lateral separation between upwelling mantle and the crustal weak zone is relatively small, perhaps equal to or less than the lateral dimensions of the upwelling zone itself. We have no direct evidence to indicate what these dimensions might be, but the distribution of continental and oceanic ages shown in Figure 1 is consistent with the small-scale adjustment implicit in our model that brings the weak zone and the upwelling locus into alignment.

Finally, continued volcanism in Saudi Arabia might be expected given the apparent migration of African-Arabian lithosphere in a hot spot reference frame (slowly north or northeast, according to most absolute plate motion models). Our model requires migration of the lithosphere with respect to a zone of hot, upwelling asthenosphere, and it is reasonable to ask if this horizontal plate motion affects the pattern of vertical upwelling in any way. Shear flow at the base of the lithosphere is one likely consequence, deflecting the upwelling "plume" in the direction of plate motion (e.g., Richards and Griffiths, 1989) (Figure 2). The amount of deflection will depend on the relative rates of vertical (asthenosphere) and horizontal (lithosphere) motion, both presumably slow in this example. The deflection of hot, rising asthenosphere in the direction of absolute plate motion causes advective distortion of isotherms. This results in higher temperatures at the base of the Saudi Arabian lithosphere relative to lithosphere on the other side of the Red Sea, perhaps enhancing the likelihood of continued volcanism in Saudi Arabia (Figure 2). The distortion of isotherms that we predict may be similar to the asymmetries seen in time-dependent convection simulations between adjacent zones of differing horizontal vorticity (e.g., Figure 7 of Christensen and Yuen, [1989]). The extent of young volcanism in the Saudi Arabian shield (a few hundred km from the Red Sea coast; Figure 1) may provide some indication of the magnitude of lateral deflection of upwelling asthenosphere, suggesting a test of the hypothesis through comparison with quantitative convection models.

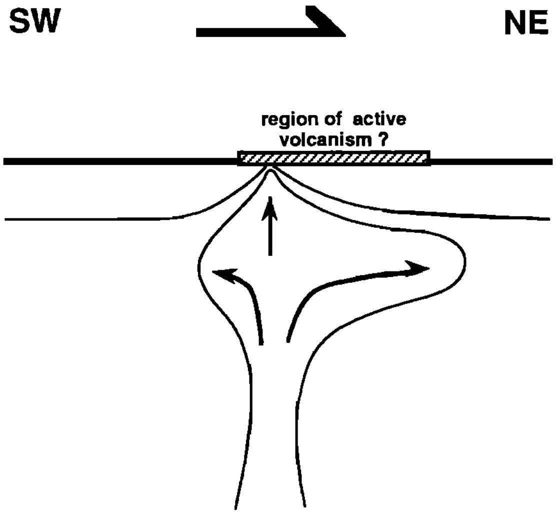

Fig. 2. Cartoon showing cross-section of the Red Sea region and deflection of upwelling asthenosphere by lithosphere moving in the direction indicated. Light lines represent isotherms. The possibility of continued volcanism on the northeast plate (Saudi Arabia) is enhanced due to the presence of excess hot material at the base of the lithosphere.

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(Received November 23, 1990;
accepted December 31, 1990.)