Cenozoic evolution of Neotethys and implications for the causes of plate motions

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[1] Africa-North America-Eurasia plate circuit rotations, combined with Red Sea rotations and new estimates of crustal shortening in Iran define the Cenozoic history of the Neotethyan ocean between Arabia and Eurasia. The new constraints indicate that Arabia-Eurasia convergence has been fairly constant at 2 to 3 cm/yr since 56 Ma with slowing of Africa-Eurasia motion to <1 cm/yr near 25 Ma, coeval with the opening of the Red Sea. Ocean closure occurred no later than 10 Ma, and could have occurred prior to this time only if a large amount of continental lithosphere was subducted, suggesting that slowing of Africa significantly predated the Arabia-Eurasia collision. These kinematics imply that Africa's disconnection with the negative buoyancy of the downgoing slab of lithosphere beneath southern Eurasia slowed its motion. The slow, steady rate of northward subduction since 56 Ma contrasts with strongly variable rates of magma production in the Urumieh-Dokhtar arc, implying magma production rate in continental arcs is not linked to subduction rate. *INDEX TERMS:* 8102 Tectonophysics: Continental contractional orogenic belts; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8155 Tectonophysics: Evolution of the Earth: Plate motions—general; 8158 Tectonophysics: Plate motions—present and recent (3040). **Citation:** McQuarrie, N., J. M. Stock, C. Verdel, and B. P. Wernicke, Cenozoic evolution of Neotethys and implications for the causes of plate motions, *Geophys. Res. Lett.*, *30*(20), 2036, doi:10.1029/2003GL017992, 2003.

1. Introduction

[2] The last 30 years have brought fundamental advances regarding the driving forces behind plate tectonics mainly deduced through geodynamic modeling (e.g., [*Forsyth and Uyeda*, 1975; *Hager and O'Connell*, 1981; *Conrad and Lithgow-Bertelloni*, 2002]). It seems clear that changes in relative plate motion would in general provide the deepest insights into the dynamics of plate motion, but thus far they have proved a challenge to incorporate into geodynamical models (e.g., [*Lithgow-Bertelloni and Richards*, 1998]). One of the most promising examples is mid-Tertiary slowing of Africa-Asia relative motion, because tectonic events along the northern margin of the African and Arabian plates can be used to constrain the evolution of stresses acting on the plate boundary (e.g., [*Jolivet and Faccenna*, 2000]). The collision of Arabia reflects the final demise of the Neotethys Ocean, which gradually closed via northward subduction of oceanic lithosphere producing the Andean-type Urumieh-Dokhtar arc in Iran [*Dewey et al.*, 1973]. In this same window of time, a new ocean basin, the Red Sea, was formed as Arabia separated from Africa. The concentration of diverse plate boundaries, including ridges, subduction zones and transform faults in association with the change in motion of Africa (Figure 1) offers significant potential to understand its origin.

[3] Understanding basic cause-and-effect relationships between plate boundary forces and plate motions hinges on a precise knowledge of: (1) the age of collision between the Arabian and Eurasian margins in Iran, (2) the original width and closure history of Neotethys, (3) the relationship between the opening of the Red Sea and Africa-Asia relative motion, and (4) the relationship between ocean closure and magmatic events in the Urumieh-Dokhtar arc. To date, there are no direct means of dating collision between Arabia and Eurasia. The timing of collision has been inferred to be anywhere from late Cretaceous to Pliocene, based on a wide variety of presumed geologic responses to collision such as: (1) ophiolite obduction in the late Cretaceous and coeval development of a foreland basin on the Arabian margin [*Alavi and Mahdavi*, 1994; *Berberian and King*, 1981]; (2) an Eocene foreland basin in the Zagros [*Beydoun et al.*, 1992; *Hempton*, 1987] and Eocene angular unconformities in Central Iran; (3) Early to mid- Miocene transition from marine to nonmarine sedimentation [*Dercourt et al.*, 1986; *Dewey et al.*, 1986; *Sengör and Natal'in*, 1996]; and finally (4), a latest Miocene/Pliocene influx of coarse clastics into the foreland basin, rapid cooling in the Alborz Mountains, and rapid subsidence of the Caspian Sea [*Allen et al.*, 2002; *Axen et al.*, 2001; *Beydoun et al.*, 1992; *Dewey et al.*, 1973].

2. Arabia-Eurasia Plate Motions and Continent-Continent Collision

[4] The motions of Africa and Arabia with respect to Eurasia presented here are based on updated locations of sea floor magnetic anomalies and fracture zones in the North and Central Atlantic [*Klitgord and Schouten*, 1986; *Srivastava et al.*, 1990; *Srivastava and Tapscott*, 1986] and reconstructions across the Red Sea [*Joffe and Garfunkel*, 1987]. The anomalies used in this study have well defined, sharp boundaries that allow for quantitative error determination. We calculated positions of points on both Arabia and Africa for the times of the old edge of anomaly 5 (10.6 Ma), the centers of anomalies 6 (19.6 Ma), 13 (35.3 Ma), 18 (39.3 Ma), 20 (43.2 Ma), 21 (47.1 Ma), 25 (56.1 Ma), and the reversed polarity interval between anomalies 30 and 31 (67.7 Ma). For each reconstruction, uncertainties expressed as partial uncertainty rotations for each pair of adjacent plates [*Stock and Molnar*, 1983] have been combined to

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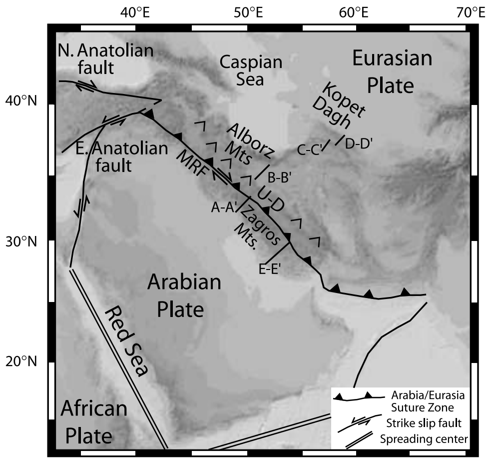


Figure 1. Shaded topography of the Arabia-Eurasia collision system. Shortening estimates for the northern margin of Arabia are based on retrodeformed sections A-A′ and E-E′ and represent contraction within the Zagros Mountains [*McQuarrie*, 2003]. Shortening estimates for the southern margin of Eurasia are marked by B-B′, C-C′ and D-D′ and represent contraction of the Kopet Dagh Mountains, Alborz Mountains and Iranian Plateau respectively (this study, [*Emami*, 1982; *Haghipour et al.*, 1987; *Lyberis and Manby*, 1999]). U-D and v-pattern shows location of the Urumieh-Dokhtar arc and MRF is the active, strike-slip, Main Recent fault.

yield uncertainty ellipses representing 95% confidence regions [*Molnar and Stock*, 1985] (Auxiliary Figure 1, Table 1 and 2[1]).

[5] A critical step in determining the onset of continent-continent collision using plate reconstructions is setting limits on the location of the edges of each of the continents in question, which are now in contact just south of the Urumieh-Dokhtar arc (Figure 1). We reconstruct the northern margin of Arabia by obtaining minimum shortening estimates for platform strata in the Zagros Mountains, which lie at the northern margin of the Arabian Plate (Figure 1). Through the Mesozoic, Southern Eurasia grew through the amalgamation, displacement and rotation of a complex system of continental fragments. By latest Cretaceous [*Sengör and Natal'in*, 1996], these fragments were in their present relative positions, although contraction of minor ocean basins between some of these fragments may have continued into the early Tertiary [*Sengör*, 1990]. Mid-Tertiary to present shortening estimates for Eurasia are based on cross-section lines through platform strata across the Kopet Dagh, Alborz and Central Iran (Figure 1), allowing for the reconstruction of the southern Eurasian margin prior to collision. Shortening in the Zagros Mountains ranges from 67–85 km (AA′ and EE′ Figure 1 [*McQuarrie*, 2003]), while post-collisional shortening within Eurasia is 65–75 km through the Kopet Dagh Mountains (DD′ Figure 1 [*Lyberis and Manby*, 1999]) and 18 km across Central Iran (BB′ and CC′ Figure 1 [*Emami*, 1982; *Haghipour et al.*, 1987]). Accounting for shortening of platform strata in Arabia and Eurasia therefore expands the northern and southern continental margins into the Neotethys at least 80 km and 70 km, respectively.

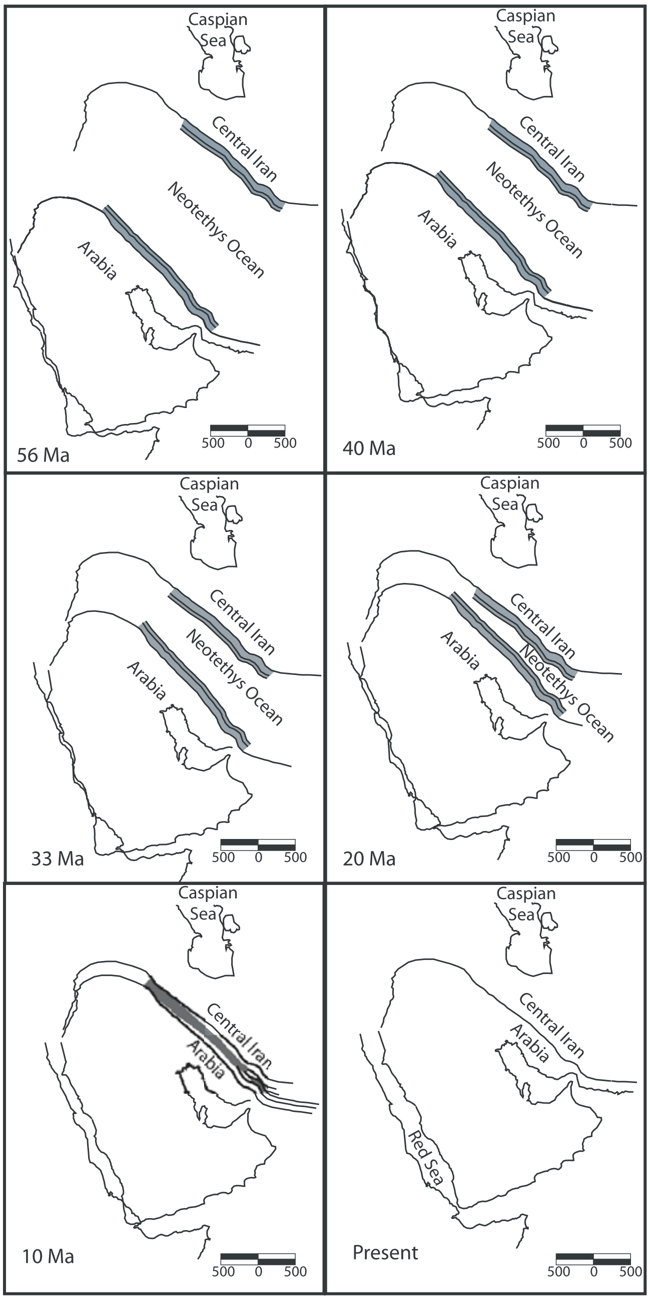
[6] In addition to the 150 km of tectonic shortening of the platforms, the width of the Neotethys Ocean must also account for a narrow (~50 km) passive margin that must have existed on both sides of the ocean basin, but is not preserved in the geologic record on either side of the suture zone [*Berberian and King*, 1981; *Murris*, 1980; *Stocklin*, 1968]. In our calculations, a minimum passive margin width of 50 km is added to both sides of the reconstructed platforms by analogy with the narrowest continent-ocean transitions proposed for the Red Sea [*Bohannon*, 1986].

[7] It is unlikely that significant deformation of these external platforms occurred prior to collision, given their position either on the downgoing plate (Zagros) or up to 400 km north of the suture (Kopet Dagh). Deformation within the immediate overriding plate (the Sanandaj-Sirjan zone between the suture and the volcanic arc) is not included in these calculations. The age of deformation is post-5 Ma for both the Kopet Dagh Mountains [*Lyberis and Manby*, 1999] and Central Iran [*Emami*, 1982; *Haghipour et al.*, 1987], and post-20 Ma for the Zagros [*Hessami et al.*, 2001; *Koop and Stonely*, 1982].

[8] Combining these constraints with plate kinematics shows that at ~56 Ma the ocean basin was ~1300 km wide (Figure 2). Overlap of the reconstructed margins occurred by 10 Ma, indicating the latest possible age of collision and therefore the onset of continent-continent convergence at an average rate of ~2 cm/yr. Larger shortening estimates through Central Iran, or allowing for more extensive passive margins (say, an additional 100 km of continental width for each margin) would indicate an age of collision as early as 20 Ma. However, the lack of evidence for alpine-style shortening in Iran, or any remnants of a wide passive margin implies a time of initial collision closer to 10 Ma. If this estimate is correct, and the onset of Red Sea opening occurred between 30 and 20 Ma, then any genetic relationship between collision and rifting is precluded. Even through the plate tectonic estimate provide the latest possible time of collision (10 Ma), the reconstructions also place reasonable bounds on a maximum age of collision. For example, for Arabia to collide with Eurasia at ~30 Ma, coincident with the opening of the Red Sea [*Jolivet and Faccenna*, 2000], approximately 500 km of continental lithosphere (20 Myr of convergence at 2.5 cm/yr) must be removed from the system, presumably via subduction (Figure 2).

[9] Even though collision could not have occurred later than ~10 Ma, events at ~5 Ma, including rapid unroofing of the Alborz Mountains [*Axen et al.*, 2001], subsidence of the south Caspian Sea [*Allen et al.*, 2002], onset of oceanic spreading in the Red Sea [*Joffe and Garfunkel*, 1987] and possibly initiation of tectonic extrusion to the east and west of the collision zone [*Axen et al.*, 2001; *Westaway*, 1994], suggest a widespread change in the mechanism by which shortening of Eurasia was accommodated. Thus shortening may have initially been accommodated by rapid shortening in the Zagros fold-thrust belt near 10 Ma, followed by more

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL017992.



Rates of convergence and subduction

age	convergence rates	arc-normal rates	arc-parallel rates
0-10 Ma	20±4 mm/yr	17 mm/yr	14 mm/yr
10-20 Ma	24±2 mm/yr	18 mm/yr	16 mm/yr
20-33 Ma	31±1 mm/yr	30 mm/yr	
33-56 Ma	32±2 mm/yr	31.5 mm/yr	

Figure 2. Maps showing the evolution of the Neotethys, and the relationship between opening of the Red Sea and collision of Arabia and Eurasia (as show by the overlap of the shaded region). The wide gray-shaded bands represent the amount of shortened crust (70 km) on the Arabian plate and in Eurasia (80 km). Narrower (inside) bands represent passive margins (50 km) on both the north and south side of the Neotethyan ocean basin (see text for explanation). Rates of convergence are for a point located at 32.70°N, 50.38°E.

broadly distributed shortening that included the Eurasian plate beginning at ~5 Ma.

3. Long-Term Convergence Rates

[10] The rate of motion of Arabia with respect to Eurasia has been fairly constant between 2 and 3 cm/yr since 56 Ma (Figure 2). The opening of the Red Sea at ~25 Ma, at rates estimated between 10 and 16 mm/yr [*Chu and Gordon*, 1998; *Joffe and Garfunkel*, 1987], therefore does not correspond to any significant change in the rate of convergence between Arabia and Eurasia, but is instead coincident with a marked deceleration of Africa-Eurasia relative motion (Figure 3). To first order, this observation suggests that the negative buoyancy associated with a subducting slab under Eurasia played a key role in the balance of forces that governed the rate of northward motion of the African plate.

[11] The reconstructions also show the direction of Arabia-Eurasia motion changes from northeast from 56 to ~25 Ma to due north since ~25 Ma, altering the rate of arc-normal subduction. After 10 Ma, the rate of oblique convergence resolves into an arc-normal component of 17 mm/yr reflected in shortening of the Zagros, Alborz and Kopet Dagh, and an arc-parallel component of 14 mm/yr, part of which may be taken up by 50–70 km of right-lateral, strike-slip displacement on the Main Recent Fault, the northern boundary of the Zagros Mountains [*Talebian and Jackson*, 2002], and part on other active strike-slip faults in northern Iran [*Axen et al.*, 2001; *Priestley et al.*, 1994] (Figure 2).

4. Slow Steady Subduction and Episodic Volcanism

[12] The Urumieh-Dokhtar arc ranges in age from Cretaceous to Recent, but is dominated by 50–35 Ma intermediate to silicic volcanics and plutons [*Alavi*, 1980; *Berberian et al.*, 1982; *Berberian and King*, 1981]. The highest rates of arc-normal convergence occurred during

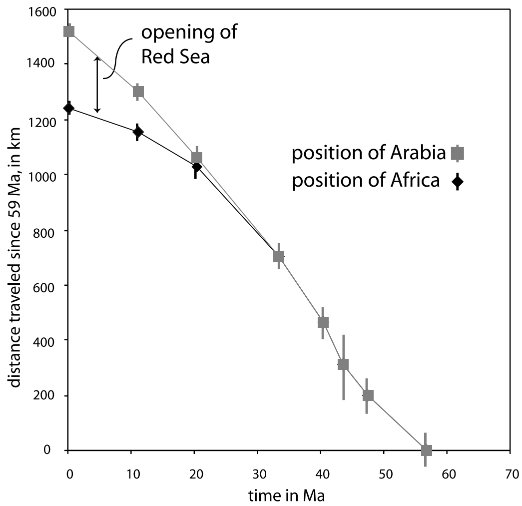


Figure 3. Graph showing the position of a reference point (38°N, 48°E) representing Arabia with respect to Eurasia versus time, both including (gray boxes) and excluding (black diamonds) rotation describing the opening of the Red Sea [*Chu and Gordon*, 1998; *Joffe and Garfunkel*, 1987].

this interval, but the rates of convergence (~30 mm/yr) are still a factor of 2 to 3 smaller than those seen in Andean-type arcs in North and South America. Comparison of the rates of volcanic accumulation in Iran and Cenozoic arc successions in western North America indicate the mid-Tertiary Urumieh-Dokhtar arc generally accumulated 3 to 4 times more volcanic strata per unit time (up to 1.8 mm/yr at its peak, versus 0.5 mm/yr for the most productive western U. S. sequences; Auxiliary Figure 2). Because arc-normal convergence was no more than half of Farallon-North America convergence in the Tertiary (Auxiliary Figure 2), the productivity of the Iranian arc per kilometer of arc-normal plate convergence appears to be nearly an order of magnitude greater, implying exceptionally fertile source rocks for a restricted period of time.

[13] The enigmatic mid-Tertiary volcanic pulse begs the question of whether a history of subduction more complex than northward subduction of a single plate is possible, which in turn bears on the question of whether Arabia and Africa were mechanically coupled to a single south-facing arc prior to opening of the Red Sea. For example, active spreading in the Neotethys from 50–35 Ma could accelerate subduction rates and magmatic production, but would decouple Africa from the subducting slab beneath the Urumieh-Dokhtar arc, thereby removing the effect of slab pull on the plate [*Conrad and Lithgow-Bertelloni*, 2002]. Although the creation and rapid subduction of a large microplate under the Urumieh-Dokhtar volcanic arc would help explain the voluminous mid-Tertiary magmatism, there is only a small range of possible spreading rates (4–6 cm/yr) and spreading ridge locations (50–200 km from the northern edge of Arabia) that could produce subduction rates comparable to modern Andean settings from 50 to 35 Ma.

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