Retrodeforming the Arabia-Eurasia collision zone: Age of collision versus magnitude of continental subduction

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ABSTRACT

The Arabia-Eurasia collision has been linked to global cooling, the slowing of Africa, Mediterranean extension, the rifting of the Red Sea, an increase in exhumation and sedimentation on the Eurasian plate, and the slowing and deformation of the Arabian plate. Collision age estimates range from the Late Cretaceous to Pliocene, with most estimates between 35 and 20 Ma. We assess the consequences of these collision ages on the magnitude and location of continental consumption by compiling all documented shortening within the region, and integrating this with plate kinematic reconstructions. Shortening estimates across the orogen allow for ~350 km of Neogene upper crustal contraction, necessitating collision by 20 Ma. A 35 Ma collision requires additional subduction of ~400–600 km of Arabian continental crust. Using the Oman ophiolite as an analogue, ophiolitic fragments preserved along the Zagros suture zone permit ~180 km of subduction of the Arabian continental margin plus overlying ophiolites. Wholesale subduction of this more dense continental margin plus ophiolites would reconstruct ~400–500 km of postcollisional Arabia-Eurasia convergence, consistent with a ca. 27 Ma initial collision age. This younger Arabia-Eurasia collision suggests a noncollisional mechanism for the slowing of Africa, and associated extension.

INTRODUCTION

When did continents collide, and how is convergence partitioned after collision, are first-order questions that seem to defy consensus along the Alpine-Himalayan orogen, our classic example of continent-continent collision. Although estimates for the age of the Arabia-Eurasia collision have ranged from the Late Cretaceous to Pliocene, most authors prefer a collision age between 20 and ca. 35 Ma (Jolivet and Faccenna, 2000; McQuarrie et al., 2003; Agard et al., 2005; Allen and Armstrong, 2008; Fakhari et al., 2008; Horton et al., 2008; Ballato et al., 2011). Is the difference of ~15 m.y. critical? A ca. 35 Ma collision would predate, and hence potentially facilitate, the opening of the Red Sea and the slowing of Africa, which in turn may have caused slab rollback and accompanying extension in the Mediterranean at ca. 30 Ma (Jolivet and Faccenna, 2000). The closing off of the Tethyan seaway would enable a reorganization of ocean currents that may have aided Late Eocene global cooling (Allen and Armstrong, 2008). In contrast, a 20 Ma collision disconnects the slowing of Africa, extension in the Mediterranean and Red Sea, and the start of global cooling from the Arabia-Eurasia collision. An early age of collision would predate rapid cooling of rocks and syntectonic sedimentation recorded on the both the Eurasian and Arabian plates by 10–20 m.y. (Guest et al., 2007; Ballato et al., 2008; Fakhari et al., 2008; Morley et al., 2009; Gavillot et al., 2010; Khadivi et al., 2012; Rezaeian et al., 2012), and would require an additional process to enhance tectonic deformation, uplift, and exhumation at ca. 25–20 Ma.

The only direct means of dating the collision between Arabia and Eurasia is to uniquely identify sediment with a Eurasian provenance on the Arabian plate. These Early Miocene synorogenic strata (Agard et al., 2005; Fakhari et al., 2008) only provide an upper estimate for the collision, while permitting collision at any earlier time. We test viable collision ages by compiling all documented shortening within the orogen and integrating that shortening history into Arabia–Nubia–North America–Eurasia plate circuit rotations. This approach provides precise estimates of the relative positions between the northern Arabian margin, its overlying ophiolites, and the southern Eurasian margin for the Cenozoic.

GEOLOGIC BACKGROUND

Ophiolite Obduction

The earliest period of contractional deformation along the northern Arabian margin after Permian opening of the Neotethyan Ocean was the emplacement of ocean floor and associated radiolarite-rich sedimentary rocks and arc remnants onto the Arabian passive margin (Berberian and King, 1981; Agard et al., 2011). The precollisional geometry of the ophiolite belt obducted on to the Arabian margin is exemplified by the fully preserved Semail ophiolite of Oman (e.g., Searle and Cox, 1999). Using the preserved extent of the Oman ophiolite as the type example, the Late Cretaceous obduction may have emplaced Iranian ophiolites (Kermanshah and Neyriz) over ~180 km of the Arabian continental margin and created a flexural foreland basin that stretched ~200 km (restored extent) to the south (Robertson, 1987; Koop and Stoneley, 1982; Homke et al., 2009) (Fig. 1). The foreland basin and overlap deposits contain

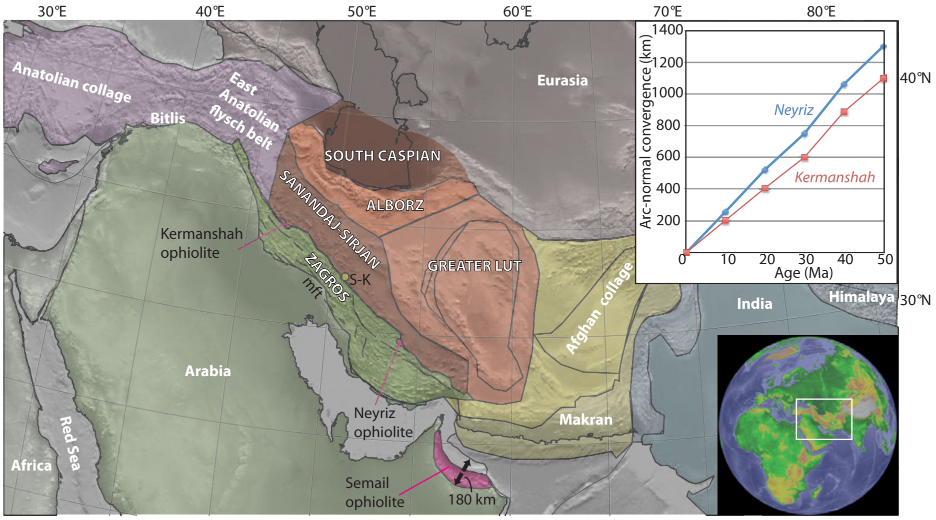

Figure 1. Tectonic and topographic map of the Arabia-Eurasia collision zone, with the main tectonic elements used for the reconstruction in this paper. mft—mountain front thrust; S-K—Shahr-Kord. Inset: Arc-normal component of Arabia-Eurasia convergence for locations of Kermanshah and Neyriz (Iran) using the plate circuit detailed in the text. Error bars for all data points are smaller than the dots (<30 km).

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ophiolitic erosion products such as detrital chert, serpentinite, altered feldspar, pyroxene, and chlorite, chromite, and limestone fragments (Homke et al., 2009). After emplacement of ophiolites onto the Arabian margin, the remaining Neotethyan Ocean basin (>1000 km wide) continued to subduct under the Eurasian continent (e.g., Agard et al., 2011). Thus ophiolitic erosion products on Arabia cannot be used as a conclusive age marker for continent-continent collision.

Collision Age Constraints

Sedimentary rocks with a Eurasian provenance deposited on the Arabian plate are indisputable evidence of Eurasia-Arabia collision. South of Shahr-Kord, Iran (Fig. 1), Lower Miocene synorogenic strata with growth structures adjacent to the Main Zagros fault require collision before 23–20 Ma (Fakhari et al., 2008). To the northwest, in the region of Kermanshah (Fig. 1), Oligocene–Lower Miocene conglomerate and overlying limestone seal major thrusts between Paleocene–Eocene magmatic arc rocks of the Eurasian plate, ophiolites, and Arabian passive-margin sediments, requiring collision with Eurasia prior to 23–25 Ma (Agard et al., 2005, 2011). The youngest documented ages in the emplaced Eocene arc are 39 ± 1 Ma, which brackets the age of collision between 39 ± 1 Ma and 24 ± 1 Ma (Agard et al., 2011). What complicates using the young age as the age of collision is upper plate deformation, exhumation, and sedimentation located 600–1200 km north of the suture, with ages that cluster between 30 and 36 Ma. These data are used to argue for an older, 36 Ma, collision age (Vincent et al., 2007; Ballato et al., 2011; Rezaeian et al., 2012).

Age of Deformation

Although low-angle (15°) unconformities within the Zagros fold-and-thrust belt have been interpreted to represent latest Eocene–Early Oligocene deformation (Hessami et al., 2001), rapid exhumation in the High Zagros from 19 to 15 Ma is the earliest definitive age of deformation within this region (Gavillot et al., 2010). A broadly southward progression of deformation is indicated by growth structures in synorogenic sedimentary rocks that young from 15 to 14 Ma just south of the High Zagros thrust, to 8–3 Ma at the mountain front thrust (e.g., Mouthereau et al., 2012) (Fig. 1).

The next period of significant deformation on the Eurasian plate after early Cenozoic exhumation and sedimentation is from 17.5 Ma to 11 Ma (Guest et al., 2007; Ballato et al., 2008; Rezaeian et al., 2012). Compressional deformation initiated later in central Iran, with pronounced folding and growth structures dated at ca. 10 Ma (Morley et al., 2009). The age of strike-slip faulting that is pervasive through central Iran can only be constrained as younger than Eocene (Allen et al., 2011).

METHODS: PLATE TECTONIC RECONSTRUCTIONS

Arabia–Nubia–North America–Eurasia plate circuit rotations provide precise estimates of the relative plate motions between stable Arabia and Eurasia. These plate rotations are constrained by marine magnetic anomaly and fracture zone–based reconstructions of the central (Müller et al., 1999) and northern Atlantic Ocean (Gaina et al., 2002), combined with Red Sea rotations (Joffe and Garfunkel, 1987). We limit our reconstruction to the collision of Arabia with the "Cimmerian" continents of Iran that collided in Late Triassic time with Eurasia (rust-colored blocks in Fig. 1). The Iranian blocks are bounded at the Turkey-Iran border by a north-south–trending paleo–transform fault separating Iran from an eastern Mediterranean microcontinent system (e.g., Sengör and Natal'in, 1996).

A critical step in determining the onset of collision using plate reconstructions is documenting the location of each continental edge, now in contact along the Zagros suture zone (Fig. 1). We reconstruct both margins by restoring shortening from the Zagros Mountains (including the "crush zone"; Agard et al., 2005), central Iran, and the Alborz/Kopet Dagh (Table 1). Because the nature of our question is how early collision could have occurred, we use the highest values for the shortening estimates listed in Table 1.

GPlates freeware (http://www.gplates.org; Boyden et al., 2011) was used for the reconstruction. Polygons representing the boundaries of each domain move with respect to each other during the time span of deformation. The only segment that changes area in the reconstructions is the northern margin of Arabia. To simplify viewing the magnitude and location of shortening through the region, we divide the Eurasian orogen into "blocks" that are modeled to not internally deform but move with respect to each other. The magnitude of shortening within Eurasia is shown as open spaces between individually defined blocks. From north to south, these blocks are the South Caspian (with the northern boundary being the Aspheron ridge; Jackson et al., 2002), the Alborz block, the "Greater Lut" block (i.e., the Lut block and surrounding Jurassic–Cretaceous ophiolites and flysch belts), and Sanandaj-Sirjan (including the Urumieh-Dokhtar volcanic arc). Zagros shortening is reconstructed in a northeast-southwest direction, and is depicted as the modern width of the Zagros Mountains increased by the maximum estimates of shortening that occurred to the southwest of, and structurally below, the obducted ophiolite remnants. Shortening accommodated by the northeastern Arabian margin includes shortening in the crush zone, which also accounts for overthrust of Eurasia onto Arabia, thrust faulting in the High Zagros, and the Zagros fold-and-thrust belt (Table 1). The reconstruction of Zagros shortening identifies the southwesternmost position that the Cretaceous ophiolites reached after their Cretaceous obduction onto Arabia. The strike-slip component of oblique Arabia-Eurasia convergence is entirely reconstructed along the suture zone, although we note that this component is partitioned throughout the orogen; this does not affect the collision age.

TABLE 1. DISPLACEMENTS USED IN THE RECONSTRUCTION

Structure/region	Sense	Published amount (km)	Modeled amount (km)	Age/duration (Ma)	References
Zagros	Thrust	110–175	175		McQuarrie, 2004; Agard et al., 2005; Sherkati et al., 2006; Gavillot et al., 2010; Vergés et al., 2011; Khadivi et al., 2012
Crush zone before 23 Ma		10–20		>23	
Crush zone after 20 Ma		50–70		20–15	
High Zagros		20–30		19–10	
Zagros fold-and-thrust belt		30–55		15–0	
Underthrust Arabian margin		150–300	350 (Zagros + ophiolite)		Paul et al., 2010
Sanandaj-Sirjan zone		0	0		Agard et al., 2005
Central Iran	Thrust	38–50	50	10–0	Morley et al., 2009
	Strike-slip	50*	50	20–4	Allen et al., 2011
Alborz	Both	50	50	16–0	Rezaeian et al., 2012; Guest et al., 2006; Ballato et al., 2008
Caspian Sea (Aspheron ridge)	Thrust	?	25	10–0	
Kopet Dagh	Thrust	65–75	75	16–0	Lyberis and Manby, 1999

*Estimated from 250 km of strike slip calculated by Allen et al., 2011, assuming block rotation.
?—25 km of thrust sense displacement balances disparity in shortening amounts between Alborz and Kopet Dagh.

RESULTS

Rotating the restored Eurasian and Arabian margins back in time using the plate circuit indicates that at 35 Ma, the southwestern front of the Cretaceous ophiolites on the Arabian plate was still ~400 km (northwest, Kermanshah ophiolite) to 600 km (southeast, Neyriz ophiolite) away from the restored Eurasian margin, in the direction of shortening (Fig. 2). At 20 Ma, the restored position of the Kermanshah ophiolite overlaps with the Eurasian margin. This shows that post–20 Ma shortening is equal to convergence of Arabia and Eurasia, consistent with the age of deformation within the High Zagros (Agard et al., 2005; Gavillot et al., 2010). Collision of Arabia with Eurasia earlier than 20 Ma, as required by Eurasian-derived synorogenic sediments deposited on Arabia (Agard et al., 2005; Fakhari et al., 2008), is only possible if the Arabian passive margin, together with obducted oceanic crust, was (almost) entirely subducted during the early phase of collision (e.g., Ballato et al., 2011), or if major (~400 km) pre-Miocene shortening has remained unnoticed on the Eurasian side or in the Zagros. The ophiolitic fragments on the Arabian plate are tied to their foreland basin that extends ~200 km southward of the ophiolite remnants after accounting for Zagros shortening (Koop and Stoneley, 1982; Homke et al., 2009). This relationship limits shortening of Arabia to documented estimates. Wholesale subduction of an ophiolite-covered Arabian margin may have been facilitated by the high density of the overlying ophiolites. Assuming this, we may assess the maximum collision age by adding a width of Arabia's continental margin corresponding to the current overlap of the Oman ophiolite over Arabian continental crust that resulted from Late Cretaceous obduction (~180 km) (Fig. 1). This displacement magnitude on the ophiolite sole thrust is similar to the upper limit for crystalline thrust sheets (e.g., Hatcher, 2004). Using the plate circuit constraints, a 180-km-wide "continental margin with overlying ophiolites" would allow for initial collision as early as 28–27 Ma (Fig. 2). The combined displacement of Zagros shortening and ophiolite subduction would predict 355 km of underthrust Arabian continental lithosphere, similar to the upper limit (~300 km) shown in receiver function analyses (Paul et al., 2010). To obtain a 35 Ma age of collision of the distal Arabian margin and overlying ophiolites with Eurasia would require that the Cretaceous ophiolites obducted Arabia over a distance of 400 km (Kermanshah ophiolite) to 600 km (Neyriz ophiolite). A more likely scenario is that at 35 Ma, 220–420 km of the Neotethyan Ocean was still separating the northeastern margin of Arabia from Eurasia.

DISCUSSION

Signals of Collision

Arguments for a 35 Ma or older age of collision rest on a change in kinematics from an extensional to a contractional regime at ca. 35 Ma, linked to a significant decrease in arc magmatism in central Iran (e.g., Ballato et al., 2011). These responses have been attributed to the initiation of a soft continental collision with the subduction of a stretched and denser continental Arabian lithosphere with overlying ophiolites beneath Eurasia (Ballato et al., 2011; Mouthereau et al., 2012). We suggest that instead of collision, the mild deformation, exhumation, and the change in overriding-plate volcanism recorded at ca. 35 Ma represent the transition from an extensional to a moderately compressional backarc, while the volcanic arc changed from an anomalously voluminous extension-related system from 50 to 35 Ma (Verdel et al., 2011) to a lower-flux, background state. A 28–27 Ma collision age agrees with the oldest preserved synorogenic sediments on the Arabian margin (Agard et al., 2005; Fakhari et al., 2008), the ca. 20 Ma age of onset of deformation within the High Zagros (Agard et al., 2005; Gavillot et al., 2010), as well as 24 Ma fission-track cooling ages in detrital apatites deposited in 19–18 Ma foreland basin sediments (Khadivi et al., 2012).

Paleogene Geodynamics: Consequences of the Arabia-Eurasia Collision?

A ca. 27 Ma collision age for Arabia and Eurasia would remove collision of Arabia with Eurasia as a first-order driver of the slowing of Africa, which initiated at ca. 30 Ma (Jolivet and Faccenna, 2000; McQuarrie et al., 2003), falls

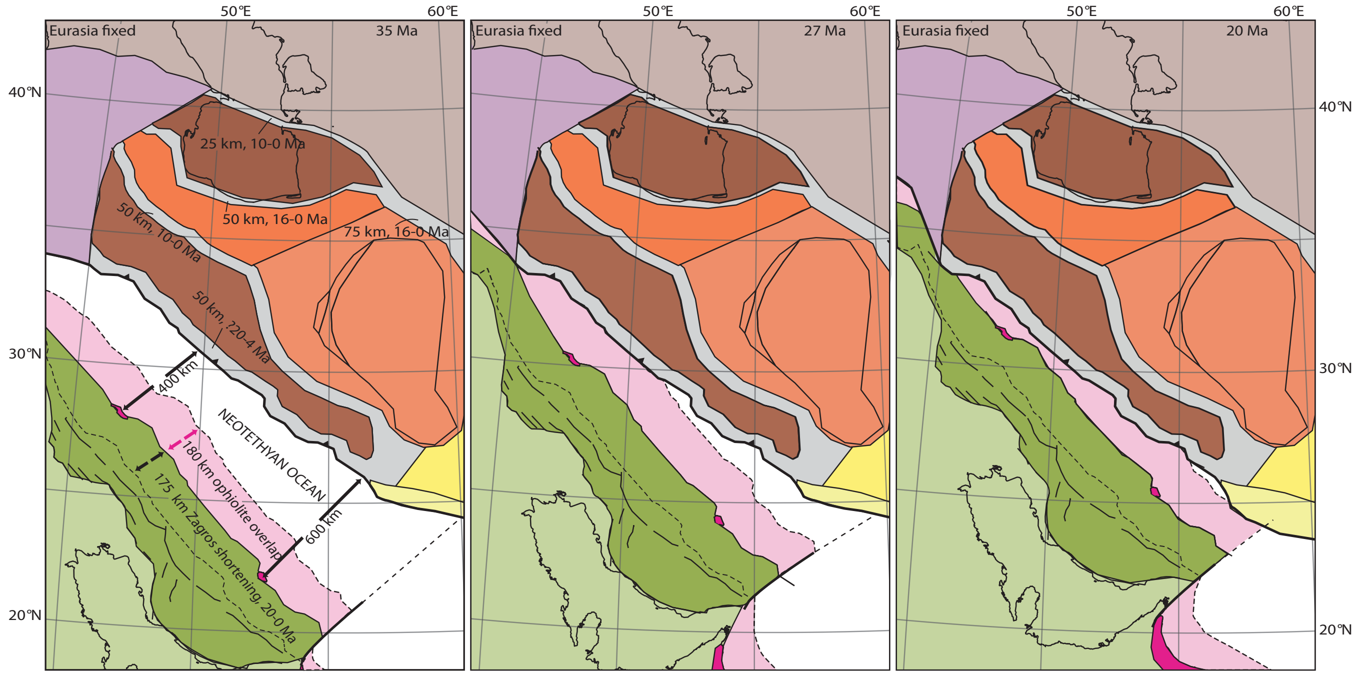

Figure 2. Summary of data on block diagram of moving parts, and reconstructions at 20, 27, and 35 Ma of the Arabia-Eurasia collision. See Table 1 for shortening estimates, and see the GSA Data Repository[1] for the reconstruction files.

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[1] GSA Data Repository item 2013084, instructions for downloading and using the rotation and shape files in GPlates format, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

within the window of time proposed for opening of the Red Sea (25–30 Ma), and postdates (albeit barely) the initiation of extension in the Mediterranean (Jolivet and Faccenna, 2000). While the overlap in time of all four processes makes it tempting to link them, our reconstructed collision age implies that the collision was either felt instantly, or even anticipated 1–2 m.y. before initiation of collision. Unless 220–420 km of additional Oligocene shortening is documented in Eurasia, or ophiolites can be proven to obduct onto continental margins over distances of 400–600 km, the dynamic causes of the plate kinematic changes at 30 Ma need to be sought elsewhere.

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