Stratigraphic response and mammalian dispersal during initial India-Asia collision: Evidence from the Ghazij Formation, Balochistan, Pakistan

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ABSTRACT

Initial continental collision between India and Asia is thought to have caused significant changes to global climate and biota, yet its timing and biogeographic consequences are uncertain. Structural and geophysical evidence indicates initial collision during the early Paleogene, but sedimentary evidence of this has been controversial owing to the intense deformation and metamorphism along the suture zone. Modern orders of mammals that appeared abruptly on northern continents coincident with the global warming event marking the Paleocene-Eocene boundary are hypothesized to have originated on the Indian subcontinent, but no relevant paleontological information has been available to test this idea. Here we present new paleomagnetic, sedimentologic, and paleontologic evidence to show that the lower Eocene Ghazij Formation of western Pakistan records continental sedimentation and mammalian dispersal associated with initial India-Asia collision. Our results are consistent with the initial collision occurring near the Paleocene-Eocene boundary, but modern orders of mammals appeared later in Indo-Pakistan and thus did not likely originate on the Indian subcontinent.

Keywords: India, Asia, collision, paleomagnetism, mammals.

INTRODUCTION

Deformation and metamorphism of the High Himalaya have obscured much of the sedimentary record associated with initial India-Asia continental collision. The sedimentary evidence that does exist is controversial because of structural complications and a lack of contextual information that could link it to other (e.g., geophysical and paleontological) records of initial collision (Bossart and Oittinger, 1989; Rowley, 1996; Najman et al., 2001). Reliable stratigraphic records of early collision are critical for testing proposed links of India-Asia tectonics to global climatic and biotic change during the early Paleogene (Beck et al., 1998) and for constraining the structural evolution of the collision zone (Burbank et al., 1996). The lower Eocene Ghazij Formation in the western part of Pakistan preserves a thick sequence of unmetamorphosed sedimentary rocks that records a dramatic shift from marine to continental deposition (Warwick et al., 1998; Johnson et al., 1999). Here we report new results that indicate that the Ghazij was deposited in response to initial India-Asia continental collision. Paleomagnetic data indicate that Ghazij deposition occurred just before a pronounced decrease in the seafloor spreading rate of the Indian Ocean (Patriat and Achache, 1984). Large fossil mammal assemblages show strong endemism in the middle part of the formation, but increasing cosmopolitanism and affiliation with northern continents higher in the formation. No other sedimentary unit along the suture zone preserves such an integrated sedimentary, geophysical, and paleontological record of this early stage of collision.

GEOLOGIC SETTING

The Ghazij Formation is well exposed along the northwest margin of the Indo-Pakistan plate near its suture with Asia (Fig. 1). Sedimentologically, it exhibits a clear transition from shallow-marine facies in the lower part, to paralic deltaic facies in the middle part, to continental fluvial facies in the upper part (Johnson et al., 1999). Continental facies dominate in the western part of the field area, where conglomerate thicknesses exceed 400 m. Marine facies dominate in the eastern part of the field area, indicating the existence of a shallow-marine basin between the deposition of Ghazij continental facies and the main Indian craton (Fig. 1). We have measured current directions from fluvial sandstones across the entire extent of the Ghazij, and they show consistent northwest to southeast flow (Fig. 1). This direction is opposite the flow direction recorded by the underlying Cretaceous Pab Formation, interpreted to be associated with continental runoff from India during its isolation (Waheed and Wells, 1990; Sultan, 1997). Petrography of Ghazij sandstones shows a dominance of sedimentary lithic fragments and recycled monocrystalline quartz grains (Warwick et al., 1998; Johnson et al., 1999). Compositions vary strongly across the field area, according to the lithology of underlying Mesozoic rocks. For example, Ghazij sandstones in Kingri have abundant monocrystalline quartz grains and rare grains of tourmaline diagnostic of the underlying Cretaceous Pab Formation, which is particularly well developed in this region. Ghazij sandstones near Quetta are dominated by limestone fragments that coincide with the underlying Cretaceous Pab Limestone and Jurassic Chil¬tan Limestone. This sedimentary evidence indicates that streams depositing middle and upper Ghazij sandstones had sources in nearby uplifted areas on the northwest margin of Indo-Pakistan and that Mesozoic shelf sedimentary rocks were exposed and being eroded at that time.

PALEOMAGNETIC ANALYSIS

We undertook a paleomagnetic study of the Ghazij Formation in an effort to better understand its geochronology and tectonic setting. Most paleomagnetic studies of rocks near the suture zone are characterized by strong overprints (Klootwijk et al., 1994), and the Ghazij is no different. However, through extensive pilot sampling, we were able to identify two lithologies—gray marine shales and red paleosol mudstones—that showed good potential for preserving characteristic remanent magnetizations. By targeting these facies, we were able to isolate well-defined characteristic directions for 22 sites (83 samples) in 4 different locations (Shin Ghwaza, Deghari, Pir Ismail Ziarat, and Kingri; Fig. 1 and Table DR1). All of these sites are characterized by three or more samples that exhibited characteristic directions defined by principal-component anal-

GSA Data Repository item 2003163, Table DR1 and Figures DR1–DR2, is available online at www.geosociety.org/pubs/ft2003.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
ysis of four or more demagnetization points with a maximum angular deviation of ±15°. Samples were analyzed in paleomagnetic laboratories at the University of New Hampshire and the University of Michigan.

Gray shale samples were weakly magnetized and characterized by unblocking temperatures of ±580 °C and coercivities of tens of milliTesla, consistent with a diffuse magnetite carrier (Fig. DR1A; see footnote 1). Red palaeosol mudstones were characterized by relatively strong magnetizations and typically had an intermediate-temperature normal-polarity overprint (unblocking temperatures < −600 °C) and a high-temperature-dual-polarity characteristic magnetization (unblocking temperatures ~690 °C; Figs. DR1B–DR1E; see footnote 1). Mean characteristic directions of gray shale samples and red mudstone samples are statistically indistinguishable. Characteristic magnetizations for these sites pass the fold test and reversal test at the 95% confidence limit (Tauxe, 1998) and exhibit a mean declination and inclination of 334.6° and 4.0° (α95 = 6.7) in bedding-corrected coordinates when all reversed-polarity sites are inverted (Fig. DR2A; see footnote 1).

Site directions are Fisher distributed; however, there is a slight azimuthal streaking of directions that indicates minor vertical-axis rotations (Fig. 2A). Pilot samples analyzed from other sites close to major fault zones show even greater amounts of vertical-axis rotation. We suspect that these rotations are associated with the structural development of the Quetta synclise, but further sampling will be required to quantify this.

In one location, Shin Ghwaza (Fig. 1), we sampled a 500 m section through the Ghazij Formation at 5–10 m intervals to make a magnetostratigraphic correlation to the geomagnetic polarity time scale (GPTS; Cande and Kent, 1995). For evaluating magnetic polarity throughout this section, we augmented the site determinations with other samples that preserved well-defined characteristic directions but came from sites that did not otherwise meet the criteria already outlined herein. For some samples, magnetization directions followed a great circle path during demagnetization and a characteristic direction was determined by using the method of McFadden and McElhinny (1988).

The bottom of the Shin Ghwaza section is characterized by reversed polarity with a clear change to normal polarity ~140 m above the base of the section (Fig. 3). The upper part of the section is dominated by normal polarity but contains one poorly sampled reversed polarity zone between 220 and 260 m. We correlate the well-sampled polarity reversal at 140 m to the chron C24r–C24n reversal in the GPTS. This correlation is constrained by foraminiferal biostratigraphy that indicates an early or middle Ypresian age (early Eocene) for the lower and middle Ghazij from this area (reviewed in Gingerich et al., 1997). Correlation of the poorly constrained upper reversed zone is more difficult because there is no precise age control on the upper Ghazij here. Further to the east in Rakhi Nala (Fig. 1), the Drug Limestone is correlated to the P9 planktonic foraminifera zone (Afzal, 1996) and directly overlies the Ghazij Formation, meaning that the upper reversed zone at Shin Ghwaza could be one of the short reversals in the middle of chron C24r or more likely C23r.

**TECTONIC INTERPRETATION**

With these constraints, we interpret the age of the Ghazij to range from ca. 56 to 50 Ma. By using this age range, we compare our paleomagnetic results for the Ghazij with independently derived derived paleolatitude estimates using the most recently published apparent polar wander path (APWP) for the Indian subcontinent (Besse and Courtillot, 2002). Our paleomagnetic results from the Ghazij indicate that it was deposited at a low paleolatitude of 2°N ± 3.4°. This is indistinguishable from the expected latitudinal position (4°N ± 4.3°) for the area during this time determined by using the Indian APWP (Besse and Courtillot, 2002). The observed overlap between these two data sets shows that Ghazij deposition occurred just before a significant decrease in India’s rate of northward migration (Fig. 2). This change in northward movement has been linked to decreased spreading rates along mid-ocean ridges in the Indian Ocean and is interpreted to represent the slowing of convergence between India and Asia due to initial continental collision (Patriat and Achache, 1984). The first decrease in convergence rate began ca. 55 Ma (Besse and Courtillot, 2002), but the most obvious deceleration occurred ca. 50 Ma. We interpret this lag between the onset of Ghazij sedimentation and the most significant slowing of ocean spreading to represent a time when the thin continental shelf on the leading edge of the Indian plate was undergoing compression during its initial subduction under Asia (Butler, 1995).

Our results support the hypothesis that ini-

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2Note added in proof: Our paper uses the synthetic apparent polar wander path for India that was reported in Table 5 of Besse and Courtillot (2002). Consequently, the results are not affected by the recently published correction, Besse and Courtillot (2003), to the master apparent polar wander path reported in their Table 4.
MAMMALIAN DISPERSAL

Fossil mammals have been recovered from three intervals of the middle and upper Ghazij Formation (Gingerich et al., 1997, 1998, 1999, 2001; Ginsburg et al., 1999). These assemblages show significant stratigraphic change in composition (Fig. 4). The middle Ghazij fauna associated with coal deposits is dominated by an endemic family of archaic mammals, Quetacyonidae, that has not been observed elsewhere. The fauna from the lower part of the upper Ghazij has a mixture of endemic quetacyonids and cosmopolitan taxa known elsewhere on northern continents (e.g., tillodonts and perissodactyls). The uppermost Ghazij fauna is known from a well-sampled assemblage near Kingri that is dominated by cosmopolitan taxa found on northern continents (e.g., perissodactyls, primates, and artiodactyls; Gingerich et al., 2001). Ghazij mammal faunas exhibit a pattern of decreasing endemism, increasing holarctic affiliation, and increasing modernity through time (Fig. 3).

The latest Cretaceous vertebrate fauna of Balochistan is Gondwanan (Wilson et al., 2001), but our results indicate that well-developed connections to northern continents (via Asia) were in place by late Ghazij time. It is interesting to note that the Kuldana and Kalakot faunas of early middle Eocene age show an endemic diversification within some holarctic groups that first appeared during Ghazij time (e.g., artiodactyls). Thus, early dispersal corridors were probably temporary, and endemism was initiated anew when the subcontinent was again partially isolated by marine incursions during early middle Eocene time.

Many modern orders of mammals first appeared on northern continents at or near the global warming event marking the Paleocene-Eocene boundary (e.g., perissodactyls, artiodactyls, and primates; Clyde and Gingerich, 1998; Bowen et al., 2002), and it has been hypothesized that these dispersed from the Indian subcontinent at the time of initial collision (Krause and Maas, 1990). Our results indicate the opposite. It appears that during initial collision, modern orders of mammals dispersed into India rather than out of it.

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