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Notes

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ABSTRACT

Modern generations of apparent polar wander paths (APWPs) show the occurrence in North American and African coordinates of a major and rapid shift in pole position (plate shift) during the Middle to Late Jurassic (175–145 Ma) that alternative curves from the literature tend to underestimate. This Jurassic massive polar shift (JMPS), of vast and as-yet unexplored paleogeographic implications, is also predicted for Eurasia from the North Atlantic plate circuit, but Jurassic data from this continent are scanty and problematic. Here we present paleomagnetic data from the Kimmeridgian–Tithonian (upper Jurassic) Garedu Formation of Iran, which was part of Eurasia since the Triassic. Paleomagnetic component directions of primary (pre-folding) age indicate a paleolatitude of deposition that is in excellent agreement with the latitude drop predicted for Iran from APWPs incorporating the JMPS. Moreover, we show that paleolatitudes calculated from these APWPs, used in conjunction with simple zonal climate belts, better explain the overall stratigraphic evolution of Iran during the Mesozoic. As Iran drifted from the tropical arid belt to the mid-latitude humid belt in the Late Triassic, carbonate platform productivity stopped while widespread coal-bearing sedimentation started, whereas as Iran returned to arid tropical latitudes during the JMPS, carbonate platform productivity and evaporitic sedimentation resumed. These results illustrate (1) the potent, but often neglected, control that plate motion (continental drift and/or true polar wander) across zonal climate belts exerts on the genesis of sedimentary facies; and (2) the importance of precisely controlled paleogeographic reconstructions for tectonic interpretations, especially during times of fast plate motion like the Jurassic. As a suggestion for future research, we predict that the adoption of Eurasian reference paleopoles incorporating the JMPS may lead to a reconciliation (or reinterpretation) of existing geologic and paleomagnetic data regarding the deformation history of central Asia.

INTRODUCTION

A recent global apparent polar wander path (APWP) based on a compilation of inclination flattening–free paleomagnetic poles from North America and other continents (Kent and Irving, 2010) shows the existence of a previously undetected, major polar shift (plate shift) of ~30° from high latitudes at 160 Ma in the Oxfordian (Late Jurassic; time scale of Walker et al., 2012) to lower latitudes by the end of the Jurassic at 145–140 Ma (Fig. 1A). A recent compilation of flattening-free paleomagnetic poles from Adria (the African promontory) and Africa shows a polar shift of similar magnitude between ca. 183 Ma (near the Pliensbachian-Toarcian boundary) and ca. 151 Ma (early Tithonian) (Muttoni et al., 2013). This Jurassic massive polar shift (JMPS) is associated with high plate velocities, ~20 cm/yr, as deduced for Africa from the Kent and Irving (2010) APWP (Fig. 1B). Previous APWPs from the literature (e.g., Besse and Courtillot, 2002, 2003; Torsvik et al., 2012) show instead less pronounced decreases in pole paleolatitudes (Fig. 1A) and no substantial variations of plate velocity (Fig. 1B) during the Middle to Late Jurassic, possibly as the result of the inclusion in these compilations of sparse and lesser quality Jurassic paleopoles from Europe (Kent and Irving, 2010; Muttoni et al., 2013).

The implications of the JMPS for global paleogeography and the overall distribution of paleolatitude-sensitive sedimentary facies are potentially vast. While the western margin of the North American craton underwent rapid increases of paleolatitude of as much as 20°, locations in Africa drifted southward by similar amounts and rates; for example, Adria drifted from the mid-latitude temperate belt in the Early Jurassic to subequatorial paleolatitudes conductive to chert deposition in the Late Jurassic (Muttoni et al., 2005, 2013). The Atlantic plate circuit would also predict (variable) decreases in paleolatitude during the JMPS for the southern margin of Eurasia, which was attached to North America until the Cenozoic opening of the North Atlantic Ocean. However, reliable paleomagnetic data from Eurasia are lacking for this time interval, with the exception of data from Crimea indicating low paleolatitudes (Meijers et al., 2010), in apparent agreement with the JMPS prediction.

We present new paleomagnetic data from the Garedu Formation, of Late Jurassic age, from central Iran (Fig. 2), which is considered a lithospheric block attached to Eurasia since the Late Triassic (Muttoni et al., 2009a, 2009b; Zanchi et al., 2009). The Garedu Formation represents a critical testing field for the JMPS hypothesis because previous paleomagnetic data yielded contradictory paleolatitude estimates (Wensink, 1982; Soffel et al., 1989). We show that our results are in full agreement with a rapid southward motion of the Eurasian plate compatible with the JMPS, and that paleolatitudes derived from APWPs incorporating the JMPS (Kent and Irving,

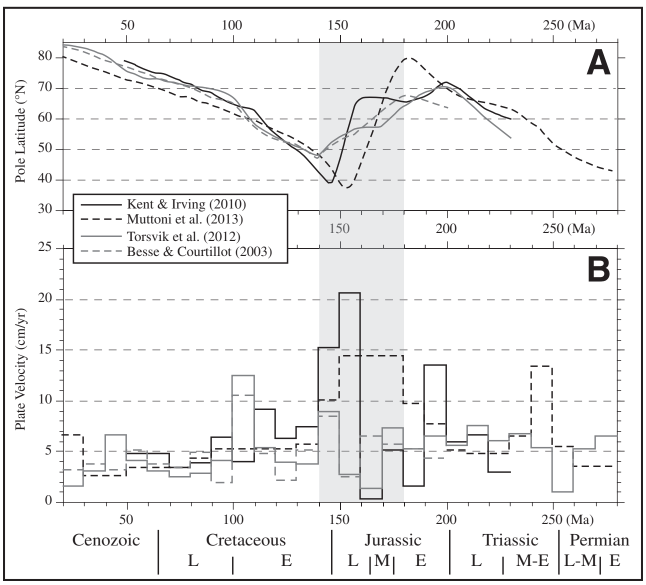

Figure 1. A: Latitudes of paleomagnetic poles from different apparent polar wander paths (APWPs) from the literature, in African coordinates; drop of pole latitude during Jurassic massive polar shift (JMPS; within gray vertical band) is evident in the Kent and Irving (2010) and Muttoni et al. (2013) APWPs. B: Velocity of African plate calculated from different APWPs; high plate velocity characterizes the JMPS, especially according to the Kent and Irving (2010) APWP. L—late; M—middle; E—early.

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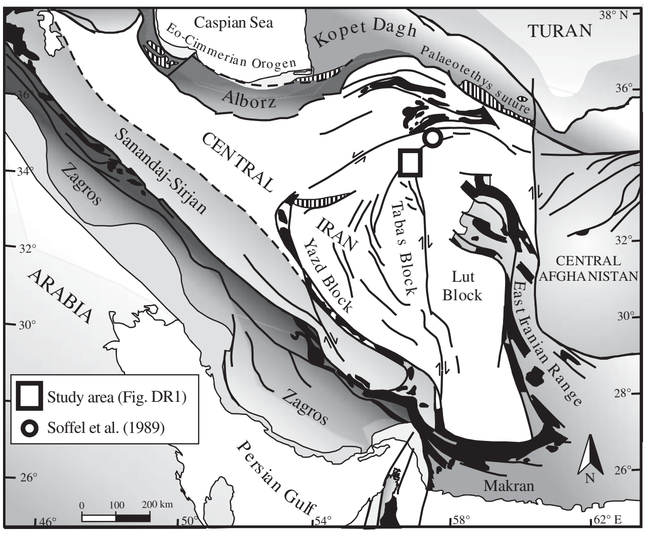

Figure 2. Tectonic sketch map of Iran. Black—Mesozoic ophiolites; hachures—ophiolites and metamorphic rocks related to Cimmerian orogeny. For a geologic map of study area, see Figure DR1 (see footnote 1).

2010; Muttoni et al., 2013) more effectively explain the overall evolution of climate-sensitive sedimentary facies of Iran during the Jurassic.

GEOLOGY AND PALEOMAGNETISM

The Garedu Formation crops out in the Tabas area of central Iran (Fig. 2) at the core of a north-northeast–trending syncline extending for more than 80 km along the western margin of the Shotori Range (Fig. DR1 in the GSA Data Repository[1]). The Garedu Formation comprises several hundred meters of red conglomerates, sandstones, siltstones, and shales of fluvial channel and flood-plain origin, intercalated with shallow-marine gray limestones (Ruttner et al., 1968), and overlies the Callovian–early Kimmeridgian marine carbonates of the Esfandiar Limestone. In the study area, the Garedu Formation is sealed by conglomerates attributed to the Paleocene Kerman Formation (Ruttner et al. 1968), but elsewhere in central Iran, marine carbonate platform and shallow basinal sediments were deposited as consequence of a generalized Early Cretaceous transgression (Wilmsen et al., 2005). The Garedu Formation is attributed to the Kimmeridgian–Tithonian (Late Jurassic, ca. 157–145 Ma) based on (sparse) marine fossils and stratigraphic relationships with underlying and overlying strata (Wilmsen et al., 2003; Seyed-Emami et al., 2004; Wilmsen et al., 2005).

We sampled for paleomagnetism nine sites in red marls and siltstones from the two limbs of the syncline. A total of 86 cylindrical core specimens (1 specimen = 1 sample) was subjected to thermal demagnetization in steps of 50–10 °C from room temperature to a maximum of 690 °C, and the natural remanent magnetization was measured after each demagnetization step with a 2G Enterprises cryogenic magnetometer. Standard least-square analysis was used to calculate magnetic component directions from vector end-point demagnetization diagrams, and standard Fisher statistics were used to compute site and overall mean directions. Component directions with maximum angular deviation >15° were rejected. Rock-magnetic analyses on representative samples from the studied sites were performed (by Cifelli et al., 2013) and used to indicate the presence in the Garedu Formation of a dominant high-coercivity magnetic phase with maximum unblocking temperatures of ~670 °C, interpreted as hematite.

Thermal demagnetization analyses indicate the occurrence in most of the specimens of initial A component directions isolated between room temperature and ~180–280 °C (occasionally to 400 °C) and oriented north and steeply down in in situ (geographic) coordinates (Fig. DR2) with a mean direction (declination = 353.9°, inclination = 51.7°, α_{95} = 7.0°, k = 55, N = 9 sites) that is broadly aligned along the geocentric axial dipole field direction expected at the sampling area. After correction for bedding tilt, these A component site-mean directions become more scattered, with a negative fold test (minimum ζ1 at 6% of complete unfolding) according to McFadden (1990).

After removal of this initial viscous overprint, 78% of the samples show the presence of intermediate B component directions isolated up to 580 °C (Figs. DR2a–DR2h) or occasionally 620–660 °C (Figs. DR2i and DR21), and oriented northwest and down in in situ coordinates. Site-mean B component directions are clustered in in situ coordinates, while after correction for bedding tilt, they become sensibly more scattered, with a negative fold test (minimum ζ1 at 0% of complete unfolding) according to McFadden (1990) (Fig. 3A; Table DR1), suggesting that they originated from a post-folding remagnetization event of normal polarity, possibly associated with the Cretaceous deformation phase described by Ruttner et al. (1968).

A well-defined characteristic Ch component is observed in 59% of the samples from eight sites at higher temperatures from 480 to 620 °C to ~670 °C (Fig. DR2). Site-mean Ch component directions are scattered in in situ coordinates, while after correction for bedding tilt, they cluster either to the northwest and down (sites GA01–GA03 and GA08) or southeast and up (sites GA04–GA06 and GA09) (Fig. 3A; Table DR1). Based on the presence of normal and reverse magnetic polarities, which show a positive reversal test classified as Rc (γ_o = 15.9°; γ_c = 19.8°) according to McFadden and McElhinny (1990), and a fold test that is positive at 99% level of confidence (McFadden, 1990), we consider this high-temperature Ch component as primary in origin and acquired during (or shortly after) deposition of the Garedu Formation.

Previous studies yielded discrepant paleomagnetic results from the Garedu Formation. Wensink (1982) obtained characteristic component directions of high inclination, interpreted as pre-folding in age (albeit with an inconclusive fold test; Wensink 1982), that we argue probably represent a record of the post-folding, high-inclination B component magnetizations we also identify. Soffel et al. (1989) isolated, at sites located to the northeast of the study area (Fig. 2), characteristic component directions of dual polarity that are similar to the pre-folding, low-inclination characteristic component directions of this study. Inclusion of these results yields an overall mean characteristic component direction based on 12 sites (Fig. 3A; Table DR1) that indicates a paleolatitude of 10°N ± 5° for the deposition of the Garedu Formation in the Kimmeridgian–Tithonian. This paleolatitude could be underestimated because of sedimentary inclination shallowing. A formal elongation-inclination test is hampered by the limited sample size (Tauxe et al., 2008). The flattening factor was therefore calculated using the anisotropy of isothermal remanence (Kodama, 2012) on three representative samples of the Garedu Formation, using individual particle anisotropy for hematite of 1.37 (Bilardello and Kodama, 2010). The measured flattening factor is between 0.92 and 0.85 (average of 0.89), and indicates a corrected paleolatitude of deposition of ~12°N.

PALEOGEOGRAPHIC IMPLICATIONS

We calculated the paleolatitudes expected at a nominal point in central Iran (34.5°N, 57.2°E) from several published APWPs (Besse and Courtillot, 2003; Kent and Irving, 2010; Torsvik et al., 2012; Muttoni et al., 2013) migrated to Arabian and Eurasian coordinates (Table DR2). Previous paleomagnetic data indicate that the Iranian

[1]GSA Data Repository item 2014193, Figure DR1 (geological map of the study area), Figure DR2 (vector end-point demagnetization diagrams), Table DR1 (paleomagnetic data from the Garedu Formation), and Table DR2 (apparent polar wander paths), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

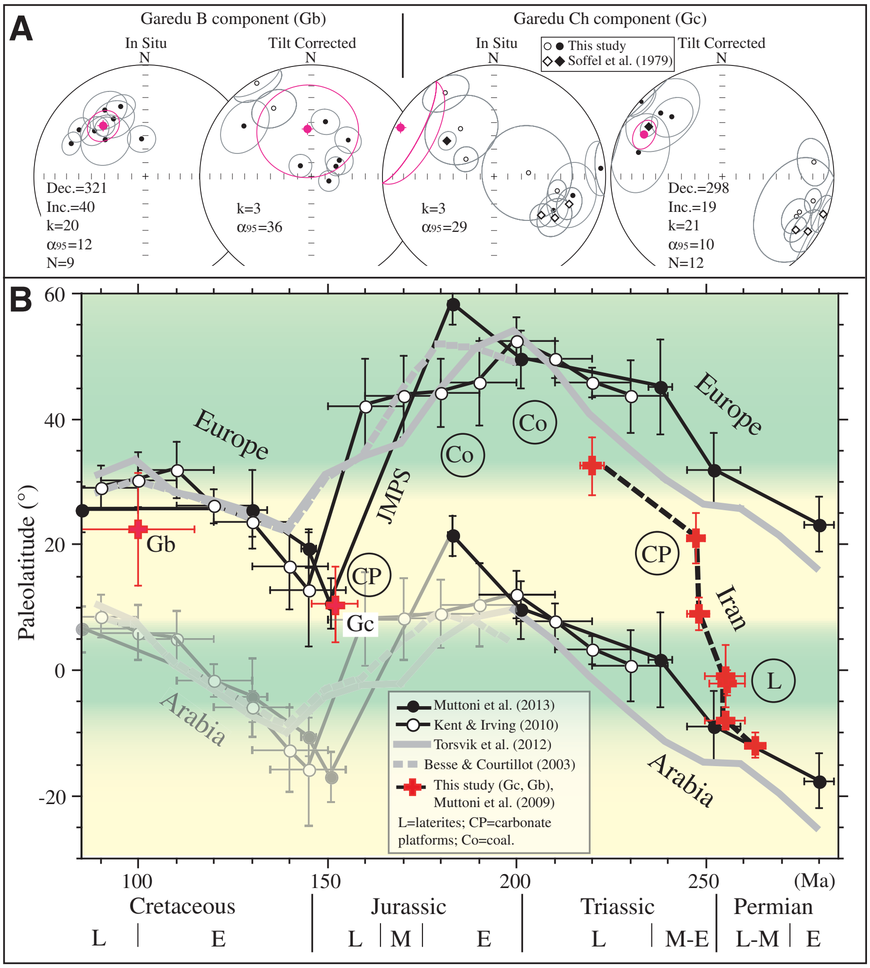

Figure 3. A: Equal area projections of post-folding B and pre-folding Ch component site-mean directions (violet symbols) of the Garedu Formation in tilt-corrected and in situ coordinates; closed symbols represent down-pointing directions, open symbols represent up-pointing directions. Dec.—declination; Inc.—inclination. B: Paleolatitudes derived from paleomagnetic data from Iran in conjunction with paleolatitudes expected for central Iran from different apparent polar wander paths (APWPs) from the literature are used to investigate the influence of continental drift across standard zonal climate belts (green—humid; yellow—arid). APWPs incorporating Jurassic massive polar shift (Kent and Irving, 2010; Muttoni et al., 2013) neatly explain overall architecture of climate-dependent sedimentary facies of Iran. L—late; M—middle; E—early. See text for discussion.

block was located close to the Arabian margin of Gondwana in the Paleozoic, drifted off this margin, and attained subequatorial paleolatitudes in the late Permian–early-Early Triassic, and approached the Eurasian margin by the late-Early Triassic (Fig. 3B). Subsequently, the Iranian block maintained Eurasian affinity, as deduced from Late Triassic and Cretaceous data (Muttoni et al., 2009a, 2009b). The post-folding B component directions of this study, probably acquired during a Cretaceous remagnetization event, yield a mean paleolatitude that confirms the Eurasian affinity of Iran in the Cretaceous (Gb in Fig. 3B).

A corrected paleolatitude of 12°N (±~5°) for the deposition of the Garedu Formation in the Kimmeridgian–Tithonian (Gc in Fig. 3B) is in better agreement with the low paleolatitude predicted for Eurasia by APWPs incorporating the JMPS (Kent and Irving, 2010; Muttoni et al., 2013) than with the paleolatitude predicted by curves displaying less pronounced polar wandering over the Jurassic (Besse and Courtillot, 2002, 2003; Torsvik et al., 2012) (Fig. 3B).

The ability of APWPs incorporating the JMPS to predict paleolatitudes can also be gauged by correlating climate sensitive sedimentary facies with zonal climate belts that have proven relatively stable with respect to latitude, even for variable pCO_2 levels (Manabe and Bryan, 1985). We assumed an equatorial humid belt between 5°S and 5°N, tropical arid belts extending from 5° to 30° latitude, and temperate humid belts from 30° to the latitudinal limits of our paleolatitudinal reconstruction (Fig. 3B).

The vertical sequence of climate sensitive facies changed as Iran passed from one climate belt to another. Laterites are common in the late Permian record (e.g., Leven and Gorgij, 2011), when the Iran block crossed the equator (Muttoni et al., 2009a, 2009b) (Fig. 3B). Platform carbonates (e.g., Elikah Formation; Seyed-Emami, 2003) are widespread from the Early Triassic to near the Carnian-Norian boundary (ca. 227 Ma), when the Iran block drifted through the arid tropical belt of the Northern Hemisphere (Muttoni et al., 2009a) (Fig. 3B). Coal measures associated with highly carbonaceous, siliciclastic sediments bearing abundant plant remains (e.g., Shemshak Formation; Fürsich et al., 2005) characterize the sedimentation from the Late Triassic (ca. 227 Ma) to the Bajocian (Middle Jurassic, 168–170 Ma), when Iran, attached to Eurasia, was stationed in the mid-latitude temperate belt (Muttoni et al., 2009a) (Fig. 3B).

The demise of carbonate platform productivity and the onset of coal-bearing continental sedimentation (Elikah-Shemshak transition) are interpreted to reflect the crossing of the arid-humid zonal boundary at ~30°N; the erosion and karstification of the top of the Elikah Formation (Seyed-Emami, 2003) possibly resulted from enhanced hydrological regimes typical of the mid-latitude temperate belt rather than deformation associated with the early Cimmerian shortening (Seyed-Emami et al., 2004). A marked shift from siliciclastic deposition to reefal platform carbonates (e.g., Esfandiar Formation, Lar Formation; Wilmsen et al., 2003; Fürsich et al. 2005) occurred in the late-Middle Jurassic (Callovian, 166–165 Ma), and appears to have coincided with the drop to arid tropical latitudes during the JMPS (Fig. 3B). Conditions remained tropical-arid throughout the Kimmeridgian–Tithonian, when the Magu Gypsum Formation, a lateral equivalent of the Garedu Formation, was deposited (Wilmsen et al., 2003) (Fig. 3B).

CONCLUSIONS

Our paleolatitude estimate for the upper Jurassic Garedu Formation of Iran, based on prefolding paleomagnetic component directions of dual polarity, confirms the remarkable latitude drop predicted for Eurasia by APWPs incorporating the JMPS, a major and previously underestimated event of plate motion observed in independent paleomagnetic data sets from different plates (North America, Africa, Eurasia; Kent and Irving, 2010; Muttoni et al., 2013; this study). Paleolatitudes predicted by APWPs incorporating the JMPS adequately explain the distribution of climate-sensitive sedimentary facies of Iran under the assumption of simple zonal climate belts. The switch from carbonate platform to coal-bearing sedimentation in the Late Triassic represents the crossing of the arid-humid zonal boundary at ~30°N, whereas the return to carbonate platform deposition in the late-Middle Jurassic appears to coincide with the drop to arid tropical latitudes during the JMPS.

Had we used alternative APWPs from the literature for comparison with data from the

Garedu Formation, we would have erroneously concluded that Iran became tectonically displaced relative to Eurasia after collision in the Late Triassic, in contradiction to the available geologic and paleomagnetic data (Muttoni et al., 2009a, 2009b; Zanchi et al., 2009). The choice of reference paleopole for tectonic reconstructions is of crucial importance, especially during times of fast plate motion like the Jurassic. We argue that several open issues in the paleogeographic and tectonic evolution of Eurasia during the Jurassic (e.g., the extension and closing history of the Mongol-Okhotsk Ocean between Siberia and the China blocks; strike-slip motion of Siberia relative to Europe during the formation of the Eurasian plate; Metelkin et al., 2007) may have arisen from, and been fueled by, the adoption of reference APWPs for Europe that underestimate Jurassic plate motion.

Cusps in APWPs like the JMPS represent candidates of true polar wandering (TPW) events. Previous analyses based on the extraction from a global APWP of mean (cumulative) rotations of all major continents around their common center of mass, corresponding to equatorial geoid heights, indicate clockwise TPW in the Jurassic (Torsvik et al., 2012) that appears broadly consistent in time and sense of rotation with the JMPS. Approximately 80% of the ~10° arc distance between the 160 and the 140 Ma paleopoles of Torsvik et al. (2012) (in African coordinates) is attributed to TPW (while the remaining ~20% is attributed to continental drift; see Torsvik et al., 2012). The arc distance between the 160 Ma and the 140 Ma paleopoles of Kent and Irving (2010) (in African coordinates) is 2.4 larger than in Torsvik et al. (2012). Whether this extra polar displacement represents larger TPW or a larger contribution from continental drift remains speculative. In any case, our prime goal for the geologic community is to stress the importance of the first-order control that plate motion (TPW plus continental drift) exerts on sedimentary facies deposition. The message of this and similar analyses (Muttoni et al., 2013) is that a simple zonal climate model coupled with the geocentric axial dipole hypothesis for establishing paleolatitudes in precisely controlled paleogeographic reconstructions can explain many of the climate patterns observed in sedimentary records, especially during times of rapid (and generalized) plate motion like the Jurassic.

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