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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 Kimberidgian–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 Triassic–Jurassic 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., 2009, 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, capable of movement both with respect to Eurasia, which was attached to North America until the Cenozoic opening of the North Atlantic Ocean, and with respect to the 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 Kimberidgian–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.

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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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 Repository1). 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 carbones 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 remnant 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 situ (geographic) coordinates (Fig. DR2) with a mean direction (declination = 353.9°, inclination = 51.7°; α95 = 7.0°, κ = 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 DR2l), and oriented northwest and down in situ coordinates. Site-mean B component directions are clustered 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 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 = 15.9°; γ = 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 sampled 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 Iraqi
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 paleolatitude 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 Middle Jurassic (Cullovian, 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 (Wilmansen et al., 2003) (Fig. 3B).

### CONCLUSIONS

Our paleolatitude estimate for the upper Jurassic Garedu Formation of Iran, based on pre-folding paleomagnetic component directions of dual polarity, confirms the remarkable latitude drop predicted for Eurasia by APWPs incorporating the JMPS. Conditions remained tropical-arid throughout the Kimmeridgian–Tithonian, when the drop to arid tropical latitudes during the JMPS.

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., 2009a) than with the paleolatitude predicted by curves displaying less pronounced polar wandering over the Jurassic (Kent and Irving, 2002, 2003; Torsvik et al., 2012) (Fig. 3B).
The Geological Survey of Iran.

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