Post-Cimmerian (Jurassic-Cenozoic) paleogeography and vertical axis tectonic rotations of Central Iran and the Alborz Mountains

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ABSTRACT

According to previous paleomagnetic analyses, the northward latitudinal drift of Iran related to the closure of the Paleo-Tethys Ocean resulted in the Late Triassic collision of Iran with the Eurasian plate and Cimmerian orogeny. The post-Cimmerian paleogeographic and tectonic evolution of Iran is instead less well known. Here we present new paleomagnetic data from the Upper Jurassic Bidou Formation of Central Iran, which we used in conjunction with published paleomagnetic data to reconstruct the history of paleomagnetic rotations and latitudinal drift of Iran during the Mesozoic and Cenozoic. Paleomagnetic inclination values indicate that, during the Late Jurassic, the Central-East-Iranian Microcontinent (CEIM), consisting of the Yazd, Tabas, and Lut continental blocks, was located at low latitudes close to the Eurasian margin, in agreement with the position expected from apparent polar wander paths (APWP) incorporating the so-called Jurassic massive polar shift, a major event of plate motion occurring in the Late Jurassic from 160 Ma to 145–140 Ma. At these times, the CEIM was oriented WSW-ENE, with the Lut Block bordered to the south by the Neo-Tethys Ocean and to the southeast by the Neo-Sistan oceanic seaway. Subsequently, the CEIM underwent significant counter-clockwise (CCW) rotation during the Early Cretaceous. This rotation may have resulted from the northward propagation of the Sistan rifting-spreading axis during Late Jurassic-Early Cretaceous, or to the subsequent (late Early Cretaceous?) eastward subduction and closure of the Sistan oceanic seaway underneath the continental margin of the Afghan Block. No rotations of, or within, the CEIM occurred during the Late Cretaceous-Oligocene, whereas a second phase of CCW rotation occurred after the Middle-Late Miocene. Both the Late Jurassic-Early Cretaceous and post Miocene CCW rotations are confined to the CEIM and do not seem to extend to other tectonic regions of Iran. Finally, an oroclinal bending mechanism is proposed for the origin of the curved Alborz Mountains, which acquired most of its curvature in the last 8 Myr.

1. INTRODUCTION

The present-day structural configuration of Iran (Fig. 1) is the result of a complex history of geodynamic events. These include the collision of the Central-East-Iranian Microcontinent (CEIM *sensu* Takin, 1972), comprised of the Yazd, Tabas, and Lut blocks, with the southern margin of Eurasia during the Late Triassic Cimmerian orogeny (Sengör, 1984; Zanchi et al., 2006; Zanchi et al., 2009a,b; Muttoni et al., 2009a), the Late Jurassic-Cretaceous opening of small oceanic basins around the CEIM, and the closure of these basins during Late Cretaceous, in connection with the northward motion of the Arabian Plate and closure of the Neo-Tethys Ocean (Stöcklin, 1974; Dercourt et al., 1986; Sengör et al., 1988; McCall 1997; Stampfli and Borel 2002; Bagheri and Stampfli 2008; Rossetti et al., 2010). Since the Cenozoic, shortening related to the Arabia-Eurasia convergence has been taken up mainly by tectonic displacements in the Zagros, Alborz, and Kopeh Dagh thrust-and-fold belts, whereas the intervening, fault-bounded crustal blocks of the CEIM seem to show little internal deformation (Fig. 1).

The Alborz and Kopeh Dagh Mountains in north Iran constitute a system of strongly curved, mostly double-verging orogens (Fig. 1). In particular, the Alborz range is a ca. 100-km-wide, sinuous orogenic belt that stretches E-W for ca. 600 km (e.g., Allen et al., 2003; Guest et al., 2006), and comprises Late Triassic Cimmerian structures (Zanchi et al., 2006) reactivated during the Late Cenozoic Arabia-Eurasia convergence and associated relative motion between the stable and rigid South Caspian Basin in the north and the CEIM in the south (e.g., Jackson et al., 2002; Allen et al. 2003).

The most peculiar feature of the CEIM (to the south of the Alborz-Kopeh Dagh range) is the occurrence of an Upper Mesozoic ophiolitic ‘ring’, the so-called ‘Coloured Mélange’, which bounds its most internal part (Fig. 1). This ophiolitic ring is a remnant of Mesozoic peri-Tethyan oceanic basins that formed in the upper plate of the Neo-Tethyan subduction, and document a polyphase tectonic evolution during its Mesozoic–Cenozoic consumption along the Sanandaj-Sirjan Zone (Stöcklin, 1974; Sengör et al., 1988). The CEIM is affected by a complex system of N–S-trending dextral faults, which separate the Yazd, Tabas and Lut blocks causing intensive N–S dextral shearing in the whole area (Walker and Jackson 2004) (Fig. 1). The left-lateral Great Kavir–Doruneh fault system, crossing the northern part of the CEIM, currently bounds this deformational system to the north.

Despite this complex tectonic history, paleomagnetic data from Iran are very sparse and have been mainly used to unravel its pre-Cimmerian tectonic evolution (Muttoni et al., 2009a,b; see also Besse et al., 1998). These data show that the Iranian block(s) was (were) located close to the Arabian margin of Gondwana in the Paleozoic, drifted off this margin attaining subequatorial palaeolatitudes in the Late Permian-early Early Triassic, and approached the Eurasian margin by the late Early Triassic. In contrast, several open issues regarding the tectonic and stratigraphic evolution of Iran have not been targeted by paleomagnetic research. These include discrepant views on the Mesozoic paleogeography of the CEIM in Central Iran (compare Stampfli and Borel, 2002; Barrier and Vrielynck, 2008; Wilmsen et al., 2009), the debated origin of the curved shape of the Alborz and Kopeh Dagh ranges (Hollingsworth et al., 2010; Alimohammadian et al., 2013), and the latitudinal drift of Iran and its relationships with the Turan plate after the Cimmerian collision (see Mattei et al., 2014 for a discussion).

In this paper, we revise previously published paleomagnetic data from CEIM (Conrad et al., 1981; Wensink, 1982; Bina et al., 1986; Soffel et al., 1989; Soffel et al., 1996; Mattei et al., 2014) and Alborz Mts. (Wensink and Varekamp, 1980; Cifelli et al., in press) and present new paleomagnetic data from the Upper Jurassic Bidou Formation from Central Iran (CEIM). We anticipate that these paleomagnetic data are suitable to identify two main episodes of counter-clockwise (CCW) vertical axis rotations that occurred in Central Iran in the Late Jurassic-Early Cretaceous and after the Middle-Late Miocene, and to constrain the timing of Neogene oroclinal bending in the Alborz range. A brief summary of previous results (Muttoni et al., 2009a,b; Mattei et al., 2014) is also provided on the post Cimmerian latitudinal drift of Iran and the long-term evolution of climate-sensitive sedimentary facies deposition during the Late Paleozoic-Mesozoic.

2. PREVIOUS PALEOMAGNETIC RESULTS

2.1 Jurassic paleomagnetic data

2.1.1 CEIM

Mattei et al. (2014) report paleomagnetic results from Kimmeridgian-Tithonian red beds of the Garedu Red Bed Formation cropping out in the Garedu syncline of the western Shotori Mountains (#15 in Fig. 1; Table 1) (see also Cifelli et al., 2013). A well-defined ChRM component direction, stable at temperatures from 580–620 °C to ~670 °C, was isolated, and based on the presence of normal and reversed magnetic polarities and a positive fold test, it was considered primary in origin and acquired during (or shortly after) the deposition of the Garedu Red Bed Formation (Mattei et al., 2014). Soffel et al. (1989) isolated, at sites located near Bardeskan, ChRM directions of dual polarity that are similar to the pre-folding, low inclination ChRM directions of Mattei et al. (2014) (#13 in Fig. 1; Table 1). In contrast, the ChRM directions of high inclination obtained by Wensink (1982), interpreted as pre-folding in age (albeit with inconclusive fold test; Wensink 1982), most probably represent a record of the post-folding, high inclination B component directions as isolated by Mattei et al. (2014). Soffel et al. (1989) reported paleomagnetic directions from 5 sites sampled from Jurassic sandstones and red sandstones from the Bidou area north of Kerman. Results show ChRM component directions of normal and reverse polarities that, after correction for bedding tilt, cluster either to the northwest or southeast with shallow inclination (#12 in Fig. 1; Table 1), and are similar to the ChRM directions of the Garedu Red Bed Formation (Mattei et al., 2014). In the Tabas Block, Soffel et al. (1989) report results from two sites of Jurassic age that have ChRM directions oriented to the northwest and down or southeast and up (#10,11 in Fig. 1; Table 1). In the Lut Block, one site of Jurassic age reported by Soffel et al. (1989) shows ChRM directions oriented southwest and up (#25 in Fig. 1; Table 1).

2.2 Cretaceous paleomagnetic data

2.2.1 CEIM

Paleomagnetic directions from Cretaceous units of the CEIM are very few and limited to the Tabas and Yazd blocks. Wensink (1982) sampled 6 sites from middle Cretaceous red sandstones and red limestone from the Dehuk village, to the east of the Shotori Range in the Tabas block (#8 in Fig. 1; Table 1). The mean ChRM direction for the analysed sites is oriented northwest and up, and is better grouped after than before tectonic correction, suggesting that the ChRM has a pre-folding origin. Soffel et al. (1989) reported results from Cretaceous volcanic and sedimentary rocks from the Shirkuh Pass area with a mean ChRM direction, calculated from 8 sites, oriented northwest and down (#6 in Fig. 1; Table 1). Soffel et al. (1996, also reported in Besse et al., 1998) sampled Cretaceous limestone from the Saghand area in the eastern Yazd block. The ChRM mean direction, calculated from 33 specimens, is oriented northwest and down (#9 in Fig. 1; Table 1). Mattei et al. (2014) observed an intermediate B component direction oriented northwest and down in *in situ* coordinates in the Late Jurassic Garedu Red Bed Formation of the Shotori Mountains area (#7 in Fig. 1; Table 1). Site mean B component directions are clustered in *in situ* coordinates, while after correction for bedding tilt, they become sensibly more scattered, suggesting that they originated from a post-folding magnetic overprinting event of normal polarity, possibly associated with the Cretaceous deformation phase described by Ruttner et al. (1968).

2.2.2 Alborz

Wensink and Varekamp (1980) obtained ChRM directions oriented to northwest and down from 20 sites distributed in 3 different localities from several Cretaceous lava flows from the Chalus and Haraz valleys in the Western Alborz Mountains (#29,30,31 in Fig. 1; Table 1).

2.3 Paleogene paleomagnetic data

2.3.1 CEIM

Conrad et al. (1981) first reported paleomagnetic results from Paleogene volcanics from the southern part of the Lut Block of the CEIM. ChRM directions isolated in 17 samples from different localities are oriented to the east and up (#24 in Fig. 1; Table 1), and are better grouped after than before correction for bedding tilt (Conrad et al., 1981). Bina et al. (1986) reported paleomagnetic directions from Paleocene and Eocene volcanics from 3 different localities of the Lut Block. After correction for bedding tilt, the site-mean ChRM directions cluster either to the northwest and down or to the southeast and up (#17, 21, 22 in Fig. 1; Table 1). Soffel et al. (1989) reported results from a large number of sites sampled from 3 different localities in the Yazd Block (#3, 4, 5 in Fig. 1; Table 1) as well as from 5 localities in the Lut Block (#16, 18, 19, 20, 23 in Fig. 1; Table 1). The ChRM directions isolated in these sites are oriented either to the northwest and down or southeast and up.

2.3.2 Alborz

Bina et al., (1986) reported data from volcanics from the Karaj area in the Western Alborz. Reliable results have been obtained for 15 samples, which show a mean ChRM direction oriented northeast and down (#28 in Fig. 1; Table 1).

2.4 Neogene paleomagnetic data

2.4.1 CEIM

Mattei et al. (2012) published paleomagnetic results from red marls and siltstones of the Upper Red Formation sampled in 2 localities of the CEIM (Tabas and Anarak,

#1 and #2 in Fig. 1, respectively). In these localities, ChRM component directions were isolated and considered as primary in origin on the base of the positive reversal and fold tests. In tilt corrected coordinates, these component directions are oriented either to the northwest and down or southeast and up (#1 and #2 in Fig. 1; Table 1).

2.4.2 Alborz

Ballato et al. (2008) and Cifelli et al. (in press) reported paleomagnetic results from red marls and siltstones of the Upper Red Formation from two localities from the western and eastern sides of the southern Central Alborz. Ballato et al. (2008) isolated ChRM component directions from 216 samples from the Eyvaneikey magnetostratigraphic section, which are oriented either to the northeast and down or southwest and up (#27 in Fig. 1; Table 1). Cifelli et al. (in press) isolated ChRM component directions from 26 samples from the Abdolabad section, which are oriented either to the northwest and down or southeast and up (#26 in Fig. 1; Table 1).

3. PALEOMAGNETIC SAMPLING AND RESULTS

In the Kerman area of Central Iran (as part of the CEIM), we sampled 9 sites in the red marls and siltstones of the Upper Siliciclastic Member (Late Jurassic-Early Cretaceous) of the Bidou Formation (Zamani-Pedram, 2011), a lateral equivalent of the Magu Gypsum Formation and Garedu Red Beds Formation cropping out in the northern Tabas block (Wilmsen et al., 2009; Zamani-Pedram, 2011) (Fig.1). Sampling was carried out along the different flanks of the N–S-oriented Bolbulieh and Hossienabad fold systems, located to the southeast and east of Kerman, respectively (Azizan et al., 2009). The magnetic mineralogy of the sampled sediments was investigated on representative specimens using standard rock magnetic techniques. The stepwise acquisition of an isothermal remanent magnetization (IRM) was imparted using a pulse magnetizer up to 2.0 T fields. A three component IRM was imparted at 2.7 T, 0.6 T, and 0.12 T fields along samples orthogonal axes and thermally demagnetized according to the procedure of Lowrie (1990).

All samples show a progressive increase of IRM that does not reach saturation up to 2.0 T, suggesting the presence of a dominant high coercivity ferromagnetic mineral (Fig. 2a). Thermal demagnetization of a three component IRM confirms these results and helps defining the nature of the magnetic mineral. High-coercivity magnetic phases are prevalent and show maximum unblocking temperatures of about 680°C, which can be attributed to hematite (Fig. 2b).

A total of 84 cylindrical core specimens were subjected to progressive stepwise thermal demagnetization and the natural remanent magnetization (NRM) was measured after each demagnetization step with a 2G Enterprises DC-SQUID cryogenic magnetometer. The low-field magnetic susceptibility was measured after each heating step to monitor thermally induced alterations of the magnetic mineralogy. Heating steps of 100°C, reduced to 15-20 °C close to critical unblocking temperatures, were carried out from room temperature to a maximum of 670°C. The least-square analysis (Kirschvink, 1980) was applied to determine magnetic component directions. The maximum angular deviation (MAD) of the isolated magnetic components was generally <10°. Site-mean paleomagnetic directions were calculated using Fisher (1953) statistics.

Most of the samples show the presence of an initial A component isolated between room temperature and 180-240 °C, occasionally up to 400 °C (Fig. 3). This A component is generally oriented north and steeply down in *in situ* coordinates (Fig. 3), whereas upon correction for bedding tilt, it becomes more scattered. The A component, with an *in situ* overall mean direction of Dec. = 356.0° E, Inc. = 40.3° (α_{95} = 24.2°), is within error range aligned along a recent geocentric axial dipole field direction (GAD inclination = 54°), and is therefore interpreted as a recent viscous overprint.

After removal of the low-temperature A component, a well-defined characteristic remanent magnetization (ChRM) component is observed in 40% (34/84) of the samples at higher temperatures between average values of c. 580–620°C or occasionally up to 670°C (Fig. 3). Demagnetization diagrams indicate stable behavior with demagnetization vectors aligned along linear paths directed toward the origin of vector component diagrams. Reliable site mean directions have been obtained from seven out of nine sampled sites (Table 2). Site mean directions are scattered in *in situ* coordinates, while after correction for bedding tilt, they cluster east and southeast and up (sites GA12, GA14, GA15, GA18) or southeast with a subhorizontal inclination (sites GA10-11) (Table 2; Figure 4). Site GA16 shows ChRM component directions broadly aligned along the present-day GAD magnetic field in *in situ* coordinates or oriented northeast and up in tilt-corrected coordinates; these component directions have been excluded from further analysis as possibly overprinted during recent times.

The overall mean ChRM component direction based on 6 site-mean directions is Dec. = 111.7°E, Inc. = -21.1° (k = 6, α_{95} = 29.6°) in *in situ* coordinates, whereas in tilt corrected coordinates, it becomes Dec. = 105.7°E, Inc. = -19.6° (k = 12, α_{95} = 20.1°) (Fig. 4; Table 1).

Site-mean directions show declination scattering that persists after tectonic correction (from 74.1° E at site GA15 to 127.1° E at site GA12), and that is possibly related to local tectonic rotations. A tilt-corrected overall mean inclination of -19.6° (±17.2°, k = 16), calculated using the inclination-only statistics of McFadden and Reid (1982), confirms the result obtained with the Fisher statistics (see above).

Acknowledging these complexities, and based on a fold test that is positive at 99% level of confidence (McFadden, 1990), we consider this high-temperature ChRM component as primary in origin and acquired during (or shortly after) deposition of the Bidou Formation.

Paleomagnetic directions obtained from the Bidou Formation sites are similar to those obtained from the coeval Garedu Red Beds Formations from northern Tabas Block (Mattei et al., 2014), reinforcing the finding of a low-latitude position of Central Iran during Late Jurassic and the large amount of CCW rotation experienced by Central Iran since that time.

4. CHOICE OF REFERENCE PALEOMAGNETIC POLES

Previous paleomagnetic analyses indicate that the CEIM was located close to the Arabian margin of Gondwana in the Paleozoic, drifted off this margin attaining subequatorial palaeolatitudes in the Late Permian-Earliest Triassic, and approached the Eurasian margin by the late Early Triassic, to then maintain Eurasian affinity as deduced from Late Triassic and Cretaceous data (Muttoni et al., 2009a,b and references therein; see also Besse et al., 1998). Mattei et al. (2014) reported a low paleolatitude (~12° N ± ~5°) for the deposition of the Kimmeridgian–Tithonian (Late Jurassic) Garedu Red Bed Formation from the northern Tabas Block, which was found to be in good agreement with the low paleolatitudes predicted for Eurasia by the apparent polar wander paths (APWPs) of Kent et al. (2010) and Muttoni et al. (2013). These APWPs show the occurrence of a major and rapid shift in pole position of major plates (referred to as Jurassic massive polar shift; Mattei et al., 2014) during the Middle to Late Jurassic that alternative curves from the literature tend to underestimate, and, for our purposes here, confirm an Eurasian affinity of Iran during the Jurassic (see Mattei et al., 2014 for a discussion). Therefore, Jurassic-Cenozoic paleomagnetic data from the CEIM and the Alborz Mountains have been compared to the Eurasian reference APWP curves to determine the amount of vertical axis rotations for each locality. In particular, we use the Kent and Irving (2010) North America APWP migrated into Eurasian coordinates for the time interval comprised between 200 and 90 Ma (Mattei et al., 2014), whereas for ages comprised between 80 and 10 Ma, we use the Besse and Courtillot (2002) Eurasian APWP.

5. VERTICAL AXIS ROTATIONS OF THE CEIM AND ALBORZ RANGE

Rotation values and associated 95% confidence limits, calculated according to the method of Demarest (1983), are reported in Table 1. In Figure 5, paleomagnetic rotations are displayed according to age of sampled rocks.

Jurassic paleomagnetic directions have been obtained for the CEIM at six localities in the Tabas and Yazd blocks (Fig. 5, #10-15) and one locality in the Lut block (Fig. 5, #25). All Jurassic sites from the CEIM show significant amounts of counter-clockwise (CCW) rotations, ranging between 45° (± 11°) and 82° (± 14°), with a mean value of 66° (± 13°).

Cretaceous paleomagnetic directions have been obtained at four localities in the CEIM (Fig. 5, #6-9) and three localities in the Western Alborz (#29-31). Paleomagnetic directions from the CEIM show CCW rotations comprised between 18° (± 13°) and 47° (± 13°), with a mean value of 34° (± 15°). In the Western Alborz, three paleomagnetic site-mean directions indicate CW rotation, comprised between 12° (± 11°) and 35° (± 18°), with a mean value of 28° (± 15°).

Paleogene paleomagnetic directions have been obtained at twelve localities in the CEIM (Fig. 5, #3-5 and #16-24) and one locality in the Western Alborz (#28).

Paleomagnetic directions from the CEIM show CCW rotations ranging between 91° (± 20°) and 20° (± 9°), with a mean value of 43° (± 14°), whereas the single locality from the Western Alborz (# 28) is rotated CW by 50° (± 15°).

Neogene results have been obtained from the Upper Red Formation of the CEIM (Fig. 5, #1-2) and in southern Central Alborz (#26-27). In the CEIM, paleomagnetic directions are rotated CCW (#1–2), whereas in southern Central Alborz, paleomagnetic directions from the Eyaneykey and Abdolabad sections (#26-27) indicate CW and CCW rotations, respectively.

A summary of the mean paleomagnetic rotations *versus* age is shown separately for the CEIM and Western Alborz in Figure 6. In the CEIM, we observe two distinct phases of CCW vertical axis rotations: an older phase, which occurred during the Early Cretaceous with an average amount of ≈30° CCW, and a more recent phase, which accomplished an additional ≈35° CCW, ≈20° of which occurred in the last 10 Myr (see also Mattei et al., 2012). In contrast, in the Western Alborz, no significant vertical axis rotations occurred in the time interval comprised between the Cretaceous and Paleocene, whereas opposite vertical axis rotations have been recorded in the Middle-Upper Miocene units cropping out along the two arms of the curved Alborz orogen (Fig. 6; see also Fig. 5).

6. PALEOGEOGRAPHIC EVOLUTION OF THE CEIM AND ALBORZ RANGE

Paleomagnetic results of this study and the literature give some new constraints on the tectonic and paleogeographic evolution of Iran. In particular, we focus our attention on the tectonic and paleogeographic evolution of the CEIM during Middle Jurassic-Late Cretaceous, taking into account latitudinal drifting events, vertical axis rotations, facies distribution, and main geodynamic processes in the area.

6.1 CEIM

Paleomagnetic results from upper Jurassic units of the CEIM confirm the latitude drop predicted for Eurasia by APWPs incorporating the Jurassic massive polar shift (Mattei et al., 2014; see also discussion above). In particular, during the Middle Jurassic (170 Ma, Fig. 7a), the CEIM, attached to Eurasia, was stationed in the mid-latitude (≈ 40°N) temperate belt, whereas during the Late Jurassic (145 Ma, Fig. 7b), it shifted to the low latitude tropical arid belt (≈ 15°N). This latitude shift explains the switch from coal-bearing sedimentation to carbonate platform deposition in the late Middle Jurassic (e.g. Fürsich et al., 2003), which appears to coincide with the drop to arid tropical latitudes during the Jurassic massive polar shift (see Mattei et al., 2014 for a detailed discussion on this issue). Paleomagnetic data from Upper Jurassic units also show that the CEIM rotated ≈ 65° CCW since the Late Jurassic, without significant differences among the Yazd, Tabas, and Lut blocks. These results are coherent with facies analyses and stratigraphic relationships (Dercourt et al., 1986; Fürsich et al., 2003; Wilmsen et al., 2003; 2009; 2010), which suggest that, during the Late Jurassic, the Yazd, Tabas, and Lut blocks of the CEIM were oriented east-northeast/west-southwest, and had the same lateral arrangement with respect to each other as they have today, arguing against significant horizontal displacement and differential vertical axis rotations along the block-bounding faults (Fig. 7b). The stratigraphy and facies distribution show that the Yazd Block was emergent for most of the Jurassic period and that marine influence increased from the Tabas to the Lut blocks. On this basis, the Lut Block should represent an area close to the oceanic basin and should therefore face the Neo-Tethys Ocean to the south and southeast (Fig. 7a).

The first episode of vertical axis rotation of the CEIM occurred during the Late Jurassic-Early Cretaceous. This event is suggested by the difference of ≈ 30° between the large CCW rotations measured in Late Jurassic red beds from different localities of the Tabas, Yazd and Lut blocks of the CEIM, and the smaller CCW rotation measured in Late Cretaceous units of the same areas. On the basis of its timing and regional distribution, we relate the ≈ 30° CCW rotation of the CEIM to the Early Cretaceous opening and subsequent closure of oceanic seaways, relics of which are preserved in the Nain-Baft, Sabzevar, and Sistan ophiolitic domains surrounding the CEIM (Fig. 7c). In particular, several pieces of evidence suggest that the oceanic seaways that faced the southeastern side of the CEIM were already formed during the Early Cretaceous. Babazadeh and De Wever (2004 a,b) suggested that the Sistan Ocean was already open at the beginning of the Aptian (121 Ma), based on the presence of Early Cretaceous (Albian-Aptian) radiolarian faunas in pelagic cherts within the Sistan ophiolitic assemblage. In the Makran accretionary prism of southeast Iran, geochronological studies on igneous rocks from ophiolite complexes have yielded ^{40}Ar/^{39}Ar hornblende cooling ages of 156-139 Ma (Kananian et al., 2001) and 143–141 Ma (Ghazi et al., 2004), indicating formation of oceanic crust around the CEIM in Late Jurassic to early Early Cretaceous times. Furthermore, radiometric ages on high-pressure metamorphic rocks suggest that subduction of oceanic lithosphere along the eastern margin of the Sistan Ocean had begun prior to 125 Ma (Early Cretaceous) (Fotoohi Rad et al., 2009), whereas high-pressure granulites in the Sabzevar units seems to suggest the occurrence of early (106 Ma) subduction of the Sabzevar oceanic seaway (Rossetti et al. 2010). Our data are not conclusive for indicating if the measured CCW rotation of the CEIM resulted from the northward propagation of rifting-spreading in the Sistan basin during Late Jurassic to Early Cretaceous times (Fig. 7b), or to the subsequent (late Early

Cretaceous?) eastward subduction and closure of the Sistan oceanic basin underneath the continental margin of the Afghan Block (Fig. 7c, Rossetti et al., 2010).

From the Late Cretaceous to the Oligocene, no significant paleomagnetic rotations have been observed in Central Iran. Late Cretaceous–Oligocene data from Central Iran show similar amounts of CCW rotations (comprised between ≈30° and ≈40°). Most of these CCW rotations occurred after the Middle–Late Miocene and accommodated NNE–SSW shortening related to the Arabia-Eurasia convergence: the CEIM became and area dominated by CCW-rotating crustal blocks bounded by N–S oriented right-lateral faults, whereas CW rotations occurred north of the Great-Kavir fault where ENE–WSW oriented left lateral strike-slip faults prevail (Mattei et al., 2012) (Fig. 1).

6.2 Alborz

Paleomagnetic data from the Alborz Mountains show a very different pattern with respect to the CEIM. Data from Cretaceous volcanic rocks from the Western Alborz are characterized by CW rotations comprised between ≈ 10° and ≈ 35°, without significant trends with age. Data from the sedimentary units of Middle–Late Miocene age from the Eyvanekey section and the Abdolabad area, located along the western and eastern arms of the Alborz curved orogen, show rotations of about 11° (±5°) CW and 37° (±7°) CCW, respectively. Taken altogether, these paleomagnetic data indicate that the western arm of the central southern Alborz, oriented ESE–WNW (Fig. 1), rotated CW, whereas the eastern arm, oriented WSW-ENE, rotated CCW. Hence, the Alborz orogen resulted from secondary bending, with most of its curvature acquired after about 8 Ma (Late Miocene), which is the upper age of the Upper Red Formation (Ballato et al., 2008).

7. CONCLUSIONS

Our new paleomagnetic results from Upper Jurassic Bidou Formation integrated with published paleomagnetic data from Iran, lead us to the following conclusions:

(1) During the Late Jurassic, the CEIM was located at low latitudes close to the Eurasian margin, in agreement with the position predicted for Eurasia from the Kent and Irving (2010) APWP during the so-called Jurassic massive polar shift (Mattei et al., 2014).

(2) The Jurassic latitudinal drift of Eurasia fully explains the sedimentary facies evolution of Iran under the assumption of standard zonal climate belts (see Mattei et al., 2014 for details).

(3) During the Late Jurassic, the different blocks forming the CEIM (Yadz, Tabas, Lut) were oriented WSW–ENE, with the Lut block facing the Neo-Tethys Ocean in the south and the Sistan oceanic seaway in the southeast.

(4) Large CCW rotations characterized the CEIM; these rotations occurred in two distinct phases, during the Early Cretaceous and after the Middle–Late Miocene. These rotations are confined to the CEIM and do not extend to the other tectonic provinces of Iran (e.g., Alborz).

(4) No detectable vertical axis rotations of, or within, the CEIM occurred during the Late Cretaceous–Oligocene time interval.

(5) The origin of the curved shape of the Alborz Mountains is due to an oroclinal bending mechanism, with most of its curvature acquired after about 8 Ma (Late Miocene).

REFERENCES

Alimohammadian, H., Hamidi, Z., Aslani, A., Shahidi, A., Cifelli, F., Mattei M., 2013. A tectonic origin of magnetic fabric in the Shemshak Group from Alborz Mts. (northern Iran), Journal of Asian Earth Sciences 73, 419-428. doi.org/10.1016/j.jseaes.2013.05.014.

Allen, M. B., Ghassemi M. R., Shahrabi M., and Qorashi M. 2003. Accommodation of late Cenozoic oblique shortening in the Alborz range, northern Iran. Journal of Structural Geology 25, 659-672.

Azizan, A., Shahraki, A., Seifouri, S., 1999. Geological map of Kerman, Series No 7450 (Scale 1:100000), Geological Survey of Iran (Tehran).

Babazadeh. S.A., De Wever, P., 2004a. Early Cretaceous radiolarian assemblages from radiolarites in the Sistan Suture (eastern Iran). Geodiversitas 26, 185–206.

Babazadeh, S.A., De Wever, P., 2004b. Radiolarian Cretaceous age of Soulabest radiolarites in the ophiolite suite of eastern Iran. Bulletin de la Société Géologique de France 175, 121–129.

Bagheri, S., Stampfli, G.M., 2008. The Anarak, Jandaq and Posht-e-Badam metamorphic complex in central Iran: new geological data, relationships and tectonic implications. Tectonophysics 451, 123–155.

Ballato, P., Nowaczyk, N. R. Landgraf, A. Strecker, M. R. Friedrich, A. Tabatabaei, S. H., 2008. Tectonic control on sedimentary facies pattern and sediment accumulation rates in the Miocene foreland basin of the southern Alborz mountains, northern Iran. Tectonics 27, 1-20

Barrier, E., Vrielynck, B. 2008. Palaeotectonic maps of the Middle East. Tectono-sedimentary-palinspastic maps from Late Norian to Pliocene. 14 maps. Paris: CGMW/CCGM.

Besse, J., Torcq, F., Gallet, Y., Ricou, L.E., Krystyn, L., Saidi, A., 1998. Late Permian to Late Triassic palaeomagnetic data from Iran: Contrains on the migration of the

Iranian block through the Tethyan Ocean and initial destruction of Pangea. Geophysical Journal International 135, 77–92, doi:10.1046/j.1365-246X.1998.00603.x.

Besse, J., Courtillot, V., 2002. Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr. Journal of Geophysical Research 107, doi:2310.1029/2000JB000050.

Bina, M. M., Bucur, I., Prévot, M., Meyerfeld, Y., Daly, L., Cantagrel, J. M., Mergoil, J., 1986. Palaeomagnetism, petrology and geochronology of Tertiary magmatic and sedimentary units from Iran. Tectonophysics 121, 303–329.

Cifelli, F., Mattei, M., Rashid, H., Ghalamghash, J., 2013. Right-lateral transpressional tectonics along the boundary between Lut and Tabas blocks (Central Iran). Geophysical Journal International doi:10.1093/gji/ggt070.

Cifelli, F., Ballato, P., Alimohammadian, H., Sabouri J., Mattei., M. Tectonic magnetic lineation and oroclinal bending of the Alborz range: implications on the Iran-Southern Caspian geodynamics. Accepted in Tectonics.

Conrad, G., Montigny, R., Thuizat, R., Westphal, M., 1981. Tertiary and Quaternary geodynamics of Southern Lut (Iran) as deduced from palaeomagnetic, isotopic and structural data. Tectonophysics 75, T11–T17.

Demarest, H.H., 1983. Error analysis for the determination of tectonic rotation from paleomagnetic data. Journal of Geophysical Research 88, 4321–4328, doi:10.1029/JB088iB05p04321.

Dercourt, J. E. A., Zonenshain, L. P., Ricou, L.-E., Kazmin, V. G., Le Pichon, X., Knipper, A. L., et al. , 1986. Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. Tectonophysics 123(1), 241–315.

Fisher, R. A. 1953. Dispersion on a sphere. Proceedings of the Royal Society of London, Ser. A 217, 295-305.

Fotoohi Rad, G.R., Droop, G.T.R., Burgess, R., 2009. Early Cretaceous exhumation of high-pressure metamorphic rocks of the Sistan Suture Zone, eastern Iran. Geological Journal 44, 104–116.

Fürsich, F.T., Wilmsen, M., Seyed-Emami, K., Schairer, G., Majidifard, M.R., 2003. Platform/basin transect of a large-scale Middle-Late Jurassic carbonate platform system (Shotori Mountains, Tabas area, east-central Iran). Facies 48, 171-198.

Ghazi, A.M., Hassanipak, A.A., Mahoney, J.J., Duncan R.A., 2004. Geochemica characteristics, 40Ar–39Ar ages and original tectonic setting of the Band-e-Zeyarat—Dar Anar ophiolite, Makran accretionary prism, S.E. Iran. Tectonophysics 393, 175–196.

Guest, B., Stöcklin, D. F., Grove, M., Axen, G. J., Lam, P. S., Hassanzadeh J., 2006. Thermal histories from the central Alborz mountains, northern Iran: Implications for the spatial and temporal distribution of deformation in northern Iran. Geological Society of America Bulletin 118, 1507-1152.

Hollingsworth, J., Fattahi, M. Walker, R. Talebian, M. Bahroudi, A. Bolourchi, M. J. Jackson, J., Copley, A., 2010. Oroclinal bending, distributed thrust and strike-slip faulting, and the accommodation of Arabia-Eurasia convergence in NE Iran since the Oligocene, Geophys. J. Int. 181, 1214-1246.

Jackson, J., Priestley, K. Allen, M., Berberian M., 2002. Active tectonics of the South Caspian Basin, Geophysical Journal International 148, 214 - 245.

Kananian, A., Juteau, T., Bellon, H., Darvishzadeh, A., Sabzehi, M., Whitechurch, H., Ricou, L-E., 2001. The ophiolite massif of Kahnuj (western Makran, southern Iran): new geological and geochronological data. Comptes Rendus de l’Académie des Sciences—Series IIA Earth and Planetary Sciences 332, 543–552.

Kent, D.V., Irving, E., 2010. Influence of inclination error in sedimentary rocks on the Triassic and Jurassic apparent polar wander path for North America and implications for Cordilleran tectonics. Journal of Geophysical Research 115, B10103, doi:10110.11029/12009JB007205.

Kirschvink, J. L., 1980. The least-squares line and plane and the analysis of paleomagnetic data. Geophysical Journal of the Royal Astronomical Society 62, 699-718.

Lowrie, W., 1990. Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. Geophysical Research Letters 17, 159–162.

Mattei, M., Cifelli, F., Muttoni, G., Zanchi, A., Berra, F., Mossavvari, F., Safar Ali, E., 2012. Neogene block-rotation in Central Iran: evidence from paleomagnetic data. Geological Society American Bulletin 124, 943-956 doi:10.1130/B30479.1

Mattei M., Muttoni, G., Cifelli, F., 2014. A record of the Jurassic massive plate shift from the Garedu Formation of central Iran. Geology. doi:10.1130/G35467.1.

McCall, G.J.H., 1997. The geotectonic history of the Makran and adjacent areas of southern Iran. Journal of Asian Earth Sciences 15, 517–531.

McFadden, P. L., 1990. A new fold test for paleomagnetic studies. Geophysical Journal International 103, 163-169.

McFadden, P. L., Reid, A., B., 1982. Analysis of palaeomagnetic inclination data. Geophys. J. R. Astr. Soc. 69, 307-319

Muttoni, G., Mattei, M., Balini, M., Zanchi, A., Gaetani, M., Berra, F., 2009a. The drift history of Iran from the Ordovician to the Triassic, in Brunet, M.-F., et al. , eds., South Caspian to Central Iran Basins. The Geological Society of London Special Publications 312, 7–29.

Muttoni, G., Gaetani, M., Kent, D.V., Sciunnach, D., Angiolini, L., Berra, F., Garzanti, E., Mattei, M., Zanchi, A., 2009b. Opening of the Neo-Tethys Ocean and the Pangea B to Pangea A transformation during the Permian. GeoArabia 14, 17–48.

Muttoni, G., Dallanave, E., Channell, J.E.T., 2013. The drift history of Adria and Africa from 280 Ma to Present, Jurassic true polar wander, and zonal climate control on Tethyan sedimentary facies. Palaeogeography, Palaeoclimatology, Palaeoecology 386, 415–435, doi:10.1016/j.palaeo.2013.06.011.

Rossetti, F., Nasrabady, M., Vignaroli, G., Theye, T., Gerdes, A., Razavi, M., Vaziri, H.M., 2010. Early Cretaceous migmatitic mafic granulites from the Sabzevar range (NE Iran): implications for the closure of the Mesozoic peri-Tethyan oceans in central Iran. Terra Nova 22, 26–34.

Ruttner, A., Nabavi, M., and Hadjian, J., 1968, Geology of the Shirgesht area (Tabas area East Iran): Geological Survey of Iran, Report No. 4.

Sengör, A.M.C., 1984. The Cimmeride orogenic system and the tectonics of Eurasia, pp. 82 Geological Society of America, Special Paper 195.

Sengör, A.M.C., Altiner, D., Cin, A., Us- tomer, T., Hsu, K.J., 1988. The origin and assembly of the Tethyside orogenic collage at the expenses of Gondwana land, in Gondwana and Thethys, Vol. 37, pp. 119–181, eds Audley-Charles, M.G. and Hallam, A., Geological Society Special Publication.

Soffel, H.C., Davoudzadeh, M., Rolf, C., 1989. Palaeomagnetic investigations on Phanerozoic formations from Iran: reinterpretation of measurements between 1972 and 1982. Muenchner Geophysikalische Mitteilungen, Münchner Univers. Schriften. 4, 23–56.

Soffel, H. C., Schmidt, S., Davoudzadeh, M., Rolf, C., 1996. New palaeomagnetic data from Central Iran and a Triassic palaeoreconstruction. Geologische Rundschau 85(2), 293–302.

Stampfli, G.M., Borel, G.D., 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones. Earth Planetary Science Letters, 196 17–33.

Stöcklin, J., 1974. Possible ancient continental margins in Iran. In: Burk, C.A., Drake, C.L. (Eds.), The Geology of Continental Margins. Springer, New York, pp. 333–357.

Takin, M. 1972. Iranian geology and continental drift in the Middle East. Nature 235, 147–150.

Walker, R., Jackson, J., 2004. Active tectonics and late Cenozoic strain distribution in central and eastern Iran. Tectonics 23, TC5010, doi:10.1029/2003TC001529.

Wensink, H., 1982, Tectonic inferences of paleomagnetic data from some Mesozoic formations in Central Iran. Journal of Geophysics 51, 12–23.

Wensink, H., Varenkamp, J.,C., 1980. Palaeomagnetism of basalts from Alborz: Iran part of Asia in the Cretaceous. Tectonophysics 68, 113–129

Wilmsen, M., Fürsich, F.T., Seyed-Emami, K., 2003, Revised lithostratigraphy of the Middle and Upper Jurassic Magu Group of the northern Tabas Block, east-central Iran Newsletter of Stratigraphy 39, 143–156.

Wilmsen, M., Wiese, F., Seyed-Emami, K., Fürsich, F.T., 2005. First record and significance of Turonian ammonites from the Shotori Mountains, east-central Iran. Cretaceous Research 26, 181–195, doi:10.1016/j.cretres.2004.10.004.

Wilmsen, M, Fürsich, F.T., Seyed-Emami, K., Majidifard, M.R., 2009. An overview of the lithostratigraphy and facies development of the Jurassic System on the Tabas

Block, east-central Iran, in South Caspian to Central Iran Basins, pp. 323–344, eds Brunet, M.F., Wilmsen, M. and Granath, J., Geol. Soc. Lond., Spec. Publ. 312.

Wilmsen, M., Fürsich, F.T., Seyed-Emami, K., Majidifard, M.R., Zamani-Pedram, M., 2010. Facies analysis of a large-scale Jurassic shelf-lagoon: The Kamar-e-Mehdi Formation of east-central Iran. Facies 56, 59-87.

Zamani-Pedram, Z., 2011. Source, Facies, and Sedimentary Environments of the Middle to Upper Jurassic Strata in the Kerman and Tabas Areas, East-Central Iran", PHD Thesis, Bayerischen Julius-Maximilians-Universität, Würzburg, Germany.

Zanchi, A., Berra, F., Mattei, M., Ghassemi, M.R., Sabouri, J., 2006. Inversion tectonics in central Alborz, Iran. Journal of Structural Geology 28, 2023–2037.

Zanchi, A., Zanchetta, S., Garzanti, E., Balini, M., Berra, F., Mattei, M., Muttoni, G., 2009a. The Cimmerian evolution of the Nakhlak-Anarak area, Central Iran, and its bearing for the reconstruction of the history of the Eurasian margin. In: Brunet, M.F., Wilmsen, M., Granath, J. (Eds.), South Caspian to Central Iran basins, Geological Society of London Special Publication 312, 261–286, doi:10.1144/SP312.13.

Zanchi, A., Zanchetta, S., Berra, F., Mattei, M., Garzanti, E., Molyneux, S., Nawab, A., Sabouri, J. 2009b. The Eo-Cimmerian (Late? Triassic) orogeny in north Iran, *in* Brunet, M.-F., et al. , eds., South Caspian to Central Iran Basins: Geological Society of London Special Publication 312, 31–55, doi:10.1144/SP312.3.

FIGURE CAPTIONS

Fig. 1. Tectonic map of Iran showing the main tectonic provinces and the main active faults. Numbers represent sampling localities from the literature discussed in the text (see also Table 1). The red square represents the location of the paleomagnetic

sites of this study from the siliciclastic member of the Bidou Formation from the Kerman area.

Fig. 2. Isothermal Remanent Magnetization (IRM) acquisition curves (a) and thermal demagnetization of a three-component IRM (b) from representative hematite-rich samples of the Bidou Formation red beds.

Fig. 3. Vector component diagrams for the progressive demagnetization of representative samples from Bidou Formation red beds. Open and solid symbols represent projections on the vertical and horizontal planes, respectively.

Fig. 4. Equal area projections of ChRM component site mean directions (violet symbols) of the Bidou Formation red beds in tilt-corrected and *in situ* coordinates; closed symbols represent down-pointing directions, open symbols represent up-pointing directions. Dec. = declination; Inc. = inclination.

Fig. 5. Paleomagnetic rotation from the Central-East Iranian Microcontinent (CEIM) and the Alborz Mountains, calculated relative to the Kent and Irving (2010) North America Apparent Polar Wonder Path (APWP) migrated into Eurasian coordinates for the time interval comprised between 200 and 90 Ma, and the Besse and Courtillot (2002) Eurasian APWP for the time interval comprised between 80 and 10 Ma. Numbers refer to data listed in Table 1.

Fig. 6. Rotation (a) and age-mean rotations (b) values (in °) plotted *versus* age for the Central-East Iranian Microcontinent (CEIM) and the Alborz Mountains. See text for explanation about data processing. The illustrated paleomagnetic data are the same as those reported in Figure 5 and Table 1.

Fig. 7. Paleogeographic reconstructions of the Central-East Iranian Microcontinent (CEIM) - comprised of the Yazd, Tabas, Lut blocks - during the Middle Jurassic-Late Cretaceous time interval. Paleolatitudes are derived from paleomagnetic data

from Iran (B, C) in conjunction with paleolatitudes expected for the CEIM from different apparent polar wander paths (APWPs) from the literature (A). Standard zonal climate belts (columns in the right side of paleogeographic reconstructions) are also reported to visualize the influence of continental drift on the distribution of climate-sensitive sedimentary facies of Iran. The Neo-Tethys Ocean (A, B, C) and the Sistan oceanic subduction and subsequent closure (C) are also reported, together with the inferred position of the rift axis in the Sistan, Sabzevar, and Nain-Baft marginal basins. The orientation of the CEIM is derived by paleomagnetic data and by facies distribution of Middle–Late Jurassic carbonate platform-to-basin depositional system (Dercourt et al., 1986; Fürsich et al., 2003; Wilmsen et al., 2003; 2009, 2010). Y = Yazd; T = Tabas; L = Lut; A = Alborz; SCB = Southern Caspian Basin; CA = Central Afghanistan.