Late Permian to Late Triassic palaeomagnetic data from Iran: constraints on the migration of the Iranian block through the Tethyan Ocean and initial destruction of Pangaea

J. Besse, F Torcq, Y. Gallet, L E Ricou, L Krystyn, A Saidi

Geophys. J. Int. (1998) **135,** 77–92

Late Permian to Late Triassic palaeomagnetic data from Iran: constraints on the migration of the Iranian block through the Tethyan Ocean and initial destruction of Pangaea

J. Besse,[1] F. Torcq,[1] Y. Gallet,[1] L. E. Ricou,[1] L. Krystyn[2] and A. Saidi[3]

[1] *Laboratoire de Paléomagnétisme, Institut de Physique du Globe de Paris. E-mail: besse@ipgp.jussieu.fr*

[2] *Institute for Palaeontology, Vienna, Austria*

[3] *Geological Survey of Iran, Teheran, Iran*

Accepted 1998 April 4. Received 1998 March 16; in original form 1997 May 30

SUMMARY

A palaeomagnetic study of Late Permian to early Jurassic rocks from the Alborz and Sanandaj–Sirjan zones in Iran and a compilation of selected palaeopoles from the Carboniferous to the present provide an updated history of the motion of the Iranian block within the Tethys Ocean. The Iran assemblage, part of Gondwana during the Palaeozoic, rifted away by the end of the Permian. We ascertain the southern-hemisphere palaeoposition of Iran at that time using magnetostratigraphy and show that it was situated close to Arabia, near to its relative position today. A northward transit of this block during the Triassic is shown, with an estimated expansion rate of the Neotethyan ridge of 100–140 km Myr^{-1}. The northward convergence with respect to Eurasia ended during the Ladinian (Middle Triassic), and is marked by a collision in the northern hemisphere with the Turan platform, which was the southern margin of the Eurasian continent at that time. No north–south component of shortening is evidenced north of Iran afterwards. An analysis of the declinations from the Late Permian to the present shows different, large rotations, emphasizing the important tectonic phases suffered since the Triassic. Finally, we propose palaeomagnetic reconstructions of the Tethys area during the Late Permian and the Late Triassic, showing that the Palaeotethys Ocean was narrower than previously thought, and did not widen its gate to the Panthalassa before the Triassic period.

Key words: Iran, palaeomagnetism, Permian, Tethys, Triassic.

INTRODUCTION

Geological evidence led Stöcklin (1968) to propose that Iran is a set of continental blocks that detached from Gondwana and collided with Eurasia during the Triassic. A new ocean, the Neotethys, was created to the south, and the ancient Palaeotethys Ocean was closed north of it, as presently shown by two sutures in the north and south of Iran (Fig. 1). Sengör & Hsu (1984) then generalized this concept, suggesting that Iran belonged to a nearly continuous belt of continental blocks (the 'Cimmerian continent'), originally extending along the northern periphery of Gondwana and comprising parts of Afghanistan, Tibet and Indochina. This assemblage rifted from Gondwana and collided with Eurasia during the Triassic (the 'Cimmerian collision'). This mechanism has contributed to the construction of Eurasia at the expense of Gondwana (Ricou 1994). Pioneering palaeomagnetic studies by Soffel, Förster & Becker (1975), Wensink (1979, 1981, 1982), Wensink & Varekamp (1980), Soffel & Förster (1980) and Soffel *et al.* (1995, 1996) have documented this scenario in Iran. However, there are still large uncertainties in the interpretation of the available palaeomagnetic data. Large unit rotations, even very recent ones, show the importance of the deformation caused by the successive tectonic phases described in the literature (Stöcklin 1968; Takin 1972; Berberian & King 1981; Davoudzadeh & Schmidt 1984; Stampfli, Marcoux & Baud 1991; Ricou 1994; Saïdi 1995; Saïdi, Brunet & Ricou 1997). Iran does not appear to be a single crustal block, but an assemblage of zones comprising the Alborz Range, the Sanandaj–Sirjan sliver and central Iran. An important period of Late Cretaceous rifting led to the formation of oceanic crust marked nowadays by the Nain–Baft and Nain–Sabzevar ophiolite alignments (Fig. 1). This disruption episode within Iran was followed during the Eocene by a subduction zone from the southern edge of the Alborz mountain range to the Khopet Dagh, and then by a general collision context, Iran

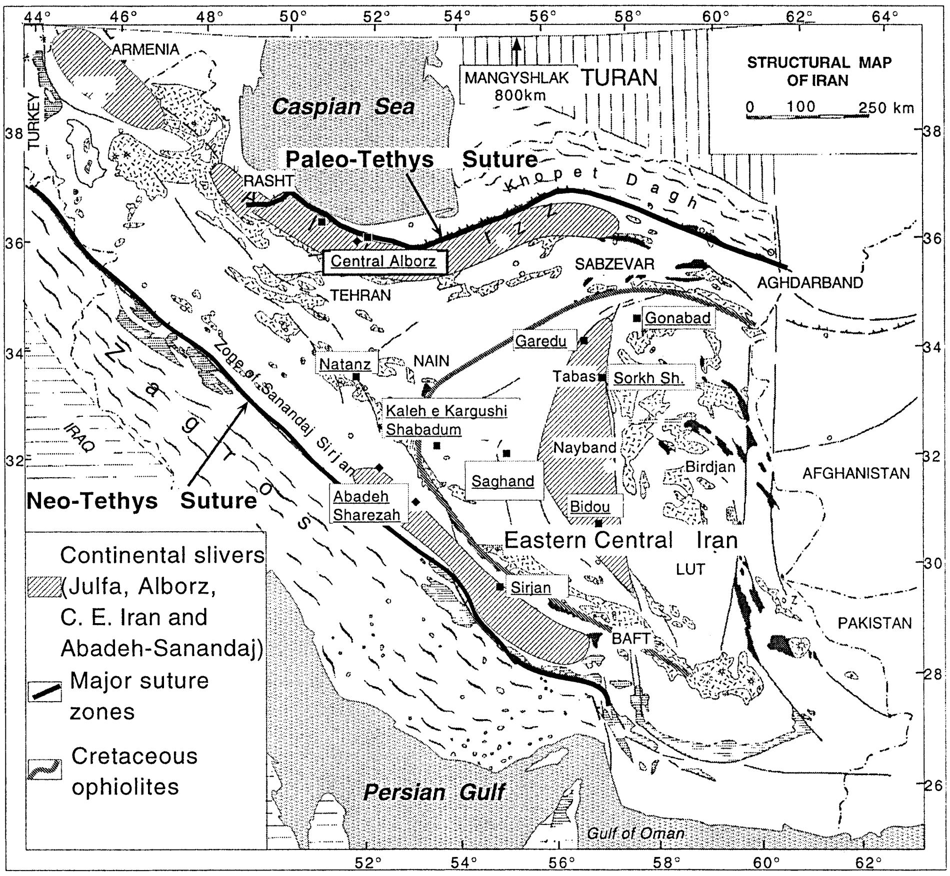


Figure 1. Simplified geological map of Iran showing the locations of the palaeomagnetic sampling sites (diamonds, this study; squares, other studies), the main Palaeo- and Neotethyan sutures, and the Nain–Sabzevar and Nain–Baft alignements corresponding to Cretaceous ophiolites.

being sandwiched between Asia and Africa. This complex tectonic heritage obscures, to some extent, the interpretation of palaeomagnetic data. The first problem, linked to very large rotations, is the uncertainty in the hemisphere determinations for periods older than the Jurassic. This problem becomes increasingly important when going back in time and may even cast some doubts on the Gondwanian origin of the Iran blocks. The second problem is the age of the collision and the amount, timing and location of the related shortening with respect to Eurasia. The age of the collision should be older than the continental Shemshak sediments of Late Norian age (Late Triassic) found in both the Iran and Turan parts of Eurasia. However, the set of available palaeomagnetic data leaves open the possibility of either a Triassic or a mid-Jurassic age for the final accretion (Wensink 1981; Van der Voo 1993, Feinberg *et al.* 1996). In order to solve these problems, we have sampled Late Permian and Late Triassic/early Jurassic series in the Alborz mountain range and in the Sanandaj–Sirjan sliver (in the southern part of central Iran). We have used, when possible, magnetostratigraphic correlations to assess the hemisphere of deposition.

PALAEOMAGNETIC RESULTS

Standard cores were taken, using a portable gasoline drill, and oriented using magnetic and sun compasses. Natural remanent magnetizations (NRMs) were measured using a CTF cryogenic magnetometer in a shielded room at the Institut de Physique du Globe in Paris. Stepwise thermal demagnetizations were carried out up to 600 °C. The bulk magnetic susceptibility of each specimen was measured at each demagnetization step in order to monitor magnetic mineral transformations during progressive heating. The magnetic directions were analysed by principal-component analysis and the site mean direction calculated using Fisher (1953) statistics. We describe our results by the regions of sampling and by age within these regions. Fig. 1 displays the location of the sampling sites on a simplified structural map of Iran. The palaeomagnetic directions of the sites are presented in Table 1.

Alborz

Late Permian Ruteh sedimentary formation

This formation comprises 110 m of dolomitic limestones and 150 m of grey to black biogenic limestones. The Ruteh Formation, diachronous between the central and eastern Alborz, is dated by fusulinides, corals and algae (Assereto & Gaetani 1964), yielding a Late Sakmarian to Murgabian age (Late Permian). We sampled the black limestones in the Amol section described by Glaus (1965) on the road from Amol to Teheran. Two components were found (Fig. 2a). The low-temperature component was isolated between 20 and 250 °C and its direction ($I_g = 53.1°$, $D_g = 355.3°$, $\alpha_{95} = 5.5°$) is not distinct from that of the present earth field (PEF) computed in this area (55.5° for the dipole field). The high-temperature

Table 1. Palaeomagnetic data from this study. D_g, I_g, mean declination and inclination (*in situ*); k_g, k_s, precision parameter *in situ* and after tilt correction, respectively; α_{95}, confidence interval at the 95 per cent level; D_S, I_S, declination and inclination (tilt-corrected); *n*, number of samples; *N*, number of sites; Plat., Plon., latitude (°N) and longitude (°E) of the palaeopole.

Site	D_g	I_g	α_{95}	*k*	D_s	I_s	α_{95}	*k*	*n*	Plat.	Plon.	Age
Ruteh sediments, Late Permian												
High-temp. component	24.3	49.8	16.9	4.8	5.9	54.6	5.0	48.0	19	82.9	147	Remagnetized
Abadeh, Late Permian–early Triassic												
Medium-temp. component	12.4	59.7	2.0	57.1	31.1	55.5	2.4	41.0	88			
High-temp. component	334.0	29.5	2.9	23.7	315.0	15.2	3.0	24.0		41.6	305	Dorashamian/ Griensbachian
Sharezha, Early Triassic												
Medium-temp. component	31.4	63.2	4.5	30.3	266.0	58.1	5.4	22.0	33			
High-temp. component	149.0	−9.2	4.3	41.2	142.0	−4.3	4.3	42.0	31	43.4	290	Dorashamian
Ruteh Iavas, Late Permian												
High-temp. component												
IR16	136.0	15.8	2.0	680.0	125.0	21.4	2.0	680.0	9	−19	111	Midian/Murgabian
IR17	132.0	21.5	4.7	261.0	123.0	23.6	4.7	261.0	5	−19	111	Midian/Murgabian
Abadeh, Late Triassic												
Medium-temp. component	47.8	30.1	15.7	15.8	73.9	44.1	61.1	1.9	7			Cretaceous?
High-temp. component												
L1	22.2	6.0	7.3	87.6	240.0	48.7	7.1	92.0	6	−7	4	Norian
L2	17.4	62.0	12.5	38.5	210.0	47.6	12.5	38.0	5	−24	24	Norian
L4	339.0	−46.0	10.9	20.6	317.0	−55.0	10.9	21.0	7	13.2	267	Norian
S49	302.0	−57.0	12.9	55.3	295.0	−55.0	12.9	55.0	5	1	280	Norian
L8	322.0	−70.0	6.2	50.7	23.4	−53.0	6.2	51.0	12	22.5	211	Norian
Mean inclination for $n=5$		48.8	38.9	4.8		51.9	4.6	266.9	35			

component of single normal polarity was determined between 240 and 400 °C and yields a mean direction close to the PEF ($I_s=54.6°$, $D_s=5.9°$, $\alpha_{95}=5°$) after tilt correction (Fig. 2b). The fold test between the corrected and uncorrected directions is positive at the 99 per cent level. Anticipating the final interpretation, the mean inclination obtained from the high-temperature component leads to an unacceptable palaeolatitude of 35°N, topologically not compatible with the position of the Tethyan margins during the Permian (see Gondwana and Laurussia reconstructions in Fig. 11). Choosing a latitude of 35°S (implying a large rotation of the sampling zone) points to the same conclusion. A very recent pre-folding remagnetization is thus likely.

Late Permian volcanics (sites IR16 and 17)

Two sites (16 cores) from two different lava flows were drilled in the Late Permian volcanics of the Kuh-e-Siahsang mountain on the road from Baladeh to Varzah. These sites complete laterally the study made by Wensink (1979). The lavas are stratigraphically intercalated between the Ruteh Formation and the limestones or calcareous sandstones of the Nesen Formation, the base of which is diachronous between central and western Alborz, between Late Murgabian and Midian (A. Baud, personal communication). The NRM intensities are around 1 A m^{-1} (Fig. 2c). A single component passing directly through the origin was determined between 20 and 580 °C. The magnetization is thus most probably carried by a mineral of the titanomagnetite family, and not by haematite as for the sites studied by Wensink. All directions (shown on Fig. 2d) cluster well. The bedding correction improves the grouping of the directions (Table 1), which are indistinguishable from those found by Wensink. This latter study was based on five 'Middle' Permian volcanic sites in the same region (Table 2). We cannot compute a mean direction from our sites and those of Wensink together since no directions at the site level were given in Wensink (1979). All directions point to the south and downwards, and thus suggest, according to Wensink, a southern hemisphere of deposition during a reversed-polarity interval. However, the recently dated Murgabian to Midian age of the volcanic flows (i.e. slightly younger than the Kiaman long-reversed-polarity interval) may call into question this hemispheric attribution.

Early Jurassic Shemshak Formation

We sampled 13 sites (104 samples) of the Shemshak Formation on the road to Elika. The Shemshak Formation is represented by a very thick continental Late Norian–Liassic unit (latest Triassic, early Jurassic) of grey, locally coal-bearing sandstones uncomformably deposited on the Triassic Elika Formation (Glaus 1965; Saïdi 1995). This series, common to Iran and Eurasia, stratigraphically post-dates the collision, and was thus of first palaeomagnetic importance. Unfortunately only a low-temperature component of single polarity was isolated between 20 and 200 °C (Fig. 2e). Its *in situ* mean direction, $D_g=2.6$, $I_g=58.6$, $\alpha_{95}=10°$ (Fig. 2f) is close to the PEF ($I=55°$ for the present axial dipole) and the bedding correction yields a negative fold test at the 99 per cent level. Above 200 °C, the directions became erratic and we were not able to isolate a primary direction of magnetization.

Abadeh region

Late Permian and Early Triassic

Permo-Triassic boundary sections in the region of Abadeh (Sanandag–Sirjan continental sliver) were first described by

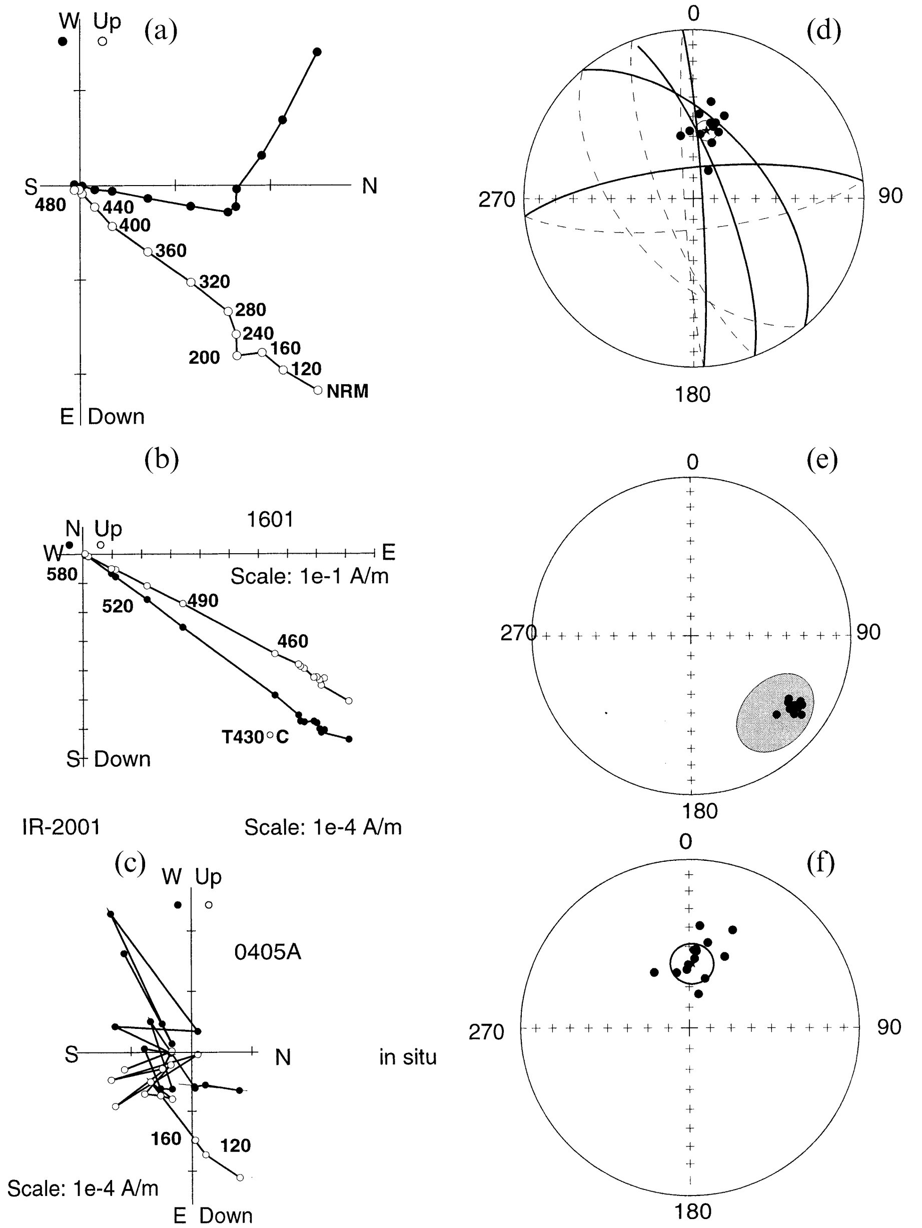


Figure 2. (a)–(c) Orthogonal vector diagrams in stratigraphic coordinates of progressive thermal demagnetization of (a) Late Permian black limestones, (b) Late Permian basalt from the Alborz and (c) grey sandstone from the Shemshak Formation in central Alborz. The filled and open symbols refer to the horizontal and vertical plane respectively. (d)–(f) Equal-area projections showing the directions of the characteristic components. Demagnetization small circles are also shown in (d). The shaded area in (e) represents the confidence limit of the direction of other Late Permian volcanic rocks from Alborz studied by Wensink (1979).

Taraz (1969, 1971) and their stratigraphy was then refined by the Iranian–Japanese Research Group (1981). In order to make precise the magnetic polarity timescale at the Permo-Triassic boundary, we sampled 80 specimens from a single site in the Dzhulfian/Dorashamian nodular red limestones of the Hambast Formation close to the city of Shahreza (Fig. 1). The same formation was also sampled 160 km to the southeast [the so-called Abadeh section; for location, see Iranian–Japanese Research Group (1981)], where we also sampled the overlying Griesbachian/Dienerian grey limestones of the Elika Formation (Early Triassic). A total of 101 samples were collected from this latter section. The age of the Shahreza and Abadeh sections is well constrained by conodont and ammonoid zonations (Iranian–Japanese Research Group 1981). The palaeontological data and magnetostratigraphic implications will be published elsewhere.

Zijderveld diagrams obtained from the Shahreza and Abadeh sections are shown in Figs 3(a)–(d). Two or three components of magnetization were found, either in the red or the grey limestone. The first component was removed by a temperature of 250 °C and clearly shows a direction close to the present Earth field in geographic coordinates. A second, medium-temperature component was sometimes found between 250 and 425 °C and gives a negative fold test at the 99 per cent level. This component is thus a remagnetization. Finally, a high-temperature component was isolated between 450 and

Table 2. Selected palaeomagnetic data for Iran from the GPMD database (McElhinny & Lock 1995). D_{age}, age uncertainty; Slat., Slon., latitude (°N) and longitude (°E) of the sites; *B*, number of sites; *N*, number of samples; *D*, *I*, declination and inclination; Plat., Plon., latitude (°N) and longitude (°E) of the palaeopole; A_{95}, confidence limit on the palaeopole at the 95 per cent level; d_p, d_m, semi-axes of the confidence ellipse at the 95 per cent level.

Place	Mean age	D_{age}	Slat.	Slon.	*B*	*N*	*D*	*I*	Plat.	Plon.	A_{95}, d_p, d_m	Study
Kuh-e-Kaleh-e-Kargushi series	36.5	3.0	32.2	53.2	5	36	241	−34.2	34.2	141.2	5.9	Bina *et al.* 1986
Kuh-e-Shabadum, volcanics	53.0	6.0	32.1	53.3	5	29	226.9	−50.4	51.1	129.2	17	Bina *et al.* 1986
Bajestan-Gonabad series	59.5	7.0	34.5	58.3	5	24	166.2	−54.4	78.6	334.5	9	Bina *et al.* 1986
Chalus Valley	89.5	2.5	36.4	51.1	5	46	42.8	44.1	52.2	145.0	16.6	Wensink & Varekamp 1980
Chalus Valley	112.5	4.5	36.4	52.1	9	69	22.2	48.7	70.2	154.9	8.6	Wensink & Varekamp 1980
Haraz Valley	134.0	20.0	36.1	52.3	6	38	41.3	46.8	54.4	143.5	18.1	Wensink & Varekamp 1980
Saghand	120.0	10.0	32.5	55.2		33	340.7	26.3	64.4	283.1	2.2, 4.1	Soffel *et al.* 1996
Bidou Beds	153.5	12.5	30.7	57.0	5	33	48.2	−32.5	−23.0	6.5	12.3, 21.7	Wensink 1982
Garedu Beds	150.5	4.5	34.0	56.9	4	58	3.9	41.6	79.4	217.1	10.4, 17.0	Wensink 1982
Abadeh Late Triassic	219.0	1.0	31.0	52.9	5	35		51.9	57.9		3.7	This study
Natanz	240.0	10.0	33.3	51.5	5	161	33.3	25.1	53.6	167.6	5.4, 10	Soffel *et al.* 1995, 1996
Sirjan	240.0	10.0	29.4	55.1	1	25	113.7	34.8	−9.8	116.5	2.3, 3.7	Soffel *et al.* 1995, 1996
Sorkh shales	243.0	2.0	33.3	57.3	5	51	288.9	20.8	21.6	326.2	7.9, 14.9	Wensink 1982
Abadeh	250.0	5.0	30.9	53.2	1	101	314.5	15.2	−41.6	124.1	1.6, 3.1	This study
Shahreza	252.5	2.5	32.0	52.0	1	31	322	4.3	−43.4	109.9	2.2, 4.3	This study
Ruteh Iava	260.0	10.0	36.3	52.2	2	13	124.7	22.6	19.3	289.9	1.9	This study
Alborz Mountains	260.0	10.0	36.5	51.5	5	71	132.7	27.6	22.5	281.8	11.6, 21.2	Wensink 1979
Alborz Mountains	344.0	2.0	36.5	51.5	5	31	210.8	66.9	0.2	312.1	3.9, 5.3	Wensink 1979

580 °C, showing that the magnetization is essentially carried by a mineral of the titanomagnetite family. Although sometimes noisy, this component passes through the origin. The two sections show high-temperature components with antipodal directions (Fig. 3e for Abadeh, and Fig. 3f for Shahreza). In both cases, the reversal test of McFadden & McElhinny (1990) is positive at the 95 per cent level ($\gamma = 3.87 < \gamma_c = 5.91$ for Abadeh, and $\gamma = 8.49 < \gamma_c = 9.12$ for Shahreza). There is no significant trend in the palaeomagnetic directions between the Dorashamian and the Griensbachian parts of the Abadeh section. The mean directions obtained from Shahreza and Abadeh are similar, with only a slight relative rotation of $7° \pm 5.2°$ (Table 1). In both sections, a clear magnetostratigraphic sequence is obtained, showing 14 magnetic intervals in Abadeh and eight intervals in Shahreza (Fig. 4). A clear correlation can be proposed between these two sequences (Fig. 5). The magnetic zonation also provides the possibility of finding which hemisphere these sediments were deposited in by comparing our data with other available magnetostratigraphic results of the same age. The first magnetic interval observed in the Griesbachian of South China, Armenia and the Canadian Arctic (Fig. 5) (Kotlyar *et al.* 1984; Ogg & Steiner 1991; Heller *et al.* 1995) is of normal polarity. The Griesbachian of the Abadeh section is well recognized thanks to biostratigraphic data, and the upward-pointing inclinations observed during the beginning of this time interval require the Iranian sections to be situated in the southern hemisphere. The region has thus suffered a large clockwise rotation of some 130° with respect to the Earth's spin axis since the Early Triassic.

Late Triassic of the Abadeh area

Six sites of Late Triassic reddish limestones were sampled in the Abadeh area, close to the city of Waliabad. The Early Norian age (Lacian 1) is well constrained by conodonts (*Norigondolella navicula*, *Epigondolella primitia*) collected throughout the drilled interval, and by the Uppermost Carnian age (Tuvalian 3/II) of the ammonites (*Goniatites italicus*, *Projuvavites* sp.) found in the directly underlying rocks. The different bedding attitudes of the strata provide a fold test. Two sites were also sampled in the underlying volcanoclastic sediments. They unfortunately displayed an unstable behaviour during thermal demagnetization, preventing the obtaining of any significant results, and will not be discussed further. With the exception of these sites, the thermal demagnetizations showed two or three components. The NRM intensities ranged, in all sites, from 10^{-4} to 10^{-3} A m^{-1}. A low-temperature component was isolated in all sites up to 200 °C, with a direction in geographic coordinates ($I_g = 49.2°$, $D_g = 357.4°$, $\alpha_{95} = 3.8°$, $n = 7$) close to the PEF ($I = 49.1°$). The fold test performed on this component was negative at the 99 per cent level. A middle-temperature component of single polarity was also found between 200 and 400 °C (Fig. 6). A comparison of the precision parameters *k* before and after the bedding correction yields a negative fold test at the 99 per cent level (Figs 7a, and b and Table 1). This component is thus interpreted as a remagnetization. The inclination before the tilt correction is low, and would intersect the latest-Jurassic/Cretaceous segment of the predicted inclination segment computed from Besse & Courtillot's (1991) European apparent polar wander path.

A high-temperature component (HTC) was isolated in five sites (Fig. 6 and Figs 7c–g). The mean direction for each site was determined using either a least-squares component analysis (Kirschvink 1980) or a combination of directions and great circles, following the method of McFadden & McElhinny (1988).

The sites L1 and L2 were sampled in the reversed and normal flanks, respectively, of an anticline. The HTC was found in only four out of 11 samples from site L1 (Fig. 7c) and in six samples from site L2 (Fig. 7d). The high rejection rate for site L1 is due to noisy demagnetization endpoints.

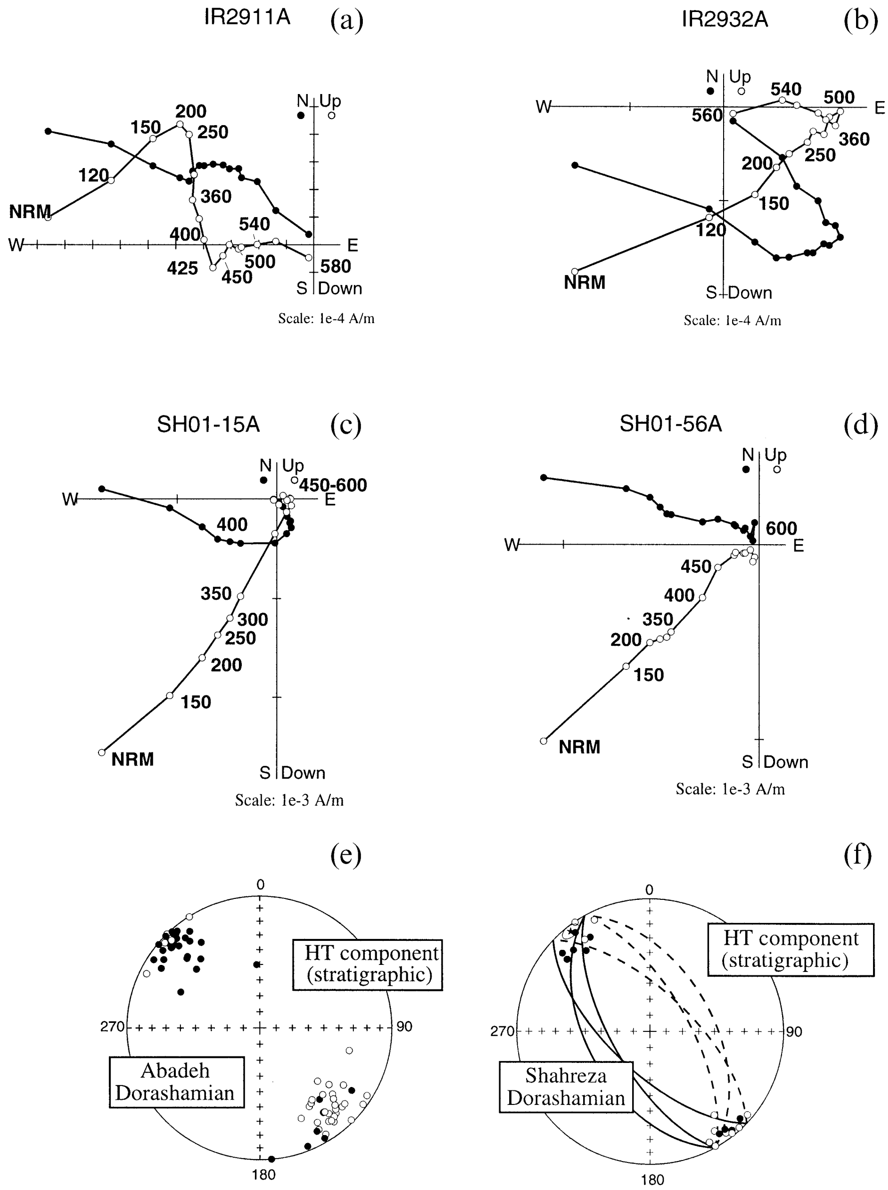


Figure 3. (a)–(d) Orthogonal vector diagrams in stratigraphic coordinates of progressive thermal demagnetization of samples from the Dorashamian of (a), (b) Abadeh and (c), (d) Shahreza. The filled and open symbols refer to the horizontal and vertical plane, respectively. (e), (f). Equal-area projections of the characteristic high-temperature directions for (e) Abadeh and (f) Shahreza.

Unblocking temperatures around 580 °C suggest a mineral of the titanomagnetite family as a carrier of remanence. The final mean direction for site L1 was computed using the four well-determined directions and two great circles.

In site L8, a magnetostratigraphic analysis was performed on 15 levels. The directions obtained in the bottom of the section (group 1) are opposite to those of the upper levels (group 2), and of the same polarity as in sites L1 and L2 (the inclination vectors point down). The unblocking temperatures for this component were found to range between 440 and 580 °C, also suggesting a mineral of the titanomagnetite family. Only samples from group 2 yield a component going straight to the origin. For the samples from group 1, demagnetization shows great circles which pass by the antipodes of group 2 (Fig. 7e). We have therefore used a great-circle analysis to compute the final mean site pole.

Sites L1, L2 and L8 yield directions that cluster strongly after bedding correction (95 per cent positive fold test at the sample level).

A high-temperature component was also found in site L4 within the same blocking-temperature range (Fig. 7f). In site S49 a combined circle/direction analysis allowed the determination of a mean direction close to that of site L4 with the same polarity (Fig. 7g). For these two sites, some samples displayed only the low- and medium-temperature components described above.

The directions of the five sites are plotted in Figs 7(h) and (i), before and after tilt correction. After tilt correction, there are two groups of directions: the mean directions of S49 and L4 are situated in the fourth quadrant, while L1, L2 and L8 contain opposite directions in both the first and the third quadrants. The directions of the five sites are not grouped, but

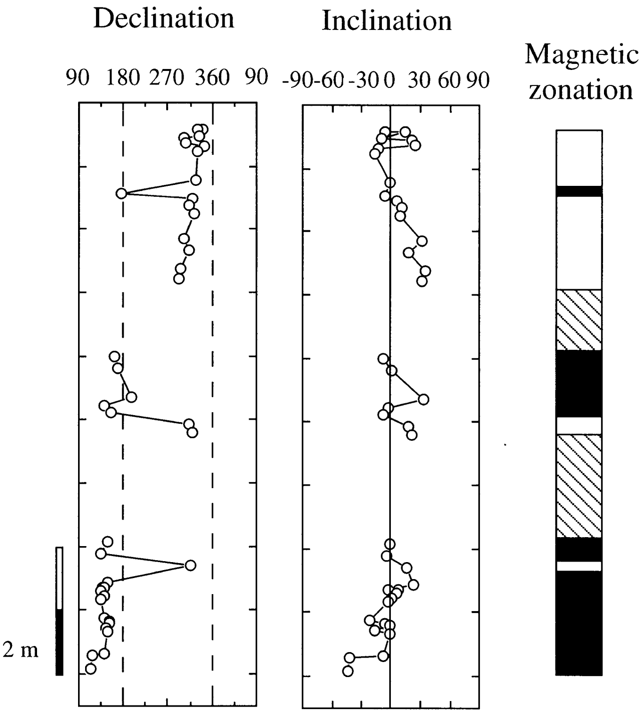


Figure 4. Magnetostratigraphy of the Hambast Formation (Dorashamian) in the Shahreza area. Left to right: declinations, inclinations and magnetic zonation versus stratigraphic depth. The polarity zonation is shown assuming a southern hemisphere of deposition.

the inclinations are close to one another. These directions may represent the same component, with relative rotation between sites. Indeed, a fault mapped in the field may have rotated sites 49 and L4, while sites L8, L2 and L1, remote from this fault, show a very similar declination. This interpretation is strengthened by the following facts. (1) The *k* ratio computed from the inclinations only before and after bedding correction, respectively, indicates a positive fold test at the 99 per cent level [McFadden & Reid (1982) statistics]. (2) There is an internal positive fold test at the 99 per cent level within sites L8, L2 and L1. (3) The magnetic polarities of site L8 correlate with the polarities of sites L1 and 49, in agreement with the conodont zonation.

DISCUSSION

The Iranian palaeomagnetic database

Numerous palaeomagnetic studies (Soffel *et al.* 1975; Wensink 1979, 1981, 1982; Soffel & Förster 1980; Wensink & Varekamp 1980; Bina *et al.* 1986; Soffel *et al.* 1995, 1996) have resulted in a very large amount of data of uneven quality. The nearly continuous tectonic activity in Iran from the Permian to the present, leading to remagnetizations and local, important rotations, often obscures the palaeomagnetic interpretations. In order to clarify the situation, we first established a selection of the available data. We retained poles with a 95 per cent confidence interval smaller than 20° and with evidence of successful alternating-field and/or thermal demagnetization. We also only retained poles with an age range (or uncertainty) smaller than 25 Myr. The number of sites was not a strong rejection criterion (we retained studies with more than 20 samples). Finally, we rejected studies where the precise geographic location of the sites was not given. These rather generous criteria lead nevertheless to a sparse database, detailed in Appendix A (see also Table 2).

The selected Late Permian poles from Iran are plotted in Fig. 8(a). The magnetostratigraphy of the Abadeh section fixes

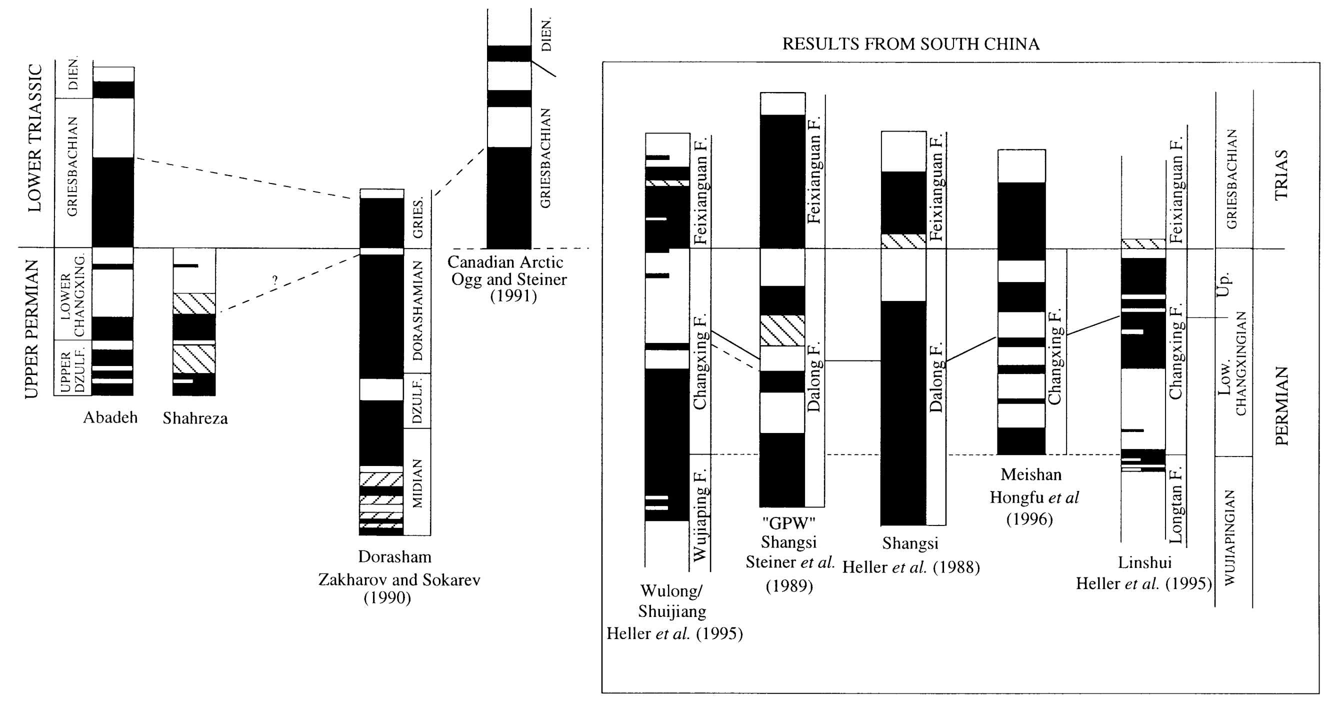


Figure 5. Correlation of Permian–Triassic magnetostratigraphic sections from Iran (Abadeh and Shahreza, this study), south China, Canadian Arctic and the former USSR.

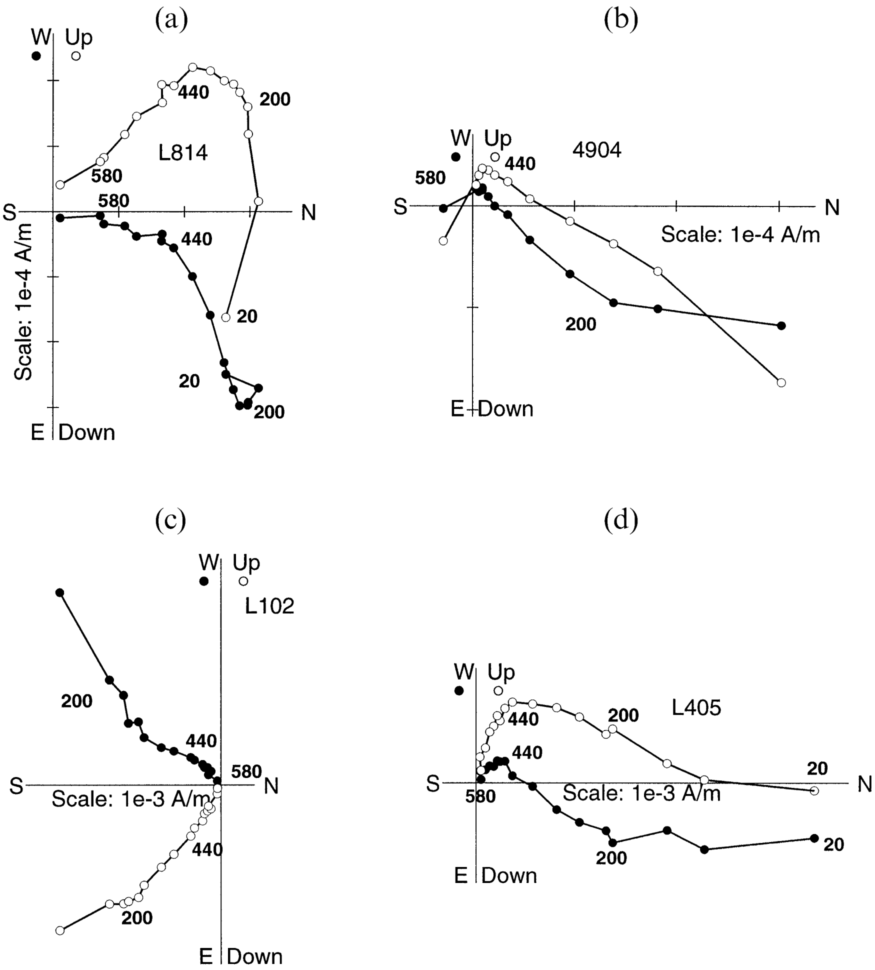


Figure 6. Orthogonal vector diagrams in stratigraphic coordinates of progressive thermal demagnetization for samples from the Norian limestones of the Abadeh region. The filled and open symbols refer to the horizontal and vertical plane, respectively. Three components are observed in each of these four examples.

the hemisphere of deposition of this region, and palaeopoles were computed according to this constraint. Fig. 8(a) shows the excellent agreement between the palaeolatitudes derived from the Alborz lavas and south-central Iran. The large clockwise rotation of the Abadeh region is well evidenced. A small circle representing the possible locus of the palaeopoles is shown in Fig. 8(a). Its radius and the associated uncertainty at the 95 per cent level were computed using the method of Mardia & Gadsden (1977) and the PaleoMac software package written by J. P. Cogné (available on request to cogne@ipgp.jussieu.fr). We have plotted in the same figure the apparent polar wander path (APWP) for west Gondwana, which combines the compilations of Besse & Courtillot (1991) for the 0–190 Ma segment and Besse, Théveniaut & Courtillot (1996) for the 200–380 Ma segment. The small circle and its error bars intersect the west Gondwana APWP in the 255–285 Ma time range: Iran was thus situated at a palaeolatitude with respect to Arabia similar to that of today.

Fig. 8(b) shows the poles available for the Early to Middle Triassic. We have plotted for comparison the APWP of Laurussia by Van der Voo (1993). The poles from the Early Triassic Sorkh Shales (Wensink 1982) and Natanz (Soffel *et al.* 1995, 1996), both from central Iran, are situated at the same angular distance from their sampling sites as the Sirjan poles (Soffel *et al.* 1995, 1996), which are from the southernmost continental sliver of Iran. The Alborz, central Iran and Sanandaj–Sirjan units had a common northward motion during the Late Permian and Early Triassic. Wensink (1982) suggested, on the basis of the Sorkh Shales study, that the shift to the north of the Iran block took place in the Late Triassic, and placed Iran at 11°S during the Early Triassic, close to the coast of Arabia. However, no palaeomagnetic arguments can discard an 11°N palaeolatitude of deposition. We prefer this latter solution because the subsidence data of Saïdi *et al.* (1997) favour a departure of the Iran block from Gondwana after the Early Permian and a collision with Eurasia during the Middle Triassic.

Because the northern margin of Gondwana was on the equator during the Late Triassic, there is no critical hemispheric ambiguity. A palaeolatitude of Iran at 30°S would thus be topologically impossible (see also Fig. 11). A small circle (Fig. 8c) was computed using our Late Triassic pole from the Abadeh region. A 15° angular difference between poles of Early to Middle and Late Triassic age shows a period of rapid northward motion of Iran. This is also the case for the Eurasian APWP, and one must take care to compare poles with well-matched ages. The mean Late Triassic small circle for Iran cuts the Eurasian APWP at 220 Ma, probably indicating that

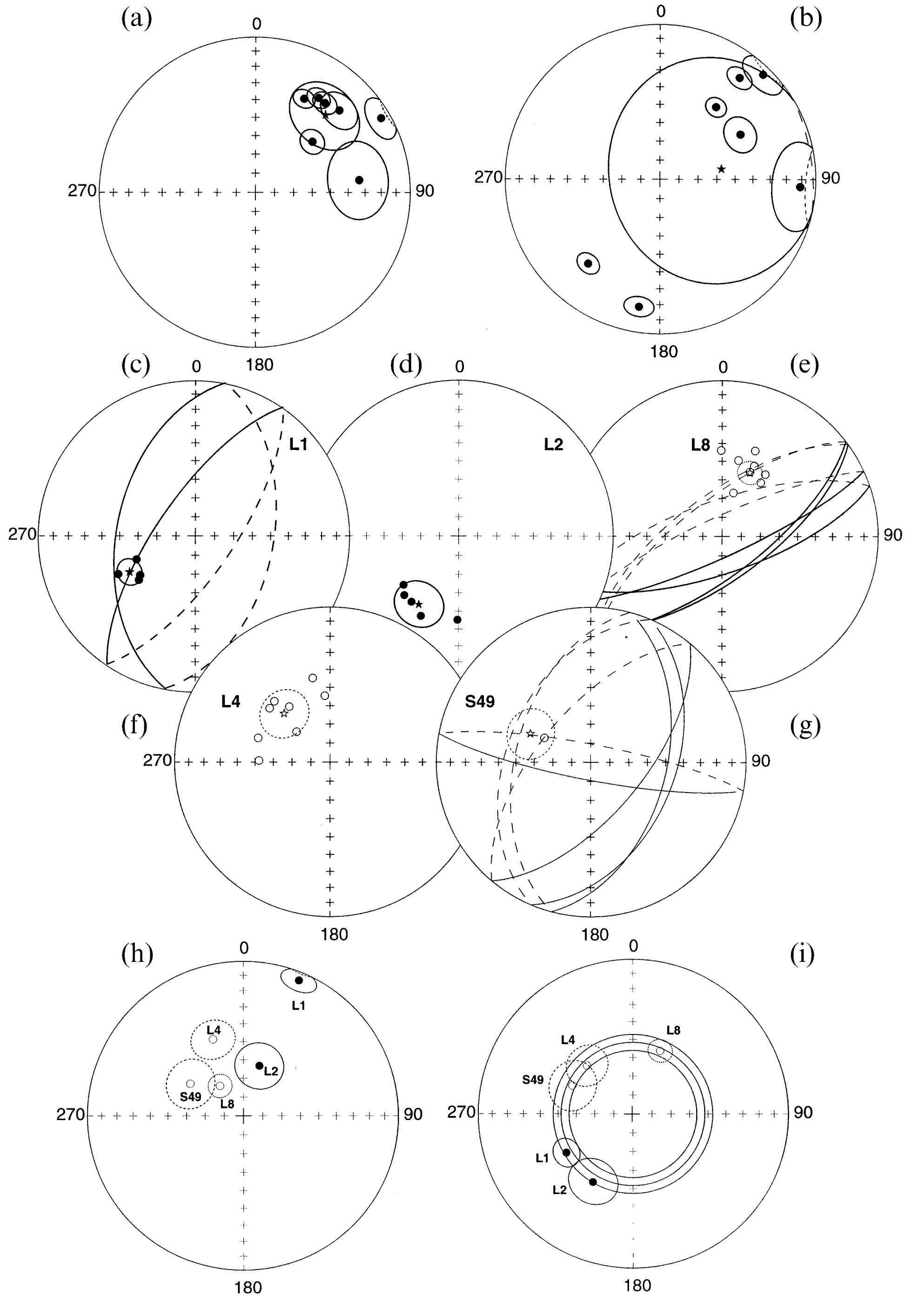


Figure 7. (a), (b) Equal-area projections of the middle-temperature component directions of Abadeh samples (a) before and (b) after bedding corrections. (c)–(g) Equal-area projections in stratigraphic coordinates of the directions carried by the characteristic high-temperature component of samples from Abadeh (sites S49, L1, L2, L4, L8). (h), (i) Equal-area projections of the mean directions carried by the characteristic high-temperature component of samples from Abadeh (Norian) before and after bedding correction. The difference in declinations indicates relative rotations between these sites.

Iran had already collided with Eurasia at that time. Large clockwise rotations of the same order of magnitude as those observed in the Permo-Triassic are evidenced: the post-Norian rotation constitutes an additional argument which strengthens the hypothesis of a southern-hemisphere palaeolatitude of Iran during the Permian.

The three lowest-Cretaceous/late Jurassic poles (Fig. 8d) are in good agreement. Rotations within the central Iran block appear to be discrepant: a large clockwise rotation is evidenced for the Bidou beds, while the Garedu region has suffered no significant rotation. The small circle computed from the three studies (134, 150 and 153 Ma) cuts the 140 Ma pole of Eurasia. No relative latitudinal motion between Iran and Asia is therefore evidenced by palaeomagnetism.

The four Early Cretaceous poles from Alborz (Fig. 8e) are well grouped in colatitude. The small circle and its error bars

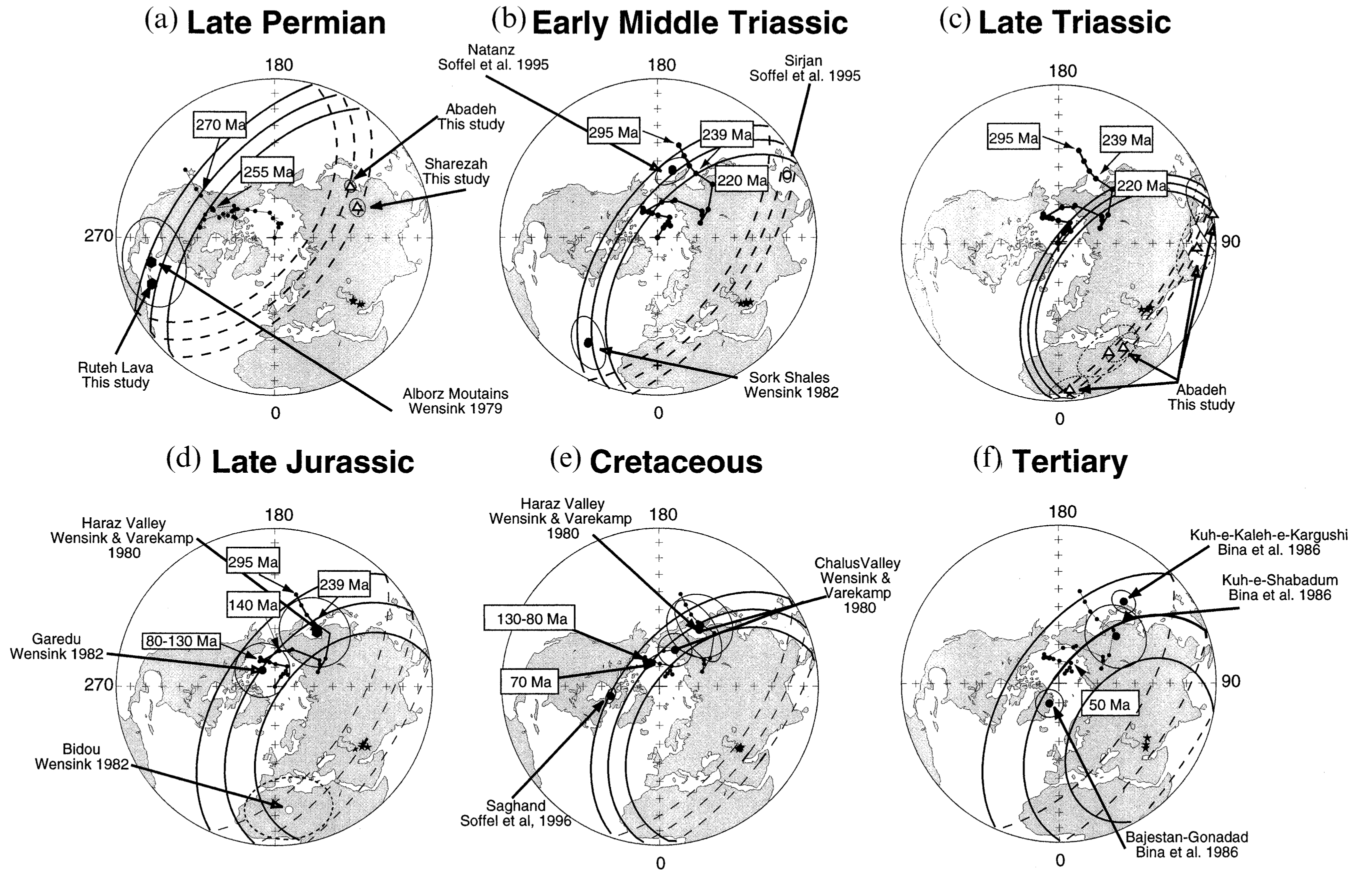


Figure 8. Equal-area projection showing our Iranian selected directions for six time windows: (a) Late Permian, (b) Early–Middle Triassic (c) Late Triassic, (d) late Jurassic, (e) Cretaceous and (f) Cenozoic. The poles are listed in Table 2 and described in Appendix A. Poles from Alborz are indicated by hexagons, poles from central Iran by circles, and poles from the Sanandaj–Sirjan zone by triangles. Poles in the upper and lower hemisphere are represented by filled and open symbols, respectively. The Gondwanian apparent polar wander path (APWP) is shown in (a) and the Eurasian APWP in (b)–(f). The small circles representing the possible loci of poles are centred on the sampling sites (represented by stars).

cut the APWP of Eurasia in the 60–140 Ma time segment, showing a slight clockwise rotation of Alborz with respect to Eurasia and central Iran and again no noticeable relative motion in latitude.

Finally, the small circle through the three Cenozoic poles cuts the APWP at around 50 Ma. Rotations are obvious, showing that tectonic activity has scattered the distribution of the virtual geomagnetic poles (VGPs) on the small circle, and post-dates the late Tertiary.

Relative motions between Iran, Africa and Eurasia

The observed Iranian and predicted Eurasian palaeolatitudes are compared in Fig. 9(a). Owing to the large area of Iran and its former geological divisions, each predicted direction has been computed at the site to which it is compared. A rapid northward motion with respect to Eurasia since 260 Ma is evident. We computed the intersection of a linear fit, using the data between 260 and 220 Ma, with the axis of null latitude difference: an age of 230 Ma was found. Estimation of the errors leads to a minimum age of 210 Ma and a maximum of 250 Ma. An identical age of collision (Ladinian) has been inferred from geological evidence (Saïdi *et al.* 1997). Subsidence curves from various parts of the Iran block itself, which indicate a common behaviour during the Permian to the Middle Triassic, point to a Ladinian tectonic reorganization through uplift of the (collisional) northern parts and foundering events in the southern and eastern parts. Moreover, continent-derived conglomerates reached Iran [Nakhlak section, near Nain (Fig. 1)] during the Ladinian. Subduction-related magmatism at the southern edge of Eurasia [Aghdarband (Fig. 1)] ended during the Anisian (Baud, Stampfli & Steen 1991), and migrated to the southern margin of Iran during the Late Triassic [Abadeh (Fig. 1)]. This documents a shift of the subduction boundary that can be considered as resulting from the collision. The end of the collision between Iran and Eurasia is marked by the Late Norian Shemshak continental coal-bearing sediments, found in Iran and in nearby areas of Eurasia.

We do not confirm an earlier collisional stage proposed from a later stabilization in latitude with respect to Eurasia (syn/post-collisional northern shortening), as discussed by Théveniaut (1993). From a magnetostratigraphic study of a Permo-Triassic section in Mangishlak (western Kazakhstan), Feinberg *et al.* (1996) also argued for an important post-Early Triassic northward motion ($17^\circ \pm 5^\circ$) of the Turan plate with respect to stable Eurasia. This latter possibility, unfortunately, relies on data in which the reversed and normal directions show a strong non-antipodality of some 30°. This result conflicts with the directions extracted from the GPM database (McElhinny & Lock 1995) for 11 Permo-Triassic Russian

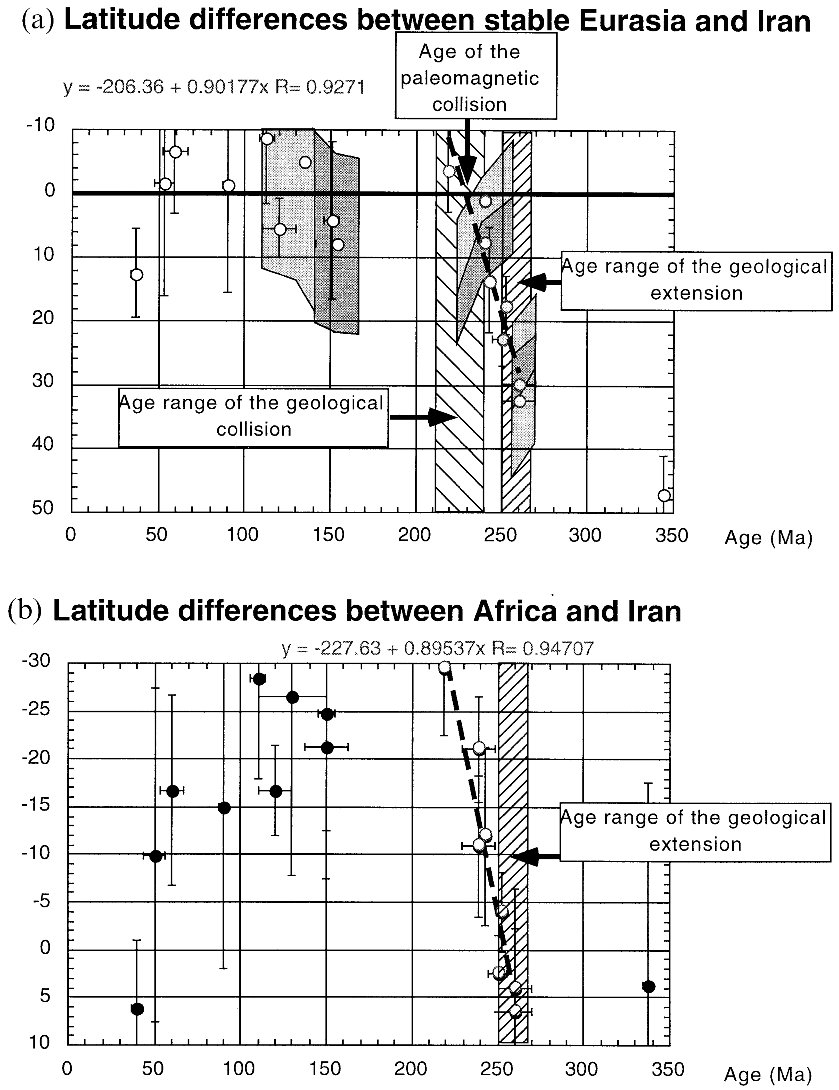


Figure 9. (a) Differences between the observed Iranian and predicted Eurasian palaeolatitudes. The horizontal error bars are the age errors in the Iranian data, and the vertical error bars are the errors of latitude difference computed as $(\lambda^2_{\mathrm{predicted}}+\lambda^2_{\mathrm{observed}})^{1/2}$, where λ is the palaeolatitude. The grey areas represent the corresponding errors for the poles, with age uncertainties of ± 10 Myr. The dashed line is an estimation of the palaeomagnetic age of collision made using a linear regression on data between 260 and 219 Ma. Note the high value of the correlation coefficient *R*. (b) Difference between predicted Iranian and expected Gondwanian palaeolatitudes. The symbols are the same as in (a). The northward component of the motion of Iran with respect to Africa is around 10 cm yr^{-1}.

studies of the Turan region showing a positive fold test, which yield a latitude difference of only $3^\circ \pm 7^\circ$ with respect to Eurasia. However, the demagnetization procedures used here were barely acceptable. More data are thus required to solve this problem. Evidence for a significant post-Triassic shortening relies on two poorly determined poles, which do not fulfil our selection requirements: the first pole is from a study of volcanic rocks in Alborz (Wensink 1979), with large age uncertainties between underlying Middle/Late Triassic sediments and overlying early/middle Jurassic ones, giving an age range of deposition between about 240 and 160 Ma. The second pole includes possibly the Shemshak and overlying Hojedk formations, and perhaps basalts (Soffel & Förster 1980), for which no useful information on age and position is given by the authors [this pole is even not quoted in McElhinny & Lock's (1995) palaeomagnetic database]. We were ourselves unable to extract useful information from this facies, despite extensive sampling. We feel that our Late Triassic data from the Abadeh region (moreover, situated in the southernmost Iranian unit) may represent a better determination.

The mean computed for the results younger than 153 Ma yields an insignificant difference of $-1.2^\circ \pm 2.7^\circ$ with respect to Eurasia (Fig. 9a). Thus, no significant post-Late Triassic motion in latitude can be traced out between Eurasia and Iran within the uncertainties of the palaeomagnetic method. Note that there is presently a lack of early/late Jurassic data of good quality. The creation of ophiolites during the Late Cretaceous, now traced out by the Nain–Sabzewar and Nain–Baft lineaments, probably corresponds to a north–south opening not wider than 300 km.

Fig. 9(b) represents the difference between the observed Iranian and expected Gondwanian palaeolatitudes, using the APWP of Besse & Courtillot (1991) for periods between the present and 200 Ma, and the APWP of Besse *et al.* (1996)

transferred onto South African coordinates for older periods. The West Gondwanian Permo-Triassic pole of Torcq *et al.* (1997) has also been used. In order to increase the precision, we interpolated the predicted African directions between the two nearest periods matching a given age of the Iran data. The first data at 344 Ma (close to the Devonian/Carboniferous boundary) (Wensink 1979) confirm the Gondwanian origin of Iran, although large uncertainties due to the ill-defined pole for Gondwana exist. There are no palaeomagnetic data to date exactly when Iran rifted away from Gondwana. But the beginning of rifting was stratigraphically dated by Saïdi (1995) and Saïdi *et al.* (1997) as late Early Permian. Assuming a constant spreading rate of the Tethyan ridge during the transit of Iran, a linear fit between the Permian and Triassic data provides an estimate of the mean northward velocity of Iran with respect to Gondwana of some 100 km Myr^{-1}.

Rotations in Iran

Earlier discussions by Wensink (1979, 1981, 1982), Wensink & Varekamp (1980), Soffel & Förster (1980), Davoudzadeh & Schmidt (1984), Bina *et al.* (1986), Soffel *et al.* (1995, 1996), Saïdi (1995) and Saïdi *et al.* (1997) suggested the importance of rotations at different scales. Considering the complex deformation history and the small amount of data in both space and time, one should bear in mind that interpretation of rotations may only address phenomena of local importance. Nevertheless, we have tried to extract some general tendencies. We summarize in Fig. 10 the relative rotations between Eurasia and the major structural regions in Iran (Alborz, Abadeh–Sirjan sliver and east central Iran) derived using the selected data set. As discussed earlier, there is a large general post-Triassic clockwise rotation of the Abadeh–Sirjan zone. The timing of rotation cannot be determined at present since there is no study available on rocks of a younger age. There are only a few pieces of data for the central Alborz, but they represent several epochs. An important counter-clockwise rotation occurred between 260 and 225 Ma, which is probably linked to the Middle Triassic collision. More results would be necessary all along the Alborz to ascertain the existence of this rotation throughout this area. The data available for the Cretaceous show a mean 30° clockwise rotation. The Karaj volcanic data at 45 Ma (Bina *et al.* 1986) indicate rotations that are even younger than the Eocene. Concerning east central Iran, the Sorkh Shales, situated close to a fault, and the Kuh e Khaleh e Kargushi e Shabadum sites, too close to the Eocene suture, may have only local significance and were not used. The rotations from the Jurassic to the Palaeocene are counter-clockwise and homogenous (30°) for the northern part (Tabas–Birdjan–Gonabad) of this unit. On the other hand, the Jurassic Bidou sites, situated in the southern part, show a larger counter-clockwise rotation of 153° since the Jurassic. This discrepancy between the north and south in the Jurassic is not consistent with the interpretation of Soffel & Förster (1980), who argued for a counter-clockwise rotation of some 90° since the Triassic and 75° since the Jurassic in east central Iran, taken as a single rigid block. Their 90° rotation value is derived in fact from the mean of some directions consistently rotated counter-clockwise, but with very different magnitudes. We recall that the interpretation of these authors is based on mean poles without an indication of the sites or a detailed description of the studies, which we therefore did not retain in our compilation.

A Tethyan reconstruction between the Late Permian and the Late Triassic

We try to reconstruct the evolution of the Tethyan area between the end of the Permian (260–250 Ma) and Late Triassic (220 Ma) in Fig. 11. The chosen Pangea reconstruction at 260–250 Ma is of B type (Irving 1977; Torcq *et al.* 1997). In this configuration, South America faces North America during the Late Permian. After the Permian final collision, Gondwanaland moves south-eastward with respect to Laurussia during the Triassic along a dextral megashear. The Atlantic pre-opening position is then reached by the end of the Middle Triassic, as shown by the Carnian/Norian age of the continental basins in eastern North America and Morocco

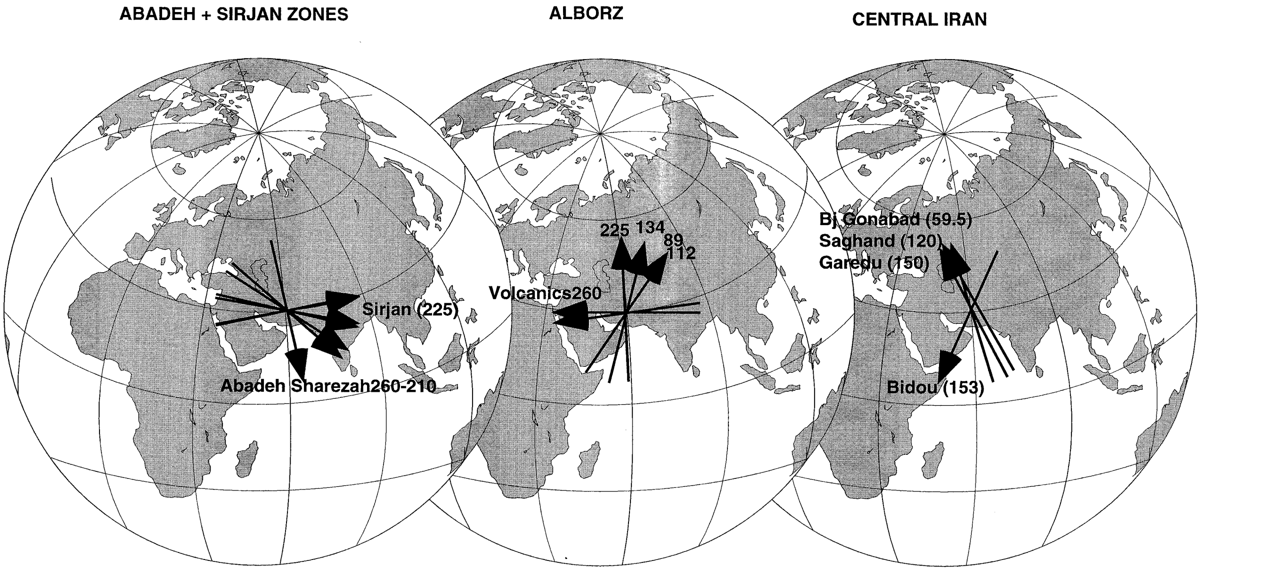
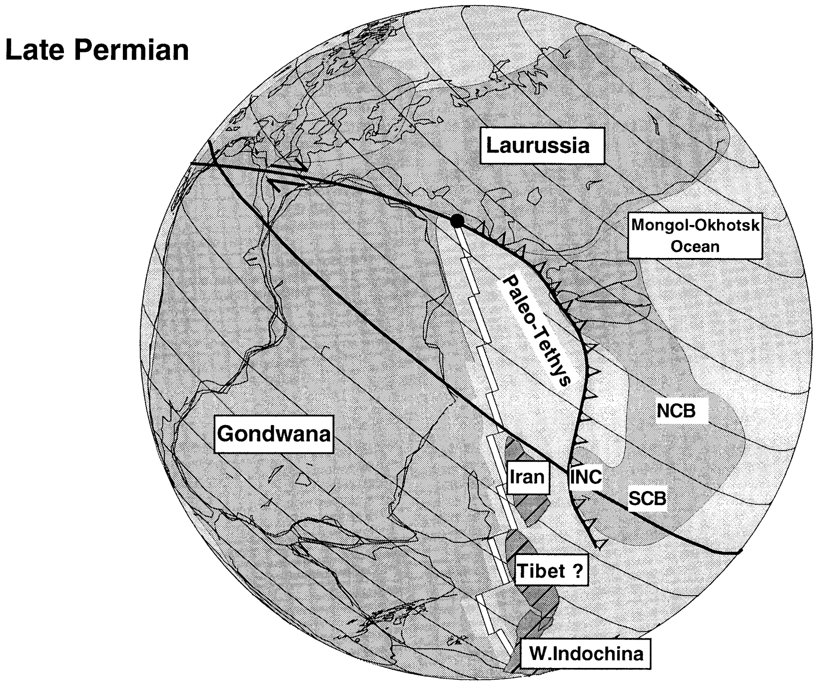


Figure 10. Difference between observed Iranian and expected Eurasian declinations for three Iranian regions. Note the very large rotations showing the complex tectonic history of these regions.



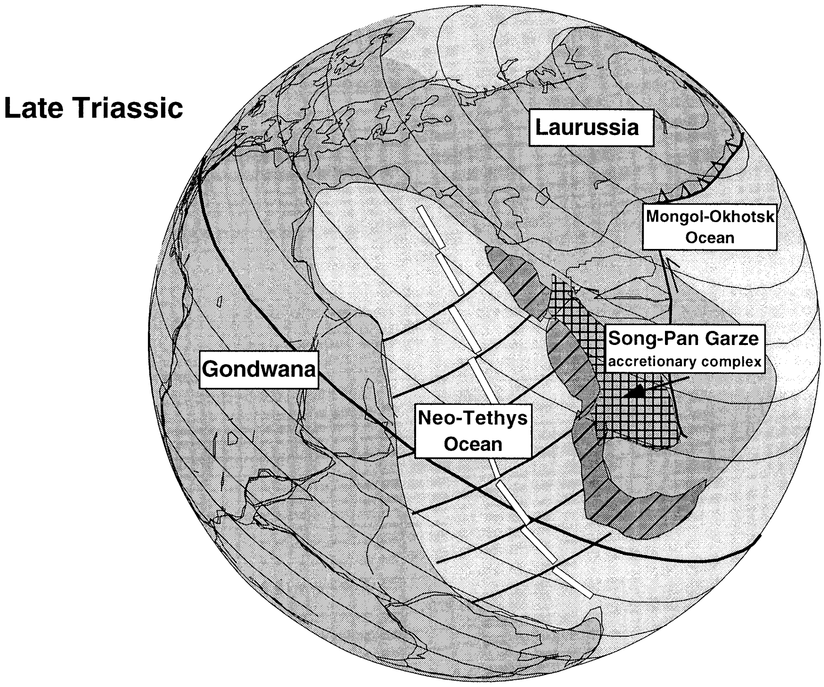


Figure 11. Palaeogeographic reconstruction of the Tethyan ocean and its bordering continents during the Late Permian and the Late Triassic. Cross-hatched areas, Cimmerian blocks; solid line, palaeoequator; the heavy lines perpendicular to the ridge indicate the motion of the Iranian blocks between Gondwana and Laurussia (indicated as transform faults). Open triangles, subduction zones; filled circle, the fault–ridge–trench triple junction. NCB, North China block; SCB, South China block; INC, Indochina.

(Manspeizer 1982). The mean strike-slip velocity calculated by Torcq *et al.* (1997) reaches some 130 km Myr^{-1} during the Triassic. The northward velocity component of the Iran units with respect to Gondwana (Neotethyan ridge) from the Late Permian to the Late Triassic derived from this study is around 100 km Myr^{-1}. To the east of the system, the south of the Turan plate is a subduction zone, as attested by the presence of calc-alcaline volcanic rocks at Aghdarband in the Khopet Dagh region (Kazmin, Ricou & Sbortshikov 1986). This plate-boundary configuration leads to a fault–ridge–trench triple junction; this configuration is stable in time as long as the directions of the strike-slip fault and of the trench are roughly the same. We restored the palaeoposition of Iran with respect to Africa by the end of the Permian and with respect to Eurasia during the Late Triassic. These two successive positions were used to compute one of the possible Eulerian poles of rotation describing the Iran/Africa motion, at $\lambda = 18°N$, $\phi = -41°E$, angle of rotation = 30° (Africa kept fixed). The azimuth of the Neotethyan ridge can be qualitatively approximated at about 120–140°N close to the triple junction, translating into a 100–140 km Myr^{-1} spreading rate of the Tethyan ridge. Although slightly slower, this velocity is similar to that of India (166 km Myr^{-1}) before the Indian/Asian collision during the Tertiary (Patriat & Achache 1984). Tibet and the western part of Indochina were tentatively replaced in our reconstruction, although no palaeomagnetic data are available for these blocks. We also considered other blocks of southeast Asia (China, Indochina, Tarim and Kunlun) as discussed by Enkin *et al.* (1992). The 250 Ma reconstruction shows that the Paleotethys ocean was narrower than previously thought, and did not widen its gate to the Panthalassa before Triassic times. Easy terrestrial connections between Indochina, China, Iran and Arabia (Gondwanaland) are therefore evidenced. Such a reconstruction is in agreement with a southern route for Cathaysian plants to enter Arabia, as proposed by Broutin *et al.* (1995).

ACKNOWLEDGMENTS

The authors wish to thank Dr Amhadzadeh Heravi and the Geological Survey of Iran for inestimable help. We also thank Rob Van der Voo and Heinrich Soffel for very constructive reviews. The computations were performed using the PaleoMac software package kindly provided by J. P. Cogné. This work was funded by the CNRS-INSU programme 'Terre profonde'. This is INSU contribution No. 106 and IPGP contribution No. 1539.

REFERENCES

Assereto, R. & Gaetani, M., 1964. Nuovi dati sul Devoniano della catena dell'Imam Zadeh Hashim (Elburz Central-Iran), *Riv. Ital. Pal. Start.,* **LXX. 4,** 631–636.

Baud, A., Stampfli, G. & Steen, D., 1991. The Triassic Aghdarband Group: volcanism and geological evolution, in *The Triassic of Aghdarband, NE-Iran, and its Pre-Triassic Frame,* ed. Ruttner, A.W., *Abh. Geol. B.,* A, **38,** 125–137.

Berberian, M. & King, G.C.P., 1981. Towards a paleogeography and tectonic evolution of Iran, *Can. J. Earth Sci.,* **18,** 210–265.

Besse, J. & Courtillot, V., 1991. Revised and synthetic polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma, *J. geophys. Res.,* **96,** 4029–4050.

Besse, J., Théveniaut, H. & Courtillot, V., 1996. Apparent polar wandering paths for North America, Africa, Laurussia and West Gondwana since the Upper Carboniferous: a review, in *Tethys Paleoenvironments, Ocean Basins and Margins,* pp. 71–97, eds Nairn, A.E.M., Ricou, L., Vrielinck, B. & Dercourt, J., Plenum Press, New York.

Bina, M.M., Bucur I., Prévot, M., Daly, L. & Cantagrel, J.M., 1986. Paleomagnetism, petrology and geochronology of Tertiary magmatic and sedimentary units from Iran, *Tectonophysics,* **121,** 303–329.

Broutin, J., Roger, J., Paltel, J.P., Angiolini, L., Baud, A., Bucher, H., Marcoux, J. & Al Hasmi, H., 1995. The Permian Pangea. Phytogeographic implications of new paleontological discoveries in Oman (Arabian Peninsula), *C. R. Acad. Sci. Paris,* **321,** 1069–1086.

Davoudzadeh, M. & Schmidt, K., 1984. A review of the Mesozoic paleogeography and paleotectonic evolution of Iran, *N. Jb. Geol. Paläont. Abh.,* **168,** 182–207.

Enkin, R., Yang, Z., Chen, Y. & Courtillot, V., 1992. Paleomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the present, *J. geophys. Res.,* **97,** 13 953–13 989.

Feinberg, H., Gurevitch, E.L., Westphal, M., Pozzi, J.P. & Khramov, A.N., 1996. Paleomagnetism of a Permo-Triassic sequence in Mangislak (Kazakhstan, CIS), *C. R. Acad. Sci. Paris,* **322,** 617–623.

Fisher, R.A., 1953. Dispersion on a sphere, *Proc. R. Soc. Lond.,* **217,** 295–305.

Glaus, M., 1965. *Die Geologie des Gebietes nördlich des Kandevan-Passes (Zentral-Elburz), Iran,* Schmidberger & Müller, Zürich.

Heller, F., Lowrie, W., Li, H. & Wang, J., 1988. Magnetostratigraphy of the Permo-Triassic boundary section at Shangsi, *Earth planet Sci. Lett.,* **88,** 348–356.

Heller, F., Haihong, C., Dobson, J. & Haag, M., 1995. Permian-Triassic magnetostratigraphy—new results from South China, *Phys. Earth planet. Inter.,* **89,** 281–295.

Hongfu, Y., Shunbao, W., Meihua, D., Kexin, Z., Jinnan, T., Fengquin, Y. & Xulong, L., 1996. The Meishan section, candidate of the global stratotype section and point of Permian Triassic Boundary, in *The Palaeozoic–Mesozoic boundary,* pp. 31–48, Hongfu, Y., China University of Geoscience Press, Wuhan.

Iranian–Japanese Research Group, 1981. The Permian and the Lower Triassic Systems in Abadeh Region, Central Iran, *Mem. Fac. Sci., Kyoto Univ. Ser. Geol. Mineral.,* **47,** 61–133.

Irving, E., 1977. Drift of the major continental blocks since the Devonian, *Nature,* **270,** 304–309.

Kazmin, V.G., Ricou, L.E. & Sbortshikov, I.M., 1986. Structure and evolution of the passive margin of the eastern Tethys, *Tectonophysics,* **123,** 153–179.

Kirschvink, J.L., 1980. The least squares line and plane and the analysis of paleomagnetic data, *Geophys. J. R. astr. Soc.,* **62,** 699–718.

Kotlyar, G., Kommissarova, R., Khramov, A. & Chediya, I., 1984. Palaeomagnetism of Upper Permian rocks from Transcaucasia, *Dokl. Akad. Nauk SSSR,* **276,** 669–674 (in Russian).

McElhinny, M.W. & Lock, J. 1995. Four IAGA databases released in one package, *EOS, Trans. Am. geophys. Un.,* **76,** 266.

McFadden, P.L. & McElhinny, M.W., 1988. The combined analysis of remagnetization circle and direct observation in paleomagnetism, *Earth planet Sci. Lett.,* **87,** 161–72.

McFadden, P.L. & McElhinny, M.W., 1990. Classification of reversal test in paleomagnetism, *Geophys. J. Int.,* **103,** 725–729.

McFadden, P. & Reid, A.B., 1982. Analysis of paleomagnetic inclination data, *Geophys. J. R. astr. Soc.,* **69,** 307–319.

Manspeizer, W., 1982. Triassic–Liassic basins and climate of the Atlantic passive margins, *Geol. Rundschau,* **77,** 897–917.

Mardia, K.V. & Gadsden, R.J. 1977. A small circle of best fit for spherical data and areas of vulcanism, *Appl. Stat.,* **26,** 238–245.

Ogg, J. & Steiner, M. 1991. Early Triassic magnetic polarity time scale: integration of magnetostratigraphy, ammonite zonation and sequence stratigraphy from statotype sections (Canadian Arctic Archipelago), *Earth planet. Sci. Lett.,* **107,** 69–89.

Patriat, P. & Achache, J., 1984. India–Eurasia collision chronology has implications for crustal shortening and driving mechanisms, *Nature,* **311,** 615–621.

Ricou, L.E., 1994. Tethys reconstructed: plates, continental fragments and their boundaries since 260 Ma from to south-eastern Asia, *Geodyn. Acta,* **7,** 169–218.

Saïdi, A., 1995. Calendrier de la migration Permo-Triassique et morcellement Mésozoïque des éléments continentaux de l'Iran: apports de la subsidence et du paléomagnétisme, *Thèse de Doctorat,* Université Paris 6.

Saïdi, A., Brunet, M.F. & Ricou, L.E., 1997. Continental accretion of the Iran block to Eurasia as seen from Late Paleozoic to Early Cretaceous subsidence curves, *Geodyn. Acta,* **10,** 189–208.

Sengör, A.M.C. & Hsu, K.J., 1984. The Cimmerides of Eastern Asia: history of the Eastern end of Paleo-Tethys, *Mem. Soc. geol. France,* **147,** 139–167.

Soffel, H.C. & Förster, H.G., 1980. Apparent polar wander path of central Iran and its geotectonic interpretation, *J. Geomag. Geoelectr.,* **32,** 117–135.

Soffel, H.C., Förster, H.G. & Becker, H., 1975, Preliminary polar wander path of Central Iran, *J. Geophys.,* **41,** 541–543.

Soffel, G., Davoudzadeh, M., Rolf, C. & Schmidt, S., 1995. New paleomagnetic data from Iran, *Geo-sciences, Geol. Surv. Iran,* **4.**

Soffel, G., Davoudzadeh, M., Rolf, C. & Schmidt, S., 1996. New paleomagnetic data from central Iran and a Triassic reconstruction, *Geol. Rundsch,* **85,** 293–302.

Stampfli, G., Marcoux, J. & Baud, A., 1991. Tethyan margins in space and time, *Palaeogeog. Palaeoclimat. Palaeoecol.,* **87,** 373–409.

Steiner, M., Ogg, J., Zhang, Z. & Sun, S. 1989. The late Permian/Early Triassic magnetic polarity time scale and plate motions of south China, *J. geophys. Res.,* **94,** 7343–7363.

Stöcklin, J., 1968. Structural history and tectonics of Iran: a review, *Am. Assoc. Petrol. Geol. Bull.,* **52,** 1229–1258.

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

Taraz, H., 1969. Permo-Triassic section in central Iran, *Am. Assoc. Petrol. Geol. Bull.,* **53,** 688–693.

Taraz, H., 1971. Uppermost Permian and Permo-Triassic transition beds in central Iran, *Am. Assoc. Petrol. Geol. Bull.,* **55,** 1280–1294.

Théveniaut, H., 1993. Evolution de la Téthys occidentale et de la Pangée au Trias. Les apports de la magnétostratigraphie et du paléomagnétisme en France et en Turquie, *Thèse de Doctorat,* Université Paris 7.

Torcq, F., Besse, J., Vaslet, D., Marcoux, J., Ricou, L.E., Halawani, M. & Basahel, M., 1997. Paleomagnetic results from Saudi Arabia and the Permo-Triassic Pangea configuration, *Earth planet. Sci. Lett.,* **148,** 553–567.

Van der Voo, R., 1993. *Palaeomagnetism of the Atlantic, Tethys and Iapetus Oceans,* Cambridge University Press.

Wensink, H., 1979. The implications of some paleomagnetic data from Iran for its structural history, *Geologie en Mijnbouw,* **58,** 175–185.

Wensink, H., 1981. Le contact Gondwana-Eurasie en Iran d'après les recherches paléomagnétiques, *Bull. Soc. géol. France,* **7,** 547–552.

Wensink, H., 1982. Tectonic inferences of paleomagnetic data from Mesozoic formations in central Iran, *J. Geophys.,* **51,** 12–23.

Wensink, H. & Varekamp, J.C., 1980. Paleomagnetism of basalt from Alborz: Iran part of Asia in the Cretaceous, *Tectonophysics,* **68,** 113–129.

Zakharov, Y.D. & Sokarev, A.N., 1991. Permian–Triassic paleomagnetism of Eurasia, in *Proceedings of Shallow Tethys 3, Sendai, 1990, Saito Ho-on Kai Spec. Publ.,* **3.**

APPENDIX A: SELECTED POLES FROM IRAN

Details of these poles are listed in Table 2.

Palaeomagnetic data from central Iran

The Kuh-e-Shabadum volcanics (Bina *et al.* 1986) are a sequence of andesitic tuffs and flows with some interbedded calcareous layers of Eocene age. Two samples yielded K/Ar ages of 26 Ma, which may represent the post-metamorphic cooling age: metamorphic parageneses are sometimes observed in these rocks. Palaeomagnetic samples were taken from six flows or tuffs. The most frequent mineral is haematite, but titanomagnetites are also present.

The Kuh-e-Kaleh-e-Kargushi series, situated close to the Kuh-e-Shabadum series, is a shoshonitic association of late Eocene age. Five volcano-sedimentary formations were sampled. K/Ar ages of 23.5 Ma for a basic lava and 20.7 Ma for a dacitic one were obtained. These results are also interpreted as representative of the age of the metamorphic or metasomatic episode of the Oligocene–Miocene boundary. Bina *et al.* (1986) emphasize the fact that thermal demagnetization of samples having only haematite as a magnetic carrier shows directions remaining constant after heating to 350 °C (the maximum temperature of the metamorphism), thus leaving untouched the primary Eocene directions. The volcanics all contain titanomagnetite. Both of these series give indications of the age of rotations, but care must be taken since structural corrections are problematic in this kind of geological context.

The Bajestan–Gonabad volcanic series (Bina *et al.* 1986), situated at the extreme north of the Lut block, was sampled in a monoclinal structure. These rocks are very altered and rich in secondary products. No metamorphism was detected. The radiometric ages obtained correspond to the Palaeocene (54, 61 and 62 Ma). The presence of secondary minerals of hydrothermal origin makes these ages a minimum for the volcanism. For stratigraphic reasons, the volcanism should not be very much older. The main magnetic carrier is haematite, which would result from the martitization of titanomagnetite and oxidation of silicates. The mean directions vary little from one flow to another. This suggests that the hydrothermal episode around 60 Ma occurred shortly after the eruption.

The Saghand area is located in the centre of central Iran. Samples of Cretaceous age (112 samples) were collected. Alternating-field (AF) and thermal treatments were applied. Only 33 samples yielded a stable component but the component is regarded as primary by the authors, although this was not ascertained by a fold or reversal test.

The pole from the Bidou beds (Wensink 1982) corresponds to an analysis of dark-brown sandstones alternating with shales. Limestone intercalations containing fossils give an age which ranges from late–middle Jurassic to very early Cretaceous. 39 specimens from five sites were correctly demagnetized (AF or AF plus thermal demagnetizations). The remanence directions deviate from the PEF. They all have the same polarity and their mean direction (Table 2) may be interpreted as reflecting a southern hemisphere of deposition for the Bidou beds with a clockwise rotation of about 50° or a northern hemisphere of deposition with a large rotation of 130° counterclockwise. This last solution is the more probable because Iran was surely a part of Eurasia at this time.

The pole from the Garedu beds (Wensink 1982) corresponds to an analysis of reddish silty shales and sandstones containing sparse fossils giving a most likely Kimmeridgian to Tithonian age. 52 specimens taken in four sites were thermally and AF demagnetized. A first component, removed by a few tenths of a millitesla or 250 °C, is close to the PEF and corresponds to a component of remagnetization. Another component, of higher temperature or higher coercivity, was found in all samples and is only of normal polarity. This direction (Table 2) reflects a northern hemisphere of deposition with little rotation. The fold test was inconclusive and the primary origin of the magnetization cannot be proven.

44 oriented cores (five sites) of uppermost-Scythian–Middle Triassic sandstones, and dolomites and limestones of Upper Triassic age were studied by Soffel *et al.* (1995, 1996) in the Natanz area. A total of 161 specimens were thermally demagnetized. Almost all sites contained normal or reversed directions, and a fold test (relying on one site) was positive at the 99 per cent level of probability. The direction is thus thought to be of primary origin. The mean direction (Table 2) reflects a small clockwise rotation of 30° if these sediments were deposited in the northern hemisphere.

Triassic volcanics from the Sirjan area (Soffel *et al.* 1995, 1996) were subjected to AF demagnetization. Two groups of stable directions were found. The first group is interpreted as a Tertiary-age remagnetization. The second group was also found in another group of specimens which were thermally demagnetized. This group comprises normal and reversed directions, and the magnetization is thus regarded as primary. No radiometric dating is available. The mean direction reflects a huge rotation of 110° clockwise for a northern hemisphere of deposition.

Thin-bedded reddish shales from the Sorkh Shale Formation (Wensink 1982), thought to be of Early Triassic age, were taken in five sites (51 specimens). Thermal demagnetization of these samples gave a characteristic remanence direction in 43 cases, with normal and reversed directions. The fold test was not positive at the 95 per cent level but a better clustering of directions after tilt correction (α_{95} changes from 16.9° to 14.2°) suggests a primary origin of the magnetization.

Results from Alborz

The Chalus formation in the central Alborz (Wensink & Varekamp 1980) is a very thick sequence of volcanic flows alternating with limestones. It overlays late-Jurassic–Early Cretaceous formations composed of limestones with sandy intercalations, and is overlain by thick-bedded limestones and marls with abundant *Globotruncana* giving a Late Cretaceous age. Member 1 of this formation is made of dark-coloured basic lavas with thin intercalations of tuffite. It is overlain by member 2 (limestones with orbitolines) dated as Late Barremian and Early Aptian. The last member of this formation (member 5) consists of lavas and agglomerates. Eight lava flows and two beds of tuffite were sampled in member 1 and AF or thermally demagnetized. Sites with normal and reversed polarities were found. The alteration of the lavas is mentioned to be moderate. The main magnetic carriers are magnetite and ilmenite. Six sites from member 5 were also sampled. These flows are also slightly weathered. One of them showed viscous magnetization and no directions could be isolated. Thermal demagnetization led to directions of normal polarity (there were no secondary components of magnetization). The main magnetic carrier was titanomagnetite.

The gypsum–melaphyr formation (Vensink & Varekamp 1980), of post-Malm and pre-Aptian age, lies southeast of Mount Damavand in the central Alborz. The formation, which consists of porphyritic olivine basalts, intergranular basalts and olivine basalts rich in feldspar, is slightly altered. Thermal and AF demagnetization carried out on samples from the seven sites drilled displayed a characteristic direction of remanence above 400 °C or 40 mT. The main magnetic carrier was titanomagnetite. The authors found antipodal normal and reversed directions, thus suggesting a primary magnetization.

A volcanic Permian sequence situated in the Alborz mountains was studied by Wensink (1979). It lies on epicontinental deposits of middle Permian age and is covered by fossiliferous limestones with a middle to Late Permian age. The real age of the flows is in fact between Murghabian and Midian. A total of 71 specimens from five sites were subjected to thermal demagnetization up to 675 °C to remove the remanence intensity. AF demagnetization between 25 and 40 mT was used to isolate the characteristic remanence direction. No palaeomagnetic test is available.