J Geophys (1982) 51:12–23

Journal of Geophysics

Tectonic Inferences of Paleomagnetic Data from Some Mesozoic Formations in Central Iran

Hans Wensink

Department of Structural Geology and Paleomagnetic Laboratory, Utrecht State University, Budapestlaan, 3508 TA Utrecht, The Netherlands

Abstract. Material for paleomagnetic research has been collected from sedimentary rocks of Mesozoic age from four localities in Central Iran. Detailed paleomagnetic analyses have been carried out using partial progressive demagnetization procedures both with alternating magnetic fields and with heating in order to isolate the characteristic remanence. The following results were obtained: Early Triassic Sorkh Shales with $D=289°$, $I=21°$, $\alpha_{95}=14°$; Late Jurassic Garedu Red Beds with $D=4°$, $I=42°$, $\alpha_{95}=14°$; Late Jurassic – Early Cretaceous Bidou Beds with $D=48°$, $I=32.5°$, $\alpha_{95}=19°$; Middle Cretaceous Dehuk Sandstones with $D=326°$, $I=38.5°$, $\alpha_{95}=21°$. The large α_{95} values are due to the rather small collections of specimens, roughly 50 each. From the paleomagnetic data we conclude that in Early Triassic times Central Iran, which forms part of the Iranian-Afghan micro-continent, belonged to Gondwana; since Early Jurassic times the area has been positioned close to the Eurasian continent. The scatter in the declination of the remanence directions can be explained in terms of rotations of individual blocks along the main Central-Iranian fault systems.

Key words: Paleomagnetism – Demagnetization procedures – Continental drift – Alpine tectonics – Iran

Introduction

Sedimentary rocks of Mesozoic age, collected at four localities in Central Iran, have been the subject of paleomagnetic research (Fig. 1).

1. Near Espakh, about 40 km SE of Tabas, thin-bedded reddish shales are exposed and these alternate with pale reddish limestones. These rocks belong to the Sorkh Shale Formation. This formation, with a maximum thickness of 123 m, forms the central part of the Tabas Group, a sedimentary sequence ranging in age from Middle Permian to Middle Triassic. The Sorkh Shales are probably of Early Triassic age (Stöcklin et al., 1965).

2. East of Shirgest, near the village of Hassanabad, reddish silty shales and sandstones are found in a few isolated hills. These sediments belong to the Garedu Red Beds. Ruttner et al. (1968) report that near the Garedu Lead Mine, about 25 km further to the NE, these sediments have a thickness of up to 470 m. The sparse fossils point to a Late Jurassic age, most likely Kimmeridgian to Tithonian.

3. Dark brown sandstones alternating with shales are exposed in the core of the Nassirabad syncline along the Kerman – Ravar road, about 10 km NE of Deh Ziar. These sediments belong to the Bidou Formation, which has a thickness of more than 1,500 m in the Gav syncline, 25 km to the N. Limestone intercalations in this mainly detrital formation contain some

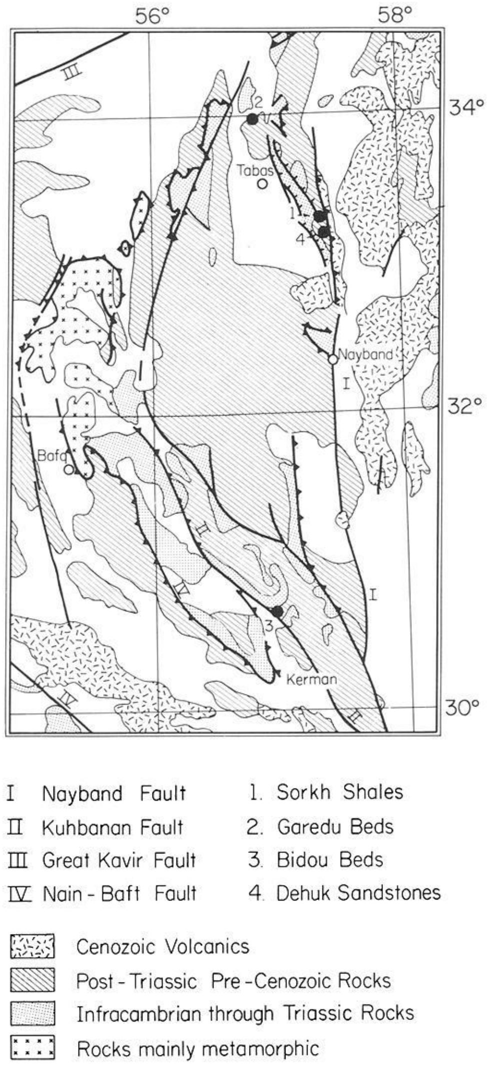

Fig. 1. Map of Central Iran showing the main faults. The sampling localities for paleomagnetic research are indicated by numbers 1–4. **1**, Sorkh Shales (Early Triassic; WSS sites); **2**, Garedu Red Beds (Late Jurassic; WSG sites); **3**, Bidou Formation (Late Jurassic – Early Cretaceous; WSJ sites); **4**, Dehuk Sandstones (Middle Cretaceous; WSK sites)

fossils, the age of which seems to range from Late Middle Jurassic to very Early Cretaceous (Huckriede et al., 1962).

4. East of the Shotori Range, about 1.5 km N of the village of Dehuk, one comes across brownish red sandstones and reddish sandy limestones. Stöcklin et al. (1965) report a maximum thick-

0340-062X/82/0051/0012/$02.40

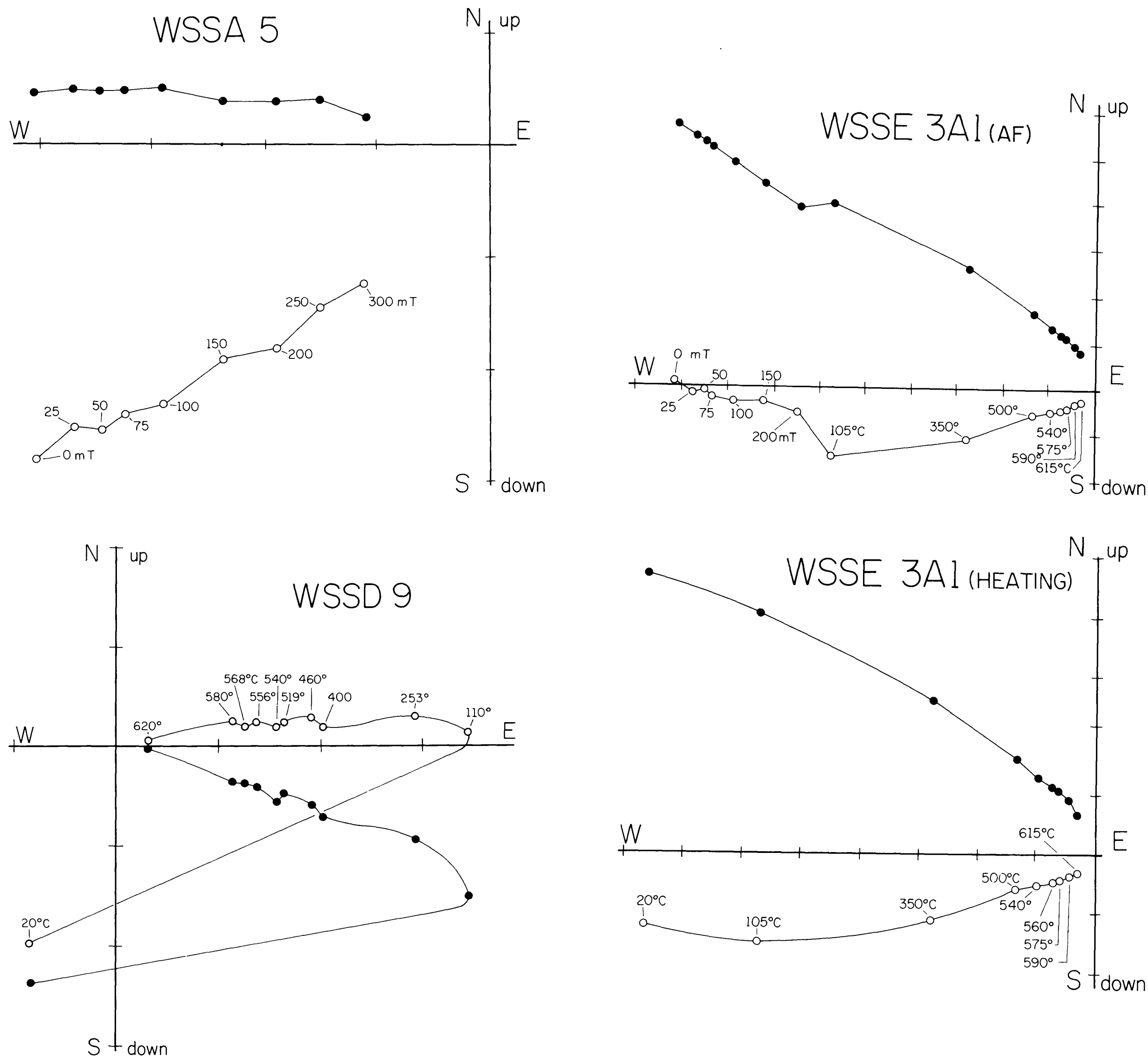

Fig. 2. Diagrams showing the progressive demagnetization of specimens from WSS sites of the Sorkh Shale Formation, with alternating magnetic fields (AF), with AF and subsequent heating, and with heating only: WSSA 5, WSSE 3Al, and WSSD 9, respectively. The plotted points represent successive positions in orthogonal projection of the end of the resultant NRM vector during progressive demagnetization. *Solid* and *open circles* denote the projections on a horizontal and on an east-west vertical plane. The *numbers* represent with AF treatment, the peak strength in mT (1 mT = 10 Oe), and, with heating, the temperature applied in °C. In the diagrams each unit on either axis represents $0.5 \cdot 10^{-3}$ A/m ($5 \cdot 10^{-7}$ emu/cc). The characteristic remanence is obtained if the vector of remanence is a straight line which is directed towards the centre of the coordinate system and which decreases in length only, without changing its direction during subsequent steps of progressive demagnetization

ness of 210 m. The sediments have yielded fossils, mainly Orbitolinas, which are thought to indicate an Albian-Cenomanian age.

Structural History of Central Iran

The area of Central Iran is strongly influenced by tectonism. Platform sediments were deposited during Late Precambrian, Paleozoic and Mesozoic times, but not during the Jurassic. The sedimentary sequence is not affected by any significant orogenic event before the end of the Triassic but there are indications that strong tectonic movements occurred in Late Triassic times. Angular unconformities between Triassic and overlying Jurassic rocks are found at many localities in Central Iran. In the Early Jurassic the N-S trending "Shotori Swell", a horst-like structure came into existence; this structure has influenced the subsequent sedimentary history of the area. In Jurassic times a few troughs developed, which received piles of sediments, usually over 1,000 m thick. Although in Late Jurassic times a tectonic event occurred, more important crustal movements took place in the Early Cretaceous; these movements occurred mainly in the western parts of Central Iran. The deformation phase that took place at the Cretaceous-Tertiary boundary is usually held responsible for the main structural features; but, in some regions in the N and in the NE of Central Iran the orogenic movements reached their climax in Late Eocene to Early Oligocene times (Stöcklin, 1968, 1974; Stöcklin et al., 1965; Ruttner et al., 1968).

Central Iran is intersected by a number of fundamental faults that are still active. The exact age of these faults is unknown;

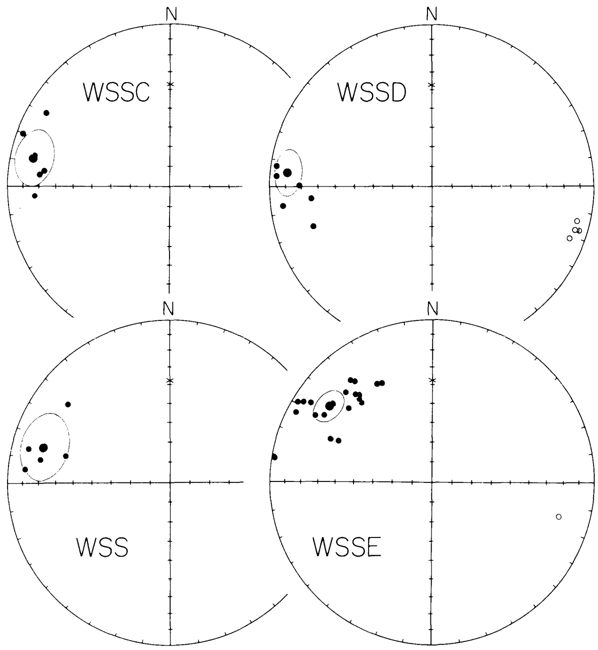

Fig. 3. Equal area projections showing the characteristic remanence directions of specimens from sites WSSC, WSSD, and WSSE, and the mean directions of 5 WSS sites with their overall mean. All projections are provided with 95% ovals of confidence. *Open symbols* denote upward-pointing directions; closed symbols denote downward-pointing directions. The *cross* marks the downward-pointing local direction of the present axial geocentric dipole field

however, they definitely were already active during the tectogenesis in Mesozoic times. Important faults are the NW-SE trending Kuhbanan Fault and the N-S trending Nayband Fault (Fig. 1).

Paleomagnetic Procedures

Both oriented hand samples and oriented cores were collected from the sediments; the cores were obtained with portable drilling equipment. In the laboratory we made cylindrical specimens with a diameter of 25 mm and a length of 22 mm and these were measured on a superconducting magnetometer. We applied progressive partial demagnetization procedures both with alternating magnetic fields (AF) and with heating. Many specimens were progressively heated subsequent to a progressive AF treatment.

The paleomagnetic data obtained from the measurements were collected automatically via a microcomputer system designed by J. van den Berg; subsequently these data were compiled on the Control Data Cyber 175 computer of the Utrecht State University. C.G. Langereis revised the computer programs for the analysis of the paleomagnetic data.

We have used a graphical method in orthogonal projection to present the successive results during the partial progressive demagnetization of a specimen (Zijderveld, 1975; Roy and Lapointe, 1978).

Paleomagnetic Results from the Sampling Localities

General

Here the paleomagnetism is described taking the material from each locality in turn. We shall also discuss the reliability of the final results. The consequences of the paleomagnetic data for the original positions of the sampling localities and for the configuration of land masses at the time of the deposition of the sediments will be examined in the following section.

Sorkh Shale Formation

The Sorkh Shale Formation is presumed to be of Early Triassic age. From the sedimentary layers which dip steeply to the SW and to the WSW and are even partly overturned we collected 10 hand samples and 27 cores at 5 sites (WSSA–E). All 51 specimens available were subjected to paleomagnetic analyses.

Progressive demagnetization procedures were applied to all specimens. We treated 36 specimens with AF demagnetization in 8–14 successive steps up to 300 mT (3,000 Oe) peak value (Fig. 2, WSSA 5). However, even after treatment in fields of 300 mT peak value many specimens still had rather high intensities of natural remanent magnetization (NRM) of up to 50% of their initial values. In all, 33 specimens were subsequently subjected to further analyses with progressive heating in 4–10 successive steps up to temperatures above 600° C. This resulted in a rapid decrease in the NRM intensity; moreover, we noticed that quite often during heating the direction of the NRM changed slightly (Fig. 2, WSSE 3A1: 2 diagrams). We applied progressive heating only to 15 specimens in 10–14 successive steps with a maximum of 680° C (Fig. 2, WSSD 9). We could isolate characteristic remanences in 43 specimens. The characteristic remanence directions of the specimens of three individual sites and the mean directions of magnetization of all sites included in the ultimate analysis with the overall mean direction are all plotted in equal area projections (Fig. 3). The paleomagnetic results are listed in Table 1.

Table 1. Paleomagnetic data from the Sorkh Shales of Early Triassic age near Espahk

Sites	Strike-dip	*E*	*N*	AF	Th	AF+Th	*D*	*I*	*k*	α_{95}
WSSA	145–85	1	5 (1)	–	2	3	286.9	34.6	60	12.0
WSSB	141–84	3	8 (2)	–	3	5	283.0	20.8	29	14.3
WSSC	141–84	–	6 (0)	2	3	1	286.5	12.3	31	12.2
WSSD	141–87	1	11 (4)	–	3	8	278.4	12.4	32	8.7
WSSE	168–100	2	21 (1)	1	4	16	310.5	22.3	23	7.4

Strike and dip denote the attitude of the layer from which the samples were collected: dip direction is 90° clockwise from strike direction. *E* and *N* are the number of specimens excluded from and included in the ultimate analysis, respectively, with – between brackets – the number of specimens with upward directed inclinations (reversed). AF, Th, and AF+Th are the demagnetization procedures applied to the indicated number of specimens, with alternating magnetic fields, heating, and alternating magnetic fields and subsequent heating, respectively. *D* and *I* are the declination and inclination in degrees of the characteristic magnetization direction after correction of tilt. *k* is the precision parameter; α_{95} is the semi-angle of the cone of 95% confidence, in degrees (Fisher, 1953)

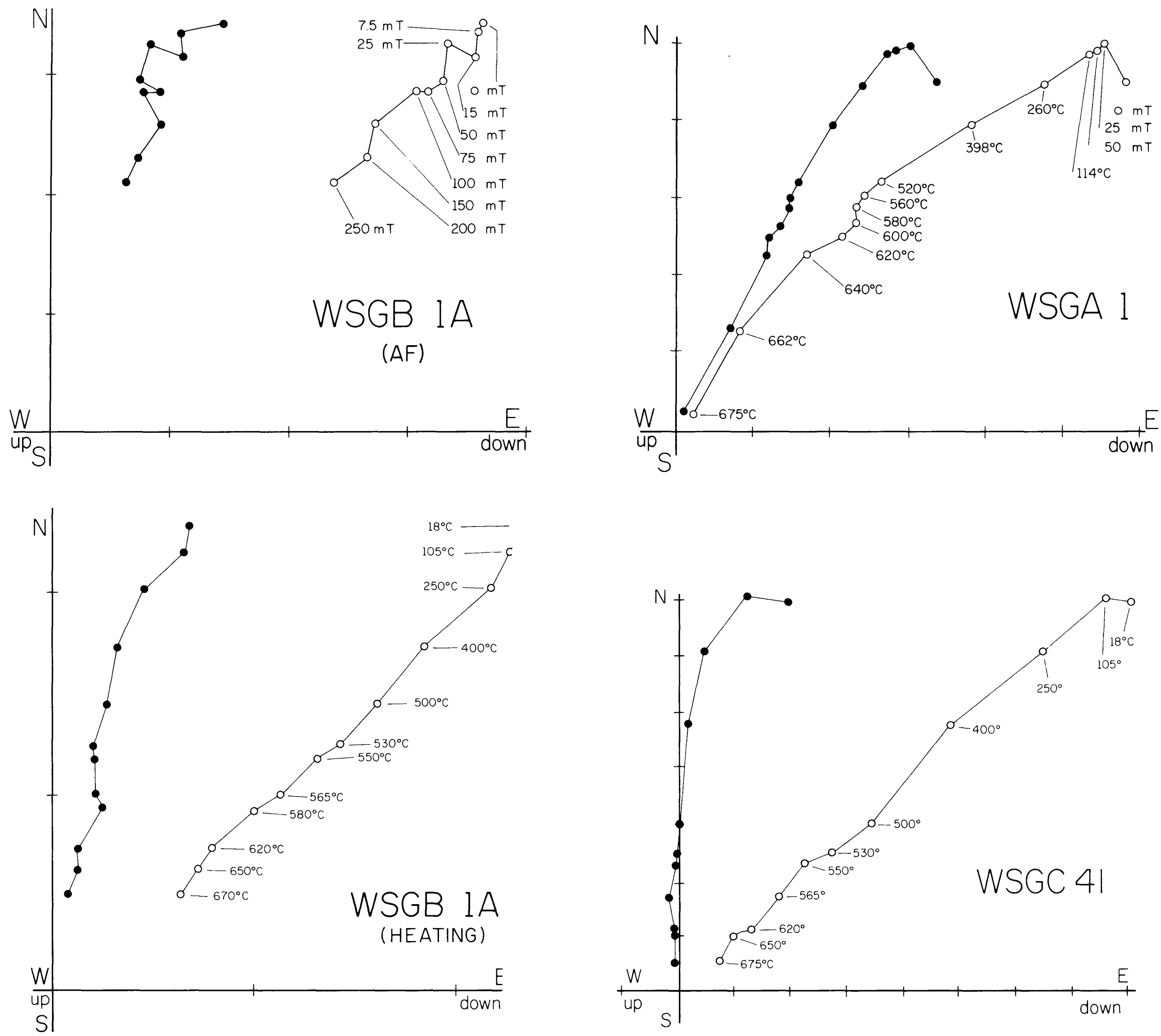

Fig. 4. Demagnetization diagrams of specimens from WSG sites of the Garedu Red Beds after application of AF (WSGB 1A), after subsequent heating of the same specimen (WSGB 1A), after AF and subsequent heating (WSGA 1, in one diagram), and after heating only (WSGC 41). Each unit on either axis of the diagrams represents $1 \cdot 10^{-3}$ A/m ($1 \cdot 10^{-6}$ emu/cc). See also caption to Fig. 2

Thermal progressive demagnetization reveals that both normal and reversed characteristic remanence directions occur. In fact we come across both polarities in four sites. However, our section of Sorkh Shales is fairly short, and shows a series with a thickness of not more than 50 m. We believe that this rapid change in polarity is not in conflict with earlier observations, for in Triassic times the earth's magnetic field changed its polarity several times (Burek, 1967).

We can try to apply a fold test, because the individual sites correspond to sediment layers with varying attitudes. The statistics reveal values of 16.9° and 14.2° for α_{95}, before and after tectonic correction, respectively. Though not positive on the 95% level, the outcome of the test is sufficiently convincing.

In view of the fact that reversals are present and the fold test has a convincing result, we conclude that the isolated characteristic remanence directions of the Sorkh Shales are primary NRM directions, which the sediments acquired during deposition or shortly afterwards.

Garedu Red Beds

The sediments of the Garedu Red Beds of Late Jurassic age dipping E to SE gave us 20 hand samples at four localities (WSGA–E). All 52 cylindrical specimens obtained from these hand samples were subjected to progressive demagnetization procedures. We applied AF demagnetization to 18 specimens in 10 successive steps up to 250 mT peak value. After a maximum field strength had been applied it became evident that the NRM intensity had decreased by only 30–40% in relation to the initial NRM intensity. Subsequently, these 18 specimens were heated in 12 successive steps up to 675° C (Fig. 4, WSGB 1A: two diagrams). A second group of 17 specimens underwent AF treatment in only 3 steps up to 50 mT peak value, and were then heated in 10 successive steps up to 675° C (Fig. 4, WSGA 1). Thermal analyses only were applied to 17 specimens in 11 successive steps up to 675° C (Fig. 4, WSGC 41).

From the orthogonal projections we learn that most speci-

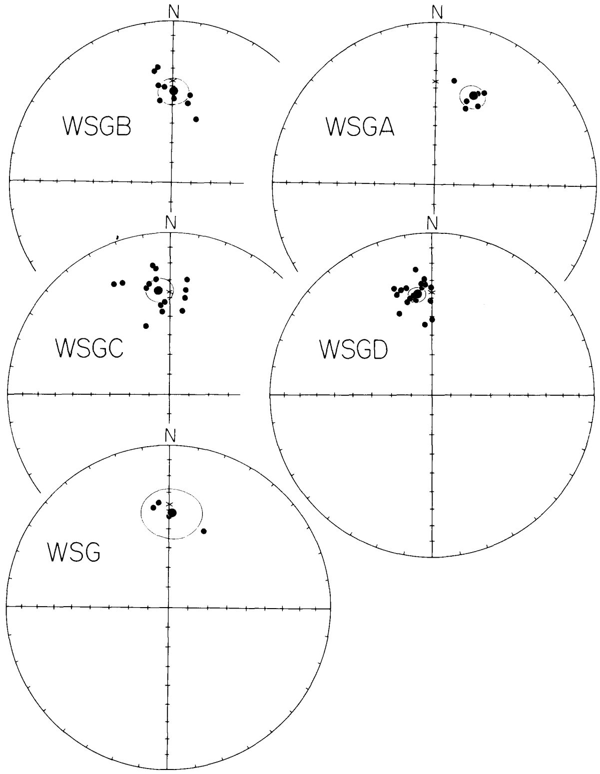

Fig. 5. Equal area projections showing the characteristic remanence directions of specimens from sites WSGA, WSGB, WSGC, and WSGD, and the remanence directions of the mean directions of these four sites with the overall mean, all provided with the 95% ovals of confidence. See also caption to Fig. 3

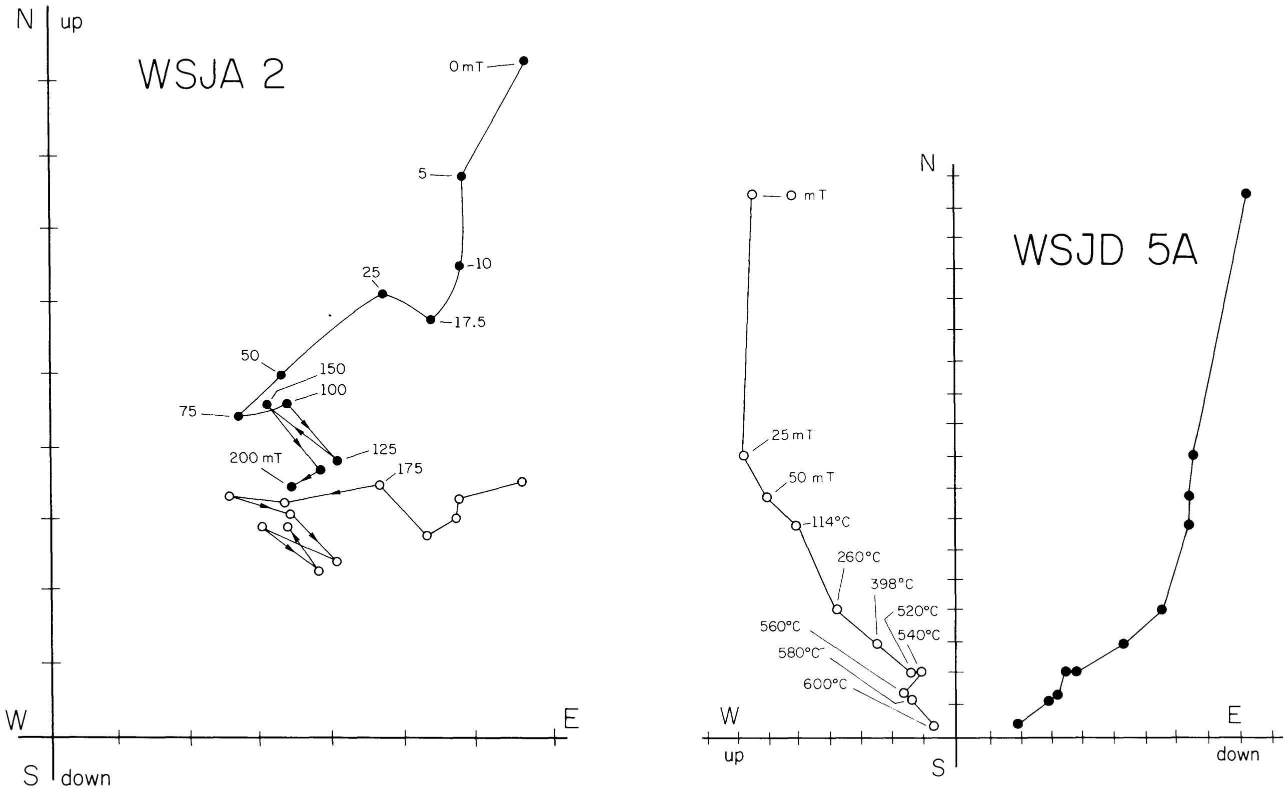

Fig. 6. Demagnetization diagrams of specimens from WSJ sites of the Bidou Formation with AF treatment (WSJA 2), and with AF treatment and subsequent heating (WSJD 5A). Each unit on either axis represents $1 \cdot 10^{-4}$ A/m ($1 \cdot 10^{-7}$ emu/cc). See also caption to Fig. 2

mens contain a secondary component of magnetization of small intensity and with a low coercive force; usually, this component is aligned according to the present direction of the earth's magnetic field. AFs of some tens of mT or heatings up to about 250° C are enough to remove this component (Fig. 4). The characteristic remanence directions of the specimens of individual sites and the mean direction of individual sites with their overall mean are plotted in equal area projections (Fig. 5). The paleomagnetic results are listed in Table 2. We found characteristic remanence directions with normal polarities only.

Table 2. Paleomagnetic data from the Garedu Red Beds of Late Jurassic age near Hassanabad

Sites	Strike-dip	E	N	AF	Th	AF+Th	D	I	k	α_{95}
WSGA	33–85	4	6	–	3	7	26.6	47.1	56	8.1
WSGB	33–42	–	9	–	2	7	2.7	43.1	49	7.4
WSGC	6–28	–	15	–	5	10	356.7	35.6	36	6.4
WSGD	59–34	–	18	–	7	11	353.4	37.8	74	4.1

For explanation of symbols see Table 1

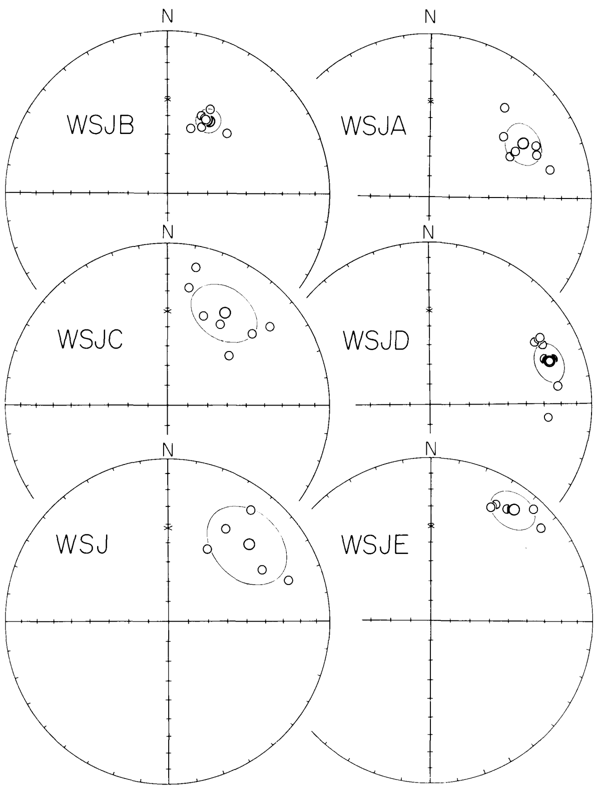

Fig. 7. Equal area projections showing the characteristic remanence directions of specimens from sites WSJA, WSJB, WSJC, WSJD, and WSJE, and the remanence directions of the mean directions of these sites with their overall mean. See also caption to Fig. 3

It is possible to apply a fold test, because there is a scatter in the attitudes of the strata from which the samples were collected. After tectonic correction the value of α_{95} only decreases from 14.4° to 13.9°. However, we see in Table 2 that the characteristic remanence direction of the WSGA site deviates slightly from the directions of the other sites. After elimination of the WSGA site, the values of α_{95} are 16.6° and 8.1°, respectively, calculated before and after tectonic correction. The results of the fold test indicate that the characteristic remanence is of pre-tectonic origin; the primary origin of the magnetization cannot be demonstrated, because of the absence of reversals.

Bidou Formation

The strata of the Bidou Formation are of Late Jurassic to Early Cretaceous age. A collection of 31 cores and 3 hand samples was made at five sites (WSJA–E) in the layers which dip steeply to the N and locally are even overturned. This furnished us with a total of 39 specimens for the paleomagnetic analyses. We applied an AF treatment to 15 specimens in 12 successive steps up to 200 mT peak strength. The remaining 24 specimens received an AF treatment in only 3 successive steps up to 50 mT peak value, and were subsequently heated up to 660° C in a maximum of 10 steps. With AF demagnetization up to applied fields with a maximum strength of 50 mT, the NRM intensity usually decreased to about 50% of its initial value (Fig. 6, WSJA 2). The application of stronger AF however resulted in a very slow decrease in the NRM intensity. The demagnetization graphs show that the characteristic component of remanence becomes isolated after treatment with AF of 50 mT peak strength, or after heating at about 250° C (Fig. 6, WSJD 5A).

The diagrams for specimens treated with progressive AF ranging from 100 mT–200 mT peak strength show irregular patterns (Fig. 6, WSJA 2); these irregular paths can be explained in terms of the introduction of a component of gyromagnetic magnetization: viz. a disturbing remanence that magnetic material can acquire during AF treatment (Dankers and Zijderveld, 1981). To prevent the introduction of this magnetic component, the secondary group of specimens was treated with AF up to 50 mT peak strength only; these specimens were subsequently treated thermally (Fig. 6, WSJD 5A). After application of a temperature of 580° C the NRM intensity was reduced to about 5%; further heating had no effect. Therefore, magnetite is probably the main carrier of remanence here.

The characteristic remanence directions are plotted in equal area projections (Fig. 7) and the paleomagnetic data are listed in Table 3. Note that all specimens reveal remanence directions with upward-directed inclinations.

The result of the application of a fold test is not promising, because of the large scatter between the mean remanence directions of the sites (Table 3). Nevertheless, the test is slightly positive with values of 19.5° and 19.2° for α_{95} before and after tectonic correction, respectively. The remanence directions deviate markedly from the present direction of the axial geocentric dipole field; for the Bidou sediments, however, a primary remanence cannot be proven.

Dehuk Sandstones

In the sediments of Albian-Cenomanian age near Dehuk, the strata of which dip partly towards the NE and partly towards the W, 42 cores were drilled at 6 sites (WSKA–F). A total of 57 specimens has been subjected to paleomagnetic analyses. We applied progressive AF procedures to 39 specimens. A group of 12 specimens was treated in 9 successive steps up to 200 mT peak strength. We found that with AF treatment the NRM intensity decreased very slowly; after application of peak fields of 200 mT 80% of the initial NRM intensity was still present. These 12 specimens were subsequently treated by heating in 10 successive steps up to 660° C. The remaining 27 specimens, treated with AF, were given 6 successive peak fields up to 100 mT; subsequently thermal analysis was applied in 10 successive steps up to 645° C (Fig. 8, WSKC 4). We carried out thermal treatment only on 18 specimens in up to 15 successive steps; the maximum temperature applied was 680° C (Fig. 8, WSKE 1).

Table 3. Paleomagnetic data from the Bidou Rocks of Late Jurassic – Early Cretaceous age near Deh Ziar

Sites	Strike-dip	*E*	*N*	AF	Th	AF+Th	*D*	*I*	*K*	α_{95}
WSJA	278–78	–	7	3	–	4	62.5	–34.5	40	9.6
WSJB	271–92	1	6	3	–	4	30.0	–48.0	123	6.1
WSJC	290–82	–	7	3	–	4	33.6	–33.7	17	15.0
WSJD	273–71	–	8	3	–	5	72.6	–23.7	47	8.2
WSJE	275–75 271–57	5	5	3	–	7	38.5	–17.0	60	10.0

For explanation of symbols see Table 1. Samples of site WSJE were collected from layers with different attitudes

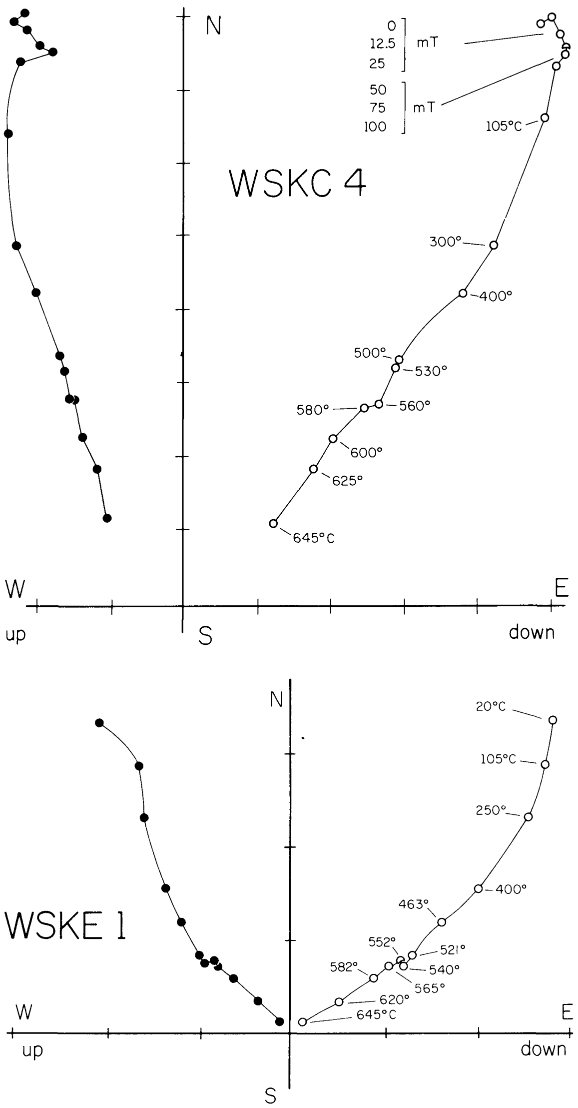

Fig. 8. Demagnetization diagrams of specimens from WSK sites of the sediments near Dehuk with AF treatment and subsequent heating (WSKC 4) and with heating only (WSKE 1). Each unit on either axis represents $1 \cdot 10^{-3}$ A/m ($1 \cdot 10^{-6}$ emu/cc). See also caption to Fig. 2

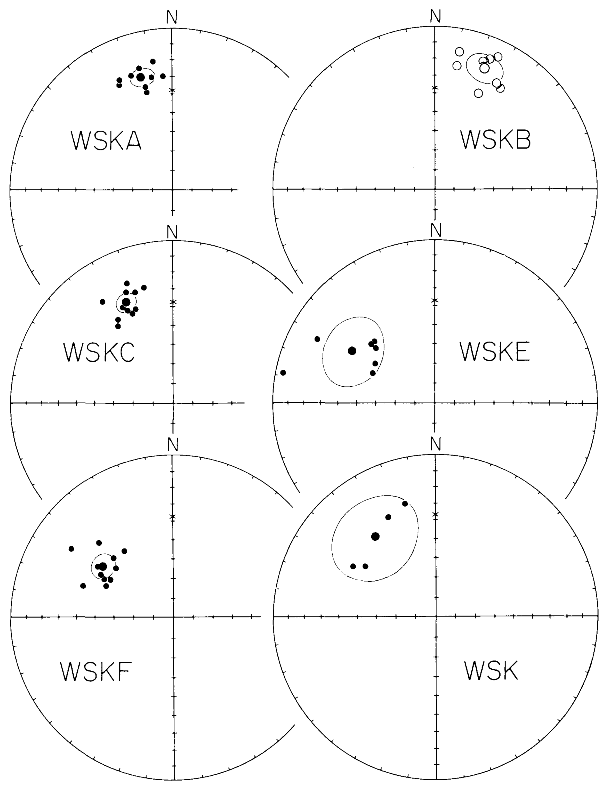

Fig. 9. Equal area projections showing the characteristic remanence directions of specimens from sites WSKA, WSKB, WSKC, WSKE, WSKF, and the mean directions of the sites with their overall mean. See also caption to Fig. 3

Characteristic remanence directions could be isolated in nearly all specimens except most of those from the WSKD site. Site WSKD has been excluded in the ultimate analysis. The characteristic remanence directions have been plotted (Fig. 9). The paleomagnetic results are listed in Table 4. The characteristic remanence directions derived from the specimens of site WSKB deviate strongly (Table 4). We have no explanation for this; site WSKB is located about 2 m above site WSKA in the same rock sequence, and for both sites we applied the same tectonic correction. The result for site WSKB has been excluded from the computation of the ultimate mean direction of remanence.

The scatter in the attitudes of groups of strata permits the application of a fold test. The test is positive, because the values for α_{95} are 33.2° and 21.4° before and after tectonic correction, respectively. The characteristic remanence has a pre-folding origin; its primary direction cannot be proven.

Implications from the Paleomagnetic Data

General Aspects

The mean characteristic directions of magnetization derived from sediments of Mesozoic age from four localities in Central Iran are listed in Table 5. The corresponding virtual pole positions are listed in Table 6. The positions of these poles are very scat-

Table 4. Paleomagnetic data from the Dehuk sediments of Middle Cretaceous age near Dehuk

Sites	Strike-dip	*E*	*N*	AF	Th	AF+Th	*D*	*I*	*K*	α_{95}
WSKA	320–54	2	9	–	3	6	347.5	28.9	95	5.3
WSKB	320–54	1	8	–	2	6	25.3	–21.2	53	7.7
WSKC	314–42	–	11	–	3	8	337.6	32.6	87	4.9
WSKE	205–40	–	7	–	3	4	304.4	40.5	15	16.1
WSKF	205–43	–	11	–	3	8	308.8	45.8	56	6.1

For explanation of symbols see Table 1

Table 5. Mean characteristic remanence directions of rock units of Mesozoic age from Central Iran

Locality	Rock unit	Age	*E*	*N*	*D*	*I*	*K*	α_{95}
Espakh	Sorkh Shales WSS	Early Triassic	–	5	288.9	20.8	30	14.2
Hassanabad	Garedu Red Beds WSG	Late Jurassic	–	4	3.9	41.6	45	13.9
Deh Ziar	Bidou Formation WSJ	Late Jurassic-Early Cretaceous	–	5	48.2	–32.5	17	19.2
Dehuk	Dehuk Sandstones WSK	Middle Cretaceous	1	4	326.1	38.5	19	21.4

E and *N* are the number of sites excluded from and included in the ultimate analysis, respectively. See also caption to Table 1

Table 6. Virtual geomagnetic pole positions of rock units of Mesozoic age from Central Iran

Rock unit	Position of rock unit		Position of pole		Paleo-latitude
	latitude (°N)	longitude (°E)	(°N)	(°W)	(°N/S)
Sorkh Shales WSS	33.3	57.3	21.6	33.8	11.0
Garedu Beds WSG	34.0	56.9	79.4	142.9	23.9
Bidou Beds WSJ	30.7	57.0	23.0	173.5	17.7
Dehuk Sandstones WSK	33.2	57.5	58.0	44.8	21.7

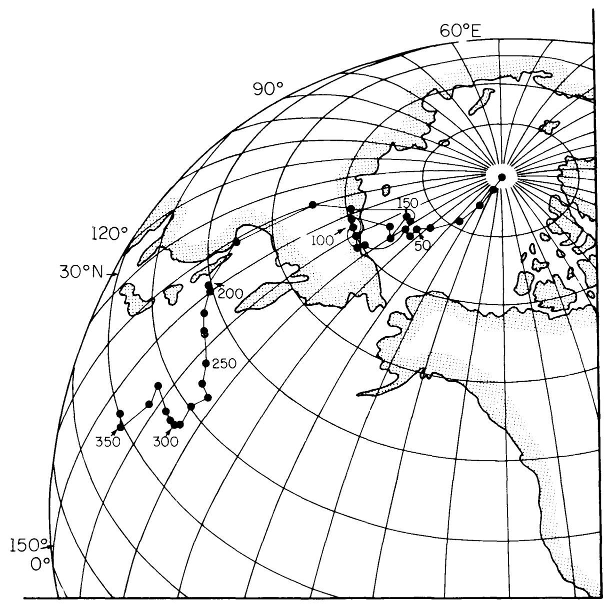

Fig. 10. Map showing the apparent polar wander relative to northern Eurasia in the course of 350 m.y., after Irving (1977)

tered. We can compare the positions of these poles are very scattered. We can compare the positions of our poles with the pole positions of the same age of neighbouring continents, viz. with those on the Eurasian (Fig. 10) and on the African (Fig. 11) polar wander curves. However, none of the poles presented in this paper coincides either with Eurasian or African positions of poles of the same age. This implies that none of the Central Iranian localities has a stable, unchanged position relative to either Eurasia or Africa. The large scatter in the positions of our poles might indicate that the various areas of deposition performed individual movements.

In earlier papers (Wensink et al., 1978; Wensink, 1979) we argued that the paleomagnetic data derived from rocks of the Alborz Mountains in N Iran indicate that in Paleozoic and in Early Mesozoic times the area was positioned off the coast of Arabia. The greater part of Iran, probably with Afghanistan attached – the Iranian-Afghan micro-continent (Krumsiek, 1976, 1980) – has formed part of Gondwana, being positioned at its northern edge (Becker et al., 1973; Soffel et al., 1975; Kürsten, 1980). Paleomagnetic data from rocks of Jurassic and Cretaceous age from the Alborz Mountains (Wensink and Varekamp, 1980) indicate that at that time the Iranian-Afghan block was already attached to Eurasia. In our opinion, the separation of Iran (probably with Afghanistan) from Gondwana and its subsequent shift to the N took place in Late Triassic times during a period of strong crustal movements.

We shall try to find out whether the characteristic remanence directions of the rocks of Mesozoic age, presented in this paper, can be explained in terms of rotations of corresponding blocks, and whether the paleomagnetic data enable us to propose what the original positions of the respective areas were relative to

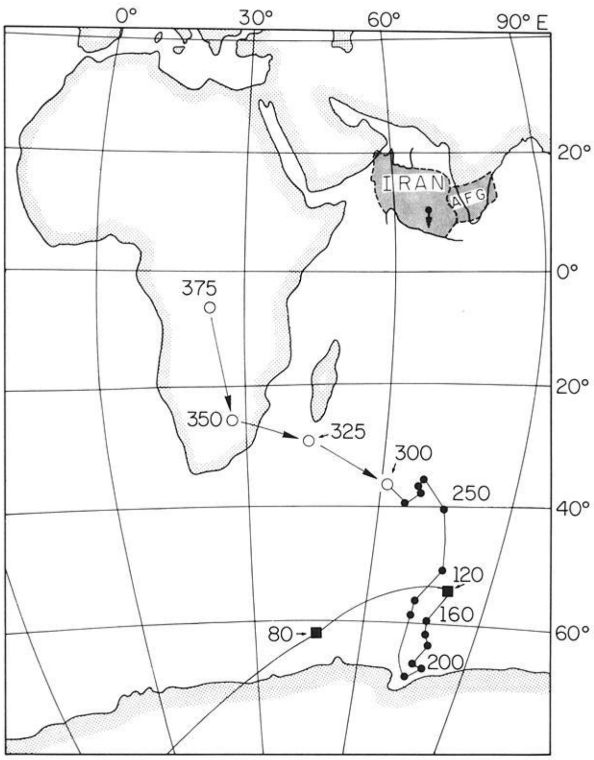

Fig. 11. Map showing the apparent polar wander of Gondwana relative to Africa between 375 m.y. and 160 m.y. ago, after Irving (1977), and the polar wander relative to Africa since that time. *Open circles* denote the pole positions between 375 m.y. and 300 m.y. ago at intervals of 25 m.y.; *full dots* indicate the successive positions up to 160 m.y. ago at intervals of 10 m.y.; *full squares* denote a few pole positions of Africa after the initial break-up of Gondwana. Moreover, we see the possible location of the Iranian-Afghan micro-continent relative to Africa in Early Triassic times (210 m.y. ago); this location is based on the remanence data derived from the Sorkh Shales

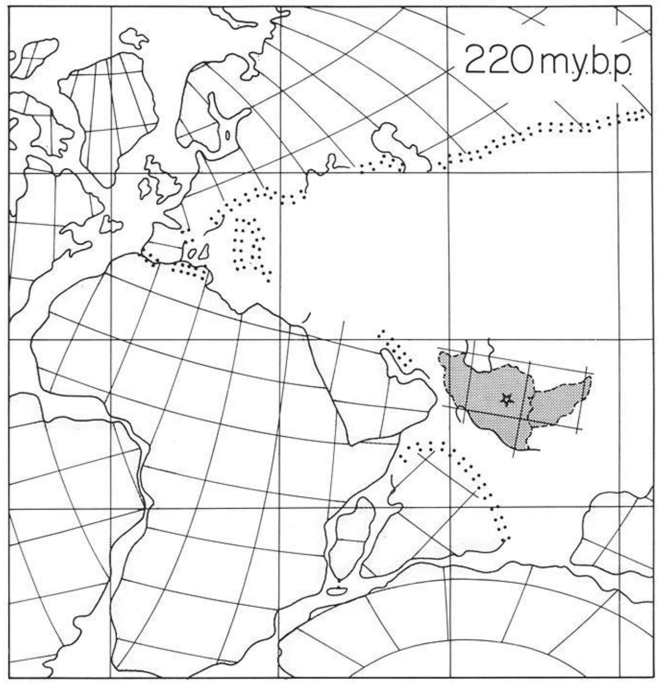

Fig. 12. Map showing the distribution of land masses about 220 m.y. ago (after Smith et al., 1981), and the possible position of the Iranian-Afghan microcontinent. *Asterisk* indicates the locality where the Early Triassic Sorkh Shales were sampled. Every 30° both the parallels and the meridians are given with the equator in the middle of the map.

the distribution of land masses in the corresponding periods of time. From the inclination of the mean characteristic remanence direction of a rock sequence we can derive the paleolatitude, viz. the latitude at which the rock originated. If we accept that the sampling areas remained at approximately the same positions within the main Iranian-Afghan block (although they may have rotated), we can propose original positions for the entire micro-continent for the successive periods. Paleolongitudinal positions cannot be obtained from the paleomagnetic data. This leaves us free to determine the paleolongitudinal positions of the localities under study. This freedom is restricted, because of the distribution of the main land masses presented by Smith et al. (1981).

The localities will be discussed in succession.

Sorkh Shale Locality

We shall discuss the different positions of the area where the Sorkh Shales could have been deposited about 220–210 m.y. ago. From the inclination of the characteristic remanence direction we can derive both the paleolatitude of the sampling area and the polar distance. For the Sorkh Shale area the paleolatitude is 11°, either N or S; the polar distance is thus 79°.

First we shall look at the possible location of the Iranian-Afghan micro-continent in Early Triassic times relative to Gondwana, which implies relative to Africa, because Africa remains in position in the various Gondwana reconstructions. The Gondwana pole was positioned at 68° S, 72° E 210 m.y. ago (Irving, 1977), see also Figure 11. On the map of Figure 11 we have placed the Iranian-Afghan block at a polar distance of 79° from the Early Triassic pole, on the basis of the paleomagnetic data from the Sorkh Shales. The block is placed in a position very close to Africa, which is a likely position if at that time the block formed part of Gondwana. Of course, this is not the only possible location for the micro-continent.

Next we have drawn the Iranian-Afghan block on a map, where the distribution of land masses 220 m.y. ago was reconstructed by Smith et al. (1981), with the sampling locality at the paleolatitude of 11° S (Fig. 12). The position of the micro-continent in Figure 12 is only slightly to the north of that in Figure 11. The location of the micro-continent in Early Triassic times in the southern hemisphere near to the Arabian coast implies that this block still formed part of the Gondwana mega-continent.

Regarding the possible, original position of the Sorkh Shale area at 11° N latitude, we see in Figure 12 that there is ample space for the area between positions to the north of Arabia and positions to the north-east of Arabia. However, none of these positions corresponds to the location of the Iranian-Afghan micro-continent in the Gondwana reconstructions.

Garedu Red Beds Locality

The mean characteristic remanence direction of the Late Jurassic Garedu Red Beds indicates that the paleolatitudinal position of the sampling area was 24° (Table 6). These sediments are unlikely to have been located in the southern hemisphere, because this would imply that after Early Triassic times Iran moved from its position near the Arabian peninsula further to the SE.

In order to assess the location of deposition of the red beds in the northern hemisphere, we have to consider the Eurasian pole position about 160 m.y. ago, in Late Jurassic times (Fig. 10).

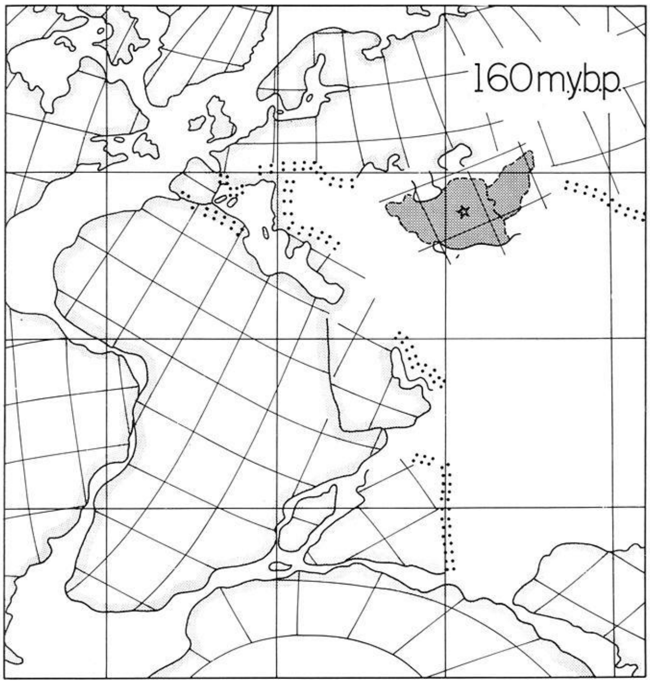

Fig. 13. Map showing the distribution of land masses about 160 m.y. ago (after Smith et al., 1981), and the possible position of the Iranian-Afghan microcontinent. *Asterisk* indicates the locality where the Late Jurassic Garedu Red Beds were sampled

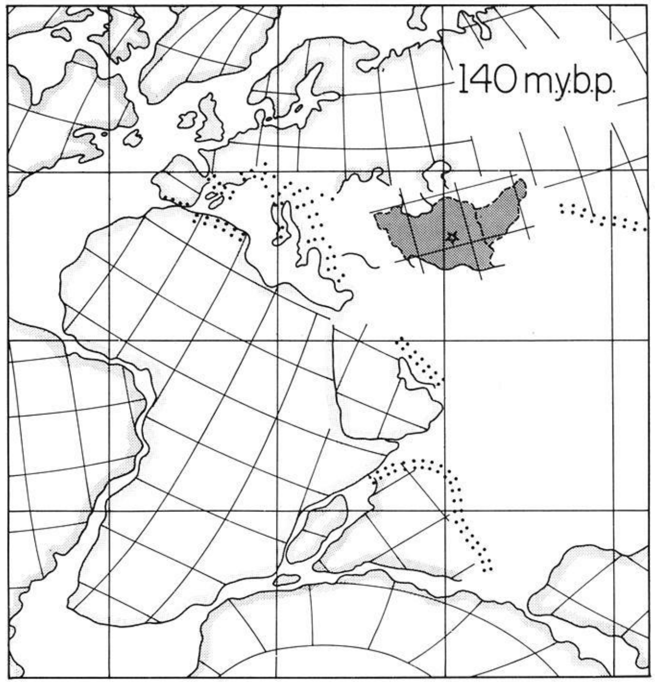

Fig. 14. Map showing the distribution of land masses about 140 m.y. ago (after Smith et al., 1981), and the possible position of the Iranian-Afghan microcontinent. *Asterisk* indicates the locality where the late Jurassic – Early Cretaceous Bidou Beds were sampled

This pole is positioned at 76° N, 162.5° E (Irving, 1977). The present polar distance between the area of sampling and the Late Jurassic Eurasian pole is 61°. From the paleomagnetic data we get a polar distance of 66°. Thus, relative to its present location, the original position of the deposition area is possibly 5° to the SW. This implies that if translation movements with considerable displacements did not occur within the Iranian block with respect to the present position, then the entire block 160 m.y. ago was located about 5° to the SW.

In the configuration of land masses in Figure 13 160 m.y. ago the number of possible positions for Iran-Afghanistan is restricted because of the paleolatitudinal position of 24° established for the sampling area. If the proposed configuration in Figure 13 is approximately correct, the sampling area will have performed only a very small counter-clockwise rotation with respect to the main block.

Bidou Beds Locality

The paleomagnetic data derived from red beds of the Bidou Formation of Late Jurassic to Early Cretaceous age indicate a paleolatitudinal position of 18° for the area of deposition (Table 6). First we shall discuss the possibility that the area was in the northern hemisphere. The polar distance between the area of sedimentation and its corresponding pole is 72°. About 140 m.y. ago – the time of deposition of the Bidou sediments – the Eurasian pole was located at 73° N, 173° E (Fig. 10) which implies a polar distance of 67° between this Eurasian pole and the present location of the Bidou Formation. Therefore, relative to the present situation, the area of deposition may have had an original location about 5° to the SW. If we follow the same line of reasoning as in the previous sections, we are able to propose what the position of the micro-continent might have been 140 m.y. ago (Fig. 14). If this was the true location we would expect from rocks 140 m.y. old a remanence direction with a declination somewhat to the E of N and a downward directed inclination during a period with a normal magnetic polarity; if there was a period with reversed polarity we would expect a declination somewhat to the W of S and an upward directed inclination. Our sediments revealed an upward directed inclination (−32.5°) and a declination of 48° (Table 5). This implies that if during the deposition of the Bidou Beds the area was situated in the northern hemisphere, the rocks were magnetized during a period with reversed polarity. Then the area must have performed a large counter-clockwise rotation.

We shall now investigate whether or not the area may have had a paleoposition in the southern hemisphere. The Late Gondwana pole 140 m.y. ago was located at 61° S, 73° E relative to stable Africa. We see in Figure 14 that, because of the distribution of land masses about 140 m.y. ago, in ancient times the Bidou area may have been located at 18° S latitude. We propose that the entire micro-continent – with the Bidou area at a polar distance of 72° from the African pole of 140 m.y. ago – was close to the Arabian coast with the present meridians of Iran-Afghanistan parallel to those of 140 m.y. ago. If so the position of the micro-continent was slightly to the NE of its shaded configuration in Figure 11. In this position the remanence of rocks with an age of 140 m.y. has a direction with a declination of roughly N or S. In the southern hemisphere the negative inclination (−32.5°, Table 5) points to a period of normal magnetic polarity; then the declination was about N. In its original position in the southern hemisphere not only did the Bidou area perform an additional clockwise rotation, but the entire block also shifted to the N.

We cannot draw a definite conclusion from the paleomagnetic data derived from the Bidou sediments: the sediments may have been deposited in the northern or in the southern hemisphere.

Red Beds near Dehuk

The characteristic paleomagnetic data from the red-coloured sediments of Albian-Cenomanian age near Dehuk point to a position at a latitude of 22° during their deposition about 100 m.y. ago (Table 6). First we shall investigate whether the Red Beds could have been located in the northern hemisphere. The polar distance between the sampling area and its corresponding pole is 68° A hundred million years ago the Eurasian pole was positioned at 71° N, 157° E (Fig. 10) which implies a present polar distance of 62° between the area near Dehuk and this Eurasian pole. Thus, from the data available, including the land mass configuration 100 m.y. ago after Smith et al. (1981), we see that the original location of the sedimentation area with respect to its present position could have been further to the SW A paleomagnetic study of volcanics of Cretaceous age from the Alborz Mountains in N Iran revealed a remanence direction with a declination of 33° (Wensink and Varekamp, 1980). If this value is representative for the whole of Iran the Dehuk area must have performed a counter-clockwise rotation of about 60°

We cannot rule out the possibility that the Dehuk area was originally situated in the southern hemisphere. About 100 m.y. ago the African pole was located at 60° S, 60° E. Relative to this African pole, the polar distance of 68° puts the deposition area in the present Indian Ocean, just off the coast of Somalia, where at that time no other land mass was situated. However, as we have seen, the Dehuk sediments revealed a positive inclination. A positive inclination in the southern hemisphere implies that the earth's magnetic field has a reversed polarity. But the sediments were deposited during the Magnetic Quite Interval when the earth's magnetic field had a normal polarity; this interval lasted from 108 m.y.–82 m.y. ago. Therefore, it is very unlikely that the Dehuk area was originally situated in the southern hemisphere.

Paleomagnetic Data from Mesozoic Rocks of Central Iran from Recent Publications

Recently, Soffel and Förster (1980, 1982) have presented paleomagnetic data derived from rocks of Central Iran. As far as their results from rocks of Mesozoic age are concerned, they report that sediments from both the Nakhlak and the Naiband formations reveal a remanence direction with $D=271.7°$, $I=45.9°$ The declination value corresponds with our result from the Sorkh Shales, but the inclination value is higher than the one we found. However, the Naiband sediments, which have a very Late Jurassic age and which are deposited after the period of tectonic unrest in the Late Triassic, are considerably younger than the Sorkh Shales (Stöcklin et al., 1965).

From the coal-bearing sandstones of Early to Middle Jurassic age the authors report a mean remanence direction with $D=312.4°$, $I=27.8°$ We believe that the paleolatitude of the deposition area of these sediments, which is about 15°, fits in rather well with our conception of the successive positions of the Iranian-Afghan micro-continent in Mesozoic times. Soffel and Förster (1980, 1982) have obtained a characteristic remanence direction with $D=347.6°$, $I=38.4°$ from the Garedu Red Beds, which are of very Late Jurassic age. This result also corresponds quite well with our data derived from the same formation.

Conclusions

In previous papers we discussed the tentative concept that the Iranian-Afghan micro-continent formed part of Gondwana untill Late Triassic times. Some post-Triassic paleomagnetic data (Wensink, 1979; Soffel and Förster, in press 1982), and the stratigraphic arguments based on rocks of Jurassic and Cretaceous age support a link between the whole of Iran and the land mass to the N of it since Early Jurassic times (Bratash, 1975). Most likely, this holds true as well for Central Afghanistan (Krumsiek, 1980). The paleomagnetic data presented in this paper are not in conflict with this concept. It is reasonable to accept that the sedimentation regime of the Sorkh Shales was in the southern hemisphere within the Gondwana supercontinent, thus before the Iranian-Afghan block broke away in the Early Triassic. The remaining sedimentary sequences, treated in this paper, were most likely deposited in the northern hemisphere after this break-away.

We cannot present exact, original positions for the three post-Triassic sedimentary regimes relative to Eurasia, because we are not sure about the precise paleolongitudinal locations of these regimes. However, the possible positions are restricted because of the distribution of land masses during the Jurassic and the Cretaceous. Our paleomagnetic data lead us to believe that the original positions of the areas were about 500–700 km SW to SSW of their present locations. We do not know precisely by how much the areas rotated. Soffel and Förster (in press 1982) have concluded that the entire Central Iranian area performed a counterclockwise rotation. We conclude from our data that the sedimentation regimes of the Bidou and the Dehuk deposits did rotate considerably. This is not surprising, because a number of fundamental faults traverse the area of Central Iran (Fig. 1), along which minor blocks may have rotated.

Acknowledgements. The author is much indebted to his colleagues of the Paleomagnetic Laboratory, State University of Utrecht, for their interest and help in this study. Financial support was received from the Netherland's Organisation for Pure Scientific Research (ZWO). I wish to thank the referees for their constructive criticism.

References

Becker, H., Förster, H., Soffel, H.: Central Iran, a former part of Gondwana? Paleomagnetic evidence from Infra-Cambrian rocks and iron ores of the Bafq area, Central Iran. Z. Geophys. **39**, 953–963, 1973

Bratash, V.I.. Kerman – Kashmertrough, Iran and the problem of the junction between pre-Jurassic structures of the Turonian plate and the Mediterranean belt. Geotectonics (Engl. ed.) **9**, 101–107, 1975

Burek, P.J. Korrelation invers magnetisierter Gesteinsfolgen im Buntsandstein (Trias) in SW-Deutschland und Frankreich. Geol. Jahrb. **84**, 591–616, 1967

Dankers, P.H.M., Zijderveld, J.D.A.· Alternating field demagnetization of rocks, and the problem of gyromagnetic remanence. Earth Planet. Sci. Lett. **53**, 89–92, 1981

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

Huckriede, R., Kürsten, M., Venzlaff, H.. Zur Geologie des Gebietes zwischen Kerman und Sagand (Iran). Geol Jahrb. **B 51**, 198 pp., 1962

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

Krumsiek, K.. Bewegung der Iranisch-Afghanischen Platte. Geol. Rundschau **65**, 909–929, 1976

Krumsiek, K.: Zur plattentektonischen Entwicklung des Indo-Iranischen Raumes (Resultate paläomagnetischer Untersuchungen in Afghanistan). Geotekt. Forsch. **60**, 1–11, 1–223, 1980

Kürsten, M. Zur geodynamischen Entwicklung des Iran, ein Beispiel interkratonischer struktureller Vorgänge. Geol Rundsch. **69**, 22–40, 1980

Roy, J.L., Lapointe, P.L.: Multiphase magnetizations: problems and implications. Phys. Earth Planet. Int. **16**, 20–37, 1978

Ruttner, A., Nabavi, M.H., Hajian, I.: Geology of the Shirgesht area (Tabas area, East Iran). Geol. Surv. Iran Rept. **4**, 133 pp., 1968

Smith, A.G., Hurley, A.M., Briden, J.C.: Phanerozoic paleocontinental world maps. Cambridge: Cambridge University Press 1981

Soffel, H., Förster, H., Becker, H.: Preliminary polar wander path of Central Iran. Z. Geophys. **41**, 541–543, 1975

Soffel, H.C., Förster, H.G.: Apparent polar wander path of Central Iran and its geotectonic interpretation. J. Geomagn. Geoelectr. **32**, suppl. III, 117–135, 1980

Soffel, H.C., Förster, H.G.: Polar wander path of the Central Iran Microplate including new results. N. Jahrb. Geol. Paläontol. Monatshefte, in press 1982

Stöcklin, J., Eftekhar-nezhad, J., Husmand-zadeh, A.: Geology of the Shotori Range (Tabas area, East Iran). Geol. Survey Iran Report **3**, 90 pp., 1965

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

Stöcklin, J.: Possible ancient continental margins in Iran. In: The Geology of Continental Margins, A. Burke and C.L. Drake, eds: pp. 873–887. Berlin, Heidelberg, New York: Springer 1974

Wensink, H., Zijderveld, J.D.A., Varekamp, J.C.: Paleomagnetism and ore mineralogy of some basalts of the Geirud Formation of Late Devonian – Early Carboniferous age from the southern Alborz, Iran. Earth Planet. Sci. Lett. **41**, 441–450, 1978

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

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

Zijderveld, J.D.A.: Paleomagnetism of the Esterel rocks. Krips Repro Meppel, 199 pp., 1975

Received January 4, 1982; Revised version March 1 and 31, 1982
Accepted April 6, 1982