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Palaeomagnetic and Radiometric Dating Results from Jurassic Intrusions in South Morocco

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Summary

Samples collected from three Jurassic igneous formations in South Morocco carry a stable component of magnetic remanence, giving a mean palaeomagnetic pole-position at 61° S, 71° E, $A_{95} = 14°$. Two of the formations were situated in the stable Saharan Shield region, and one within the Central High Atlas fold-belt. There is no systematic difference between the pole-positions derived from these two regions of contrasting tectonic history, and furthermore, no significant difference between the mean Jurassic pole-position for Morocco and that for South-east Africa. It is concluded that no significant post-Jurassic relative motion has occurred between NW and SE Africa.

Two of the formations studied were previously thought to be Upper Palaeozoic, but radiometric age determinations presented in this paper give consistent values of between 181 and 187 My. These results indicate the occurrence of a widespread episode of Jurassic igneous activity, producing structures which frequently parallel the coastline, and are possibly related to the break-up and dispersal of the fragments of Pangaea during the Mesozoic.

1. Introduction

Comprehensive palaeomagnetic surveys have been carried out in many parts of East, Central and South Africa during the past decade (McElhinny *et al.* 1968), but pre-Tertiary palaeomagnetic data from the north-western part of this continent are almost completely non-existent. In an attempt to fill this gap in the data, and to facilitate palaeomagnetic comparisons and correlations across a large, relatively stable continental area, an extensive palaeomagnetic survey of Morocco has been undertaken by this Department. The first results of this survey, from rocks of Jurassic age, are reported in this paper.

2. Geology

Three igneous formations have been studied. Two of these, the Draa Valley sills and the Foum-Zguid dyke lie in the Anti-Atlas belt, a region which has remained tectonically stable since at least the end of the Hercynian orogeny (Marcais & Choubert 1956). The third formation, the Central Atlas intrusives, lies within the Mesozoic to Tertiary High Atlas fold-belt (Fig. 1).

The Draa Valley sills are a set of very fresh and well-exposed dolerites, injected at various levels into the Devonian and Carboniferous sedimentary sequence. They outcrop discontinuously over an area of some 20 000 sq km. along the north-western rim of the Sahara (Hollard 1970). They appear to be closely related to the Foum-Zguid dyke, a large quartz-dolerite body, approximately 100 metres wide and extending in an almost continuous line in a NE–SW direction for some 200 km across south Morocco. Stratigraphic evidence indicates that these two formations are post-Stephanian and pre-Lower Cretaceous, and previous authors have referred to them as 'Heicynian', implying an Upper Palaeozoic age (e.g. *Carte Géologique du Maroc* 1959). Results reported in this paper indicate that they are in fact of Jurassic age. The dyke appears to be slightly younger than the sills, since the latter were folded at the same time as the adjacent strata, whereas the former has remained vertical and undeformed.

The Central Atlas intrusives comprise several elongate gabbro bodies, an alkaline complex, and numerous related dykes, lying within the Central High Atlas mountain belt, and following the ENE–WSW trend of this belt. These bodies intrude Triassic and Jurassic strata, but are themselves overlain discordantly by continental Infra-cenomanian (basal Cretaceous) deposits. Choubert & Faure Muret (1962) have suggested that they were intruded during the important post-Portlandian, pre-Cretaceous tectonic phase.

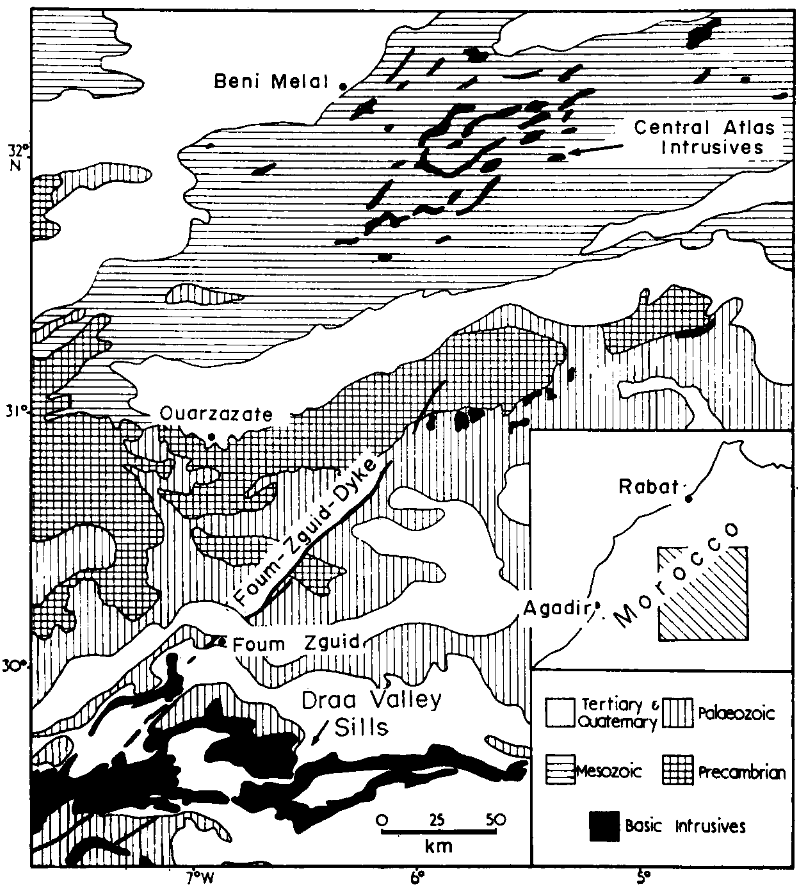

FIG. 1. Outline geological map of South Morocco, showing locations of formations studied.

3. Sampling and measurement

The formations were sampled by means of a portable coring drill (Hailwood 1968), and six separately oriented 2·5-cm diameter cores were collected at each site. Sun-compass and magnetic-compass bearings were taken for each core, and these rarely differed by more than 1–2 deg. A total of 16 sites were sampled in the Draa Valley sills, five sites in the Foum-Zguid dyke, and six sites in the Central Atlas intrusives. Three of the latter were situated in a single gabbro intrusion, the Tassent gabbro, and three in related dykes (one site per dyke). Measurements of remanence were performed on a PAR SM2 spinner magnetometer, and the stability of remanence was tested by subjecting one sample from each site to standard alternating field demagnetisation tests (Irving, Stott & Ward 1961) with a maximum peak field of between 525 and 900 Oe. These pilot-sample results were then inspected to establish the optimum treatment for least scatter of remanence directions, and the remaining samples from each site were treated at this value. After magnetic cleaning, occasional sample directions differed significantly from the main group of directions formed by other samples from the same site. In such cases it was concluded that the stable component of remanence, isolated in the other samples, had not been isolated in the aberrant samples and the latter were not included in the final statistical analysis.

4. Results

4.1 *Draa Valley Sills*

Intensities of natural remanence of these rocks were generally high, ranging from 0·1 to $3{\cdot}0 \times 10^{-2}$ Gauss, and between-site scatter of directions was appreciable, with an α_{95} of 20° (Fig. 2(a) and Table 1). Partial A.F. demagnetization of pilot-samples resulted in two differing types of behaviour (Fig. 2(b) and (c)). Approximately half of the samples (Group I) carried an unstable component of remance, which disappeared in fields of 150–225 Oe, revealing a more stable underlying component. The other samples (Group II) carried only a single component of stable remanence, requiring fields of 375 to 450 Oe for its destruction. Bulk treatment in appropriate fields resulted in a considerable improvement in between-site groupong (Fig. 2(a)) and a general reduction of within-site scatter (Table 1).

4.2 *Foum-Zguid Dyke*

Initial intensities of remanence ranged from 0·5 to $1{\cdot}5 \times 10^{-3}$ Gauss, and were an order of magnitude lower than those of the Draa Valley sills. Pilot demagnetization tests (Fig. 3(b)) indicated the presence of a stable component of remanence existing through the range of treatment from 75 –300 Oe; beyond this value the remanence directions scattered randomly. Bulk treatment at 150–300 Oe resulted in a decrease of between-site scatter from 16° to 4° (Fig. 3(a) and Table 2).

4.3 *Central Atlas intrusives*

N.R.M. intensities of samples from the gabbro intrusion were fairly weak, in the range 0·5 to $1{\cdot}5 \times 10^{-4}$ Gauss, but those from the dykes were generally stronger, varying from 10^{-4} to 10^{-1} Gauss. Initial mean-site directions of remanence were widely scattered (Fig. 4(a) and Table 3), and pilot-sample demagnetization results again indicated the isolation of a stable component of remanence after treatment at 150–300 Oe. (Fig. 4(b)). Although bulk A.F. treatment resulted in a significant reduction of between-site scatter (Fig. 4(a)), this remained large compared with that of the other two formations.

After treatment the inclinations of the mean-site remanence vectors of the gabbro sites were systematically lower than those of the dyke sites, and this may be the result of deformation within the gabbro body during the folding and uplift of the

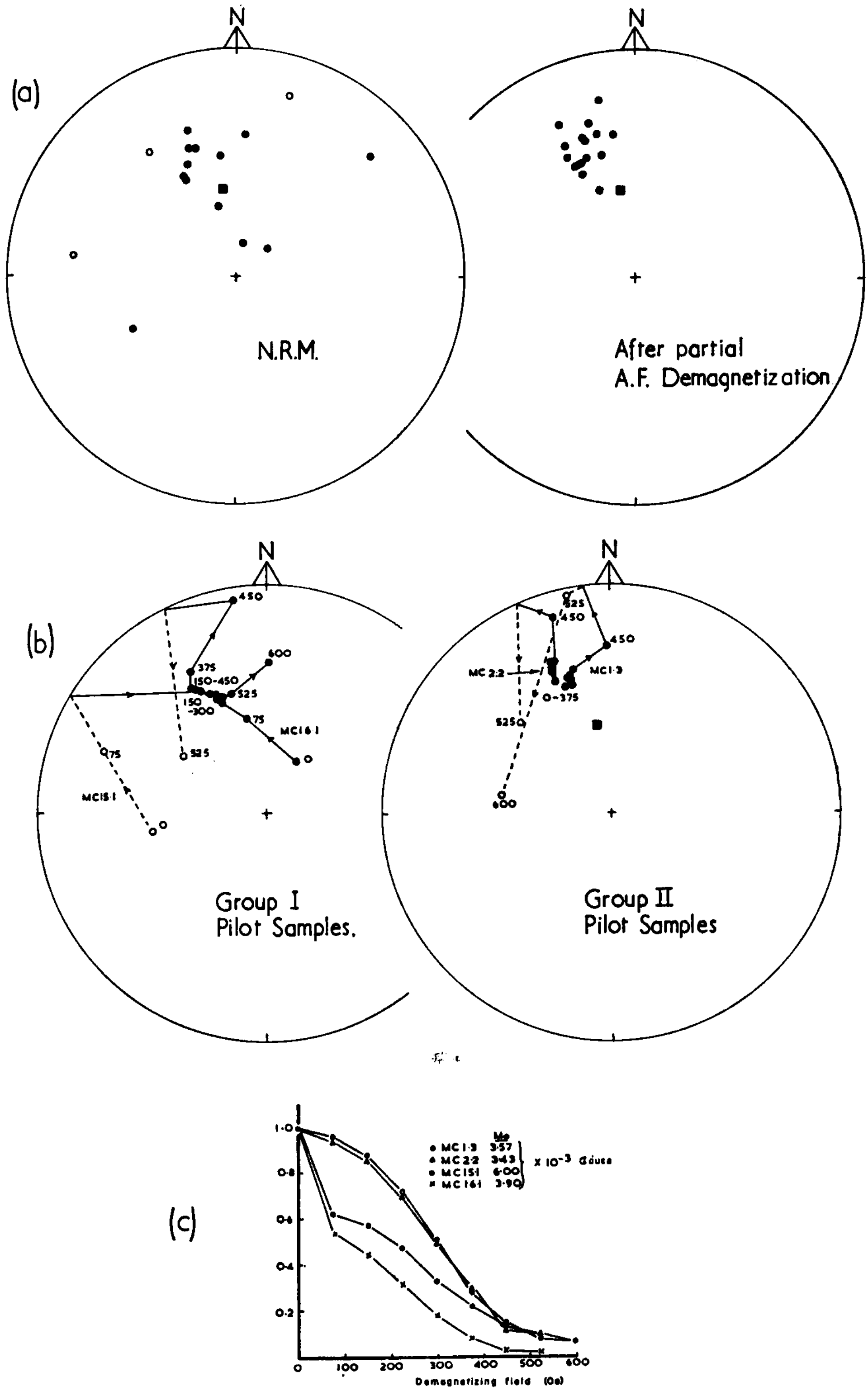

FIG. 2. Results from the Draa Valley Dolerites. Stereographic projections of directions of remanence after correction for tectonic tilting. Solid symbols lower hemisphere, open symbols upper hemisphere. Numbers indicate peak field in Oe. ■ indicates present field direction. (a) Mean site directions of remanence before and after partial A.F. demagnetization. (b) Examples of typical pilot-sample behaviour during stepwise demagnetization. (c) Normalized intensity decay curves for there pilot-samples.

Table 1

Draa Valley Sills: site mean directions of magnetization, palaeomagnetic pole positions & statistical parameters

Site No.	N.R.M. D	I	N	R	k	α_{95}	Peak field	After A.F. treatment D	I	N	R	R	α_{95}	Palaeomagnetic south pole Lat.	Long.	A_{95}
MC1	343·0	+28·5	6	5·959	122	6	335	345·0	+24·0	5	4·993	590	3	68·0° S	35·0° E	3
MC2	342·0	+22·0	6	5·990	503	3	330	343·5	+19·5	5	4·976	165	6	64·5° S	35·0° E	6
MC3	340·0	+27·5	6	5·983	303	4	300	339·5	+24·0	5	4·994	735	3	64·5° S	45·5° S	3
MC4	352·5	+33·5	6	5·654	15	18	250	340·0	+25·0	4	3·971	105	9	65·5° S	45·0° E	10
MC5	48·5	+13·0	6	4·339	3	47	330	350·5	+25·0	6	5·882	42	10	71·5° S	23·5° E	8
MC6	16·5	−10·5	6	5·959	122	6	338	348·5	+13·0	6	5·844	32	12	64·5° S	20·0° E	12
MC7	13·5	+72·5	6	5·989	453	3	330	333·5	+16·5	6	5·973	188	5	57·5° S	48·0° E	3
MC8	325·5	+23·0	6	5·663	15	18	300	332·0	+24·0	6	5·991	536	3	59·0° S	55·5° S	2
MC9	242·0	+36·5	6	5·993	716	2·5	300	330·5	+28·0	6	5·944	89	7	58·5° S	61·5° S	7
MC10	333·0	+37·0	6	5·877	40	11	300	338·0	+31·0	6	5·990	489	3	66·0° S	54·5° E	3
MC11	333·0	+38·5	6	5·991	562	3	300	335·0	+31·5	6	5·976	212	5	64·0° S	59·5° S	5
MC12	346·5	+54·5	6	5·887	44	10	225	338·0	+45·5	5	5·979	192	5	70·5° S	80·5° E	6
MC13	336·5	+33·5	6	5·979	239	4	225	334·0	+32·0	6	5·980	256	4	63·0° S	61·0° E	4
MC14	4·0	+25·5	6	5·990	516	3	225	345·5	+32·0	6	5·993	771	2	71·5° S	42·5° E	2
MC15	277·0	−19·0	6	4·608	4	41	300	332·0	+32·0	6	5·954	110	6	61·5° S	63·0° E	7
MC16	51·0	+68·5	6	5·800	25	14	300	333·0	+36·5	6	5·960	125	6	63·5° S	68·0° E	4
Overall mean	343·5	+36·5	16	12·522	4	20	225 to 335	339·0	+27·5	16	15·785	70	4·5	65·5° S	50·5° E	3·5

D = declination (E of N) in degrees

I = inclination (positive downwards) in degrees

N = No of samples averaged

R = length of vector resultant of N unit remanence vectors relative to bedding plane

k = precision parameter

α_{95} = radius of 95 per cent confidence circle about mean direction

A_{95} = radius of 95 per cent confidence circle about mean pole

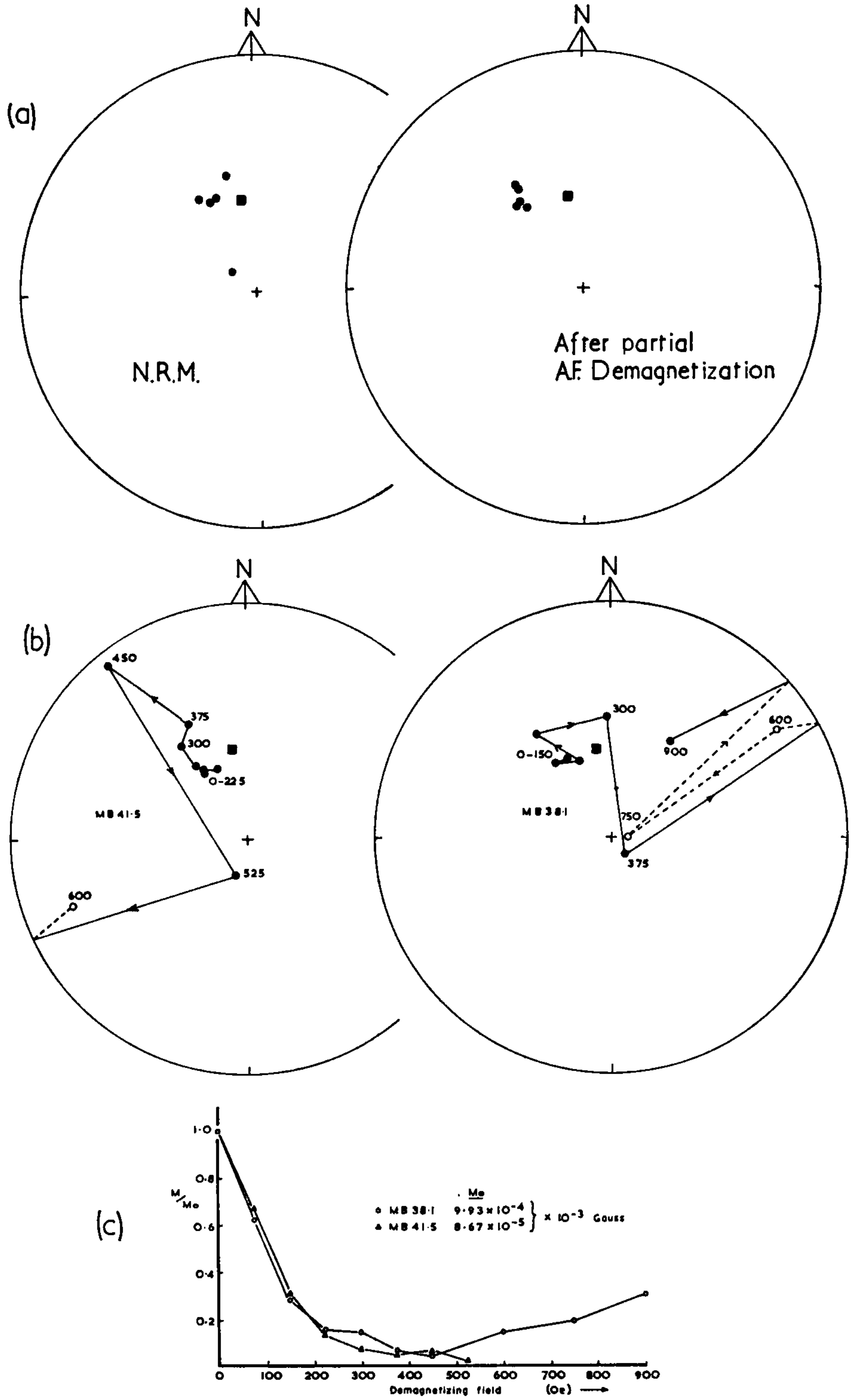

FIG 3 Results from the Foum-Zguid dyke. Notation as in Fig. 2.

Table 2

Foum-Zguid dyke

Site No.	N.R.M. D	I	N	R	k	α_{95}	Peak field	After A.F. treatment D	I	N	R	k	α_{95}	Palaeomagnetic south pole Lat.	Long.	A_{95}
MB37	334·0	+44·0	5	4·989	357	4	250	327·0	+35·0	5	4·952	84	8	58·5° S	71·0° E	7
MB38	337·5	+43·5	5	4·991	460	4	225	327·0	+36·5	5	4·992	502	3	58·5° S	72·5° E	3
MB39	329·0	+40·5	5	4·974	157	6	150	321·5	+42·0	6	5·920	63	8	55·0° S	83·5° E	8
MB40	308·5	+74·5	6	4·413	3	45	300	325·0	+45·0	3	2·983	118	11	59·5° S	85·5° E	10
MB41	346·5	+36·0	6	4·913	5	35	300	324·0	+41·5	4	3·945	54	12	58·0° S	81·0° E	14
Overall mean	334·5	+48·0	5	4·826	23	16	150–300	325·0	+40·0	5	4·987	316	4	58·0° S	79·0° E	4

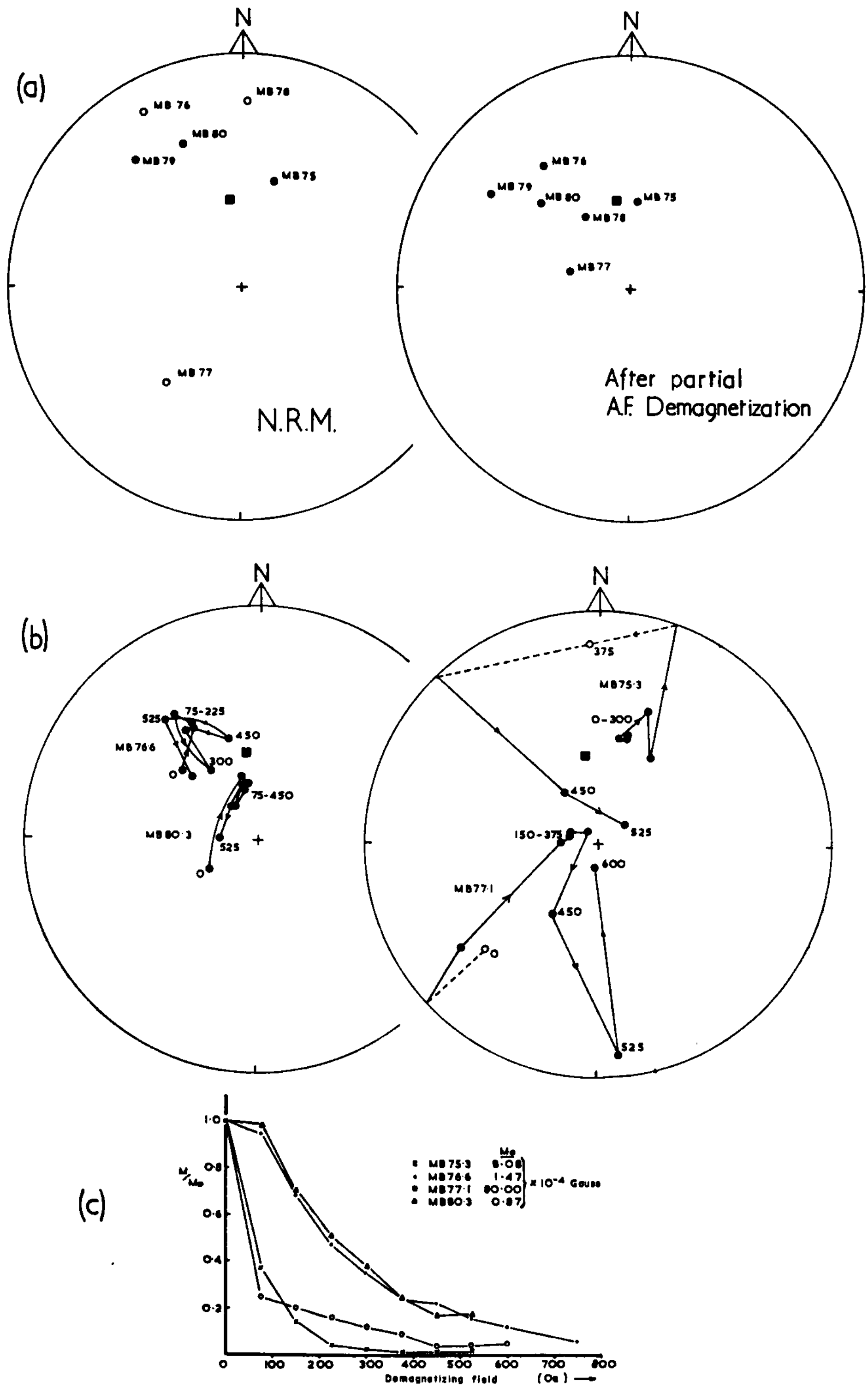

Fig. 4. Results from the Central Atlas Intrusives. Notation as in Fig. 2.

Table 3

Central Atlas intrusives

Site No.	N.R.M. D	N.R.M. I	N.R.M. N	N.R.M. R	N.R.M. k	N.R.M. α_{95}	Peak field	After A.F. treatment D	After A.F. treatment I	After A.F. treatment N	After A.F. treatment R	After A.F. treatment k	After A.F. treatment α_{95}	Palaeomagnetic south pole Lat.	Palaeomagnetic south pole Long.	Palaeomagnetic south pole A_{95}
MB75	8·0	+47·0	6	5·986	351	4	150	6·5	+48·0	3	2·996	494	6	83·5° S	66·0° W	7
MB76	331·0	−8·0	6	5·958	120	6	150	324·5	+23·5	4	3·990	305	5	52·0° S	61·0° E	5
MB77	209·0	−29·5	5	4·949	78	9	225	284·0	+59·5	4	3·982	167	7	30·0° S	116·0° E	11
MB78	2·0	+26·0	6	5·223	6	29	225	330·0	+43·5	3	2·933	32	22	64·0° S	78·0° E	22
MB79	320·0	+19·5	6	5·962	131	6	225	301·0	+20·0	4	3·974	114	9	32·0·0 °S	76·5 °E	5
MB80	337·5	+22·5	6	5·266	7	28	225	308·5	+23·5	3	2·998	1144	4	39·0° S	73·5° E	2
Overall mean	332·0	+19·0	6	3·895	2·38	56	150–225	318·4	+38·5	6	5·494	10	22	53·0° S	81·5° E	24

Table 4

Site No.		Percentage of K_2O	Radiogenic argon $mm^2\ g^{-1}$	Atmospheric contamination (%)	Age (My)
			Draa Valley sills		
MC14	Whole rock	0·61	$(3\cdot87\pm0\cdot07)\ 10^{-3}$	73·0	180±4
			$(3\cdot94\pm0\cdot07)\ 10^{-3}$	69·6	183±4
MC15	Whole rock	0·56	$(3\cdot62\pm0\cdot05)\ 10^{-3}$	60·2	186±3
			$(3\cdot55\pm0\cdot05)\ 10^{-3}$	57·4	183±3
MC16	Whole rock	0·57	$(3\cdot62\pm0\cdot05)\ 10^{-3}$	65·4	183±3
			$(3\cdot58\pm0\cdot08)\ 10^{-3}$	60·8	181±4
			Foum-Zguid dyke		
MB37	Whole rock	1·03	$(6\cdot62\pm0\cdot09)\ 10^{-3}$	51·1	186±3
			$(6\cdot47\pm0\cdot08)10^{-3}$	54·9	182±3
MB38	Whole rock	0·53	$(3\cdot42\pm0\cdot07)\ 10^{-3}$	64·6	187±4
			$(3\cdot32\pm0\cdot08)\ 10^{-3}$	71·3	182±4
			Central Atlas intrusives		
Tassent Gabbro					
MB76	Biotite	6·01	$(3\cdot22\pm0\cdot06)\ 10^{-2}$	29·0	155±3
			$(3\cdot14\pm0\cdot05)\ 10^{-2}$	25·5	152±3
MB79	Biotite	6·80	$(3\cdot67\pm0\cdot05)\ 10^{-2}$	26·8	157±2
			$(3\cdot62\pm0\cdot07)\ 10^{-2}$	26·8	154±2
MB80	Biotite	5·51	$(3\cdot05\pm0\cdot05)\ 10^{-2}$	24·9	160±3
			$(3\cdot00\pm0\cdot06)\ 10^{-2}$	28·4	158±3
Dykes					
MB77	Whole rock	0·80	$(3\cdot28\pm0\cdot06)\ 10^{-3}$	40·6	121±3
			$(3\cdot22\pm0\cdot05)\ 10^{-3}$	42·9	119±3
MB 78	Whole Rock	0·51	$(2\cdot36\pm0\cdot04)\ 10^{-3}$	54·9	134±3
			$(2\cdot31\pm0\cdot04)\ 10^{-3}$	56·1	131±3

$\lambda_e = 0\cdot584$—$10^{-10}\ yr^{-1}$
$\lambda_\beta = 4\cdot72$—$10^{-10}\ yr^{-1}$
$40k/k = 1\cdot19$—10^{-2} atom per cent.

mountains. No such deformation was obvious at any of the sites visited, but a tilt correction, estimated from adjacent strata, has been applied to the remanence vectors from all of the gabbro sites, and reduces the between-site scatter from 34° to 22°.

5. Potassium–argon age determinations

Potassium–argon age determinations were performed on cores chosen from those used for palaeomagnetic measurements. Selection was carried out after consideration of a thin section of each core sample, and according to the criteria outlined by Dalrymple & Lanphere (1969). Whole-rock analyses were performed on the 16–30 mesh sieve-fraction from the crushed cores of the fine-grained rocks. In the case of the coarser-grained samples from the Tassent gabbro, biotite was separated from the 85–100 mesh fraction using a shaking table. Triplicate potassium analyses were perfoımed by flame photometry using a lithium internal standard, and duplicate argon analyses were performed by the isotope dilution method on an Omegatron mass spectrometer using an argon extraction system similar to that described by Miller & Brown (1965). The results are shown in Table 4.

Ages obtained from the Draa Valley sills and the Foum-Zguid dyke indicate that these formations are Jurassic rather than Upper Palaeozoic, and that they are contemporaneous within the range of experimental error. The significance of the

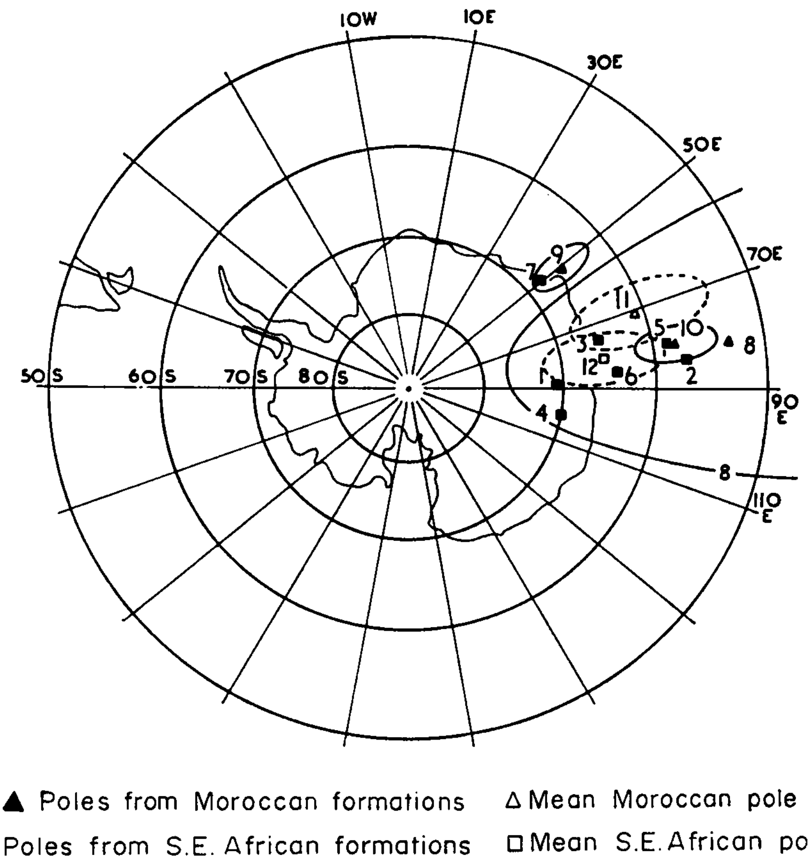

FIG. 5. African Upper Triassic to Jurassic south palaeomagnetic pole positions, plotted on a polar stereographic projection. Ovals of 95 per cent confidence are shown around new Moroccan poles (solid lines), and mean N.W. African and S.E. African poles (broken lines). For pole reference numbers see Table 5.

Table 5

African Upper Triassic to Jurassic Mean Formation Palaeomagnetic Poles

Pole Ref. No. (Fig. 5)	Formation	Lat.	Long.	A_{95}	References
1	Stormberg Lavas, S. Africa and Botswana	71° S	89° E	15	Irving 1964
2	Karroo Lavas, Cen. Africa	57° S	84° E	8	McElhinny *et al.* 1968
3	Karroo Dolerities, S. Africa and Rhodesia	65·5° S	75° E	12·5	McElhinny & Jones 1965
4	Marangudzi Ring Complex, Rhodesia	70° S	105° S	9	Gough *et al.* 1964; Brock 1968
5	Mateke Hills Ring Complex, Rhodesia	58·5° S	79·5° E	8·5	Gough *et al.* 1964
6	Shawa Ijolite, Rhodesia	64° S	85·5° E	14	Gough & Brock 1964
7	Red Sandstone Formation, Zambia	68° S	49·5° E	5	Opdyke 1964
8	Central Atlas intrusives, S. Morocco	53° S	81·5° E	24	This paper
9	Draa Valley sills, S. Morocco	65·5° S	50·5°E	3·5	This paper
10	Foum-Zguid dyke, S. Morocco	58° S	80° E	3·5	This paper
11	Mean Pole for S.E. Africa (Mean of 1–7)	65·5° S	81° E	6·5	
12	Mean Pole for N.W. Africa (Mean of 8–10)	61° S	71° E	14	
13	Mean African Pole (Mean of 1–10)	64° S	78° E	5·5	

ages obtained from the Tassent gabbro are less certain, owing to its complex tectonic history subsequent to emplacement (Choubert & Faure-Muret 1962), but the results may be considered as a stratigraphic upper limit for the age of intrusion, confirming the previous Jurassic classification. Ages from the Central Atlas dykes are subject to similar uncertainty but the results are thought to be valid estimates of the emplacement ages on the basis of thin-section criteria as well as concordancy between different samples. The intrusion of the dykes occurred, therefore, at a time close to the Jurassic–Cretaceous boundary.

6. Discussion

The palaeomagnetic results indicate the isolation of a stable component of remanence, most probably of primary origin, from all three formations. The corresponding mean palaeomagnetic pole-positions have been calculated and are listed in Table 5, together with all other reliable published African poles of similar age. These poles are plotted in Fig. 5, and it is clear that there is a significant difference between the pole from the Draa Valley sills (Pole 9) and that from the Foum-Zguid dyke (Pole 10), but no significant difference between the latter and the pole from the Central Atlas intrusives (pole 8). This difference is puzzling since the first two formations gave radiometric age determinations in close agreement with each other, but substantially different from that of the Atlas intrusives. Furthermore these two formations lie in the stable Saharan Shield region, whereas the Atlas Intrusives were involved in post-Jurassic orogenic movements. The anomalous pole from the Draa Valley sills is based on a large number of sites, corrected for tectonic tilting, and is considered to be more reliable than the other two Moroccan poles.

One pole from East Africa, that from the Zambian red sandstone formation, agrees with the pole from the Draa Valley sills, whereas the other six poles from South-East Africa are in better agreement with those from the Foum-Zguid dyke and Central Atlas intrusives. The age of the Zambian red sandstone formation is quoted as 180–200 My (McElhinny *et al.* 1968), and it is possible that this formation and the Draa Valley sills have recorded a small temporary excursion of the pole away from the mean Mesozoic position calculated by McElhinny *et al.* Since this excursion is not recorded in the Foum-Zguid dyke, the time taken to return to the mean Mesozoic position must have been less than the range of uncertainty in the radiometric age determinations. Geological evidence indicates that the intrusion of these two formations was separated by a sufficient period of time for a significant episode of folding to have occurred.

The mean Moroccan Jurassic pole, calculated by assigning unit weight to each formation, is plotted in Fig. 5 (Pole 12), together with the mean South-east African pole (Pole 11), and the corresponding ovals of 95 per cent confidence. There is no significant difference between these two mean poles at the 95 per cent confidence level, and it is concluded that there has been no significant relative tectonic movement between North-west and South-east Africa since at least the Jurassic.

Radiometric ages from the Moroccan dolerites indicate a widespread episode of Jurassic igneous activity in N.W. Africa. Jurassic and Lower Cretaceous age determinations reported by Siedner & Miller (1968) on dolerites from S.W. Africa have been interpreted as being functionally related to the initiation of the break-up of Gondwanaland at this time. The ages reported here indicate that during the Jurassic period vulcanism occurred along a more extensive section of the present African Atlantic coastline than had hitherto been suspected. Siedner and Miller have also pointed out that in S.W. Africa the general trend of late Mesozoic dyke swarms is roughly North–South and parallel to the local coast-line. A similar parallelism between coast-line, Mesozoic intrusions and structural trends can now be identified in the North-west African cratonic block. Sets of Jurassic dolerite dykes, adjacent to, and paralleling the eastern coast of North America, have been described by de Boer (1968), and may be expressions of the same period of vulcanism as the Moroccan intrusives. Like the latter, they were probably associated with the initial fracturing of the original landmass.

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