SHEAR IN THE TETHYS AND THE PERMIAN PALEOMAGNETISM IN THE SOUTHERN ALPS, INCLUDING NEW RESULTS

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SUMMARY

To verify paleomagnetic proof for megatectonic translation in the Tethys a large collection of samples from a key area, the Bolzano Quartz Porphyry Plateau in the Southern Alps, was examined. Their natural remanent magnetization was analyzed with thermal, and mainly alternating field demagnetization. The result is a well-established paleomagnetic direction of $D: 150^\circ$ and $I: -19.5^\circ$ ($\alpha_{95} = 4.9$), obtained from 152 samples from 39 sites distributed over 12 volcanic units. It is argued that the inclination of this result is not significantly different from that which can be extrapolated for the Southern Alps from Early Permian paleomagnetic directions of the stable European shield. Consequently it is concluded that a paleomagnetic indication for megatectonic translation of the Southern Alps is virtually absent. But a large counterclockwise deviation of the declination is evident, and is easily explained by a counterclockwise rotation of 50° of the Southern Alps with respect to stable Europe. Since the paleomagnetic direction of the Early Permian volcanics of the Southern Alps fits in reasonably well with the (poorly known) Early Permian paleomagnetic pattern of Africa, a coherence between both regions is presumed.

INTRODUCTION

The discovery of an anomalous Permian paleomagnetic pole position for the Southern Alpine realm by Van Hilten (1960) initiated extensive discussions among geotectonic scientists concerned with the geotectonic movements in this area. In particular, when in later years several paleomagnetic studies (see Table I) on neighbouring rocks supported Van Hilten's Bolzano pole (De Boer, 1963; Guicherit, 1964; Van Hilten and Zijderveld, 1966; Zijderveld and De Jong, 1969), it became clear that relative movements between the Southern Alps and stable (extra-Alpine) Europe must have occurred since the Triassic Period.

However, the nature and extent of these movements is still a matter of dispute. Did the Southern Alps once form part of the drifting African continent, as has tentatively been suggested by Van Hilten and Zijderveld (1966)? Or did they just drift, or maybe only rotate individually as a

TABLE I

Relevant Permian paleomagnetic data from the Southern Alps (northern Italy)

Locality	Number of samples	Number of sites	Number of flows	Tests ¹	D ²	I ²	α_{95}^3 (N) ⁴	Reference and remarks
Bolzano/Val-di-Non	33	10	6	A.C.	150	-31	4	Van Hilten (1960)
Bolzano/Lagorai	33	9	?	A.C.	143	-15	11	Findhammer (See Table III)
Bolzano	152	39	12	A.C., th, unf.	150	-19.5	5	present investigation
Chiusa	8	1	—	A.C.	173	-8.5	—	Nijenhuis in Guicherit (1964)
East Lombardy	43	5	5	A.C.	135	-21	20	Zijderveld and De Jong (1969)
Lugano	11	4	3	A.C.	143.5	-17	8.5	Van Hilten and Zijderveld (1966)
Southern Alps (11°E, 46°15'N)	280	68		A.C., th	148	-20	4	(68) mean direction of magnetization
Not acceptable for the computation of an Early Permian paleomagnetic direction for the Southern Alps:								
Bolzano/Merano	51	28	?	A.C.	164	-10.5		Dietzel (1960); secondary magnetizations have not completely been removed
Bolzano/Cavalese	6	1	1	A.C.	162	-23		Van Lookeren Campagne in Guicherit (1964); the result is inconclusive, being based on six samples, which display a large scatter
Vicentinian Alps	7	1	—	A.C.	148	-29		De Boer (1963); these samples of the Posina Mass have a Triassic age
Vicentinian Alps	5	1	—	A.C.	150	-22		De Boer (1963); these sediment samples (Grödener) have a late Permian/Triassic age
Vicentinian Alps	19	7	—	A.C.	328	+34		De Boer (1963); these samples (Camparno and Staro) have a Late Permian/Triassic age

¹ Tests: A.C. and th refer to alternating current and thermal demagnetization techniques; unf. = unfolding test.² D and I: declination and inclination in degrees

smaller tectonic unit, as a result of movements in the Tethys zone?

This paper presents new data from the same formation (Bolzano Quartz Porphyries) which Van Hilten studied (1960), but now on the basis of a recent geologic and petrographic study by one of us (M.N.) and a collection of 206 samples. Finally, we will undertake a renewed comparison between the increasing number of paleomagnetic directions derived from Permian rocks from the extra-Alpine areas in Europe, the African Shield and from the Southern Alps, in order to establish some reasonable limits to the wide range of suggestions and interpretations.

GEOLOGY OF THE BOLZANO QUARTZ PORPHYRIES

After the Hercynian orogeny and subsequent peneplenization, a thick sequence of predominantly ignimbritic flows (rhyodacites and rhyolites) was deposited over a large area in the Southern Alps (Fig.1). Tuffs, lava flows, conglomerates and sandstones are intercalated. An Early Permian

Fig.1. Sketch map of the Bolzano volcanics. The sampling sites of Van Hilten (1960), R. Findhammer (in Guicherit, 1964) and the present investigation are indicated.

Fig.2. Two schematic cross sections (north-south and northeast-southwest) of the Bolzano volcanics. The sampling sites of the present investigation are indicated.

age has been accepted (see, for instance, Pichler, 1959). A schematic cross-section is presented in Fig.2. For an extensive geologic and petrographic description of the sequence the reader is referred to Andreatta (1959), Pichler (1959), Mittempergher (1962), Ghezzi (1967) and the Geological Map of Italy (sheets Trento, 1968, M. Marmolada, 1970 and Feltre, 1970). For the paleomagnetic investigation samples were collected from ten flows and two tuff layers (46 sites). The sampling site distribution is shown in the geological sketch map of Fig.1.

On top of the volcanic series follow Upper Permian sandstones (Grödener s.s.), the Upper Permian evaporites and limestones and finally the Triassic sequence. The whole sequence has remained fairly undisturbed, with minor faulting and moderate dips. In the course of our collection of the oriented hand samples, special care was taken in the determination of the tectonic strike and dip of the flows, thus restricting the sampling to tectonically unambiguous sites.

THE NATURAL REMANENT MAGNETIZATION OF THE BOLZANO VOLCANICS

The initial measurements revealed that the natural remanent magnetization (N.R.M.) of nearly all sample groups had intensities ranging between 10 and $500 \cdot 10^{-6}$ emu/cm³ and Q -values well above 1. Only some sample groups of the dacitic lavas showed higher intensities up to $2000 \cdot 10^{-6}$ emu/cm³. On the other hand, some sample groups of the rhyolites had N.R.M. intensities down to $0.5 \cdot 10^{-6}$ emu/cm³, accompanied by low Q -values of less than 1. The directions of the initial N.R.M.'s showed a large within-site consistency. For the majority of the sites the N.R.M. was directed southeast with an upward inclination.

The N.R.M. of all samples was examined with alternating field and thermal demagnetization techniques, using standard methods described previously (As and Zijderfeld, 1958; As, 1960; Zijderfeld, 1967a). From each site at least one pilot sample was stepwise demagnetized with alternating fields of up to 3,000 Oe (peak value). These progressive demagnetizations confirmed that in the majority of samples the N.R.M. was entirely or practically singular, i.e. only one direction of magnetization persisted during the demagnetization (Fig.3). Only in the samples of 6 sites did a secondary magnetization make up an important part (more than 15%) of the N.R.M. Since this additional magnetization usually was directed along the recent local geomagnetic field, it obviously must be of recent origin. At one site the samples contained this soft secondary magnetization exclusively. However, in 50% of the samples of the Bolzano volcanics, the secondary magnetization made up less than 5% of their total N.R.M. (Fig.3: HAZ 197 and 121), or was entirely lacking (Fig.3: HAZ 64, 113 and 141). The secondary magnetization was fairly soft and could be strongly decayed with alternating fields below 300 Oe. In some cases the slight change in direction of the decreasing N.R.M., as a consequence of removing the secondary magnetism, persisted until treatment with alternating fields as high as 2,000 Oe (Fig.3: HAZ 129).

The principal magnetization, dominant in all samples, has a characteristic southeastern declination and an upward inclination. There is no reason to suspect that this characteristic magnetization should not be the original

Fig.3. Demagnetization diagrams: thermal progressive demagnetization (HAZ 7) and A.C. magnetic field demagnetizations. Plotted points represent successive positions - in orthogonal projection - of the end point of the magnetic vector. Full symbols represent projections on the horizontal plane; open symbols represent projections on the north-south vertical plane. Numbers denote furnace temperatures in °C or A.C. magnetic field intensities in Oersted (Oe).

Fig.3. D,E. For legend see p.644.

remanence of the Bolzano volcanics. This characteristic magnetization turned out to be notably hard. A very small decay of the N.R.M. in alternating fields below 500 Oe is often typical. In practically all samples some part of the characteristic N.R.M. remained after treatment with our strongest alternating fields of 3,000 Oe, though in 24% of the samples the characteristic N.R.M. was almost eliminated with this 3,000 Oe (Fig.3: HAZ 197). On the other hand, the characteristic N.R.M. of 26% of the samples was only slightly affected with alternating fields up to 3,000 Oe (Fig.3: HAZ 129 and 121). Altogether, in 50% of the samples more than half of the characteristic N.R.M. remained after treatment with alternating fields as high as 1,000 Oe.

Fig.3. F,G. For legend see p.644.

Some samples were demagnetized thermally by heating them stepwise to progressively higher temperatures in a large furnace¹, and measuring their remanence at room temperature between the successive heating steps. The thermal demagnetizations confirmed the results of the alternating field demagnetizations and added moreover some new data. The secondary magnetizations proved to be eliminated after heat treatments up to temperatures varying between 200°C and 400°C. The directions of the remaining characteristic natural remanent magnetizations were entirely consistent with those obtained with alternating field demagnetizations. There was also a relationship between the blocking temperatures and the hardness of the characteristic magnetizations. The characteristic magnetizations which could be almost eliminated with 3,000 Oe were largely (not entirely) decayed after heat treatment with 580°C. The characteristic magnetizations which resisted alternating fields up to 3,000 Oe were decayed mainly by temperatures over 600°C (Fig.3: HAZ 7). This proves that these very hard characteristic remanences reside for a large part in hematite, which could be expected with these ignimbritic flows.

¹ Constructed at the Utrecht Paleomagnetic Laboratory by F.G. Mulder.

After alternating field and thermal progressive demagnetization of the pilot samples, all further samples were treated with three or four steps of the higher alternating field trajectory (between 500 and 3,000 Oe), in order to ascertain whether the remaining magnetization was single, i.e. that only a linear decrease of the magnetization vector occurred. In this way we could verify whether even small secondary components were eliminated and thus the characteristic directions given are entirely reliable.

Although there appeared to be a close similarity in properties of the natural remanence of the samples from each single site, there was no such similarity between the sites attributed to the same flow (Fig.4).

Fig.4. Stratigraphical sequence of the sampled units of the Bolzano volcanics. The mean directions of magnetization of the 39 sites have been plotted. *N* is the number of samples involved.

For calculating the ultimate mean characteristic direction of our sample collection we selected only those samples of which the demagnetization diagram displayed a single characteristic magnetization whose direction could be determined with high accuracy. The samples of a fairly large number of sites (39) comprising 152 samples, satisfied these conditions. The mean characteristic directions of these 39 sites are presented in Fig.5 and in Table II. They show a large between-site dispersion. This dis-

TABLE II

Site mean directions of natural remanent magnetization of Bolzano volcanics (new results)

Flow	Site no.	Samples used/ collected	Total N.R.M. with respect to horizontal			Characteristic N.R.M. with respect to horizontal			Strike and dip of bedding	Characteristic N.R.M. with respect to bedding			
			D	I	K	α_{95}	D	I		K	α_{95}	D	I
Rd 4	8	4/5	128.5	-28.5	307	5.3	129	-30	379	4.7	178-12	125	-20.5
	20	4/5	140	-31.5	429	4.4	141	-33.5	360	4.9	273-30	148.5	-8.5
	21	5/5	129	-40	62	9.8	146.5	-38.5	112	7.3	283-22	155	-22
	30	4/4	115.5	-23	495	4.1	120.5	-25	318	5.2	293-32	133	-17
	40	3/3	151.5	-31	1540	3.1	150.5	-33.5	1350	3.4	282-12	154.5	-24
An 2	4	2/5	146.5	-14			146.5	-14.5			248-15	147	+0.5
	13	2/2	171.5	-4			172	-7.5			48-18	175	-22
	15	5/5	151	-29	59	10.1	151	-27.5	59	10.1	148-20	141	-26.5
	29	6/7	119.5	+3.5	6	29.3	117	-11.5	126	6.0	293-32	122.5	-7.5
	31	7/8	148	-4.5	219	4.1	148	-5	252	3.8	23-16	150	-18
Rd 3	3	0/2									248-15		
	16	4/5	168.5	-48.5	401	4.6	162.5	-43	503	4.1	233-28	157.5	-16
	19	4/4	132.5	-35	200	6.5	134.5	-34.5	254	5.8	273-30	144	-12.5
	24	3/5	157.5	-30	185	9.1	155.5	-31.5	235	8.1	263-22	158	-10.5
	41	3/3	149.5	-25.5	45	18.5	148.5	-27	41	19.6	282-12	152	-18
ta Rd 2/3	12	2/3	169.5	+19.5			169.5	-20			48-18	175	-34.5
Rd 2	18	5/5	145.5	-29	124	6.9	149	-32.5	163	6.0	273-30	149.5	-2.5
	27	5/5	149	+3.5	4	42.1	162	-31	33	13.5	303-25	170	-14
	39	5/6	168.5	-7	114	7.2	169.5	-10.5	107	7.4	258-4	169.5	-7
Rd 2	1	0/5									258-4		
	2	2/3	153	-36			154.5	-34			248-15	155	-19
	6	3/5	134.5	-19.5	41	19.4	144	-27.5	51	17.5	228-15	143.5	-13
	7	5/6	130	-23.5	1083	2.3	131	-27.5	927	2.5	138-15	123.5	-25

	9	3/3	133.5	-8	314	7.0	141	-7.5	182	9.2	98-23	136	-22.5
	14	4/5	163.5	-28.5	40	14.7	163	-27	41	14.5	148-20	152.5	-30
	17	5/5	166	-15.5	348	4.1	167.5	-19.5	430	3.7	178-10	164	-17.5
	26	4/5	145	-21.5	62	11.8	144.5	-24.5	59	12.1	233-20	144	-4.5
	28	5/5	114	-15	161	6.1	113.5	-20	322	4.3	293-32	124.5	-16.5
	32	5/5	161.5	-12.5	184	5.7	161	-16.5	186	5.6	88-6	160.5	-22
	42	2/2	122	-24			122.5	-25			282-12	127	-20
	44	2/3	176.5	-9			175.5	-12.5			88-6	175.5	-18.5
	46	5/5	166.5	-11	353	4.1	165.5	-13	537	3.3	88-6	165	-19
Rd 1	23	3/3	129	-34.5	180	9.2	134.5	-37	196	8.8	263-22	141.5	-19
	25	4/5	147	-45	312	5.2	150	-44	281	5.5	233-20	148.5	-24.5
	43	2/2	152.5	-35			152	-37.5			338-16	164	-37.5
	45	5/5	173	-4	57	10.3	173.5	-12	117	7.1	88-6	173.5	-18
R 1	10	5/5	123	-17	61	9.9	123	-24	96	7.9	38-10	122.5	-34
	38	0/5									218-15		
ta R 1/2	5	4/4	145.5	-12.5	32	16.6	147.5	-21.5	25	18.9	138-13	142	-23
R 2	11	0/5											
	22	3/3	148	-32.5	8	46.0	155	-29.5	79	13.9	208-20		
	34	0/5									235-16		
	37	0/5									328-15	154	-13.5
											218-15		
Ror	33	0/5											
	36	3/5	138.5	+16.5	2		143.5	-23	196	8.8	328-15	142.5	-8.5
R 3	35	5/5	175	-36.5	2		164.5	-47.5	281	4.6	218-15	157.5	-35

persion is not due to any scatter of direction within the sites, since the site means have relatively high precision parameters (Table II). Moreover, we were unable to find any correlation between the characteristic N.R.M. directions and the stratigraphy of the volcanic units (Fig.4). For these reasons we computed the mean characteristic direction for the Bolzano volcanics giving unit weight to sites: $D = 150^\circ$, $I = -19.5^\circ$ and $\alpha_{95} = 4.9^\circ$. The differences in tectonic dip of all sites permits an unfolding test, which is positive since in our case with 39 units α_{95} decreases from 5.3° to 4.9° .

Fig.5. Equal area projection of the geomagnetic directions in the Southern Alps (11°E , $46^\circ15'\text{N}$), computed from Permian virtual pole positions found for stable Europe (Zijderveld, 1967b) and the Southern Alps (Table I). Each symbol represents a geomagnetic direction of a flow or site mean. Full (open) symbols point downwards (upwards) with a negative (positive) inclination.

This mean direction moreover is supported by a three dimensional histogram (Fig.6). This histogram, an equal area projection with a density distribution of the 39 site means, has been constructed by plotting the directions of magnetization regardless of polarity in the upper hemisphere and counting the number of directions present in each "equal area" all over the projection. The highest concentration (the top or modus) coincides with the mean direction ($D = 150^\circ$, $I = -19.5^\circ$) given above, which would not be the case if we had averaged a strongly asymmetrical distribution.

Fig.6. Density distribution of the 39 mean directions of magnetization of the sites, for explanation see text.

PERMIAN PALEOMAGNETISM IN THE SOUTHERN ALPS

Including the results presented in this paper, a fair amount of reliable Permian¹ data is now available and, fortunately, this enables us to be selective in our choice of material. Since all results have been obtained with the aid of alternating current - and, more recently, thermal - demagnetizations, this selectivity is mainly concerned with the age of the samples. In our opinion six investigations (Table I and Table III) covering an age strictly between Late Carboniferous and Late Permian meet the conditions for our purpose. Not acceptable, and entered in brackets in Table I, are results presented by De Boer (1963), since most of his samples proved to be younger. His sediment samples have a Late Permian/Triassic age (Grödener) and some of his igneous samples are even of a Triassic age (De Vecchi, 1965). Although De Boer ascribed a Permian age to them, basing himself on the similarity of the paleomagnetic directions, this is certainly reasoning in a circle and his arguments should therefore be dis-

¹We confine ourselves to Permian data for the following reasons. The data for other periods from Eurasia available for comparison, are scarce and very few of them have been obtained with the aid of demagnetization techniques. The results for other periods from the Southern Alps, moreover, are until now scarce or inconclusive. Added in proof: meanwhile Manzoni (1970), studying Triassic rocks from the Southern Alps, was led to similar conclusions as reported in this paper.

TABLE III

Site mean directions of N.R.M. of the quartz porphyries from the Lagorai range, collected near the Passo del Rolle by Findhammer (1959). A preliminary mean direction of magnetization was published by Guicherit (1964).

Field location number	Samples used/collected	Strike and dip of bedding	Mean characteristic N.R.M. with respect to bedding			
			D	I	K	α_{95}
67 + 101	3/4	242-25	154.5	-10.5	161	9.8
68	3/3	210-32	145.5	-12.5	42	19.4
109	10/10	258-20	119	-16.5	82	5.4
169	1/2	256-20	144.5	-10	-	-
170	3/3	252-20	138	-16.5	269	7.5
171	2/3	283-10	151	-4.5	184	18.5
172	0/2	296-20	-	-	-	-
173	3/3	229-23	159	-45	57	16.5
174	3/3	262-20	146.5	-19	53	17.2
175	5/5	259-50	134.5	-0	100	7.7

counted (De Boer, 1963: pp.64, 150–151). Also unacceptable is a result given by Dietzel (1960) since secondary magnetizations apparently have not been completely removed from his samples.

The six investigations we accept cover a region of $250 \cdot 60 \text{ km}^2$. Although the computation of a mean direction of magnetization, while giving unit weight to investigations, may be the more common technique, we do not favour such a mean direction for the Southern Alps, because of the enormous difference in the number of samples involved. Therefore, the mean direction of magnetization, $D = 148^\circ$ and $I = -20^\circ$ is based on the mean directions of magnetization from 68 sites ($\alpha_{95} = 4$). Altogether some 280 samples are involved.

THEORIES CONCERNING SHEAR IN THE TETHYS ZONE

It may be relevant before we compare paleomagnetic data from the Southern Alps with results from Eurasia and Africa, to review the current ideas regarding the major tectonic movement in the area under consideration.

A first-order problem, of course, is the ancient arrangement of the two continental units Africa and Eurasia. It is obvious that any comparison with the two different Permian data from Africa (Briden, 1967), though of special interest, gives a solution of limited value. Further paleomagnetic work on Upper Paleozoic rocks in Africa is highly desirable. Nevertheless, it has repeatedly been pointed out that the general trend in the Permian and moreover the Mesozoic paleomagnetic data, would imply a considerable overlap of Africa and stable Europe in these times if they had been on the same (relative) longitude as they are now (Van Hilten, 1964; Irving, 1967). This forces us to accept a mutual translation, and leads us to the concept of a shear zone in the Mediterranean area (Carey, 1958; Van Hilten, 1964). In this view two groups of hypotheses have been forwarded, implying either sinistral or dextral shear.

The sinistral-shear hypothesis implies an eastward translation and a counterclockwise rotation of about 40° of Africa with respect to Eurasia in Late Mesozoic and Tertiary times. This movement has had the most publicity, having been advocated by Carey (1958) as an explanation of the tectonic history of the Mediterranean; by Bullard et al. (1965) to explain the ancient continental configuration of the Atlantic-bordering continents (Fig.7) and recently by Funnel and Smith (1968) as an explanation of the structure of the Atlantic Ocean. It received strong support from paleomagnetic studies by Creer (1968) in which he tested reconstructions for the Paleozoic periods. In a previous paper (Van der Voo and Zijdeveld, 1969) we demonstrated that Bullard's reconstruction is supported by the Late Paleozoic pole positions of Eurasia, North America and Africa with only one exception, that of the Ecca redbeds of Tanzania (see Fig.7), whilst we also suggested that sinistral shear might be indicated by the counterclockwise rotations of several paleoblocks in the Western Mediterranean area (Spain, Corsica, Sardinia and the Southern Alps).

Disagreeing with these ideas, Van Hilten (1964) developed a hypothesis of dextral shear, the so-called Tethys-twist concept. In recent times this concept has been adopted by Irving (1967), while Van Bemmelen (1969) also

Fig.7. Azimuthal equidistant projection with relative positions of North America, Eurasia and Africa according to the fit of these continents after Bullard et al. (1965), with the Late Paleozoic and Mesozoic paleomagnetic poles. The data from North America are selected from Roy (1966), Laroche (1967, 1968) and Laroche and Currie (1967); the data from Africa are from Briden (1967); the data from Europe are from Van der Voo and Zijdeveld (1969).

favours a Tethys twist originating from a postulated pattern of mega-undations (see also Van Bemmelen, 1965, 1966). To fit in the available paleomagnetic data, a position of Africa is required somewhere in the (present) Indian Ocean with respect to Eurasia, followed by a translation, with a counterclockwise rotation of about 40° in Late Mesozoic and Tertiary times. The arguments of Van Hilten (1964) are based upon the combined two Permian pole positions for Africa (which indeed, as has just been mentioned, do not agree with the Bullard reconstruction) and are also based upon an assumed ancient dextral character of many strike-slip faults in the Tethys shear zone: the peri-Adriatic fault in Italy (De Jong, 1967a), faults in Jugoslavia, the north Anatolian fault zone in Turkey etc. Some of these faults are still active at present (Ritsema, 1969). Strong support moreover was thought to be supplied by a paper of De Boer (1963, 1965) in which he claimed that the anomalous Permian paleomagnetic results of the Southern Alps could only be interpreted as having been caused by dextral strike-slip movements of the order of 5,000 km, the so-called megatectonic translations (Van Bemmelen, 1965). The results presented in this paper are highly relevant to this question and we will discuss De Boer's reasoning in more detail in the next section.

MEGATECTONIC TRANSLATIONS OF THE SOUTHERN ALPS?

De Boer (1963, 1965) and Van Hilten (1964) were the first to analyse the then available paleomagnetic data of stable Europe and the Southern Alps. They came to the conclusion that a significant difference existed between the observed paleomagnetic directions in the Southern Alps and the Permian paleomagnetic field for this region as extrapolated from stable Europe. They stated that: (1) the deviating declination of Permian rocks in northern Italy indicates a counterclockwise rotation of about 50° ; and that (2) the Southern Alps showing a mean inclination of about -30° had to be situated on the -30° Permian paleo-isocline of stable Europe. According to De Boer's compilation this paleo-isocline crosses the mobile Tethys belt in the Himalaya area, which led him to the conclusion that the Southern Alps underwent a westward megatectonic translation of at least 5,000 km. Thinking of a mechanism for this translation, an easy solution then appeared to him to be a westward drift of Africa of the same order of magnitude.

However, we realise nowadays that several assumptions of De Boer have lately been found to be incorrect. Part of the older paleomagnetic data for stable Europe are to be discarded, which is common knowledge now among paleomagnetic workers (Storetvedt, 1967; Zijdeveld, 1967b; Krs, 1968; Hospers and Van Andel, 1969). In addition, our knowledge of the Permian paleomagnetic field in the Southern Alps has been enriched with new results (Guicherit, 1964; Van Hilten and Zijdeveld, 1966; Zijdeveld and De Jong, 1969 and the present paper). For these reasons De Boer's comparison of the paleo-inclination as extrapolated from stable Europe (-5°) and the observed mean inclination for northern Italy of -30° is no longer valid. Instead, the Permian inclination extrapolated from modern and reliable observations of stable Europe (Zijdeveld, 1967b; Hospers and Van Andel, 1969) must have been -15° in northern Italy, whereas the mean inclination

value computed from reliable paleomagnetic data of this region is -20° (Table I). In a statistical analysis Hospers and Van Andel (1969) computed the 95% confidence limits for the extrapolated inclination as $-15^\circ \pm 13^\circ$. They concluded that no statistically significant deviation was present, even though they used De Boer's mean inclination value, recomputed by them as $-24^\circ \pm 11^\circ$, which is now rendered out of date. This conclusion becomes even more evident when we also consider the data published since 1964, the resulting value being $-20^\circ \pm 4^\circ$ (Table I).

Consequently, it follows that megatectonic translations of the Southern Alps cannot be based on paleomagnetic arguments. This does, of course, not imply that such movements have not occurred, but that paleomagnetic arguments for such a theory do not exist. De Jong remarked that geologic arguments can be found, for instance, in the crustal shortening in the Alps (Oberhauser, 1965; De Jong, 1967b) which might indicate a northward translation of at least 500 km of the Southern Alps in relation to stable Europe, thus increasing the inclination difference. But even a translation of this order of magnitude would not result in a significant difference in the inclinations found in northern Italy and those extrapolated from data for stable Europe. Furthermore, we would like to emphasize that the amount of crustal shortening is a matter of dispute.

PALEOGEOGRAPHICAL CONCLUSIONS

Although there is no need to invoke large mutual translations between stable Europe and the Southern Alps, there is one conclusion from the studies by Van Hilten and De Boer that is becoming more and more firmly established: a counterclockwise rotation of the Southern Alps of about 50° with respect to stable Europe. In recent review articles Hospers and Van Andel (1969) and Van der Voo and Zijdeveld (1969) have drawn attention to the paleomagnetically determined rotations of several paleoblocks in the Western Mediterranean area. The rotations of the Iberian Peninsula, Sardinia and the Southern Alps display a striking similarity, being counterclockwise over approximately 35° – 50° (Fig.8).

Although the drift relationship between Africa and stable Europe as yet remains ambiguous (page 653), we will try to illustrate the importance of this relationship in explaining these rotations and the paleogeographical situation of the Southern Alps.

In this connection, a comparison between the paleomagnetic data from the Southern Alps and the African Shield seems to be relevant, but here we can be brief. In Fig.9 the Permian paleomagnetic data from the African Shield are compared with the Italian data and it is easily seen that there are no significant differences either in inclination or in declination (see also Van Hilten and Zijdeveld, 1966). Keeping in mind that the Permian data from Africa badly need support, a tentative conclusion might be that Africa and the Southern Alps seem to have been facing each other as they do now, at least since Permian times.

We can now return to the continental-drift relationship of Africa and Eurasia, and, considering the points above mentioned, two independent paleogeographical constructions can be advanced, as shown in Fig.10, 11.

Fig.8. Map of Europe showing the Permian isoclines derived from reliable measurements on igneous rocks collected from the stable part of the European continent (Zijderveld, 1967b). The directions of the arrows, plotted where the rocks were sampled, represent the declination, whereas the inclination is also indicated. The dotted line shows the southern boundary of stable Europe.

Fig.9. Equal area projection of the geomagnetic directions in the Southern Alps (11°E , $46^{\circ}15'\text{N}$), computed from Permian virtual pole positions found for Africa (Briden, 1967) and the Southern Alps (see Fig.5 and Table I).

Fig.10. Reconstruction of the Atlantic-bordering continents for the Permian Period, after Bullard et al. (1965). Supposed positions of the Iberian Peninsula (Van der Voo, 1969) and Italy (viz., the Southern Alps), compatible with paleomagnetic data, have been indicated (black).

A third possibility, individual drifting of the Southern Alps as a small tectonic unit on its own, seems to be very unlikely.

In Mesozoic and Tertiary times the two reconstructions of Fig.11 and Fig.10 would then be followed by either: (1) dextral shear: a large westward drift relative to Eurasia of the African Shield with the Southern Alps attached to it, together with a counterclockwise rotation of about 50° ; or (2) sinistral shear: a short eastward drift of Africa relative to Eurasia. This implies for the Southern Alps an original position somewhere in the

Fig.11. Reconstruction of the Atlantic-bordering continents for the Permian Period, after Van Hilten (1964) and Irving (1967). Positions of the Iberian peninsula and Italy (black), as proposed by Irving (1967) have been indicated with minor modifications.

Western Mediterranean area, not far from its present position as can be seen in Fig.10. In other words, this implies hardly any relative movements with respect to Africa and only a counterclockwise rotation around a vertical axis over approximately 50° with respect to stable Europe. This movement is similar to those previously suggested for other paleoblocks in the Western Mediterranean area attributed to sinistral shear as well (Van der Voo and Zijdeveld, 1969).

Until further Permian paleomagnetic data for Africa have become available, we are not in a position to make a choice on the basis of paleomagnetic data, but it seems that evidence from the structure of the Atlantic Ocean floor is in favour of the latter (sinistral-shear) hypothesis (Funnel and Smith, 1968).

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REFERENCES

- Andreatta, C., 1959. Aufeinanderfolge der magmatischen Tätigkeiten im grössten Permisch-vulkanischen Schild der Alpen. *Geol. Rundschau*, 48: 99-111.
- As, J.A., 1960. Instruments and measuring methods in paleomagnetic research. *Mededel. Verhandel. K.N.M.I.*, 78: 56 pp.
- As, J.A. and Zijdeveld, J.D.A., 1958. Magnetic cleaning in paleomagnetic research. *Geophys. J.*, 1: 308-319.
- Briden, J.C., 1967. Recurrent continental drift of Gondwanaland. *Nature*, 215: 1334-1339.
- Bullard, E.C., Everett, J. and Gilbert Smith, A., 1965. A symposium on continental drift. *Phil. Trans. Roy. Soc. London, Ser. A.*, 258: 41-51.
- Carey, S.W., 1958. A tectonic approach to continental drift. *Symp. Continental Drift, Hobart*, pp. 177-355.
- Creer, K.M., 1968. Arrangement of the continents during the Paleozoic Era. *Nature*, 219: 41-44.
- De Boer, J., 1963. Geology of the Vicentinian Alps with special reference to their paleomagnetic history. *Geol. Ultraiectina*, 11: 178 pp.
- De Boer, J., 1965. Paleomagnetic indications of megatectonic movements in the Tethys. *J. Geophys. Res.* 70 (4): 931-944.
- De Jong, K.A., 1967a. Paläogeographie des ostalpinen oberen Perms, Paläomagnetismus und Seitenverschiebungen. *Geol. Rundschau*, 56: 103-115.
- De Jong, K.A., 1967b. Tettonica gravitativa e raccorciamento crostale nelle Alpi Meridionali. *Boll. Soc. Geol. Ital.*, 86: 749-776.
- De Vecchi, G., 1965. La presenza di rocce monzonitiche nel territorio di Laghi (Posina). *Mem. Acad. Patavina Sci. Lettere Arte., Classe Sci. Math. Nat.*, 77: 297-314.
- Dietzel, G.F.L., 1960. Geology and Permian paleomagnetism of the Merano region, province of Bolzano, Italy. *Geol. Ultraiectina*, 4: 57 pp.
- Findhammer, R., 1959. *Internal Rept. Geol. Inst., Utrecht*, 22: 27 pp.
- Funnel, B.M. and Smith, A.G., 1968. Opening of the Atlantic Ocean. *Nature*, 219: 1328-1333.
- Ghezzi, C., 1967. Le vulcaniti paleozoiche nell'area centro-orientale del complesso effusivo atesino. *Mineral. Petrog. Acta (Bologna)*, 13: 339-408.
- Guicherit, R., 1964. Gravity tectonics, gravity field and paleomagnetism in north-eastern Italy. *Geol. Ultraiectina*, 14: 125 pp.
- Hospers, J. and Van Andel, S.I., 1969. Paleomagnetism and tectonics, a review. *Earth-Sci. Rev.*, 5: 5-44.
- Irving, E., 1967. Paleomagnetic evidence for shear along the Tethys. In: C.G. Adams and D.V. Ager (Editors), *Aspects of Tethyan Biogeography - Systematics Association Publication*, 7: 59-76.
- Krs, M., 1968. Rheological aspects in paleomagnetism? *Intern. Geol. Congr., 13th, Prague 1968, Rept.*, 5: 87-96.
- Laroche, A., 1967. 1. Paleomagnetic directions of a basic sill in Prince Edward Island. 2. Preliminary data on the paleomagnetism of the North Mountain basalt, Nova Scotia. *Geol. Surv. Can. Paper*, 67: 39 pp.
- Laroche, A., 1968. Paleomagnetism of the Monteregian hills: new results. *J. Geophys. Res.*, 73: 3239-3246.
- Laroche, A. and Currie, K.L., 1967. Paleomagnetic study of igneous rocks from the Manicouagan Structure, Quebec. *J. Geophys. Res.*, 72: 4163-4169.
- Manzoni, M., 1970. Paleomagnetic data of Middle and Upper Triassic age from the Dolomites. *Tectonophysics*, 10 (4): 411-424.
- McElhinny, M.W., 1964. Statistical significance of the fold test in paleomagnetism. *Geophys. J.*, 8(3): 338-340.
- Mitterperger, M., 1962. Rilevamento e estudio petrografico delle Vulcaniti paleozoiche della Val Gardena, *Atti Soc. Toscana Sci. Nat. Pisa, Proc. Verbal Mem.*, Ser. A, 69(1962): 41 pp.

- Oberhauser, R., 1965. Zur Geologie der West-Ostalpen-Grenzzone in Vorarlberg und im Prätigau unter besonderer Berücksichtigung der tektonischen Lagebeziehungen. *Verhandl. Geol. Bundesanstalt, Sonderheft G.* 1965: 184-190.
- Pichler, H., 1959. Neue Ergebnisse zur Gliederung der unterpermischen Eruptivfolge der Bozener Porphyry-Platte. *Geol. Rundschau*, 48: 112-131.
- Ritsema, A.R., 1969. Seismic data of the West Mediterranean and the problem of oceanization. *Verhandel. Koninkl. Ned. Geol. Mijnbouw Genoot., Geol. Ser.*, 26: 105-120.
- Roy, J.L., 1966. Désaimantation thermique et analyse statistique des directions de sédiments carbonifères et permians de l'est du Canada. *Can. J. Earth Sci.*, 3: 139-161.
- Servizio Geologico d'Italia, 1968. Geological map of Italy, 1 : 100,000, Trento. *Servi. Geol. Italia, Rome.*
- Servizio Geologico d'Italia, 1970a. Geological map of Italy, 1 : 100,000, M. Marmalado. *Serv., Geol. Italia, Rome.*
- Servizio Geologico d'Italia, 1970b. Geological map of Italy, 1 : 100,000, Feltre. *Serv. Geol. Italia, Rome.*
- Storeyvedt, K.M., 1967. A synthesis of the Paleozoic paleomagnetic data for Europe. *Earth Planetary Sci. Letters*, 3(5): 444-448.
- Van Bemmelen, R.W., 1965. Mega-undations as a cause of continental drift. *Geol. Mijnbouw*, 44: 29-57.
- Van Bemmelen, R.W., 1966. On mega-undations: a new model for the earth's evolution. *Tectonophysics*, 3(2): 83-127.
- Van Bemmelen, R.W., 1969. Origin of the western Mediterranean Sea. *Verhandel. Koninkl. Ned. Geol. Mijnbouw Genoot., Geol. Ser.*, 26: 13-52.
- Van der Voo, R., 1969. Paleomagnetic evidence for the rotation of the Iberian Peninsula. *Tectonophysics*, 7(1): 5-56.
- Van der Voo, R. and Zijderfeld, J.D.A., 1969. Paleomagnetism in the western Mediterranean Area. *Verhandel. Koninkl. Ned. Geol. Mijnbouw Genoot., Geol. Ser.*, 26: 121-138.
- Van Hilten, D., 1960. Geology and Permian paleomagnetism of the Val-di-Non area. *Geol. Ultraiectina*, 5: 95 pp.
- Van Hilten, D., 1964. Evaluation of some geotectonic hypotheses by paleomagnetism. *Tectonophysics*, 1: 3-71.
- Van Hilten, D. and Zijderfeld, J.D.A., 1966. The magnetism of the Permian porphyries near Lugano (northern Italy/Switzerland). *Tectonophysics*, 3: 429-446.
- Zijderfeld, J.D.A., 1967a. A.c. demagnetization of rocks: analysis of results. In: D.W. Collinson, K.M. Creer and S.K. Runcorn (Editors), *Methods in Paleomagnetism*. Elsevier, Amsterdam, pp. 254-286.
- Zijderfeld, J.D.A., 1967b. The N.R.M. of the Exeter volcanic traps (Permian, Europe). *Tectonophysics*, 4(2): 121-154.
- Zijderfeld, J.D.A. and De Jong, K.A., 1969. Paleomagnetism of some Late Paleozoic and Triassic rocks from the eastern Lombardic Alps, Italy. *Geol. Mijnbouw*, 48(6): 559-564.