EVALUATION OF SOME GEOTECTONIC HYPOTHESES BY PALEOMAGNETISM

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SUMMARY

All available Carboniferous and younger paleomagnetic data (some 220 individual observations) have been studied and are presented by pole positions and isoclines, averaged over the geological period and continental block to which they belong (Plate I). In view of the growing evidence for global expansion, the data have also been worked to adapt them to globes of smaller size (Plate III). The paleomagnetic data show: (1) that continental drift must have occurred and (2) that large-scale movements in the alpine areas have taken place during some stage of the alpine orogeny.

Paleomagnetic data as yet provide only two of the three parameters required to reconstruct exactly the ancient continental configurations; but these two parameters provide nonetheless a valuable check on continental arrangements as predicted in the various geotectonic hypotheses, and it is with this in view that paleomagnetic data are used in the present paper.

The reconstruction presented has many affinities with the well-known drift theories, but is rather unorthodox in other respects; it tries to establish a connection between orogeny and continental drift, and takes into account first-order structural features such as the mid-oceanic ridges and large strike-slip faults.

INTRODUCTION

During the past decade, the geological literature has been flooded by a wave of papers on geotectonic processes; topics range from continental drift, convection currents and orogenesis up to global expansion and neo-formation of oceanic basins. Obvious reasons for the revival of almost forgotten theories, and for the origin of new ones, are important discoveries in different geologic domains; valuable data have become available on the morphology of the ocean floors, whose topographic eminences appear to coincide with geophysically well-defined zones of high but shallow seismicity and increased heatflow. From all over the world, a series of large-scale strike-slip faults is reported; they are mainly found in alpine regions, running there almost parallel to the orogenic trends; but such fracture zones can now also be recognized in the ocean basins, and the amount and sense of their displacement gauged. Finally, a type of observation with most promising prospects for the geologist is furnished by one of the youngest branches of geophysics: paleomagnetism.

The theoretical grounds on which continental drift hypothesis were shipwrecked during the first half of this century have been pushed aside by the discovery of strike-slip faults with the dimensions required for continental displacements. The theoreticians, aware of the turning of the tide, now even invent highly detailed stream patterns of convection currents as transport mechanisms for the drifting continents. The rising columns of these currents should be situated under the mid-oceanic ridges, the world-encircling zones of tension and high heat-flow. According to other authors, these mid-oceanic rifts are to be explained rather as the scars produced by a post-Carboniferous expansion of the earth. Paleomagnetic observations indicate mutual displacements of the continents, thus reinforcing the classic arguments for continental drift as derived from paleoclimatology, paleontology, similarity of opposing coast-lines, and interrupted structural trends found at either side of ocean basins. The large-scale strike-slip faults in the alpine chains have been elected by some authors as the basis of new orogenic theories: in their views, enormous longitudinal displacements occurred in an early stage of the orogenesis, though two conflicting opinions have been launched. Carey takes these movements to be left-lateral, but Ashgirei (1962). De Boer (1964) and Pavoni (1961) have found right-lateral displacements.

The paleomagnetic data do not yet supply an independent solution of the problems of continental drift. It has been pointed out that these data give the distance (latitude) and orientation of a continental block with respect to an ancient pole, but that the ancient longitudinal positions of the continents cannot be distilled from them. It is emphasized that in theory also the ancient longitudes can be found (Van Hilten, 1964) but that the paleomagnetic data obtained up till now do not suffice for the application of this theory. However, the paleomagnetic data offer a welcome tool to *check* and *evaluate* hypotheses in which continental displacements are assumed, and it is as such that they are used in this paper. Such a check may be considered positive, and therefore an affirmation of the hypothesis tested, when the continents can be arranged in such a manner that the requirements of the ancient magnetic dipole field as well as those of the hypothetical configuration are met.

The reader will understand that I assume, like most students of paleomagnetism, that the ancient geomagnetic field was dipolar, geocentric and axial, when taken over a time long enough to average out effects from secular variation. Arguments for this assumption have been given before by many authors, see for instance Cox and Doell (1960, p.739), and Briden and Irving (1963).

THE POST-DEVONIAN PALEOMAGNETIC DATA

All post-Devonian paleomagnetic data known to this author are listed in Appendix I. Most of them are taken from the review articles by Cox and

Doell (1960), Irving (1960a, 1960b, 1961, 1962a, 1962b), Kalashnikov (1961) and Nairn (1963). The list contains a far greater number of observations that were used in my previous analysis (Van Hilten, 1962). They are grouped according to geological period and to the continent from which they are derived. This conforms to one of the earliest findings in paleomagnetism, that paleomagnetically determined virtual poles of equal geological age for the same continent form a more or less well-defined cluster on the globe. In some instances, remarks have been added where I have excluded certain data from consideration, either because they look unreliable, or because more trustworthy results have been obtained from the same rocks.

The investigation is confined to post-Devonian times for two reasons: (1) the scatter of the virtual poles of older periods is considerably greater; their use would only increase the speculative character of the comparisons, and (2) few of the published reconstructions of continental positions go further back in geological time than the Late Paleozoic.

For each geological period, the mean virtual pole position for every continent was calculated. The mean virtual pole positions are given in the upper part of Table I, together with the number (N) of independent observations used for the calculation, and the value k , a precision parameter known from the equation:

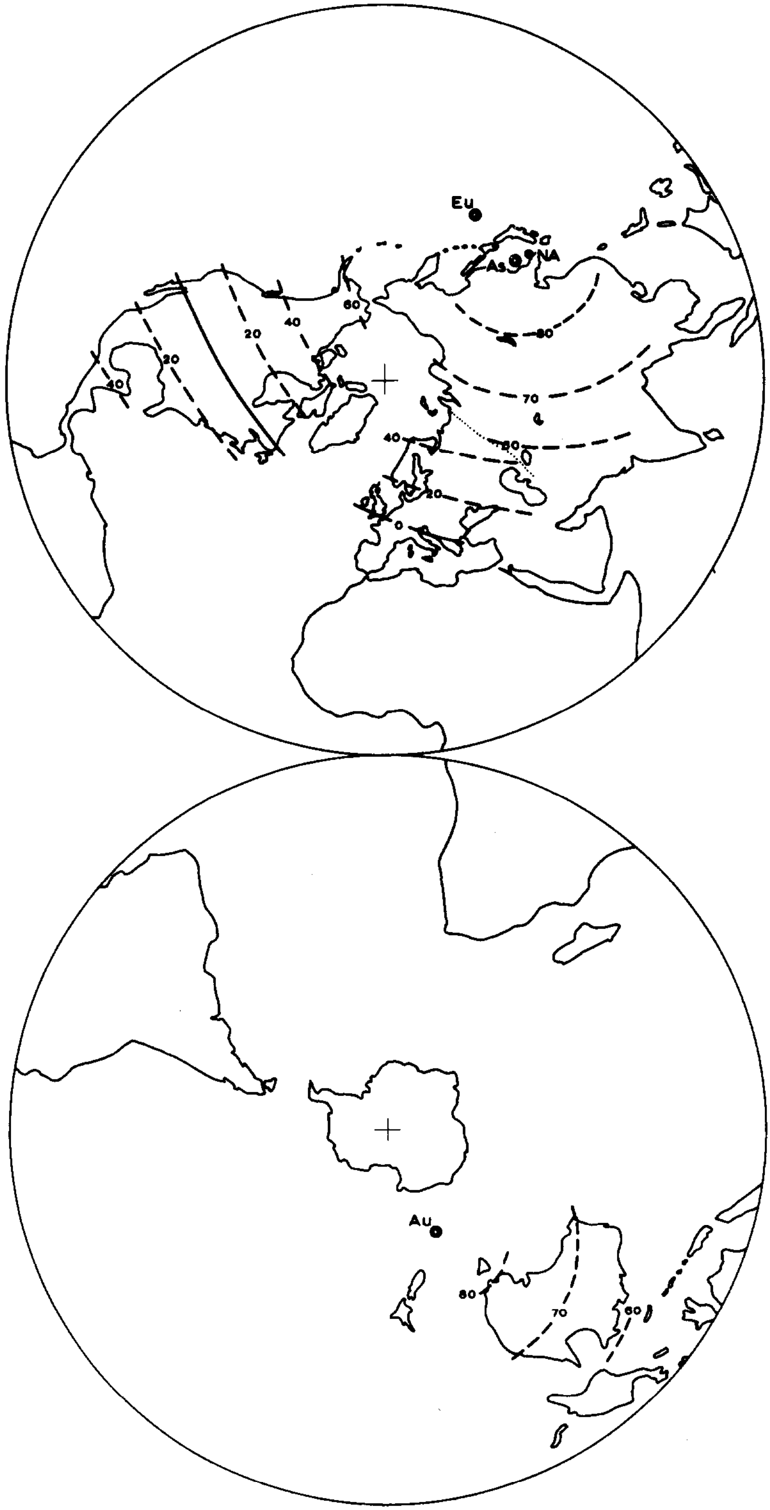
$$k = \frac{N - 1}{N - R}$$

where R is the length of the resultant vector of the N vectors of unit length. The value k has been added in the Table to provide an estimate of the scatter of the virtual pole positions, though in many instances where the number of poles is very small (2-4), the reality of this k value is doubtful. Some of the k values have been put in brackets: this is to indicate that the distribution of the virtual pole positions does not provide the required axial symmetry about their mean direction, a condition which should be satisfied to justify the use of this statistical method (Fischer, 1953).

In Fig.1, these mean virtual pole positions have been plotted, and the poles of each continent have been connected in chronological order, so that polar wandering paths originate. In the figure, distinction has been made between reliable and less reliable mean pole positions, indicated by full and open symbols respectively. This distinction is based upon the appreciation of the number of independent investigations, their techniques of testing the stability of the magnetization, the scatter in the measurements of the directions in magnetization, "streaking"-phenomena (Creer, 1962b), and the radial symmetry of the virtual poles plotted on the globe. Short arguments on this subjective distinction are given in Appendix I.

Table I has been divided in two parts, the upper one refering to continental masses and blocks, the lower part dealing with structural units of the alpine orogenic chains. This devision is of primary importance and may be regarded as one of the most interesting fruits of paleomagnetic research. For it appears that *all* virtual pole positions derived from areas within the alpine realm diverge appreciably from the poles determined from rocks on the stable parts of the continents. This is clearly demonstrated by the Permian pole positions determined from European rocks

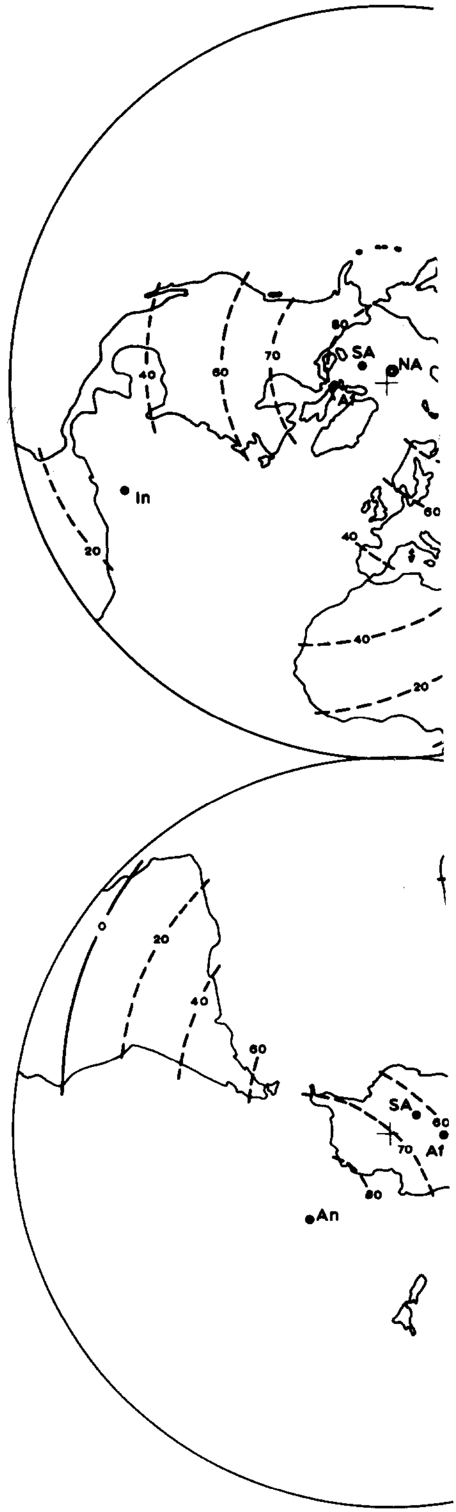
PLATE I. Carboniferous and younger paleomagnetic data represented by pole positions, and isoclines drawn on the corresponding continents. The pole positions are the same ones as given in Fig.1; their reliability is shown again by full dots (reliable) and open symbols (less reliable).
A polarity can be attributed to the Permian poles and isoclines.
Af = Africa; An = Antarctica; As = Asia; Au = Australia; Eu = Europe; Gr = Greenland; In = India; Mad = Madagascar; NA = North America; SA = South America.



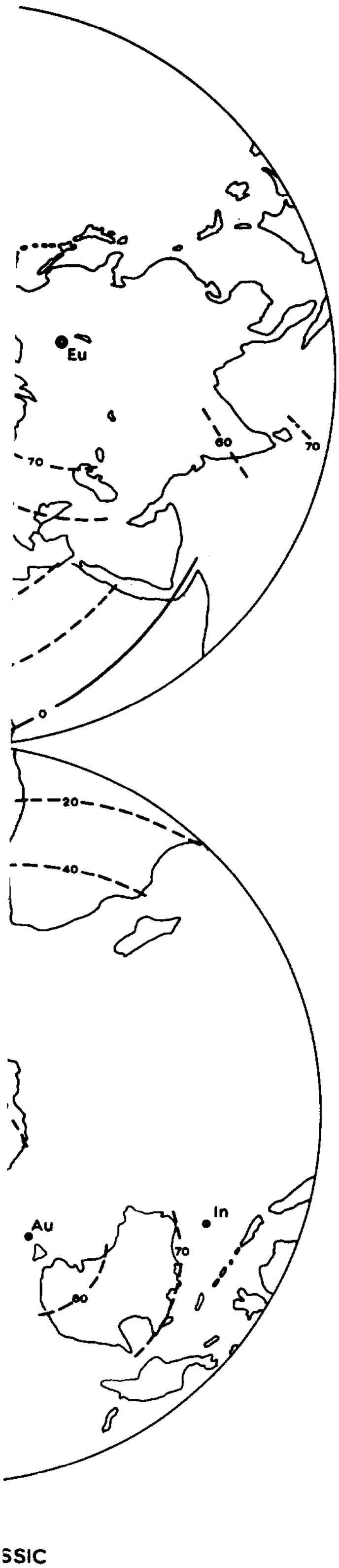
CARBONIFEROUS

PERMIAN

TRIASSIC



JURAS



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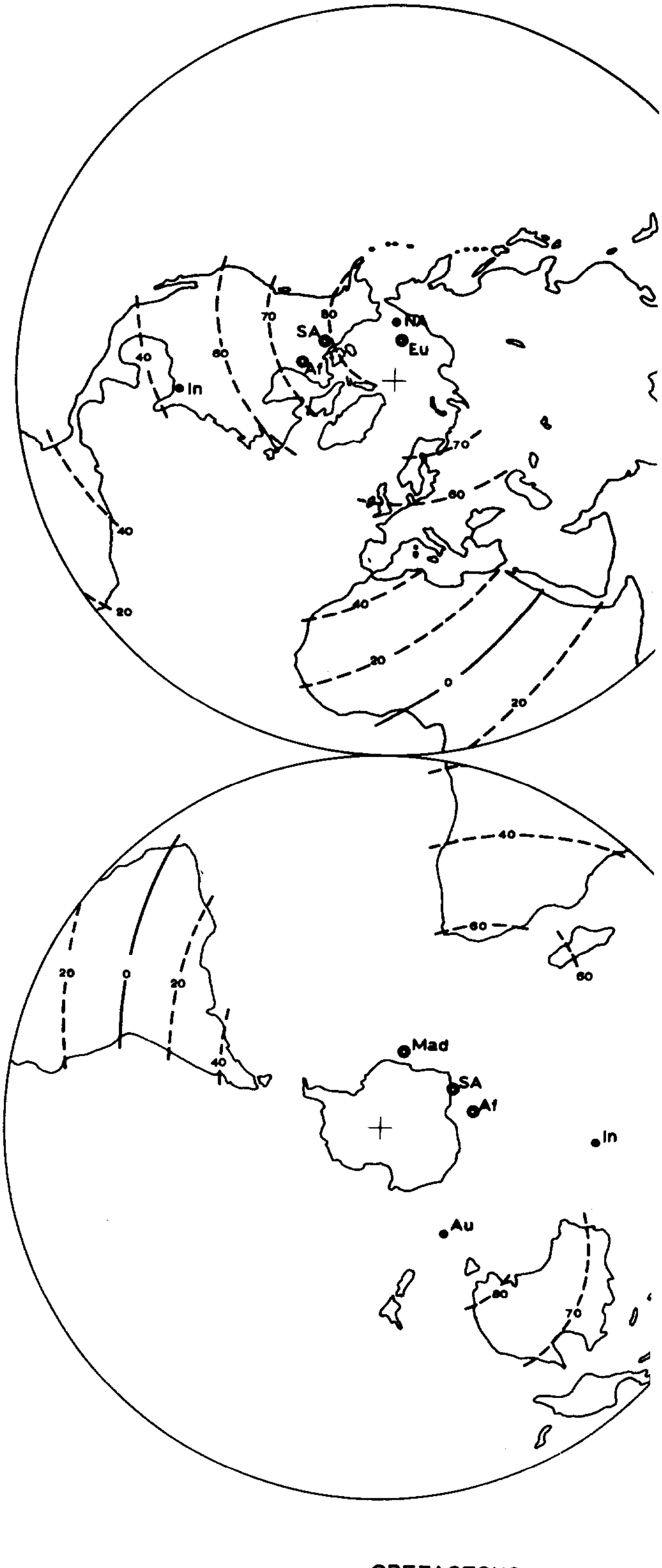
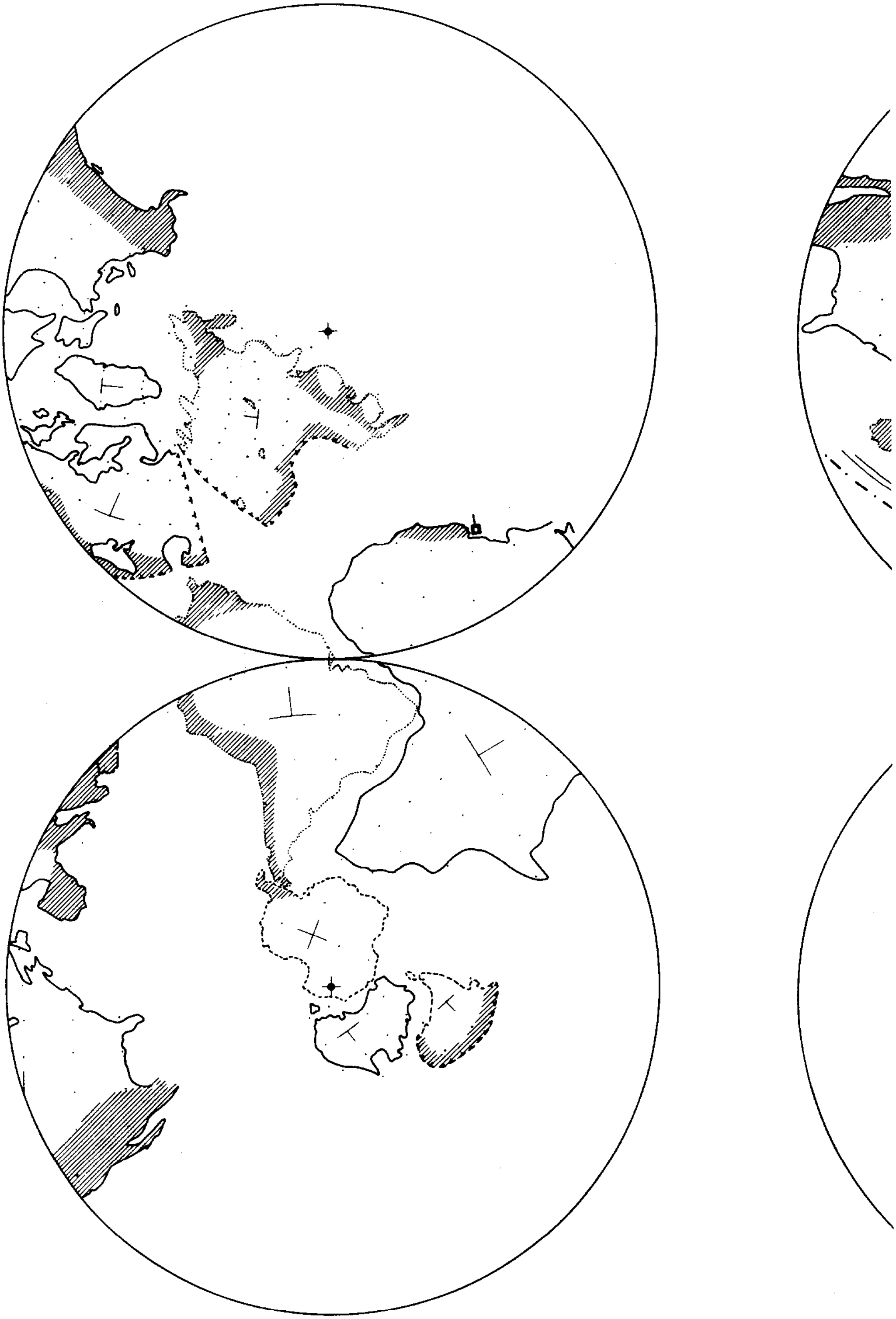
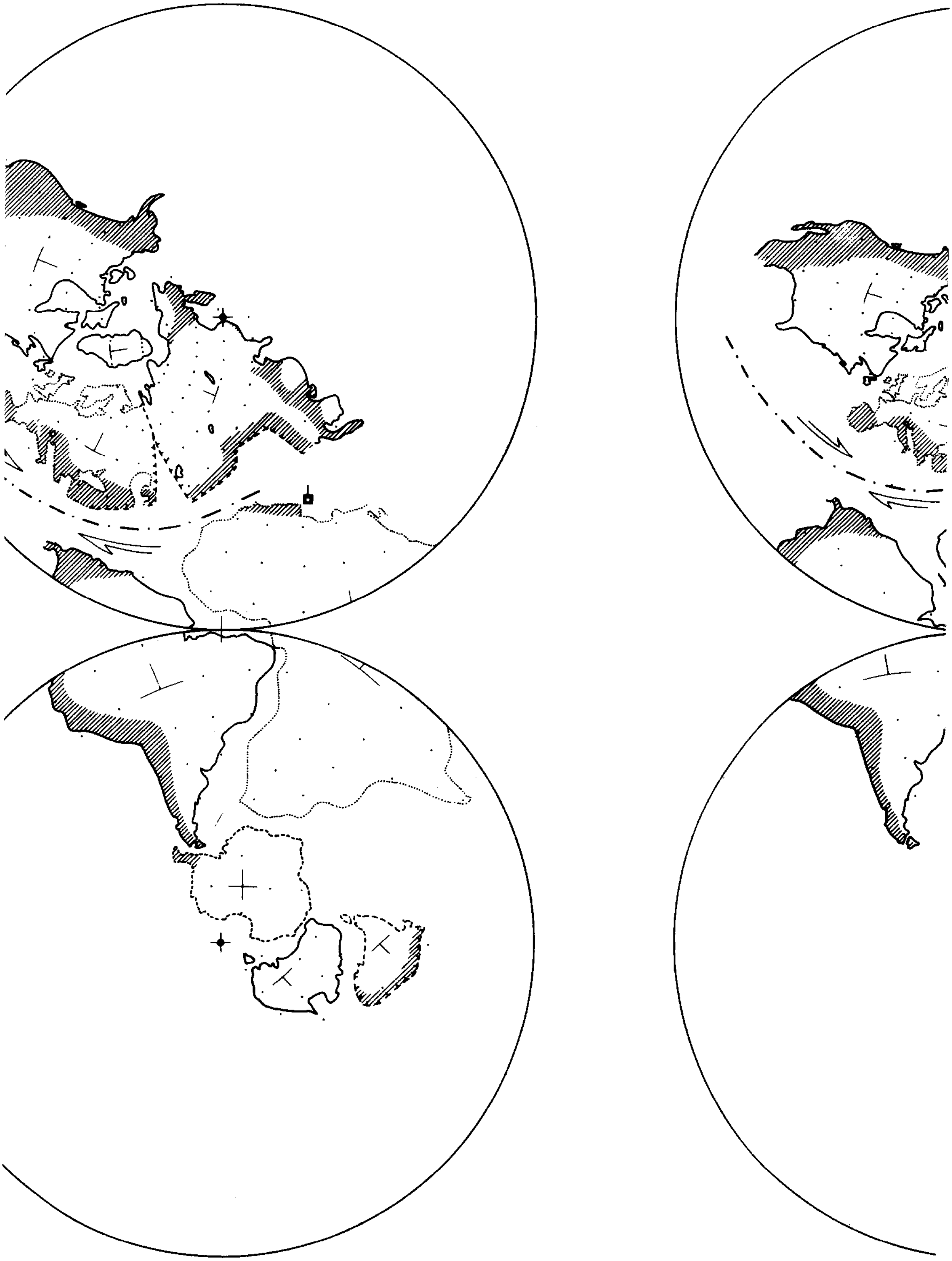


CRETACEOUS

EOCENE



PERMIAN



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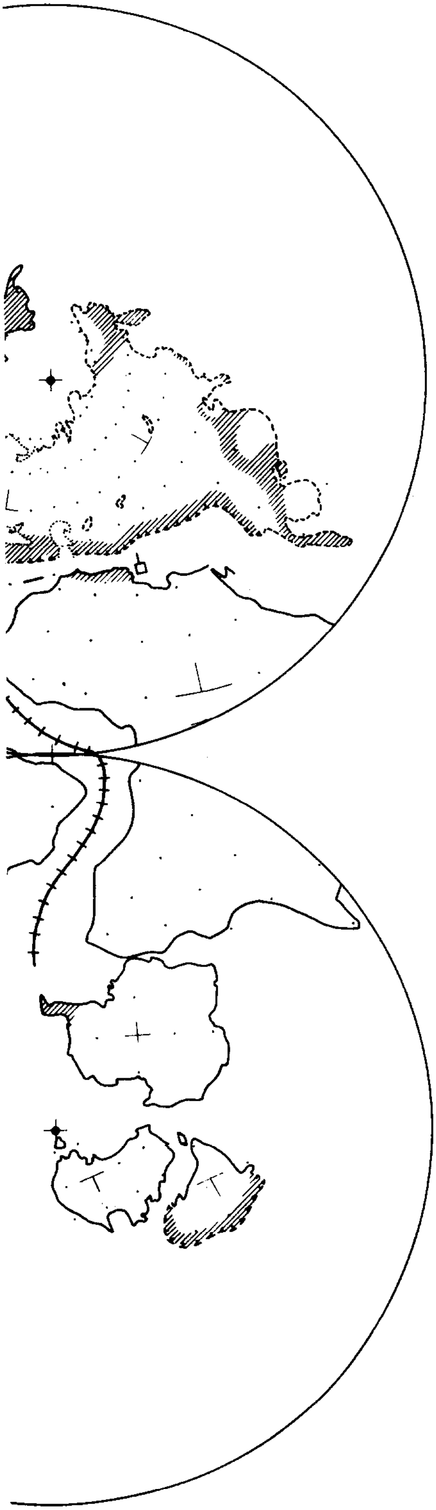

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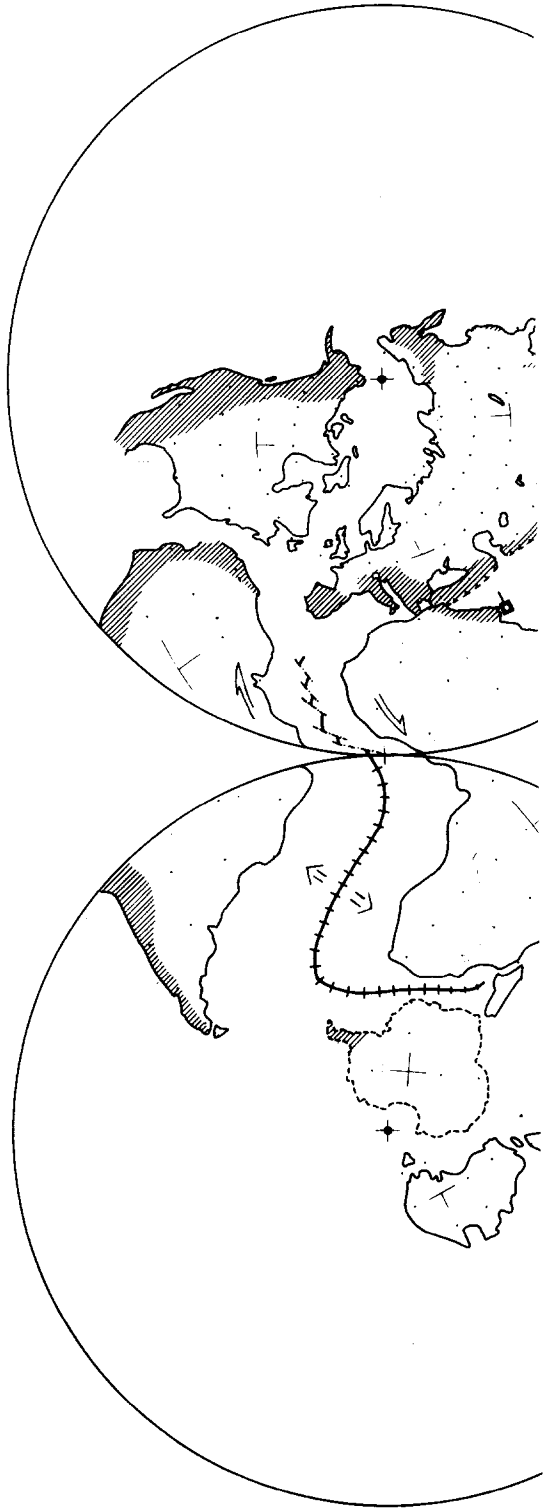


CRETACEOUS

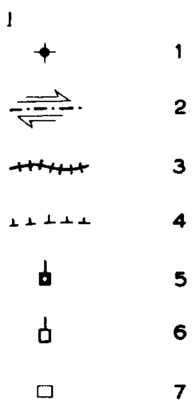
EOCENE

PRESENT - DAY

PLATE II . Reconstruction of ancient continental arrangements on basis of the paleomagnetic data and according to the principles discussed on p.37, to fit other geological and structural needs. Stereographic projection. Full drawn continental outlines = continent's position in agreement with paleomagnetic observations; dashed continental outlines = no paleomagnetic data available on which to base the continent's position; dotted continental outlines = position of continent not in agreement with paleomagnetic data (see text). Dots on continents give intersections of parallels and meridians (Greenwich) at 10° intervals. In about the centre of each continental block a mark has been placed giving the present-day north-direction; in Fig.5 these marks have been compiled, producing thus "continental wandering paths". Shaded areas on continents give the zones of later alpine tectonic movements. The continental outlines there should not be taken too strictly, because of later orogenic modelling.

In the present-day arrangement attention has been paid to some large-scale structural features: trends of alpine chains, faults and fault-zones with indications of relative displacement where known, and large rift systems.

1 = ancient geomagnetic pole in centre of projection;
2 = strike-slip fault, with relative displacement;
3 = rift, central line of mid-oceanic ridge;
4 = assumed seam along which continents have been welded together;
5 = position of alpine tectonic unit, with its present-day north-direction. according to the paleomagnetic data (southern Alps and Oregon units);
6 = like (5), but not in agreement with the paleomagnetic data ;
7 = final position in the orogene of the alpine tectonic units of (5).



Mean virtual pole positions, calculated from the data of Appendix I[1]

	Carboniferous	Permian	Triassic	Jurassic	Cretaceous	Eocene
Europe	37° 152.5°E 26 (14.7)	43° 170.5°E 29 83	52° 154°E 14 (27)	59° 110°E 8 (5.5)	77.5° 173°E 5 (23)	75° 170.5°E 13 23
North America	36.5° 131°E 6 46	38° 104°E 5 (36)	67° 90°E 12 22	85.5° 161.5°E 2 53	72° 176.5°W 5 100	82.5° 166°W 3 400
Asia	39.5° 130.5°E 8 13	41.5° 153.5°E 2	49° 144°E 9 (23)			
Greenland		38° 163°E 1	68° 160°E 1			
South Ameria		19° 50.5°E 1	81.5° 37°E 2 28	80° 126.5°W 2 200	65.5° 118.5°W 1	69.5° 107.5°E 1
Africa		58° 106°W 1	70° 39.5°W 2 13	74° 89°W 6 28	62° 101°W 1	
Australia	56.5° 25°W 1	44° 48°W 1	53° 27.5°W 2 110	47° 34°W 5 57	53.5° 31.5°W 2 130	63° 41.5°W 2 400

Antarctica			54^{O} 41^{O}E 4 120		
India			16.5^{O} 68^{O}W 2 400	30.5^{O} 87^{O}W 1	53^{O} 75.5^{O}W 1
Madagascar				66.5^{O} 163.5^{O}W 1	
Japan (NE)			68^{O} 73^{O}E		80^{O} 96^{O}W
Japan (SW)			63^{O} 130^{O}W	42^{O} 153^{O}W	81^{O} 109^{O}W
Southern Alps (Italy)	50^{O} 119^{O}W	58^{O} 112^{O}W	50^{O} 175^{O}E	64^{O} 161^{O}W	74^{O} 148^{O}W
Oregon (U.S.A.)					37^{O} 49^{O}W
East Siberia					55^{O} 172^{O}E

[1] Pole positions given by north latitude, and longitude. Below the positions follow on the left hand corner the number of observations used for the calculation, on the right hand corner the k values. When placed in brackets the distribution of the population of poles does not satisfy the conditions of the statistic model.

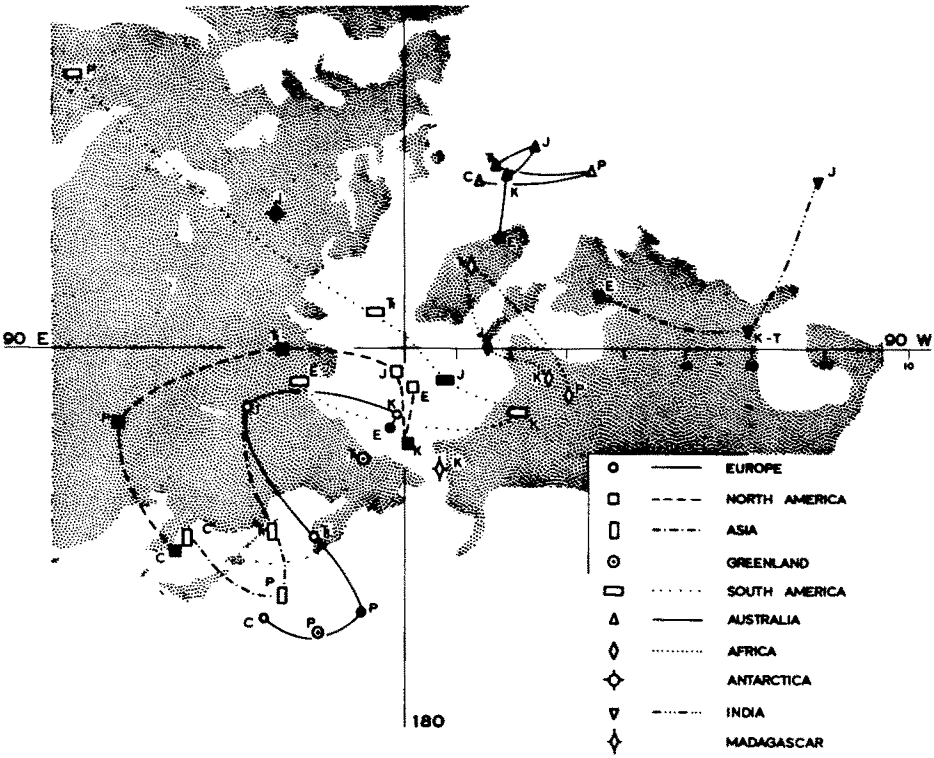


Fig.1. Mean pole positions of the continents for the various geological periods (stereographic projection). The co-ordinates of these positions are given in Table I. Full symbols represent the most reliable pole positions. C = Carboniferous; P = Permian; Tr = Triassic; J = Jurassic; K = Cretaceous; E = Eocene; T = Tertiary.

shown in Fig.2. Of the 30 poles from central and northern Europe, i.e., north of the alpine chains (see also Fig.4, where the sampling sites of these poles are shown with corresponding numbers), 29 poles form a distinct cluster about the mean position at 43° N 170.5° E. The nine poles from rocks within the alpine realm, denoted by open circles in Fig.2, are situated clearly outside this cluster, and one does not have to be a statistician to understand that the difference between Permian poles from stable Europe and alpine Europe is significant. The measurements on eight of these alpine investigations have been made in the laboratory at De Bilt, The Netherlands, under the supervision of Prof.Dr.J.Veldkamp, and it need scarcely be said that all possible tests and corrections have been applied to these measurements. Their divergence from the poles derived from stable Europe must be imputed to the only thing they have in common: their occurrence in the alpine chains. Just as continental drift is

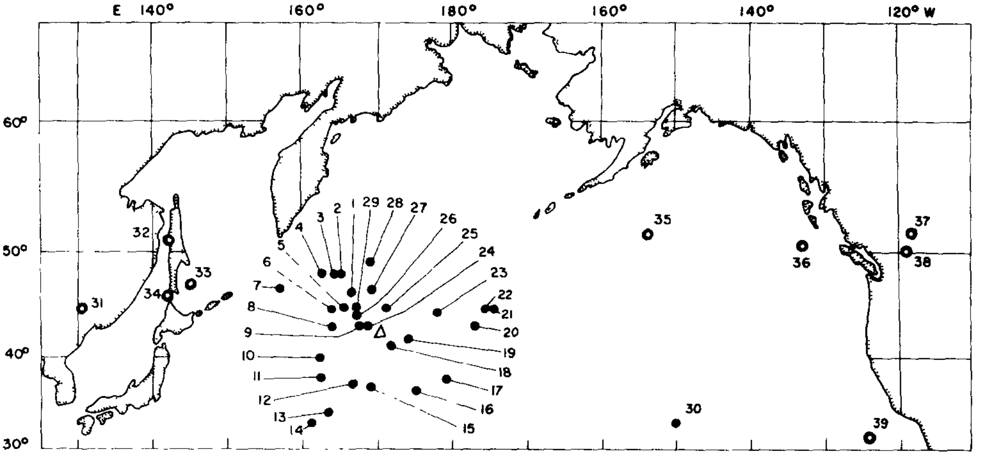


Fig.2. Permian pole positions derived from European rocks. Open circles represent poles from rocks within the alpine areas, south of the dotted border in Fig.4; these poles deviate clearly from the cluster of poles from extra-alpine stable European regions (full dots). The average position of the latter is indicated by the triangle. Numbers refer to the sites in Fig.4, and to the numbers on the right hand corners in Appendix I, under the Permian of Europe.

a logical explanation of the diverging continental poles, it has now become equally necessary to assume large-scale movements in the alpine belt during its orogenic evolution. Besides this example from the Permian of Europe, such divergent behaviour is encountered in many other instances where observations from alpine areas are available. They are shown in Fig.3, and in the lower part of Table I.

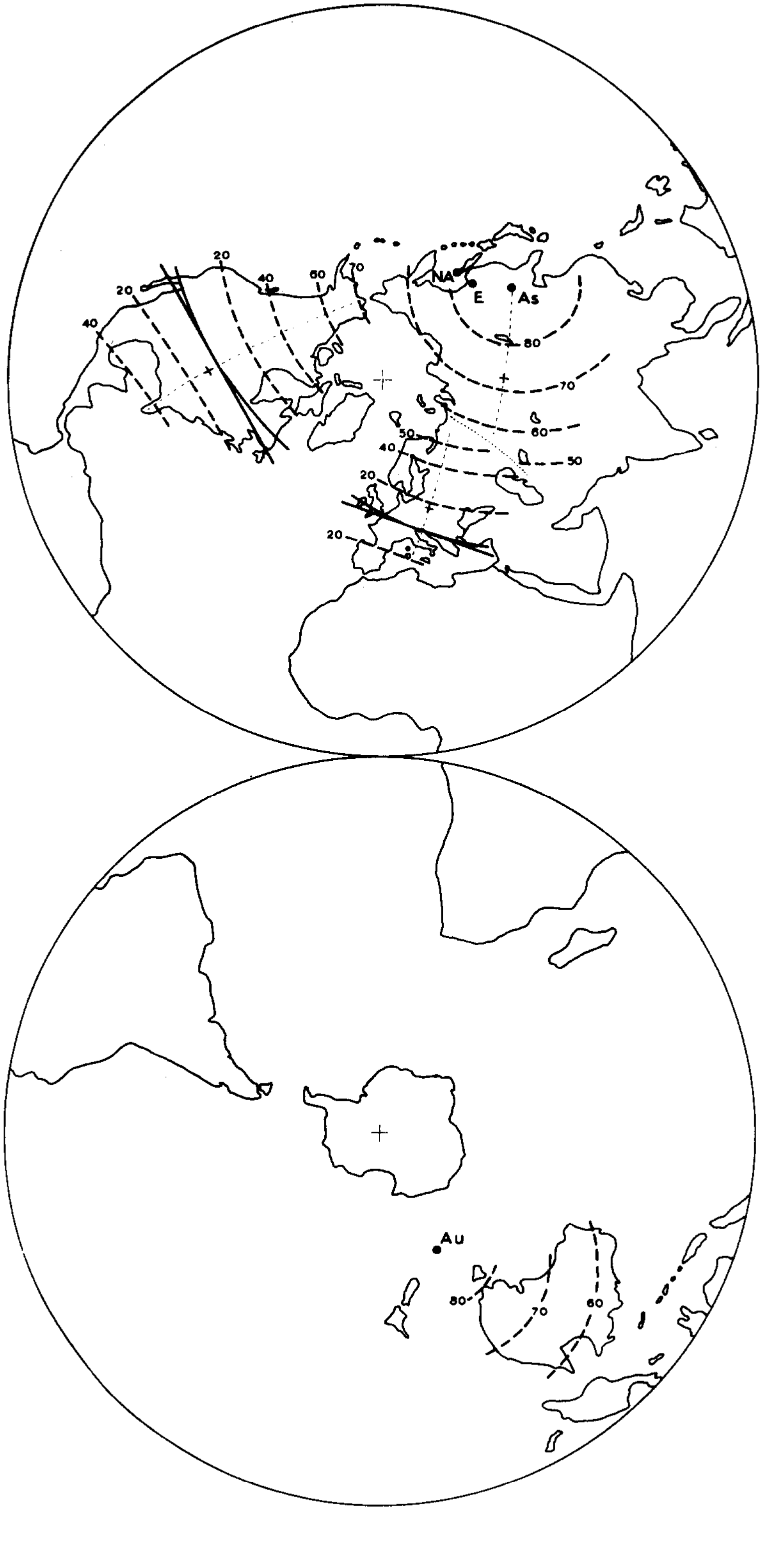
Presentation by isoclines

In order to illustrate what information paleomagnetic measurements provide about ancient continental configurations the conventional way of representing these data by virtual pole positions is extended. Instead of calculating and plotting only the mean virtual pole position (Fig.1) of a continent for a given period (the pole position is the point where the inclination of the ancient geomagnetic field was 90°), we can as well construct series of points of equal inclination (isoclines). The points where the inclination (I) was 80° will be situated on a (small) circle with the pole position in its centre; the radius p of the circle is known from the dipole formula:

$$\cot p = \tfrac{1}{2} \tan I$$

The ancient magnetic equator, the isocline where the inclination was 0°, will be formed thus by the great circle at 90° distance from the pole position.

R = 0.795 R_p

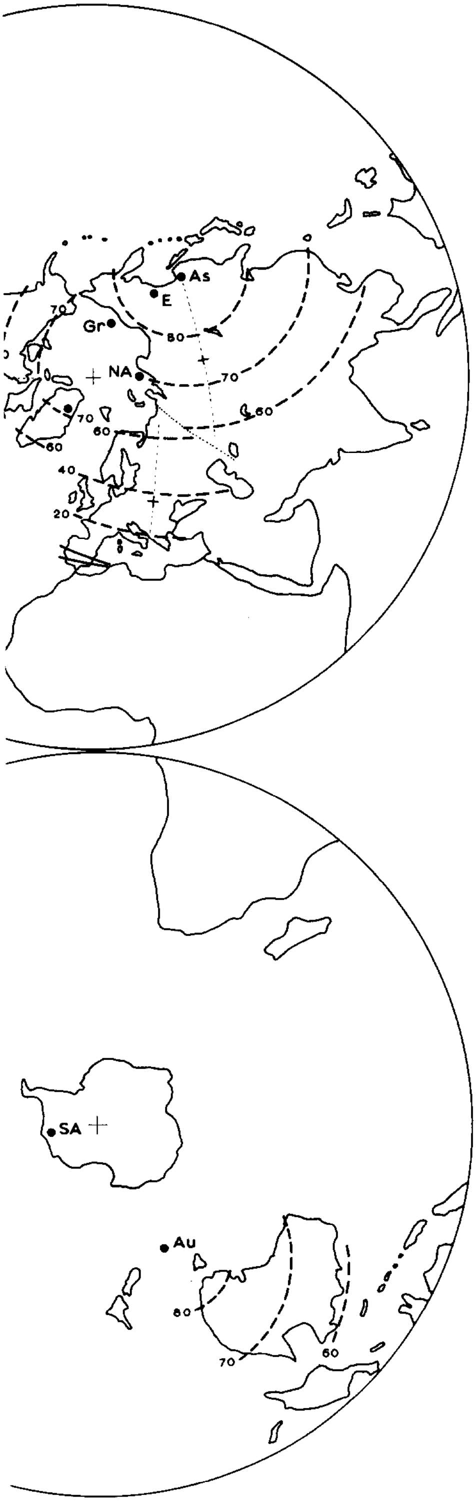


CARBONIFEROUS

$R = 0.830\ R_p$

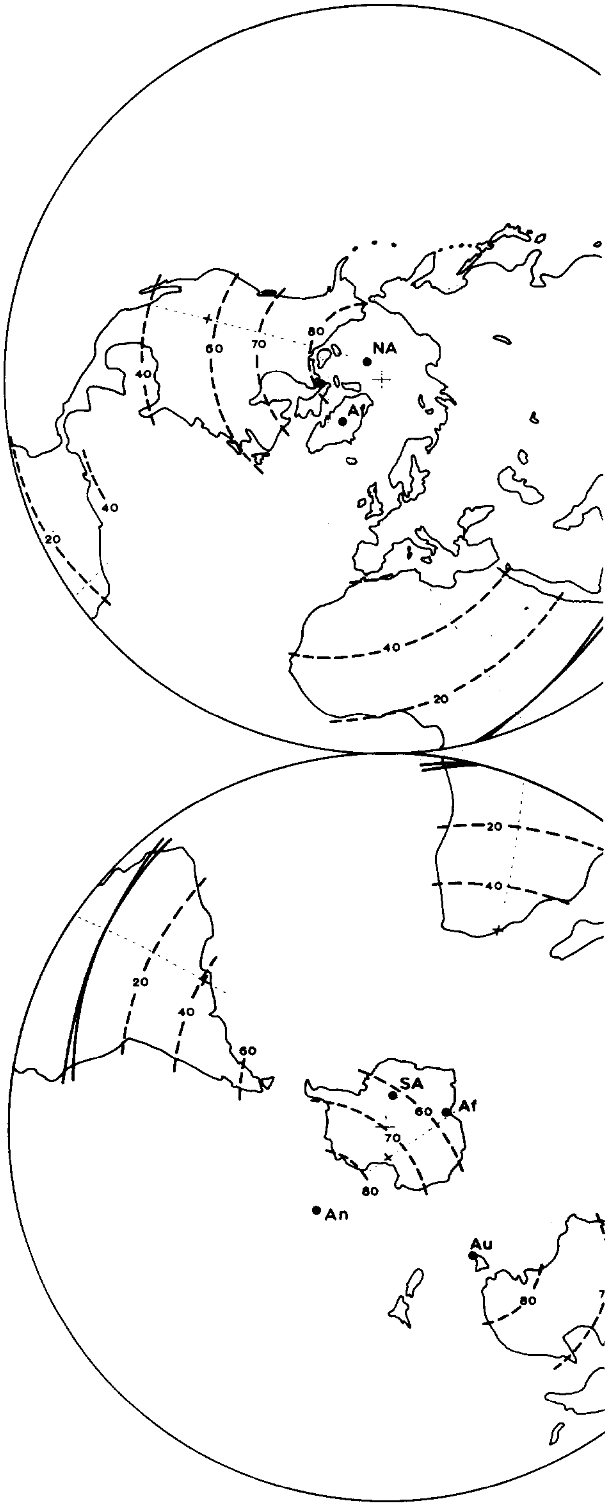
PERMIAN

R = 0.870 R_p



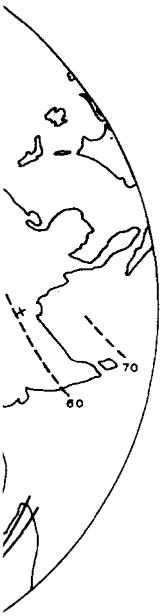
TRIASSIC

R = 0.895



JURASSIC

Rp



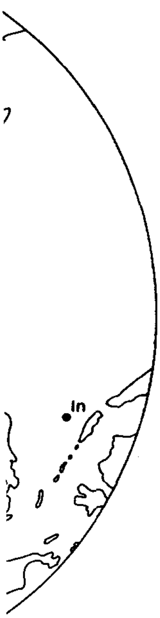


PLATE III. Carboniferous, Permian, Triassic and Jurassic paleomagnetic data, adapted to smaller earth's sizes, assuming a rate of expansion as favoured by Carey (1958), Heezen (1959), and as is indicated also by paleomagnetic data (Van Hilten, 1963b). The data are represented by pole positions and isoclines; see legend to Plate I for designation of poles. Crosses on the continents mark mean sampling positions.

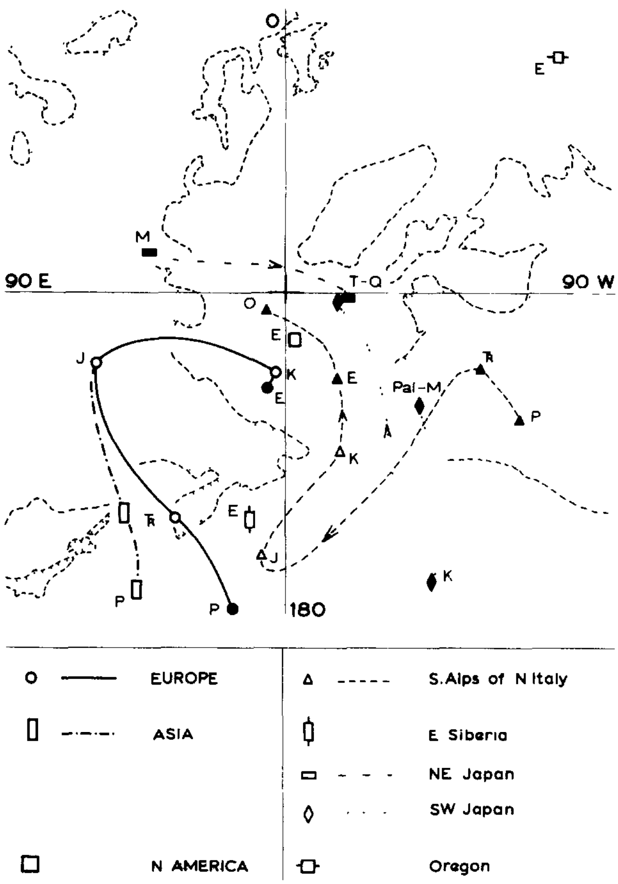


Fig.3. Pole positions from alpine regions compared with those for the stable parts of the corresponding continents, which appear to differ systematically. Pal = Paleozoic; M = Mesozoic; O = Oligocene; Q = Quaternary. Other symbols as in Fig.1.

Plate I now shows the paleomagnetic data represented by isoclines of 0°, 20°, 40°, 60°, 70°, 80°, and 90° (= pole position). These isoclines have been drawn on each continent for measurements made within its boundaries. The main advantage of this isocline method is that it enables us to see at a glance: (1) what movements of the various continents are required in order to have these conform to the ancient dipole field, and (2) what points on the coasts of different continents must have been opposite one another at the time in question. For when corresponding isoclines on two continents are brought opposite one another, so that the circle of the one forms the continuation of that of the other, the respective poles of these continents follow the movement and will come to coincide.

On the isocline maps of Plate I the reliability of the paleomagnetic data has been indicated as in Fig.1: The solid dots represent the reliable pole positions, the less well established poles are shown by open symbols. Between Europe ans Asia an artificial (stippled) boundary had to be drawn, chosen to coincide roughly with the Ural mountain chain; for it appears that the European and Asian isoclines are not in line with one another during the Carboniferous, Permian, and Triassic, which suggests that movements have taken place between these two continental blocks.

Of special interest is a feature of the geomagnetic field during the Permian. In measurements from all continents it has become apparent that during the greater part of the Permian – from late Carboniferous up till the upper-most Permian – no reversals of the geomagnetic field have occurred; Irving and Parry (1963, p.410) proposed to name this span of time the Kaiman Magnetic Interval. This property of the geomagnetic field is very welcome, because it permits us to attribute a polarity to the Permian poles and isoclines (see Plate I), from which it may be decided which continents were on the northern, and which on the southern hemisphere during this geological period.

Reviewing the harvest of paleomagnetic data, we see that Europe, North America and Australia have a fairly complete paleomagnetic record, though the reliability of the Mesozoic data from Europe may be disputed. For the remaining southern continents the Jurassic observations contrast favorably with that of the other geological periods. Data from alpine regions are still very scarce.

RECONSTRUCTING THE ANCIENT CONTINENTAL CONFIGURATIONS

Plate II shows a series of ancient continental arrangements. In all these figures the axis of rotation of the earth (= geomagnetic pole) has been placed in the centre of the stereographic projection. The reconstructions have been developed according to a well-defined program:

(1) A continent's latitudinal position and its orientation, both with respect to the ancient pole, are calculated from paleomagnetic data. The calculation is easily checked by comparing the reconstructed position with the original data, expressed in the isoclines shown in Plate II. When for a certain period no paleomagnetic data were available, the continent's position was guessed; in Plate I this is shown by dashed outlined of the continents instead of full-drawn outlines. The third method in which continental borders are depicted, by means of dots, demonstrates that the continent's position is not in agreement with the paleomagnetic observations. Such disagreement was only allowed when the reliability of the paleomagnetic data might be doubted, and when strong geologic or strucural arguments could be advanced.

(2) We are still free now to change the continent's longitudinal position, i.e., to rotate it around the ancient pole in the centre of the projection by which procedure the continent's latitude and orientation are not altered. An effort was to fit by means of such rotations the continents into one of the well-known.

(3) These assemblages were investigated to see whether they were consistent with paleomagnetic evidence in geological time, and how they could have developed towards the present-day configuration of continents,

taking into account important new geological findings like the mid-oceanic ridges, large strike-slip faults, and the paleomagnetic findings in the alpine belts and how they could have developed (Fig.5).

In the paragraphs that follow the arguments will be advanced which made me choose the arrangements of continents shown in Plate II. Because of the relative scarcity of the data of the Carboniferous, the reconstruction of continental arrangements was started with the Permian. Comparison of the Carboniferous and Permian isoclines shows that no great changes will have occurred in between. The technique of fabricating these reconstructions has been discussed earlier (Van Hilten, 1962a, p.417).

Continental drift

After the almost forgotten publication by Antonio Snider in 1858 (see Holmes, 1952, p.489) serious interest in continental movements dates from about the beginning of this century. Taylor (1910), and Wegener in 1912 (see Wegener, 1922), started from continental arrangements in late Paleozoic time which either comprised all continents in one block (Pangaea) or formed clusters of continents (Gondwanaland and Laurasia). This theme is repeated with small variations in the works of later advocates of continental drift, as for instante Du Toit(1937), Carey (1958) and Ahmad (1961).

Laurasia

At present the Laurasian block is divided into two parts by the Arctic and North Atlantic Oceans. The main arguments that these oceans had not yet opened during the early Mesozoic are provided by stratigraphical and facies resemblances between Devonian formations – many of them are freshwater deposits – in Greenland, Norway, Scotland, and the eastern United States. Carboniferous coal belts run through both North America and Europe, showing that these areas were together near the equator then. Identical, hot climates in both continents are also suggested by the late Paleozoic and Triassic evaporites. Structural evidence for the North America-Europe fit is provided by the Caledonian and Hercynian fold belts that form continuous systems when the Atlantic Ocean is closed (Carey, 1958) in contrast with the present-day situation, where the fold belts finish abruptly at both sides of the ocean. The same goes for the Great Glen Fault of Scotland and its possible continuation in America, the Cabot Fault (Wilson, 1962): both faults are of great extent, and displace the same types of rocks, and both are probably sinistral transcurrent faults, which come perfectly in line when Newfoundland and Scotland are placed next to one another in the Laurasian assembly.

The paleoclimatologic data are very definitely supported by the paleomagnetic results. For the isoclines (Plate I) on North America, Europe and Greenland show that these regions were in low latitudes (= small values of the inclination) during the Carboniferous and Permian, and that from the Triassic on their latitude increased gradually to its present-day value. In the reconstruction of Plate II the near-equatorial positions of these continents during the Permian is seen again. In regard to the longitudes of the

Laurasian group, a neat block can be made of North America, Europe, Asia, and Greenland which accords well with the ideas mentioned above; the Arctic and North Atlantic Oceans are closed so that the opposed continental shelves almost touch one another, the Caledonian and Hercynian mountain chains form continuous belts, and the Great Glen and Cabot Faults have been brought in line. Still more important is the fact that the paleomagnetic data allow this Laurasian block to stay coherent until the Cretaceous time, so that its continents move together up to their present latitudes, where they start drifting apart in Tertiary time. In its broad outlines this development seems clear, some deficiences in detail should, however, be mentioned: the reconstructions show that the Triassic and Jurassic positions of Europe are inconsistent with the paleomagnetic data (dotted outlines). The reason why these deviations have been allowed is one of simple logic. During the Permian, Cretaceous and Eocene – for the first of which we have one of the most reliable determinations ever made for a continent (see k value in Table I) – the reconstruction of the northern continents in conformity with the geological evidence is easily carried out. Strict application of the less reliable Triassic and Jurassic measurements of Europe would suggest that during these periods Europe performed some individual movements and returned to its place in the system again in the Cretaceous. Such improbable excursions are avoided by small adjustments for the sake of the long-term scheme as a whole; I am fully aware that such manipulations introduce a subjective element into the reconstructions.

Another feature of the Permian reconstruction deserves attention: between Europe and the Siberian block a wide gap is shown, for the existence of which there is no geological evidence. I had long been puzzled by this enormous rift, until quite recently a solution suggested itself. As will be demonstrated below, this rift disappears completely, and Europe and Siberia can be fitted very well together (see Fig.8) when it is assumed that the Permian earth's radius was appreciably smaller than the present one ($R_{\text{Permian}} = 0.830\ R_{\text{present}}$). This value is in agreement with the rate of growth advocated by Carey (1958) and by Heezen (1959), and with other paleomagnetic evidence for an expanding earth (Van Hilten, 1964b).

Gondwanaland

In the southern hemisphere it is possible to reconstruct Gondwanaland. Many authors have brought in evidence for the existence of such a continental block near the ancient South Pole, composed of South America, Africa, Madagascar, Antarctica, Australia, and India. But the number of different ways in which these continents have been fitted together is even greater. The facts to be explained are well-known: the late Paleozoic glaciation, the traces of which (tillites, striated pavements) have been found in South Amerika, Africa, Australia, and India, the glacial striations indicating movement of glaciers from the present oceans land-inward; the remarkable similarities in flora, fauna, and in development of formations, between the different blocks; structural resemblances, and finally the famous parallism of the opposing coasts of South America and Africa. A comprehensive review of the various arguments is given in the work of

Ahmad (1961), to which the reader is referred for further information.

With the continents in their present positions these observations are wellnigh incomprehensible, and the obvious solution is to suggest that these southern continents once formed one continuous mass which started splitting up into its present parts during the Mesozoic. The difficulty now seems to be how this former Gondwanaland should be reassembled, for each author shows different fits of the continents. General agreement, however, exists on the arrangement of South America and Africa; their almost perfect fit was demonstrated by Carey (1958, fig.21, p.223) and was recently checked by means of a computer (Bullard, 1964). Geological and structural resemblances between these continents are reported by Maack (1960) and Pflug (1963).

Also the side by side positions of northwestern Australia and eastern India up till Tertiary time look fairly well established (Ahmad, 1960, 1961). But different views are held on the relative positions of these two ancient blocks (South America-Africa and India-Australia) and in particular on the position of Antarctica in this former Gondwana-continent. This is understandable as the geologic information on Antarctica is still very scanty. A devision into an Andean-province, between the 50° W and 180° meridians, and a Gondwana-province, formed by the rest of the continent seems clear (Doumani and Long, 1962; Adie, 1962), but it leaves a wide range for speculations as to how precisely this Gondwana-province was fixed to the other continents. Even the position of Madagascar appears not to be as sure as it was formerly believed to be.

The paleomagnetic record from the continents of the southern hemisphere is less complete and convincing than that of the northern continents, though an exception should be made for Australia, where a series of trustworthy observations has been made. Furthermore, the Jurassic measurements look reliable for all the continents; they have been made on the basic extrusives and dykes of this age, which are found on all continents belonging to the former Gondwanaland. One might readyly suppose that this widespread basic volcanism is somehow related to the breaking-open along rifts of this former continent.

The reconstructions of Plate II show that the southern continents can also be reassembled into a Gondwana configuration on the basis of their paleomagnetic history. A key-position is attributed to the Jurassic reconstruction, because of its greater reliability; for Antarctica this is the only period for which data are available, and for India the earliest data are of Jurassic age. One of the noteworthy features of this reconstruction is that Australia and India can be put in the desired side by side position through the Jurassic up till late Cretaceous time, after which India moves away to its present-day position on the northern hemisphere. This fact has been used as a justification for the Permian position of India next to Australia, where it belongs also according to the geologic data mentioned before.

As to the South America-Africa fit, pre-Jurassic paleomagnetic data from these continents are few. There is a reliable Permian measurement from Africa which has been treated with AC-fields (Nairn, 1963 and 1964), but the Permian measurements from South America are very scattered. For the Triassic the South American data look better than the African ones.

Using only the more reliable observations for the Permian and Triassic reconstructions – and fitting the two continents in the well-known closest position (Carey, 1958, fig.21) – South America and Africa drift quietly together, developing gradually towards the better founded Jurassic situation, where they start moving apart. This quiescence on the southern hemisphere is also strongly suggested by the stable position of Australia near the South Pole from the Permian up to Cretaceous time.

As compared with other reconstructions of Gondwanaland, the position of Antarctica in the present reconstruction is slightly unusual, because most authors have Antarctica in a more northerly position off the east coast of Africa; their views are not substantiated by the Jurassic Paleomagnetic evidence.

We have seen that two primitive continental blocks can be reconstructed in conformity with the paleomagnetic and geological evidence available. It is emphasized that it is not possible to collect all continents into single assemblage, usually called Pangaea; anyway not in the arrangement proposed originally by Wegener, in which North America and Europe are the northern neighbours of South America and Africa respectively. The paleomagnetic data do not allow such a arrangement during the late Paleozoic and early Mesozoic, because they indicate that large parts of North America and Europe were in the southern hemisphere during the Permian, while a good deal of Africa and South America were situated on the northern hemisphere. The only way to avoid superposition of continents is to assume extensive twisting of the two blocks as depicted in the reconstructions. A similar shear movement has recently been suggested on structural grounds by Pavoni (1962) and De Boer (1963,1964). In a later paragraph on orogenesis the rotational movements of the two blocks will be discussed more elaboratory, and it will be shown that the irreality is more likely than might be suspected at first sight.

Taking a good look at the two Permian continental masses – Laurasia and Gondwanaland – we observe that they both are bordered by the future alpine chains, the shaded areas on the reconstructions. This means that the Permian, Mesozoic, and part of the Tertiary formations which now make up these chains, must have been deposited at continental borders, so illustrating beautifully the theories on continental accretion. In this connection the recent paper by Dietz (1963) on sedimentation on the continental shelf and margin is most interesting. Laurasia is almost completely encircled by shaded zones, around Gondwanaland the situation is less clear. It should be remembered however, that large, mostly alpine, regions have been omitted from the reconstructions: for instance, the Caribbean and Middle American areas, Arabia and other Middle-East territories, most of the Indonesian archipelo, New Zealand, and so on. These should all be fitted in somewhere around our continents, perhaps making thus the circum-continental sedimentation picture complete. All guesses on their positions seem rather premature to me because of the complicated character of the paleomagnetic observations made up till now in the Alps, which seem to predict the most unexpected displacements of the tectonic units (see paragraph on orogenesis).

The mid-oceanic ridges

From the recent thorough investigations of ocean bottom topography it has become clear that a first order feature of the earth's crustal structure has been traced in the world-encircling system of oceanic ridges (Heezen, 1960, 1962; Heezen and Ewing, 1960, 1063; Heezen et al. 1959, 1961, 1964; Krishnan, 1960; Wilson, 1963a, 1963b). For most part the ridges lie just halfway between the adjoining continents. Their tensional, actively volcanic, character; their coincidence with the well-known row of earthquake epicentres of shallow depth, together with the measurement on them of higher heat-flow values than anywhere on the globe, are all best explained by regarding these mid-oceanic ridges as the lines from which the drifting continents have moved apart, and where possibly the oceanic crust has been renewed continuously since. Of special interest is that the age of the oceanic volcanic islands increases with their distance from the ridge (Wilson, 1963a, 1963b). An analoguous feature has been suggested in Iceland by Bodvarsson and Walker (1964); they find a steady widening by dyke injection of this island, situated on the Mid Atlantic Ridge, during Tertiary and Quaternary time. They estimate the present rate of this Icelandic rifting process at some 0.3-0.6 cm/year, which is in good agreement with the findings of Bernaver (1943). For the purpose of this paper the important thing is that when placed in our reconstructions, the mid-oceanic rifts fit well between the continental blocks, showing that the formation of mid-oceanic rifts by the drifting-apart of the continents is in agreement with paleomagnetic observations.

The rifting process seems to have started between South America and Africa during the Jurassic, and to have extended in two directions. If this is correct, it means that the ends of the ridges in the Arctic Ocean, the Red Sea, and the Gulf of California form the youngest branches of the ridge system. In the last case, this assumption is supported by the present geological activity of that region.

The fracture zones in the equatorial part of the Mid-Atlantic Ridge between South America and Africa (Heezen et al.,1961, 1964) seem to be a logic result of the prolonged drifting apart of these two continents during the Cretaceous: on the N-S trending branch of the ridge, in the southern hemisphere, the stresses were purely tensional (see arrows in Cretaceous reconstruction), but where the ridge is running more in an E-W direction in the equatorial zone, shearing movements seem to prevail.

Our knowledge of the development of the ridge system in the Indian Ocean and in the southern Pacific is rather poor because paleomagnetic data from Antarctica are scarce and because of the complexity of structure and probable movement pattern at the northeastern border of the Indian Ocean: the only thing we know is that India has been moving there with the highest velocity ever met in continental drift.

The search for a mechanism behind continental drift and the mid-oceanic rifting – convection currents and/or global expansion – is still extremely controversial.

The alpine orogeny

It has been shown (p.5; Fig.2,3) that all paleomagnetic measurements from rocks in alpine regions deviate *systematically* from contemporaneous data obtained from the stable part of the same continent. This inevitably leads to the conclusion that the tectonic units of the orogene must have performed large-scale movements with respect to the continent to which they belong now.

The possibility of fairly large displacements has been recognized since long ago when the overthrusting of the alpine nappes was first generally accepted. Of more recent date is the detection of enormous strike-slip faults of great length, running almost parallel to the trends of the alpine orogenic system. Good examples of such faults are found in the San Andreas Fault of North America.

As these lines are written, paleomagnetic evidence seems to be swinging the balance to the side of global expansion (see paragraph on global expansion). In relation to possible mechanisms the recent calculations made by Collette (1964) on the estimated maximal depth of the source of the increased heat-flow on the mid-oceanic ridges are of great interest. Starting from the relatively narrow zone in which this heat-flow is anomalously high, he finds that the maximal depth of a point-like source for this heat-flow cannot exeed a depth of some 35 km; his calculation is rather similar to that in which the depth of a body with high specic gravity is deduced from the shape and width of the gravity anomaly measured at the earth's surface. Such a shallow depth agrees well with the newly expressed ideas of intrusive dykes near the centre of the oceanic ridges (Bodvarsson and Walker, 1964), but it can hardly be reconciled with the picture we associate with convection currents, which postulate a rising current of hot material that branches off into two streams parallel to the earth's surface, along which they are cooled off gradually. The process of dyke intrusions, however, might be regarded as the mechanism by which the earth's crust is enlarged during global expansion. The recent discovery of magnetic anomalies trending parallel to the mid-oceanic rifts (Vine and Matthews, 1963) seems to support this view: these anomalies might be regarded as reflections of the reversals of the earth's magnetic field, fossilized in the various intruded dykes on the ridge, and transported progressively outwards during the expansion of North Africa (Rod, 1962, in Europe's Vardar zone (Brunn et al., 1963), in Anatolia (Pavoni, 1961; Ashgirei, 1962), in Iran (Huckriede et al., 1962), in Sumatra (Durham, 1940), in the Philippines (Allen, 1962) and in New Zealand (Kingma, 1959). The relative displacements along these faults have been indicated on the present-day tectonic map of Plate II. It is seen that for many of these faults, viz. those of South America, North Africa, Europa, Anatolia, Iran, and Sumatra, the relative displacements agree with that of the dextral shearing movement between Laurasia and Gondwanaland. Also in the Appalachians a dextral transcurrent fault has been reported (Woodward, 1964) which might be correlated with this shear-system.

The zone in which this shearing occurred is formed by a belt of alpine chains in America, between Africa and Europe, and in southern Asia, and it is a special feature of this belt that in many places its trends are laid in garland-like curves of various dimensions. In central America we observe the wide bend formed by the Caribbean and Antillean orogene, in northern Africa and Europe such distinct festoons are found in the Riff chain (Gibraltar), in the western Alps (eastern France), in Rumania and Bulgaria, in southern Italy and Sicily. Similar arcs are beautifully developed in the Indonesian archipelago. Such garland structure of the alpine belts have been called oroclines (bent mountain-chains) by Carey (1958). Though this primary structure must have struck any student of the Alps, an explanation for it had never been advanced until Carey proposed his orocline-concept in 1958. His idea is that the mobile, newly deposited formations at the edges of the continents have been crumples up into such festoons by the wrenching of Laurasian and Gondwanian masses in what he called the Tethys megashear system. The only difference with the present reconstruction is that Carey assumes the wrenching mechanism to be sinistral, which seems to be contradicted by the dextral character of – partly new discovered – strike-slip faults in this megashear zone.

The paleomagnetic data from the European alpine regions

Fig.4 shows a detailed Permian isocline map of Europe on which the various sampling sites have been plotted, together with the paleomagnetic results derived from them. The directions of magnetization are presented by their declination (direction of arrows) and by the amount and sign of inclination in degrees. The 39 sites have been numbered (in circles) and these numbers correspond with the European Permian poles shown in Fig.2; in this latter figure the deviation of the poles derived from rocks in the alpine region (open circles) from the distinct cluster of poles from the extra-alpine rocks is clearly seen. Around the mean pole position of this cluster have been constructed the isoclines of Fig.4, and, as is to be expected, these isoclines are in accordance with the magnetic measurements at each site of extra-alpine Europe: their declinations point towards the pole position and are therefore perpendicular to the circular isoclines about this pole position, the inclinations correspond with the interpolated values between successive isoclines. The deviation of the alpine measurements can be judged by the obliqueness of their arrows to the isoclines and by the divergence from these latter of their inclination values. The advantage of this isocline map is that it enables us to estimate what displacement operations should be performed with any tectonic unit to have it fit the Permian geomagnetic field of Europe, or, in other words, what positions the various units may have had with respect to the stable part of the European continent before the alpine orogenic movements started. This might ultimately give us a better understanding of these movements proper and of the alpine orogenesis.

From paleomagnetic measurements in north Italy, carried out on volcanic and sedimentary rocks of the south-alpine tectonic unit (De Boer, 1963; Van Hilten, 1962b), it can be inferred that this unit has undergone a counter-blockwise rotation of some 50°, or a clockwise one over 310° since Permian time, as the declination of the direction of magnetization there makes an angle of about 50° with the normal to the isoclines. The inclination of -31° tells us that the south-alpine unit was situated at a

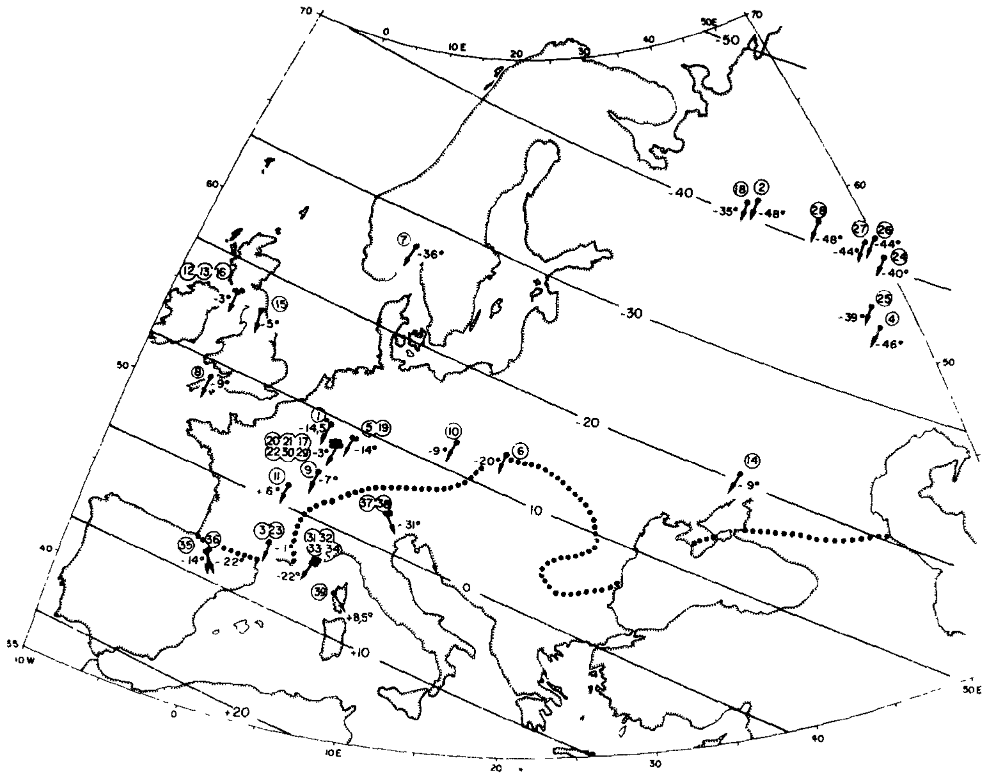


Fig.4. Permian directions of magnetization in Europe. Arrows give directions of declination; inclinations in degrees. Numbers of sampling sites (encircled) refer to corresponding pole positions in Fig.2, and to the numbers on the right hand corner in Appendix I, under Permian of Europe. Isoclines have been drawn based on the average pole position 170.5°E 43°N (triangle in Fig.2) of the poles from the extra-alpine stable part of Europe. Dotted line represents the northern boundary of the alpine chains.

The directions of magnetization of extra-alpine Europe are in agreement with the pattern of isoclines: the arrows are perpendicular to them, the inclinations correspond with the interpolated values between successive isoclines.

The directions of magnetization from the alpine regions show considerable deflections from the pattern of isoclines.

latitude where the inclination had this value; in Europe this value is found on the Baltic Shield and in the Moscow Basin, where the – interpolated – -31° isocline passes. In earlier papers (Van Hilten, 1960 and 1962b) I suggested that the south alpine measurements might represent a reversal of the (reversed!) Permian magnetic field, by which reasoning the +31° isocline, running south of Europe, may be envisaged also: a southern origin of this unit is not a geological impossibility and is even advocated by most alpine tectonists. However, the more elaborate paleomagnetic study of De Boer (1963) in this south alpine region demonstrated that this negative inclination persists from the lower up till the uppermost Permian and represents apparently the Kaiman Magnetic Interval (Irving and Parry, 1963; see also p.39),so that the unit's position on the $+31^{\circ}$ most be kept out of consideration. De Boer (1963, p.165; 1964) justly states that the original Permian position of the south-alpine unit must be sought where the -31° isocline intersects the Tethys belt, this being the only zone where post-Permian movements have taken place. As can be seen from Plate I this intersection was situated about where we find the Himalayas now, implying that the south-alpine unit must have travelled over at least 4,800 km from the site of deposition towards its present location.

Similar deviating magnetizations are seen (Fig.4) in the Permian volcanic series of the Estérel in southern France, meticulously investigated by Zijderveld (in prep.), and in the Permian rocks of the Spanish Pyrenees (Van der Lingen, 1960; Schwarz, 1963a, 1963b). In the Estérel measurements especially the inclination of -22° diverges strongly from the value to be expected between the 0° and 10° isoclines, in the Pyrenees both declination and inclination are in disagreement with the pattern of isoclines. In both instances similar lines of reasoning may be followed as in the case of the south-alpine tectonic unit, because here too the inclinations counsel us to seek Permian sites of deposition in easterly directions, where the -22° and -18° isoclines cross the Tethyan belt (see also De Boer, 1964).

As is shown in Fig.2, De Boer extended his investigations also to younger formations of the same south-alpine tectonic unit, by which its complete paleomagnetic history became known from the Permian onwards. In Plate II an attempt has been made to insert this tectonic unit in the reconstruction according to its paleomagnetic record, and a very surprising fact can be observed now: the southern Alps can be attached to the African continent from the Permian on, keeping perfectly their position and orientation with respect to this continent during all the Mesozoic, to be wiped off finally in Tertiary times when Africa and Europe sheared vigorously along one another. In Plate II the successive positions of the southern Alps are depicted by a square symbol to which a "tail" has been attached which denotes the present-day north direction of the unit; this enables us to see that rotary movements have been performed by the tectonic block. The most striking thing of this particular position on the northern edge of Africa is that Carey (1958, p.253, fig.31b) favours exactly the same po-

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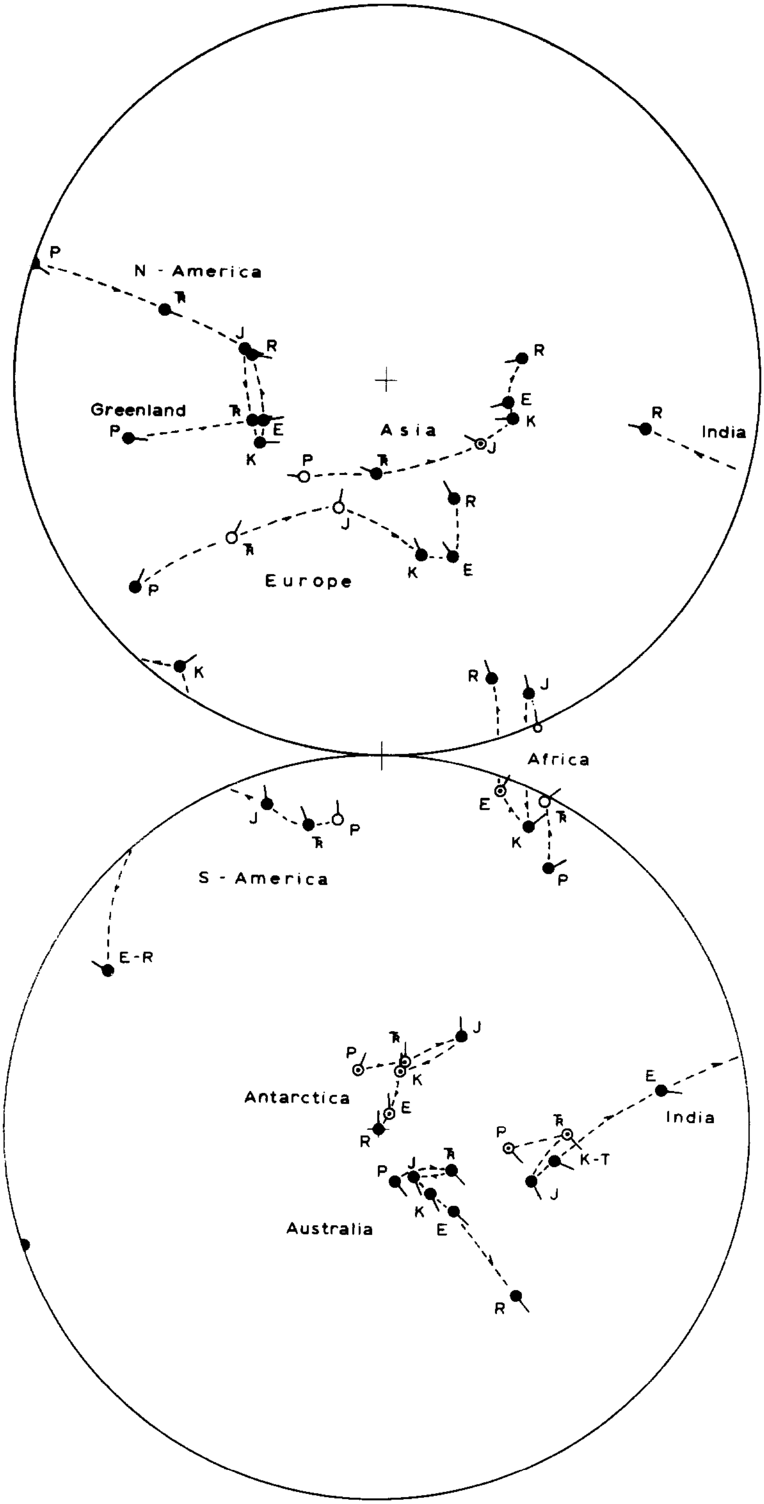
Fig.5. Continental wandering paths compiled from the reconstructions given in Plate II. The movements of the centres of the continents are shown; the "tails" attached to the circles give the orientation of the present-day north direction on each continent. R = present-day position; other letters as in Fig.1. ● = Position of continent in agreement with paleomagnetic observations; ʘ = no paleomagnetic data available; O = position of continent not in agreement with paleomagnetic evidence.


N - America
Greenland
Asia
India
Europe
Africa
S - America
Antarctica
India
Australia
E-R
K-T

sition too for his Dinaric Alps, of which the southern Alps form the immediate neighbours now. Carey's arguments however are of a completely different character, as he starts from tectonical grounds and from analogies of sedimentation and facies.

Our knowledge of the paleomagnetic history of the Pyrenees and the Estérel is limited to the Permian, but as their problem seems analogous to that of the southern Alps it might be assumed pro tempore that these units too belonged once to Africa (see De Boer, 1964); however, their positions have not been indicated in the present reconstructions.

The Tethys Twist. In the following lines a brief recapitulation will be given of the various observations and arguments which led me to the rather unorthodox but simple picture of two continental blocks – Gondwanaland and Laurasia – shearing along one another in a dextral strike-slip movement which I propose to name the *Tethys Twist.* By itself each individual fact provides but a meagre argument for such unorthodoxy; taken together, however, they can be united in a mechanically comprehensible picture supported by a considerable weight of circumstancial evidence: Gathering all the continents into two separate blocks (Laurasia and Gondwanaland) rather than in a single Pangaea, appeared necessary to prevent superposition of parts of these continental blocks, which would otherwise have occurred in Permian and early Mesozoic time, according to the paleomagnetic evidence. The clockwise character of the shearing between these blocks is evidenced by the many dextral strike-slip faults found in the Tethys shear zone, and by the dextral movement with respect to Europe of several alpine tectonic units through this same shear zone. This wrenching movement provides the only mechanism that might have produced the twisting of the alpine chains into the well-known garlands, so characteristic of this Tethys zone. The paleomagnetic record of the south-alpine tectonic unit allows that it formed part of Africa up till Eocene time; this position coincides with the one favoured by Carey upon tectonical grounds and facies analogies.

The paleomagnetic data from other alpine regions

North America. In the Rocky Mountains (Oregon) Cox (1957) observed a remarkable deviating magnetization of Eocene age; there is no reason to doubt its reliability. Attempting a reconstruction along lines similar to these developed for Europe, we find as the only sensible solution that the sampling area was somewhere near Los Angeles at the time of deposition, about 1,500 km south of its present-day position (see Plate II, reconstruction of Eocene age). Since the Eocene the tectonic unit to which it belongs would have travelled roughly parallel to the orogenic trends over this distance, probably facilitated by dextral transcurrent faults. The dextral San Andreas fault (Crowell, 1962) may have played an important part in this transport; on structural grounds Hamilton (1961) estimates the displacement along this fault alone at some 500 km, and the presence of more dextral parallel strike-slip faults farther inland has been demonstrated (Nielsen, 1962). According to Carey (1958, fig.5b, p.337) and Wise (1963) the structural pattern of the western part of the United States is best explained by a dextral shear system acting on the entire region.

Japan. Kawai et al. (1961) deduced from the declinations of the directions of magnetization of pre-Tertiary Japanese rocks that the main island Honshu should be divided into a northeastern and a southwestern part, probably separated by the geologically well-defined zone, known as the *fossa magna*. They showed that in pre-Tertiary time these parts must have been in line with one another, instead of in the knee-like bend of 40° they form now. From the inclinations it can be seen that neither part was off the same point of Asia as it is today: the values of the inclination are too small to fit the Asian isoclines of the late Paleozoic and the Mesozoic, suggesting that Japan was nearer to the equator then. Probably during the late Mesozoic and the Tertiary Japan moved northward, a trace of the movement being found perhaps in the sinistral strike-slip fault passing through the Philippines. The dating of the Japanese magnetizations is rather poor, so that I prefer to describe the phenomenon qualitatively rather than plot it in the reconstructions.

What has been said here on the alpine orogeny should, of course, be regarded as speculative and very preliminary, because the number of paleomagnetic observations in alpine regions is so limited yet, compared with the extent and complexity of the Alps. The majority of the measurements mentioned however are reliable, and it is clear therefore that enormous displacements in the mobile belts have occurred. In the alpine chains in southern and southeastern Europe an intensive paleomagnetic investigation has been started already, but it is feared that we may still wait many years for conclusive evidence from southeastern and eastern Asia. And paleomagnetism is perhaps the only means of unravelling the alpine knots.

One might wonder why the enormous strike-slip phenomena in the alpine chains as suggested here have not been discovered more generally, as for instance by Pavoni (1961) and by Ashgirei (1962). This might be due to the rather qualitative character of the geological evidence, as for instance differences in facies between two tectonic units; these differences, though fundamental to discrimination between tectonic units, do not usually supply information about the distance between units during their deposition. In the European Alps much of the structural evidence for the supposed large strike-slip displacements has probably been buried by the final orogenic movements: the uplift of the central alpine axis and the gravitative reactions of downsliding sedimentary slabs and nappes, which cover now extensive parts of the alpine area.

On the floors of the oceans we should expect to find also traces of, for instance, the enormous shear zone of the Tethys Twist indicated in the Triassic and Jurassic reconstructions of Plate II. This zone should have extended all around the globe, since two hemispheres are supposed to have twisted along it. In the Pacific Ocean indeed a number of tremendous fault-traces have been suggested by Menard (1959), Menard and Fischer (1958), and Mason and Raff (1961). Some of these fracture zones have been indicated in the present-day map of Plate II, together with their relative displacements when known. The Clarion and Clipperton fracture zones (in particular the two southernmost faults) agree fairly well with the direction of the faultzone postulated in the reconstructions. But also in the central and western part of the Pacific Ocean numerous lineations are discernable, of which it has been proposed that they might represent major faults in the earth's crust (Heezen, 1962).

In the Atlantic Ocean however, no traces of such an E-W trending faultzone can be found near the 30°N latitude (cf. Heezen et al., 1959). On second thoughts this is not surprising, because the shearing movement between Laurasia and Gondwanaland seems to have finished (Upper Cretaceous?) when the neo-formation of the Atlantic Ocean was about to begin. This implies that the bottom of the Atlantic Ocean did not witness the shearing movement and therefore cannot bear any traces of it. Drake et al. (1963) report an E-W trending dextral strike-slip fault on 40°N latitude off the east coast of North America; it borders the northern side of the Bermuda Rise, and it is shown in fig.2 of the contribution by Dr. Engelen, in this issue (pp.85-93). Except its latitudinal position this fault displays all characteristica of the Tethys Twist and it might be regarded as an auxiliary fault accompanying the main shear movement.

Global expansion

Some geotectonists think that global expansion has played an important part in determining the present face of the earth. Well-known advocates of this theory are – in order of rate of expansion proposed by them – Hilgenberg (1933, 1962), Carey (1958), Heezen (1959), and Egyed (1963a). Tectonic arguments have been advanced by Carey. Heezen thinks that the pattern of world-encircling mid-oceanic ridges is best explained by an increase in radius of the earth, the present Atlantic and Indian Oceans being formed by a steady widening of the rifts between the receding continents, with neo-formation of the ocean floor taking place near the mid-oceanic rifts.

Detection of the ancient earth's radius from paleomagnetism

Changes in the earth's radius can be detected also by paleomagnetism, provided that at least two widely separated sampling localities of rocks of equal age are available on the same stable continental block. In Fig.6 a schematic situation has been reconstructed to illustrate the paleomagnetic consequences of global expansion. The upper part shows two stereographic plots of the same continent: the one on the left represents the continent at some past time when the globe had a radius R_a ; that on the right, represents at the present-day on a larger globe of radius R_p , such that $R_a = 0.8\, R_p$. The centre of the projection has been chosen in the centre of our circular continent and this point is presumed to keep its place during the global expansion. It is assumed now that the ancient pole "P" was situated at the border of the continent, and rocks being deposited at sites A, B, C, and D will receive remanent magnetizations conforming to the dipole field about this pole position. Their declinations will point towards P, coinciding therefore with the great circles drawn through sites and P; their inclinations are known from the dipole formula ($\cot p = \frac{1}{2} \tan I$) where p is the geocentric angle between P and site. In the lower half of Fig.6 sections of the globe are shown passing through site B and pole P.

It is generally supposed that global expansion does not affect the continents, so that these keep their original size, but the oceans in between are enlarged. As a consequence all continental dimensions given in geocentric angles will undergo changes inversely proportional to the change in radius of the earth, as is easily read from the numerical examples in Fig.6. From the inclination of the rock magnetization, when measured at the present-day in the ancient rocks at sites A, B, C, and D, the geocentric angle p can be calculated, but this angle now is still in agreement with the ancient radius of the earth, and will be too great when expansion of the globe has occurred in between. This is demonstrated in Fig.6, where all the pole positions calculated from the rock magnetization at the various sampling sites come to lie at the farther side of what we know to be the real ancient pole position on the continent's edge; the great circles in line with the direction of declination pass almost through this point.

If we find now similar situations in reality, we may conclude that global expansion has occurred. An analysis of Carboniferous and younger paleomagnetic data has shown (Van Hilten, 1963b) that such intersecting great circles are present in the Carboniferous, Triassic, and Cretaceous of the North American continent, and in the Permian of Siberia. An estimate of the rate of global expansion may be found from these data in the following way: when the angle between the intersecting great-circles is not too small (like for instance in the case of sites B and C in Fig.6) the real ancient pole position may be supposed to lie at their intersection as a first good approximation. This gives some reasonable estimates of the geocentric angle p , measured on the present globe between sampling site and the point of intersection. We have argued that $p' = R_a / R_p \cdot p$, where R_a/R_p is the ratio of ancient and present earth's radii, and p the geocentric angle, adapted to the ancient earth's radius, between pole and site, the value of which is known from the inclination measured. From the equation R_a, the ancient radius of the earth at the time of deposition of the rocks investigated, is known. In the special case in which the sampling sites are in line – or almost in line – with the ancient pole position, there is no set of intersecting great circles, but the ancient radius of the earth may be found then from the equation given by Cox and Doell (1961) :

$$R_a = \frac{d}{\cot^{-1}(\frac{1}{2}\tan I_1) - \cot^{-1}(\frac{1}{2}\tan I_2)}$$

where d is the difference in ancient latitude measured along the earth's surface between the two sampling sites, and I_1 and I_2 are the inclinations measured at these localities. This situation is encountered during the Permian in western Europe, from which the most reliable measurements have been used for an R_a calculation (Van Hilten, 1963b). In Fig.4 these

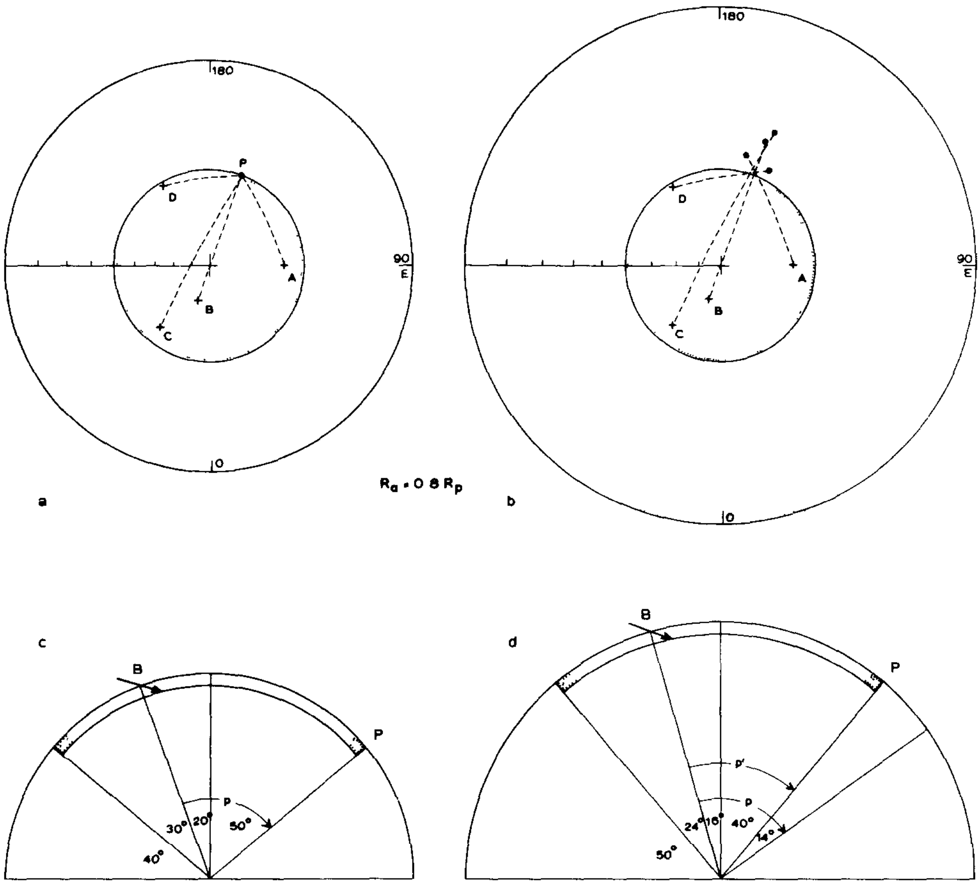


Fig.6. Effect of global expansion on paleomagnetic data. Stereographic plots (a and b) and sections (c and d) of a continent before (a and c) and after (b and d) global expansion. The expansion does not alter the size of the continent.

Rocks being deposited at sites A-D receive a magnetization parallel to the dipole field around pole P, on the edge of the continent. After the expansion the sampling sites and the pole positions calculated from their fossil magnetization, produce the typical pattern of Fig.6b with intersecting great circles where the real ancient pole once was situated. This pattern has repeatedly been found in nature (Van Hilten, 1963b) and it permits a good estimate to be made of the earth's radius at the time of deposition and magnetization of the rocks.

Numerical example

SMALL GLOBE	EXPANDED GLOBE
Ancient radius $R_a = 0.8\ R_{\text{present-day}}$	
SITE A	SITE A
Locality: 90°E 50°N	Locality: 90°E 58°N

sites are shown: no.1, 3, 5, 7, 23, and 29; it is seen that the directions of their declinations are very well in line.

The results of these analyses of paleomagnetic data are given in Fig.7, and they roughly indicate a rate of global expansion as advocated also by Carey (1958) and by Heezen (1959). It might be objected that some of the data used are not reliable enough to base such far-reaching conclusions upon. However, from unreliable data we might expect that the various analyses (circles in Fig.7) would give both greater and smaller earth's radii, instead of values that are systematically smaller than the

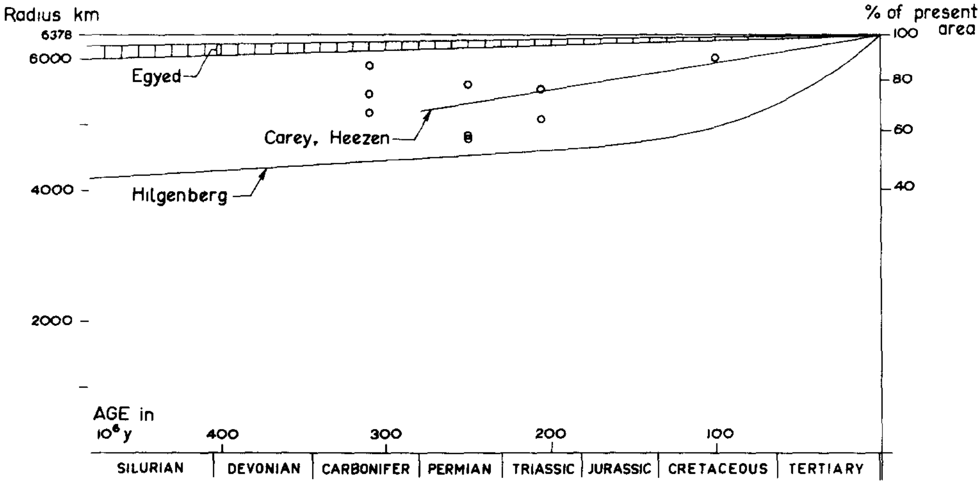


Fig.7. Change in the earth's radius with time according to Egyed (1963a), Carey (1958) and Heezen (1959), and Hilgenberg (1962). Circles show the results of the analyses of paleomagnetic data (Van Hilten, 1963b); they agree roughly with the rate of expansion advocated by Carey and by Heezen.

Fig. 6 (continued)

Magnetization received:
$D = 73^\circ$ $p = 48^\circ$
$\frac{1}{2} \tan I = \cot p$ $I = 61^\circ$

Magnetization measured:
$D = 73^\circ$ $p = 48^\circ$
$I = 61^\circ$

p' = distance measured between site A and point of intersection of great circles = 38.2°
$p' = R_a/R_p$ $R_a = 0.8\,R$

SITE B
(also shown in Fig. 6c, d)
Locality: 20°W 70°N
$D = 0^\circ$ $p = 70^\circ$
$I = 36^\circ$

SITE B

Locality: 20°W 74°N
$D = 0^\circ$ $p = 70^\circ$ $I = 36^\circ$
$p' = 56^\circ$ $R_a = 0.8\,R$

present radius. Ward (1963) who made also an analysis of paleomagnetic data to detect ancient changes in the earth's radius, confined his study to data from Europe and Siberia, assuming that no movements between these blocks have occurred. He concluded that no appreciable changes in the earth's radius are indicated by paleomagnetism, which is quite opposed to my findings (Van Hilten, 1963b); but it should be remembered that I analysed the European and Siberian observations apart from one another, finding for each region a markedly smaller earth's radius during the Permian, while I hit also on the inconsistency (Van Hilten, 1963b, p.1279) that the comparison of European with Asian data does not produce this result. I therefore decided, quite logically, that some movement between these two blocks must have taken place. These movements might be genetically connected with the global expansion, the "orange-peel effect", for which geological indications are present too.

Presentation of paleomagnetic data, assuming an expanding earth

For the sake of completeness, the pole positions and isoclines of the various continents have been constructed on the assumption that the earth's radius increased steadily from the Carboniferous on according to the rate assumes by Carey (1958). He advocates that since the Permian the earth's surface area has increased by 45%, i.e., that the Permian radius was 0.83 of the present one. In Plate III the poles and isoclines are presented. Their construction is somewhat more difficult than in the case of an earth with constant radius. For each continent the average sampling site was estimated (crosses) and a great circle was drawn through this point and the mean pole position, as given in Table I. The distance measured between these two points, p , was reduced to the value p' so that $p' = R_a/R \cdot p$; for the values of R_a/R , the ratio between ancient and present-day earth's radii, the following values were calculated, using Carey's rate of global expansion:

Carboniferous	: 0.795
Permian	: 0.830
Triassic	: 0.870
Jurassic	: 0.895

The Cretaceous and Tertiary constructions have been omitted as the differences with the isoclines presented in Plate I (constant earth's radius) are only very slight.

Around the pole positions constructed in this way isoclines have been drawn again, and their distances from the poles have also been diminished with the factor R_a/R as a result of which the isoclines are more closely spaced than in Plate I. Finally something had to go wrong, because during the assumed expansion the shape of the continents must have undergone some changes whilst these adapted themselves to a less curved surface; I suggested before (Van Hilten, 1963b) that an "orange-peel effect" might be expected; radial tears in the edges of the continents. In the isocline-maps of Plate III this discrepancy is shown by the magnetic equators (full drawn lines) which are not at a distance of 90° from the poles, but at a distance of $R_a/R \cdot 90°$. This implies that it makes a difference about which of the two (not antipodal!) pole positions the equator is constructed. In Plate III both equators are shown, warning the reader that some unknown deformation of the continental forms during the expansion has not been taken into account.

As might be expected, the differences in the positions of the isoclines on the continents presented in Plate I and III are not spectacular, and the greatest differences are found far away from the sampling sites. One feature however demands our attention: the isoclines of Plate I, and the reconstruction of Plate II, suggest that movements have occurred between Europe and Asia during the late Paleozoic and early Mesozoic, because on the maps the isoclines of both continents are out of line with one another. In the reconstruction a gap remained between Europe and Asia. The isoclines of Plate III however are reasonably well in line during these periods.

Permian arrangement of continents on a smaller globe

Finally a reconstruction had been made of a Permian arrangement of continents on a globe with smaller radius ($R_{\text{Permian}} = 0.83\ R_{\text{present-day}}$; Fig.8). To effectuare this, each continent was first enlarged by a linear factor 1 / 0.83, working from a central point. Then the continents were arranged according to the same principles as applied in the reconstructions of Plate II. An essentially similar configuration has been made as for the Permian on Plate II. The main advantage of this small-globe reconstruction is seen in the arrangement of Laurasia, where Europe and Asia fit very well together now, while on the reconstruction of Plate II Asia could not be fitted in satisfactorily, even after violating the paleomagnetic data (symbolized by its dotted outline in Plate II).

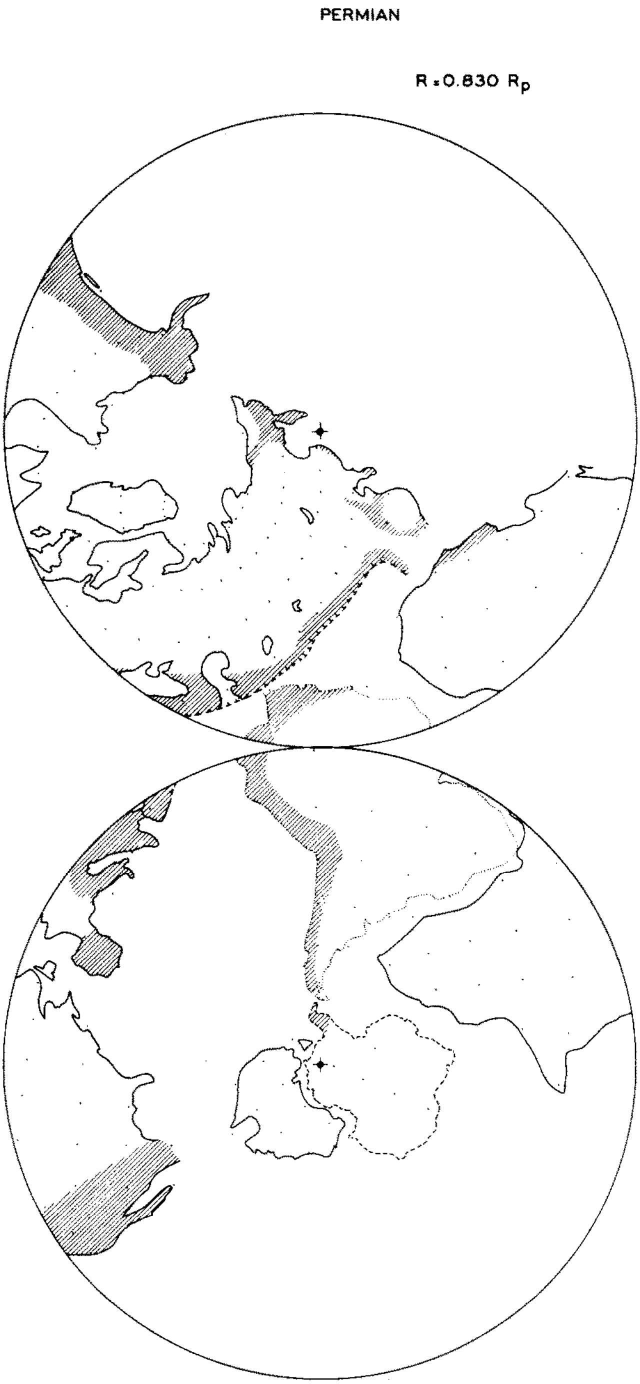
Mesozoic reconstructions on small globes have not been carried out. It is not difficult to see that the evolution from the Permian arrangement of Fig.8 towards the present-day one will run about parallel to that presented in Plate II on a globe with constant earth's radius.

Earlier reconstructions on smaller globes have been made by Carey (1958, p.277), Hilgenberg (1962, p.40) and Barnett (1962, p.447). They all keep Europe north of Africa in the same relative position as nowadays, and this fact alone renders it impossible to have them match the paleomagnetic data of these two continents in the late Paleozoic and early Mesozoic. Though Hilgenberg states that his reconstructions are in agreement with paleomagnetic evidence, his Jurassic south pole position in Brasil (Barnett, 1962, fig.10), and the Jurassic position of Australia on the equator can hardly be reconciled with the data shown in Plate I or Plate II.

Polar wandering

Contrary to general opinion, the paleomagnetic data do not give any conclusive evidence in answer to the question whether polar wandering has ever occurred (Deutsch, 1963; Van Hilten, 1963a and 1964).

Polar wandering would be probable during a geological period when the polar wandering paths of all continents were identically curved and of equal length over that period (Van Hilten, 1964), which is not the case with the Carboniferous and younger pole positions as shown in Fig.1. Also


PERMIAN
R = 0.830 Rp

from the wandering paths of the continents (cf. Fig.5) one might decide on the probability of polar wandering (Van Hilten, 1962a, fig.8 and p.424) when the majority of the continents move in one direction over the globe during some geological period: such a movement might be taken as the reflection of polar wandering in the opposite direction. The continental wandering paths based on the present paleomagnetic data, shown in Fig.5, do not produce this required parallelism, so no arguments can be advanced that make polar wandering likely.

CONCLUSIONS

With the continents in their present-day arrangement contemporaneous paleomagnetic observations (Plate I) are not in agreement with an ancient geomagnetic field produced by a geocentric dipole. In order to achieve such agreement continental drift has to be invoked. Paleomagnetism informs us about the latitude and orientation of a continent with respect to the ancient pole position, but the third requirement, the continent's ancient longitude, cannot yet be derived so that the precise position of the continent on the globe cannot be deduced.

Since the continents have drifted over the earth's surface in one way or another, an attempt has been made to find agreement between paleomagnetic data and continental arrangements and movements proposed earlier on other, mostly geological grounds. It is taken for granted that the probability of a given continental arrangement is greatly increased when it is supported by evidence from two or more independent, and essentially different, fields of research.

The reconstructions given in Plate II are for the greater part in conformity with the paleomagnetic evidence (latitude and orientation of the continental blocks) and at the same time with one or more geological observations which have a bearing on continental arrangements. Geological arguments of the following types are incorporated in these reconstructions:

(1) Paleoclimatology, similarities of paleontological, structural, depositional and petrological development. This classical evidence for continental drift and for the assembly of Gondwanaland and Laurasia agrees strikingly well with the paleomagnetic observations. In particular the agreement between the paleoclimatologically and the paleomagnetically determined ancient latitudes is most promising, as it confirms the assumption that the axis of the geomagnetic dipole was parallel to the axis of rotation of the earth.

The paleomagnetic evidence does not allow a combination of Gondwanaland and Laurasia into one late Paleozoic continent, usually called

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Fig. 8. Permian arrangement of continents according to paleomagnetic data on a globe with small radius ($R_{\text{Permian}} = 0.83\ R_{\text{present-day}}$). See also legend to reconstructions of Plate II. Compared with the arrangement on the sphere of present-day size (Plate II), this reconstruction gives a better fit of the Laurasian continental mass.

Pangaea; instead, these two ancient blocks seem to have performed an enormous rotational movement with respect to one another, tentatively named the Tethys Twist, because the shearing between Gondwanaland and Laurasia coincides with the Tethys belt. Such a dextral shearing movement, performed by the same continents, has been proposed earlier by Pavoni (1962) on structural grounds.

(2) The topographic features of the ocean floors. In the reconstructions presented the development of the mid-oceanic ridge system has been inserted, giving full credit to the genetic significance usually attributed to it. Some of the fracture zones and lineations in the Pacific Ocean are taken as the remnants of the ancient faults along which the Tethys Twist took place.

(3) Observations from alpine regions. The paleomagnetic observations derived from rocks in the alpine regions deviate systematically from contemporaneous data obtained on the stable parts of the now adjacent continents. This implies that the tectonic units of the Alps must have undergone large displacements before they reached their present-day positions. The presence of large longitudinal strike-slip faults in the Tethys belt (Caribbean, European Alps, the Near-East, Indonesian archipelago) confirms the possibility of such large displacements during some stage of the alpine orogenesis, and the dextral character of the Tethys Twist. This dextral movement may also be seen as the mechanism that transported some of the alpine tectonic units to their present position in the European Alps. Up till now the occurrence in the Tethys zone of the typical arcuate structures has only been explained by Carey's orocline concept, which invokes a shear movement in this zone by which the mobile sedimentary belts are laid in festoonlike arcs between the more rigid continental blocks of Laurasia and Gondwanaland. Carey's mechanism is quite comparable with the Tethys Twist, which agrees with the paleomagnetic observations; but the latter shear movement is dextral, and Carey originally proposed a sinistral movement. The tectonic unit of the southern Alps (northern Italy) from which the most complete paleomagnetic record is known, may, according to this evidence, have formed part of northern Africa before it was "smeared off" against Europe in Tertiary times when Africa moved by in the final stage of the Tethys Twist. The position where the southern Alps could once have been attached to Africa is exactly the spot predicted by Carey (1958) for this tectonic unit, though he based his arguments on tectonic grounds and on analogy of facies.

The available paleomagnetic data give neither direct nor indirect evidence of polar wandering in post-Devonian time.

The hypothesis of global expansion advanced by various authors is confirmed by the available paleomagnetic data. The estimated rate of expansion agrees roughly with that advocated by Carey (1958) and Heezen (1959). The Permian and early Mesozoic assembly of Laurasia fits the paleomagnetic observations better on a small globe (radius 0.83 of that of the present one) than on the present sized globe. None of the foregoing conclusions, continental arrangements or lines of reasoning need to be altered in essentials to deal with global expansion in the geological past, even at the rate proposed by Carey. This means that the problems of reconstruction, except in the case of Laurasia mentioned above, are neither increased nor decreased fundamentally when global expansion is invoked.

To summarize, the reconstructions of Plate II form a synthesis in which recently obtained, first-order geological and geophysical observations have been combined. The results of paleomagnetism have been put deliberately in the foreground as it is the only field of research which provides quantitative data bearing on displacements in the past.

POSTSCRIPT

In the final part of this paper, I want to discuss mechanisms that might be held responsible for the development of our planet along the lines depicted in the foregoing pages. I am inclined to propose that mere global expansion may have caused the variety of post-Devonian phenomena described. The expansion seems to have first manifested itself in the breaking open of the earth along the Mid Atlantic Rift, between South America and Africa. This gives the impression that the process at the base of global expansion was not spread homogeneously over the entire earth, but rather was restricted to this equatorial area in the beginning. At that moment, the increase in volume was greatest in the equatorial plane and southern hemisphere; this would affect the earth's angular momentum, making the southern part tend to rotate slower than the northern hemisphere, from which the Tethys Twist originates as a shear zone between these two units. The increase in surface area is limited to the present Atlantic and Indian Oceans, which now form one third of the total global area; that is exactly the amount required by an increase in radius at a rate as advocated by Carey, and as evidenced by paleomagnetism. Both these oceans should be regarded as the enormous scars along which the earth opened; the rest of the global surface did not substantially lose its coherence and the continents bordering the initial rifts were simply pulled aside, keeping about the same position on their substratum. Besides global expansion, no additional mechanisms, as for instance that of convection currents in the mantle, seem to be required to explain the relative movements between the continents.

Another attractive mechanism, recently proposed by Van Bemmelen (1964a, 1964b, 1964c), may have also played an important part. Above a centre where deep-seated differentiations and phase transformations take place in the mantle, accompanied by some expansion of matter, the earth's surface would tend to be elevated above the level of the geoid. The height of such elevations could only be small because of the plastic behaviour of the material involved: under gravity, this geo-tumor would flow out sideways, simultaneously displacing any continents that happened to be on its flanks. The movement pattern displayed in the Indian Ocean reminds one strongly of such a process. This mechanism would also account for compressional phenomena in the frontal parts of sliding continents, such as are found on the west coasts of South and North America, and where India pushed against the Himalayas.

The mid-oceanic ridge, once it had been formed, would remain a line of least resistance all during the expansion process, and the formation of the new oceanic crust would stay localized there. As expansion proceeds, the rift would continuously get longer at its ends and could well bifurcate occasionally. After some time, the angular velocities of the northern and southern hemispheres would become equal again when the expansion has proceded to northerly regions also; and at that moment, the Tethys Twist would finish its activity.

Of course, invoking global expansion as a mechanism to account for the observed phenomena only shifts the difficulties to another level without really showing a way out. The geophysical and geological consequences of global expansion at a rate suggested in the present paper are far from simple (Egyed, 1963b), if not insurmountable (Beck, 1961). So those who prefer an earth of constant diameter may want to devise an ingenious pattern of convection currents to explain the continental movements presented here. In this case the mechanism advocated by Van Bemmelen (1964a, 1964b, 1964c) will also be found most helpful, because it postulates no, or hardly any, expansion of the earth.

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APPENDIX I

Sources of the paleomagnetic evidence used in this paper

Following each continent, the total number of individual observations with probably reliable results is given; only these data have been used for the calculation of the mean pole positions in Table I. The numbers following the references refer to the lists of the authors in question. The numbers in brackets correspond to the ciphers given in Fig. 2 and 4. Remarks have been added dealing with the reliability, scatter and age of the poles.

Carboniferous

Europe (26):
Andreeva (1961).
Cox and Doell (1960), D 2, 5, 8, 10, 11, 12, 16, 20, 31, 33, 36.
Irving (1960b).
Irving (1962a), 19, 20, 22, 23, 24, 25.
Irving (1962b), 47.
Kalashnikov (1961), 68, 69, 70, 71, 72, 73.

North America (6):
Cox and Doell (1960), D 38, 40, 43, 45, 47, 49.

Asia (8):
Kalashnikov (1961), 74, 75, 76, 77, 78, 79, 80.
Popova (1963).

South America (0):
Creer (1962b), 10, 11a, 11b. These poles lie far apart; the age of pole 10 is not known (Upper Carboniferous or Permian), and its magnetization exhibits considerable scatter.

Africa (0):
Cox and Doell (1960), D 52, 54. The poles lie far apart; their Carboniferous age is disputed (Bain, 1963).

Australia (1):
Cox and Doell (1960), D 50, 51. As shown by Irvin et al. (1961) these rocks of the Kuttung Series contain recently induced components.
Irving et al. (1961). Upper Carboniferous, see also Briden and Irving (1963).

Permian

Europe, extra-alpine area (29):
Cox and Doell (1960), E 4 (8), 6 (12), 8 (16), 22 (13), 24 (9), 26 (11), 28 (21).
Irving (1962a), 15 (20), 16 (17), 17 (22), 18 (30).
Kalashnikov (1961), 59 (4), 60 (28), 61 (2), 62 (25), 63 (27), 64 (18), 65 (26), 66 (24), 67 (14).
Nairn (1963), A 18 (6), 20 (10).

De Magnée and Nairn (1962) 1.
Kruseman (1962), (3, 23).
Nijenhuis (1961), (5).
Roche et al. (1962), (29).

Schmucker (1959), (19).
Van Everdingen (1960), (7).

According to Miller and Mussett (1963) the age of Whin Sill, paleomagnetically investigated by Creer et al. (1959) amounts to $281 \cdot 10^6$ y., and should be reckoned therefore to the Carboniferous (see there under Irving, 1960b: 36).

Europe, alpine realm (9):
Cox and Doell (1960), E 10 (34).
Nairn (1963), A 22 (39).

As and Zijderveld (1958), (33).
De Boer (1963), (38).
Rutten et al. (1957), (31).
Schwarz (1963a), (36).
Van Hilten (1962a), (37).
Van der Lingen (1960), (35).
Zijderveld (in prep.), (32).

It was argued (Van Hilten, 1960, 1962b) that from the results of Dietzel (1960) recent magnetization has not completely removed.

North America (5):
Cox and Doell (1960), E 35, 53, 55, 59, 60.

Asia (2):
Irving (1961), 55 (one of the six intrusions dated on $250 \cdot 10^6$ y.
Popova (1963).

Greenland (1):
Bidgood and Harland (1961).

South America (1):
Creer (1962b), 9, 10. The directions of the magnetization of pole 9 show considerable streaking. Pole 10 (see remarks under Carboniferous of South America) is tentatively shown in Fig. 1 and Plate I.

Africa (1):
Cox and Doell (1960), E 63, 64.
Nairn (1963), D 3.

These three poles lie very far apart. On the measurements of Nairn (1963, p. 3) AC-demagnetization was carried out successfully and therefore only this pole has been used here (see also Nairn, 1964).

Australia (1):
Cox and Doell (1960), E 61, 62.
Irving and Parry (1963); only the pole of these latter authors is used because demagnetization tests were carried out on them.

Triassic

Europe (14):
Cox and Doell (1960), F 12, 13, 20.
Irving (1962a), 7, 8, 9, 10, 11, 12.
Kalashnikov (1961), 54, 55, 56, 57.
Leng (1955).

The poles from Spain (Cox and Doell, 1960) are not envisaged, as corrections for geological dip have not been applied.

North America (12):
Cox and Doell (1960), F 22, 39, 79, 91, 96, 98, 100, 102, 105.
Irving (1962b), 34, 35.

Asia (9):
Irving (1961), 31, 32.
Kalashnikov (1961), 47, 49, 50, 51, 52, 53, 58.

Greenland (1):
Bidgood and Harland (1961).

South America (2):
Creer (1962b), 7b, 8b. These poles were selected as most stable representatives of five poles; 6, 7a, and 8a were rejected because of their uncertain dating and highly scattered direction of magnitization.

Africa (2):
Cox and Doell (1960), F 109
Irving (1960b), 31.
These poles are 32° apart.

Australia (2):
Irving (1963), Robertson (1963).
The latter pole replaces the older, not demagnetized F 107 (Cox and Doell, 1960). F 106 is based upon azimuthally unoriented cores.

Southern Alps (Italy):
De Boer (1963).

Jurassic

Europe (8):
Cox and Doell (1960), G 5, 6, 7.
Kalashnikov (1961), 44, 45, 46.
Kruglyakova (1961), two poles.
The poles G8, 10 and 12 (Cox and Doell, 1960), all from alpine areas, are excluded from the calculation of the mean pole.
The eight poles show a considerable scatter.

North America (2):
Cox and Doell (1960), G 20, 21.

South America (2):
Cox and Doell (1960), G 52.
Creer (1962b).

Australia (5):
Boesen, Irving and Robertson (1961), three poles.
Irving (1963).
Robertson (1963).
The age of the sampled dolerites and syenite varies from 140 to $178 \cdot 10^{6}$ y., see also McDougall (1963).

Antarctica (4):
Irving (1960b), 26, 27.

Briden and Oliver (1963).
The age of the sampled dolerites has been determined upon $165 \cdot 10^{6}$ y. (McDougall, 1963).

India (2):
Cox and Doell (1960), H 10.
Athavale et al. (1963).
Bull et al. (1962).
The age of the rocks (Sylhet Traps) of the latter authors has been determined upon $150 \cdot 10^{6}$ y.

Northeastern Japan:
Irving (1962b), 14 (mean of nine poles, calculated by Irving, 1962b).
The age of the sampled rocks comprises all the Mesozoic.

Southwestern Japan:
Irving (1962b), 13 (mean of seven poles).
The age of the investigated rocks ranges from the late Paleozoic to Mesozoic.

Southern Alps (Italy):
De Boer (1963). In view of the scarcity of measured samples the reliability of this determination is small.

Cretaceous

Europe (5):
Cox and Doell (1960), H2.
Irving (1960b), 20, 21.
Irving (1962b), 15, 16.
The poles form two distinct clusters, one of the Russian samples (Irving, 1960b: 20, 21), the other of English samples.

North America (5):
Cox and Doell (1960), H4.
Irving (1962b), 17, 18.
Currie et al. (1963). Age determination: 89-79 · 10^6 y.
Larochelle and Black (1963). According to their stratigraphic position these rocks are of Lower Cretaceous age; a K/Ar age determination suggests however a Permian age.

South America (1):
Creer (1962b). According to this author recently induced magnetization is present in the samples.

Africa (1):
Gough and Opdyke (1963). The age of the sampled lavas might also be Jurassic.

Madagascar (1):
Cox and Doell (1960), H 13.

Australia (2):
Robertson and Hastie (1962). According to Irving et al. (1963, p. 2314) the age of the investigation Cygnet intrusives is 104-99 · 10^6 y.
Robertson (1963), age 93 · 10^6 y.

India:
Cox and Doell (1960, p. 732), I 59 (mean of six poles of lower Deccan Traps).
The age of the Deccan Traps is generally considered Cretaceous to Eocene.

Southwestern Japan:
Cox and Doell (1960), H 20.

Southern Alps (Italy):
De Boer (1963). This pole position is questionable in view of the small number of measured, stable samples (De Boer, 1963, p. 158).

Eocene

Europe (13):
Cox and Doell (1960), I 2, 3, 4, 7, 10, 20.
Kalashnikov (1961), 36, 37, 38, 39, 40, 41, 42.

North America (3):
Cox and Doell (1960), I 24, 25, 26.

Oregon (North America):
Cox (1957).

South America (1):
Creer (1962b).

Australia (2):
Irving (1962b), 10.
Mumme (1963). This datum replaced the older investigation of Irving and Green (1957), who did not demagnetize these rocks.

India:
Cox and Doell (1960, p. 132). I 58 (Upper Deccan Traps, mean of three poles). Age probably Eocone.

Northeastern Japan:
Irving (1962b), 12 (mean of five poles calculated by Irving, 1962b). Age is cited as Tertiary to Quaternary.

Southwestern Japan:
Irving (1962b), 11 (mean of eight poles calculated by Irving, 1962b). Age is cited as Tertiary to Quaternary.

Southern Alps (Italy):
De Boer (1963).

Eastern Siberia:
Kalashnikov (1961), 35. Age of rocks is cited as Paleogene.

Post Eocene

India: $75.5^{\circ}N$ $88^{\circ}W$.
Cox and Doell (1960), I 57. These tuffs are regarded as Miocene (Deutsch et al., 1959).

Southern Alps (Italy):
$86^{\circ}N$ $142^{\circ}E$.
De Boer (1963). Rocks are of Oligocene age.