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Palaeomagnetic Evidence for the Transitional Behaviour of the Geomagnetic Field

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Summary

A definition of transition intervals based on the definition of Normal, Intermediate and Reversed pole positions proposed by Wilson, Dagley and McCormack is used to select data for comparison with two models of the transitional geomagnetic field. The data for twenty-three transition intervals reported by various authors are reviewed.

The diversity of pole paths and common westerly trends lend support to the model in which the non-dipole field becomes dominant during the transition (Larson *et al.*). However, certain similarities and the sharp east–west changes of longitude support a purely dipole model with an independently inverting equatorial dipole but there is no common pole path nor even a preferred sector of the globe as suggested by Creer and Ispir. Neither model is preferred and a combination of a three-component dipole and non-dipole fields may be needed.

Much evidence indicates that the field passes through a minimum during a transition and the observed magnitudes suggest that the non-dipole field decreases also.

A possible link between inversions and tectonic activity is suggested by the detail recorded in some transitions while the fact that there are more transitions from the reversed mode of the field than from the normal mode implies that the two modes are not equally stable.

Introduction

Two basic models have been used to describe the behaviour of the geomagnetic field during a polarity transition. In one the main dipole field remains axial but decreases in strength during the transition so that the non-dipole field becomes dominant in the intermediate stages (see for example Larson, Watson & Jennings 1971). In the other model the non-dipole field remains a small part of the total field but the dipole is considered to have two or three components the strength, polarity and possibly orientation of which change during the transition (Creer & Ispir 1970a).

On the basis of the first model the paths of the Virtual Geomagnetic Poles (VGP) for transitions would not be the same whether recorded at a different place at the same time or the same place at a different time because of variations in the non-dipole field. The second model, on the other hand, suggests that there could be strong similarities between pole paths for the same transition seen anywhere on the Earth.

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Table 1

Transition zones in Eastern Iceland

	Rock	Lat.	Long.	N	R	Decl.	Incl.	σ	ε	K	α	P lat.	P long.	P	M	Pol.
1. $R \to N$	A031A	65·20	346·40	4	3·8106	228·67	−68·78	17·70	8·85	16	23·8	−62·5	260·9	34	40	*R*
	A031B	65·20	346·40	4	3·7831	253·79	−16·68	18·96	9·48	14	25·6	−14·5	267·6	14	26	*I*
	A032	65·20	346·40	4	3·9961	244·33	−22·32	2·54	1·27	761	3·3	−21·1	275·2	2	4	*I*
	A033	65·20	346·40	6	5·7393	277·54	−29·68	16·95	6·92	19	15·7	−11·3	242·9	10	17	*I*
	A034	65·20	346·40	4	3·9949	249·61	−24·59	2·90	1·45	585	3·8	−20·2	269·6	2	4	*I*
	A034S	65·20	346·40	8	7·5190	248·89	−17·99	19·97	7·06	15	15·0	−17·2	271·9	8	16	*I*
	A034A	65·20	346·40	4	3·8087	253·69	−41·17	17·79	8·90	16	24·0	−28·2	260·6	18	29	*I*
	A034T	65·20	346·40	8	7·7237	264·04	−44·58	15·10	5·34	25	11·2	−26·1	250·0	9	14	*I*
	A035	65·20	346·40	4	3·9202	316·88	−5·32	11·46	5·73	38	15·2	+15·3	211·5	8	15	*I*
	A037	65·20	346·40	4	3·9936	11·26	27·45	3·25	1·63	465	4·3	+38·8	152·4	3	5	*I*
	A039	65·20	346·40	4	3·9725	355·52	72·49	6·72	3·36	109	8·8	+82·3	184·4	14	16	*N*
2. $R \to N$	B006C	65·20	346·30	4	3·9985	212·10	−63·91	1·56	0·78	2036	2·0	−63·8	289·0	3	3	*R*
	B007	65·20	346·30	4	3·9911	46·27	−61·71	3·83	1·91	337	5·0	−23·9	130·9	6	8	*I*
	B008	65·20	346·30	4	3·9324	175·53	30·22	10·55	5·27	44	13·9	−8·5	350·6	9	15	*I*
	B009	65·20	346·30	4	3·9644	179·81	−4·02	7·64	3·82	84	10·1	−26·8	346·5	5	10	*I*
	B010	65·20	346·30	4	3·9953	323·06	22·77	2·78	1·39	638	3·6	31·0	209·6	2	4	*I*
	B011	65·20	346·30	4	3·9873	326·89	20·51	4·56	2·28	236	6·0	30·8	205·0	3	6	*I*
	B012	65·20	346·30	4	3·4193	359·43	83·76	31·26	15·63	5	44·9	77·5	345·7	87	88	*N*
3. $N \to R$	B022	65·20	346·30	4	3·9998	347·23	83·12	0·58	0·29	14769	0·8	78·1	331·7	1	1	*N*
	B023	65·20	346·30	4	3·9096	58·13	−22·43	12·21	6·10	33	16·2	1·9	110·0	9	17	*I*
	B024	65·20	346·30	4	3·7795	98·07	−27·12	19·11	9·56	14	25·8	−16·4	75·1	15	28	*I*
	B025	65·20	346·30	4	3·6374	118·03	−36·07	24·58	12·29	8	34·0	−29·7	59·1	23	40	*I*
	B026	65·20	346·30	4	3·9617	114·42	−60·97	7·94	3·97	78	10·5	−47·4	76·5	12	16	*I*
	B027	65·20	346·30	4	3·9668	151·90	−67·04	7·38	3·69	90	9·7	−68·7	43·3	13	16	*R*
4. $R \to N$	C022	65·10	346·20	4	3·9979	191·58	−81·83	1·86	0·93	1423	2·4	−80·3	185·4	5	5	*R*
	C022A	65·10	346·20	4	3·8841	294·54	−71·09	13·82	6·91	26	18·4	−40·5	208·7	28	32	*I*
	C023	65·10	346·20	4	3·9975	241·25	−42·60	2·01	1·00	1223	2·6	−34·3	271·7	2	3	*I*
	C023A	65·10	346·20	4	3·9236	238·64	−35·11	11·22	5·61	39	14·8	−30·5	277·0	10	17	*I*
	C024	65·10	346·20	4	3·7920	208·15	−3·07	18·56	9·28	14	25·0	−23·3	315·3	13	25	*I*
	C025	65·10	246·20	6	5·9975	212·51	3·31	1·66	0·68	1996	1·5	−19·2	311·5	1	2	*I*
	C026	65·10	346·20	4	3·5086	237·90	3·12	28·70	14·35	6	40·5	−11·5	286·4	20	41	*I*
	C027	65·10	346·20	4	3·9854	16·19	59·05	4·90	2·45	205	6·4	63·1	138·0	7	10	*N*

	Rock	Lat.	Long.	N	R	Decl.	Incl.	σ	ε	K	α	P lat.	P long.	P	M	Pol.
5. $N \to R$	L012C	64·70	345·40	4	3·9988	349·18	54·10	1·39	0·69	2558	1·8	59·2	183·0	2	3	*N*
	L013	64·70	345·40	2	1·9955	223·81	−52·81	3·86	2·73	220	16·9	−49·0	283·6	16	23	*I*
	L014	64·70	345·40	4	3·2430	168·62	−10·99	35·83	17·91	4	53·1	−30·3	358·5	27	54	*I*
	L015	64·70	345·40	4	3·8096	159·20	−38·25	17·75	8·88	16	23·9	−44·7	13·1	17	28	*I*
	L016	64·70	345·40	4	3·9541	308·38	−3·64	8·69	4·35	65	11·5	13·7	219·1	6	11	*I*
	L017	64·70	345·40	4	3·9849	121·32	71·48	4·99	2·49	198	6·5	38·9	23·0	10	11	*I*
	L018	64·70	345·40	4	3·7859	196·63	75·66	18·83	9·42	14	25·4	38·2	335·9	43	47	*I*
	L019	64·70	345·40	4	3·8620	118·80	44·38	15·09	7·55	22	20·2	12·3	39·1	16	25	*I*
	L020	64·70	345·40	4	3·9937	192·16	−73·50	3·23	1·61	473	4·2	−82·2	293·0	7	8	*R*
6. $R \to N$	M007	64·70	345·30	4	3·9527	82·45	−80·49	8·82	4·41	63	11·6	−57·1	129·9	21	22	*R*
	M008	64·70	345·30	4	3·9896	64·65	−70·04	4·14	2·07	288	5·4	−38·6	122·5	8	9	*I*
	M009	64·70	345·30	4	3·8312	120·01	−38·98	16·71	8·35	18	22·4	−32·5	57·1	16	27	*I*
	M010	64·70	345·30	4	3·8211	298·23	22·48	17·20	8·60	17	23·1	22·4	234·2	13	24	*I*
	M011	64·70	345·30	6	5·6425	65·18	31·20	19·88	8·12	14	18·6	25·7	90·7	12	21	*I*
	M011A	64·70	345·30	4	3·9712	68·32	5·56	6·88	3·44	104	9·0	11·6	93·9	5	9	*I*
	M013	64·70	345·50	4	3·9943	5·61	76·81	3·06	1·53	526	4·0	87·6	68·4	7	7	*N*

Mean directions of magnetization, virtual pole positions and associated statistics

Lat.: Latitude of collecting site, north positive
Long: Longitude of collecting site (east of Greenwich)
N: Number of directions meaned, twice number of cores
R: Length of the resultant of the N unit vectors
Decl.: Mean declination of remanent magnetization (east of true north)
Incl.: Mean inclination of remanent magnetization (positive down)
σ: Angular standard deviation, Wilson (1959)
ε: Angular standard deviation of mean, Wilson (1959)
K: Estimate of precision parameter, Fisher (1953)
α: Semi-angle of cone of 95 per cent confidence for mean direction, Fisher (1953)
P lat.: Virtual pole latitude
P long.: Virtual pole longitude
P, M: Semi-axes of oval of confidence for virtual pole position
Pol.: Polarity; N = Normal, I = Intermediate, R = Reversed. Wilson, Dagley, McCormack (1972)

In this paper we examine the evidence from reported transition intervals to determine the transitional behaviour of the geomagnetic field and to see if it is possible to choose between the models.

We define a transition interval as a period during which the Earth's magnetic field inverts its polarity and is recorded by magnetizations which are intermediate between Normal and Reversed. Normal, Intermediate and Reversed magnetizations are defined as those for which the colatitude of the VGP is in the range $0 < \theta < 40°$, $40° < \theta < 140°$ and $140° < \theta < 180°$ respectively as suggested by Wilson, Dagley & McCormack (1972b). In order to be certain that the pole path is adequately delineated only those sequences with three or more consecutive intermediately magnetized specimens, between specimens of opposite polarity, are considered.

Observed transition intervals

(a) *Eastern Iceland* (*Dagley* et al. 1967)

Previously we had identified five transition intervals (Lawley 1969). Reappraisal of the data using the new pole position criteria confirm that the six sequences A031A-A039 (Fig. 1), B006C-B013, B022-027 (Fig. 2), C022-C027 (Fig. 3), L012C-020 (Fig. 4) and M007-M013 (Fig. 5) are acceptable for analysis as transition intervals (Table 1).

The site latitude for each of these six transitions is virtually the same (64°·6 N, 345°·5 E) but the pole paths do not coincide (Figs 1–5). The differences may arise because some steps of the transitions are not recorded or, since they occurred at different times, the non-dipole field component may not have been the same for each case.

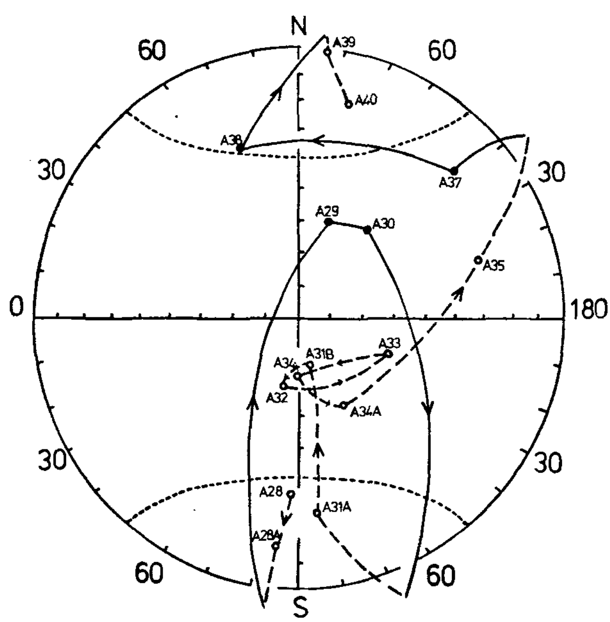

FIG. 1. Palaeomagnetic pole positions from a Tertiary transition interval, recorded in A-section, Eastern Iceland. The limits of normal and reversed pole positions, latitudes +50° N and −50° S are shown by dashed lines. Equal Area projection centred at 0° latitude, 90° longitude. Full symbols in eastern hemisphere, open symbols in western hemisphere.

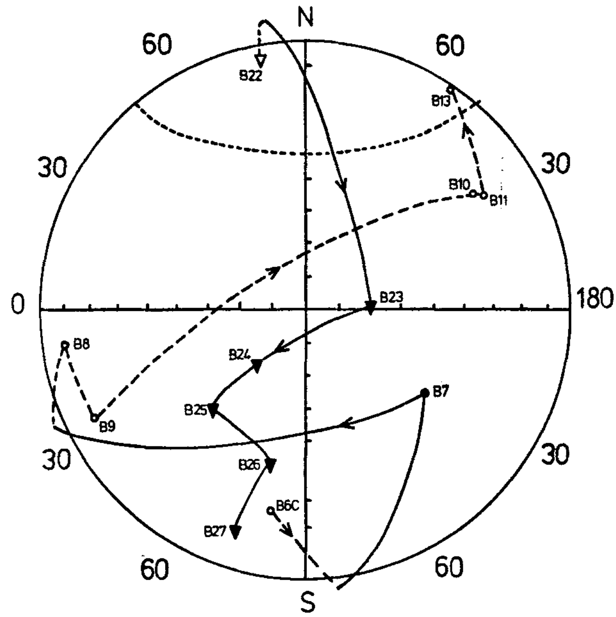

FIG. 2. Palaeomagnetic pole positions from Tertiary transitions interval recorded in B-section, Eastern Iceland.

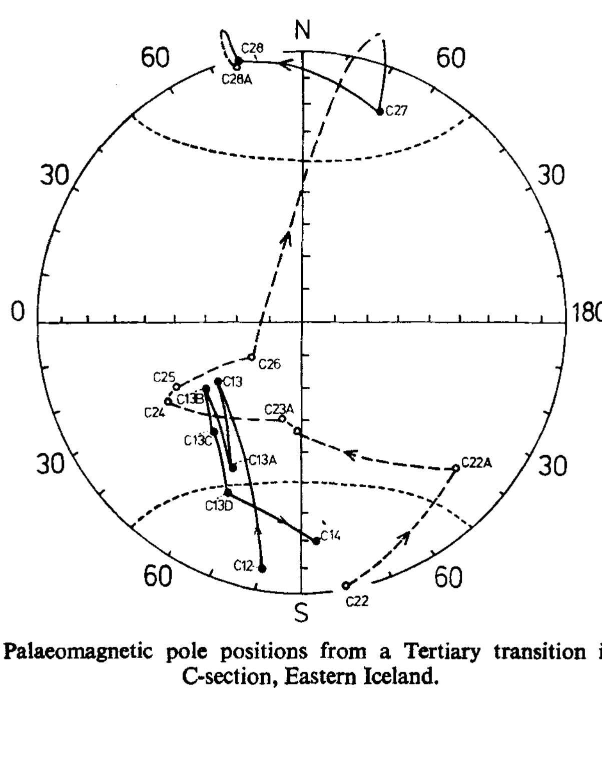

FIG. 3. Palaeomagnetic pole positions from a Tertiary transition interval in C-section, Eastern Iceland.

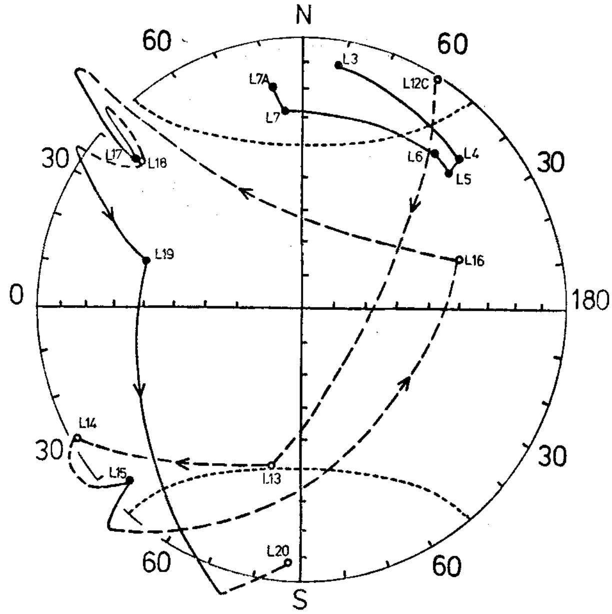

FIG. 4. Palaeomagnetic pole positions from a Tertiary transition interval recorded in L-section, Eastern Iceland.

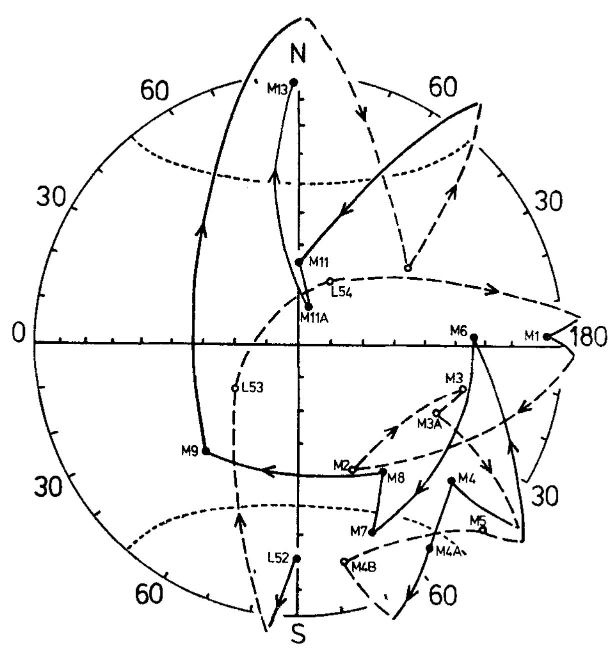

FIG. 5. Palaeomagnetic pole positions from a Tertiary transition interval recorded in M-section, Eastern Iceland. In this case the transition is preceded by a Systematic Deviation (L52–M7).

However, we note that in all cases there are large 'swings' of longitude, often greater than 90° but less than 180°, in both eastward and westward senses. There also appears to be a movement north westwards over either the East Pacific or the Americas (longitudes 210°–285°), in each transition except B022-B027.

Measurements of magnetic induction for intermediately magnetized lavas (Lawley 1969, 1970) suggest that the total magnetic field decreases during a transition.

(b) *Western Iceland* (*Sigurgeirsson* 1957; *Brynjolfsson* 1957; *Wilson* et al. 1972*c*)

Sigurgeisson reported 45 lavas with intermediate directions (VGP latitude < 50°) from four inversions ($N_4 \rightarrow R_3 \rightarrow N_3$ and $R_2 \rightarrow N_2 \rightarrow R_1$) in a collection made in Western Iceland. The $R_3 - N_3$ transition was studied in detail; it was made up of 24 samples and the sequence was judged to span a few thousand years from the appearance of the lavas and lack of sediments (Fig. 6).

Brynjolfsson reports at least seven consecutive lavas with intermediate directions showing a transition from Reversed to Normal in Iceland (Fig. 7); the pole path is very similar to the $R_3 \rightarrow N_3$ transition reported by Sigurgeirsson and it is presumed to be the same one.

This same transition has also been sampled by Wilson *et al.*, Fig. 8. All these $R_3 \rightarrow N_3$ data show a strong westward movement in mid-latitudes for only a small ($\sim$30°) change of latitude northward. The early part of the transition shows a large shift of longitude westward which Creer & Ispir (1970a) plotted as an eastward change. Sigurgeirsson's data provided little evidence for the sense of change but the composite data (Wilson *et al.* 1972c) suggests that it is westwards.

This is a quite well-defined transition; a particular feature being the large number of pole positions located around the present position of the East Indies (110°–120° E).

The sequences labelled $N_4 \rightarrow R_3$ by Sigurgeirsson (1957) (our Fig. 6) and Wilson *et al.* (1972c) (our Fig. 8) appear to be different transitions. Sigurgeirsson's indicates a predominantly N–S path whereas that of Wilson *et al.* does contain some east–west movements.

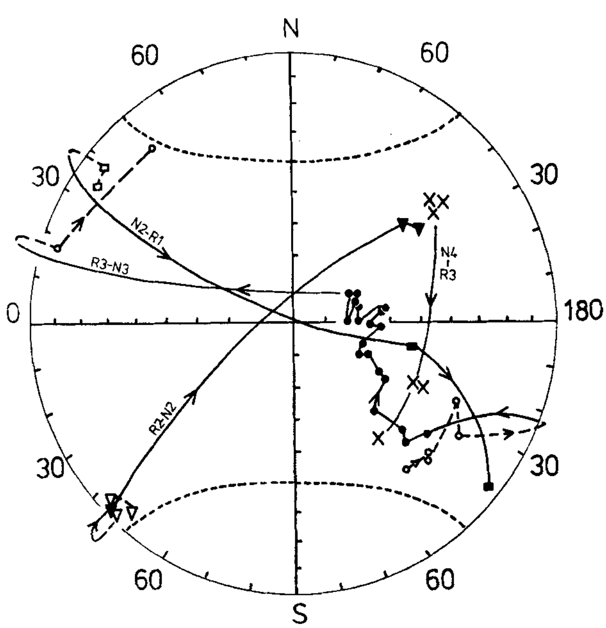

FIG. 6. Palaeomagnetic pole positions for four transition intervals recorded in Western Iceland (Sigurgeirsson 1957).

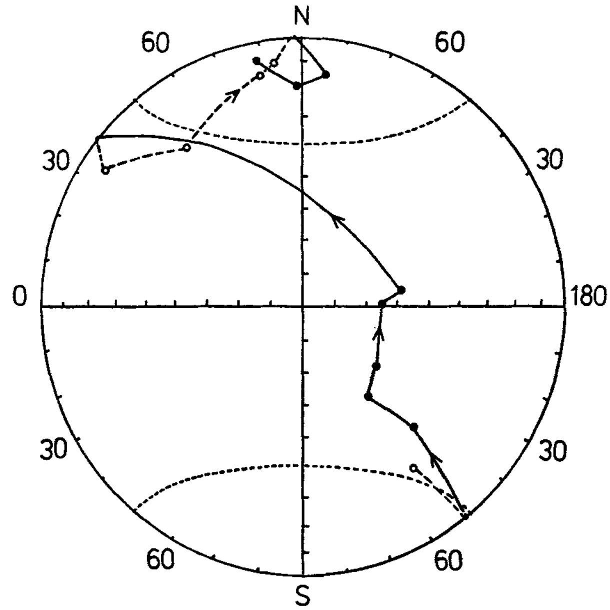

FIG. 7. Palaeomagnetic pole positions from a Tertiary transition interval recorded in Western Iceland (Brynjolfsson 1957). This transition is thought to be the R_3-N_3 transition reported by Sigurgeirsson (1957).

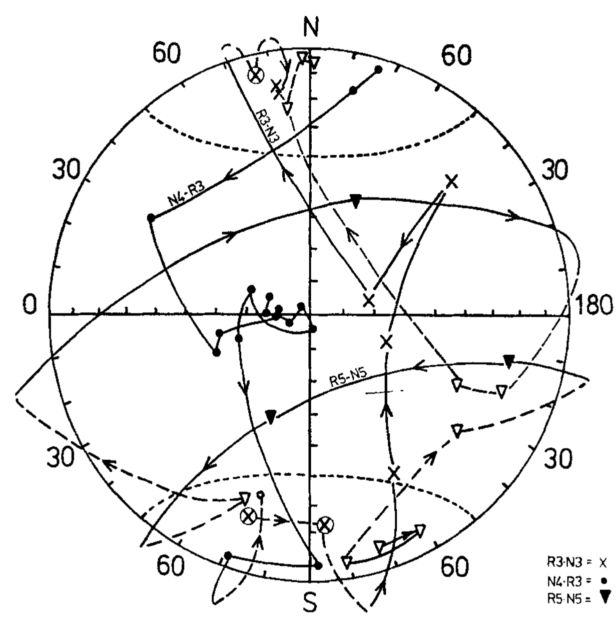

FIG. 8. Palaeomagnetic pole positions from three transitions intervals recorded in Western Iceland (Wilson *et al.* 1972). The R_3-N_3 transition is thought to be the same as those reported by Sigurgeirsson (1957) and Brynjolfsson (1957).

The transitions labelled R_2-N_2, N_2-R_1 (Fig. 6) are not so well defined but both suggest eastward trending pole paths.

The R_5-N_5 transition (Fig. 8) found by Wilson *et al.* (1972c) is less systematic but again eastward and westward ' swings ' of longitude are observed, which on Creer & Ispir's (1970a) model could be interpreted as two changes of equatorial dipole polarity during the reversal of the axial dipole as for the R_3-N_3 transition.

(c) *Steens Mountain, Oregon* (*Watkins* 1965a,b, 1969; *Goldstein, Larson & Strangway* 1969)

Watkins collected a profile of 71 lava flows for this transition at Steens Mountain (Fig. 9) and Goldstein *et al.* sampled it at Steens Mountain and Poker Jim Ridge (Fig. 10). Evernden & James (1964) dated the Steens basalt at between 14·6 and 15·0 Ma and Baksi, York & Watkins (1967) report a mean age for the transition of 15·1 ± 0·3 Ma.

The magnetic induction decreases during the transition. Coe (1967) reports values of 0·18 10^{-4} Tesla for Watkins' intermediate sample 57 and Prevot & Watkins (1969) find 0·18, 0·25 and 0·68 10^{-4} T for samples 42, 47 and 56 respectively which are to be compared to 0·35 10^{-4} T for reversed sample 69 (Coe 1967). Goldstein *et al.* (1969) report magnetic inductions from 0·056 10^{-4} T in the transition to 0·17 and 0·20 10^{-4} T at the top and bottom one of their profiles. The high value for sample 56 may indicate a genuine increase in magnetic induction just before a transition as suggested by the data of Kaporovich *et al.* (1966). The transition is from Reversed to Normal polarity and shows both eastward and westward swings along its complex path, part of which follows a northward route over the Americas and East Pacific (approximately between longitudes 245°–290°).

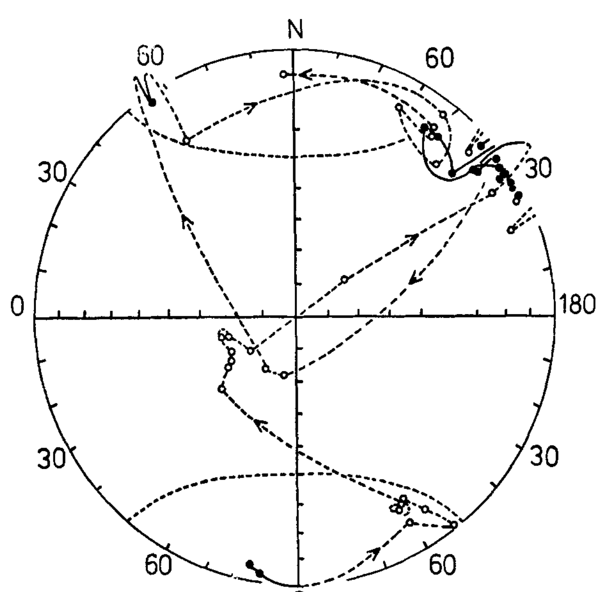

FIG. 9. Palaeomagnetic pole positions from a Miocene transition interval recorded in Steens Mountain, Oregon (Watkins 1969).
No. 1 corresponds to Watkins lava No. 20.
No. 45 corresponds to Watkins lava No. 64.

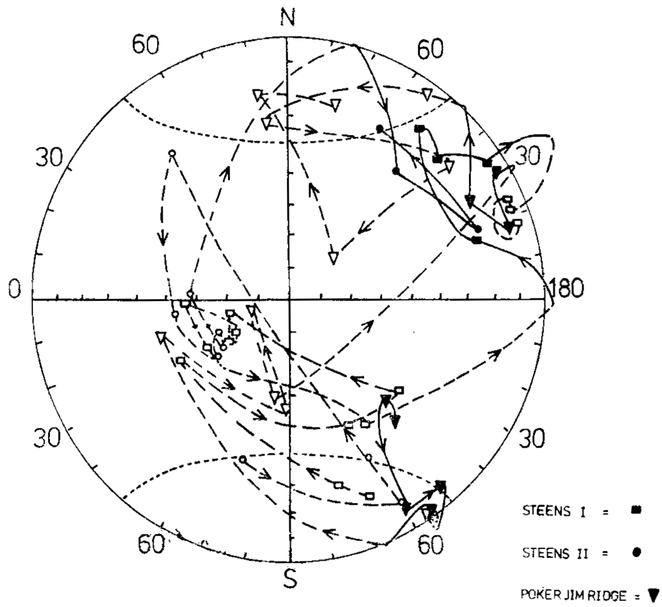

FIG. 10. Palaeomagnetic pole positions from a Tertiary transition interval recorded in Oregon (Goldstein *et al.*). These sequences are thought to be equivalent to that sampled by Watkins (1969). Steens Mt I —■—; Steens Mt II —●—; Poker Jim Ridge —▼—.

It is reported by Larson *et al.* (1971) that the Poker Jim Ridge transition (Goldstein *et al.* 1969) (Fig. 10) has been dated by York and Strangway at 18 Ma and so is different from the Steens Mountain transition. If this is so then the two transitions exhibit remarkably similar pole paths.

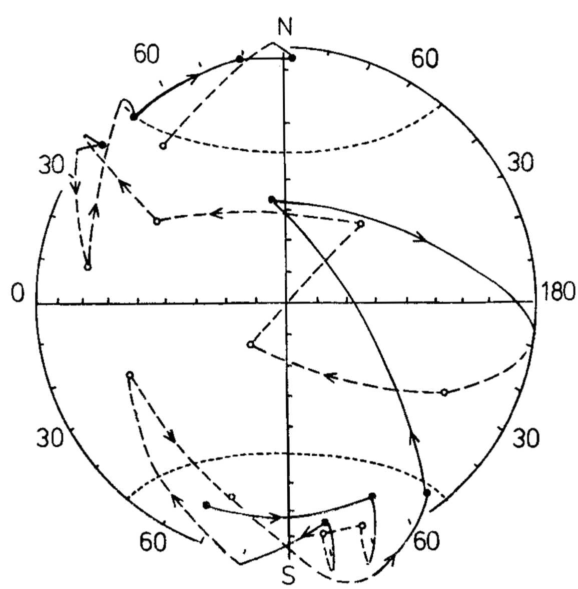

FIG. 11. Palaeomagnetic pole positions from a Tertiary transition interval recorded in the Santa Rosa Range, Nevada (Larson *et al.* 1971). This may be equivalent to the sequence sampled by Watkins (1969) and Goldstein *et al.* (1971).

(d) *Santa Rosa Range, Nevada* (*Larson* et al. 1971)

This reverse to normal transition has been dated at about 15 Ma and may be the same as that recorded in Steens Mountain. However, if pole positions are plotted (Fig. 11) the pole path does not match those for Steens Mountain closely. This may be due to differences in local fields.

Larson *et al.* have constructed a composite transition path for the *directions* from both sets of data which they claim can be explained by a constant non-dipole field drifting westwards at $0{\cdot}2^\circ\, a^{-1}$ while the intensity of an axial dipole decreases to 20 per cent of its maximum value in 15 per cent of the transition time, remains at less than 20 per cent for a further 70 per cent of the time while reversing sign, then grows to 100 per cent in the remaining 15 per cent of the time. The domination of the non-dipole field for the major part of the transition induces large east–west swings of the *local field direction.*

(e) *Laurel Hill Intrusion* (*Mt Hood, Oregon*) (*Ito* et al. 1969)

It is reported that a sequence of local field directions progressing from clearly reversed to normal has been found in the intrusion whose age is $8{\cdot}2 \pm 0{\cdot}5$ Ma. Immediately before the inversion there are major changes of direction along great circle paths. The reverse field configuration is then lost relatively rapidly, and the slower recovery of the normal field is accomplished by major ‘clockwise’ and ‘anticlockwise’ motions which eventually converge on the pole.

We should like to discourage the use of clockwise and anticlockwise to describe pole paths since the sense is ambiguous depending on the position of the ‘observer’, and the centre of the ‘clock face’.

(f) *Tatoosh Intrusion* (*Mt Rainier, Washington*) (*Dunn* et al. 1970)

Normal, reversed and intermediate samples found in the same intrusion indicate a

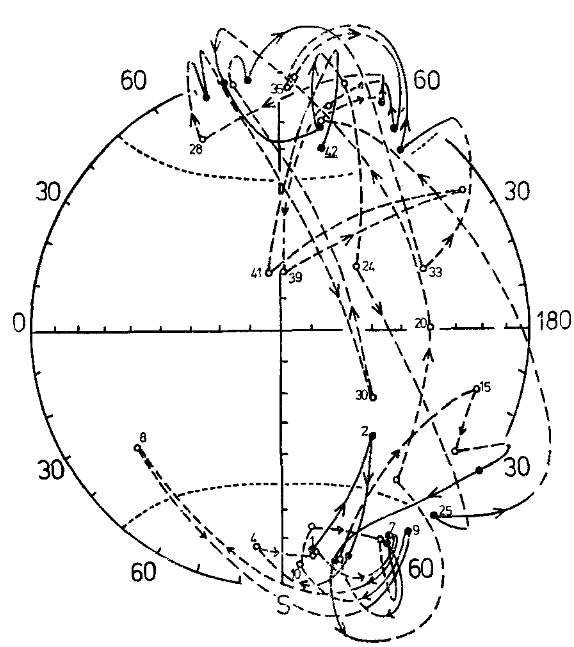

FIG. 12. Palaeomagnetic pole positions from the Tertiary transition interval recorded in the Tatoosh Intrusion, Washington (Dunn *et al.* 1971). The precision of the radiometric dating does not preclude this from being the same transition as Steen's Mountain (Watkins 1969).

transition from reversed to normal at $14{\cdot}7 \pm 1{\cdot}0$ Ma. The precision of the radiometric ages do not preclude this from being the same transition as observed at Steens Mountain.

The pole position is observed to 'swing' along great circle paths before moving northward (Fig. 12). 'Clockwise' rotations occur during the transition and the authors suggest that these are related to drifting non-dipole field anomalies. The general pole path lies in the East Pacific and the Americas (between longitudes 200° and 240°) much like those for Steens Mountain (Watkins 1969; Goldstein *et al.* 1969).

The intensity of magnetization decreases during the transition, at first without any significant change in direction. Before and after the change of polarity, transitory recovery of intensity is observed.

(g) *Lousetown formation, Nevada* (*Heinrichs* 1967)

Thirty-six cores from 61 flows were sampled. Twenty-nine give normal and reversed directions away from the expected direction and of the 34 from Lousetown Creek, the first is reversed and the last normal, the remainder being very closely grouped with the intermediate direction, −67° at 064° E. This set probably represents a $R \rightarrow N$ transition at $\sim 6{\cdot}8$ Ma during which there was very rapid extrusion of lavas over a short time.

(h) *Turkmenia and Azerbaijan* (*Kaporovich* et al. 1966)

It is claimed that the same Pliocene transition has been recorded in claybeds in Azerbaijan and redbeds in Turkmenia. The composite profile reveals an inversion from normal to reversed (labelled $N_3 \rightarrow R_2$) over about 1600a as judged from rates of sedimentation. The mean value of magnetic induction for the N and R parts at the beginning and end of the transition is $0{\cdot}13\ 10^{-4}$ T. As the transition proceeds there is a transitory increase to $0{\cdot}3\ 10^{-4}$ T Wbm^{-2} followed by a decrease to $0{\cdot}04\ 10^{-4}$ T at the time of the abrupt change of field direction. The induction then increases to $0{\cdot}13\ 10^{-4}$ T with a transitory maximum of $0{\cdot}25\ 10^{-4}$ T.

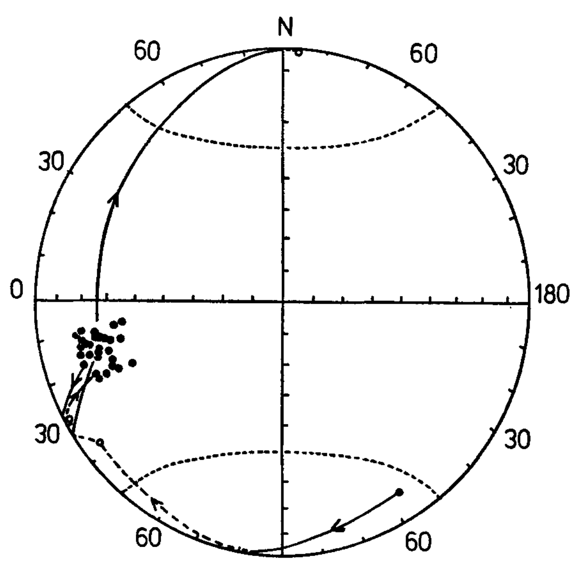

FIG. 13. Palaeomagnetic pole positions from a Tertiary transition interval recorded at Lousetown Creek, Nevada (Heinrichs 1967).

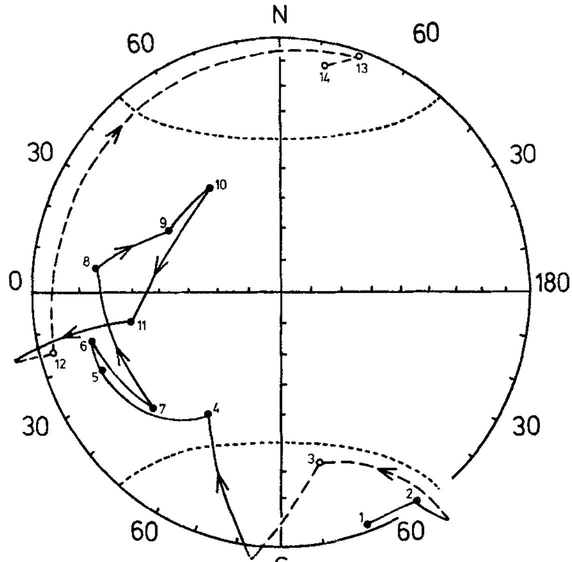

Fig. 14. Palaeomagnetic pole positions from a Pliocene transition interval recorded in Japan (Momose 1963).

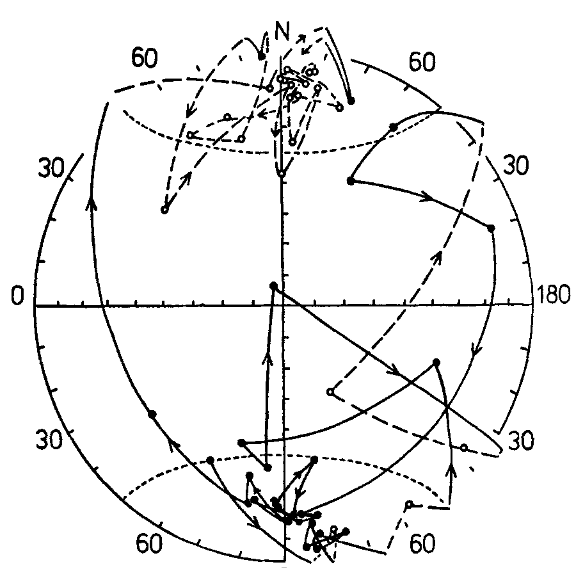

Fig. 15. Palaeomagnetic pole positions from a Tertiary transition interval recorded by the Liverpool Volcano, NSW (Wellman *et al.* 1969).

(i) *Shigarami, Japan* (*Momose* 1963)

A transition from reversed to normal appears to be defined showing a marked westward swing. The ancient field strengths associated with the intermediate directions are much lower than those associated with the normal and reverse directions.

(j) *Liverpool Volcano, NSW Australia* (*Wellman, McElhinny & McDougall* 1969)

A *R–N–R–N* sequence delineated by a number of flows from the volcano traces a rather erratic path but the first *R–N* transition satisfies our criteria. The path has eastward and westward swings but the westward one is greatest.

(k) *Stormberg lavas, South Africa* (*Van Zijl, Graham & Hales* 1962)

A reversed to normal transition zone with at least seven lavas showing intermediate directions is recorded by two profiles through the lava succession of 70 flows of Triassic–Jurassic age.

In order to compare the pole paths with the Tertiary data the spherical triangle defined by the collecting site, the Virtual North Geomagnetic pole for normally magnetized rock (occurring before or after the transition) and the intermediate pole have been rotated so that the Virtual North Geomagnetic pole moves to the north geographic pole while the longitude of the collecting site, but not the latitude, remains fixed. This is equivalent to restoring the continent to its ancient latitude and orientation with respect to the rotation axis while retaining the relationship between intermediate pole and site; as always the absolute longitude is not known.

Using an ancient pole of $+71{\cdot}0°$ N 269° E for this period (Briden 1967) the revised path does not differ greatly from the original. The south to north movement of the pole is accompanied by an overall westward movement, although both eastward and westward swings occur. Low intensities are associated with the transition zone.

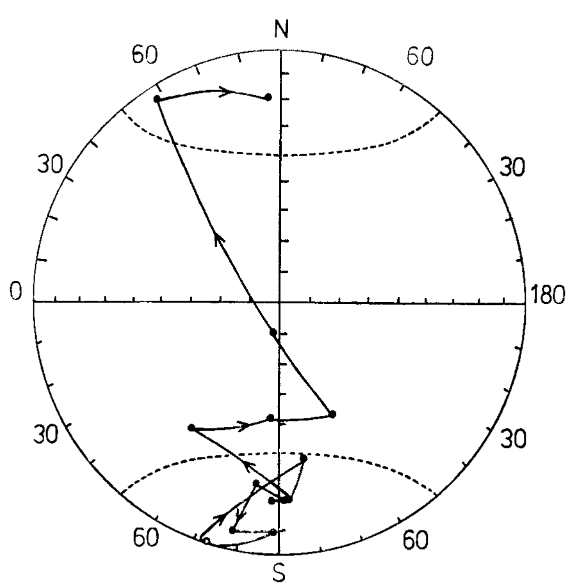

FIG. 16. Palaeomagnetic pole positions for a transition interval recorded in the Stormberg Lavas, South Africa (Van Zijl 1962). The transition occurred during the Triassic–Jurassic but the pole positions have been shifted (see text) for comparison with the Tertiary results.

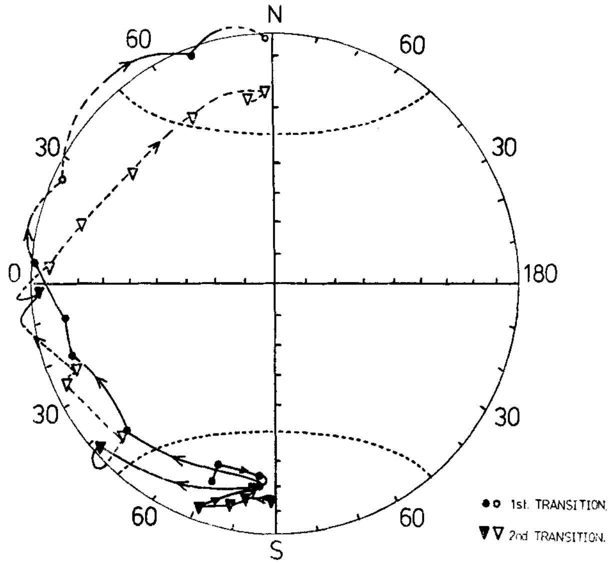

FIG. 17. Palaeomagnetic pole positions for a transition interval recorded in Krasnoyarsk Kray, USSR (Vlasov & Kovalenko 1963). The transition occurred during the Devonian but the pole positions have been shifted (see text) for comparison with the Tertiary results.

(l) *Krasnoyarsk Kray USSR* (*Vlasov & Kovalenko* 1963)

The Devonian sedimentary section sampled consists of three normal and two reversed zones but only the two reversed to normal transitions are recorded in detail. Each transition follows a very similar pole path, which suggests that non-dipole fields were either not significant or were similar for the two events (Fig. 17). The ancient pole +31·0° N, 154·0° E, quoted by the authors, was used for a rotation similar to that done for the Stormberg lavas (item (k) above).

The adjusted pole paths indicate some swinging before the transitions while the intermediate directions lie on a more or less northerly path near 0° longitude for the first transition and a northwesterly path crossing the Atlantic for the second.

Discussion

(i) *Pole paths*

The two sedimentary sequences reported by Vlasov & Kovalenko (1963) (Fig. 17) are almost identical, indicating that both dipole and non-dipole fields changed little between the two occasions. Also those transitions studied by more than one author (e.g. Brynjolfsson, Sigurgeirsson, and Wilson *et al.*; Watkins, and Goldstein *et al.* and perhaps Dunn *et al.*) are sufficiently similar that the differences could be explained by different extrusion rates, local magnetic anomalies and perhaps experimental errors.

Further, and more generally, there are a number of similar features: The swinging before the start of the polarity change, eastward and westward swings of longitude during the transition and a general trend westward in many cases.

These features, particularly the sharp east–west swings, lend some support to the dipole model of Creer & Ispir (1970a), which attributes the east–west components of the pole paths to polarity changes of an equatorial dipole. If this equatorial dipole is centred then a reversal of it would give a 180° longitude swing in the pole path but

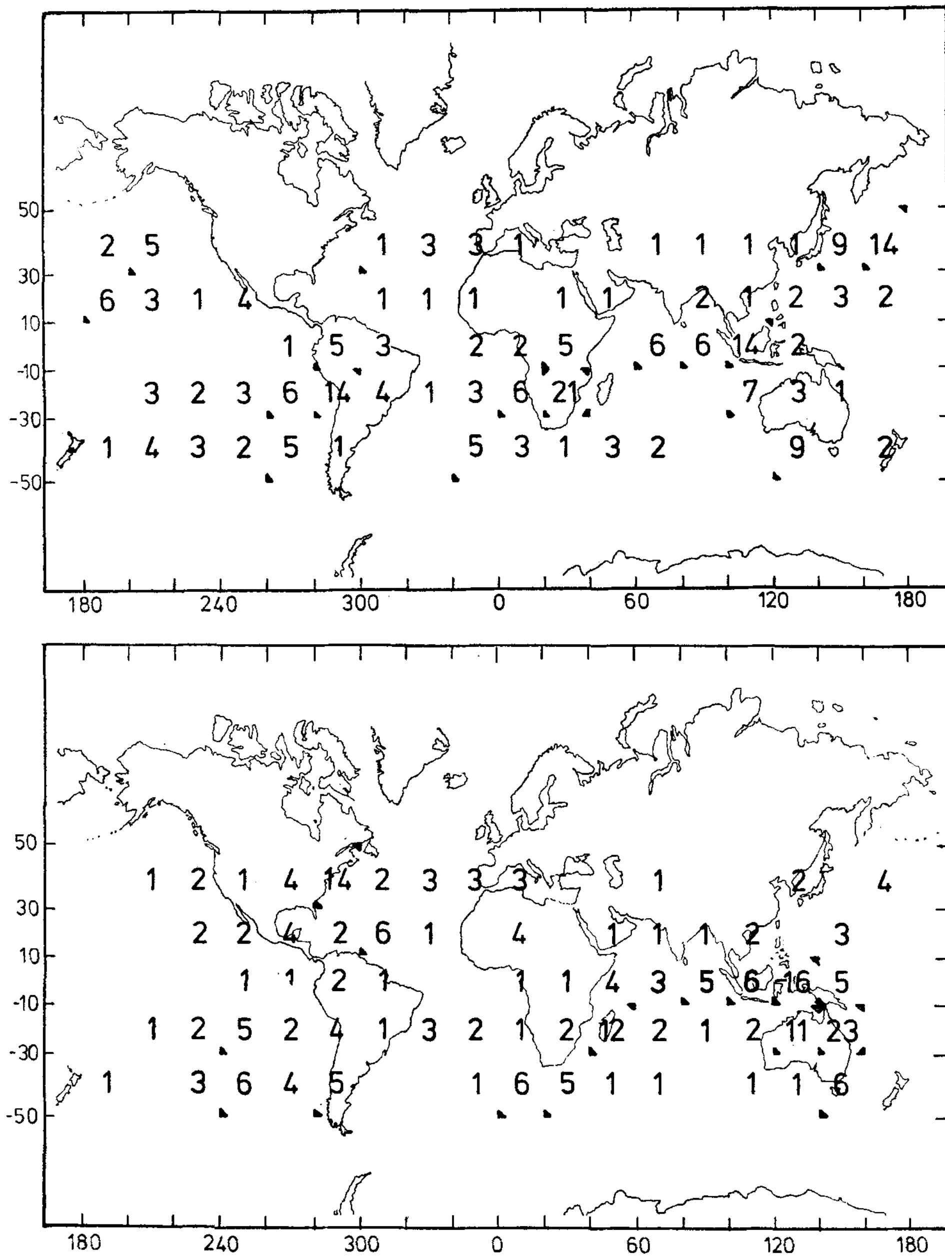

FIG. 18. Intermediate transitional pole positions. The total number of intermediate poles taken from the reported transitions falling within each 20° square is shown. In the lower diagram the longitude of each pole has been changed so that it corresponds to the site being moved to 0° longitude.

5–9; 10–14; 15–19; 20–24

if it is offset the swings would be less than 180°. A change in intensity of a fixed equatorial dipole relative to the axial component would only cause a N–S shift and this model leads to preferred paths in fixed parts of the globe. However, it is clear from the figures that there is no single common pole path for all transitions nor even a preferred sector for transitional poles. The pole paths also do not coincide if they are shifted to correspond to a common site longitude for all observers (Fig. 18) so that the differences are not simply differences in the point of observation. Independent changes of intensity and polarity of both centred dipole components could explain *all* pole paths *only* if the equatorial dipole was allowed to vary its orientation, or 'drift'. This implies two independent equatorial components. Then the pole path for the same transition observed at different sites should be closely similar, but different transitions will in general have different pole paths. This model is consistent with the observations if the explanation for the differences given in the first paragraph of this section is accepted.

If the differences cannot be explained in this manner then the non-dipole field may dominate as proposed by Larson *et al.* (1971). In common with Brynjolfsson (1957) they suggest that the westerly component of pole paths is due to the westward drift component of the secular variation and this has been used to estimate the transition time. If this is accepted, then the easterly swings could imply that at some times there was an easterly drift of the secular variation. The model of Larson *et al.* (1971) could be easily modified to incorporate an easterly drift but the rapid eastward and westward swings observed require more than a single non-dipole component drifting at $0{\cdot}2°\,a^{-1}$.

Neither model can explain the observed pole paths satisfactorily but a hybrid consisting of independently reversing axial and equatorial dipoles together with a steadily drifting non-dipole component might explain the observations.

(ii) *Field strength*

Most authors report a reduction of either the intensity of magnetization or the ancient magnetic induction during the transition and there are several reports of a large magnetic induction just before the polarity change (e.g. Kaporovich *et al.* 1966; Prevot & Watkins 1969).

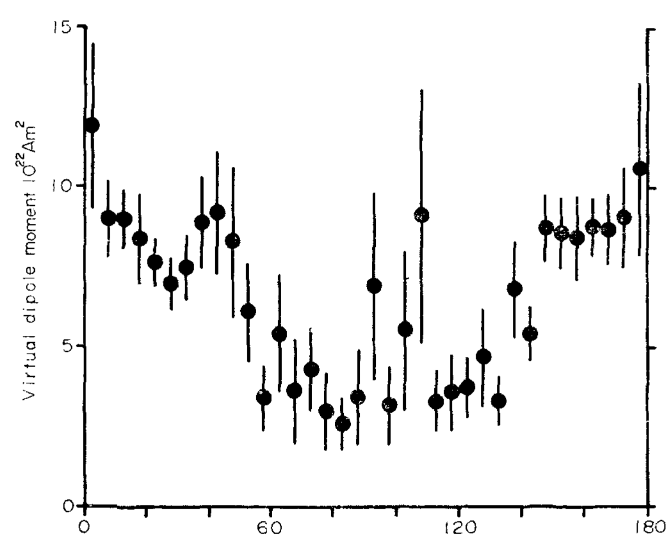

Fig. 19. Virtual dipole moment (10^{22} Am^2) as a function of polar colatitude.

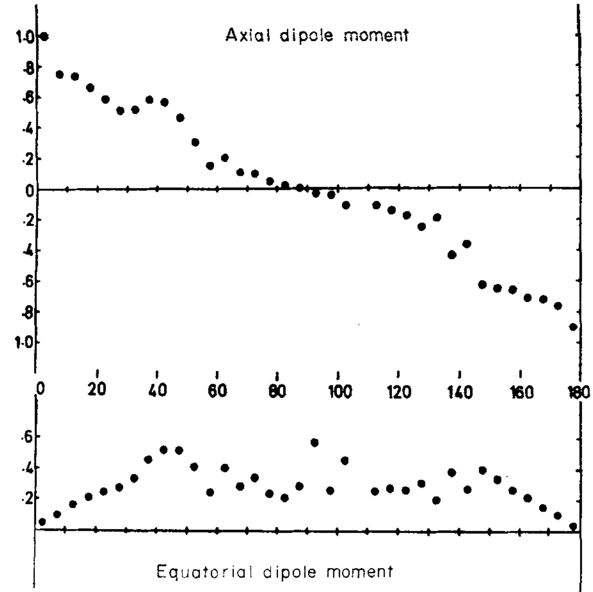

FIG. 20. Axial and equatorial components of the virtual dipole moment as functions of polar colatitude.

Dagley & Wilson (1971) and Wilson *et al.* (1972b) have discussed the evidence from Iceland relevant to the statistical variation of the dipole moment of the Earth with VGP colatitude. The data indicated that during a transition the strength of the dipole moment decreases and then increases again (Fig. 19).

Treating the dipole as the sum of axial and equatorial components (Fig. 20), the axial component decreases approximately linearly with colatitude passing through zero when $\theta = 90°$. On closer inspection there appears to be a linear decrease to half strength between $\theta = 0$ and $\theta = 30°$. There is a similar change between 150° and 180° but with a slightly different slope. At $\theta = 40°$ there is a peak and at $\theta = 140°$ there is a distinct change of slope. Between these two regions ($55° < \theta < 125°$) there is a linear change.

These three intervals also appear in the equatorial dipole. For $0 < \theta < 40°$ and $145° < \theta < 180°$ the changes of strength are linear with the same slope. Between 55° and 125° the strength of the equatorial dipole is more or less constant (could this be a statistically constant 'non-dipole' feature?).

These three intervals, corresponding to normal, intermediate and reversed polarity, show a marked similarity to the three intensity stages proposed by Larson *et al.* (1971) already noted earlier in this paper. The slope of the axial dipole moment-VGP colatitude curve (Fig. 20) between 0° and 30° is consistent with a change of moment from 100 per cent at $\theta = 0°$ to 20 per cent at $\theta = 40°$ where the change from normal to intermediate is proposed.

The peak in the dipole moment at ~40° recalls the high field strengths reported by Prevot & Watkins (1969) and Kaporovich *et al.* (1966) just prior to a change in polarity.

(iii) *Polarity inversions and volcanic activity*

Dagley *et al.* (1967) estimated that allowing for the overlap of their Icelandic profiles the total of 1079 lavas collected represented about 726 'time independent' flows. Since the overall time represented is 12 Ma (Moorbath, Sigurgeirsson &

Goodwin 1968) one lava was extruded every 16500a on average. This means that if the average time taken for the field to reverse is a few thousand years (4600a (Cox 1968); 2000a (McElhinny 1971)) many transitions will not be recorded.

On the other hand some of the transitions observed are recorded in considerable detail so that either those particular transitions took a long time to complete or they coincided with a period of increased volcanic activity.

Is there possibly a link between volcanic activity and the inversion of the magnetic field? (see for example Watkins 1965b).

(iv) *Sense of polarity changes and stability of the field*

The entries in Table 2 satisfy our criteria for transition zones. The observations clearly show a predominance of reversed to normal transitions. Allowing for those cases where the same transition has been sampled, there are 6 $N \rightarrow R$ and 17 $R \rightarrow N$ (5 $N \rightarrow R$ and 15 $R \rightarrow N$ minimum if entries 1 and 5 be identified with 12, and 7 with 7a). The probability of this distribution is 1 : 83 (1 : 68 for 5 $N \rightarrow R$; 15 $R \rightarrow N$). This observation should be considered together with imbalance of shallow reverse and shallow normal directions noted by Creer & Ispir (1970b) in Japan and Ade-Hall *et al.* (1972), Wilson 1970 and Wilson, Dagley & Ade-Hall (1972a) for the British Tertiary Province as well as with the asymmetry of the virtual dipole moment—VGP colatitude curve (Wilson *et al.* 1972b).

Table 2

Transition zones

	Author	Source and location	Sense	Age
Tertiary				
1	Dunn *et al.*	Intrusion, USA	$R \rightarrow N$	14·7±1·0
2	Heinrichs	Lavas, USA	$R \rightarrow N$	6·8
3	Ito *et al.*	Intrusion, USA	$R \rightarrow N$	8·2±0·5
4	Kaporovich *et al.*	Sediments, USSR	$N \rightarrow R$	
5	Larson *et al.*	Lavas, USA	$R \rightarrow N$	15
6	Momose		$R \rightarrow N$	
7	Sigurgeirsson	Lavas, Iceland	'$N_4 \rightarrow R_3$'	
7a	Wilson *et al.*	Lavas, Iceland	'$N_4 \rightarrow R_3$'	
8	Sigurgeirsson Brynjolfsson Wilson *et al.*	Lavas, Iceland	$R_3 \rightarrow N_3$	
9	Sigurgeirsson	Lavas, Iceland	$R_2 \rightarrow N_2$	
10	Sigurgeirsson	Lavas, Iceland	$N_2 \rightarrow R_1$	
11	Wilson *et al.*	Lavas, Iceland	$R_5 \rightarrow N_5$	
12	Watkins Goldstein *et al.*	Lavas, USA	$R \rightarrow N$	15·1±0·3
13	Wellman *et al.*	Lavas, Australia	$R \rightarrow N$	
14	Dagley *et al.* (see Table 1)	Lavas, Iceland	$R \rightarrow N$ (4) $N \rightarrow R$ (2)	
Pre-Tertiary				
15	van Zijl *et al.*	Lavas, S. Africa	$R \rightarrow N$	Triassic–Jurassic
16	Vlasov *et al.*	Sediments, USSR	$R \rightarrow N$ (2)	Devonian
		Totals	$R \rightarrow N$ 17 (15) $N \rightarrow R$ 6 (5) all 23 (20)	

Why should there be this imbalance? If transitions in one sense are more often recorded, do transitions in this sense take longer or are they accompanied by greater igneous activity than those in the opposite sense? In either case why should there be a correlation with the sense of the change?

One possible explanation is that the reversed mode is less stable than the normal mode. In this case the system would not stay in the reversed mode for long and many attempted inversions would be observed. Not all these would be successful if there was a ' barrier ' to the normal state which had to be surmounted.

The shallow reversed directions (Creer & Ispir; Ade-Hall *et al.*; Wilson; Wilson, Dagley & Ade-Hall) may indicate a stable or metastable mode for the field different from either normal or reversed.

Conclusions

A choice of models is not possible with the present data but we believe it is possible to make the following conclusions.

(i) The dipole field, although a time-average axial dipole, is better described as the sum of three-dipole components which can vary independently. A two-component model with a *fixed* equatorial component is not supported by the data.

(ii) During a transition the total intensity of the field at first decreases and then increases again as the opposite polarity is established with transitory increases in strength just before the polarity change.

(iii) The very low magnetic inductions inferred for samples of intermediate polarity suggest that if the non-dipole field does persist when the axial dipole field becomes small then it too decreases in strength. It is not possible to say whether the non-dipole field predominates at any time during the transition.

(iv) The reversed and normal modes are not equally stable.

There is still a relative dearth of reliable field intensity data for transition intervals. The methods of determining ancient field strengths need to be developed so that a reliable value can be determined for every sample collected. Then transition intervals can be studied intensively to give a fuller picture of the field during a reversal.

The data on transition intervals discussed in this paper are those known to us at the time of writing. We would like to receive data for any omitted or more recently established.

Acknowledgments

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