Geophys. J. Int. (2004) **156,** 426–430 doi: 10.1111/j.1365-246X.2004.02183.x

FAST TRACK PAPER

Flow patterns in the Siberian traps deduced from magnetic fabric studies

J.-P. Callot,[1,*] E. Gurevitch,[2] M. Westphal[3] and J.-P. Pozzi[4]

[1] *Ecole Normale Supérieure, Laboratoire de Géologie, UMR* 8538, 24 *Rue Lhomond,* 75231 *Paris, France. E-mail: j-paul.callot@ifp.fr*
[2] *VNIGRI, Laboratory of Paleomagnetism and Paleoreconstruction, Liteiny,* 191104 *St Petersburg, Russia*
[3] *EOST, UMR* 7516, *IPGS,* 5 *Rue René Descartes,* 67084 *Strasbourg, France*
[4] *Ecole Normale Supérieure, Laboratoire de Géologie, UMR* 8538, 24 *Rue Lhomond,* 75231 *Paris, France*

Accepted 2003 November 4. Received 2003 October 20; in original form 2003 June 23

SUMMARY

The Siberian traps rank among the largest flood basalt provinces in the world. Major magmatic activity is restricted to several short periods of less than 1 Myr around the Permo-Triassic boundary. We measured the anisotropy of magnetic susceptibility (AMS) of 183 basaltic samples from 28 individual lava flows belonging to the northwestern part of the flood basalt province, in order to test the reliability of such data in structural interpretation. These preliminary AMS data show a remarkably consistent pattern of magnetic lineations, that likely reflect the primary flow-related texture of the basalt. Our results also emphasize that AMS data are consistent with the well-documented petrological and geochronological data. The inferred flow directions are also consistent with flow directions expected from isopach maps. Our results suggest that the entire 2 km-thick lava pile was fed by fissure eruptions located in the rifted basin that bound the Siberian platform, and was controlled by topographical features, particularly major rift zones.

Key words: anisotropy, lava flow, magnetic susceptibility, Siberian traps.

INTRODUCTION

Large igneous provinces (LIP) include large areas covered with flood basalt such as the Deccan, Paranà-Etendeka and Siberian traps (Coffin & Eldholm 1994; Wignall 2001), but despite much recent work on LIPs, several aspects of flood volcanism remain unclear. Flood basalt provinces are generally associated with the birth of hotspots and continental lithosphere rifting, and thus belong to the controversy concerning the relative importance of rifting and plume–lithosphere interaction during continental break-up (Burke & Dewey 1973; Morgan 1981). Several workers view the spatial and temporal coincidence between LIP emplacement and lithosphere break-up as an expression of the causal link between the impact of a plume-head below the lithosphere and the rifting of the plate, as soon as this is allowed by the boundary forces (e.g. Richards *et al.* 1989; Courtillot *et al.* 1999). On the other hand, the rifting of the lithosphere, near or above an abnormally hot mantle or a mantle plume, should allow an isentropic upwelling and melting of the hot material below the rift zone that could result in flood volcanism (White & McKenzie 1989; Kent *et al.* 1992).

Although flood basalt provinces are the largest outpouring of lava in the world, it is noteworthy that the mechanisms of basaltic magma transfer through the lithosphere are poorly understood or addressed; despite that, the chronological and petrological characteristics of the provinces are generally well studied. This is true for the Siberian traps, which are among the most voluminous flood basalt provinces. Petrological, geochemical, and chronological studies of the Siberian traps are numerous (e.g. Renne & Basu 1991; Fedorenko *et al.* 1996; Westphal *et al.* 1998; Kravchinsky *et al.* 2002), but structural data are scarce particularly concerning the location and geometry of the feeder zones (Fedorenko 1991; Fedorenko *et al.* 1996). In the present study, we use the anisotropy of magnetic susceptibility (AMS) data from the western part of the Siberian traps as a structural indicator to constrain the magma dynamics. AMS measurements have been used successfully in the characterization of flood basalt emplacement in similar settings (Glen *et al.* 1997; Rochette *et al.* 1999), and may complement the existing structural data set.

THE SIBERIAN FLOOD BASALT PROVINCE

The lavas outcrop over the Siberian platform, from the Taimyr peninsula to the Tunguska syncline (Figs 1a and b). The platform is bounded by rifted basins that opened in the late Permian to early Triassic and filled with lavas and Mesozoic sediments (Sengör &

*Now at: Institut Français du Pétrole, 1–4 Av. de Bois Préau, 92852 Rueil-Malmaison, France.

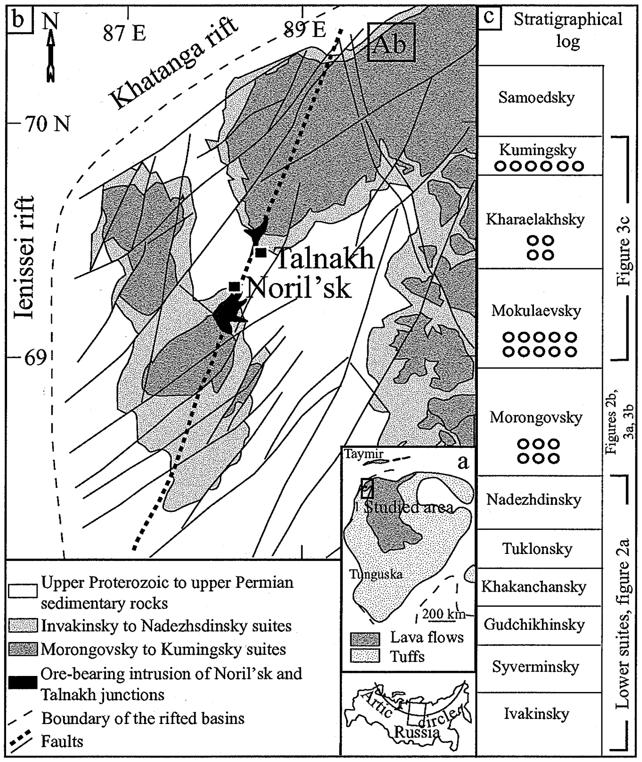

Figure 1. (a) Map showing the location of the studied area within the Siberian traps. (b) Simplified geological map of the Noril'sk area: Ab is the location of the Abagalakh section where flows are sampled; bold line shows the Noril'sk-Kharaelakh fault zone. (c) Schematic not-to-scale log; circles indicate a sampled flow. Modified from Wooden *et al.* (1993). Inset shows extent of the entire province.

Natal'in 1996). Lavas and intrusive rocks cover an area of roughly 1.5×10^6 km^2, with lava flow sequences thickness of 2500 m on average. The present-day estimate of the volume of the extrusives is 2×10^6 km^3, but may have reached up to 4×10^6 km^3 (Fedorenko *et al.* 1996). The Siberian basalts are thought to be the cause of the biologic crisis at the Permo-Triassic boundary (see Wignall 2001).

On the basis of geochemical constraints, the lava succession in the Noril'sk region has been divided into 11 suites (review in Lightfoot *et al.* 1990; Fedorenko *et al.* 1996) (Fig. 1c). The lower three suites (Ivakinsky to Gudchikhinsky) consist of 250–500 m of sub-alkalic to picritic basalts, which show a progressive decrease of fractional crystallization. The next three suites (Khakanchansky to Nadezhdinsky) are picritic to tholeitic basalts extending over 250–600 m thick. Those six suites are characterized by an elongated pattern of isopachs aligned with the major Noril'sk-Kharaelakh fault, along which differentiated intrusions outcrop (Fig. 2a, Fedorenko & Djuzhikov 1981). The maximum thickness of lava flows is observed northeast of the Noril'sk-Talnakh intrusive complexes (Fig. 2a). Above them lies the major part of the flood basalt sequence (Morongovsky to Kumginsky suites) that consists of 1200–1800 m of tholeiitic lavas contaminated by crustal rocks.

Age determinations give ages close to the Permo-Triassic boundary (248–251 Ma), with a duration of the main outburst of less than 1 Myr (e.g. Renne & Basu 1991; Renne *et al.* 1995). Palaeomagnetic studies confirm the short duration of the main phase which show only one to two reversals (Gurevitch *et al.* 1995). Nevertheless, the deep drill core SG6 situated west of the Noril'sk area shows a significantly longer polarity sequence, indicating that the volcanic activity could have lasted more than 4 Myr (Westphal *et al.* 1998), although the major part of the basaltic sequence shows only two polarities, consistent with a duration of less than 1 Myr.

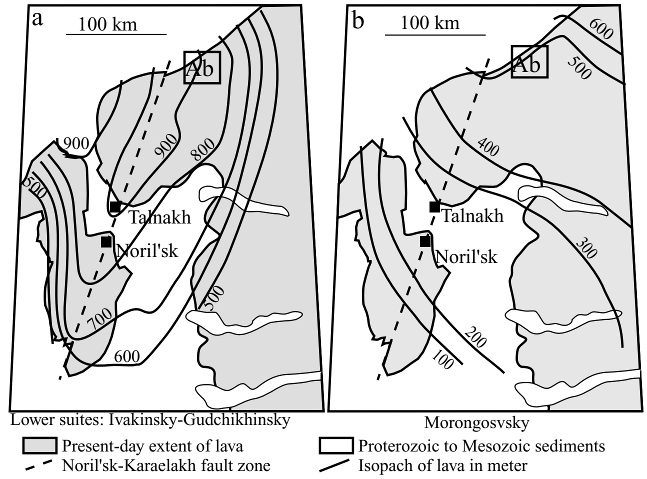

Figure 2. Isopach map for the lower three suites (left) and the Morongovsky basalts (right), modified from Lightfoot *et al.* (1990). Note the elongated pattern of isopach parallel to the Noril'sk-Kharaelakh fault zone.

AMS AND LAVA FLOW

The anisotropy of magnetic susceptibility (AMS) relates the induced magnetization of a given material to the applied external field. Under low field strength condition, AMS is described by a second order symmetric tensor with three principal values K1 (maximum), K2 (intermediate) and K3 (minimum). AMS arises from the preferred orientation of the most susceptible minerals, from the distribution of those minerals and from the preferred orientation of their lattices. The former properties relate the AMS signal to the petro- and crystalo-fabrics of the studied rock, and, due to the high sensitivity of modern apparatuses, enable the measuring of fabric of apparently weak anisotropy rocks. AMS has thus been used as an easily measured and statistically representative structural data, in various geological settings and rock types: i.e. strained sedimentary and metamorphic rocks, plutonic and effusive rocks deformed in the magmatic and plastic state as well, (for comprehensive reviews see Hrouda 1982; Rochette *et al.* 1992; Tarling & Hrouda 1993; Borradaile & Henry 1997).

AMS data have been particularly used in mafic rocks to infer magma emplacement dynamics, following the assumption that AMS is controlled by the shape preferred orientation of magnetically susceptible Fe-Ti oxides, such as magnetite, whose AMS is controlled only by the grain shape. This is supported by numerous studies of dykes and lava flows (Staudigel *et al.* 1992; Canon-Tapia *et al.* 1997; Varga *et al.* 1998). In basaltic rocks, however, AMS may reflect the distribution, rather than shape, preferred orientation of late crystallizing oxides. Fortunately, in such cases the oxides usually mimic the preferred orientation of the flow-related matrix of pre-existing silicate minerals (Hargraves *et al.* 1991). However, AMS data should be considered with care, as it has recently been clearly demonstrated that the magnetic lineation can be completely unconnected to the flow lineation (Geoffroy *et al.* 2002), and instead represent an intersection between planar zones of oxides distribution linked to the rock fabric (Callot & Guichet 2002).

The magnetic fabric of a lava flow is assumed to be flow-related when the magnetic foliation plane lies close to the lava flow plane

(Rochette *et al.* 1992). If the foliation plane shows an imbrication with respect to the basal plane of the flow, the magnetic lineation should plunge in the up-flow direction (Hillhouse & Wells 1991). In the absence of any imbrication, the magnetic lineation is tentatively correlated to the flow lineation, without indication of the flow direction (Glen *et al.* 1997).

SAMPLING AND MEASUREMENTS

Samples were collected from the four tholeiitic suites of Morongovsky, Mokulaevsky, Kharaelakhsky and Kumginsky, in the Abagalakh river section of the Siberian traps, where the flows are approximately horizontal (Fig. 1). The samples are distributed over more than 1100 m of lava flows. At least 4 to 10 cores were drilled from each site, corresponding to one cooling unit, the samples being distributed across the flow to ensure that the results are representative of the flow fabric. Samples were oriented using a magnetic compass and, whenever it was possible, with a sun compass. Afterwards, cores were cut to give standard 2.2 × 2.5 cm cylindrical specimens (diameter*length).

AMS measurements were performed on 183 unheated specimens distributed over 26 flows (see Table 1). From 4 to 21 samples were measured for each site (mean value 7). AMS measurements were obtained on a KLY3S apparatus (Geofysika, Brno), which ensures, for high susceptibility samples such as mafic rocks, reliable directions down to anisotropy ratios of 1.001. Statistical processing at the site level was performed using the tensorial mean of Jelinek (1978), but in some cases, the small number of samples precluded an accurate estimate of the means and confidence ellipses for the susceptibility axes. Susceptibility versus temperature curves (K–T curves) were measured with a CS3 apparatus.

RESULTS

Magnetic susceptibility is in general high, ranging from 6×10^{-3} SI to 5×10^{-1} SI volume units (mean value 1.7×10^{-1} SI), indicating a dominant contribution of ferromagnetic minerals to the signal. K–T curves show Curie temperatures in the range 540°–580°C, typical of low substituted titano-magnetites. The degree of anisotropy is in general low, with values less than 1.06 for site means ($P = K1/K3$). The measured magnetic ellipsoids are of oblate shape. Magnetic stratigraphy of the Abagalakh section will be reported elsewhere but the present section records only a single normal polarity.

In all the studied flows, magnetic fabrics show a magnetic foliation plane close to the basal plane of the flow, and thus likely reflect the flow-related petro-fabric. Despite the generally small number of samples measured for each flow (typically seven or fewer), the magnetic fabrics are rather well grouped. It is generally not possible to infer an imbrication of the magnetic foliation plane with respect to the stratigraphic plane, except for the lowermost flows sampled in the Morongovsky suite (Fig. 3a, flows 2 and 3). In this case, it is possible to relate the magnetic fabric to the flow direction (Hillhouse & Wells 1991; Le Pennec *et al.* 1998). The other 24 flows yield only a flow lineation through the orientation of their mean K1. The orientations of the mean K1 axes are summarized in Fig. 3(b) for Morongovsky and Fig. 3(c) for the 21 remaining flows. As it was not possible in general to infer flow directions, we will restrict the discussion to the flow lineation.

DISCUSSION AND CONCLUSIONS

The elongated pattern of the lowest suite isopachs (Ivakinsky–Nadezhdinsky, Fig. 2), which are centred on the Noril'sk fault zone

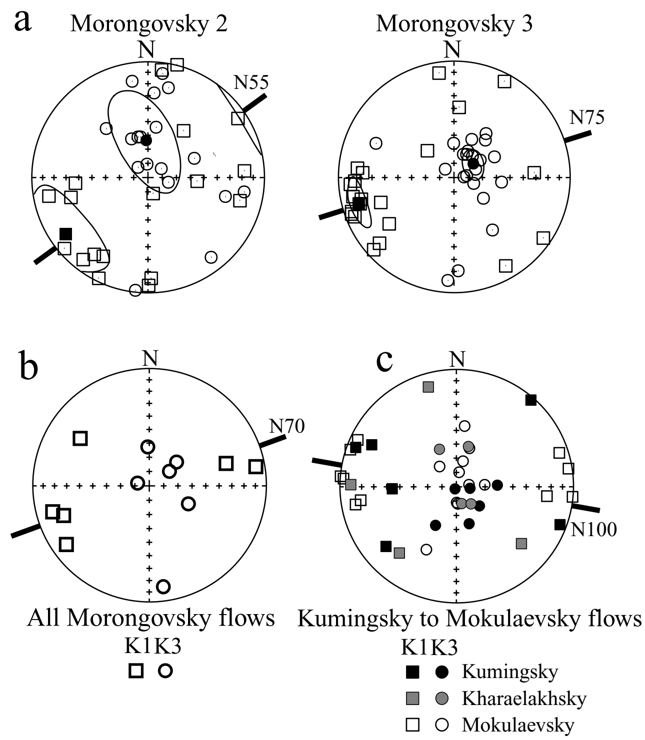

Figure 3. (a) AMS results for the two lower flows (2 and 3) of the Morongovsky unit, which show an imbrication of magnetic foliation, compatible with a SW to NE flow direction. (b) Mean K1 and K3 for the five Morongovsky flows. (c) Mean K1 and K3 for the 21 remaining flows. Thick line is the mean K1 azimuth.

(Fedorenko & Djuzhikov 1981), strongly suggests a fissural mode of lava emplacement, with feeder zones that parallel to the Noril'sk fault zone and a main feeding centre located in the Talnakh region. But, this also suggests that this elongated region was strongly subsiding during the magma emplacement, forcing the flows to concentrate along the fissural rift zone. Apparently, lava were deposited with a flat attitude over several tens of kilometres during the entire pile construction, indicating that a high rate of lava emplacement was compensated by a high rate of subsidence, i.e. *ca* 3500 m Myr^{-1} (Fedorenko *et al.* 1996).

The lowermost two flows of the Morongovsky suite give well constrained data that show an imbrication pattern consistent with a ENE directed flow of magma (Fig. 3a, geographic coordinates, the lava flow being horizontal on average with less than 5° of dip), and consistent with the trend of mean K1 axes of the other flows of the suite (Fig. 3b). Note that for the flow 2, the mean K3 may not be statistically resolved from the vertical axes. This suggests that lavas of the Morongovsky suite flowed from WSW to ENE, away from a feeder zone located in the vicinity of Noril'sk. This flow pattern roughly agrees with the isopach distribution, which shows a thickening of the suite toward a depocentre located NNE of the Noril'sk zone, the lower tuff units being chemically related to the Noril'sk 1 intrusion (Wooden *et al.* 1993).

The three other suites present a generally consistent pattern of K1 orientation that is somewhat surprising (Fig. 3c), given that the flow of lava can vary through time at a given location due to local topographic features, or variations in the style of eruption (radial flow from vents vs. fissure perpendicular flows). Except for the four flows of the Kharaelakhsky suite, these data are remarkably homogeneous and consistent with a roughly E–W flow lineation.

Table 1. Summary of AMS results: number of samples (N); mean susceptibility in SI units (Km); lineation parameter, K1/K2 (L); foliation parameter, K2/K3 (F); eccentricity parameter (P'); flattening parameter (T); standard deviation for the parameter (std); azimuth/dip for the magnetic axes (D/I); angle for the confidence ellipse (E1/E2).

FLOW	N	Km(10-3SI)	L	Std(10-3SI)	F	Std(10-3SI)	P'	Std(10-3SI)	T	Std(10-3SI)	K1(D/I)	K1 E1	K1 E2	K3(D/I)	K3 E1	K3 E2	Thickness
mor2	18	240.70	1.01	9.73	1.01	8.01	1.01	12.77	−0.05	487.19	235/14	30	21	356/64	41	19	6
mor3	21	153.80	1.01	5.27	1.01	7.74	1.02	7.96	0.33	469.96	255/15	15	7	56/74	11	7	5
mor6	7	6.70	1.01	7.31	1.01	7.16	1.02	13.19	0.02	308.40	80/8	36	23	275/81	55	16	25
mor8	7	12.90	1.01	4.93	1.02	7.15	1.03	5.15	0.42	399.25	251/23	29	6	50/66	22	8	17
mor14	5	7.60	1.01	9.43	1.02	13.67	1.02	14.69	0.50	514.02	74/32	68	24	173/14	53	16	10
mor15	6	7.90	1.02	10.23	1.03	6.37	1.05	10.30	0.22	270.01	304/9	17	10	117/60	13	7	40
mok1	6	92.40	1.01	7.97	1.03	6.91	1.05	14.12	0.44	140.12	262/18	19	4	89/71	13	6	20
mok2	6	553.00	1.01	26.21	1.01	19.43	1.02	30.09	0.26	585.66	275/0	68	58	81/7	59	31	35
mok3	5	225.90	1.00	0.55	1.02	5.79	1.02	6.38	0.92	154.66	217/38	75	15	7/48	24	10	18
mok4	5	101.10	1.01	3.58	1.02	2.19	1.02	4.60	0.53	171.22	289/4	26	4	179/78	13	6	22
mok5	5	283.90	1.01	5.45	1.01	5.03	1.02	3.74	−0.07	468.87	295/7	17	7	88/82	29	7	10
mok9	4	129.20	1.01	1.91	1.00	0.82	1.01	2.65	−0.24	102.65	81/3	46	21	183/78	26	10	6
mok10	6	155.20	1.01	10.19	1.00	5.55	1.01	15.77	−0.49	268.55	96/23	41	9	206/39	60	11	22
mok11	5	246.70	1.02	11.41	1.04	15.22	1.06	23.33	0.28	187.20	72/8	44	18	316/72	25	6	8
mok13	4	82.40	1.01	4.11	1.01	3.16	1.01	4.24	0.17	404.59	274/3	62	13	13/73	30	21	7
mok17	6	101.50	1.00	5.88	1.02	5.05	1.02	1.33	0.84	459.51	260/13	57	17	18/63	17	10	15
kahr2	6	142.90	1.01	2.32	1.02	8.09	1.02	9.64	0.52	163.09	221/26	42	11	16/62	34	15	16
kahr3	6	142.20	1.01	3.06	1.02	4.45	1.03	5.53	0.22	160.94	271/10	10	4	144/73	22	8	10
kahr6	5	201.50	1.01	1.58	1.04	11.94	1.06	14.10	0.48	68.48	344/13	28	12	167/77	50	13	16
kahr10	6	176.30	1.00	4.73	1.01	5.00	1.02	6.41	0.69	454.07	131/27	69	21	333/62	30	18	20
kum1	5	172.90	1.00	3.74	1.04	12.54	1.05	15.96	0.88	122.10	230/22	82	17	90/62	34	18	15
kum3	7	129.70	1.01	13.44	1.00	3.60	1.01	16.22	−0.80	487.15	268/44	38	20	163/15	72	27	25
kum4	6	276.30	1.00	1.83	1.01	1.72	1.01	1.17	0.36	246.97	296/20	48	13	133/69	26	14	20
kum5	9	135.10	1.00	1.09	1.00	1.79	1.00	1.54	0.59	329.11	41/3	49	34	214/87	38	13	30
kum6	10	319.80	1.01	24.56	1.02	49.99	1.02	68.79	0.45	451.60	110/6	58	61	209/58	67	30	22
kum7	6	219.20	1.00	1.38	1.01	3.78	1.01	3.44	0.36	497.76	291/8	52	15	104/81	24	15	18

This is consistent with feeding either from the eastern part of the trap, or from the western rift zones. The latter is the most likely as there is no evidence for an important feeding centre East of the Abagalakh river. Our data suggest that the Mokulaevsky-Kumginsky flows were presumably fed from the same feeding zone, located in the western rift zones, and probably in a similar fissural manner inferred for the lower suites.

In summary, published field data (isopach maps and geochemical correlations) and our preliminary AMS measurements suggest that the entire lava sequence at Abagalakh was fed from the same elongated zone, located along the northwestern border of the Siberian platform, in the rifted axes blanketed by Mesozoic sediments. They also suggest that, at least for the lower suites, the flow directions were controlled by the topographic expression of a major subsiding zone, likely an active rift zone, as proposed for the Etendeka-Paraná flood basalts (Glen *et al.* 1997). This implies that the onset of volcanism was coeval or preceded by rifting along the pre-existing lithospheric weakness which surrounds the Siberian craton (Sengör & Natal'in 1996). A shift of the depocentre from the elongated Noril'sk basin for the lower suite, to the Khatanga rift for the Morongovsky suite, suggests rapid (i.e. within less than 3 Myr, which is the duration of the main phase of magmatism (Fedorenko *et al.* 1996)) variations in the tectonic activity, and correlates to geochemical changes between the lower and upper series (Lightfoot *et al.* 1990). The AMS data presented here agree well with the available geological information, underlining their usefulness in structural studies of trap emplacement, as has been demonstrated in other magmatic provinces (Glen *et al.* 1997; Rochette *et al.* 1999).

ACKNOWLEDGMENTS

The authors would like to thank H. Horen and G. Cairanne for constructive remarks on an early draft of the manuscript. The thorough reviews by B. Housen and J. Glenn were appreciated.

REFERENCES

Borradaile, G.J. & Henry, B., 1997. Tectonic applications of magnetic susceptibility and its anisotropy, *Earth Sci. Rev.,* **42,** 49–93.

Burke, K. & Dewey, J.F., 1973. Plume-generated triple junctions: key indicators in applying plate tectonics to old rocks, *J. Geol.,* **81,** 406–433.

Callot, J.P. & Guichet, X., 2002. Rock texture and magnetic lineation in dykes, a simple analytical model, *Tectonophysics,* **366,** 207–222.

Canon-Tapia, E., Walker, G.P.L. & Herrero-Bervera, E., 1997. The internal structure of lava flows—insights from AMS measurements II: Hawaiian pahoehoe, toothpaste lava and a'a, *J. Volc. Geotherm. Res.,* **76,** 19–46.

Coffin, M.F. & Eldholm, O., 1994. Large igneous provinces: crustal structure, dimensions, and external consequences, *Rev. Geophys.,* **32,** 1–36.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P. & Besse, J., 1999. On causal links between flood basalts and continental break-up, *Earth planet. Sci. Lett.,* **166,** 177–195.

Fedorenko, V.A., 1991. Tectonic control of magmatism and regularities of Ni-bearing localities on the Northwestern Siberian platform, *Soviet Geol. Geoph.,* **32,** 41–47.

Fedorenko, V.A. & Djuzhikov, O.A., 1981. Ultrabasic-basic volcanism of the Noril'sk region, *Soviet Geol.,* **9,** 98–106.

Fedorenko, V.A., Lightfoot, P.C., Naldrett, A.J., Czamanske, G.K., Hawkesworth, C.J., Wooden, J.L. & Ebel, D.S., 1996. Petrogenesis of the flood-basalt sequence at Noril'sk, north central Siberia, *Int. Geol. Rev.,* **38,** 99–135.

Geoffroy, L., Callot, J.P., Aubourg, C. & Moreira, M., 2002. Divergence between magnetic and plagioclases linear fabrics in dykes: a new approach for defining the flow vector using magnetic foliation, *Terra Nova*, **14,** 183–190.

Glen, J.M.G., Renne, P.M., Milner, S.C. & Coe, R.S., 1997. Magma flow inferred from anisotropy of magnetic susceptibility in the Paranà-Etendeka igneous province: Evidence for rifting before flood volcanism, *Geology,* **25,** 1131–1134.

Gurevitch, E., Westphal, M., Daragan-Suchov, J., Feinberg, H., Pozzi, J.-P. & Khramov, A.N., 1995. Paleomagnetism and magnetostratigraphy of the traps from Taimyr (northern Siberia) and the Permo-Triassic crisis, *Earth planet. Sci. Lett.,* **136,** 461–473.

Hargraves, R.B., Johnson, D. & Chan, C.Y., 1991. Distribution anisotropy: The cause of AMS in igneous rocks?, *Geophys. Res. Lett.,* **18,** 2193–2196.

Hillhouse, J.W. & Wells, R.E., 1991. Magnetic fabric, flow direction, and source area of the lower Miocene Peach Spring Tuff in Arizona, California and Nevada, *J. geophys. Res.,* **96,** 12 443–12 460.

Hrouda, F., 1982. Magnetic anisotropy and its application in geology and geophysics, *Geophys. Surv.,* **8,** 37–82.

Jelinek, V., 1978. Statistical processing of anisotropy of magnetic susceptibility measured on groups of specimens, *Stud. Geophys. Geod.,* **22,** 50–62.

Kent, R.W., Storey, M. & Saunders, A.D., 1992. Large igneous provinces: sites of plume impact or plume incubation, *Geology,* **20,** 891–894.

Kravchinsky, V.A., Konstantinov, K.M., Courtillot, V., Savrasov, J.I., Valet, J.-P., Cherniy, S.D., Mishenin, S.G. & Parasotka, B.S., 2002. Palaeomagnetism of East Siberian traps and kimberlites: Two new poles and palaeogeographic reconstructions at about 360 and 250 Ma, *Geophys. J. Int.,* **148,** 1–33.

Le Pennec, J.-L., Chen, Y., Diot, H., Froger, J.-L. & Gourgaud, A., 1998. Interpretation of anisotropy of magnetic susceptibility fabric of ingnimbrites in term of kinematic and sedimentological mechanisms: An Anatolian case study, *Earth planet. Sci. Lett.,* **157,** 105–127.

Lightfoot, P.C., Naldrett, A.J., Gorbachev, N.S., Doherty, W. & Fedorenko, V.A., 1990. Geochemistry of the siberian trap of the Noril'sk area, USSR, with implication for the relative contributions of crust and mantle to flood basalts magmatism, *Cont. Min. Petrol.,* **104,** 631–644.

Morgan, W.J., 1981. Hotspot tracks and the opening of the Atlantic and Indian oceans, in *The Sea*, Vol. 7, pp. 443–487, ed. Emiliani, C., Wyley InterScience, New York.

Renne, P.M. & Basu, A.R., 1991. Rapid eruption of the Siberian traps flood basalts at the Permo-Triassic boundary, *Science,* **253,** 176–179.

Renne, P.M., Zichao, Z., Richards, M.A., Black, M.T. & Basu, A.R., 1995. Synchrony and causal relations between Permian-Triassic boundary crisis and Siberian flood volcanism, *Science,* **269,** 1413–1416.

Richards, M.A., Duncan, R.A. & Courtillot, V., 1989. Flood basalts and hot-spot tracks: plume heads and tails, *Science,* **246,** 103–107.

Rochette, P., Aubourg, C. & Perrin, M., 1999. Is this magnetic fabric normal? A review and case studies in volcanic formations, *Tectonophysics,* **307,** 219–234.

Rochette, P., Jackson, M. & Aubourg, C., 1992. Rock magnetism and the interpretation of anisotropy of magnetic susceptibility, *Rev. Geophys.,* **30,** 209–226.

Sengör, A.M.C. & Natal'in, B.A., 1996. Paleotectonics of Asia: fragments of a synthesis, in *The Tectonic Evolution of Asia*, pp. 486–640, eds Yin, A. & Harrison, M., Cambridge University Press, Cambridge.

Staudigel, H.G., Gee, J.S., Tauxe, L. & Varga, R.J., 1992. Shallow intrusive direction of sheeted dikes in the Troodos ophiolite: anisotropy of magnetic susceptibility and structural data, *Geology,* **20,** 841–845.

Tarling, D.H. & Hrouda, F., 1993. *The magnetic anisotropy of rocks*, Chapman and Hall, London, p. 217.

Varga, R.J., Gee, J.S., Staudigel, H. & Tauxe, L., 1998. Dykes surfaces lineations as magma flow indicators within the sheeted dyke complex of the Troodos ophiolite, Cyprus, *J. geophys. Res.,* **103,** 5241–5256.

Westphal, M., Gurevitch, E., Samsonov, B., Feinberg, H. & Pozzi, J.-P., 1998. Magnetostratigraphy of the lower Triassic volcanics from deep drill SG6 in western Siberia: evidence for long-lasting Permo-Triassic volcanic activity, *Geophys. J. Int.,* **134,** 254–266.

White, R.S. & McKenzie, D.P., 1989. Magmatism at rift zones: The generation of volcanic continental margins and flood basalts, *J. geophys. Res.,* **94,** 7685–7729.

Wignall, P.B., 2001. Large igneous provinces and mass extinctions, *Earth Sci. Rev.,* **53,** 1–33.

Wooden, J.L. *et al.*, 1993. Isotopic and trace-element characterization of the Siberian flood basalts of the Noril'sk area, *Geochim. cosmochim. Acta,* **57,** 3677–3704.