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Mantle Plumes, Continental Flood Basalt Volcanism and Palaeomagnetism

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ABSTRACT

Mantle plumes played a major role in plate tectonic processes leading to the breaking-up of super continents (Rodinia, Pangaea, Gondwanaland etc.) during the geological past. Especially more so in case of the Pangaea break-up during the Phanerozoic. Several cubic kilometers of basaltic magma has been poured out in short period in very quick succession over large areas covering million square kilometers. The hotspot tracks of moving continents over the mantle plumes reveal the direction of movement of the continents with progression in age. These continental flood basalts record in them signatures of the geomagnetic field at the time of their formation giving a clue to their geographic location and nature of the geomagnetic field. An examination of these magnetic signatures in some of the continental flood basaltic volcanics reveals that the Cenozoic period continental flood basalts recorded frequent reversal of the geomagnetic field while the pre-Cenozoic continental flood basalts recorded fewer geomagnetic field reversals. A detailed summary of the area of extent of continental flood basalt, radiometric dates and geomagnetic field reversals etc. of the known continental flood basaltic provinces of the Phanerozoic era are presented.

INTRODUCTION

Mantle Plumes are narrow upwelling currents in earth's mantle having a diameter of ~ 100 km and rising from low density thermal boundary layer located either at 2900 km depth i.e., near the core-mantle boundary or at 660 km deep phase transition boundary (or seismic discontinuity) (Stacey & Loper 1983; Workshop on Plume Tectonics 2000). Hotspots are the surface manifestations of the mantle plumes recognized as locus of volcanism that remains nearly stationary (Wilson 1963; Torsvik et al. 1998) relative to the moving lithospheric plates. However, recent studies have indicated that hotspots may not be as fixed as thought and a relative movement, though small, has to be invoked to explain certain observations (Christensen 1991; Torsvik et al. 1998). The arrival of a plume head at the base of the lithosphere results in uplift, eruption of flood basalts and some times continental break-up (Sleep 1990, 1995). Presence of low velocity seismic zones in the upper mantle implies high temperatures in the rock and they associate this zone with plume head that produces flood basalts (Kennet & Widiyantoro 1999; Van Decar, James & Asumpacao 1995). Fig.1 shows the global distribution of continental flood basalt volcanics and their inferred hotspot sources.

Several million cubic kilometers (10^6 x km^3) of lava was poured out in a very short period of time over large areas during continental flood basalt activity. It is providing an opportunity to study the magnetic field recorded by them and the nature and eruption rate of lava. The earth's magnetic field has changed several times in the geological past, more frequently during certain periods (frequent reversals) while remained constant during other periods (superchrons). Flood basalt volcanism from a hotspot or mantle plume, record fewer reversals of the geomagnetic field over large thickness and over large areas. The palaeomagnetic record observed in several flood basaltic provinces such as the Siberian Traps (Permo-Triassic), the Karoo Volcanics (Triassic-Jurassic), the Parana Basalts (Jurassic-Cretaceous), the Deccan Traps (Late Cretaceous-Early Tertiary), the Ethiopian Traps (Oligocene-Miocene) and the Columbia River Basalt Group (Middle Miocene) are examined and presented here to infer the nature and rate of volcanic eruption.

The Siberian Traps

The Siberian Traps with a surface area of 1.5 x 10^6 km^2 and the cumulative thickness is more than 3 to 4 km are widespread in the Tunguska syncline of the Siberian Platform and on Gorny – Taimyr, consist of hypabyssal intrusions and effusive and explosive facies of magmatism (Fig.2a). They comprise of five suites, the I and II suites being more explosive. The III and IV suites are widespread while the V suite occurs in a restricted area (Zolotukhin & Al'Mukhamedov 1988). These volcanics are of Permo-Triassic age (palaeontological). Baksi & Farrar (1991) reported Ar-Ar ages from the Tunguska basin that range between 238.4 $\pm$ 1.4 Ma and 229.9 $\pm$ 2.3 Ma. Dalrymple et al. (1991, 1995) studied the age spectrum of lavas and intrusives from the Noril'sk and Talnaka areas by Ar-Ar method and obtained an age of 249 $\pm$ 2 Ma. Ar-Ar ages from three sections of traps in Noril'sk and Putorana regions by Renne & Basu (1991) range around 248.4 $\pm$ 2.4 Ma. U-Pb ages on zircons from an intrusion from Noril'sk region by Campbell et al. (1992) shows an age of 248 $\pm$ 3.7 Ma.

Palaeomagnetic record in the Siberian Traps was investigated by Gurevitch et al. (1995) from the best-exposed section in

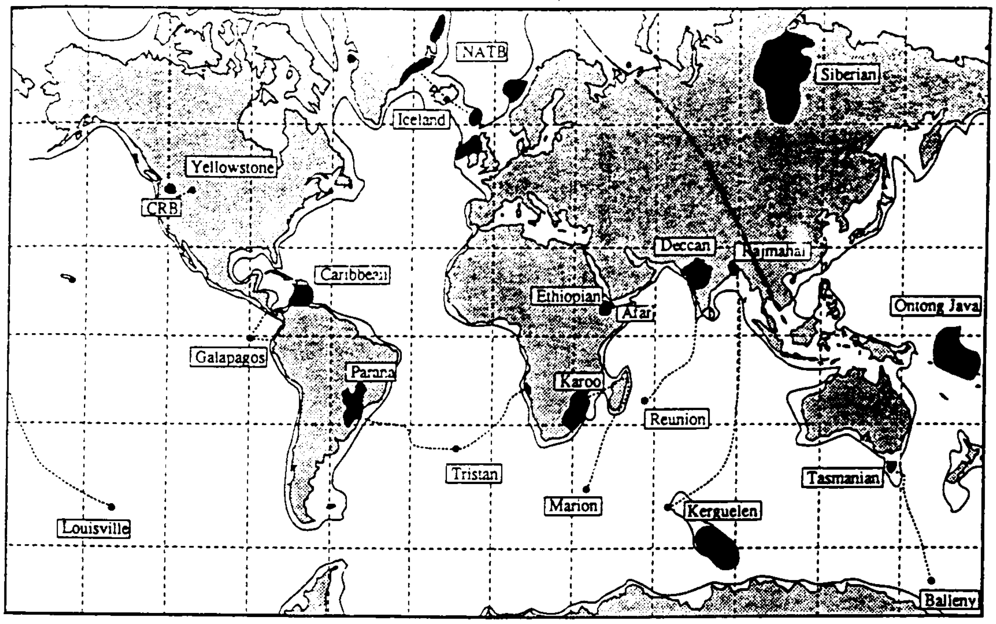


Figure 1. Worldwide distribution of continental flood basalt volcanic provinces erupted in the last 250 Ma and associated hotspots. Note that while many occur along continental margins, others have formed in the continental interiors or in ocean basins. CRB are Columbia River Basalts and NATB are North Atlantic Tertiary Basalts (after Duncan & Richards 1991).

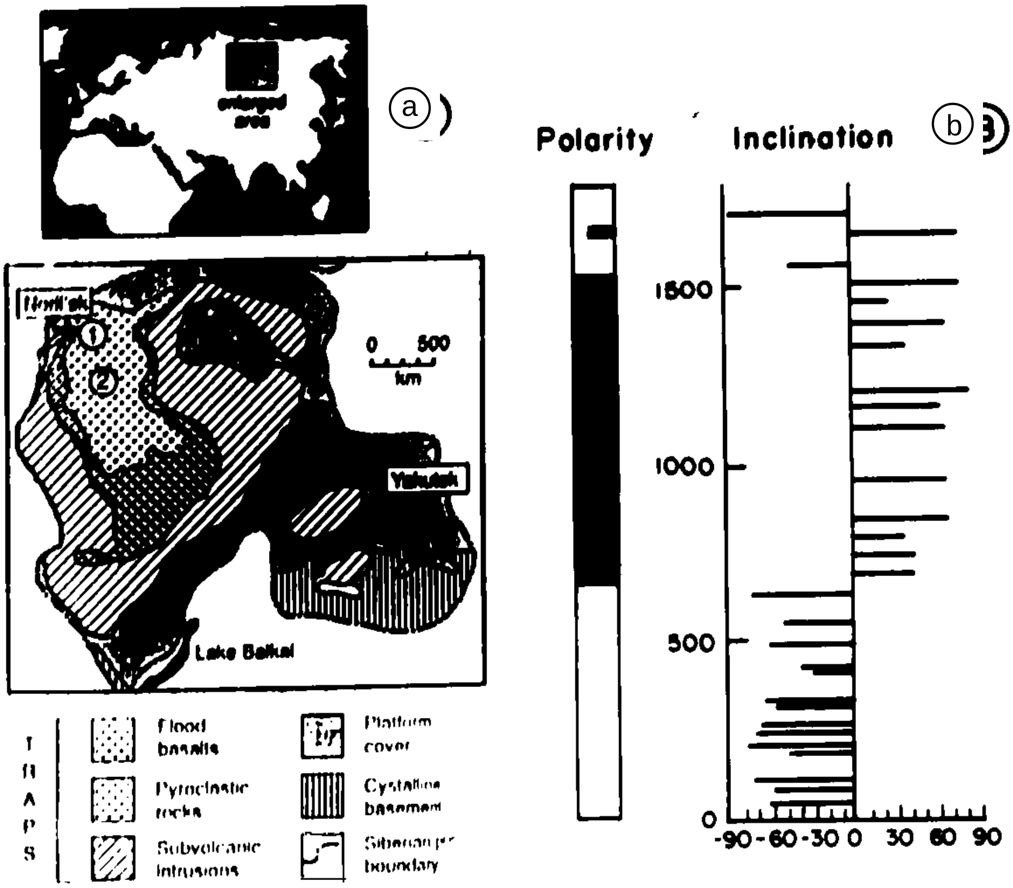
western Taimyr in the middle Syradasay section. Basaltic flows here are exposed over a vertical section of 1700 m. The magnetic polarity sequence of their ChRM vectors along the sections are shown in Fig.2b and this correlates well with magnetic polarity time scale after Haag & Heller (1991) and Steiner, Morales & Shoemaker (1993) (Fig.2c). These Siberian Traps investigated over the vertical section of 1700 m reveal a reverse chron in the bottom 660 m section and a normal chron in the top 900 m section with the topmost 150 m section showing mixed polarities. The Siberian Traps erupted at the Permo-Triassic boundary or around 248.4 $\pm$ 2.4 Ma ago with chron record of only two polarities, indicate a violent volcanic eruption. The source for the Siberian Traps due to Jan Mayo hotspot (Morgan 1981) or something else and also about its period of eruption is still debated.

The Karoo Volcanics

The Karoo volcanism is widespread in South Africa are dominantly of Lower Jurassic age and mostly rest on the sedimentary Karoo Supergroup, an intercratonic basinal sequence of Late Carboniferous – Triassic age (Tankard et al. 1982). The lavas in Namibia in Southwest Africa represent the second pulse of igneous activity of Lower Cretaceous and are correlated with the Parana province of Brazil in South America. The Karoo Province presently occupies an area of 1.5 x 10^6 km^2 being part of former 3 x 10^6 km^2 volcanics stretching 2000 km in N-S direction from Barotseland in Zambia to Suurgerg in Eastern Cape and 2800 km in an E-W direction from Etendeka in Namibia to Antonio Enes in Mozambique (Fig.3a) (Cox 1988). At present the volcanics are scattered and detached and consists of dykes and sills intruding in to the Karoo sedimentary rocks. Basic lavas of 1500 m in thickness cap the sedimentary sequence at the center of the basin and form the huge Lesotho outlier. This is notable for its variety of rock types among which low MgO basalts are dominant similar to the other flood volcanic provinces, apart from abundant picritic lavas (a feature similar to North Atlantic and Deccan provinces) and acid lavas (similar to Parana). Nephelinites are also locally abundant. Intrusives are dominantly doleritic but the central instrusive complexes consist of gabbro, granite, nepheline syenite and quartz syenite (Cox 1988).

Age determinations on Karoo volcanics (Fitch & Miller 1984, K-Ar and ^{40}Ar-^{39}Ar; Allsop et al. 1984, Rb-Sr and Allsop & Roddick 1984, Rb-Sr and ^{40}Ar-^{39}Ar) show a large range. Fitch & Miller (1984) suggest four episodes with two major ones, occurring at 193 $\pm$ 5 Ma and 178 $\pm$ 5 Ma with sporadic activity continuing towards the southern regions. Alkali igneous activity was reported around the margins of the craton and is about 204 Ma. Formation of the Karoo flood basalt volcanics has been reported to have resulted in the extinction of the faunal mass at the Triassic – Jurassic boundary (Rompino & Stothers 1988). Crozet/Marion hotspot is considered to be the source for these volcanics (Duncan & Richards 1991).

Few palaeomagnetic results on Karoo volcanic province are available and the published results record fewer magnetic chrons indicating rapid eruption of these lavas. Van Zijl, Graham & Hales (1962) studied two sections of lava sequence ranging at elevations of 1200 and 900 m. The lowermost flows indicate a



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Correlations between Siberian Trap Formations and Magnetic Polarity

Province	Noril'sk		Kureika		Kotui		W Taimyr	
Cycle	Suite	Pol	Suite	Pol	Suite	Pol	Suite	Pol
V	Samoedsky	N						
	Kumginsky	N						
	Kharaelakhsky	N	Nerakarsky	N	Meimechitic			
IV	Mokulaevsky	N	Khoamakitsky	N	Delkansky		Verhnetamsky	
	Morongovsky	N	Avamsky	N	Kogotsky	NR		
III	Nadeshdinsky	N	Dvuroginsky	N	Pravoboyarsky		Labaksky	N
	Tuklonsky	N	Tymersky	N	Arydzhansky	N		
	Khakanchansky	N	Logashinsky	N				
II	Gudochikhinsky	N						
	Syverminsky	N						
I	Ivakinsky	R					Syradasaysky	R

Figure 2. (a) Geological map of Siberian platform showing the distribution of Siberian Traps. (1) Noril'sk and (2) Putorana Sections (after Renne & Basu 1991), (b) ChRM vectors in Siberian Traps and (c) Polarity sequence observed in several formations of Siberian Traps from several sections (after Gurevitch et al. 1995).

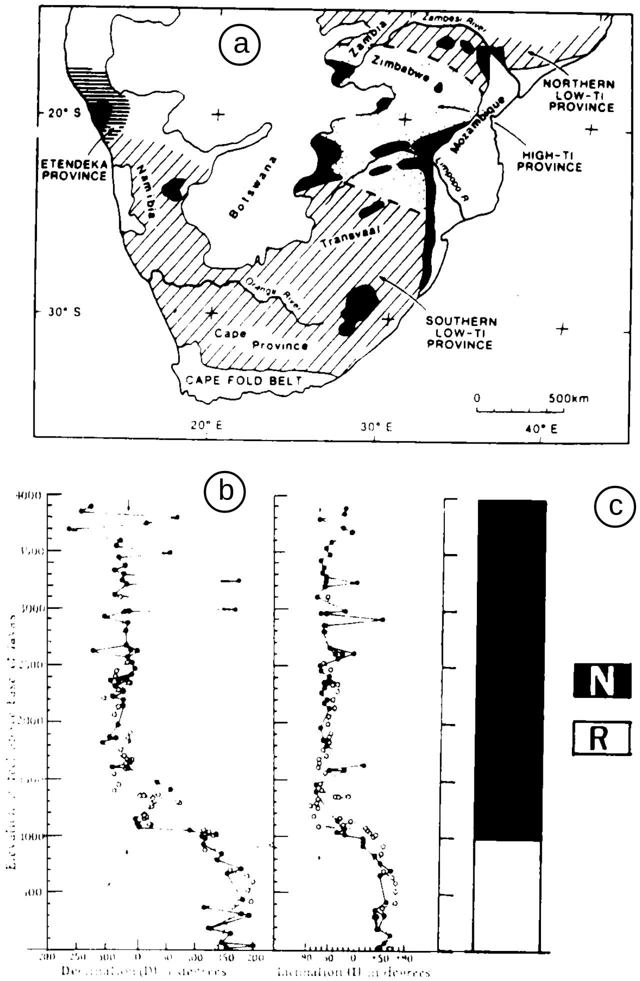

Figure 3. (a) Simplified geological map of Southern Africa showing Karoo igneous rocks (after Cox 1988), (b) Variation of magnetic declination and inclination along a vertical section of Stormberg Lavas and (c) Polarity sequence indicating N (black) Normal and R (white) Reverse polarity.

reverse polarity while the uppermost flows indicate normal polarity with the transition at 300 m in both the sections (Figs 3b & c). In another study of ring complexes dated to be 190 Ma from Southern Rhodesia, Gough et al. (1964) observed a magnetization with reverse polarity from 10 sites and normal polarity from 2 sites out of 19 sites investigated by them. This study coupled with other studies on Karoo volcanics indicate transition of the geomagnetic polarity from reverse to normal suggesting rapid volcanic activity during the Lower Jurassic which is a major event in the Karoo volcanism (Cox 1988).

The Parana – Etendeka Flood Basalts

The Parana-Etendeka flood basalt volcanism occurred in the Cretaceous before the separation of the South America and Africa during the Gondwanaland break-up. These volcanics (Serra Geral Formation) cover approximately 1.6 x 10^6 km^2 in the Parana Basin of Brazil, Argentina, Uruguay and Paraguay while the original extent was close to 2 x 10^6 km^2 (Fig.4). An additional 2.5 x 10^5 km^2 of contemporaneous flood volcanic rocks, the Etendeka Volcanics, are exposed in Namibia (Milner 1986) that got separated due to rifting of Gondwanaland. The Parana-Etendeka volcanic provinces are linked to the presently active Tristan de Cunha hotspot via Rio Grande Rise and Walvis Ridge respectively (Renne et al. 1992). The Parana province comprises chiefly of tholeiitic basalt and andesite and subordinate rhyolites and rhyodacites that are more abundant. The thickness of the volcanic rocks at the center of Parana Basin is > 1500 m and exposed sections generally lack overlying strata. The age and duration of the Parana Volcanism are poorly constrained. More than 200 K-Ar analyses available suggest ages of around 150 Ma. A recent Ar-Ar study by Baksi, Fodor & Farrar (1991) and Hawkesworth et al. (1992) show ages of 133 $\pm$ 2 Ma and 132 $\pm$ 1 Ma for stratigraphically younger volcanics and 135 Ma and 130 Ma for the inception and cessation of volcanism respectively. Renne et al. (1992) reported an Ar-Ar age of 133 $\pm$ 1 Ma that lasted for < 1 Ma, along with a palaeomagnetic study of four stratigraphic sections.

Palaeomagnetic studies (Renne et al. 1992) carried out on more than 20 stratigraphic sections of the Parana volcanic rocks ranging in elevation from 1500 – 500 m indicate fewer polarity changes in any given section (Fig.4). Since the extent of the sections is not known, it is believed that more than 1000 m thick sequence would have been accumulated in < 1 Ma as the geomagnetic field reversals are quite frequent between 140 and 120 Ma (Kent & Grandstein 1985; Harland et al. 1990). Geomagnetic field data in these volcanic rocks clearly indicate that their eruption is due to the Tristan de Cunha hotspot, at 133 $\pm$ 1 Ma and lasted for < 1 Ma. There is a suggestion that this Parana-Etendeka volcanic activity at the J-K boundary, is very nearer to the volcanic activity ranging between 135 Ma to 145 Ma. This volcanic activity thus may record the J-K boundary but further data is necessary on the boundary to support this.

The Deccan Traps

The Deccan volcanic rocks occurring in the central and western parts of the peninsular India are exposed over an area of 0.5 x 10^6 km^2, and are originally thought to have an aerial extent of 1.5 x 10^6 km^2 (Krishnan 1960) (Fig.5A). These are mainly tholeiitic in the south and southeast and alkaline and tholeiitic in the west and northwest (Bose 1980; Subba Rao 1972; Vandamme et al. 1991; Subba Rao 1999). The thick lava pile is essentially horizontal with low dips of the order of 1^o or less except towards the west and north. The sequence is thinnest in the east and thickens towards west to > 2 km in the Western Ghats. The Deccan lavas are predominantly basaltic with large variation in Nd, Sr and Pb isotopic ratios. K-Ar ages show a spectrum of ages between 80 – 30 Ma and ^{40}Ar-^{39}Ar ages give a mean age of 65 $\pm$

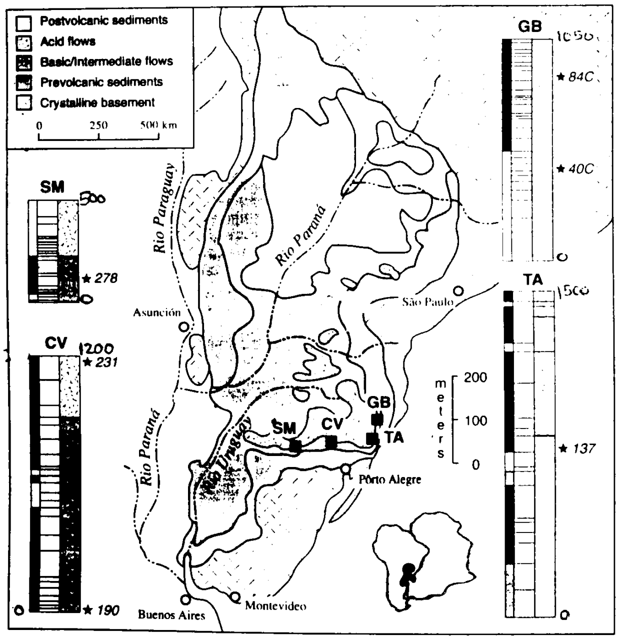

Figure 4. Geological map showing volcanic rocks in the Parana Basin. Inset map shows the pre-drift location of Parana-Etendeka flood volcanic provinces. Squares with SM, CV, TA and GB denote stratigraphic sections from which palaeomagnetic studies undertaken. Magnetostratigraphy and lithology of these sections are also shown. Black indicates normal and white indicates reverse polarity.

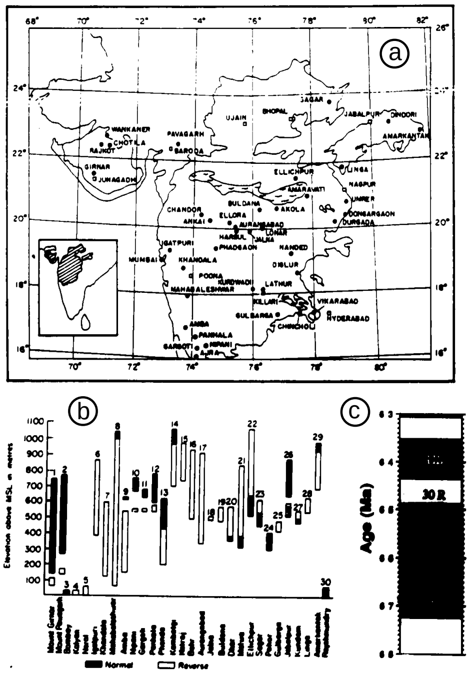

Figure 5. (a) Map showing the extent of the Deccan Traps in Central and Western parts of the Indian peninsula and sections of palaeomagnetic studies undertaken, (b) Magnetic Polarity Sequence observed at several sections in Deccan Traps and (c) Magnetic Polarity Chron Sequence observed in Deccan Traps. Black indicates normal and white indicates reverse polarity.

2.5 Ma (Vandamme et al. 1991). Duncan & Pyle (1988) reported indistinguishable ^{40}Ar-^{39}Ar dates from two samples collected from the bottom and top of vertical section of 2000 m thick (66.5 ± 0.3 Ma). Allegre et al. (1999) reported an age of 65.6 ± 0.3 Ma using ^{187}Re - ^{187}Os Systematic. Reunion hotspot is considered to be responsible for the Deccan Trap flood basalt and the major activity occurred at the K-T boundary that has been fixed at 64.5 ± 0.3 Ma (Baksi 1994). Fig.5 shows the Deccan volcanics and their magnetic reversals at several sections (Fig. 5b) and chron sequence of magnetic polarity inversions (Fig.5c).

Vandamme et al. (1991) have reviewed the isotopic dates and palaeomagnetic results on the Deccan Traps and bring in to light the palaeomagnetic record during the Deccan Trap eruption. The Deccan Traps reveal mainly three polarity chrons with N-R-N sequence. The reverse chron in this sequence at the K-T boundary (64.5 ± 0.3 Ma) is considered to be chron 29R. Figs 5b and 5c show the magnetic polarity chrons observed at different sections of Deccan flows and the magnetic polarity chron sequence at the K-T boundary respectively. It can be noticed that nearly 80% of the Deccan flows investigated reveal reverse polarity, which is considered to be a record of chron 29R (Vandamme et al. 1991). The fewer polarity chrons recorded and the very short period of Deccan Volcanic activity suggests that the Deccan Volcanic activity was due to mantle plume, Reunion hotspot.

The Ethiopian Traps

The Ethiopian Traps occur near the triple junction of the Red Sea, Gulf of Aden and East African rifts and are associated with the Afar hotspot. Most of the province lies over the African plate (Fig.6a). Prolific outpourings of basalts have built a sub aerial pile, which originally appears to have covered an area in excess of 500,000 km^2 (Mohr & Zanettin 1988) with total thickness, locally exceeding 2000 m. The Northwestern parts of the traps consist of a series of late Eocene and Oligocene fissure basalts, covered by Miocene shield volcanoes. Conventional K-Ar ages of basalts, rhyolites and ignimbrites from the plateau North of Addis Ababa range from 14 - 40 Ma (Merla et al. 1979). Berhe et al (1987) noticed prolonged stages of volcanism between 21 and 50 Ma, whereas Ebinger et al. (1993) have proposed a main phase of volcanic activity between 35 - 17.5 Ma ago, in the Southern part of the Ethiopian rift. Hofmann et al. (1997) recently reported a $^{40}Ar/^{39}Ar$ age of 30 Ma and suggested that the volcanic activity lasted for a period of 1 Ma or less. These Ethiopian basalts are fine grained and well exposed along three sections. Palaeomagnetic analysis of two sections [along Lima-Limo (3000 m) and Twegel-Tena (1000 m) sections] by Hofmann et al. (1997) from 40 flows and from a vertical section of 2000 m shows three magnetic chrons of R-N-R (11 reversed, 5 normal and 14 reversed

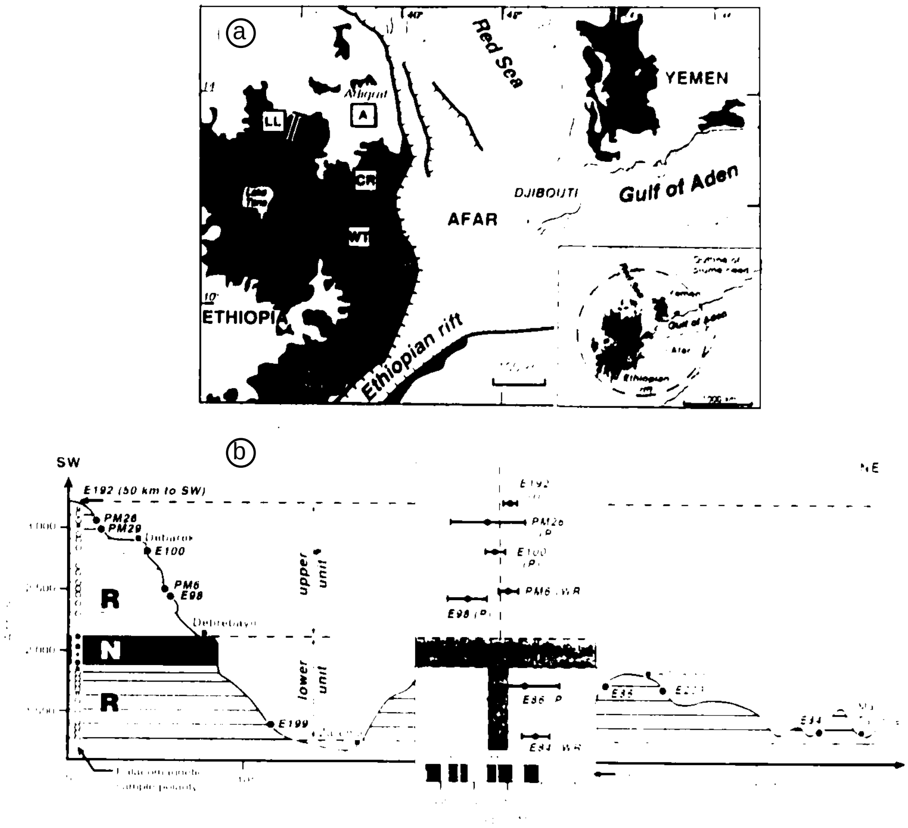

Figure 6. (a) Map showing the Ethiopian Flood Volcanics in Northern Ethiopia and Yemen, and East African Triple Junction (after Hofmann et al. 1997) and (b) Details of sample location for Ar-Ar dating and Palaeomagnetic investigations. Also shown the magnetic polarity chron sequence observed in the Ethiopian Traps.

Table 1. Some Salient Characters of Continental Flood Basalt Volcanics

Flood Basalt Province	Age Ma	Hotspot Source	Area 10^6 km^2	Geological Boundary	Magnetic Polarity
Columbia River Basalts	17.5 - 6.0	Yellowstone	0.164	Miocene	Mixed R - N
Ethiopian Taps	30	Marion	0.5	Oligocene - - Late Eocene	R – N – R
Deccan Traps	68.0 -63.0	Reunion	0.50 (1.5)	Cretaceous -Tertiary	N - R - N
Parana Basalts	130.0 -120.0	Tristan da Cunha	0.790 (1.2)	Jurassic -Cretaceous	Mixed R
Karoo / Etendeka	198.0 -204.0	Crozet / Marion	1.5 (3.0)	Triassic -Jurassic	Mixed
Siberian Traps	250.0 -245.0	Jan Mayen	1.5 (3.0)	Permian -Triassic	R - N Normal

flows) in this vertical section consisting of only two magnetic field reversals (Fig. 6b). The reversal frequency at this time period is of the order of 1.5 to 2.0 reversals per Ma and confirms that the bulk volcanism lasted for a very short period. Such magnetic record with only two reversals during their eruption support a mantle plume origin for the Ethiopian Flood Basalts probably through Marion hotspot at ~30 Ma. It is suggested that this volcanism led to the continental break-up and associated climatic changes in the region (White & McKenzie 1989; Hill 1991; Courtillot et al. 1997).

The Columbia River Basalt Group

The Columbia River Basalt Group (Fig. 7a) is one of the younger continental flood basalts (17.5 to 6 Ma) in the high plateaus of Northwest USA covering the states of Washington, Oregon and Idaho between the Cascade Range in the west and Rocky Mountain system to the east. These are essentially basalts of basaltic andesite in composition with rare dacitic to rhyolitic varieties. This is of moderate size of 164,000 km^2 with an estimated volume of 170,000 km^3 (Tolan et al. 1987) (Fig.7a). These volcanics are divided in to four groups: Imnaha (17.5 - 16.5 Ma), Grande Ronde (16.5 - 14.5 Ma), Wanapum (14.5 - 13.5 Ma) and Saddle Mountain Basalts (13.5 - 6 Ma). Of these, Grande Ronde Group approximates for over 85% while the Saddle Mountain Basalt Group with a protracted age of 13.5 - 6 Ma accounts for only about 1 % (Hooper 1988). Along the southern margin of the Columbia Plateau, there are several basalts, the Picture Gorge Basalt, the basalt of Primeville or Bowman Dam, Powder River Basalt, and Weiser Basalts that differ in composition, and mode of eruption from the Columbia River Basalt Group. These include the closest analog to the Columbia River Basalt Group in the region are the Steens Mountains flows in the southeast Oregon with an estimated volume of 65,000 km^3 and erupted roughly 15.5 Ma ago (Baksi, York & Watkins 1967; Carlson & Hart 1983, 1986). Yellowstone hotspot is considered to be responsible for the eruption of these flows through several NNW trending dykes in the region. Evaluation of K-Ar and new Ar-Ar ages indicate that 90 % of the lava was poured out between 17.2 and 15.5 Ma (Baksi 1989, Baksi & Farrar 1991)

Palaeomagnetic studies on the Columbia River Basalt Group carried out over the last four decades (Watkins & Baksi 1974; McKee, Swanson & Wright 1977; Mckee, Hooper & Kleck 1981; Martin 1984) reveal chron pattern as shown in Fig. 7b (Hooper 1988; Baksi 1990). The lower most Imnaha Basalt of 17.5-16.5 Ma shows one reversal of the magnetic field. The Grande Ronde Basalt that constitutes about 85% of the Columbia River Basalt Group, one or two reversals are seen that lasted for a period of 2 Ma between 16.5 and 14.5 Ma. However, the later phases of the Columbia River Basalt Group, that account for about 10 % by volume of volcanic activity and spreads over a large period from 14.5 - 6.0 Ma, shows several polarity changes. The Cenozoic era has witnessed a number of geomagnetic polarity changes with an average of 2-3 reversals per million years (Heirtzler et al. 1968). Hence the fewer polarity changes and the large volumes of lava of the Columbia River Basalt Group suggest a mantle plume activity (Yellowstone hotspot) for their origin in the region. The Columbia River Basalt Group was evolved in a very short period of few million years during the middle Miocene. Integration of the available magnetostratigraphy and age data pattern of lava extrusion are shown in Fig.7c.

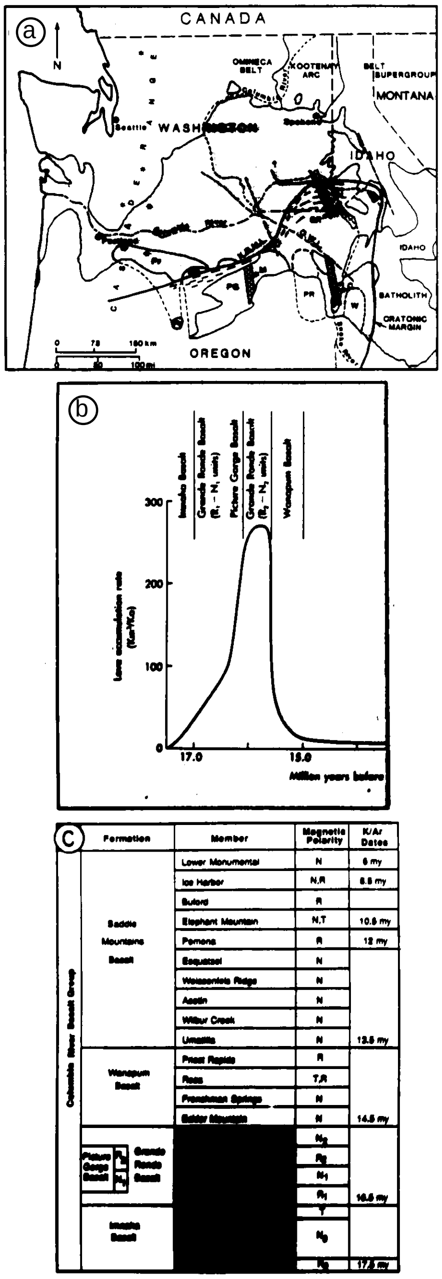

Figure 7. (a) Map showing the Columbia River Basalt Province and related rocks in the Northwest USA (after Hooper 1988), (b). Diagram showing the radiometric dates and lava accumulation rates for different groups of Columbia River Basalts along with magnetic polarities highlighting the rapid eruption of lava sequence and (c) Stratigraphy of Columbia River Basalt Group along with observed magnetic polarity and radiometric dates.

DISCUSSION

It is well established that most of the Phanerozoic continental flood basalts were formed due to mantle plumes through their surface manifestation form several hotspot sources distributed allover the globe (Fig.1). Studies on these continental flood basalts proved that they were erupted in a very quick succession at rates of the order of millions of cubic kilometers per year occupying very large areas of the order of millions of square kilometers (Table 1). The effects of outpour of these continental flood basalts are break-up of the continental crust and their migration, extinction of faunal mass that existed at different time periods and causing climatic changes (Morgan 1972; Cox 1978; Rampino & Stothers 1988; Baksi 1991). Suggestions such as continental flood basalt volcanism, faunal mass extinctions and environmental changes associated with bolide impact were also made in some quarters (Hofmann et al. 1997). It is also suggested that the hotspots are in motion in some cases and fixed mantle sources in others (Christensen, 1998; Torsvik et al. 1998). There are convincing evidences for such suggestions in case of some and evidences are not so convincing in case of others (Cox 1978; Baksi 1991; Hofmann et al. 1997; Renne et al. 1992; Rampino & Stothers, 1988). But debates are still going on in literature for such arguments to arrive at a consensus from all over the world. There are also suggestions with regard to their periodicity of flood basalt volcanism, faunal mass extinction and magnetic polarity. As argued, these are convincing in some cases and not so convincing in other cases. Of the three such cases, the two at the K/T boundary (65 $\pm$ 1) and Eocene/Oligocene boundary (34 $\pm$ 0.5 Ma) are very much convincing where precise and accurate data are used.

With regard to the nature of the geomagnetic field during the geological past, it is fairly well established that the geomagnetic field is bipolar in nature and has changed its polarity from normal to reverse and vice versa a number of times during the geological past (Brunhes 1906). It is also well established that the geomagnetic field was quiet during certain periods (superchrons) and changed quite frequently at other periods (frequent reversals) (Butler 1992). It has been suggested in some quarters that the continental flood basalt volcanism associated with bolide impact has also brought in geomagnetic field reversals at times. However, from the nature of geomagnetic field it is possible to understand the rate of magma eruption associated with several continental flood basalt volcanics distributed all over the world at different time periods during the Phanerozoic. As described in the previous sections, the continental flood volcanics were poured out in very quick succession in very short time periods of the order of one million years or less as per the isotopic dates available from them. The palaeomagnetic results of these continental flood basalts reveal very few changes in their polarity chrons also indicating their rapid rate of eruption as suggested from the radiometric ages. Large piles of lava sections occupying millions of square kilometers show one or two transitions of the geomagnetic field polarity either from normal to reverse polarity or from reverse to normal polarity from all the continental flood basalt provinces as described. In Table 1 is summarized the evidences gathered from all the world continental flood basalt provinces with regard to their area extent, hotspot source, their time period, faunal mass extincted and nature of magnetic polarity chron from all the known continental flood basalt provinces.

Therefore, the nature of the palaeomagnetic field as observed at some of the continental flood basalt volcanic provinces with one or two geomagnetic field changes and radiometric ages lasting for 1 Ma or less prove beyond doubt that the eruption of the lava is due to mantle plume activity. The mantle plumes supply the necessary heat for melting of the lower part of the lithosphere and subsequent widespread volcanic eruption has taken place through the hotspots distributed all over the globe. When the moving plates happen to travel over the active hotspots, large areas of the oceanic and continental regions experience widespread volcanic activity. In case of the Deccan Traps incubation period of 3.5 Ma has been advocated by Basu et al. (1993). The hypothesis of bolide impact, continental flood basalt volcanism, faunal mass extinction and geomagnetic field reversals needs further precise data for its confirmation.

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