Nature of flow patterns of Rajahmundry lava, Gowripatnam area, West Godavari, India: Insights from AMS studies

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Anisotropy of magnetic susceptibility (AMS) data for a single basaltic lava flow, herein named the Gowripatnam lava flow from the Rajahmundry Traps, are evaluated for determining precisely the mechanism of lava flow. At Rajahmundry, lava flows are found on both banks of the Godavari River and sandwich inter-trappean sedimentary layers in between. The ones on the west bank of the river are studied here. This study has an implication as the mechanism of lava flow or nature of lava flow patterns of Rajamundry Trap basalt is still a debatable issue. AMS directions is a powerful tool for investigating the source and direction of lava. Its application to single lava flow from Rajahmundry indicates maximum direction of susceptibility axes in almost all possible directions, indicating radial flowage from radial vent source(s). Two AMS directions (towards north-west – 14%, and north – 7%), however, have the maximum number of petals. This indicates that at least there were palaeo-flowage patterns towards these directions. Incidentally the Godavari lineament strikes NW–SE and the flow dip is due south. However, the two dominant magnetic lineation directions are due north. Hence, the possibility of the earlier suggested river piracy model for lava flow can be ruled out. The fissure eruption near Rajahmundry is pointed out as the then prevailing lava flow mechanism. This is further supported by an overall random distribution of maximum susceptibility axes apart from two dominant flow directions.

Keywords: Anisotropy of Magnetic Susceptibility, long distance lava flowage, Rajahmundry Traps, Fe–Ti oxides.

THE Rajahmundry Traps, ~400 km distant from the nearest surface exposure of the Deccan Traps, extend ~60 km on either side of the Godavari River, north of the city of Rajahmundry in Andhra Pradesh (Figure 1). On the west bank, these lavas outcrop for ~20 km, overlying sedimentary rocks, whereas on the east bank, they rest upon metamorphic basement. In both areas, they are overlain by the Cuddalore Sandstone[1]. The volcanic rocks display a thickness between 30 and 60 m, and gently dip (~5°) to the south. In each area, they are about 2 km wide, consisting of basaltic lava flows, with inter-trappean layers, a few meters thick[1]. The fossil content of (a) intra-trappean limestone suggests that the Traps cannot be older than Maastrichtian/Danian; (b) inter-trappean sediments suggest that the upper flows are of Lowermost Tertiary age[1–4]. The Rajahmundry Traps appear to have been formed at a time close to the K–T boundary. Initial correlation of the lava flows on both banks was based primarily on altitude and flatness of the lava flows[5]. Krishnan[6] refers to a lower flow overlain by a fossiliferous bed, and two upper flows. The inter-trappean sedimentary layer, consisting of limestone and marl, contains fauna of estuarine character[1]. It is clearly seen on the west bank and has been traced for ~10 km horizontally. On this bank, lava flows can clearly be designated as lying above or below the inter-trappean layer. On the left bank, the inter-trappean layer can be traced for 1 km overlain by a thin sedimentary layer consisting of unfossiliferous yellow calcareous shale[1].

On the basis of their similarities with other flood basalt provinces of the world, these traps have been interpreted to have been transported along a palaeo-valley travelling over a distance of ~1000 km from west to east coast of India[2,7–9]. A few past studies also suggest that the Rajahmundry Traps might have been erupted through faults in the Krishna–Godavari (K–G) Basin[10–12]. Thus, the genetic relationship between these two geographically distinct but geologically similar terrains (Deccan Traps in the west and Rajahmundry Traps in the east) remains unsolved to date. Published information about field geology, lithostratigraphic framework and the mode of origin of Rajahmundry Traps is limited. Our recent observations in the quarries of Rajahmundry area provide new information on the volcanological features of lava flows which favour the interpretation on the mode of eruption of Rajahmundry Traps as intra-basinal flows. Thus, the present

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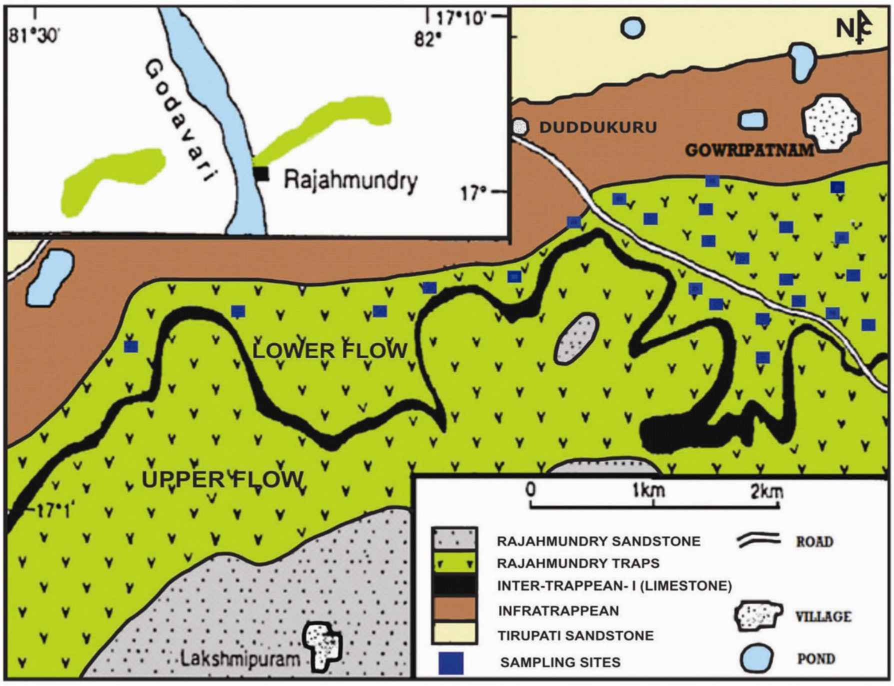

Figure 1. The generalized geological map showing the Rajamundry Traps in and around Gowripatnam, West Godavari, Andhra Pradesh[15].

study deals with all the new information related to possible modes of eruption of the Rajahmundry Trap basalt.

In the present scenario, two schools of thought exist regarding the explanation of the nature of the basaltic lava at Rajahmundry: the river piracy model and the fissure eruption model[13–15]. Here the authors attempt towards the feasibility of the models in explaining the mechanism of lava flow. Anisotropy of magnetic susceptibility (AMS), a powerful tool for petro-fabric analysis, can serve the purpose of this persisting debate regarding the mechanism of lava flow in the Rajahmundry area. Earlier researchers[16,17] have used AMS as a tool for deciphering the lava flow patterns. In this article, we have provided a combined approach consisting of petrography, magnetic mineralogy and AMS analysis to study the aforesaid problems.

Regional geology and tectonic setting

The Rajahmundry Traps of the K–G basin attracted various researchers worldwide as they are considered natural laboratories for studying long distance lava flow[7,9] and for explaining the K–T boundary mass extinction events vis-à-vis volcanism[4]. These traps can be considered as ‘materials of prominence’ in the geology of Peninsular India as they are the only extensive outcrops of basaltic lava flows along the east coast of India and are almost coeval to the Deccan Traps[14]. Further, Bakshi[3] reported new $^{40}Ar/^{39}Ar$ ages for lava flows from the Deccan Traps and Rajahmundry Basalts and critically assessed reliability of other dates available in the published literature. According to him, only six ages of the lavas from the composite Western Ghats are found to be reliable estimates of the time of crystallization. The age of the upper flow at Rajahmundry defines its formation during chron 29n. A single age from the lower reversed polarity flow appears somewhat bimodal when plotted against geo-magnetic time scale. Based on the findings, Bakshi[3] opined that the hypothesis of faunal extinction at the Deccan traps Cretaceous–Palaeogene boundary (KPgB) remains plausible, but must compete with the latest report, favouring a very close temporal connection (0.03 Ma) between the Chixculub Impact Crater and the KPgB (Duriaswami, 2017, pers. commun.). Besides these, the sedimentary horizons between the lava flows are characterized by the presence of a wide variety of invertebrate fossils. Earlier workers have considered that the Rajahmundry Traps are the eastward continuation of Deccan Traps and documented two basalt flows separated by an intra-trappean bed.

The Rajahmundry Traps are located along the south-eastern hand of the Godavari Triple Junction (GTJ). The tectonic junction present between the NW–SE trending Godavari Rift and NNE–SSW to NE–SW oriented K–G Basin is known as Godavari Triple Junction (GTJ). Figure 2 provides the disposition of the lineaments in the studied area[14]. The fascinating fact about this terrain is that it preserves the records of geological records of Mesoproterozoic to Neogene[14].

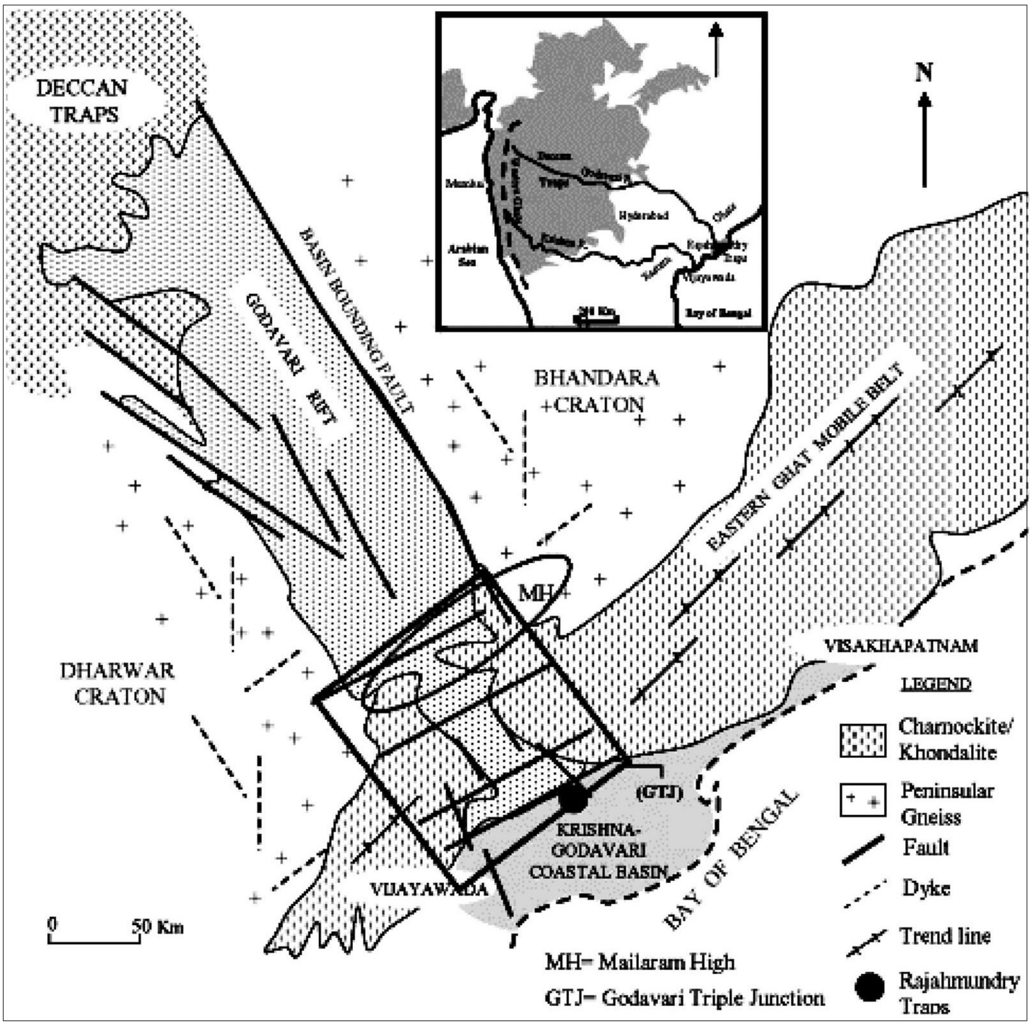

Figure 2. Lineament map of the studied area showing the Godavari Triple Junction[14].

The evidences for Palaeozoic to Mesozoic Gondwana rifting, Cretaceous continental break-up and drifting are provided by the Phanerozoic sediments exposed in this GTJ[16]. The NW–SE trending Godavari rift comprises an assemblage of grabens and half grabens developed parallel to the structural trend of Precambrian Peninsular gneissic complex. Earlier researchers)[18,19] opined that this rift commenced in response to collisional events in the adjacent Eastern Ghat Mobile Belt (EGMB) during the Mesoproterozoic and the sedimentation processes continued up till Neoproterozoic. During Carboniferous to Mesozoic, a second phase of rifting took place which led the alluvial lithic fill to get deposited in these basins which came to be known as the continental Gondwana[14]. The alluvial basins of this period constituted a network of radial drainage system of intercontinental Gondwana palaeo-drainage[21–23]. On account of the lack of the syn-sedimentational igneous activity associated with the Godavari it can be described as a crevasse type of continental rift[14,15].

Structural framework of K–G basin represents a series of NE–SW trending horst and grabens which exhibit 'throw' progressively sloping towards east and southeast that facilitated the subsidence, deposition and preservation of thick pile (~8 km) of sediments in K–G basin[18–20]. During the prolonged evolution of the Godavari rift system, the only evidence for igneous activity is in the form of basaltic lava flows of Rajahmundry Traps. These are preserved at the stratigraphic interval between the Cretaceous and Tertiary sediments in the K–G basin. The Deccan Traps basically occur as a 'cap rock' over the Cretaceous Gondwana sediments namely the Kota and Gangapur formations of early Cretaceous age in the northwestern part of the Godavari rift[14]. Tectonic temperament indicates that the traps were involved in the post-Cretaceous Gondwana rift upliftment along NE–SW and NW–SE Gondwana faults[14]. Despite the prolonged erosion, these traps are preserved as capping over the sediments. However, field evidences and reports suggest that there is no such remnant/evidence of basaltic flows along the major part of the Godavari River and its vicinity in the southeasterly direction, i.e. along the Godavari rift[14]. Based on stratigraphic, sedimentological and structural considerations, tectonic reconstruction was done. This indicated the presence of several NE–SW trending fault transecting the Godavari rift, which are further parallel to the structural trend of the Eastern Ghats[14]. On the other hand, the Mailaram High, during this tectonic reorganization, in the central part of the Godavari River started serving as a provenance for early Cretaceous sediments whose palaeo-flow was due northwest[21–23]. In succession to this, there were a series of tectonic upliftments which led the Eastern Ghats to become a prominent mountainous landform during the middle to late Cretaceous[18–21]. All these basically point towards discontinuation of the basalt flows of northwestern part of the Godavari valley to the Rajahmundry Traps. Therefore, the Rajahmundry Traps remained distinct from the main Deccan basaltic lava flows present along the northwestern tip of the Godavari rift in the present disposition.

Manifestations of the NW–SE lineaments/faults transverse to the Rajahmundry Trap include fragmentation of litho-units and dislocation of the limestone beds abutting against the flows[14]. It is between these two faults that the entire succession of traps is well preserved, and physico-volcanological features of the lava flow are well exposed. Complete succession of the Rajahmundry Traps is well exposed in Gowripatnam (17°1′55.8″N; 81°37′41″E) and Duddukuru (17°2′2.2″N; 81°35′33.3″E) quarries, located west of the Godavari River, whereas the upper flow along with overlying Rajahmundry Formation (Cenozoic sandstone) is present in the quarry sections located east of the Godavari River near Rajahmundry.

The present study deals with the rocks of the lower flow which were accessed from Gowripatnam and Duddukuru areas from fresh exposures as well as from stone quarries in and around the localities. The upper flow is described to be 20 to 30 m thick, and is unconformably underlain by infratrappean sandstone[14]. Field evidences and recent observations[14] suggest that the lower flow is characterized by columnar and/or radial joints, vesicles and some diverse physical and volcanological features, viz. rootless cones, tumuli and dyke like forms. In the quarries northeast of Duddukuru village, the lava displays features which correspond to the 'aa' or blocky type of lava. The features described above are usually due to cooling of lava flow after coming in contact with a water body[14] which, in the present scenario, is the water body in shallow marine sea within which the infratrappean beds were deposited. Besides, columnar joints are also reported on both sides of brecciated basalt cones/zones that lie strike-parallel of the basaltic flow[14]. Columnar joining basically stands as a common feature in large flood basalt provinces, viz. Columbia River Plateau and Deccan Plateau[14]. The sharp planar contact between the infratrappean limestone and lower flow is evidence that the lava flowed on a planar surface in the initial flow stage and lava additions in the later stage were probably responsible for the creation of uneven surfaces[14]. Thus, it is well understood that the joints have developed on account of cooling in an aqueous environment. Dyke-like forms of ~1–6 m wide younger basalt showing transverse relationship with the earlier formed basalts and bulging of the top are common. Detailed petrological and geochemical studies to identify the inter-relationship among various stratigraphic units are still debatable and in progress.

Methodology in study

As the study consists of a combined approach of petrographical studies and AMS studies, oriented block samples were collected from the aforesaid lava flow exposures. Cylindrical cores (varying from 6 to 8 in numbers) were drilled from each of the block samples of height 2.2 cm and diameter 2.54 cm. Besides, at least two chips were extracted (along strike and dip directions of the oriented samples) from the cores for the preparation of polished-thin sections for petrographical and magnetic-mineralogical studies.

The polished-thin sections were prepared in the section-cutting laboratory of the Department of Geological Sciences, Jadavpur University and were studied in transmitted and reflected lights using Leica optical microscopes. The magnetic susceptibility and its anisotropy were measured using the Bartington Susceptibility Meter (MS-2) with the synchronous operation of the AMS-Bar software which helps in calculating the necessary parameters related to AMS studies. The necessary parameters calculated in the present study are listed below

Mean susceptibility $(K_m) = (K_1 + K_2 + K_3)/3$ (Nagata[24]) (1)

Magnetic lineation $(L) = K_1/K_2$ (Balsley and Buddington[25]) (2)

Magnetic foliation $(F) = K_2/K_3$ (Stacey *et al.*[26]) (3)

Eccentricity $(E) = K_2^2/K_1K_3$ (Hrouda[27]) (4)

here K_1, K_2 and K_3 are the maximum, intermediate and minimum susceptibilities and E is the eccentricity of the susceptibility ellipsoid which is defined by the three principle susceptibilities as its axes.

Jelinek[28] and Hrouda[27] proposed a set of few other parameters which are designated as corrected degree of anisotropy (P_j) of the susceptibility ellipsoid and shape (T_j) of the ellipsoid which they calculated as follows

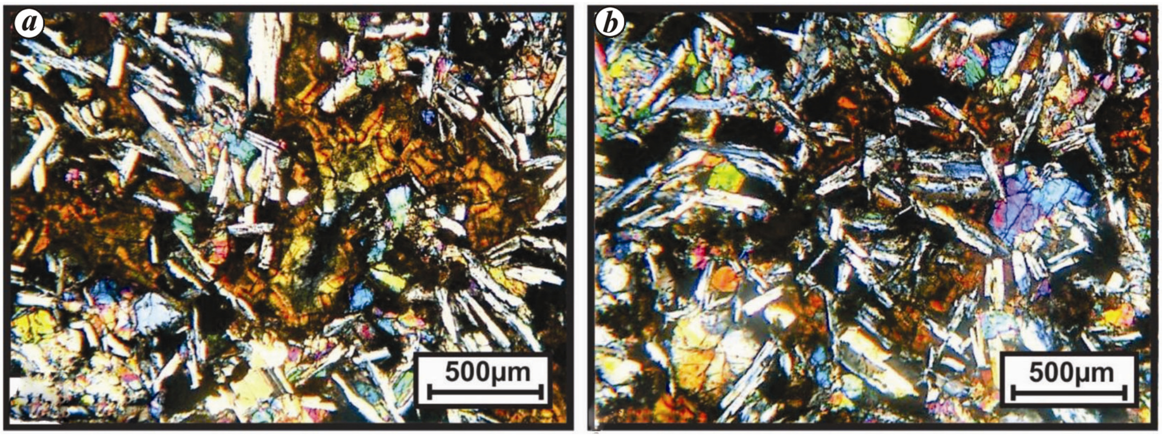

Figure 3. Photomicrograph of (***a***) hyalo-ophitic texture and (***b***) sub-ophitic texture in Basalt. Glass partially encloses elongate lath-shaped plagioclase (XPL, 40×).

$$P_j = \exp\{2[(n_1 - n_m)^2 + (n_2 - n_m)^2 + (n_3 - n_m)^2]\}^{1/2}, \quad (5)$$

$$T_j = (2n_2 - n_1 - n_3)/(n_1 - n_3); \text{ where } n_i = \log K_i. \quad (6)$$

During flow of a lava (as the present study deals with) the K_1 axes align in the direction of the flow[29] and thus its orientation can serve as a proxy for the direction of the lava flow. Further, in the present study petrography and magnetic mineralogy are used as parameters which will corroborate the ideas drawn from the AMS analysis.

Petrography and magnetic mineralogy

Petrography

The mineralogic content of the rocks are plagioclase, clinopyroxene and glass. A dense network of elongate plagioclase micro-phenocrysts and granular pyroxene, with smaller magnetite crystals are found. The lath-shaped plagioclase micro-phenocrysts partially included in larger pyroxene are associated with glass. This is typical sub-ophitic texture (Figure 3 *b*). The rocks also show hyalo-ophitic texture (Figure 3 *a*), where diversely oriented plagioclases occur within the glassy groundmass.

Plagioclase laths are arranged in a triangular fashion and the polygonal interspace left between the crystals has glassy infillings, which is of intersertal texture (Figure 3). The amount of glass in a basaltic rock is generally less than the amount of glass in more silicic volcanics, and might have developed this glassy nature, due to rapid chilling when it interacts with water.

Magnetic mineralogy

Iron–titanium oxide minerals constitute the major opaque oxides in basaltic rocks of Rajahmundry Traps. The magnetic properties of glassy basalt are found mainly as a function of their primary Fe–Ti oxide minerals. So, the primary Fe–Ti oxide mineralogy plays an important role in the study of magnetic susceptibility. The primary Fe–Ti oxide minerals in volcanic rocks constitute the members of the titanomagnetite series, which have played a significant role in controlling the bulk/volume susceptibilities of the studied samples.

During a prolonged period of time, the titanomagnetite and ilmenite minerals, which crystallize initially in igneous rocks, have a general tendency for oxidation to make stable phases of all Fe–Ti oxide mineral of volcanic rock. Two different types of oxidation of titano-magnetite can be distinguished depending upon temperature and corresponding pressure; (i) first, high temperature oxidation that occurs above 600°C and, (ii) secondly, low temperature oxidation that occurs at about 350°C or below that temperature.

Two different textural assemblages of Fe–Ti oxide minerals develop from the oxidation of titanomagnetite, (a) 'oxidation-exsolution'[30] or 'exsolution' lamellae of ilmenite along (111) parting planes in titanomagnetite, which is called trellis ilmenite[30] and (b) post-'exsolution' pseudomorphic-oxidation products rutile, titanomagnetite and pseudobrookite.

Both the assemblages develop above 600°C but at different oxygen fugacities[31]. Ilmenite, produced by oxidation-exsolution, is structurally controlled within the titanomagnetite host. With more intense oxidation, the titanomagnetite host is gradually depleted in the ulvospinel component as larger concentrations of ilmenite develop. The exsolved ilmenite continues to follow the path of oxidation without any dramatic effects on the titanomagnetite host. A saturation point is finally reached, which results in the exsolution of pleonaste solid solutions and oxidation of the residual titanomagnetite to titanohaematite.

Magneto-mineralogical study reveals rock samples that were collected from Rajahmundry Traps in and around

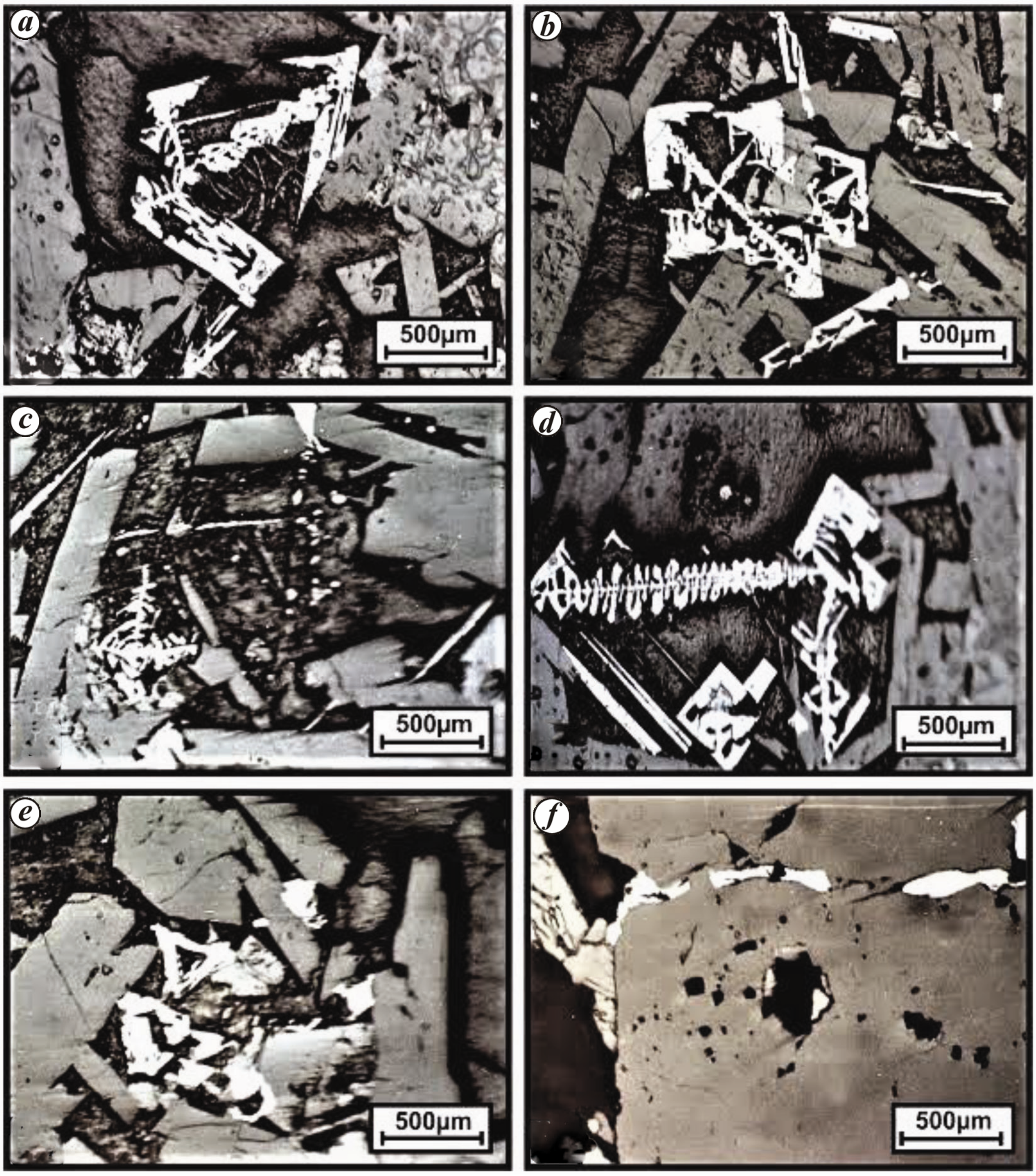

Figure 4. Photomicrograph of (***a***) Skeletal titano-magnetite with cruciform type; (***b***) skeletal titano-magnetite with cruciform type; (***c***) and (***d***) skeletal titano-magnetite showing growth parallel to (111) spinel plane along the entire length of primary cross arms; (***e***) euhedral (triangular) grain of titano-magnetite, and (***f***) generation of microcrystalline secondary ferromagnetic minerals occur along the silicate grain boundary (PPL, 200×).

Gowripatnam, West Godavari, Eastern Ghat Belt, do not show any high temperature oxidation signature of Fe–Ti oxides. But polished thin sections of glassy basalts observed under reflected light microscope unravel that titano-magnetites occur in abundance which are coarse to medium grained. Skeletal grains are also present which exhibit a progressive trend towards euhedral morphology. This trend is classified as cruciform type[31] (Figure 4 *a* and *b*). This cruciform type consists of simple sets of cross arms at right angles which correspond to the crystallographic growth axis. Growth is initiated at the extreme ends of these arms and arrow heads develop, which continue to grow until the entire set collages (Figure 4 *a* and *b*). An alternative variation to this pattern growth is parallel to (111) spinel plane, along the entire length of primary cross arms (Figure 4 *c* and *d*). Euhedral grains of triangular and rectangular shapes are also common (Figure 4 *e*).

AMS study

AMS studies were carried out to determine the orientation of the K_1 susceptibility axes, for which the magnetic susceptibility and related parameters were calculated. The values of K_1, K_2, K_3, mean susceptibility (K_m), corrected

Table 1. Mean magnetic susceptibility values and related parameters for corresponding some selected sampling sites in the studied area

K_m	K_1	K_2	K_3	K_1 (D^0/I^0)	K_3 (D^0/I^0)	P_j	T_j
1850.3	1946.8	1922.4	1681.4	273.9/1.6	136.8/87.9	1.176059	0.827605
1777.7	1826	1821.4	1685.6	334.7/1.8	209.8/86.4	1.095228	0.936946
409.2	497.6	493.1	237.0	336.3/4.1	142.2/85.7	2.343558	0.975505
396.2	484.5	483.7	220.5	41.2/1.6	182.3/87.9	2.480658	0.995802
300.8	372.2	359.6	170.7	36.1/0.0	126.2/87.2	2.414233	0.911641
510.8	614.4	601.2	316.7	76.5/0.8	180.2/86.6	2.123844	0.934454
379.4	457.2	447.0	234.1	229.6/0.1	137.2/87.4	2.139369	0.932587
329.2	397.2	396.8	193.6	310.8/3.9	158.1/85.7	2.29245	0.997196
1658.5	1896.9	1882.6	1196.0	313.7/1.7	116.0/88.2	1.696106	0.967188
436.8	434.6	434.6	188.6	303.8/2.7	170.0/86.1	2.623569	1.00000
436.8	555.8	528.3	226.2	289.5/1.5	168.6/87.0	2.747465	0.887108
435.7	540.4	512.0	254.8	300.3/2.9	183.0/83.7	2.31421	0.856391
544.9	644.1	605.5	385.2	302.6/0.5	195.1/88.5	1.753214	0.759578
2113.5	2221.4	2207.9	1911.3	6.3/1.4	205.0/88.5	1.185548	0.918914
2142.0	2259.2	2240.1	1926.8	5.5/0.5	237.9/89.2	1.196107	0.893305
2296.8	2436.2	2429.3	2025.0	312.5/1.2	166.9/88.5	1.235967	0.969316
2078.0	2189.9	2177.1	1867.0	6.6/0.8	176.7/89.2	1.198312	0.926504
2377.0	2506.2	2493.9	2130.8	216.8/0.2	120.5/88.1	1.202738	0.939361
21.6	23.8	21.2	19.7	48.3/0.6	317.3/57.4	1.21004	–0.22374

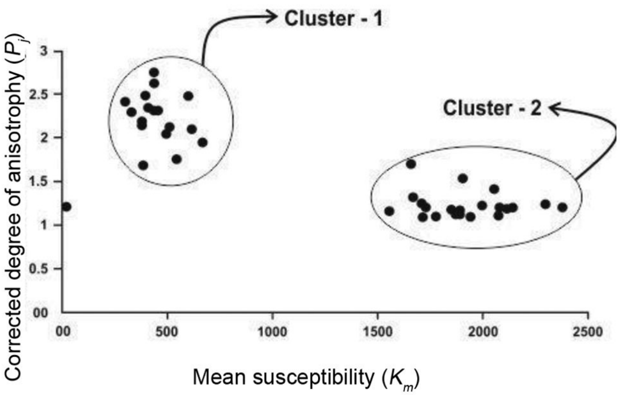

Figure 5. K_m verses P_j plots for the samples of the studied area.

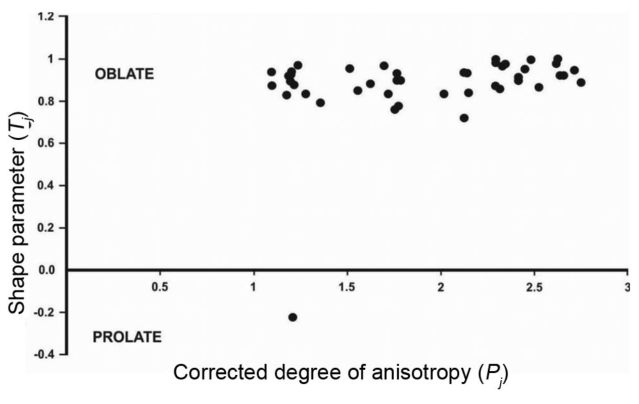

Figure 6. Jelinek type ($P_j – T_j$) plots for the samples of the studied area.

degree of anisotropy (P_j) and shape parameter (T_j) were calculated (see Table 1). The mean magnetic susceptibilities (K_m) of the rocks can be classified into two groups, one ranging from 1658–2377 × 10^{-6} CGS and another ranging between 21 and 544 × 10^{-6} CGS units. This is clearly depicted in Figure 5. The values of *F* and *L* clearly depict the dominance of foliation over lineation in the area. The *E* values also show significant variation across the different parts of the study area. It varies from 1.1 to 2.5. The corrected degree of anisotropy (P_j) lies between 1.09 and 2.74. The shape parameter (T_j) is positive in most of the samples with a few showing negative values. The plot of P_j–T_j (ref. 28) also supports the fact that the shape of the susceptibility ellipsoids is oblate.

From the Jelinek plot (Figure 6), it is also observed that the shape parameter values are constant but the different rock cores show a diverse pattern in degree of anisotropy (P_j). The K_m–P_j plots (Figure 5) of the samples collected show that the plots cluster at two zones which is evidence of two groups of susceptibility values from the studied samples, but no linear relationship between P_j and K_m exists.

It is evident from the present study that the maximum direction of a susceptibility ellipsoid has an important bearing. It denotes the flow direction of basaltic lava or dip direction of a sedimentary bed. For this purpose, all the maximum directions of susceptibility ellipsoids from the present study are plotted in a rose diagram. The rose diagram for the K_1 axes of the studied cores shows a varying nature. The petals are distributed in almost all the directions from 0° to 360° with two larger petals along the north and north-west directions. These petals are found to be of those sites which have higher P_j values. From the contoured diagrams of the K_1 axes, the oblate nature of the susceptibility ellipsoid is verified because they are found to lie along the periphery of the lower hemisphere circle.

Results and discussion

Results from magneto-mineralogy

The ore-microscopic study of the thin-polished sections of the Basalt exhibits titano-magnetite as a dominant iron–titanium oxide. In basaltic rocks of Rajahmundry Traps, the titano-magnetites occur in abundance and are coarse-to medium-grained. Skeletal grains are also present and this exhibits a progressive trend towards euhedral morphology. This trend is classified as cruciform type (Figure 4 *a* and *b*) which consists of simple sets of cross arms at right angle, and corresponds to the crystallographic growth axis. The growth is initiated at the extreme ends of the arms and arrow heads develop, which continue to grow until the entire set collages (Figure 4 *a* and *b*). An alternative variation to this pattern growth is parallel to (111) spinel plane, along the entire length of the primary cross arm (Figure 4 *c* and *d*).

Considering the textural relationship in rocks from different sampling sites, at least two generations of ferromagnetic mineral assemblage are distinguishable. The earliest one is the primary titanomagnetite in the form of skeletal growth with cruciform texture. It is mostly evident from the studied area. This first generation primary titanomagnetite is not affected by any stage of low temperature oxidation (Figure 3 *a* and *b*). Considering this textural association, this ferromagnetic variety appears to have formed due to variable amount of titanium concentration in titanomagnetite during very quick chilling from peak temperature condition. The second generation of ferromagnetic mineral is developed as numerous fine specks-shaped platelets between or along the silicate grain boundaries (Figure 3 *f*).

Results from AMS study

The Jelinek plot from the samples of the studied area shows the oblate nature of the susceptibility ellipsoids and a diverse pattern of corrected degree of anisotropy with a constant shape parameter. The oblate nature of the magnetic fabrics in the studied lava flow is due to the fact that the flow occurred in a planar surface, further evident from the fact that a sharp contact between the infratrappean beds and the studied lower flow exists. Further, it is noticed that the samples which have comparatively higher values of P_j are from the top and bottom parts of the lava flow. The values with comparatively high P_j in the oblate domain indicate that despite the quick chilling effect (which gave rise to the oblate fabric), there lies a strong non-uniformity among the K_1, K_2 and K_3 values of the samples which is clear from Table 1. Again, it is worth mentioning that such samples were from the top and bottom parts of the lava flow.

The K_m–P_j plots reveal the bimodal distribution of the susceptibility values. The K_m value for cluster-1 in Figure 5 is lower but the P_j is higher. The scenario is completely reverse in case of cluster-2. This can be explained on the basis of the location within the studied flow, from which the samples were collected. The samples, located at the top and bottom portions of the studied flow, suffered quick chilling (supported by textural evidences, viz. skeletal and cruciform grains of magnetite, ample amount of glass, etc.) which promoted the formation of fine to ultra-fine titano-magnetite grains. This resulted in lower values of K_m of the samples because of low volumes of the fine grains. The susceptibility values considered in the present study are nothing but the bulk/volume susceptibility. Thus, a decrease in the volume of ferromagnetic minerals (titano-magnetite here) will contribute towards lower K_m. However, the same samples, i.e. those which lie near the boundaries of the flow are more prone towards the development of an imbrication pattern of the ferro-magnetic mineral, thereby impinging P_j value within these samples. The reverse is the case of samples collected from the central positions of the flows which lack the aforesaid imbrication patterns within the ferromagnetic minerals causing to develop lower P_j values. The sites from the central positions of the lava have a more random fabric with low P_j as well as a high susceptibility (Figure 5). Probably in this region, the lava flow remained more turbulent and the crystallization is comparatively slower giving rise to large magnetite crystals without strong shape-preferred orientation. Also, the uneven surfaces with the flow as reported[14] are evidences of later stage lava addition to the flow which further corroborates the contention of turbulence in the central position, leading to randomness and lower degrees of anisotropy. These large magnetite crystals (having large volume in the central portion of the lava flow) point towards the higher K_m values thereby explaining cluster-2 of Figure 5.

The most important part of AMS studies in the present scenario lies in the study and explanation of the rose diagram representation of the K_1 axis. During lava flow, minerals tend to orient themselves along the direction of

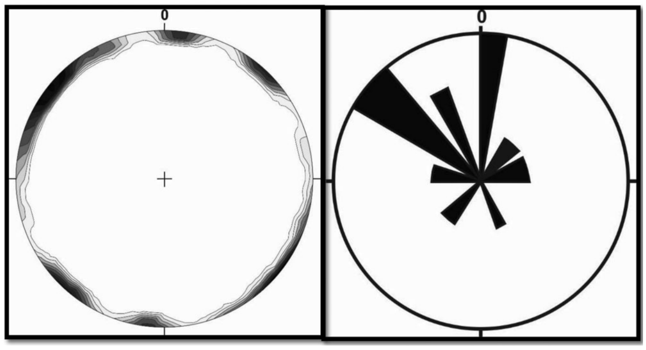

Figure 7. Lower hemispheric circular diagram representing the clusters of the K_1 axes (left) and rose diagram showing the palaeo-flow directions of basaltic lava from Rajahmundry Traps (right).

the flow. Hence, the maximum susceptibility axes, i.e. the magnetic lineation (K_1) would tend to show a particular direction of lava flow. This study has an implication as the source of the eruption/vent or nature of flow pattern of Rajahmundry Trap basalt still stands as a debatable issue. As mentioned earlier, there are two schools of thought, one believing in the river piracy model, where it is thought that the palaeo-channels of Godavari or Krishna river valley might have acted as conduits for basaltic flow of Mahabaleshwar origin. The other model indicates that fissure eruption located more towards the eastern part of the subcontinent might have a role behind the remote occurrence of trap rocks. The diagram indicates that the maximum direction of susceptibility axes is directed in almost all possible direction (Figure 7). The rapid chilling of lava may be responsible for the 360° orientation as quick chilling prevented development of preferred orientation of the axes. However, two directions (towards north-west and north) have the maximum number of petals (21%). Among them, north-west direction has 14% petals. This indicates a palaeo flow direction of the basaltic lava in all possible directions. Despite the fact that the AMS data revealed lava flow in all directions, the two larger petals in the rose diagram, towards north west and north, show at least two major palaeo-flow channels.

Conclusion

The results of this study will help determine the mechanism of the lava flow in the studied area. The AMS data revealed lava flow in all possible directions. Flow in all possible directions promotes rapid chilling of the lava and such a phenomenon is confirmed by the presence of high amount of glass and also the cruciform and skeletal nature of the magnetite grains observed in magneto–mineralogical studies[3,32]. The two larger petals of the rose diagram towards north and north-west point towards the fact that although the lava flowed in all possible directions, more dominant flow was due north. Considering the direction of river channels in the Indian sub-continent, they develop channels due south. However, the development of two dominant lava flow channels due north is probably evidence of the presence of topographic inclinations in those directions. Thus, these facts rule out the possibility of the 'river piracy' model and promotes the fissure eruption mechanism of lava flow in the area which ensures flow in all directions. Thus, in the present study AMS help in determining the precise mechanism of volcanic eruption in the Gowripatnam area, Rajahmundry.

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Further reading

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