The Origin and Formation Mechanism of the Rajahmundry Trap Basalts of Andhra Pradesh, Concealed in Mineralogical and Textural Characteristics

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Abstract

Basalts occurring in both Oceanic and continental environments are by far the largest and extensive igneous formations in the earth's crust. Rajahmundry Trap Basalts are one among the widely recognized and investigated formations which is lying as boundary (K-T boundary) between the Cretaceous and Tertiary periods. Five prominent outcrops of basalts with well-established and preserved stratigraphy have been identified. Samples were collected from three layers of basalt flows from each location and analyzed mineralogically, geochemically and texturally to arrive at a possible conclusion in regard to their Source of origin and mode of emplacement. Optical, X-ray diffraction and geochemical analyses were carried out for about 30 basalt samples. Olivine is present as phenocrysts of Forsterite and Fayalite, the end-members of the series. The essential minerals identified are olivine, Plagioclase feldspars, pyroxenes and accessory minerals are Quartz, Apatite, Ilmenite, Magnetite, K-feldspars, Stishovite. Microcrystalline minerals were identified under microscope, but minerals of cryptocrystalline size were identified by X-ray diffraction method. The mineralogical, chemical, and textural characters suggest the origin of magma for these basalt flows is in deep within the mantle probably the lower and transition zone.

Keywords: Mineralogy, Geochemistry, Texture, Mantle, X-ray diffraction, Stratigraphy and Optical.

INTRODUCTION

Basalts are extensive rock formations in the earth's crust, both in Oceanic and continental environment. They are common rock types in volcanic regions. These rocks are melanocratic, fine grained and of high density. The term 'Basalt' was first introduced by Pliny, the elder an Italian scientist, Philosopher and Naval and military commander of Roman Empire (AD 24-27) which signifies a black iron – bearing stone. Later, Agricola Father of Geology used the word basalt as a specific name in petrography. Basalts in normal sense can be defined as mafic lava consisting of minerals of felsic and mafic groups in equal proportions. The mafic or dark minerals mainly consists of Augite, Olivine, iron Oxides, apatite along with Hypersthene, Biotite or Hornblende constitute mafic group and the felsic minerals consisting of plagioclase solid solution series (Albite to Anorthite) and there can be minor amounts of K – feldspar, Quartz, and glassy matrix. But the term basalt is commonly used to the simple combination of – Augite, Labradorite, and iron oxides. If olivine is also present in significant amount, the term "Olivine basalt" is used. Basalts most commonly exhibit a vesicular structure due to gas babbles or vesicle that are trapped during the solidification of lava. These bubbles after escape of gases can give basalt a porous appearance.

Study Area:

The basalts of the study area fall between geographical coordinates 81°35′8″ to 81°50′0″ E Longitude and 17°0′0″ to 17°5′0″ N Latitude and forms the toposheet Nos. 65G/12 and 65G/16. As per the Geological time scale, the Rajahmundry Trap Flows (RTFs) are considered to be of late cretaceous to early tertiary age. These Basalt flows of the Krishana – Godavari Basin are extended~ 50km^2 on either side of the Godavari River in Andhra Pradesh (Baksi et.al., 1994; Baksi, 2001; Sen and Sabale, 2011). Some geologists considered that RTB are the distal end of Deccan Traps lava flows spreading over 1500km towards east and extending about 70km into the Bay of Bengal (Jay 2005; Keller et al. 2008; jay and Widdowson, 2008; Self et al., (2008). The basalts are striking NE - SW direction, with a dip of~5° towards the Bay of Bengal in SE direction. Rajahmundry trap flows have well-exposed and typical stratigraphic, succession underlain by of late cretaceous limestones, and overlain by the sandstone of Eocene age. The exposed thickness of RTB trap lava flows on average are 60m including two sedimentary inter layers of lime stone, shale and red bole (~2m thickness) and an over lying lateralized basalt as in some areas like Pangidi, Gowripatnam, Duddukuru, Lakshmipuram and Kateru. The lava flows are bounded by red gravel soil on the top and lime marl infratrappean, with fossiliferous layers at the bottom (Fig.1). These sedimentary intertrappeans between lower and middle traps and between middle and upper trap, indicate periods of break or non -deposition before each lava flow emplacement of unknown duration. Flows are compositionally almost similar and are having holocrystalline, to mesocrystalline texture, light black in colour with phenocrysts of olivine, Albite, Anorthite, and pyroxene embedded in ground mass of same minerals and glassy matrix and also other accessory minerals, like ilmenite, Magnetite, Quartz and secondary minerals Hematite and Goethite Kaolinite and Montmorillonite.

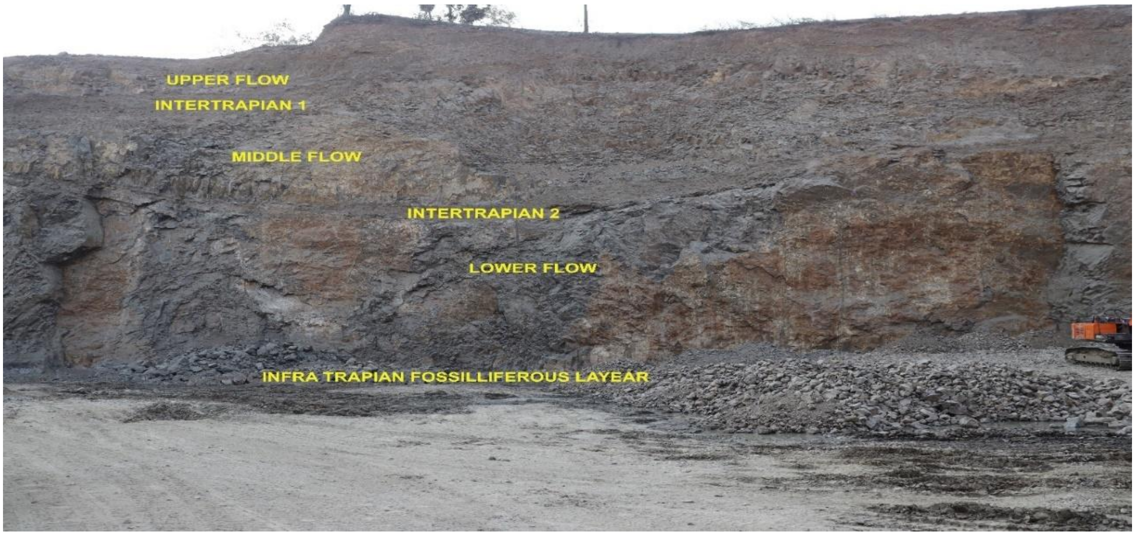

Fig No: 1. Field photograph of three basalt lava flows with intertrappean I & II and Infratrappean fossiliferous layer at the bottom in quarry cuttings observed in Sri Sivagowri stone quarry at Duddukuru.

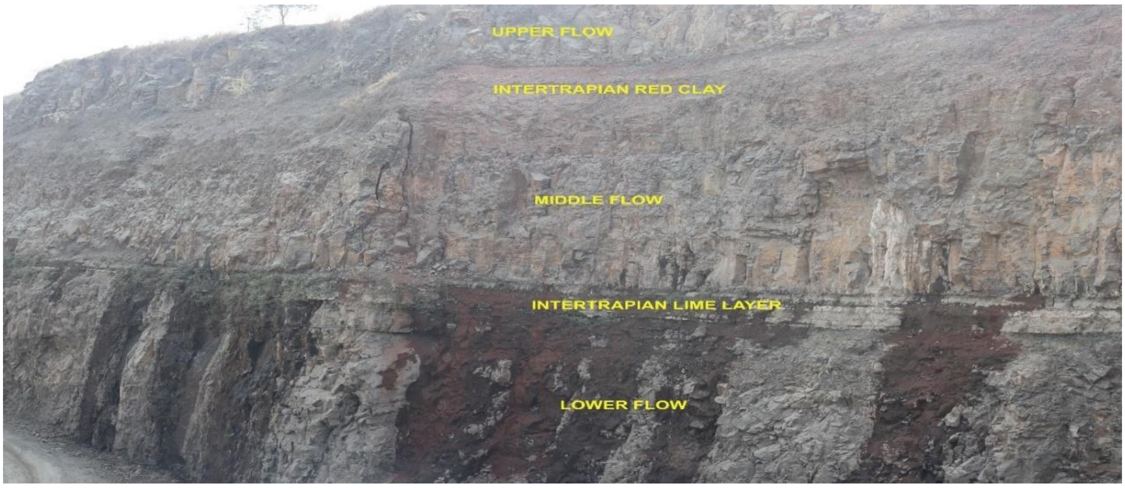

Fig. No.: 2. Field photograph of three basalt lava flows with itertrappean -1 and intertrappean -2 observed in Kondagudem quarry at Gowripatnam.

GEOLOGY OF THE AREA

The RTB are considered as part of the Godavari Triple Junction. This particular region specifically preserves an excellent stratigraphic record of Mesoproterozoic to Neogene period providing evidence for Gondwana continental break-up, in late Cretaceous and drifting (Lakshminarayana,1996, 2002; Lakshminarayana et al., 2010). A sequence of mounds that trends NE-SW between Gowripatnam, Duddukuru and Rajahmundry, covering an area of nearly 100 km^2, is represented as the RTB in the Krishna-Godavari Basin. K-G Basin has been developed during Phanerozoic due to uplift of the basement that resulted in buildup of Eastern Ghat Mobile Belt. Lakshminarayana (1995a) pointed out that a series of step faults oriented in NE - SW are the main cause for the development of major east coast basins since Mesozoic from west to east. These blocks are the Mailaram high, Dammapeta Basin, Raghavapuram Basin and Pangidi-Rajahmundry Basin extending from west to east. The Mailaram high was uplifted initially in early Mesozoic controlling the sedimentary sequence in the Dammapeta Basin. Then the Mailaram high became a watershed zone due to post Jurassic uplift, resulting in the development of small deltaic streams that flow towards east (Lakshminarayana, 1997) for the first time. Outcrops of RTB are exposed in a few areas, namely Nallajerla, Decharla, Lakshmipuram, Badapuram, Duddukuru, Gowripatnam, Pangidi, Kater, Konthamuru and Rajahmundry with intervening sedimentary bedds (GSI, 1996). But the prominent outcrops with stratigraphic successions are exposed in five areas namely Pangidi, Gowripatnam, Duddukuru, Lakshmipuram and Kateru quarries. These discrete Trap lava flows are considered as a single unit (Lakshminarayana, 1995b). These separate areas expose coastal Gondwana sediments (Cretaceous), RTBs (K-Pg boundary), Rajahmundry sandstone Formations (Paleogene) and the Quaternary sediments in the K-G Basin. The uppermost horizon of the Tirupati Formations, forms the basement of the RTB, which is known as the 'Infratrappean beds' represented by limestone, sandstone and clay (Lakshminarayana et al.,1992). The RTB are bounded by a NE-SW fault in the NW margin and are overlain by the Rajahmundry sandstone and Recent sediments towards east. The traps are traversed by NW-SE faults at Duddukuru and Pangidi areas. The entire succession of RTB is preserved between, these two faults.

The present work mainly deals with the well-exposed successions of RTB from different quarry cuttings at Pangidi (17°00'52" N and 81°38'39"E), Gowripatnam (17°01'37"N, 81°37'22"E), Duddukuru (17°01'57"N, 81°36'05"E), Lakxhmipuram (17°00'49" N 81°35'06"E) and Kateru (17°03'06" N

81°47'33"E) quarries, which are located on west and East sides of the Godavari River. The RTB succession here comprise of three prominent basaltic lava flows- lower, middle and upper with two interveing Intertrappean sedimentary layers which are disignated as Intertrappean I and II. The lower flow of 15 to 30m thick unconformably overlies the Infratrappean (Maastrichtian-Danian) sedimantation (Fig.1). The presence of physical volcanological features such as rootless cones, tumuli and dyke like forms are observed in lower basalt flows along with prominent development of single to multi-tier columnar, and radial jointing.

Intertrappean I of 2.0 to 3.0 m thick consists of limestone, marl and clay intercalations and is sandwiched between the lower and middle basalt flows. Several invertebrate fossils have been identified from this limestone horizon at Pangidi, Kateru, Gowripatnam, Duddukuru, Lakshmipuram, Dhecharla, Bandapuram. This (palaeontological) evidence has drawn geologically great attention in view of the similarities with the Intertrappean beds of central and western India (Malarkodi et al., 2010, Lakshminarayana et al., 2010;). The middle flow is 5 to 10m thick, greenish grey vesicular basalt rests unconformably over the clay and limestone of Intertrappean I. The upper lava flow is underlain by Intertrappean- II which is made of red bole or red clay. The upper flow of 5 to15 m thick, unconformably overlying the Intertrappean II is fine-grained and vesicular in character.

Age	**System**	**Formation**	**Lithology**
Recent to Sub – Recent		Alluvium	Gravel, Sand, Silt, Clay and laterite.
Mio – Pliocene		Rajahmundry	Sandstone
-------------------------------Unconformity--			
Upper Cretaceous t Lower Eocene	K /T boundary	Rajahmundry	Upper Trap (Basalt Rock) Intratrappean – II (Red clay or red bole) Middle Trap (Basalt Rock) Intratrappean -I (Lime layer) Lower Trap (Basalt Rock) Infratrappean Fossiliferous layer
Lower Cretaceous to Lower Triassic	Upper Gondwana	Thirupathi	Sandstones and Shale/ Clay
		Raghava Puram	Sandstones and Shale/ Clay
		Gollapalli	Sandstones and Shale/ Clay
	Lower Gondwana	Chintalapudi	Sandstones and Shale/ Clay
---Unconformity--			

Archaen			Khondalites, Charnokites and Gneisses

Fig. No:3. Showing Geological Succession of the study area after Manikyamba et.al. (2015) and central Ground water report (2016-2017).

FIELD WORK AND SAMPLING

Well exposed outcrops of basalt flow are identified an eastern and western side of Godavari River extending to distance of approximately 60km around Rajahmundry. Samples of basalts were collected where querying is being carried out and stratigraphic sequence is prominently exposed. Some of the prominent quarry cuttings are 1) Sri Sivagowri Quarry at Duddukuru 2) Balaji quarry at Pangidi 3) Kondagudem quarry at Gowripatnam 4) Shesha Sai quarry at Laksmipuram, all lying on the western side of Godavari River and 5) Cherukuri quarry at Kateru on the Eastern side of the Godavari River. There are also sporadic occurrences RTB in their places are exposed as small hills or mounds, but quarrying is not carried out. At all the quarrying cutting places stratigraphic sequence exhibits three basalt flows one over the other and separated by two intratrappeans and an Infratrappean at the base of lower flow and also a supertrappean on upper basalt flow. This sequence of three flows with alternating sedimentary layers is considered as the boundary between cretaceous and Eocene ages (K-T boundary). At each location representative samples of required size (~10cm) were collected from each layer of basalt flow and labelled with serial number and preserved carefully in polyethene bags which are again labelled with location and serial number. And carried to the laboratory for further analysis. Above 45 samples are collected from all the locations and representative samples were later subjected to various analytical techniques.

Some field photographs have also been taken for description of super position of stratigraphic units of basalt flows and other features like colour, texture, and vesicles and Amygdales and total elevation of cross -section of stratigraphic columns.

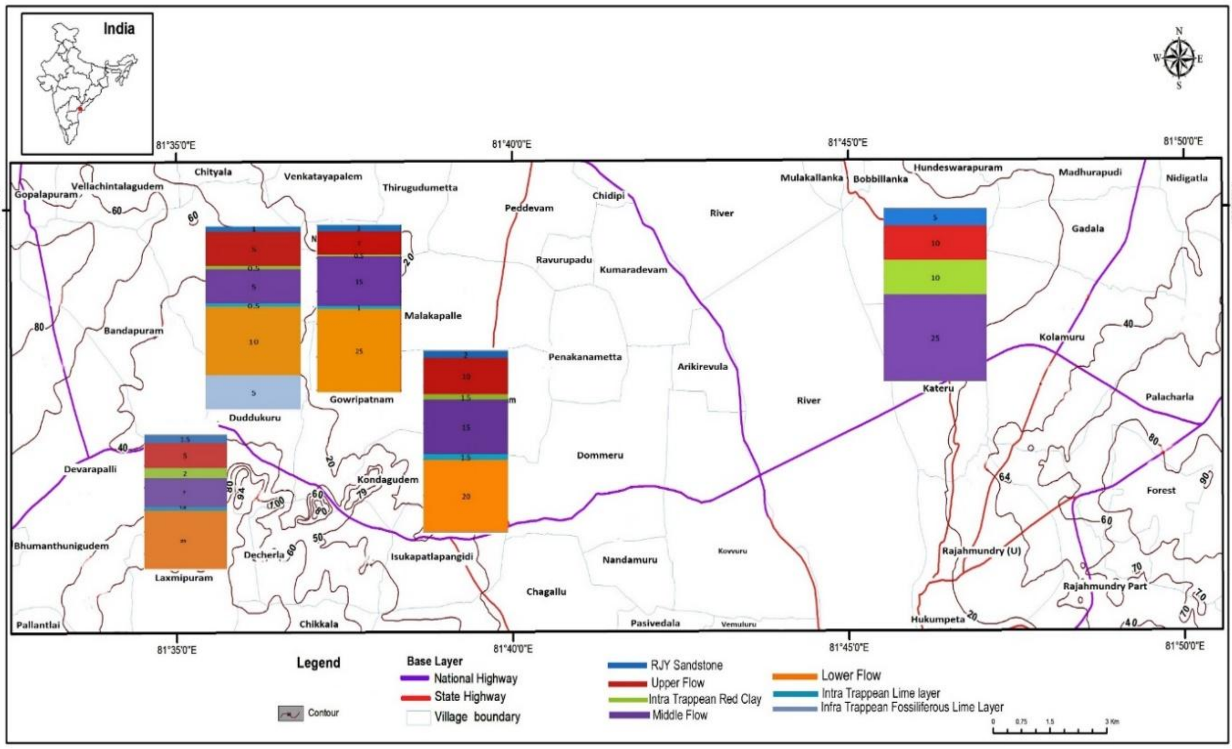

Fig. No: 4. Showing Basalt flows and intratrappean layers with approximate thickness (in meters) at different quarry areas of Rajahmundry trap Basalts, and also, samples taken from each flow representing areas in map. The sample numbers are U1,U2,M1,M2,L1,L2 from Pangidi, and sample numbers U3,U4,M3,M4,L3,L4 are from Gowripatnam, the sample numbers U5,U6,M5,M6,L5,L6 are from Duddukuru, the sample numbers U7,U8,M7,M8,L7,L8 are from Lakshmipuram and the sample numbers U9,U10,M9,M10 are from Kateru.

ANALYTICAL PROCEDURES

Various methods that are adopted for any investigation primarily dependent on the data required for the objectives set forth and availability of analytical techniques. Since the objectives of the present study on Rajahmundry Trap Basalts is to bring out certain mineralogical, and textural characteristics and their interrelationships, some advance technical and Laboratory investigations both non-destructive and destructive methods are carried out.

The widely used laboratory techniques of mineral identification are; optical mineralogy, X-ray diffraction, modal analysis and Norm calculation, initially thin sections of basalts have been prepared and examined under advanced petrological microscope for mineral identification and calculation of modal mineral percentages carried out for representative samples. Basalt samples were then ground to powder and fine fractions of – 250 mesh size were taken for analysing the minerals by X-ray diffractometer, and geochemical analysis by HR-ICPMS Spectro Photometer.

Thin sections study:

An advanced petrological microscope has been used to study certain important optical properties like Isotropy and anisotropy; extinction angle, pleochroism, birefringence, cleavages, 2V angle and R.I for identification of minerals. The minerals present in Rajahmundry Trap basalt samples are illustrated by microphotographs. (Photos No. 5 to 8) as well as major and minor interplanar ‘d’ spacings of minerals from X-ray powder pattern of samples.

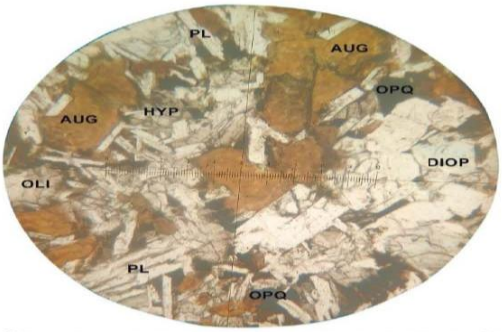

Figure : 5 Photomicrogrph showing Plagioclase laths,Augite,Diopside,Olivine,Hypersthen, and Opaque minerals in Basalt sample at Gowripatnam (X10) under plane polarised light.

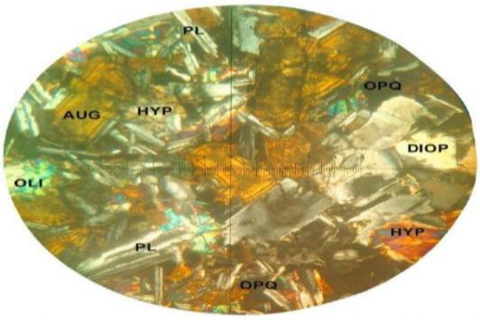

Figure : 6 . Photomicrogrph showing Plagioclase laths,Augite,Diopside,Olivine ,Hypersthen, and Opaque minerals in Basalt sample at Gowripatnam (X 10) under crossed nicols.

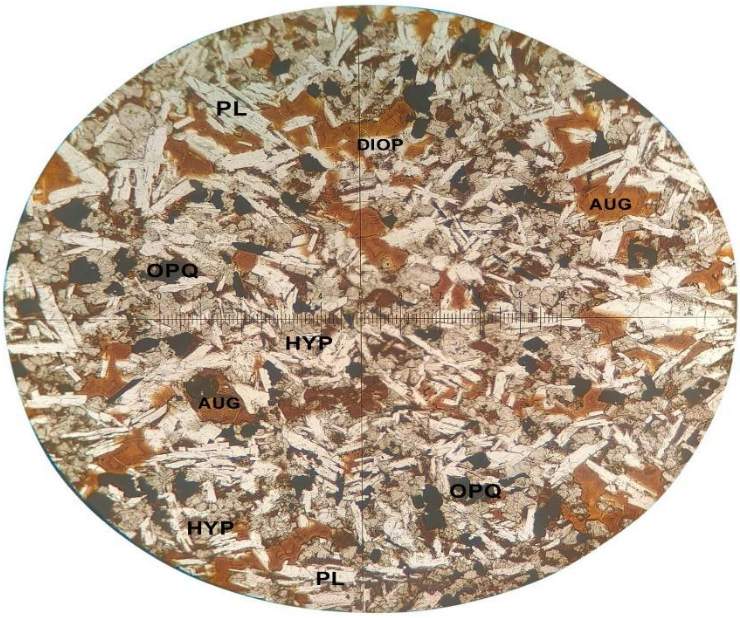

Fig :7 . Micro Photograph Showing Sub-Ophitic and intergranular texture, with Plagioclase,Augite,Diopside,Hypersthene and Opaque in Basalt Sample at Duddukuru (X 10) Under plane polarised light.

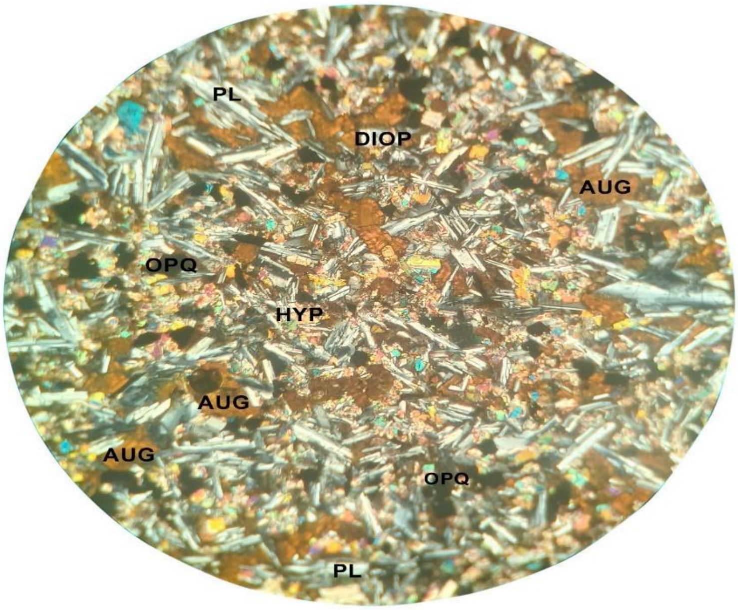

Fig : 8 . Micro Photograph Showing Sub-Ophitic and intergranular texture, with Plagioclase,Augite,Diopside,Hypersthene and Opaque in Basalt Sample at Duddukuru (X 10) Under crossed nicols.

MINEROLOGICAL STUDY

Basalt of the Rajahmundry Traps are primarily composed of plagioclase feldspars and pyroxene and sometimes olivine as essential minerals and minerals like Olivine, alkaline feldspar, quartz, Apatite, ilmenite, as accessory mineral. Nepheline and Lucite are not present in these basalts. The specific mineral composition and their proportions can vary depending upon the overall basaltic lava composition and its origin. Plagioclase feldspars are the most abundant mineral in basalts often present as labradorite, a calcium rich variety. Another essential mineral is Augite which is calcium rich pyroxene. Olivine is found in basalts particularly with high magnesium content. Olivine occurs in basalts as both the solid solution end – member's forsterite and fayalite, but in some basalt samples olivine is completely basalt. Other accessory minerals like hornblende, Quartz, Apatite, Ilmenite, and magnetite are also present in varying proportions. Occasionally orthoclase also occurs in the basalts. Due to the rapid cooling of the lava the basalts of the study area more often contains glassey matrix admixed with cryptocrystalline and amorphous material.

Understanding the complete mineral composition of basalts is crucial for geological study as it provides valuable insight in to magma generation process; tectonic setting and their proposition with in basalts along with its textures that can vary due to several factors.

Factors that control the type of minerals and texture of Basalt Rock.

Cooling rate: Faster cooling leads to finer grains size and less distinct crystals (aphanitic texture), whereas slow cooling promotes for larger crystals with in fine grained matrix (porphyritic texture).

Magma composition: The elemental makeup of the older rock plays a vital role in determining the type of minerals that will crystalline upon cooling.

Pressure and temperature conditions: The depth and heat with in the earth where magma originated influence the types and abundance of minerals formed.

Differentiation and fractional crystallization: As magma cools, minerals crystallize and separate, potentially enriching the remaining melt in certain elements and leading to basalts of diverse mineral composition.

Source mantle composition: The earth's mantle portion from which basaltic magma originate can have varying mineral composition, resulting in the production of entirely deferent types of basalts.

To have clear understanding on the genetic aspects of any rock, it is essential to have insight into its material characteristics like mineral constituents, their textural or interlocking patterns or the fabric and the geochemical elements present and their relative proportions. Order of crystallisation of minerals from the parent magma from which rocks solidify is also essential to know the genetic history of the rock. The minerals identified in Rajahmundry Trap Basalts (RTB) by various laboratory and Instrumental methods are classified into three categories 1) Essential 2) Accessory. Albite, Anorthite, Diopside, Augite, Hypersthene, Forsterite and Fayalite, constitute the essential minerals. And Magnetite, Ilmenite, Apatite, constitute the accessory minerals. Cristobalite, Stishovite, and Quartz. And secondary minerals like Kaolinite, Montmorillonite, Goethite and Hematite, which are the alteration products of primary minerals and also some cryptocrystalline and amorphous material has been identified in glassy Metrix. Various methods like optical, XRD, normative, Modal and physical characteristics, were employed for the identification and confirmation the minerals.

Olivine:

Olivine in thin sections is colourless, small crystals of six-sided polygonal outline with transversal irregular fractures, high relief, lack of cleavage and upper second – order interference colour; altered to fine granular aggregate Iddingsite or serpentine. In a few basalts samples olivine is completely absent. Normative mineral percentage of olivine is in the range of 1.2735 and10.0116. Modal percentage ranges from 1.0702 to 8.00. X-ray diffractions give characteristic major peaks with 'd 'spacings for Forsterite at 2.48A°,2.50279A°, 3.88068A° and also by the minor peaks at 5.1A°, 1.316A°, 2.03414, 1.38861. and for Fayalite by the major peaks at 2.81A°, 2.49A°, 1.792A° and also by the minor peaks at 5.21A°, 1.333A°, 1.367A°, 1.54A°, 1.41469A°, 1.275A°.

Plagioclases:

In thin sections members of plagioclase series (Albite-Anorthite) are normally colourless, subhedral to anhedral plates or laths, with one perfect and two less perfect cleavage directions; and white to pale-yellow interference colour. Crystals have Polysynthetic (albite) twinning; and black and white striped appearance under crossed Nicols. Plagioclase may alter to sericite or Epidote. Extinction angle increases gradually from Ab – An. Normative mineral percentage of plagioclase varies between 2.4628 and 26.8288 for albite and btween12.3126 and 34.1940 for Anorthite. Mineral mode percentage varies from 20.003 to 25.5026 for Albite and from 14.329 to 27.1011 for Anorthite, indicating abundance of Ca-rich members in RTB flows. X-ray diffraction reveals the presence of Albite by characteristic interplanar 'd 'spacings 4.02681A°, 3.77A°, 3.66A°, and also by minor peaks at 2.21A°, 2.28A°, 1.96A° and Anorthite by the major 'd 'spacings 3.20A°, 3.75A°, 4.04A° and also, by minor peaks at 6.48A°, 1.94A°, 6.82. Labradorite is identified by the same 'd' spacings as that of Anorthite.

Orthoclase:

K- Feldspars are colourless under microscope, subhedral to anhedral, low relief with one excellent cleavage. It exhibits first order grey and white interference colour. It shows extinction angle varying from 0 to 12° depending on orientation and composition K-feldspar may be confused with Quartz, but Quartz is usually clear without cleaves. K-Feldspar is present as small indistinct grains which is hardly distinguishable under macroscope. X-ray powder patron was made use in identifying the mineral. In some sample orthoclase is completely absent, it is identified by major peaks with 'd' spacings 3.31A°, 3.77A°, 4.22A° and also by minor peaks with 'd' spacings 6.42A°, 6.5A°,6.62A°.

Quartz:

Quartz is normally colour less in thin section, having low relief. Absence of cleavage and first order white or weak yellow interference colours, undulatory or way extinction are the identifying characteristic properties under microscope. In some samples where quartz is not obtained by CIPW Norm calculation, X-ray diffraction study reveals its presence by major 'd 'spacings at 3.34289A°, 4.26A°, 1.1802A° and also by the minor peaks at 1.19837A°, 1.2548A°, 1.45035A°, 1.288A°, 1.14356A°. This anomaly indicates that SiO_2 in the sample is present in cryptocrystalline and amorphous glassy matrix. Normative mineral. Percentage ranges from 0.012% to 9.342% whereas modal mineral percentage shows from 2.11% to 6.1%.

Augite:

Clinopyroxene mineral Augite in thin sections shows high relief and appears as short prismatic crystals with 4 or 8 sided cross sections. It is colourless or purplish brown in body colour with pale green pleochroism; Exhibits Maximum interference colour, Extinction angle varies from 36° to 45° and birefringence varies with extinction angle. It is difficult to distinguish Diopside, in thin section but diopside has greater birefringence and is less deeply coloured. Normative mineral percentage given is that of combined Augite and Diopside which varies between 1.6772 and 29.4756 and modal mineral percentage varies from 3.1026 to 16.7871. X-ray diffraction reveals characteristics major peaks with ' d ' values for Augite at 2.9985A°, 2.55A°, 2.13125A° and also by minor peaks at 1.52982A°, 1.56A°, 1.172A°, 1.073A°, 1.32052A° and Diopside by the major peaks with 'd' values at 2.98068A°, 2.91667A°, 2.52A° and also by the minor peaks at 2.02007A°, 6.39794, 1.985A°, 1.15395A°.

Hypersthene:

An Orthopyroxene Hypersthene is identified in thin section by moderately high to high relief having pale pink to green body colour, pleochroic nature, well developed prismatic crystals and square shaped basal section. Basal section has two sets of cleavage nearly at right angles; parallel extinction is observed in most cases. Normative minerals percentage ranges from 2.7612 to 36.8148. and modal mineral percentage ranges from 13.125 to 27.1201 Hypersthene is identified by X-ray diffraction by characteristic major peaks with ‘d ‘spacings 3.18265A°, 2.88A°, 2.56A° and also by minor peaks at 2.064A°, 6.38A°, 1.79A°, 1.89A°.

Ilmenite:

Ilmenite crystalising in Trigonal System is an accessory mineral in Basalts. In thin sections Ilmenites are observed as opaque, disseminated, tabular or flaky or skeletal or irregular grains. Normative minerals percentages of Ilmenite rage from 2.64 to 9.3784. Modal mineral percentages are also found to be in the ranges of 3.1021 and 8.7711 X-ray diffraction gives characteristic major peaks with ‘d ‘spacings at 2.75A°, 1.73A°, 3.74A°, and also by minor peaks at 1.34A°, 0.9A°, 1.24A°.

Magnetite:

It is also an accessory mineral in Basalts of the study area. In thin section it is opaque, and euhedral crystals of rhombohedral cross section of octahedron. Magnetite can be distinguished from ilmenite by its regular shape. Normative mineral percentage is obtained in rages from 1.2096 to 3.5264. Modal mineral percentage is also formed between 2.0721 and 5.6711. X-ray diffraction gives the characteristic peaks with ‘d’ spacings 2.53A°, 1.48A°, 2.97A° and also by minor peaks with ‘d’ spacings at 4.85A°, 1.21545A°, 1.41297A°.

Apatite:

Apatite is an accessory mineral in basalts. It is identified by its colourless habit in thin sections, moderate relief, white to gray interference colour; minute lath like hexagonal crystals or prisms, parallel extinction in longitudinal sections and poor cleavage in one direction. Normative mineral percentages ranges 0.1296 to 0.4752. It is identified in thin section with difficulty as it is confused with other prismatic lath shaped crystals. By X-ray diffraction it is identified as **Fluorapatite** with characteristic major peaks with ‘d ‘spacings at 2.82063A°, 2.0292A°, 1.82847A° and also by the minor peaks at 1.74202A°, 1.7136A°, 1.74644A°.

Cristobalite:

Cristobalite is one of the polymorphs of SiO_2, Cristobalite is colourless, white or yellowish in body colour. It is identified under microscope by its colourless nature and low relief and week birefringence and undulose extinction. It can exist above the range of 200 ^{0} C to 275 ^{0} C and stable from 1470 ^{0} C to 1713 ^{0} C. Cristobalite is a typical mineral of volcanic rock where it may occur in cavities, in association with tridymite. It is found mostly in trachytes, obsidian, andesites and olivine basalt. It is often a late product of crystallisation. it is identified under the microscope as a small octahedral crystal and as aggregate of rounded masses it is identified majority of basalt samples of the study area. Cristobalite is identified by X-ray powder pattern with characteristic ‘d’ spacings at 2.82136A°, 1.87439A°, 1.92A°.

Stishovite:

Stishovite is a High-pressure polymorph of silicon dioxide (SiO_2) with a unique structure crystalising in tetragonal system and is the member of silica group mineral. It is found as microscopic grains in ultra high-pressure rocks. Because of the fine graine nature of basalts, it is very difficult to distinguish stishovite from other colourless minerals under microscope. But Its presence in basalt is revealed by only XRD powder pattern. It is identified in almost all the basalt samples of the study area. The major diffraction peaks for ‘d’ values of Stishovite are at 1.53021 A°, 1.235A A°, 2.246 A°, 1.18 A° and also minor peaks at 1.478 A°, 1.322 A°, 2.09 A°, 1.2892 A°, 1.013 A°. It is found that Cristobalite also associated with stishovite in all the samples.

Hematite:

It is identified in majority of Basalt samples of the study area, and it is a common mineral in many kinds of rocks. It is an alteration product of all Fe – bearing minerals. In thin sections hematite appears as small anhedral crystals and masses. Exhibits high relief; It is Opaque or red coloured at their edges in transmitted light. Sometimes associated with goethite. The presence of Hematite is confirmed by X-ray studies with major peaks with 'd' spacings 2.70A°, 1.69A°, 2.50018A° and also by the minor peaks at 3.66A°, 1.70A°.

Goethite:

Goethite along with hematite is also identified in majority of basalt samples. In transmitted light it is yellow to dark brown in body colour with feeble pleochroism. It exhibits high order interference colour. The presence of goethite is confirmed by X-ray studies with major peaks with 'd' spacings 4.18A°, 2.45A°, 2.63774A°, 1.71254A°, 2.22102A°, 4.2336 A°, 3.3877A°, and other minor peaks with 'd' spacings 2.686A°, 2.2192A°, 1.370A°, 1.290A°, 2.22102A° and 1.267A°.

Kaolinite:

Clay minerals are very difficult to distinguish from each other in thin section. Clays are the end products of all types of rocks. Kaolinite is identified in majority of basalts samples of the study area. Kaolinite normally appears as massive aggregate of fine scales and shards and have grey, brown or earthy colour with low relief. Interference colours are up to middle second order. Kaolinite is mainly an alteration product of K-feldspars. Kaolinite is identified by the major 'd 'values 3.5A°, 1.49A°, 1.12624A° and also by the minor 'd' spacings 4.44A°, 4.41A°.

Montmorillonite:

Montmorillonite is identified in few basalt samples of the study area and it is colourless, yellow or green in thin section. It appears as massive aggregates of scales and shards. Montmorillonite display up to middle to second order interference colour. It can be distinguished from other clay minerals by X-ray powder pattern. Its presence is revealed by major 'd' spacings 4.97A°, 5.01A°, 1.5A°.

Area/ Element	PGD			GPT			DDU			LKMP			KATERU	
	PU1	PM1	PL1	GU2	GM2	GL2	DU3	DM3	DL4	LU5	LM6	LL6	KU9	KM1O
Albite	24.204	21.1103	21.8182	23.0965	22.0012	23.0978	25.5026	20.0003	20.2617	25.5026	23.0042	25.4472	24.332	21.022
Anorthite	22.571	24.5266	20.6363	25.4338	23.2012	23.1739	17.8371	25.6666	27.1011	17.8371	24.3012	23.6569	21.421	22.4012
Orthoclase	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diopside	8.1312	2	3.03	7.2601	3.15	8.1011	4.007	2	6.2106	4.007	3.1	7.122	8.212	4.1
Quartz	0	0	0	0	0	6.1	0	0	4.8622	0	0	0	0	0

Opaque	8	8.2141	8.1201	9	8	7.212	7	9.2241	8.9106	7	7	8.315	7	8
Olivine	5.1007	2.5214	8	5.5176	4.9958	0	5.9182	1.5214	0	5.9182	4.1051	5.2	5.1553	4.1051
Hypersthene	17.06	25.1201	23.5	12.1001	25.2391	18.1011	19.1107	27.1201	21.2112	19.1107	24.2191	13.125	16.06	23.3191
Augite	9.033	10.9311	10.03	12.5216	8.026	9.023	16.1101	10.6211	8	16.1101	6.026	11.1221	9.952	9.026
Cryptocrystalline And Glassy Matter	4.3	4.8259	3.97898	4.011	7.132	5.002	4	5.7759	3.0549	4	9.122	5.21	3.3	8.122

Table No:1. Modal mineral percentages calculated from thin section of basalts from Pangidi (PGD), Gowripatnam (GPT), Duddukuru (DDU), Lakshmi Puram (LKMP) and Kateru areas.

Area / Elements	PGD						GPT					
	PU1	PU2	PM1	PM2	PL1	PL2	GU3	GU4	GM3	GM4	GL3	GL4
Quartz	0	0	0	0	0	0	0	0	0	5.142	0	5.418
Orthoclase	0	0	0.9452	0	1.5012	0	0.6422	0	0	1.5012	0	0
Albite	23.58	25.676	22.8464	21.5888	24.104	21.484	24.4708	23.4228	23.1084	25.3048	22.6892	22.0604
Anorthite	21.1558	21.9342	21.128	23.0462	25.9652	26.966	22.4624	26.9938	22.5458	23.213	26.7158	28.0502
Diopside	16.7004	16.746	16.538	19.01	16.162	14.0084	14.5332	13.3428	18.2384	9.6444	16.6596	16.0524
Hypersthene	20.4324	16.7384	22.8344	21.5008	22.746	23.6976	18.9136	22.842	19.136	29.5096	22.368	13.0376
Olivine	5.9452	7.5176	2.4408	2.6932	1.2735	1.2736	6.3104	3.53	4.66	0	5.1784	0
Magnetite	1.972	1.9256	1.7632	1.8096	1.7864	1.7864	1.924	1.972	1.7864	1.9952	1.6992	1.7632
Ilmenite	4.3016	3.8608	3.344	3.5416	3.6024	3.42	3.8608	3.5568	3.4656	3.7088	3.6328	3.6328
Apatite	0	0	0.2574	0	0	0	0.1916	0	0	0	0	0

Table No: 2(A) Norm calculation data of basalt samples from Pangidi (PGD) and Gowripatnam (GPT) quarries.

Area/ Element	DDU						LKMP					
	DU5	DU6	DM5	DM6	DL5	DL6	LU7	LU8	LM7	LM8	LL7	LL8
Quartz	0	0	0	0	0	0	1.2232	0	0.87	0	10.134	0
Orthoclase	1.2232	1.39	1.7132	0	0	2.7048	26.3736	1.112	0	0	1.5568	2.7048
Albite	25.414	26.2	23.58	23.1084	23.1084	26.8288	24.6586	26.2	22.4796	22.7416	2.4628	26.8288
Anorthite	24.742	24.6586	23.2686	22.5736	28.5228	20.1064	5.9884	24.7976	21.2948	22.796	34.194	20.1064
Diopside	9.3756	9.03	8.8876	15.9376	18.16	5.5548	22.5364	1.9508	16.47	18.09	1.6772	5.5548
Hypersthene	18.6308	18.246	26.5636	23.664	11.14	26.6544	3.8436	29.4064	25.5248	9.3588	36.8148	26.6544
Olivine	7.5916	9.692	4.6592	0.0756	7.8876	6.8708	1.972	3.9852	0	4.4272	0	6.8708
Magnetite	1.9488	1.9488	2.0648	3.248	1.74	2.2272	2.6448	1.972	1.74	1.8328	2.2272	2.2272
Ilmenite	4.4232	2.6752	4.0128	3.5416	3.6936	3.9064	0.2282	2.5384	3.3592	3.42	3.7088	3.9064
Apatite	0.1916	0.2282	0.2902	0	0	0.2282	1.2232	0.1916	0	0	0	0.2282

Table No: 2 (B). Norm calculation data of basalt samples from Duddukuru (DDU) and Lakshmipuram (LKMP) quarries.

Area / Elements	KATERU			
	KU9	KU10	KM9	KM10
Quartz	0	0.198	9.486	4.786
Orthoclase	1.2232	0	2.0572	1.0362
Albite	26.3736	21.6411	17.9208	19.3123
Anorthite	24.6586	25.993	21.6284	22.8323
Diopside	5.9884	13.1516	26.4012	24.5011
Hypersthene	22.5364	24.0752	3.724	12.652
Olivine	3.8436	0	0	0
Magnetite	1.972	1.7864	1.904	2.895
Ilmenite	2.6448	3.6024	6.7336	6.231
Apatite	0.2282	0	0.4752	0.2135

Table No: 2 (C). Norm calculation data of basalt samples from Kateru area quarry.

Textures in Rajahmundry Trap Basalts

Texture is the intimate and mutual relationship between constituent minerals and glassy matter, making an overall unform aggregate. Texture is studied and described in detail only under the microscope. Textural character and micro structures are crucial in the study of basalts because these characters are the indication of the processes lacking place during solidification of lava and the study of these textures provide Insight into the mode of formation and geological history of the rocks.

Factors that control the texture of Basalt:

Important textural characters are to be considered to know actual arrangements of crystals in rocks of the study areas are. (1) Crystallinity (2) Granularity (3) Crystals shapes (4) Mutual relations among crystals.

Crystallinity:

Crystallinity is the extent to which the atomic structure has controlled the out-ward form of a substance. Crystallinity is the ratio between the well crystallised and non-crystalised matter. The texture is termed holocrystalline when a rock is composed only of crystals. the texture is termed is holocrystalline when consists only of glass; If the rock is composed of both glass and crystals, the term mesocrystalline is used. Since the basalts of the study area are surface deposit, majority of the samples exhibit holocrystalline and fine granular texture, but a few basalt samples exhibit mesocrystalline texture composed of both fine crystals and glassy matrix Rate of cooling viscosity and composition of the lava are the controlling factors in producing the texture. The fine texture RTB indicates the rapid rate of cooling. Large crystals present in basalt are the early crystals developed in the magma, while it is at depth, whereas the fine crystals and glassy matter indicate fast rate of cooling in the later stages of solidification on the surface. Composition of magma is also important in determine the texture. Multi component magmas crystalise normally with fine texture as composed to magma with simple composition. Since basaltic magma composed number of elements it shows in number of small crystals.

Granularity:

Size range of crystals in igneous rocks varies from almost cryptocrystalline dimensions to very large crystals of one yard diameter. The rocks are said to be phanerocrystalline, if the crystals are large to be observed with naked eye or with the help of a pocket lens, then. The term aphanitic is used if the individual crystals are not be distinguished in this way. Since the size range of crystals in basalts of study area is less then 1mm and hence microcrystalline to cryptocrystalline, individual crystals are distinguished only under microscope. Cryptocrystalline minerals are identified by X-ray diffraction technique. Like crystallinity, the granularity is also dependent upon rate of cooling and viscosity of the magma. Fine crystals indicate the fast-cooling rate and large crystals indicate slow cooling rate of the basalt magma, whereas glassy matrix indicates the extremely fast rate of cooling.

Shape of the Crystal:

The fabric of the Basaltic rock depends both on the shapes and sizes of crystals and their mutual arrangement. Crystal forms are described with reference to their perfectness of the faces. When the crystal is completely bounded by faces, in three directions of space the term **‘euhedral’** is applied to minerals Likewise, the term ‘subhedral’ is are used when there is a partial development of faces and anhedral when faces are absent, Augite an example. When crystals are equally developed in all the three directions those crystals are termed equidimentional. Crystals well developed in two directions than in the third, are termed as **‘tabular’** Example feldspar and Micas. ‘Prismatic’ Crystals are those which are better developed in one direction than in the other two. Examples are Apatite and Hornblende. There are number of crystal shapes such as ragged veins, patches, skeletons, which are described as **‘irregular’** Ex. Ilmenite. In basalts the early formed crystals are euhedral and later formed crystals are subhedral to anhedral in texture.

Mutual Relations of Crystals:

Crystal shapes and their relative and mutual orientation decide the fabric of the rock_ Textures which are due to mutual relationships may be described as 1) **Equigranular,** 2) **Inequigranular**, 3) **Directive** and 4) **Intergranular**.

When all the constituent minerals are of the same size then the texture is the termed ‘Equigranular’. When most of the minerals are subhedral the texture is termed as ‘hypidiomorphic’. When most of the crystals are anhedral, the term ‘allotriomorphic’ is used. When majority of the minerals are euhedral the term “panidiomorphic” is used. The RTB basalts when studied under microscope exhibits hypidiomorphic texture.

Inequigranular texture can be described by two terms ‘porphyrite’ and poikilitic. Porphyritic texture is largely exhibited by volcanic and hypabasal rocks. Basalts of the study area shows rarely the porphyritic texture in which micro phenocrysts of Augite, Diopside, and Olivine are enveloped by fine matrix of the same minerals and occasionally aggregates of fine mineral matrix and glassy matter. Most of the Basalt samples shows poikilitic texture. The sub-Optic texture which is a special type of poikilitic texture is observed in majority of basalt samples in which numerous small plagioclase laths are partially enclosed in large Augite plates.

Intergranular Texture:

The basalts of the study area also show in thin sections the **Intergranular** texture in which plagioclase laths are arranged in frameworks of triangular or polygonal interspaces which are filled with fine granules of Olivine, augite and iron oxides. Sometimes glassy or cryptocrystalline material constitute important amounts of infillings in which case the term **‘Intersertal’** in used.

Directive Texture:

Directive Textures are produced in lava flows during their solidification. Indications of flow structure are observed in the basalts of the study area, without destroying the overall uniformity of the rock. In directive texture Crystallites and crystals follow the stream lines of the lava. White feldspar in basalts is aften arranged in parallel position by flow. Though crystallites and crystals are drawn and aligned in one direction; there is no destruction in the overall uniformity in composition of rock.

DISCUSSION

Minerology provides a crucial information and clue to the source of Basaltic magma because the mineral composition reflects the pressure, temperature and chemical conditions of their crystallization deep within the earth's mantle. By studying the minerals present in basaltic rocks we can decipher the tectonic setting, depth of origin and temperature at which the primary magma was generated. Basaltic magma is the most common type on earth, and is presumed to have generated from the mantle which composed primarily of Peridotite, Pyroxenite and Dunite. The primary minerals in Basalts include **Plagioclase feldspars,** particularly a calcium – rich variety Labradorite, **Pyroxene** including augite and some cases Orthopyroxene, and **Olivine** including Forsterite and Fayalite in the solid solution series.

Variations in the proportions of these primary minerals along with the presence or absence of accessory minerals like Ilmenite, Magnetite, and apatite and Quartz indicate different mantle conditions and histories. The most fundamental distinction in basalt minerology relates to the degree of silica saturation in the magma which directly corresponds to the depth and extent of melting.

Basaltic Magma can carry rock fragments called Xenoliths from its mantle sources region to the surface which are vital tools to the source rock composition. The minerals that crystallize from magma as it ascends can also be diagnostic. The presence of phenocrysts of Olivine, Pyroxene and Plagioclase suggests that these minerals crystalised at different depths and temperatures as the magma moved towards surface. Sometimes complex zoning patterns within the individual mineral crystals can indicate its reaction with rest of the liquid or magma mixing with other magma with distinct chemical composition before eruption.

Mineralogical evidence for a mantle source for Rajahmundry Trap Basalts includes the specific mineral assemblages and textures as well as geochemical signatures indicative of mantle composition and magma evolution. Key features include Phenocrysts of Plagioclase and clinopyroxene, a ground mass consisting of plagioclase granular pyroxene, opaque minerals and glass. The geochemical data of these basalts suggests a low Potassium K_2O (0.06 – 0.54 w%) sub -alkaline Tholeiitic composition with moderate to High MgO (3.35 – 7.72 w%) and CaO (5.69 – 10.88w%). Studies also suggested that the RTB basalts ware generated from an enriched mantle source and undergone fractional crystallisation before eruption on to the surface. The fine – grained ground mass of Plagioclase, pyroxenes, Opaques, and glass suggest extremely rapid cooling and solidification of remaining magma after eruption. Sub-Ophitic, Intergranular and intersertal textures are commonly observed, further supporting the assumption that magma crystalised rapidly after eruption. The presence of Amygdaloid and Geode structures in the vesicular zones of the basaltic flows indicates the trapping of fluids and dissolved gases during eruption and cooling.

Olivine is the first mineral to crystalise from the magma in the deep-seated conditions under high pressure and temperatures probably >1550°c. The early formed Forsterites reacts at about 1550c with the liquid to form a ($MgSiO_3$) Pyroxene later producing the other ferromagnesium minerals in the order during the cooling of the magma. The phenocrysts of early formed Olivine in the magma are carried to the earth's surface in the process of ascent and these phenocrysts are enclosed by other fine-grained minerals like Plagioclase, Augite, and glassy metrix due to the rapid cooling of the basaltic magma. For this reason, Olivin is always found as phenocrysts in basalts being enveloped by ground mass exhibiting porphyritic texture.

The presence of plagioclase – phenocrysts also indicate a mantle derived magma that has under gone partial degree of crystallization at temperature around 1550°C before magma eruption. Labradorite is identified by the same 'd' spacings as that of Anorthite in X-ray powder pattern.

Pyroxenes are a group of ferromagnesian silicates minerals that form at high temperatures of 1000°C – 1385°C and high pressures, depending on magma composition, pressure and cooling rate. At higher temperatures calcium - rich pyroxenes like Augite crystalise and with decreasing temperature calcium poor Orthopyroxenes like Enstatite crystalises. Fast cooling rates can result in a wide verity of pyroxene compositions, with lower temperature phases being more common, whereas slower cooling rate allows for more complete equilibrium and fewer distinct pyroxene verities. Pyroxene are significant in basalts due to their abundance in mafic and ultra mafic rocks.

Magnesium- rich Orthopyroxenes are common constituents of some ultra basic rocks, such as pyroxenite, harzburgites, lherzolite, picrite in which they are commonly associated with forsterite Olivine, Diopside - Augite and Magnesium spinel. These are also common constituents in the Olivine rich inclusions in basalts. Hypersthene also occurs in basalts as phenocryst as well as fine crystalline matrix admixed with glassy matter.

Ilmenite is as an accessory mineral in many igneous rocks in the form of veins and disseminated deposits. It is one of the earlier minerals of the magmas to crystallise, but the important magmatic ilmenite ore deposits are associated with rocks rich in pyroxene rather than Olivine and the associated pyroxene is an orthopyroxene. It is always associated with magnetite and for which reason it may be difficult to distinguish from magnetite unless both are present in the same thin section.

Magnetite is the most ubiquitous and abundant oxide minerals in igneous and metamorphic rocks. It occurs typically in accessory mineral as magmatic segregations or forming magmatic bands. Magnetite is occurring as an accessory mineral also in all the samples of basalts of different locations of the study area. Alteration of magnetite leads to the formation of Limonite and Goethite.

Apatite is not actually a specific mineral but rather is name for group of similar isomorphos hexagonal phosphate minerals. It can be very difficult to distinguished between the individual minerals since they partially replace each other. Apatite can exist in many different forms with base of apatite calcium (Ca_5) and Phosphorus (PO_4) existing together. In most igneous apatite, the Flour-Apatite molecule generally dominates, often with appreciable OH in addition, forming a Hydroxy – Fluor – Apatite. Fluor -Apatite was identified in all the samples collected from three layers of the Basalt flows from different locations.

The specific composition and zoning of apatite with in basalts can offer insights into the magma evaluation processes including the behaviour of volatiles like H_2O and CO_2 and the enrichment or depletion of elements like REE and Halogens. It can also indicate the involvement of carbonatitic/ kimberlitic fluids in mantle enrichment. The xenoliths which have apatite – rich inclusions are carbonatitic or kimberlitic in origin. And also, xenoliths are enriched in REE which may be evidence for mantle heterogenity. On the whole apatite, serves as a window into mantle processes and magma evolution. Its presence often points to deep mantle derived components at high temperature with its composition revealing details about the volatile trace elements conditions of its host magma (Wei-Run Li et.al.,2024).

In some samples where quartz is not obtained by CIPW Norm calculation, X-ray diffraction study reveals its presence. This anomaly indicates that SiO_2 in the sample is present in cryptocrystalline and amorphous glassy matrix. Stishovite and cristobalite which are polymorphic forms of SiO_2 were also identified along with Quartz in some basalt samples by using X-ray powder patterns. Stishovite is considerably denser (4.35 g/cm^3) than Quartz (2.56g/cm^3) and rarely occurs on earth's surface. Stishov and Popova (1961) made stishovite by applying pressures of around 130kb and temperature 1600°C. It is evident from the laboratory experiments that stishovite was formed probably in the lower mantle. Since Stishovite is a high temperature – pressure polymorph of SiO_2 it may convert to Cristobalite in air at 900°C.

CONCLUSIONS:

1. Fine texture of basalts exhibiting sub-ophitic, intergranular and intersertal textural features are indication of extremely rapid rate of cooling while flowing on the surface.
2. Since Basaltic Magma is geochemically multicomponent system, composed of a number of minerals it crystallized in fine-grained texture.
3. Amygdales present in Basalts are also indicators of extremely fast rate of cooling since the volatiles and fluids which are dissolved in main mass could not escape into air before solidification of lava and trapped within the vesicles and later crystalized.
4. The presence of Olivine phenocrysts in basalts indicates high temperature and low silica content of the magma.
5. The occurrence of polymorphic forms of SiO_2-Quartz, Cristobalite and very high temperature – pressure phase Stishovite in these basalts indicate very deep source of magma probably the transition zone or lower mantle.
6. Presence of Fluorapatite in the basalts of the study area is an indication of deep mantle source at very high temperature.

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REFERENCES

1. Ahmad M and Shrivastava J P 2004 Iron-titanium oxide geothermometry and petrogenesis of lava flows and dykes from Mandla lobe of the eastern Deccan Volcanic Province, India; Gondwana Res. 7(2) 567–577.
2. Amy L. Lewis at., al., 2021; Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant – nutrient element release via enhanced weathering. Applied Geochemistry 132 Elsevier.
3. Anthony Hall Igneous Petrology published by ELBS 1988 produced by Longman Singapore publishers Pte Ltd printed in Singapore.
4. Aquifer Mapping and Management of Ground Water Resources Sandstone Area of East Godavari, West Godavari and Krishna Districts, Andhra Pradesh. 2016-2017.
5. Baksi A K, Byerly G R, Chan L H and Farrar E 1994 Intracanyon flows in the Deccan Province, India? Case history of the Rajahmundry traps; Geol. 22 605–608.
6. Baksi A 2001 The Rajahmundry Traps, Andhra Pradesh: Evaluation of their petrogenesis relative to the Deccan traps; Proc. Indian Acad. Sci. 110 397–407.
7. Bakshi, A.K. (2001b). The Rajahmundry traps, Andhra Pradesh: evaluation of petrogenesis relation to the Deccan Traps.

8. Bibhas Sen and A. B. Sabale Vol. 78, Nov. 2011, PP. 457 – 467 Journal Geological Society of India. Flow – types and Lav Emplacement History of Rajahmundry Traps, West of Rever Godavari, Andhra Pradesh.
9. Brown G M 1967 Mineralogy of basaltic rocks; In: The Poldervaart treatise on rocks of basaltic composition, Interscience Publishers 1 103–167.
10. Courtillot V, Feraud H, Maluski D, Moreau M G and Besse J 1988 Deccan flood basalts and the Cretaceous/Tertiary boundary; Nature **333** 843–846.
11. Cox, K.G., 1980. A model for flood basalt volcanism. Journal of Petrology 21, 629e650.
12. Cox K G and Hawkesworth C J 1984 Relative contribution of crust and mantle to flood basalt magmatism, Mahabaleshwar area, Deccan Traps; Phil. Trans. Roy. Soc. London **A 310** 627–641.
13. Deshmukh S S 1988 Petrographic variations in compound flows of Deccan Traps and their significance; In: Deccan flood basalts (ed.) Subbarao K V, Geol. Soc. India Memoir **10** 305–319.
14. Dexter Perkins Kevin R. Hence 2007 Minerals in thin section printed by Dorling Kindersley (India) Pvt.Ltd., licenses of person Education in south Asia.
15. Francis J. Turner John Verhoogen 1987 in India Igneous and metamorphic petrology. This edition has been reprinted in India by arrangement with McGrow – Hill Book Company, New York. (CBS Publications & Distributary 485. Jain Bhavan, Bhola Nath Nagar Shahdara, Delhi 110023 India.

16. Ganguly, S., Ray, J., Koeberl, C., Ntaflos, T., Banerjee, M., 2012. Mineral chemistry of lava flows from Linga area of the Eastern Deccan Volcanic Province, India. Journal of Earth System Science 121, 91e108.
17. Haina Li, Jun Han, Fengli Li, Heyang Li, Zhonghai Zhao, Yang Liu, Jiayu Chen, Yechang Yin & Yu Han 2024 Apatite textural and geochemical insights into the petrogenesis of intrusive rocks scientific Reports (2024) 14:31985.
18. Jay, A.E., 2005. Volcanic Architecture of the Deccan Traps, western Maharastra, India: An Integrated Chemi stratigraphic and Paleomagnetic Study. PhD thesis submitted to Open University, Milton Keynes, 360 pp.
19. Jay, A.E., Widdowson, M., 2008. Stratigraphy, structure and volcanology of southeast Deccan continental flood basalt province: implication for eruptive extent and volumes. Journal of Geological Society of London 165, 177e188
20. JCPDS 1980 Mineral Powder Diffraction File Data Book American Society for Testing and Materials. Published JCPDS International Centre for Diffraction Data 1601 Park Lane, Swartmore. Pennsylvania 19081 U.S.A.
21. Keller, G., Adatte, T., Gardin, S., Bartolini, A., Bajpai, S., 2008. Main Deccan Volcanism phase ends near the K-T boundary: evidence from the Krishna-Godavari Basin, SE India. Earth and Planetary Science Letters 268, 293e311.
22. Lakshminarayana, G., 1995b. Fluvial to estuarine transitional depositional setting in the Cenozoic Rajahmundry Formation, K-G basin, India. Indian Minerals 49, 163e176.
23. Lakshminarayana, G., 1995a. Gondwana sedimentation in the Chintalapudi subbasin, Godavari valley, Andhra Pradesh. Journal of Geological Society of India 46, 375e383.
24. Lakshminarayana G, Manikyamba C, Tarun C, Khanna P, Kanakadande P and Raju K 2010 New observations on Rajahmundry Traps of the Krishna–Godavari Basin; J. Geol. Soc. India 75 807–819.

25. Lakshminarayana, G., 1996. Stratigraphy and Structural Framework of the Gondwana Sediments in the Pranhita-Godavari Valley, Andhra Pradesh. Proceedings of the IXth International Gondwana symposium 1, pp. 311e330.
26. L. G. Berry Brian Mason Mineralogy published by CBS Publishers & Distributary 485, Jain Bhavan, Bhola Bath Nagar Shahdara, Delhi.
27. Lindsley D H 1983 Pyroxene thermometry; Am. Mineral. 68 477–493.
28. Manikyamba C, Sohini Ganguly, M.Santhosh, Abhishek Saha, G. Lakshminaryana 2015 Geochemistry and petrogenesis of Rajahmundry trap basalts of Krishna-Godavari Basin, India. Elsevier Geoscience Frontiers 6 (2015) 437-451.
29. M.Satyanarayana, V.Balaram, S.S Sawant, etc. NGRI. Hyd. Rapid Determination of REEs, PGEs, and other trace elements in Geological and Environmental Materials by High resolution Inductively Coupled Plasma Mass Spectroscopy. Atomic Spectroscopy Vol. 39(1) January/Feb. 2018.
30. N Malar Kodi, U. Mallikarjuna August 2010 Sequence stratigraphy soma quarry section, near Gowripatnam, Rajahmundry area, Andhra Pradesh. Geological Society of India Vol. 76.
31. N.Malarkodi, G. Keller, P.J. Fayazudeen and U.B. Mallikarjuna 2010 Foraminifera from the Early Danian Intertrappean Beds in Rajahmundry Quarries, Andhra Pradesh. Journal Geological Society of India. Vol. 75, pp. 851-863.
32. Rao A T, Srinivasa Rao K and Vijaya Kumar V 2002 Basic volcanism along K-boundary from Rajahmundry, east coast of India; J. Geol. Soc. India 60 583–586.
33. Self S, Jay A E, Widdowson M and Kaszthelyi L P 2008 Corelation of the Deccan and Rajahmundry trap lavas: Are these the longest and largest lava flows on Earth? J. Vol. Res. 172 3–19.
34. Sen G 1986 Mineralogy and petrogenesis of the Deccan Trap flows around Mahabaleswar; J. Petrol. 27 627–663.
35. Sen, B., Sabale, A.B., 2011. Flow-types and lava emplacement history of RTB, west of river Godavari, Andhra Pradesh. Journal of Geological Society of India 78, 457e467.
36. Sethna S F, Czygan W and Sethna B S 1987 Iron–titanium oxide geothermometry for some Deccan Trap tholeiitic basalts, India; J.Geol.Soc. India29 483–488.
37. Sethna S F and Sethna B S 1988 Mineralogy and petrogenesis of Deccan Trap basalts from Mahabaleswar, Igatpuri, Sagar–Nagpur areas, India; In: Deccan Flood Basalts (ed.) Subba Rao K V, J.Geol.Soc. IndiaSpec.Publ. 10 69–90.
38. W. A. Deer F.R.S; R.A. Howie; J. Zussman 1966 An Introduction to the Rock – Forming Minerals. Published by the English Language Book Society and Longman.
39. William E. Ford 1985 Danas textbook of minerology printed by wiloy Eastern Limited.
40. Wei-Ran Li, Olivier Bernard, Sri Budhi Utami and Marcus Phua 2024 Volatile systematics in terrestrial igneous apatite: from microanalysis to decoding magmatic processes. Contributions to Mineralogy and Petrology (2024) 179.76. Springer.