Geochemical Investigation of Basaltic Rocks and Zeolitic Alterations

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***Abstract*—Basaltic rocks form a major component of the Earth's crust and play a critical role in deciphering the geochemical evolution of volcanic provinces. Their alteration frequently gives rise to secondary zeolite minerals, which not only provide insights into post-eruptive processes but also represent a valuable natural resource. This study examines the geochemical characteristics of a basaltic sequence in the Naigaon–Dattapur area (Deccan Volcanic Province, Maharashtra, India), ranging from RL 459 m to RL 546 m, where fifteen distinct basaltic flows were identified. The sequence includes compact, amygdaloidal, porphyritic, aphanitic, and tachylytic basalts, along with volcanic breccias, each displaying variable jointing, weathering intensity, and secondary mineralization. Zeolitization is most prominent in amygdaloidal flows (notably flows 2, 4, 6, 7, 10, and 12), where vesicles are filled with zeolites, chlorophaeite, and silica. Geochemical analyses show that these zeolites are predominantly silica- and alumina-rich (SiO_2: ~65–70 wt.%; Al_2O_3: ~10–15 wt.%), with calculated Si/Al ratios between 3.5 and 5.5, indicating a dominance of clinoptilolite–heulandite group minerals. The distribution of zeolites is strongly influenced by vesicularity, hydrothermal alteration, and supergene weathering, with compact basalt flows acting as impermeable barriers and breccias enhancing fluid circulation. The findings highlight the geological and geochemical conditions controlling zeolite mineralization in the Deccan Trap basalts and underscore their dual significance—both as tracers of alteration processes and as a potential resource for industrial, agricultural, and environmental applications.**

key words—Geochemical Investigation, Basaltic Rocks, Zeolitic Alterations, Deccan Traps, Amygdaloidal Basalt, Hydrothermal Alteration.

INTRODUCTION

The Basalt rock provides the foundational framework of a significant portion of the Earth's crust and a source of essential raw materials, zeolites. It plays a significant role in understanding the geochemical evolution of the crust, while also serving as a vital resource in construction, aggregate production, and soil fertility. Zeolites, commonly formed through the alteration of basalt, are microporous aluminosilicate minerals with exceptional ion-exchange, adsorption, and catalytic properties, making them highly valuable in water purification, agriculture, environmental remediation, and various industrial applications.

Zeolites are a group of microporous, crystalline aluminosilicate minerals characterized by a three-dimensional framework of interconnected cages and channels. This unique structural arrangement allows them to selectively adsorb molecules, exchange cations, and facilitate catalytic reactions. Owing to these properties, zeolites have become highly significant in a wide range of industrial applications, including catalysis in petroleum refining, ion-exchange in water treatment, and molecular separation in gas and chemical industries.

The primary purpose of this study is to investigate the geochemical characteristics of basaltic rocks and their associated zeolitic alterations in order to understand the processes governing mineral transformation, elemental mobility, and the formation of secondary zeolite minerals. By analyzing the chemical composition and alteration patterns, this research aims to provide insights into the geological significance of basalt–zeolite systems and their potential industrial applications.

Chemical Composition Zeolites

Hydrated aluminosilicate minerals with a three-dimensional framework of SiO_4 and AlO_4 tetrahedra linked by shared oxygen atoms. The substitution of Al^{3+} for Si^{4+} generates a net negative charge, which is balanced by exchangeable cations such as Na^+, K^+, Ca^{2+}, and Mg^{2+}. Their general chemical formula can be expressed as:

Zeolites are hydrated aluminosilicates with a general formula:
Mx/n·[(AlO2)x(SiO2)y]·zH2OM_{x/n} \cdot [(AlO_2)_x(SiO_2)_y] \cdot zH_2OMx/n·[(AlO2)x (SiO2)y]·zH2O

where *M* represents the exchangeable cation (Na, K, Ca, Mg), *n* its valency, and *z* the number of water molecules.

In the present study, zeolites occurring in amygdaloidal basalts show a composition dominated by silica (SiO_2: ~65–70 wt.%) and alumina (Al_2O_3: ~10–15 wt.%), with minor Fe_2O_3, CaO, Na_2O, and K_2O. Loss on ignition (LOI) ranges from 8–10 wt.%, reflecting structural water and loosely bound molecules. Calculated Si/Al ratios range between ~3.5 and 5.5, suggesting the predominance of clinoptilolite–heulandite type zeolites. The relatively high CEC values (135–180 meq/100 g) confirm their significant ion-exchange capacity, consistent with their framework chemistry.

Geological Formation of Zeolites through Hydrothermal Alteration

Zeolites commonly form as secondary minerals in volcanic terrains through the process of hydrothermal alteration, where hot, chemically active fluids circulate through volcanic rocks such as basalt and tuff. These fluids, enriched in dissolved ions, penetrate the pore spaces, fractures, and vesicles of the host rocks, gradually altering the primary minerals into zeolitic phases.

The temperature and pressure conditions play a crucial role in determining the type of zeolite formed. At relatively low temperatures (50–150 °C), minerals like analcime and heulandite are typically developed, while higher temperature conditions (150–250 °C) promote the crystallization of zeolites such as laumontite. Pressure influences the stability fields of different zeolite species, with higher pressures extending the range of zeolite stability.

This hydrothermal alteration not only modifies the mineralogical composition of basaltic rocks but also enhances their porosity and permeability through the development of zeolite-filled cavities. The resulting zeolites exhibit well-defined crystal frameworks of interconnected cages and channels, which are directly inherited from the interplay between fluid chemistry, host rock composition, and geothermal gradients.

Zeolite filling in Basaltic rock

The diagram illustrates the process of zeolite formation through hydrothermal alteration of basaltic rocks. Basalt flows are shown with vesicles, fractures, and pore spaces. Hot, chemically active fluids, rich in dissolved ions (e.g., Na^+, Ca^{2+}, Al^{3+}, Si^{4+}), percolate through these fractures and cavities under elevated temperature and pressure conditions. Interaction between the circulating fluids and basalt minerals leads to the dissolution of primary phases (such as feldspars and volcanic glass) and the precipitation of secondary zeolites.

Different zeolite species form under varying geothermal conditions:

- Low-temperature zones (50–150 °C): Analcime, heulandite.
- Intermediate to high temperatures (150–250 °C): Laumontite, chabazite.

The cavities and fractures within the basalt become progressively filled with well-crystallized zeolite minerals, producing a porous, framework-rich structure characteristic of altered volcanic terrains. Arrows in the diagram represent fluid circulation pathways, while shaded zones indicate alteration halos around fractures.

Geological Formation of Zeolites through Alteration of Volcanic Ash

One of the most common and widespread modes of zeolite formation occurs through the alteration of volcanic ash and glass. When freshly deposited volcanic ash accumulates in closed-basin lakes, saline soils, or other alkaline environments, it comes into prolonged contact with groundwater enriched in alkalis. The volcanic glass is unstable under these geochemical conditions and gradually dissolves, releasing silica and alumina into solution. These components then recombine with alkali and alkaline-earth cations (such as Na^+, K^+, and Ca^{2+}) to form secondary zeolite minerals.

The stability of different zeolite species depends on the chemistry of the groundwater and the degree of alteration. Under such low-temperature diagenetic conditions, common zeolites formed include clinoptilolite, phillipsite, and chabazite. These zeolites typically occur as fine-grained, pore-filling cements or as replacements of volcanic glass shards within tuffaceous sediments.

This process not only stabilizes volcanic deposits but also enhances their porosity and adsorption capacity, making zeolitized volcanic rocks important natural resources for industrial, agricultural, and environmental applications.

The formation of zeolites through the alteration of volcanic ash in alkaline environments. A closed-basin lake is shown with layers of deposited volcanic ash and tuff along its margins and bottom. Groundwater, enriched in alkaline cations (Na^+, K^+, Ca^{2+}), infiltrates the ash layers.

Volcanic glass shards within the ash dissolve upon prolonged contact with the alkaline groundwater, releasing silica and alumina into solution. These dissolved components recombine with available cations to precipitate secondary zeolites.

- Clinoptilolite forms as pore-filling cements in ash beds.
- Phillipsite occurs within fine-grained layers of altered tuff.
- Chabazite commonly crystallizes in vesicles and pore spaces.

Arrows in the diagram indicate the downward percolation and lateral movement of alkaline groundwater through the ash layers. Shaded alteration zones highlight areas of zeolitization within the sedimentary sequence.

Geological Formation of Zeolites in Sea Sediments

Zeolites also form in marine environments, particularly within deep-sea sediments containing significant amounts of volcanic ash. When volcanic eruptions deposit ash over the ocean surface, these fine particles gradually settle to the seafloor and become incorporated into pelagic and hemipelagic sediments.

On the seafloor, the volcanic glass present in the ash undergoes very slow chemical alteration due to prolonged interaction with pore waters. Unlike hydrothermal systems or alkaline lake basins, the marine environment is relatively low in temperature and has slower fluid circulation, which makes zeolite formation an extremely gradual process, often taking millions of years.

Through this long-term alteration, the volcanic glass is dissolved and reprecipitated as zeolitic minerals. Common zeolites formed in deep-sea sediments include clinoptilolite, mordenite, and phillipsite, which often occur as fine-grained replacements of glass shards or as cements within pelagic clay layers.

This deep-sea mode of formation highlights the role of burial diagenesis and slow geochemical exchange processes in generating zeolites, contrasting sharply with the relatively rapid alteration observed in hydrothermal and lacustrine environments.

Geological Formation of Zeolites in Metamorphic Environments

Zeolites can also form under low-grade metamorphic conditions, a process commonly referred to as zeolite facies metamorphism. This occurs when volcanic and sedimentary rocks containing volcanic glass or pre-existing zeolites are buried to greater depths, where they are subjected to elevated temperatures and pressures, typically in the range of 200–300 °C and low to moderate pressure conditions.

In these environments, circulating fluids continue to play a role in mobilizing ions, but the primary driver of mineral transformation is the progressive increase in temperature and pressure. Zeolite minerals such as analcime, laumontite, and heulandite are stable within this facies. However, with further burial and heating, they undergo metamorphic reactions that lead to the development of higher-grade minerals.

As conditions move beyond the stability field of zeolites, they are gradually replaced by minerals typical of the prehnite–pumpellyite facies, including pumpellyite, prehnite, and epidote. This transition marks the breakdown of zeolite frameworks and the onset of more thermally and structurally stable mineral assemblages.

Thus, zeolite facies metamorphism represents an important stage in the continuum from diagenesis to regional metamorphism, recording the transformation of porous, low-temperature zeolitic minerals into denser and more crystalline phases under increasing metamorphic grade.

Geological Occurrence and Distribution

Stratigraphic Occurrence

Zeolites are most commonly associated with volcanic rocks and their alteration products. They occur abundantly in altered volcanic tuffs, where volcanic glass has reacted with alkaline groundwater, and in vesicular basaltic lava flows, where cavities and fractures are filled with secondary zeolite minerals. In stratigraphic sequences, zeolites often appear as pore-filling cements, replacements of volcanic glass shards, or as amygdaloidal fillings in basalt. Their presence provides key insights into diagenetic and low-grade metamorphic processes, as well as the fluid–rock interactions that shape volcanic terrains.

Significance in Geosciences

Paleonenironmental

Zeolites are valuable tools for reconstructing past environments because their formation is strongly controlled by water chemistry and depositional settings. The occurrence of specific zeolite species in sedimentary sequences can provide clues about the alkalinity, salinity, and geochemical composition of ancient lakes and basins. For example, the presence of clinoptilolite and phillipsite is commonly linked to alkaline lake environments, while chabazite can suggest saline or evaporitic conditions. Thus, zeolites act as mineralogical fingerprints of paleoenvironmental conditions.

Diagenetic and Metamorphic

In sedimentary basins, the distribution and transformation of zeolite minerals serve as important markers of diagenetic alteration and low-grade metamorphism. Different zeolite species are stable at specific ranges of temperature, pressure, and burial depth. For instance, low-temperature zeolites such as heulandite and analcime typically indicate shallow burial conditions, while higher-temperature species like laumontite mark deeper burial and higher geothermal gradients. As rocks continue to experience increasing pressure and temperature, zeolites may transform into minerals characteristic of the prehnite–pumpellyite facies, providing a record of the basin's thermal history.

Geochemical Tracers

Zeolites also act as geochemical tracers of fluid–rock interactions within the Earth's crust. Their open, microporous frameworks allow them to readily exchange cations and host water molecules, making them sensitive to the chemistry of circulating fluids. By studying zeolite composition and distribution, geologists can track the pathways of hydrothermal fluids, groundwater migration, and ion exchange processes in volcanic and sedimentary systems. These insights are essential for understanding crustal fluid dynamics and the geochemical evolution of volcanic terrains.

Occurrence of Zeolite in different basaltic flow in Naigaon Dattapur area

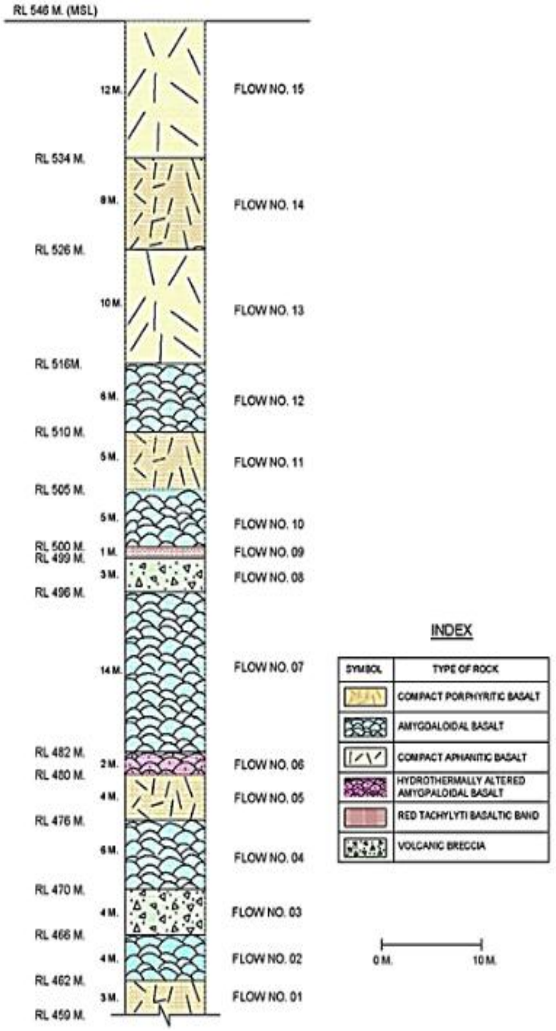
Naigaon Dattapur named after Penganga-Godavari river basin in Mehkar block. This area is covering SOI top sheets 55D/11 and 55D/12. The minimum elevation is 480 m at Sultanpur phata 2 km south west of Mehkar; whereas the maximum elevation of 546 m is recorded at Naygaon Dattapur.

The watershed is bounded by latitude 20º12'03"N to 20º21'57"N and longitude 76º21'58"E to76º33'33"E . The area under the study falls in tropical and the semi-arid region of Maharashtra Geology of the area: the area falls in the terrain of Deccan Trap Basalt consisting of two major types of basaltic flows viz. Compact Basalt and Amygdaloidal Basalt. Compact Basalt is thick extensive flow. It may aphanitic or porphyritic in nature. In the study areas following different flows have been demarcated and litholog has been prepared.

Stratigraphic Occurrence

- Zeolite-bearing flows: Flows 2, 4, 6, 7, 10, and 12 show abundant zeolitization, with amygdales filled by zeolites, chlorophaeite, and silica. These represent the most favorable horizons for secondary mineral development.
- Compact flows: Flows 1, 5, 11, 13, 14, and 15 exhibit tight or prismatic jointing with negligible zeolite content, indicating poor vesicularity.

Volcanic breccia and tachylytic flows: Flows 3, 8, and 9 show intense weathering and red bole formation, which may have contributed to hydrothermal circulation and facilitated zeolite deposition in nearby amygdaloidal horizons.



Flow no.1: this is Compact basalt occurring from RL 459 m to RL 462 m. This flow is having inconsistent and broadly spaced jointing pattern. Almost all the joints are tight and show no separation.

Flow no. 2: Amygdaloidal Basalt is occurring from RL 462 m to 466 m. in which fine to medium sized amygdales are filled by accessory minerals like chlorophaeite, zeolites and silica. As Zeolites content is more, it looks like Volcanic Breccia. Extensive weathering is observed in this rock.

Flow no. 3: This consists of volcanic breccia with red Tachylytic basaltic lava matrix is occurring from RL 466 m to 470 m. The rock has undergone intense weathering. Tachylytic part has been converted to red bole at places.

Flow no. 4: this flow consists of Amygdaloidal Basalt and is occurring from RL 470 m to 476 m. Due to intermediate stage of weathering, sheet jointing has been observed. Fine to medium sized amygdales have been filled up by chlorophaeite, zeolites and silica. Zeolites content is more.

Flow no. 5: this is Compact Porphyritic basalt occurring from RL 476 m to 480 m. in which consistent closely spaced jointing is observed. The joints have been opened up at places. Brown colored stains are developed along these joints.

Flow no.6: this flow consists of hydrothermally altered Amygdaloidal Basalt. Fine to medium sized amygdales have been filled up by chlorophaeite, zeolites and silica. No discontinuities are observed.

Flow no. 7: this flow consists of Amygdaloidal Basalt and is occurring from RL 482 m to 496 m. these are small irregular chaotic piles overlain one above the other. Due to intermediate stage of weathering, sheet jointing has been developed. Fine to medium sized amygdales have been filled up by chlorophaeite, zeolites and silica. These are quite visible on the right abutment of Pentakli dam having latitude 20º15'57"N and longitude 76º28'25" E.

Flow no.8: this is volcanic breccia with the grey lava matrix. This is fresh and does not show joints in it. This is occurring from RL 496m to RL 499m.

Flow no. 9: From RL 499 m to 500 m Red Tachylytic Basalt is occurring. Three sets of jointing pattern are prominent. The flow has been severely weathered converted in to red bole.

Flow no. 10: Hydrothermally altered Amygdaloidal Basalt is occurring from RL 500 m to 505 m. these are irregular piles overlain one above the other. Fine to medium sized amygdales have been filled up by chlorophaeite, zeolites and silica. Due to intermediate stage of weathering, sheet jointing has been developed at places.

Flow no.11: Compact porphyritic basalt is occurring from RL 505 m to 510 m. This flow is having inconsistent and closely spaced jointing pattern. Spheroidal weathering is observed at places.

Flow no. 12: Thin irregular amygdaloidal basalt is occurring from RL 510 m to 516 m. Fine to medium sized amygdales have been filled up by chlorophaeite, zeolites and silica. At placed a sheet jointing has been observed due to the effect of weathering.

Flow no. 13: Compact Aphanitic basalt is occurring from RL 516 m to 526 m. This flow is having inconsistent and broadly spaced jointing pattern. Almost all the joints are tight and show no separation.

Flow no.14: Compact porphyritic basalt is occurring from RL 526 m to 534 m. This flow is having inconsistent closely spaced jointing pattern. Prismatic jointing is prominent. This flow is occurring at latitude 20º12'03"N and longitude 76º23'33"E.

Flow no. 15: Compact aphanitic basalt is occurring from RL 534 m to 546 m. This flow is having inconsistent and broadly spaced jointing pattern. The joints are tight and show separation from a few millimeters to 5 centimeters. At places spheroidal weathering is observed.

CONCLUSION

The study of the basaltic sequence from RL 459 m to RL 546 m reveals a diverse occurrence of basaltic flows with variable jointing patterns, weathering intensity, and mineralization. Zeolite mineralization is dominantly associated with amygdaloidal basalts (Flows 2, 4, 6, 7, 10, and 12), where fine to medium-sized amygdales are characteristically filled with chlorophaeite, silica, and abundant zeolites. These flows represent favorable horizons for secondary mineral development, often enhanced by hydrothermal alteration and intermediate stages of weathering.

Compact basalts (Flows 1, 5, 11, 13, 14, and 15) exhibit jointing features ranging from tightly closed to spheroidal and prismatic patterns, but zeolite occurrence is notably absent, indicating that massive flows with limited vesicularity are less conducive to secondary mineral infill. Volcanic breccias (Flows 3 and 8) and tachylytic basalts (Flows 9 and parts of 3) display intense weathering and red bole formation, further influencing the hydrothermal regime that supports zeolite precipitation in adjacent flows.

Overall, the zeolite distribution is strongly controlled by primary vesicularity, hydrothermal alteration, and subsequent weathering processes. Amygdaloidal flows with interconnected voids provided ideal pathways for circulating fluids, leading to significant zeolitization. In contrast, compact and massive basalt flows acted as relatively impermeable barriers, limiting zeolite deposition.

Thus, the stratigraphic position of zeolite-bearing flows within the sequence not only reflects volcanic facies variations but also highlights the geological processes of alteration, fluid movement, and mineralization in the Deccan basalt province. This understanding is critical for both academic insights into basaltic petrology and potential applied uses of zeolite resources.

SIGNIFICANCE

This study highlights the diverse pathways of zeolite formation, including hydrothermal alteration of basaltic rocks, alteration of volcanic ash in alkaline lake basins, slow diagenetic processes in deep-sea sediments, and low-grade metamorphism in burial environments. Each mode of occurrence reflects distinct geochemical and geological conditions, making zeolites highly valuable as indicators of paleoenvironmental settings, diagenetic evolution, and fluid–rock interactions. Their stratigraphic associations with volcanic tuffs and basaltic flows, along with their wide geographic distribution, further underscore their importance in interpreting Earth's dynamic processes.

Beyond their scientific significance, natural zeolites possess notable economic value due to their abundance and versatile applications in agriculture, environmental remediation, and industrial processes. Their unique microporous structures provide insights not only into geological transformations but also into sustainable resource utilization.

Looking ahead, the study of zeolites presents promising avenues for future research. Their potential role in carbon sequestration, environmental clean-up, and even as a source of strategically important elements such as rare earths highlights the need for continued interdisciplinary investigations. Ultimately, zeolites remain a bridge between fundamental geoscience and practical applications, offering critical perspectives on both Earth's history and its sustainable future.

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