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Multi-stage secondary mineralization in the Deccan Traps (India): Insights from Deep Subsurface Continental Flood Basalts

ANITH KUMAR MISHRA[1], JAY R BLACK[1], MEGHALIM PHUKAN[2], VYASULU VENKATA AKKIRAJU[3], ACHYUT MISHRA[4] AND RALF R HAESE[1]

[1]The University of Melbourne
[2]Udak Environment Private Limited
[3]Borehole Geophysics Research Laboratory, Ministry of Earth Sciences, Government of India
[4]Indian Institute of Technology Gandhinagar

The Deccan Traps represent one of the world's largest igneous provinces and are renowned for extensive secondary mineralization. This study investigates the secondary mineralization history of the Deccan Traps using continuous core samples recovered from ~400-1200 m depth in the Koyna-Warna region, Maharashtra, India. Petrography, optical microscopy, SEM/EDS imaging, and EPMA analyses are integrated to reconstruct mineral paragenesis and associated fluid-rock interaction history.

Results reveal a multi-stage secondary mineralization history with variable paragenetic conditions. The earliest cavity-lining phase is dominantly Fe-Mg smectite (Stage-IA, Figure-1), resulting from initial meteoric water interaction with recently erupted basalt, accompanied by the hydrolysis of basaltic glass and primary minerals (olivine, pyroxene), under acidic and reducing conditions [1]. In some vesicles, smectite is followed by celadonite, indicating continued glass dissolution with K-mobilization, likely under the influence of progressively oxic meteoric water (Stage-IB, Figure-1).

While zeolites lack the classical regional systematic vertical zonation [2], heulandite-, stilbite-, and chabazite-group dominate most samples (Stage-IIB, Figure-1). However, mordenite-group occurs at greater depths (>800 m), reflecting later pulses of Si-rich hydrothermal fluids overprinting earlier burial-related alteration (Stage-IIC, Figure-1). In contrast, laumontite is restricted to flow-top breccias where it forms the first cavity-lining mineral instead of smectites. This indicates a distinct, permeability-controlled hydrothermal pathway involving advective transport of hot (>200 °C), Ca-rich fluids (Stage-IIA, Figure-1). Subsequent inward precipitation of calcite alongside heulandite-stilbite records progressive cooling and chemical evolution (e.g.; CO_2 degassing) of the system (Stage-IIB, Figure-1).

Smectite-chlorite mixed-layer assemblages emerge toward vesicle centers in deeper samples, indicating progressive burial metamorphism with hydrothermal overprinting, as chlorite formation requires temperatures of >220 °C. This late-stage alteration likely reflects proximity to a hydrothermal source near the basalt-basement interface (Stage-IIIA, Figure-1). Zeolites locally post-date these assemblages, confirming repeated fluid ingress, while sporadic tin-oxide occurrences record localized, pathway-controlled fluid pulses (Stage-IIIB, Figure-1). Collectively, these observations demonstrate multi-stage fluid-rock interactions and underscore the principal control of volcanic pathway architecture on fluid flow, geochemical evolution, secondary mineralization, and pore-space modification within the Deccan Traps.

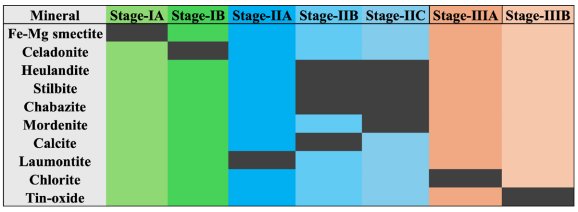

Figure 1: Schematic paragenetic sequence illustrating multi-stage secondary mineralization in the Koyna–Warna Deccan Traps

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