Zeolites and associated secondary minerals in the Deccan Traps of Western India

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SUMMARY. Zeolites (eight species) and the associated secondary minerals (minerals akin to zeolites, chlorites and related minerals, silica, and calcite) in the Deccan Traps of Western India have been examined in some detail on the basis of chemical, optical, and X-ray studies. The three zeolite zones (laumontite, scolecite, and heulandite, in ascending order) suggested by Walker have been recognized. Efforts have been made to understand their genesis. On available field and laboratory data it is suggested that the different zones of zeolitization are the result of increasing depth and the action of the circulating fluids on the rocks. The activity of such solutions was probably enhanced in the wake of the structural disturbances and intrusive activity that affected the rocks of this area.

ZEOLITES and other secondary minerals in the Deccan Traps, though reported in the last century (Dana, 1854, 1868), have received scant attention as far as their formation and distribution in the lava flows are concerned. Fermor (1925) attempted to postulate their origin in the lavas of the Eastern Deccan Traps at Bhusawal. Christie (1925) described gyrolite and okenite from Bombay Island, while Hey (1933, 1936) made X-ray and other physical and chemical studies of zeolites from the Poona region. Since then not much work seems to have been done, except for short notes by Sowani and Phadke (1964) and Belsare (1969, 1971), and a recent paper by Roy (1971).

The present paper mainly deals with the secondary minerals in the Deccan Traps of Western India. Different species of zeolites and chlorites with other closely related minerals, silica, and calcite have been established on the basis of physical, optical, chemical, and X-ray studies. An introductory note on the physical characters and mode of occurrence of these minerals has been published (Sukheswala et al., 1972).

It may be pointed out that the zeolites and allied minerals of large dimensions and in bulk do not occur everywhere in the Western Deccan Traps, but are restricted to certain localities around Bombay, Baroda, Poona, and Nasik. Mention, however, may be made of some of the beautifully well-developed, large specimens collected earlier from these localities, mostly from the railway cuttings and tunnels of Bhor Ghat (Khandala Ghat in the Poona region) and Thul Ghat (Kasara Ghat in the Nasik region) in the Syhadree (Sahyadry) Mountains. These minerals, especially the zeolites, tend to distribute themselves in more or less regular zones from the base to the top of the lava piles in the areas examined.

The zonal distribution of zeolites (fig. 1) in the Western Deccan Traps was first recognized by Walker (1969). The present work includes a preliminary study of these
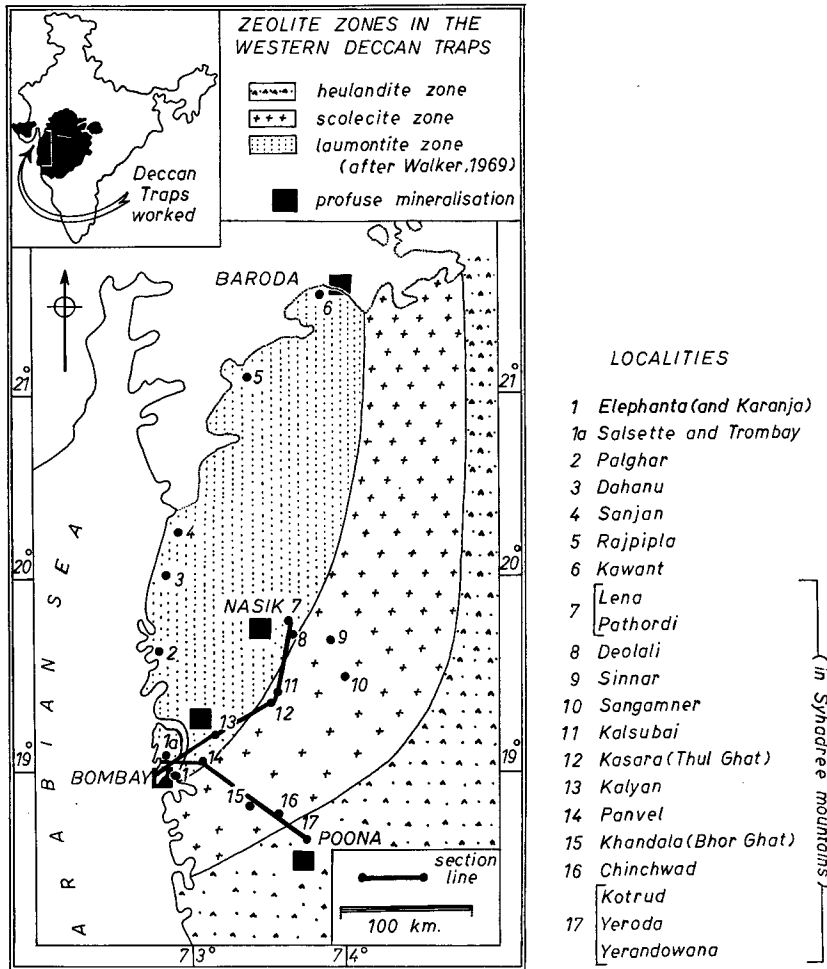
ZEOLITE ZONES IN THE
WESTERN DECCAN TRAPS

heulandite zone

scolecite zone

laumontite zone
(after Walker,1969)

profuse mineralisation

Deccan
Traps
worked

BARODA

LOCALITIES

1   Elephanta (and Karanja)
1a Salsette and Trombay
2   Palghar
3   Dahanu
4   Sanjan
5   Rajpipla
6   Kawant
7   Lena
    Pathordi
8   Deolali
9   Sinnar
10 Sangamner
11 Kalsubai
12 Kasara (Thul Ghat)
13 Kalyan
14 Panvel
15 Khandala (Bhor Ghat)
16 Chinchwad
17 Kotrud
    Yeroda
    Yerandowana

(in Syhadree mountains)

ARABIAN SEA

NASIK

BOMBAY

POONA

section
line

100 km.

FIG. 1. Map of the Bombay region showing the principal zeolite localities: 1, Elephanta (and Ka-ranja); 1a, Salsette and Trombay, 2, Palghar; 3, Dahanu; 4, Sanjan; 5, Rajpipla; 6, Kawant; 7, Lena and Pathordi; 8, Deolali; 9, Sinnar; 10, Sangamner; 11, Kalsubai; 12, Kasara (Thul Ghat); 13, Kal-yan; 14, Panvel; 15, Khandala (Bhor Ghat); 16, Chinchwad; 17, Kotrud, Yeroda, and Yerandowana. Localities 7 to 17 are in the Syhadree Mountains.

zones, with an attempt at the probable mode of origin and paragenesis of the secondary minerals occurring in them.

SECONDARY MINERALS

The large number of secondary minerals in the lavas of the Western Deccan Traps may be grouped as: hydrous silicates (zeolites, minerals resembling zeolites, chlorites, and related minerals); silica (crystalline and cryptocrystalline); and non-silicates

(calcite and pyrite). During the field-work it was noticed that minerals of all types appear to a greater or lesser extent in all the zones.

Zeolites and related minerals

Heulandite and stilbite constitute the major bulk of the zeolites. They are more widespread in the lavas at higher altitudes in the Poona region, and gradually decrease westwards down the plateau. In the low-lying coastal tract they are reduced to a minimum, and occur only sparsely distributed in the cavities, associated with laumontite, which then becomes prevalent.

They are very similar in appearance, and are often found together in cavities. In their colour (colourless to different shades of cream and pinkish-red; when freshly exposed they may be distinctly red, but gradually fade on exposure) and in size they show considerable variations from place to place. Though both form aggregates of radiating plates, heulandite is easily distinguished by its characteristic coffin-shaped outlines in contrast to stilbite, which is characterized by the presence of six-sided rhombic plates. In thin sections plates of the latter exhibit sectoral growth illustrating their twinned character. In heulandite, the positive acute bisectrix is normal to the cleavage, whereas in stilbite the third mean line is normal to the cleavage.

Scolecite and mesolite[1] are fairly abundant in the lavas of the Nasik region, especially south-east of Nasik, where they form excellent glassy crystals with almost perfect faces. Both normally develop radiating acicular aggregates but it is not unusual to find them as grotesquely-shaped drusy masses of interlocked needles. Scolecite is more frequent and is better crystallized than mesolite, which often appears as tufts of fine, delicate, silky needles resembling mordenite. At times the scolecite crystals attain a length of up to 35 cm with a varying thickness of about 1 to 2 cm. The haphazard aggregates of such large sticks often show intergrowths of finer glassy needles of mesolite. The morphological features of both are nearly identical, but they show a marked contrast in their optics with mesolite having very low birefringence;[2] scolecite has inclined (18 °) extinction, with negative elongation, and is invariably twinned.

Laumontite and mordenite. Of these two highly delicate and brittle zeolites laumontite is fairly abundant in the lava flows of the coastal tract, especially in and around Bombay. Crystals of laumontite occurring at Nasik and Panvel are fairly big (up to 4 cm in length) and well shaped.[3] Compared to laumontite, mordenite crystals are extremely thin, almost capillary size, and either form radiating tufts or tangled woolly clumps adhering to the walls of cavities or some early crystallized minerals. It was formerly confused with mesolite (and is so mis-labelled in many collections), but is distinguished by its lower refractive index ($\beta = 1\cdot47\pm0\cdot002$), and by chemical and X-ray analyses.

Thomsonite occurs sporadically in all the zeolite zones. In the Nasik region it

[1] Poonahlite, at one time identified with scolecite, has been shown by Bowman (1909) to be mesolite.

[2] Mesolite crystals sometimes give inclined extinction; as shown by Hey (1934), this is due to the crystal not being quite normal to the microscope axis.

[3] When quite fresh they are often transparent and distinctly pink, but readily lose water and become opaque, and tend to crumble into a fine powder.

appears as spherical aggregates of perfectly transparent tiny crystals developing on the bluish chalcedony. In the Poona region it is seen as extremely fine earthy white granular aggregates. Apparently it may be confused with silica, but is distinguished by its orthorhombic form, perfect cleavage, biaxiality ($2V\gamma = 50°$), and perceptible twinkling ($\alpha = 1.52$, $\gamma = 1.54$).

Chabazite is rather rare in the Western Deccan Traps. The crystals, though occurring in aggregates, are well developed with steep rhombohedral habit. Often composite growth and bent edges are visible. It has a low refractive index ($\epsilon = 1.48$, $\omega = 1.49$) like mordenite, but is uniaxial negative.

Prehnite is quite common in Bombay in association with laumontite in the spilites. It is much harder than the zeolites, and is characterized by its marine-green colour and almost cryptocrystalline mammillary or stalactitic form. It remains coated with films of silica. Under the microscope it can be distinguished from zeolites and allied minerals by its higher refractive index ($\alpha = 1.62$, $\beta = 1.63$, $\gamma = 1.65$), high $2V\gamma$ ($70°$), and one set of prominent cleavages.

Apophyllite is fairly widespread and usually forms aggregates of small to medium sized (0.1 to 10 mm) prismatic or tabular crystals studded over early-formed minerals. The best crystals, up to 10 cm in size, are encountered in the Poona and Nasik regions. Striations on prism faces are characteristic. Often crystals in thin sections show sectoral growth and anomalous optical characters due to lattice distortion, also observed by Saha and Roy (1969).

Gyrolite and okenite occur at many localities and are associated with almost all the secondary minerals. Both develop rather late in the sequence of mineralization and consequently form encrustations on the earlier-formed secondary minerals. In the Poona region gyrolite develops in considerable quantity encrusting the walls of large pockets and veins, but mostly the crystals are small and feathery. The best specimens of large size gyrolite and okenite come from Bombay Island, where they occur in abundance with laumontite, calcite, prehnite, and quartz. In the Nasik and Poona regions okenite is found as thin needle-shaped crystals encrusted over mesolite, laumontite, and apophyllite. Gyrolite is easily distinguished from okenite by its micaceous appearance and strong pearly lustre, and by its uniaxiality. Thin sections of these minerals mounted in canada balsam are characterized by their nearly non-existent relief.

Chlorites and related minerals

This group includes minerals of the chlorite family, delessite and clinochlore, and two other related types, celadonite and chlorophaeite. Mostly they occur as infillings in cavities, but interstitial forms in the rock groundmass are not uncommon. Though chlorites and celadonite are both green, the former distinguish themselves by their deeper shades in hand-specimens, flaky nature, prominent pleochroism, and birefringence. Delessite shows straight extinction and is pseudouniaxial, whereas clinochlore has a low extinction angle and is optically positive with moderate $2V$.

Chlorophaeite is black, waxy, and infrequently alters to orange or saffron-red vitreous matter. Under the microscope it presents shades of green and brown, the

two often occurring together in the same patch. It is mostly isotropic but the fibrous variety is perceptibly pleochroic. These varieties probably represent different phases of chlorophaeite described by Stokes (1971).

Epidote occurs as lamellar aggregates in the spilites of the basal laumontite zone and is associated with laumontite, prehnite, and calcite. It is faintly pleochroic from almost colourless (α) to yellowish-green (γ) and is easily distinguished from chlorites by its higher refractive index ($\beta = 1\cdot73\pm0\cdot002$), $2V\alpha = 20-5°$, and $\alpha:[001] = 15°$.

Silica minerals

Both crystalline and cryptocrystalline forms of silica occur abundantly along with zeolites. Among these are amethyst, quartz, tridymite, chalcedony, and a combination of chalcedony and quartz termed zebra-banded silica.

Amethyst. Well-crystallized pale lavender-blue to purple amethyst occurs in the cavities of basalt at Chinchwad in the Poona region, and Lena in the Nasik region. Often crystals are coated with films of cryptocrystalline silica and are rendered dull and rough.

Tridymite occurs associated with quartz in the form of thin, colourless to white, wafer-like, brittle lamellae composed of aggregates of grains and plates adhering to the walls of the veins. In thin sections it differs from quartz in having biaxial, low-angle positive character, and low negative relief ($\beta = 1\cdot48\pm0\cdot002$).

Zebra-banded silica. This striped silica from Poona region is composed of alternate bands of colourless granular quartz and reddish-black chalcedony. The late formation of quartz is evident from the fact that some bands of chalcedony have been pushed apart and even stranded as isolated patches in the crystalline silica.

Non-silicate minerals

Amongst these may be mentioned pyrite and calcite. *Pyrite* is found as small well-crystallized, golden-yellow metallic cubes in some of the cavities in spilites of Bombay.

Calcite occurs throughout the Western Deccan Traps, but is especially abundant in the spilites of Bombay where it occurs with laumontite, prehnite, quartz, gyrolite, okenite, and apophyllite. It exhibits a large number of crystalline forms and habits, and always develops late in the sequence of secondary minerals, either filling up the space between earlier-formed minerals or studded over them. Often it encloses the early formed minerals, conspicuous being laumontite in calcite at Bombay, and mordenite in calcite at Chinchwad. Quite often the different forms of calcite are coated with rough granular silica and as a result are rendered hard and resistant.

CHEMISTRY OF SECONDARY MINERALS

Chemical analyses of some of the Deccan Trap secondary minerals have been reported earlier (Dana, 1896; Belsare, 1969, 1971; Roy, 1971). We now present twenty-one new analyses of zeolites (pure and hand-picked well-crystallized samples) and associated secondary minerals. The 'balance errors' of the present zeolite analyses (Table I) have been calculated on the basis of the formula adopted by Passaglia (1970). The results indicate that most of them are within limits of permissible error (±10 %).

The presence of magnesium in these samples is rather on the high side. Amethyst is pure silica with a trace of Fe_2O_3, which may account for its colour. Tridymite (Table II) contains aluminium, calcium, and alkalis, and is more hydrous. Celadonite (Table II) is distinguished from chlorophaeite by its high potash-content. The latter appears to be related chemically to the chlorophaeite (phases II and III) described by Stokes (1971).

TABLE I. *Chemical analyses of zeolites from the Deccan Traps*

	Mordenite 6	Stilbite			Heulandite			Scolecite 15	Mesolite 5	Laumontite 11	Chabazite 4
		I	Ia	13	3	3a	9				
SiO_2	67·35	55·49	54·72	55·26	56·34	57·16	57·17	45·52	45·98	50·90	47·88
Al_2O_3	13·10	16·30	17·90	16·70	17·90	17·65	17·28	25·50	26·30	20·30	20·10
Fe_2O_3	—	tr	—	tr	tr	—	tr	—	—	1·20	tr
MgO	0·35	0·55	0·40	0·45	0·76	0·55	0·70	0·65	0·35	0·69	0·32
CaO	4·20	7·85	7·90	7·95	7·29	6·57	6·89	14·32	10·32	11·20	9·23
Na_2O	2·00	1·00	1·10	1·20	1·50	1·50	1·50	0·80	4·50	0·93	1·30
K_2O	0·30	0·03	0·02	0·25	0·25	0·23	0·30	0·05	0·03	0·38	0·12
H_2O	12·58	18·70	18·92	18·44	16·36	16·26	16·31	13·90	12·78	15·22	21·82
Total	99·88	99·92	100·96	100·25	100·40	99·92	100·15	100·74	100·26	100·82	100·77

Number of ions on the basis of:

	48 O	72 oxygen			72 oxygen			80 O	30 O	48 O	72 O
Si	19·59	26·63	26·06	26·43	26·19	26·50	26·56	23·77	8·93	15·95	24·11
Al	4·47	9·22	10·05	9·42	9·81	9·65	9·48	15·69	6·02	7·50	11·93
Fe^{3+}	—	—	—	—	—	—	—	—	—	0·28	—
Mg	0·15	0·39	0·28	0·32	0·53	0·38	0·49	0·51	0·10	0·32	0·24
Ca	1·31	4·04	4·03	4·07	3·63	3·39	3·43	8·01	2·15	3·76	4·98
Na	1·12	0·93	1·02	1·11	1·35	1·34	1·34	0·81	1·70	0·57	1·27
K	0·11	0·02	0·01	0·15	0·15	0·11	0·17	0·03	0·01	0·15	0·08
H_2O	12·21	29·94	30·05	29·42	25·37	25·14	25·26	24·21	8·28	15·91	36·65
E*	+7·70	−5·99	+4·05	−6·36	−0·07	+8·90	+1·48	−12·21	−2·88	−12·39	+1·23

*E = Balance error   (Courtesy, Professor Galli)

6 Woolly mordenite, Chinchwad, Poona.
I White, radiating stilbite, Yerandowana, Poona.
Ia White, platy stilbite, Yerandowana, Poona.
13 Pinkish-white stilbite, Nasik.
3 Colourless heulandite, Yerandowana, Poona.
3a Milky-white, heulandite, Yerandowana, Poona.

9 Pinkish heulandite, Yerandowana, Poona.
15 Large, white scolecite, Nasik.
5 White, fine acicular mesolite, Kotrud, Poona.
11 Laumontite, Sewree, Bombay.
4 Pinkish chabazite, Yerandowana, Poona.

X-ray diffraction patterns of the chemically and optically analysed samples show negligible variations. A slight shift in peaks of heulandite, stilbite, and apophyllite indicates minor disturbances in their chemical structures. A few additional peaks in heulandite, stilbite, mesolite, chabazite, prehnite, and gyrolite probably show slight chemical variations. Mesolite, an intermediate species between natrolite and scolecite, may have been slightly contaminated by scolecite. Gyrolite, one of the last minerals to develop, has a little contamination by a zeolite—probably laumontite.

ZONES OF SECONDARY MINERALIZATION

The Deccan Traps present a definite pattern of the occurrence of vesicular basalts, which tend to occur more towards the western side near the coastal region where also

a large number of known dykes are concentrated (Walker, 1969). The lavas in the coastal tract contain laumontite as the principal zeolite along with quartz, calcite, and prehnite. In the higher scarp region of the plateau, laumontite is replaced by scolecite and then by heulandite.

TABLE II. *Chemical analyses of minerals from the Deccan Traps*

	Prehnite		Okenite		Gyrolite 12	Apophyllite		8	16	17
	7	7a	10	10a		2	14			
SiO_2	43·00	43·10	54·04	54·28	52·28	52·54	52·10	94·68	48·25	40·55
Al_2O_3	21·54	20·55	0·12	0·20	—	—	—	2·30	5·60	1·20
Fe_2O_3	3·73	4·75	—	—	—	—	—	tr	10·75	19·98
FeO	—	—	—	—	—	—	—	—	8·48	4·00
MgO	1·00	0·79	—	—	—	—	—	0·30	9·25	4·60
CaO	25·62	25·58	27·20	27·53	32·67	25·31	25·18	1·95	0·50	3·25
Na_2O	1·47	1·50	0·90	1·20	1·00	1·30	1·25	0·08	tr	0·50
K_2O	0·02	0·28	0·03	0·04	0·05	5·00	5·10	0·01	6·10	tr
H_2O	4·42	4·20	17·46	17·34	14·45	16·28	16·96	1·63	10·53	26·75
Total	100·80	100·75	99·75	100·59	100·45	100·43	100·59	100·95	99·46	100·83

Ionic proportions on a basis of:

	24 (O, OH)		20 O		24 O
Si	5·91	6·01	7·81	7·77	6·59
Al^{iv}	0·06	— ⎱			
Al^{vi}	3·46	3·41 ⎰	0·02	0·07	—
Fe^{3+}	0·38	0·51	—	—	—
Mg	0·21	0·16	—	—	—
Ca	3·81	3·87	3·76	4·23	4·41
Na	0·40	0·41	0·26	0·33	0·24
K	0·02	0·05	0·01	0·01	0·01
OH	4·08	3·96			
H_2O			16·82	16·54	12·54

7 Pale green, mammillated prehnite, Sewree, Bombay.
7a Prehnite, Sewree, Bombay.
10 Woolly, fibrous okenite, Yerandowana, Poona.
10a Radiating, spherical okenite, Sewree, Bombay.
12 Pearly, micaceous gyrolite, Sewree, Bombay.
16 Celadonite, Kotrud, Poona.

2 Colourless, transparent apophyllite, Yerandowana, Poona.
14 Whitish, semi-transparent apophyllite, Nasik.
8 Whitish, wafery tridymite, Kotrud, Poona.
17 Chlorophaeite, Chinchwad, Poona.

The basal laumontite zone spreads along the coastal tract from Bombay to Baroda. In the scarp region of the plateau, it varies considerably in height between Nasik and Poona, being highest in the north at Nasik with laumontite occurring at a height of 600 m. It gradually tapers down southwards to about 300 m at Kasara, and finally to a few metres at Panvel in the Bombay region (fig. 2).

The significant character of this zone is the presence of albitized lavas in its lowest reaches. They are especially widespread at Salsette, Bombay, and are seen sporadically in distant areas including Palghar, Dahanu, Sanjan, and Baroda, which are at the lowest altitudes in the coastal plain. More significant may be considered the formation of pillow spilite and hyaloclastites in Bombay where laumontite has developed in

profusion along with prehnite, calcite, quartz, chlorite, and even epidote, suggestive of a submarine environment (Sukheswala, 1974).

The scolecite and heulandite zones overlie the laumontite zone in the plateau region. Of the two, the scolecite zone is lower and directly overlies the laumontite zone in the border region of the plateau. In the Nasik region where the laumontite zone is rather thick, the scolecite zone is exhibited only by superficial lavas. East of Nasik, where the ground level rises, it grows gradually thicker and scolecite is encountered at greater heights in the hills of Sinnar and Sangamner, rising up to 90 m from ground level
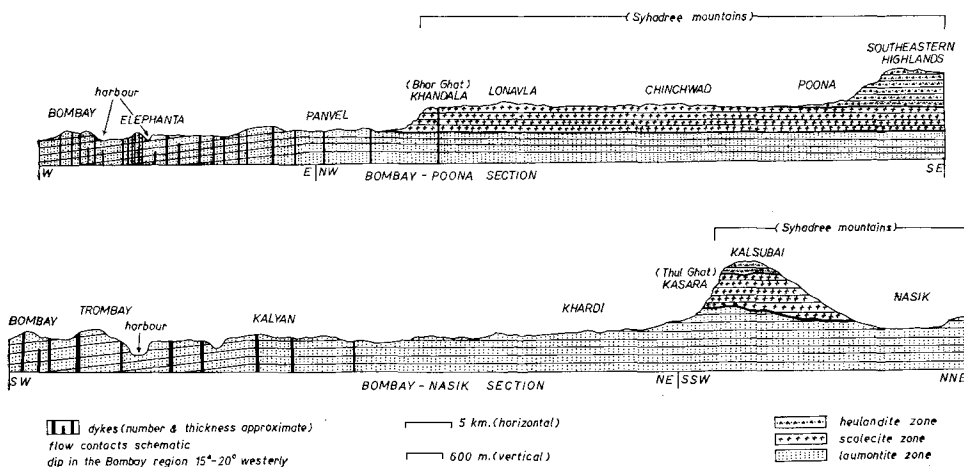
FIG. 2. Sections on two lines, from Bombay to Poona and from Bombay to Nasik.

(600 m above sea level). Southwards in Panvel–Lonavla Ghats this zone appears to be the thickest and extends upwards from Panvel (60 m) to Lonavla (450 m).

The uppermost heulandite zone is best exposed in the highlands of the plateau in the Poona region, especially at Poona and to the south-east of it. North of Poona it tapers down considerably and is encountered only at the top of very high hills, such as Kalsubai hill in the Nasik region (fig. 2).

The lava flows in the west of the plateau region are compound in nature with highly vesicular pahoehoe flow units exhibiting glassy ropy upper surfaces (Walker, 1971). They are best exposed at Yerandowana, Kotrud, and Yeroda in the Poona region, and at Pathordi and Deolali in the Nasik region where flow units thin out considerably (5 to 10 m) and show intense secondary mineralization in the upper 1 to 3 m of extremely vesicular and blistered zone.

The basalts of these flows are normal types with labradorite (An_{50-55}) and pyroxene (γ: [001] 45–6°; $2V\gamma$ 42–6°; β 1·68±0·002). Clinochlore and delessite develop out of pyroxene as well as glass, which is abundant in some of the rocks. The glass also alters to chlorophaeite and celadonite, of which the former is more abundant in the coarser, darker, almost non-vesicular rocks, whereas celadonite and delessite are more abundant in the highly vesicular varieties.

Anomalous position of the younger coastal lavas in relation to the basal laumontite zone

In the stratigraphic sequence of the Deccan Traps the laumontite-bearing Bombay lavas are considered to be the youngest, probably even younger than the western ghat basalts, as borne out by the palaeomagnetic studies (Sahasrabude, 1963). If this age relationship is accepted, the formation of the laumontite zone in Bombay basalts in relation to the scolecite and heulandite zones of Poona looks somewhat anomalous.

It is now fairly well established that the Deccan Traps along the western coastal margin are structurally disturbed. In Bombay and surroundings they dip little south of west at an angle of 15–20°, and are faulted (Fox, 1925; Sukheswala, 1953). Auden (1949) records a higher amount of dip (about 50° north-easterly), and possible folding in the north of Salsette. He has marked the position of the Panvel flexure to run through Panvel and Kalyan, and correlated the concentration of dykes in the area parallel and perpendicular to this monoclinal fold axis. West of this axis the lavas dip westwards, whilst to its east they are flat-lying. Also, according to him, the traps in the Rajpipla hills show higher angles of dip, as much as 20°, and are corrugated into definite folds. The greatest concentration of dykes is in zones of folded lavas, though dyke clusters and networks of dykes also occur in unfolded traps. From the dyke clusters related to the Panvel flexure and Rajpipla folding Auden draws a broad conclusion that the dykes should be considered later than the lavas. These structural disturbances help us to visualize the younger lavas of Bombay being carried to much greater depths in comparison to the older horizontal lavas of the Ghats. If this is so a very thick cover of lavas overlying the spilites and the albitized lavas of the coastal tract appears to have been removed (fig. 2).

SEQUENCE OF SECONDARY MINERALS IN THE CAVITIES OF THE DECCAN TRAP LAVAS

The sequence of secondary minerals in the cavities is worked out on the basis of an examination of the cavities in the lavas of the three zones of zeolitization. From the wall to the core of the cavities the following four broad stages of crystallization are discernible:

Hydrous iron-magnesium silicates (wall). Two trends of development of hydrous iron-magnesium silicates, namely celadonite–delessite and chlorophaeite, are recognized on the basis of frequency of these minerals. Field observations reveal that green celadonite and delessite predominate where zeolitization is profuse in the highly vesicular lavas, whereas green-brown chlorophaeite prevails in the sparsely vesicular lavas in which chalcedony and highly siliceous zeolites predominate.

Formation of celadonite denotes alteration by solutions rich in alkalis, especially potash. Comparatively delessite is better crystallized and may be considered an advanced stage of alteration involving further leaching of silica and alkalis. The formation of chlorophaeite, on the other hand, suggests strong hydration with consequent increase in Fe_2O_3 and water. Significantly the zeolites developing in association with chlorophaeite are also more hydrous, e.g. stilbite and mordenite.

Silica minerals (prehnite in laumontite zone). The second layer in the cavities is frequently of cryptocrystalline silica, chalcedony, or agate, which is either released during the formation of hydrous iron-magnesium silicates, or is a direct consequence of mineralizing solutions. In the case of chlorophaeite development, which does not utilize silica, abundant crystalline silica in the form of quartz or amethyst develops over the chalcedony layer. Silica also appears at various stages after the formation of zeolites, and even after the last-stage volatile-bearing minerals such as apophyllite and calcite, probably due to its release in the complex process of zeolitization. In such cases it develops as thin films or as granules over different minerals.

In the basal laumontite zone prehnite develops either with silica or alone in the early stage and forms the foundation over which the late-crystallizing minerals laumontite, calcite, apophyllite, okenite, and gyrolite develop.

Zeolites. Next to appear in the cavities are the zeolites, but the individual species vary considerably in their order of appearance even in the same zone of zeolitization.

In the basal zone laumontite predominates with quartz. In the middle scolecite zone slightly lower-temperature zeolites, namely scolecite and mesolite, are common, and are first to crystallize amongst the zeolites. In the same cavity they may be followed by still more hydrous and silicic species, heulandite and stilbite. In the top zone more silicic and hydrous heulandite becomes prominent along with chalcedony. It is often followed by stilbite or yet more silicic mordenite. Mordenite at times appears in the lower hotter zones of less silicic scolecite in the localities where profuse chalcedony also develops as observed at Chinchwad.

Highly hydrous and volatile-bearing minerals. Last to crystallize in the cavities are the highly hydrous minerals, gyrolite and okenite. Also, the volatile-bearing minerals, apophyllite and calcite, which crystallize at this stage, are deposited over early formed minerals. The late crystallization of these relatively low-temperature minerals is indicative of the accumulation of water and volatiles in the final stage.

ZEOLITIZATION IN THE WESTERN DECCAN TRAPS

Our work on the Deccan Trap zeolites and the associated secondary minerals has brought us closer to the facts and observations of other workers who have concluded that zeolitization, chloritization, and to some extent formation of secondary silica are the results of hydrothermal activity on the rocks. Recently considerable data have been collected on their formation in geosynclinal environments (Coombs, 1958; Coombs *et al.*, 1959; Miyashiro and Shido, 1970), in geothermal areas (Hewett *et al.*, 1928; Aver'ev *et al.*, 1961; Seki, 1966) and also in volcanic piles (Walker, 1960*a*, 1960*b*). Senderov (1965) concludes that these minerals develop in low-temperature hydrothermal environments.

Zeolites have been shown to develop most ideally from artificial or natural glasses or hydrogels (Roy and associates, 1952 to 1963, quoted by Eitel, 1966; DiPiazza *et al.*, 1959; Saha, 1959, 1961). In rocks they frequently develop from similar metastable glasses and glassy pyroclastic materials (Bramlette and Posnjak, 1933; Harris and Brindley, 1954; Coombs, 1958; Coombs *et al.*, 1959; Bonatti, 1963, 1965; Miyashiro and Shido, 1970; Robinson *et al.*, 1970).

In the case of the Deccan Trap basalts the relative freshness of their constituent minerals—plagioclase and pyroxene—except for the albitization of the former in the lowermost reaches of the basal laumontite zone in the coastal tract, leads us to believe that 'the abundant glass which appears to be a universal feature of these lavas, including even the coarsest dolerites' (Pascoe, 1962), played an important role in the process of zeolitization. The multiple compound lavas in the Western Deccan Traps may have afforded maximum opportunity for the formation of natural glass in their chilled and vesicular top surfaces. Most significant is the formation of spilites with a thick sequence of hyaloclastites in the Bombay Island, in which zeolitization and chloritization of glass are clearly evident. The spilite–hyaloclastite sequence in Bombay is attributed to the sub-aqueous eruption of the lavas (Sukheswala, 1974).

Zonal variation of zeolites and silica. Of late, many different areas in plateau basalt terrains including those of Ireland, Iceland, and Keweenawan (Walker, 1960a, 1960b; Jolly and Smith, 1972) have been studied for the genesis of zeolites. This has helped to establish zeolite zones with increasing depths depending on the stability range of the respective zeolites.

In the Deccan Traps of Western India zeolite zoning was first suggested by Walker (1969). Our fieldwork seems to confirm the presence of three zones, laumontite, scolecite, and heulandite, in ascending order. The zonal distribution points to their varying physico-chemical conditions of formation. Heulandite and stilbite in the top zone are more hydrous and silicic and less stable than the scolecite and mesolite of the middle zone. Laumontite of the basal zone has the highest stability range up to 300 °C (Miyashiro and Shido, 1970). It is also realized that these zeolites are calcic, in keeping with the tholeiitic host rocks.

Silica also seems to play an important role during the zeolitization process (Kostov, 1960). The close association of silica with other secondary minerals in the Deccan Trap lavas is observed in most areas. Significant are the variations in the amount and crystallinity of silica in keeping with the variation of zeolites in different localities of the three zones. In the top heulandite zone where more hydrous and silica-rich zeolites predominate, chalcedony and microscopic globules of fibrous silica (originally hydrogel) are abundant. Crystalline silica, quartz, gradually increases downwards in the lava pile, and appears at various places in the lower scolecite zone and especially in the laumontite zone. These associations of crystalline and cryptocrystalline silica with specific zeolites may be explained on the basis of silica activity under the prevailing physico-chemical conditions. Coombs *et al.* (1959) have shown that silica-rich zeolites do not develop with crystalline silica; on the other hand, profuse quartz crystallizes along with laumontite.

The influence of silica on zeolitization in the Deccan Traps is further illustrated by the formation of mordenite. The presence of mordenite—a silica-rich zeolite—in association with profuse silica globules and chalcedony at Chinchwad in the relatively silica-poor scolecite zone is anomalous but suggestive. This fact may be supported by the work of Coombs *et al.* (1959) and of Senderov (1965) in which mordenite is shown to crystallize outside its stability range in presence of amorphous silica or silica hydrogel.

Silica activity in hydrothermal solutions is believed to be governed by their alkalinity (Wyart and Sabatier, 1955; Corwin *et al.*, 1957; Morey, 1953, 1956). This also explains the occurrence of tridymite with zeolites in the basalts of Poona region at rather low temperatures (Mason, 1953, 1955; Buerger, 1954; Roy *et al.*, 1957). The gradual decrease in the silica-content of the Deccan Trap zeolites at increasing depths may also suggest increase in alkalinity of the circulating fluids in the lava pile (Senderov, 1965).

Burial of lavas. The basal laumontite zone of Bombay has in association prehnite, quartz, calcite, chlorite, and to some extent epidote, an assemblage very much akin mineralogically to the zeolite facies of Coombs *et al.* (1959). Also, the host lavas are mainly albitized, with a very significant occurrence of spilite–hyaloclastite sequence in Bombay Island (Sukheswala, 1974). Recently Jolly and Smith (1972) have identified similar mineralogy in the subaerial tholeiitic lavas of Keweenawan, and ascribe the formation of a laumontite assemblage to the burial metamorphism of lavas. The formation of zeolites in the compound lavas of the Western Deccan Traps is also well explained by these authors' remarks that the amygdular tops of each flow act as channelways for migrating fluids during a regional metamorphic event.

In the case of the Western Deccan Traps basalts it may be presumed that the increase in geo-isotherms was attained during structural disturbances of the type of faulting and folding, and also during widespread intrusive and extrusive activity, which gave rise to pyroclastics and differentiates (Sukheswala and Poldervaart, 1958). The laumontite zone of Bombay and the coastal tract may therefore be considered a result of 'degradation and aggradation" (Jolly, 1972), the latter a stage of "diagenetic or low grade metamorphic adjustments involving redistribution of components' in a rapidly chilled basalt (Vallance, 1965). As in the case of Keweenawan lavas it may be that at greater depths in Bombay the pumpellyite and epidote zones may be traced.

The influence of the structural disturbances and the network of dykes in the Western Deccan Traps seems to be reflected in the distribution of the zeolite zones. The laumontite zone, indicating higher temperature, shows a maximum thickness in the north and north-east of Bombay where such disturbances are reported. It may, therefore, be that in this sector the circulating fluids have been activated to a greater degree resulting in the widespread albitization of the rocks, and the production of the metamorphic assemblage of laumontite–prehnite–quartz–chlorite and even epidote.

<div align="center">CONCLUSIONS</div>

In light of the work done the following conclusions may seem to have been reasonably established:

Laumontite, scolecite, and heulandite zones in ascending order are recognized in the Western Deccan Traps.

Lavas of the coastal belt are albitized and different from the lavas in the Ghats. The formation of the laumontite zone (recognized for the first time in the Deccan Traps) at the base is indicative of burial metamorphism.

Increase in glass content in the rock has resulted in greater amounts of zeolite formation when favourable conditions prevailed. Silica activity in different forms

<div align="center">T t</div>

conditioned the formation of specific zeolites. Occurrence of mordenite in the low-silica scolecite zone is considered possible on the basis of amorphous silica activity in solution. Formation of different forms of silica, e.g. tridymite, was influenced by the alkalinity of the solutions.

The crystallization sequence in cavities appears to be mainly temperature-controlled, with low-temperature, strongly hydrous minerals developing last.

Zeolitization and formation of associated secondary minerals postdate the structural disturbances in the Deccan Traps of Western India. Hence zeolite zones are oblique to the lava stratigraphy (fig. 2).

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