Magma underplating and storage in the crust-building process beneath the Kutch region, NW India

N. R. Karmalkar*, M. G. Kale, R. A. Duraiswami and M. Jonalgadda

Department of Geology, University of Pune, Pune 411 007, India

Not all the magma produced during the partial melting of the mantle always reaches the Earth’s surface. Most of it cools and may freeze during its ascent through the lithosphere when the ascent rates are not sufficiently high. In continental flood basaltic provinces magmatic underplating is a quantitatively important mechanism of crustal growth and evolution. Beneath continental areas, likely areas to trap basaltic magmas are located near the Moho or within the crust. Seismic studies and other geophysical means have provided evidence for underplated bodies beneath the Hawaiian Islands, La Reunion, Ninetyeast ridge, and the Deccan Trap. However, the ubiquitous occurrence of cumulate xenoliths in the lavas is perhaps the best and most direct petrological evidence for the significance of magma intrusion and accumulation beneath continental areas. In this article, we review occurrence of suite of ultramafic xenoliths entrained in the alkaline lavas, especially the cumulate xenoliths from Mt. Sayala, Kutch region, Gujarat in the western part of Deccan Flood Basaltic Province, India and its implication in understanding sub-crustal level magmatic and crust-building processes. In relation to the underplating process we discuss the importance of various other igneous intrusions and their role in the tectonomagmatic evolution of this part of the Deccan Flood Basalt.

Keywords: Crust-building process, magma, ultramafic xenoliths, underplating and storage.

The Kutch region is situated to the west of the main Deccan Trap Province and is proximal to two major conjugate rift systems, Narmada and Cambay. The landscape comprises rocky highlands standing out like ‘islands’ amidst the vast plains of the Great and little Ranns of Kutch. The highlands are the areas of uplift made of Mesozoic sediments, whereas the plains of low lands represent structural basins between the uplift (Figure 1).

The tectonic evolution of the Kutch region has been attributed to the rifting process and the region accordingly marks the site of palaeo-rift graben whose evolutionary history dates back to the Mesozoic times. The Kutch Rift Basin (KRB) occurs as a block and the Nagar Parkar Fault (and ridge) and Kathiawar Fault separate this 400 km × 150 km block from the Precambrian granitic rocks under the Thar Desert to the north and Saurashtra peninsula to the south. To the east it is separated from the Cambay rift basin by an uplifted subsurface arch associated with gravity highs called Radhanpur–Barmer Arch, while the continental shelf marks the western boundary.

The Kutch Basin has evolved in two major stages. The first is described as rift stage where the rifting process began during the extensional phase of the break-up and separation of the Indian plate from Gondwanaland in Late Triassic–Early Cretaceous time followed by syn-rift sedimentation. The second is the inversion stage in Late Cretaceous, when the rifting was aborted and the basin uplifted. The break-up and separation of Madagascar along the west coast during mid–late Cretaceous, which was followed by a ridge jump giving rise to the thermal influx may possibly be cause of the uplift. A unique feature of this basin is the NNE–SSW trending wide ‘median high’ zone of elevated topography across it. On the basis of sediment thickness and facies change, Biswas indicates that this high came into existence in late Oxfordian time, which he regards as the earliest tectonic movement marked by the late Oxfordian unconformity.

In the Kutch region, the Deccan Traps are confined to a narrow, long strip bordering the Mesozoic highlands from Lakhpat on the northwest to Anjar in the east. Seven flows have been identified; they dip gently southward and rest disconformably on Mesozoic sediments. The flows are notably absent in the central and northern parts of the Kutch, where sills and dykes are conspicuous. Plugs of basanites/melanephelinites, considered to be volcanic centres, occur to the north and northwest of the main Deccan Province, within areas once covered by Deccan lavas that are now seen as inliers. The trap flows in the Kutch are considered to be the earliest Deccan eruptions. However, a series of field traverses taken by the present authors has indicated that alkaline magmatism in the Kutch is not restricted to only plugs, cones and sheet-like intrusions, but also occurs as lava flows of limited extent. At places, for example, at Sumarasar two flows are seen emanating from an alkaline plug and run for 1–2 km distance. There are also incidences of the Deccan tholeite flows resting over alkaline flows.

*For correspondence. (e-mail: nrkarmalkar@gmail.com)
Several alkaline rocks with the entrained mantle xenoliths occur in the Kutch as plugs and cone- or sheet-like bodies of over 500 m diameter, intruding into flat-lying or gently dipping Jurassic sandstones. Alkaline magmatism was considered either as a late phase purely on the basis of their non-relation with Deccan tholeiitic flows at outcrop level or consanguineous (67–64 Ma) on the basis of Ar–Ar dating of these two group of magmatic rocks. However, on the basis of detailed field studies and geological mapping, it has now been shown that alkaline magmatism in the Kutch predates the tholeiite emplacement. The alkaline rocks here are interesting as they entrain spinel peridotite xenoliths. These are more commonly seen in the basanites and melanephelinites of Bhuja, Dhrubia, Sayala Devi, Dinodhar Dongar and Lodai. Most xenoliths range in diameter from 1 to 2 cm; xenoliths 4–5 cm in diameter are recorded from Bhuja, Dhrubia and Sayala Devi. The xenoliths vary in shape from rounded to subrounded to elongated and are mostly granular in nature; although a few samples are weakly foliated. At Bhuja and Lodai, the xenoliths are concentrated in the central portion of the sheet-like intrusion, while at Dhrubia and Sayala Devi they occur mainly at the lower levels of the plug and cone respectively. Sayala Devi has yielded xenoliths of type-I (Cr–diopside–spinel) lherzolites and type-II (Al–augite) xenoliths, both mantle and cumulate in origin respectively.

**Ultramafic xenoliths: the shallow SCLM**

**Petrography of the xenoliths**

Olivine, orthopyroxene (opx), clinopyroxene (cpx) and spinel in order of abundance, dominate the xenoliths. The relatively small size of the xenoliths precludes the determination of precise mineral modes. However, an attempt has been made to determine the average modal abundances by point counting at least 50 samples from different areas. The olivine content varies between 50 and 60%, opx between 15 and 20%, and cpx between 2 and 13%. The reddish-brown aluminous spinel ranges from 0.5 to 4%. The spinel peridotites typically are fine-grained (0.5–2 mm) and unfoliated, and are of type-I (Cr–diopside–spinel) lherzolites. They exhibit mostly protogranular or xenomorphic granular microstructures. However, a few samples from Sayala Devi locality are coarse-grained with weakly defined planar fabric. Olivine in all samples displays strain shadows and kink bands and in most samples, olivine contains trails of fluid inclusions. The cpx occurs mostly as discrete grains smaller than the olivines or opx, and shows finely spaced exsolution lamellae of opx. Spinel in the xenoliths is reddish-brown in colour and occurs in close association with opx and cpx. Neoblasts of olivine, opx and cpx are sometimes observed armouring the large porphyroclasts of olivine and opx. Such
neoblast formation has been ascribed to in situ heating and metasomatism during magmatism in the xenoliths from Canary Island. Glass in the xenolith is generally of two types, colourless and dark green to brownish in colour, the details of which are described elsewhere. Volatile-bearing phases such as amphibole or phlogopite have not been observed in any of the xenoliths studied.

In the Sayala Devi plug-like intrusion two kinds of xenoliths have been recovered, one with mantle mineralogy with Cr-diopside as the main clinopyroxene phase, and the other dominated by augite clinopyroxene and typically showing cumulate texture and belonging to type II (Al-augite) xenoliths. The cumulate rock types consisting of the assemblage clinopyroxene ± orthopyroxene ± olivine ± spinel are found in close association with spinel peridotite xenoliths of mantle origin. Both olivine and pyroxene in these xenoliths are strain-free, and olivines do show the presence of fluid inclusions. The spinels in these xenoliths are reddish-black in colour.

The major element composition of minerals was determined on polished thin sections using a CAMEBAX SX-50 electron microprobe in wavelength dispersive mode, and a mixture of natural and synthetic mineral standards. The detailed data for 17 xenoliths and their hosts have been reported elsewhere. Here only the relevant dataset is discussed. Similarly, the major oxide data for two xenoliths from Bhujia and three xenoliths from Drubia and Bhuj reported is also considered.

The clinopyroxene in the ultramafic xenoliths of mantle origin is chrome diopside with composition Wo47.49 En52.49, while it is Al augite in the cumulate xenoliths of Sayala Devi. The cpx has higher Al2O3 than the opx (2.5–5.6%); TiO2 and Al2O3 decrease with increasing Mg#. The Al content of the cpx decreases with increasing Cr/Cr + Al of spinel, giving excellent correlation of Cr# between spinel and cpx. In the suite as a whole, the CaO content of cpx is negatively correlated with Al2O3 content. In the xenoliths from Drubia, high-Al2O3 cpx is found in rocks with higher modal cpx (10.5–11.5%), while low-Al2O3 cpx is associated with low modal cpx (5.3%).

Orthopyroxene also shows a limited range in composition (En80–89). Al2O3 contents vary between 3 and 3.5 wt%, except for two xenoliths from Sayala Devi which have opx with 1.9–2.2% alumina; some of these pyroxenes contain exsolved spinel. Most opx grains are zoned, with increasing MgO and decreasing Al2O3 and Ca/(Ca+Mg) from core to rim. The Al2O3 content of opx were found to positively correlate with the Al2O3 content of the coexisting spinel. The TiO2 and Al2O3 contents of opx decreased with increasing Mg#.

Temperatures calculated for these xenoliths using different methods generally showed close correspondence and a narrow temperature range (Figure 2). Using the Ca-in-opx thermometer, the temperatures calculated for the core of grains averaged 882 ± 55°C, while the Cr–Al–opx thermometer gave a mean of 918 ± 23°C. Based on Ca solubility and Mg–Fe exchange in coexisting orthopyroxenes, a temperature of 1052 ± 70°C has been reported for xenoliths from Bhujia Hill. Similarly, using the high Ca content in olivine rims at contact with the clinopyroxene, a probable range of heating duration of 19 and 168 days, assumed to be synchronous with the ascent time has been reported for two Bhujia xenoliths.

Low equilibrium temperatures (884–972°C) indicate entrainment of lherzolite xenoliths from shallow depths within the lithosphere. The Sayala Devi samples of cumulate origin do not show large difference in the temperatures obtained, but show close correspondence in the temperature values computed for the mantle xenoliths from other localities.

Although there is no suitable method for calculating pressures for this mineral assemblage, absence of both plagioclase and garnet in the xenoliths constrains the pressure limit between ~10 and ~20 kb. These estimates are consistent with the Al/Cr ratios in the spinels, which indicate a pressure of 12–15 kbar. Referring the temperatures to the West Coast geotherm yields pressure estimates of ~15 kbar (40–45 km depth). The experimental data show that the pressure dependence of Al content of orthopyroxene in the temperature range 900–1100°C is insignificant. The pressure range of the stability of spinel lherzolites at these temperatures is fixed approximately at 6–18 kbar. Minimum heat flow of 60–70 mW/m² has been computed for the Kutch xenolith (Bhujia Hill), which is closely comparable to the oceanic geotherm. On the contrary, our data indicate that only a few xenoliths show proximity to the oceanic geotherm.

Igneous activity and its significance

Igneous intrusions are fairly common in all the uplift areas. These are present in a variety of forms, viz. plugs, cones, sheets, laccoliths, dykes and sills. These are seen concentrated in the tectonized zones accompanying the master faults. A fault-controlled emplacement of the Sadara sill compositionally transitional between alkali
basalt and tholeiite from the Pacham Island is one such magmatic event. A differentiated plutonic complex occurs around Nir Wandhan in Pacham Island to the east of Sadara. A series of igneous plugs occur along a belt in the central region of the Kutch mainland. These plugs consist of basanite and/or melanephelinite and entrain ultramafic xenoliths. The trace element systematics of these alkaline rocks is similar to those of ocean-island basalts, but there is considerable compositional variation, which is related to a strong overprint from the lithosphere on plume-derived magmas. Significant is the string of asymmetric domes that occur along the tectonized margins of the uplifts in the Kutch region. The major domal structures include Habbo, Jhara, Keera, Nara, Junara and Jara, which are associated with the Kutch Mainland Fault and consist of Mesozoic rocks. Gabbroic laccoliths associated with domed-up Mesozoic strata are common along the northern marginal faults of the Kutch mainland. The stream which bisects the Habbo dome to the north of the Dhrung Village, exposes one such gabbroic laccolith (Figure 3). Here the exposed maximum thickness of the gabbroic intrusion in the central part is about 20–25 m, while the exposed width of the intrusion is over a kilometre; the intrusion leaves apophyses and tongues into the overlying Dhosa limestone horizon, suggesting its post-Dhosa nature. The eastern and western limits of the domes are marked by N–S transverse faults. Such distribution clearly indicates a close genetic relationship of magmatism and tectonism in this part of the Kutch.

Epeirogenic uplift and formation of the plateau that has maintained its elevation result from intrusion of large thickness of basic magma in the lower part of the continental crust. The uplift of the flood basalt plateau can be related to two processes: ‘real uplift’ by the process of thickening of the crust by underplating, and ‘apparent’ uplift by isostatic adjustments. Direct measurements of uplift rates on the Kutch region are lacking. A unique feature of the Kutch Basin is a NNE–SSW trending wide ‘median high’ zone of elevated topography across the basin. Seismic tomographic studies have revealed the presence of a large mafic body with fluids in the lower crust, close to the mantle at a depth of 35–40 km. It is speculated that the median high might be the surface expression of this. The median high came into existence in late Oxfordian, which Biswas regards as the earliest tectonic activity. This period also coincides well with the peak transgressive event represented by iron-rich oolite (Dhosa Oolite) of Oxfordian age. This is followed by the deposition of black carbonaceous shale siltstone and sandstone sequence. This may suggest a fundamental difference in palaeogeographic setting between the deposition of the lower two units (Jhurio and Junara formations) and the upper units (Jhuran and Bhuj formations). The lower units may represent a rising sea-level stage or marine incursion since Bathonian. The regression commenced from Kimmeridgian and sea water began to withdraw in response to the uplift related to the large-scale magmatic underplating. Similar conclusions are drawn from the sedimentary record as supporting evidence for the uplift and generation of Emeishan flood basalts of southwest China. The beginning of uplift at this juncture is also evident from the penecontemporaneously deformed sedimentary structures such as convolute laminations, load pouches and sand blows observed in the middle members of the Jhuran formation. Moores and Twiss considered such features to be the result of liquefaction during an earthquake, and are palaeoseismic indicators. The dominantly elastic nature of the upper two units (Jhuran and Bhuj formations), especially the fluvio-deltaic nature of the Bhuj Formation against the carbonate-dominated lower units (Jhurio and Junara formation) of shallow marine origin, may further support uplift-induced change in the palaeogeographic setting of this region. Uplift will

**Figure 3.** Generalized litholog of the Habo Dome with igneous intrusion at the base (modified after Patel et al.).
also lead to shoaling and thinning of sedimentary packages. The uppermost unit of the Mesozoic succession of the Kutch region is marked by the Bhuj formation, which shows thinning towards east and is unconformably overlain by Deccan Trap basalts. This upheaval ceased before the onset of the Tertiary, as evidenced by gently dipping Tertiary rocks which overlie the eroded Mesozoic folds, east and southeast of the Kutch Mainland. The uplift probably ended just before the beginning of the Tertiary because the new transgression and depositional onlap started at that time. The early Miocene sequence which is recorded by the Vinjhun shale exposed along the Khari Nadi near village Chharsa represents a transgressive, tide-dominated, storm-affected sequence. The change from regression to transgression at the boundary between the Cretaceous and Tertiary may have resulted from crustal uplift and subsequent thermal subsidence, probably due to the cooling of the underplated material.

In the light of the geophysical data and field observations, one may distinguish between two modes of uplift in the Kutch region: a more deep-seated uplift on the regional scale due to underplating sensu lato and a more local uplift due to shallow intrusions. The first mode of uplift thus provides explanation for marine transgression as has been preserved and discussed above in the sedimentary record of this region. The presence of median high and the supporting geophysical data indicate more deep-seated uplift. The second mode of uplift is caused by the subcrustal intrusions. The existence of shallow plutonic bodies is clearly evidenced by the occurrence of gabbroic laccolith at Dhrung in the Habai Dome and many other domed up strata with igneous intrusions in the central part along the Kutch Mainland Fault, where the uplift is of the order of 15–20 m. Besides, a host of basic dykes, cone sheets and sills are commonly seen in the mainland. In Wagad highland and the northern chain of islands, basic dykes are the most common with a few plugs along the marginal faults. Such distribution clearly indicates a close genetic relationship between magmatism and tectonism in this part of the subcontinent.

Discussion

In the overall understanding and evolution of the Deccan Volcanic Province, the Kutch region occupies a key position as the trap flows in the Mesozoic Kutch basin are considered to be the earliest Deccan eruptions although some younger dates have also been reported. The Kutch region is interesting for many reasons, viz. its northerly location in relation to the main phase of Deccan tholeiitic eruption; for the alkaline rocks, many of which entrain ultramafic xenoliths of mantle origin; alkaline lava flows, some of which are seen to be fed by plugs, and its proximity to the inferred triple junction. These various intrusives only represent a fraction of the large volume of melt generated during the various stages of the overall evolution of this region. Occurrence of ultramafic xenoliths of both mantle and cumulate (igneous) origin helps in constraining the composition and evolution of the subcontinental lithospheric mantle and the magmatic processes responsible for the crust-building process. The temperatures obtained using various methods for the xenoliths of both mantle and igneous origin show a narrow range and also show closely corresponding values. Low equilibrium temperatures (884–972°C) indicate entrainment of xenoliths from shallow depths within the lithosphere. The estimated pressure obtained on the basis of the absence of both plagioclase and garnet in the xenoliths and by referring the temperatures to the West Coast geotherm is ~15 kbar (40–45 km depth). These values for the crust–mantle boundary are in close correspondence to the magnetic interface at a depth of 40 km as has been deduced from the 2D Magsat vertical intensity map. Similarly these estimates also agree well with the calculated Curie depth based on the heat flow data and the depth to Moho for the area estimated by both gravity and DSS data.

The ultramafic xenoliths of cumulate origin found in the Sayala Devi plug have densities (2.74–3.24 g/cm³) similar to the uppermost mantle (3.24–3.37 g/cm³) in which they have formed, and are intimately juxtaposed with it. Such an ultramafic cumulate suite was considered by Wilkinson to represent fractionates of tholeiitic within the crust, related to igneous intrusions near the crust–mantle boundary, especially in the uppermost mantle. Zones with abundant horizontal reflectors are observed at depths of 15–35 km in many parts of the continental crust. These zones are in many cases described as continental crust and the seismicly transparent zone below this as the mantle. It is argued that such studies do not constitute evidence that either the Moho or the base of the layered zone corresponds to the crust–mantle boundary. Because of the intermixing of mafic rocks as sub-horizontal lenses within the mantle material, such zones will have a bulk density and Vp intermediate between ‘crust’ and ‘mantle’ values. To reconcile the petrological and seismic data in such areas, the crust–mantle boundary has been placed in the middle of the layered zone. The mafic layers are interpreted to have been formed by repetitive intrusion and ponding of basaltic melts near the crust–mantle boundary due to density contrast between crustal rocks and mafic magmas. The ultramafic xenoliths exhibiting cumulate texture found in the alkaline plug at Sayala Devi represent such mafic lenses within the mantle material. Considerable geophysical studies have been carried out in the Kutch region following the devastating earthquake of 26 January 2001. Studies on aftershock data of this earthquake indicated the presence of a large mafic igneous body with fluids in the lower crust, close to the mantle, at depths of 35–40 km. The temperature–pressure data obtained for the cumulate xenoliths thus are consistent with the reported geophysical observations.
The gravity data have been modelled in the Kutch region using constraints from seismic lines to the south and east\(^5\). The model indicates a crust–mantle boundary lying at 35–40 km, and a zone of anomalously light mantle (density \(\approx 3.1\) g/cm\(^3\)) making up a thickness of ca. 10 km below the boundary. This is in turn underlain by material with a density of 3.2 g/cm\(^3\), extending for another 8–10 km. The model suggests a gradual increase in density with depth below the crust–mantle boundary, as is observed in many volcanic areas such as eastern Australia\(^7\). Rifting and/or mantle plume activity may give rise to a large-scale underplating of mafic and ultramafic material in the deep crust, as has been pointed out by several studies\(^8,40\), and this will be reflected in the Bouguer gravity signatures of such regions. Bouguer gravity anomaly data thus indicate underplating of high-density material in the Kutch–Saurashtra–Cambay region. The temperatures suggest that the xenoliths studied here resided in the uppermost part of the mantle at the time of entainment in the alkaline magmas, and many have cooled from significantly higher temperatures before they finally were entrained. Several samples retain evidence of an early high-T history, recorded by high Al and/or Ca in the cores of pyroxene grains; these give temperatures as high as 1360°C using various geothermometers\(^7,22-24\).

It is proposed that each eruption (the individual alkaline plug or cone) in the Kutch region is fed by relatively small ephemeral magma reservoirs in the lower lithosphere and asthenosphere, rather than by a single magma chamber. Limited volumes of individual eruptions, as has been evident by the limited lateral spread of alkaline flows, strong mineralogical and chemical zonation, and occurrence of rock types with compositional diversity precluding large homogenizing reservoirs, are some of the evidences supporting this contention. The lateral variation in the composition of the SCL and asthenosphere can also be a contributing factor in the compositional diversity of the rock types.

After segregation from the melting region where porous flow along a melt network dominates, rapid and effective magma transport may occur along buoyancy-driven vertical hydrofractures (dikes), once a critical overpressure threshold has been reached\(^50\). Else magma ascent may cease temporarily or permanently at a level of neutral buoyancy (LNB), where magma density equals that of the host rock and buoyancy becomes zero\(^51,52\). Near the LNB, magma tends to accumulate and spread laterally as dikes or sills\(^51\). Dike–sill networks are an important part of the continental flood basaltic provinces (CFBs). CFBs that are eroded exhibit dense dike swarms that arguably represent congealed magma-filled fissures through which once lavas poured out. Depending on the rate of magma supply and the rate of dike emplacement, these lateral intrusions may either solidify or may combine and ultimately result in the formation of magma chambers\(^53\). Beneath the continents, likely areas to trap basaltic magmas are located near the Moho or within the crust. Accumulation of magma at the base of the crust is known as underplating. Therefore, it is visualized that the magma chambers beneath the Kutch region occur as plexus of interconnected dikes and magma pockets from which the magma was periodically expelled. Similar observations have been made for the alkaline magmatism on Canary Islands from the Atlantic Ocean\(^50\). A more direct evidence comes from the occurrence of a gabbroric laccolith beneath the Habai dome at Dhrung emplaced at sub-crustal depths. Diapirically rising melts ponding at the crust–mantle boundary create additional stress for thermal doming of the mantle. This underplating process may have contributed substantially to the crustal growth in the Kutch region and the mafic rocks may have significantly influenced the bulk density of the uppermost mantle.


ACKNOWLEDGEMENTS. We thank the Head, Department of Geology, University of Pune for providing necessary facilities. Thanks are also due to Profs W. L. Griffin and Susane O’Reilly for providing the necessary analytical facilities and for constant encouragement. We also thank P. K. Sarma, S. P. Chauhan and Vilas Bhoskar for assistance in the field. N.R.K. and R.A.D. acknowledge support from Department of Science and Technology, Government of India. We also thank the anonymous reviewers for their supportive and critical comments that helped improve the quality of the paper.

Received 16 April 2007; revised accepted 1 May 2008.