

The Shallow Magmatic Plumbing System of the Deccan Traps, Evidence from Plagioclase Megacrysts and Their Host Lavas

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Abstract

We investigate the shallow plumbing system of the Deccan Traps Large Igneous Province using rock and mineral data from Giant Plagioclase Basalt (GPB) lava flows from around the entire province, but with a focus on the Saurashtra Peninsula, the Malwa Plateau, and the base and top of the Western Ghats (WG) lava pile. GPB lavas in the WG typically occur at the transition between chemically distinct basalt formations. Most GPB samples are evolved basalts, with high Fe and Ti contents, and show major and trace elements and Sr-Nd-Pb isotopic compositions generally similar to those of previously studied Deccan basalts. Major element modeling suggests that high-Fe, evolved melts typical of GPB basalts may derive from less evolved Deccan basalts by low-pressure fractional crystallization in a generally dry magmatic plumbing system. The basalts are strongly porphyritic, with 6–25% of mm- to cm-sized plagioclase megacrysts, frequently occurring as crystal clots, plus relatively rare olivine and clinopyroxene. The plagioclase crystals are mostly labradoritic, but some show bytownitic cores (general range of anorthite mol%: 78–55). A common feature is a strong Fe enrichment at the plagioclase rims, indicating interaction with an Fe-rich melt similar to that represented by the matrix compositions (FeO up to 16–17 wt%). Plagioclase minor and trace elements and Sr isotopic compositions analyzed by laser ablation inductively coupled plasma mass spectrometry show evidence of a hybrid and magma mixing origin. In particular, several plagioclase crystals show variable $^{87}\text{Sr}/^{86}\text{Sr}_i$, which only partially overlaps with the $^{87}\text{Sr}/^{86}\text{Sr}_i$ of the surrounding matrix. Diffusion modeling suggests residence times of decades to centuries for most plagioclase megacrysts. Notably, some plagioclase crystal clots show textural evidence of deformation as recorded by electron back-scatter diffraction analyses and chemical maps, which suggest that the plagioclase megacrysts were deformed in a crystal-rich environment in the presence of melt. We interpret the plagioclase megacrysts as remnants of a crystal mush originally formed in the shallow plumbing system of the Deccan basalts. In this environment, plagioclase acquired a zoned composition due to the arrival of chemically distinct basaltic magmas. Prior to eruption, a rapidly rising but dense Fe-rich magma was capable of disrupting the shallow level crystal mush, remobilizing part of it and carrying a cargo of buoyant plagioclase megacrysts. Our findings suggest that basaltic magmas from the Deccan Traps, and possibly from LIPs in general, are produced within complex transcrustal magmatic plumbing systems with widespread crystal mushes developed in the shallow crust.

Keywords: crystal mush, magma differentiation, plagioclase megacrysts, Deccan Traps, Large Igneous Province

INTRODUCTION

Studies of Large Igneous Provinces (LIPs) have historically focused on identifying mantle sources and melting mechanisms, on the role of assimilated crustal components involved in the genesis of the basaltic magmas and, recently, on the link of LIPs with global climate change events (e.g. Bond & Grasby, 2017; Ernst & Youbi, 2017; Clapham & Renne, 2019). In contrast, with some exceptions (e.g. Cox, 1980; Marsh, 2004; Karlstrom & Richards, 2011; Black & Manga, 2017; Krans et al., 2018; Moore et al., 2018; Ernst et al., 2019; Mittal et al., 2021; Black et al., 2021), relatively little attention has been given to the plumbing system of LIP magmas, i.e. the

architecture and evolution of the magmatic system from the MOHO (crust-mantle boundary) to the shallow crust. The relative scarcity of studies focusing on the transcrustal magma system of LIPs is partially due to the geochemical characteristics of LIP magmas. These are dominated by moderately evolved basalts typically having 8–4 wt% MgO, whereas primary or near-primary mantle melt compositions (MgO > 10 wt%) as well as strongly evolved andesitic to rhyolitic products are rare (Cox & Hawkesworth, 1985; Melluso et al., 2006; Sheth et al., 2013; Marzoli et al., 2019). Thus, the relatively uniform compositions of LIP magmas combined with their generally simple mineralogy dominated by plagioclase and

augitic pyroxene hinder recognition of differentiation processes acting in the magma plumbing system of LIPs.

LIP magmas are relatively homogeneous in composition and were erupted at rates as high as 50–250 km³/year in pulses lasting years to centuries (Black *et al.*, 2021; Self *et al.*, 2022). This may suggest that LIP magmas differentiated in large reservoirs that controlled and buffered the composition of the erupted magmas (Ernst *et al.*, 2019). In this sense, LIP magmas seem to be significantly different from those of ocean islands or arcs, where the eruption rates are usually relatively low, and the magmatic plumbing system is complex and frequently long-lived (Cashman *et al.*, 2017; Sparks *et al.*, 2019). Moreover, in subduction-zone settings, magmas rise, stall, and differentiate across the entire crustal depth, from the MOHO to the shallow crust in a transcrustal magma plumbing system (Cashman *et al.*, 2017). In magmatic plumbing systems, volatile species (CO₂ in particular) possibly exsolve from the magma upon decompression and then rise into the shallow crust, where they flux and remobilize stagnant crystalline mushes triggering eruptions (Cashman *et al.*, 2017; Caricchi *et al.*, 2018; Giordano & Caricchi, 2022). Even though it is still unclear to what degree the plumbing system of LIP magmas resembles those of arc magmas, there is growing evidence that LIP basaltic magmas can be quite rich in volatiles (Self *et al.*, 2008; Edmonds, 2008; Callegaro *et al.*, 2014; Capriolo *et al.*, 2020; Hernandez Nava *et al.*, 2021; Boscaini *et al.*, 2022), which may have triggered the eruptions of the basalts.

The goal of this study is to investigate the shallow plumbing system of the Deccan Traps LIP in India (Fig. 1a). The Deccan LIP was actively erupting across the Cretaceous–Paleogene boundary (Renne *et al.*, 2015; Schoene *et al.*, 2015, 2019; Sprain *et al.*, 2019) and is presently represented by widespread and thick lava flow fields in central and western India and in the Seychelles (Cox & Hawkesworth, 1985; Beane *et al.*, 1986; Mahoney, 1988; Melluso *et al.*, 1995; Kale *et al.*, 2020; Self *et al.*, 2021), as well as a yet unknown extent of lavas in the Arabian Sea (Mittal *et al.*, 2022, and references therein). Deccan lavas are mainly tholeiitic basalts with volumetrically minor alkaline or silicic lavas and were possibly produced by a mantle plume system during the northward migration of the Indian Plate (e.g. Glišović & Forte, 2017; but see also Sheth, 2005).

The Deccan LIP is characterized by plagioclase-megacrystic lavas, which have been noted in the Deccan Traps for decades (e.g. Karmarkar *et al.*, 1971; Hooper *et al.*, 1988) and are sufficiently abundant that the term Giant Plagioclase Basalts (GPBs; or Giant Phenocryst Basalts) has been coined and is in common usage today. The definition of a GPB varies between workers but generally centers on phenocryst size, which typically is 2 cm or greater. We find that size-based definitions are somewhat arbitrary, as many GPB flow fields or lobes have highly heterogeneous plagioclase megacryst dimensions and abundances that can vary on the scale of a few cm (Fig. 2a,b; e.g. Hooper *et al.*, 1988; Higgins & Chandrasekharam, 2007; Shandilya *et al.*, 2021). In fact, plagioclase megacrysts may be abundant (30–50% in volume) and very large (>2 cm) in only restricted flow lobes from pahoe-hoe lava flow fields. Other lobes from the same lava flow field may contain fewer (5–20 vol%) and smaller plagioclase crystals (0.5–2 cm). One of the puzzling aspects of the Deccan GPBs is that despite their megacryst load, they appear to be very widespread to the extent that they are used as stratigraphic markers delineating contacts between different geochemically defined formations (e.g. Beane *et al.*, 1986; Hooper *et al.*, 1988; Kale *et al.*, 2020; Shandilya *et al.*, 2021). An extreme case is the Rajgad GPB flow field, which is exposed over an area greater than 30 000 km² (Shandilya *et al.*, 2021),

always at or near the base of the Mahabeshwar Fm. Given that the concentration of megacrysts locally exceeds 50 vol% in many GPB flow lobes, their effective viscosity should have hindered eruptibility and apparent capacity to flow overland for large distances (e.g. Marsh, 1981).

Although their origin is still debated (Sen *et al.*, 2006; Higgins & Chandrasekharam, 2007; Borges *et al.*, 2014; Sheth, 2016; Krishnamurthy, 2020), there is general agreement that the plagioclase megacrysts recorded a relatively long period of evolution of the basaltic magma plumbing system. Despite their potential importance for the understanding of the differentiation processes of Deccan basalts, so far relatively few data have been published for the plagioclase megacrysts, i.e. their major element composition (e.g. Hooper *et al.*, 1988) or Sr isotopic ratios (e.g. Borges *et al.*, 2014). Moreover, with a few exceptions (Mahoney *et al.*, 2000; Alexander & Purohit, 2019), studies have been limited to the Western Ghats (WG) section.

For this study, we analyzed the major and trace element concentrations of 23 megacrystic basaltic samples from GPB lavas that span a large geographic (i.e. the WG, Mandla Lobe, Malwa Plateau, and Saurashtra Peninsula; Fig. 1) portion of the Deccan Volcanic Province and cover most of its duration. On a subset of 11 samples, we analyzed the textures, the major and trace element contents and Sr isotopic compositions of plagioclase megacrysts from plagioclase-rich samples as well as major element concentrations in coexisting olivine and clinopyroxene. Combined with the geochemical analyses of their host lavas, our data elucidate the origin of these large plagioclase crystals, of the magma that carried them to the surface, and on the shallow crustal magmatic plumbing system from which they originated over a large area of the Deccan from north (Saurashtra and Malwa) to south (WG).

The Deccan Traps

Deccan volcanism straddled the K-Pg (Cretaceous–Paleogene) boundary, contributed to the forcing of the end-Cretaceous climate through emissions of volcanic gasses (e.g. SO₂ and CO₂), which are quite abundant in at least some Deccan basalts (Self *et al.*, 2008; Callegaro *et al.*, 2014; Hernandez Nava *et al.*, 2021). This LIP was probably related to a mantle plume impinging under the northward moving Indian continental plate. Deccan magmatic rocks are mainly tholeiitic basalts and subordinate basaltic andesites. These rocks display a quite uniform mineralogy, which is similar to most other tholeiitic LIPs, e.g. dominated by moderately Mg-rich clinopyroxenes and moderately Ca-rich plagioclase (Melluso & Sethna, 2011). Silicic and alkaline magmatic rocks are present in the Deccan, in particular in the north and west of the province (e.g. Basu *et al.*, 2020b; Melluso *et al.*, 2021).

Deccan volcanism has been most intensively studied in the WG, where hundreds of successive lava flows formed a lava pile, which is cumulatively more than 3 km thick, referred to as the Deccan Group (e.g. Beane *et al.*, 1986; Kale *et al.*, 2020). The stratigraphic sequence in the WG (Fig. 1b) has been divided into three main lava flow packages: the Kalsubai, Lonavala, and Wai subgroups, from bottom to top. These subgroups have been subdivided into 12 main lava flow formations, each characterized by distinctive geochemical features, as seen in discriminant function diagrams and in Sr–Nd–Pb isotopic space (see Kale *et al.*, 2020, for discussion of the basis, history, and applicability of this nomenclature). The lower subgroups, Kalsubai and Lonavala in particular, show quite enriched incompatible trace element and isotopic compositions pointing to a significant involvement of enriched mantle and crustal components (e.g. Peng *et al.*, 1994;

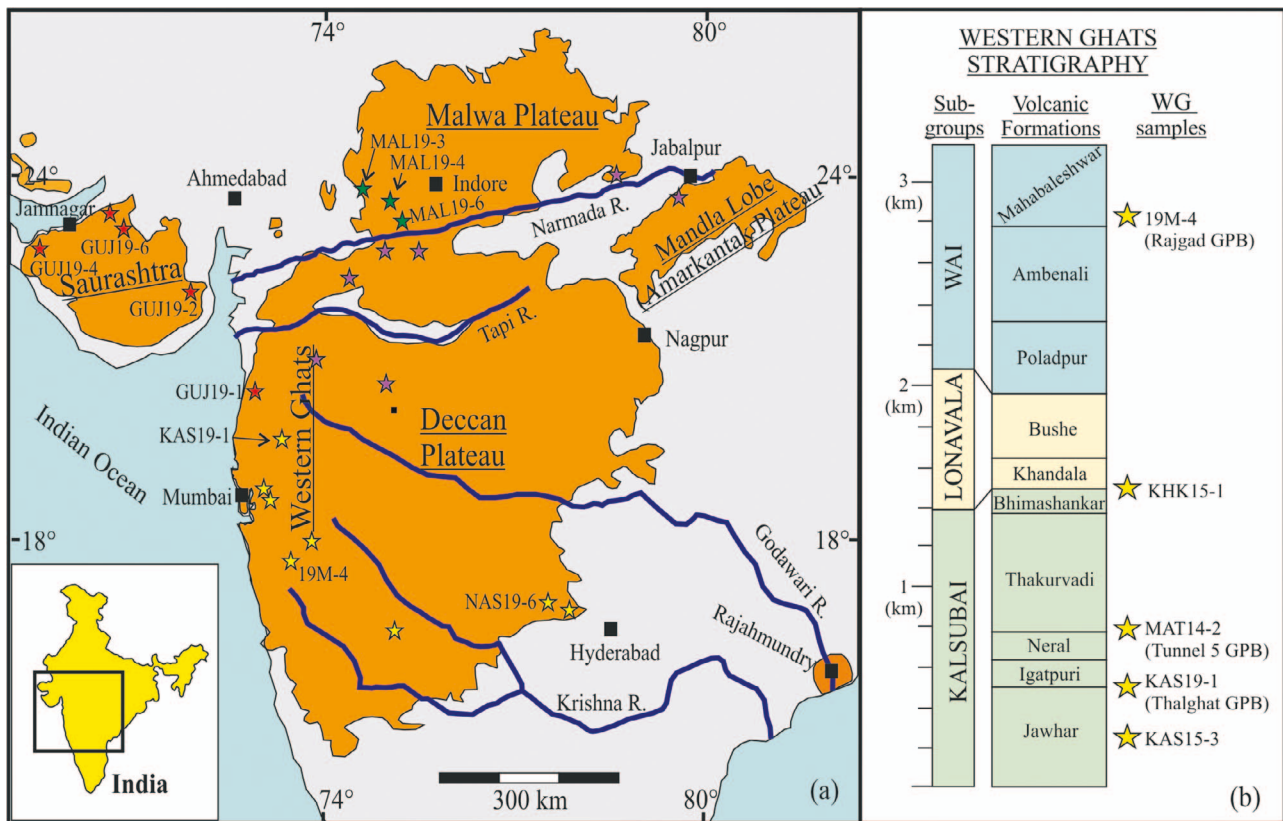


Fig. 1. (a) Schematic map of the Deccan Traps (in orange) Large Igneous Province in India (inset). Stars show sampling locations, the sites of some important samples are labeled. Sampling coordinates are reported in Table 1. (b) Composite stratigraphic section of the WG (modified after Beane *et al.*, 1986; Sprain *et al.*, 2019). Samples from that region are shown by yellow stars.

Basu *et al.*, 2020a). In contrast, the earliest Paleogene Wai subgroup lavas have less enriched compositions and suggest involvement of the shallow upper mantle and possibly of Reunion-like mantle-plume components in their genesis. The total duration of WG volcanism is about 0.8 Ma (Renne *et al.*, 2015; Schoene *et al.*, 2015, 2019; Sprain *et al.*, 2019), but each of the volcanic formations was possibly formed by a few short-lived eruption pulses, each lasting a few centuries (Chenet *et al.*, 2008; Self *et al.*, 2022).

The oldest Northern Deccan lavas appear to be older than those from the WG (Basu *et al.*, 1993; Schöbel *et al.*, 2014; Parisio *et al.*, 2016; Eddy *et al.*, 2020; Basu *et al.*, 2020b), as the Indian Plate rapidly migrated northward over the magma sources. The geochemical characteristics of basaltic lavas from the Malwa Plateau and from the Saurashtra Peninsula partially overlap with those from the Lonavala and Wai subgroups of the WG (Melluso *et al.*, 1995; Peng & Mahoney, 1995; Cucciniello *et al.*, 2015, 2019, 2020; Haase *et al.*, 2019). However, in the Malwa Plateau, Wai-type lavas dominate in the lower part of the volcanic pile (Haase *et al.*, 2019). Further details on the geochemical compositions of WG, Malwa Plateau and Saurashtra Peninsula rocks are reported in the Electronic Appendix 1.

METHODS

Mineral major and minor element compositions were analyzed at Milano University (Italy), with a JEOL JXA 8200 Superprobe, and at the U.S. Geological Survey (USGS) in Menlo Park with a JEOL JXA 8530 F+ Hyperprobe. Detailed core-rim traverses on plagioclase (33 crystals), clinopyroxene (17), and olivine (5) crystals were measured at Milano. Other analytical details on electron micro-

probe (EMP) analyses are reported in the Electronic Appendix 2, Table S1.

Electron backscatter diffraction (EBSD) analysis was performed on two thin sections at the Department of Geosciences Padova University (Italy) with a CamScan tungsten filament MX2500 scanning electron microscope (SEM) equipped with an Oxford Instruments NordlysNano EBSD detector. The X-ray maps for sample KAS19-1 were collected on a Tescan Solaris Fib-Feg-SEM (Department of Geosciences, University of Padova) equipped with an Ultim[®] Max 65mm² Silicon Drift Detectors for Energy Dispersive X-Ray spectroscopy (EDS) analysis from Oxford Instruments.

Strontium isotopes and trace elements in plagioclase crystals were analyzed on five samples by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Department of Geosciences at Aarhus University (Denmark). A Resolution Resonetics laser system coupled to first an Agilent 7900 quadrupole ICP-MS and then Nu Instruments Plasma Multi-Collector ICP-MS were used to analyze the trace elemental and Sr isotopic composition, respectively, of the same points of the plagioclase crystals, following procedures outlined in Hagen-Peter *et al.* (2019). For the trace element and Sr isotopic analysis, we used a spot size of 60 and of 154 μm , respectively.

A total of 23 whole-rock and 11 matrix samples were analyzed for major element and selected trace element concentrations by X-ray fluorescence (XRF) at Washington State University (USA) with a Philips PW2400 spectrometer, following methods described in Johnson *et al.* (1999). Analytical uncertainties range from 1% to 2% for major elements and from 10 to 15% for trace elements. Trace elements on the same samples were also analyzed by

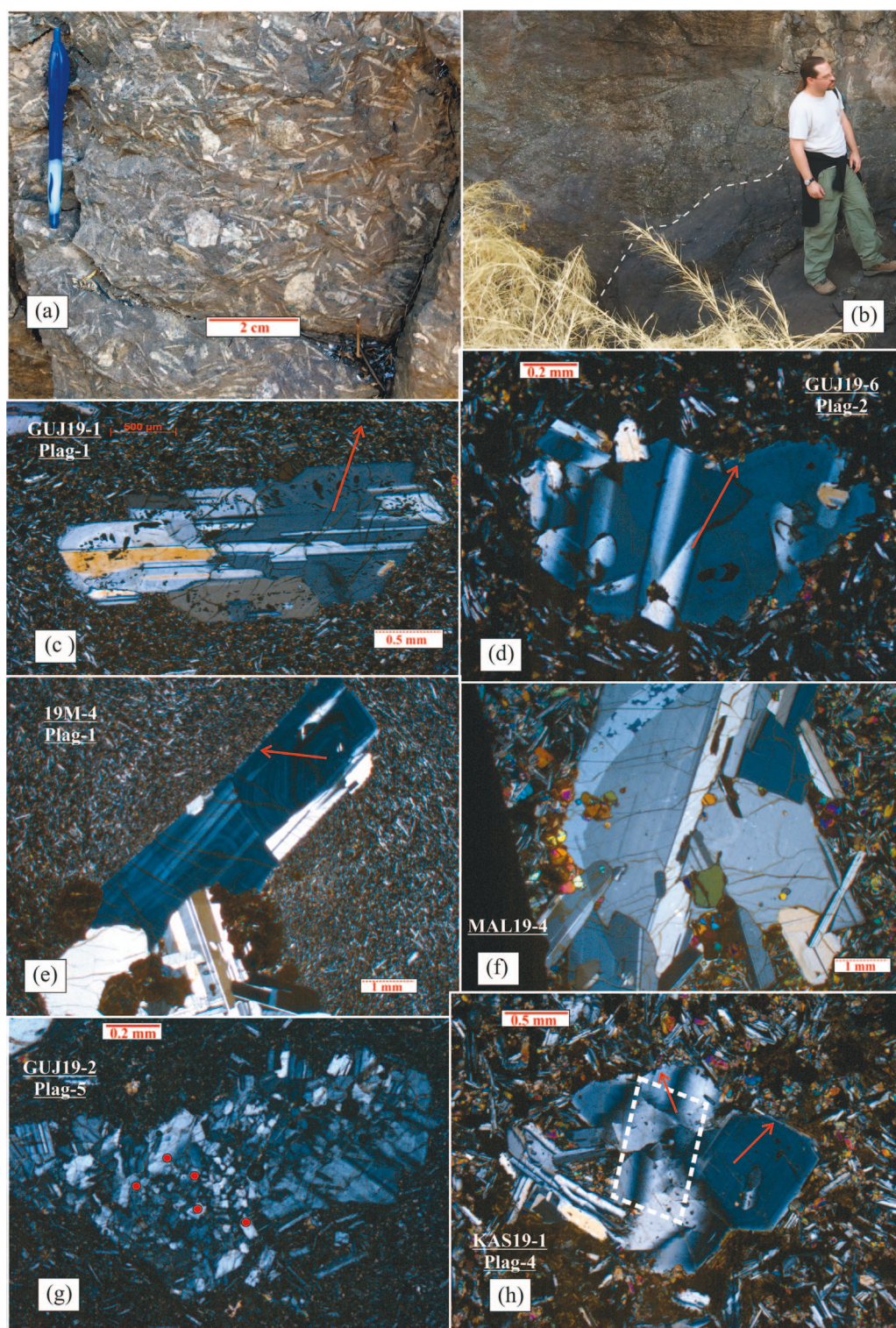


Fig. 2. (a, b) Field pictures of the Thalghat GPB flows, from which we collected KAS19-1; geologist is Loyc Vanderkluisen. (c–h) Thin section cross-polarized images of representative plagioclase crystals from the studied Deccan basalts. Red arrows and dots indicate traverses and spots analyzed by electron microprobe. (c) Partially sieved plagioclase from GUA19-1 (Plag-1). (d) Possibly deformed small plagioclase aggregate from GUA19-6 (Plag-2). (e) Large oscillatory zoned plagioclase from 19 M-4. (f) Large plagioclase aggregate from MAL19-4 with olivine inclusions. (g) Strongly fractured, possibly deformed and recrystallized plagioclase clots from GUA19-2. (h) Deformed plagioclase aggregate from sample KAS19-1 (Plag-4, white rectangle marks area analyzed by EBSD).

ICP-MS at Washington State University (USA) following analytical methods described in Knaack *et al.* (1994). For ICP-MS analyses, analytical accuracy and precision are estimated at 2–9% and less than 2%, respectively (Knaack *et al.*, 1994).

Sr-Nd-Pb radiogenic isotope ratios on seven matrix and one whole-rock samples (MAT14-2) were measured at the Department of Earth Sciences, University of Geneva (Switzerland) using a Thermo Neptune PLUS Multi-Collector ICP-MS with methods as

described in detail in Chiaradia *et al.* (2011) and Béguelin *et al.* (2015). Further details for all analytical methods can be found in the Electronic Appendix 1.

RESULTS

Sampling

We analyzed 23 samples from northern (Saurashtra Peninsula, Malwa Plateau, Mandla Lobe) to southern Deccan (WG). Details of the samples' contexts, and the role of some samples in previous studies, are discussed in the Electronic Appendix 1; sampling location coordinates are reported in Table 1. Some of the studied rocks were used in previous geochronological studies. The plagioclase megacrysts of GPBs have proven to be exceptionally useful for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology because they have generally low Ca/K (<50) and are relatively unzoned compared with phenocrysts in other Deccan lavas. For example, samples KHK15-1, KAS15-3, and MAT14-2 (equivalent to MG7, the Tunnel 5 GPB) are among the most precisely dated samples of Sprain *et al.* (2019).

GPB lava flow fields, including those studied here, are highly variable in their plagioclase content (c. 20–50% in volume). On the outcrop and in hand specimen, the analyzed rocks generally show a random distribution of plagioclase crystals, which lack a clear preferential orientation. Some workers define giant plagioclase crystals as being at least 2 cm in length (e.g. Seth, 2017) and these are abundant (30–50 vol%) in only restricted flow lobes from pahoehoe lava flow fields. Other lobes from the same lava flow field may contain fewer (5–20 vol%) and smaller plagioclase crystals (0.5–2 cm long). Thus, we consider the 2 cm threshold for definition of GPBs to be arbitrary. Portions of flows containing the largest plagioclase crystals are generally altered, so we focused our sampling and analyses on lobes with smaller, but fresher, plagioclase crystals.

In the comparatively well-studied WG, GPBs tend to occur at the transition between successive geochemically defined lava flow formations, e.g. the Thal Ghat and Tunnel 5 GPBs studied herein occur at the very top of the Jawhar and Neral formations, respectively (e.g. Beane *et al.*, 1986; Hooper *et al.*, 1988). In the WG, GPBs occur at the transition of all formations of the Kalsubai subgroup, but are absent in the Lonavala and rare in the Wai subgroups. In the northern Deccan sub-provinces of the Saurashtra Peninsula, Malwa Plateau, and Mandla Lobe, outcropping lava piles are absent or less well exposed, hindering a precise definition of the stratigraphic position of the studied samples. Sampling sites are shown in Fig. 1. Further details on sampling can be found in the Electronic Appendix 1.

Petrography

The studied rocks are characterized by a fine-grained matrix (except in the samples TM18-3, MAL19-3 and MAL19-4) and by large plagioclase crystals representing 5–20% of the thin section surface area (Figs 2 and 3). The size of the largest plagioclase exceeds 4 mm in all samples and exceeds 1 cm in several samples (e.g. KAS19-1, KAS15-3, MAL19-4, 19M-4, TM18-3, 19P-5, MAT14-2; Figs 2a, b, e, f and 3 f, g). In most samples, small plagioclase crystals (<100 μm) are rare, while large to very large crystals are dominant (see the thin section scans; Fig. 3 e, f, g). Such features are similar to those described by Higgins & Chandrasekharam (2007), who did a detailed analysis of crystal size distribution of GPBs. Among the samples studied herein, only MAL19-3, GUJ19-2 (Fig. 3h), and GUJ19-3 show a range of plagioclase crystal sizes from small (<100 μm) to relatively large (c. 5 mm).

Most of the analyzed plagioclase crystals range in size from 0.5 to 10 mm, and in most cases occur in glomerophytic aggregates (crystal clots) of several plagioclase crystals. More generally, single isolated plagioclase crystals (monocrysts) are rare or even absent at the thin section scale of some samples (Fig. 3 e–h). Only a few analyzed plagioclase megacrysts occur as monocrysts and are euhedral, for example Plag-1 in GUJ19-1 (Fig. 2c) and Plag-1 in KAS19-1. In plagioclase clots, many crystal rims in contact with the matrix are euhedral, i.e. in apparent equilibrium with the groundmass. However, a few crystals show rounded shapes (e.g. GUJ19-6 Plag-2, KAS19-1 Plag-4; Fig. 2d, h), while others show embayed rim areas, possibly related to resorption or rapid growth. A frequent feature of the large plagioclase crystals is their oscillatory zoning, which is observed in plagioclase crystals from all samples, but is particularly striking in 19 M-4 (Fig. 2e). Partially resorbed cores are also relatively common, they occur for example in GUJ19-1 (Fig. 3d), GUJ19-2, GUJ19-6, MAL19-4, MAL19-6, and KAS19-1. Partial dissolution, i.e. sieve-textured zones occur in some plagioclase crystals from GUJ19-1 (Fig. 2c), GUJ19-2, and GUJ19-3.

Plagioclase aggregates occasionally show microstructures that may be indicative of deformation. These include high angle grain boundaries at points of impingement, accompanied by subgrain boundaries that propagate from here through the impinging plagioclase crystals, recrystallized growth twins, and deformation twins. Other typical microstructures are undulatory extinction, curved grain boundaries and twin lamellae with sharp triangular tips (e.g. Fig. 2d, h). A relatively large aggregate of plagioclase microcrysts is observed in GUJ19-2 (Fig. 2g). Such fabrics are observed in several samples (e.g. in GUJ19-1, GUJ19-2, GUJ19-6, MAL19-6, KAS19-1), although only in a few crystals per sample, and are similar to those found in clearly deformed plagioclase crystals from LIPs (cf. Holness *et al.*, 2017, 2022) and subduction-related basalts (Spiess *et al.*, 2017).

In addition to plagioclase, the only other large crystals (>100 μm in maximum axis) are rare augitic clinopyroxene and olivine (Figs 2f and 3a, b). These minerals make up less than 4 vol% in all investigated thin sections, and less than 1 vol% in a few samples (e.g. 19 M-4). Olivine is very rare and small (<50 microns) in about half of the studied samples and absent in the other samples. Olivine occurs as phenocrysts surrounded by matrix only in KAS19-1 (Fig. 3b), while it is relatively abundant (1–3 vol%) as an inclusion in plagioclase megacrysts in about half of the samples (e.g. MAL19-3 and MAL19-4; Fig. 2f).

Clinopyroxene crystals are also rare and occur either as inclusions in plagioclase (e.g. in 19P5, MAL19-4, MAL19-6, GUJ19-1, GUJ19-5, KHK15-1, and 19M4), as single crystals (e.g. in 19P5, KAS15-3, GUJ19-6) or in crystal clots (in GUJ19-1, GUJ19-2, NAS19-6) in the matrix. The largest augite crystals reach about 200 μm along the maximum axis; however, most do not exceed 100 μm . Ca-poor pyroxene (pigeonite) was identified as small phenocrysts (KAS15-3, GUJ19-1, GUJ19-5), as inclusions in large plagioclase crystals (KAS15-3, GUJ19-1, GUJ19-5, KHK15-1, and 19M4), and in the groundmass (KAS15-3, GUJ19-5, KHK15-1, and 19M4). Oxides, mainly magnetite and rare ilmenite, are abundant as small crystals (<50 μm) within the groundmass, of which they represent about 4–10 vol%.

Whole-rock and matrix compositions

Twenty-three whole-rock samples were analyzed for major and trace elements. We also analyzed the matrix for major and trace elements of ten samples. Matrix samples were obtained by crushing the rock to an approximate grain size of 100 μm and by

Table 1: Sampling coordinates and matrix and whole-rock compositions of the analyzed Deccan rocks

Sample	MATRIX							
	MAL19-3	MAL19-4	MAL19-6	GUJ19-1	GUJ19-2	GUJ19-4	GUJ19-5	GUJ19-6
Latitude (N)	23°06.370'	22°34.098'	22°18.697'	20°13.746'	21°43.863'	22°12.421'	22°30.530'	22°38.145'
Longitude (E)	74°31.611'	75°13.539'	75°29.790'	77°04.291'	72°05.322'	68°34.230'	70°45.183'	70°53.108'
Area	Malwa Plateau				Saurashtra			
SiO ₂ wt%	50.08	47.53	48.28	49.07	54.12	48.22	48.72	47.08
TiO ₂	2.423	4.164	3.309	3.467	1.549	1.478	3.538	3.679
Al ₂ O ₃	13.23	11.89	12.49	12.37	14.70	13.85	12.50	12.55
FeO _t	14.04	17.62	15.87	16.36	10.85	13.61	15.81	15.98
MnO	0.232	0.292	0.244	0.237	0.158	0.225	0.223	0.265
MgO	5.25	4.83	5.01	5.30	4.35	6.40	5.09	5.26
CaO	10.44	8.68	9.87	9.56	7.92	11.69	9.24	10.28
Na ₂ O	2.53	2.30	2.62	2.56	2.84	2.43	2.40	2.39
K ₂ O	0.48	1.22	0.76	0.63	1.97	0.37	0.83	0.66
P ₂ O ₅	0.239	0.272	0.354	0.361	0.251	0.203	0.304	0.371
Sum	98.93	98.79	98.82	99.58	98.70	98.47	98.66	98.51
LOI %	0.81	0.87	0.63	0.18	0.67	1.10	0.85	1.09
Ni ppm	43	43	55	41	15	64	65	52
Cr	34	51	42	25	11	119	105	50
Sc	38	36	37	35	31	48	33	37
La	16.27	22.59	30.26	26.47	35.12	11.81	25.34	28.05
Ce	37.05	49.48	66.35	54.28	70.91	23.12	57.02	62.59
Pr	5.06	6.63	8.63	6.91	8.50	2.86	7.73	8.32
Nd	22.83	28.60	36.92	28.58	33.75	12.14	33.64	35.91
Sm	6.02	7.42	8.69	7.05	7.14	3.20	8.60	8.85
Eu	2.12	2.29	2.80	2.22	1.96	1.28	2.69	2.91
Gd	6.73	7.81	8.97	7.66	6.99	4.05	9.20	9.15
Tb	1.19	1.31	1.47	1.31	1.13	0.75	1.50	1.48
Dy	7.06	7.70	8.60	7.84	6.90	4.99	8.68	8.79
Ho	1.39	1.46	1.68	1.55	1.40	1.09	1.64	1.66
Er	3.59	3.80	4.27	3.94	3.63	2.92	4.12	4.18
Tm	0.49	0.51	0.59	0.54	0.53	0.44	0.57	0.56
Yb	2.90	2.99	3.42	3.28	3.13	2.66	3.29	3.23
Lu	0.44	0.44	0.52	0.51	0.50	0.43	0.49	0.49
Ba	132.37	227.55	243.28	267.55	400.63	138.14	199.78	220.81
Th	2.89	5.44	4.98	6.19	10.60	1.63	4.64	3.84
Nb	13.99	16.34	27.94	15.79	16.48	11.60	17.48	30.97
Y	34.55	36.41	40.27	37.84	34.92	26.97	40.59	40.34
Hf	4.24	6.03	6.35	5.30	5.86	1.98	6.49	6.38
Ta	0.96	1.12	1.86	1.09	1.12	0.68	1.23	2.11
U	0.68	1.38	1.19	1.23	1.98	0.38	0.98	0.87
Pb	2.46	4.14	3.83	6.66	6.64	1.28	3.58	2.80
Rb	16.67	39.98	23.91	35.39	68.69	5.05	14.12	18.44
Sr	245.95	213.21	311.75	221.81	198.17	202.49	269.18	353.09
Zr	158.35	219.78	241.29	199.66	234.67	74.41	242.55	241.82
⁸⁷ Sr/ ⁸⁶ Sr	0.706309(5)		0.705995(5)	0.709675(6)	0.718463(6)			0.704984(4)
⁸⁷ Sr/ ⁸⁶ Sr _i	0.706125		0.705787	0.709242	0.717522			0.704842
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512693(1)		0.512693(1)	0.512309(1)	0.511894(1)			0.512857(1)
¹⁴³ Nd/ ¹⁴⁴ Nd _i	0.512624		0.512631	0.512245	0.511839			0.512793
EpsilonNd _i	1.39		1.53	-6.02	-13.93			4.68
²⁰⁶ Pb/ ²⁰⁴ Pb	19.782(2)		19.634(1)	19.120(1)	21.735(1)			19.011(1)
²⁰⁷ Pb/ ²⁰⁴ Pb	15.826(2)		15.806(1)	15.963(1)	16.101(1)			15.634(1)
²⁰⁸ Pb/ ²⁰⁴ Pb	40.494(4)		40.295(2)	40.846(1)	43.782(2)			39.623(2)
²⁰⁶ Pb/ ²⁰⁴ Pb _i	19.531		19.339	18.835	21.468			18.726
²⁰⁷ Pb/ ²⁰⁴ Pb _i	15.814		15.792	15.949	16.089			15.620
²⁰⁸ Pb/ ²⁰⁴ Pb _i	40.191		39.943	40.673	43.359			39.259
MATRIX				WHOLE ROCKS				
Sample	19M-4	KAS19-1	MAL19-3	MAL19-4	MAL19-5	MAL19-6	GUJ19-1	GUJ19-2
Latitude (N)	17°55.507'	19°41.046'	23°06.370'	22°34.098'	22°22'18"	22°18.697'	20°13.746'	21°43.863'
Longitude (E)	73°37.430'	73°30.793'	74°31.611'	75°13.539'	75°28.842'	75°29.790'	77°04.291'	72°05.322'

(Continued)

Table 1: Continued.

Area	Western Ghats			Malwa Plateau			Saurashtra	
SiO ₂ wt%	49.07	46.94	49.89	49.91	49.06	48.36	48.03	53.89
TiO ₂	3.467	3.113	2.173	2.212	2.842	3.005	2.538	1.406
Al ₂ O ₃	12.37	12.82	14.49	15.34	13.16	13.86	15.78	16.06
FeO _t	16.36	15.26	12.78	12.16	14.01	13.89	13.10	9.82
MnO	0.237	0.197	0.206	0.171	0.227	0.215	0.164	0.141
MgO	5.30	5.96	5.05	4.79	5.03	5.08	5.15	4.09
CaO	9.56	10.23	10.73	9.51	10.37	10.09	9.76	8.51
Na ₂ O	2.56	2.49	2.54	2.62	2.53	2.67	2.82	2.89
K ₂ O	0.63	0.86	0.41	0.95	0.39	0.53	0.97	1.81
P ₂ O ₅	0.361	0.259	0.203	0.215	0.268	0.308	0.264	0.219
Sum	99.92	98.12	98.47	97.89	97.89	98.02	98.59	98.83
LOI %	0.00	1.37	1.14	1.86	1.84	1.67	1.20	0.81
Ni ppm	57	101	45	32	55	50	86	17
Cr	77	244	41	53	39	34	146	13
Sc	38	34	33	27	35	34	26	29
La	23.67	19.56	14.37	18.49	19.92	27.10	20.98	32.85
Ce	53.98	43.38	32.45	40.12	45.43	59.34	45.38	65.62
Pr	7.28	5.87	4.44	5.37	6.19	7.74	6.09	7.83
Nd	32.40	26.66	19.82	23.25	26.95	32.75	26.65	30.55
Sm	8.34	6.98	5.45	6.09	7.09	7.85	6.84	6.73
Eu	2.66	2.28	1.90	1.96	2.35	2.53	2.29	1.79
Gd	9.24	7.62	5.98	6.31	7.48	7.90	7.29	6.37
Tb	1.51	1.27	1.03	1.06	1.26	1.29	1.20	1.06
Dy	9.11	7.57	6.23	6.11	7.38	7.65	7.03	6.36
Ho	1.79	1.49	1.22	1.19	1.43	1.46	1.37	1.28
Er	4.54	3.74	3.16	2.99	3.68	3.73	3.56	3.29
Tm	0.63	0.51	0.43	0.41	0.50	0.51	0.48	0.46
Yb	3.69	3.00	2.58	2.41	2.96	3.00	2.84	2.88
Lu	0.57	0.46	0.39	0.36	0.45	0.44	0.43	0.44
Ba	186.93	249.21	116.39	195.31	161.40	213.82	277.95	372.82
Th	3.04	2.45	2.56	4.30	2.93	4.45	2.33	9.79
Nb	21.78	11.92	12.25	10.91	18.18	24.98	11.95	15.07
Y	43.41	35.91	30.05	29.15	35.47	35.65	33.80	31.74
Hf	6.11	5.40	3.78	4.52	4.99	5.64	5.09	5.45
Ta	1.46	0.78	0.86	0.79	1.25	1.72	0.81	1.04
U	0.72	0.47	0.60	1.06	0.82	1.04	0.51	1.81
Pb	3.21	3.26	2.13	5.16	2.33	3.17	3.37	6.25
Rb	16.08	13.79	13.82	29.65	11.98	17.99	20.27	61.35
Sr	247.88	232.82	256.70	262.84	275.64	333.31	286.18	218.15
Zr	233.85	198.50	134.37	162.30	185.02	212.76	186.77	214.07
⁸⁷ Sr/ ⁸⁶ Sr	0.705068(5)	0.709494(3)						
⁸⁷ Sr/ ⁸⁶ Sr _i	0.704893	0.709333						
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512685(1)	0.512330(1)						
¹⁴³ Nd/ ¹⁴⁴ Nd _i	0.512618	0.512261						
EpsilonNd _i	1.27	-5.69						
²⁰⁶ Pb/ ²⁰⁴ Pb	17.990(1)	18.460(1)						
²⁰⁷ Pb/ ²⁰⁴ Pb	15.490(1)	15.681(1)						
²⁰⁸ Pb/ ²⁰⁴ Pb	38.329(2)	39.672(2)						
²⁰⁶ Pb/ ²⁰⁴ Pb _i	17.804	18.330						
²⁰⁷ Pb/ ²⁰⁴ Pb _i	15.481	15.675						
²⁰⁸ Pb/ ²⁰⁴ Pb _i	38.095	39.486						
WHOLE ROCKS								
Sample	GUJ19-3	GUJ19-4	GUJ19-5	GUJ19-6	NAS19-6	GNG-498	KAS19-1	KAS15-3
Latitude (N)	21°21.504'	22°12.421'	22°30.530'	22°38.145'	17°14.396'	17°20.637'	19°41.046'	19°38.327'
Longitude (E)	71°53.958'	68°34.230'	70°45.183'	70°53.108'	77°53.648'	77°35.30'	73°30.793'	73°28.991'
Area	Saurashtra			SE-Deccan			Western Ghats	
SiO ₂ wt%	50.19	48.31	49.61	47.21	49.32	49.32	48.16	50.41
TiO ₂	1.312	1.167	3.121	3.358	3.322	2.94	2.253	3.02
Al ₂ O ₃	15.80	15.68	13.71	13.80	13.84	13.28	15.37	13.44
FeO _t	13.15	11.94	14.31	14.78	12.49	13.96	12.13	14.13

(Continued)

Table 1: Continued.

MnO	0.192	0.205	0.199	0.222	0.170	0.20	0.143	0.21
MgO	4.97	5.91	4.85	5.06	4.80	4.59	5.50	4.51
CaO	8.97	11.84	9.38	10.32	9.62	9.26	10.42	9.01
Na ₂ O	2.97	2.44	2.57	2.41	2.53	2.50	2.68	2.70
K ₂ O	0.78	0.32	0.82	0.62	0.54	0.59	0.76	1.07
P ₂ O ₅	0.190	0.181	0.288	0.328	0.342	0.31	0.219	0.28
Sum	98.51	98.00	98.86	98.10	96.98	96.96	97.63	98.79
LOI %	0.91	1.61	0.90	1.44	2.40	2.52	1.79	0.63
Ni ppm	12	61	62	52	64	51	102	36
Cr	4	99	81	53	84	62	202	28
Sc	29	41	30	34	31	32	29	30
La	24.29	10.36	24.22	25.57	22.77	23.66	17.18	24.80
Ce	48.23	20.18	53.92	56.89	50.91	52.68	37.77	55.03
Pr	5.84	2.46	7.22	7.55	6.86	7.09	5.05	7.40
Nd	23.07	10.47	31.51	32.47	30.27	31.10	22.17	32.50
Sm	5.58	2.74	8.18	8.16	7.75	8.28	6.04	8.26
Eu	1.69	1.18	2.57	2.73	2.53	2.58	2.02	2.64
Gd	6.16	3.43	8.44	8.39	8.29	8.58	6.51	8.37
Tb	1.06	0.64	1.40	1.36	1.35	1.41	1.07	1.34
Dy	6.66	4.18	8.04	7.78	8.12	8.48	6.40	7.78
Ho	1.37	0.90	1.54	1.47	1.57	1.62	1.23	1.49
Er	3.62	2.54	3.92	3.72	3.95	4.13	3.20	3.85
Tm	0.50	0.38	0.52	0.51	0.53	0.56	0.42	0.52
Yb	3.12	2.33	3.09	2.92	3.14	3.32	2.58	3.04
Lu	0.46	0.37	0.45	0.43	0.45	0.48	0.37	0.45
Ba	277.06	121.71	188.23	196.44	169.14	221.73	223.38	237.50
Th	6.15	1.45	4.29	3.45	2.65	3.46	2.09	4.22
Nb	9.40	9.61	15.69	28.14	20.38	13.65	9.48	15.25
Y	33.92	22.93	37.32	36.07	38.25	39.63	30.43	37.16
Hf	4.16	1.63	5.97	5.74	5.44	5.90	4.45	5.95
Ta	0.65	0.59	1.13	1.92	1.37	0.93	0.68	1.09
U	1.16	0.34	0.94	0.79	0.60	0.75	0.40	0.98
Pb	6.71	1.06	3.12	2.33	3.20	3.82	2.74	3.81
Rb	65.42	4.10	13.15	19.85	13.73	16.97	11.79	28.98
Sr	178.97	212.05	270.27	370.20	324.48	265.50	262.27	282.14
Zr	155.92	62.56	218.01	216.18	206.62	223.23	163.54	220.73
WHOLE ROCKS								
Sample	MAT14-2	KHK15-1	19M-4	19P-5	JATH17-3	TM18-3	KH-275	
Latitude (N)	19°00.436'	18°45.728'	17°55.507'	18°16.855'	17°00.970'	21°50.724'	22°19.347'	
Longitude (E)	73°18.534'	73°21.13'	73°37.430'	73°58.843'	75°12.239'	74°27.354'	75°03.163'	
Area	Western Ghats				Northern Deccan			
SiO ₂ wt%	48.95	50.08	49.50	48.21	48.52	50.01	49.43	
TiO ₂	3.26	3.18	3.329	2.650	2.73	3.01	3.20	
Al ₂ O ₃	12.96	13.77	13.22	17.57	14.15	13.57	13.52	
FeO _t	15.32	13.42	15.09	11.36	12.26	12.68	14.18	
MnO	0.22	0.20	0.226	0.147	0.18	0.19	0.22	
MgO	4.24	4.82	5.20	3.36	5.54	5.26	4.41	
CaO	9.11	8.94	9.67	10.48	10.14	9.69	9.38	
Na ₂ O	2.76	2.51	2.68	2.79	2.37	2.52	2.74	
K ₂ O	0.54	1.03	0.59	0.36	0.41	0.88	0.87	
P ₂ O ₅	0.36	0.35	0.337	0.272	0.26	0.38	0.35	
Sum	97.73	98.28	99.84	97.21	96.57	98.19	98.29	
LOI %	1.76	1.18	0.00	2.38	2.73	1.07	1.04	
Ni ppm	64	61	55	78	89	67	45	
Cr	127	101	76	119	156	127	56	
Sc	39	32	36	22	31	31	33	
La	27.62	22.07	22.46	22.07	21.70	29.42	34.21	
Ce	61.02	47.16	50.84	47.16	48.07	65.04	72.88	
Pr	8.11	6.26	6.87	6.26	6.32	8.63	9.29	
Nd	35.62	26.69	30.59	26.69	27.24	36.98	38.85	
Sm	8.83	6.54	7.93	6.54	6.78	8.72	9.18	
Eu	2.80	2.28	2.63	2.28	2.31	2.72	2.84	
Gd	9.20	6.67	8.61	6.67	7.01	8.71	9.08	

(Continued)

Table 1: Continued.

Tb	1.52	1.06	1.42	1.06	1.11	1.40	1.43
Dy	8.72	6.20	8.42	6.20	6.54	8.12	8.57
Ho	1.67	1.18	1.66	1.18	1.24	1.51	1.65
Er	4.20	2.98	4.23	2.98	3.22	3.92	4.28
Tm	0.56	0.40	0.58	0.40	0.43	0.53	0.58
Yb	3.37	2.32	3.52	2.32	2.52	3.11	3.47
Lu	0.50	0.34	0.51	0.34	0.39	0.46	0.51
Ba	250.97	146.93	176.49	146.93	189.07	239.97	288.69
Th	4.62	2.71	2.84	2.71	3.21	3.49	6.31
Nb	17.06	21.08	20.28	21.08	19.27	25.23	29.74
Y	41.09	28.61	40.69	28.61	30.75	37.73	40.71
Hf	6.32	4.63	5.68	4.63	4.65	6.42	6.66
Ta	1.17	1.44	1.39	1.44	1.29	1.68	2.04
U	1.05	0.56	0.67	0.56	0.65	0.77	1.45
Pb	3.81	2.31	2.90	2.31	2.81	3.31	4.90
Rb	28.63	12.04	14.84	12.04	5.62	22.88	31.38
Sr	292.93	403.59	250.21	403.59	329.25	303.64	326.76
Zr	237.09	177.84	216.02	177.84	179.02	252.59	252.92

WHOLE-ROCKS

Sample	SSF20-2	SK20-1	JD20-1
Latitude (N)	20°44.485'	23°25.481'	22°51.279'
Longitude (E)	073°57.043'	78°37.358'	079°46.337'
SiO ₂ wt%	47.52	49.34	48.35
TiO ₂	4.12	2.94	3.32
Al ₂ O ₃	13.14	14.06	13.69
FeO _t	15.65	13.20	13.78
MnO	0.22	0.20	0.221
MgO	4.96	5.53	5.45
CaO	9.94	9.73	10.43
Na ₂ O	2.32	2.74	2.46
K ₂ O	0.61	0.63	0.23
P ₂ O ₅	0.42	0.34	0.359
Sum	98.90	98.71	98.28
LOI %	0.73	1.03	1.45
Ni ppm	97	64	93
Cr	168	84	173
Sc	28	31	35
La	22.34	25.16	19.48
Ce	52.40	55.50	44.75
Pr	7.45	7.38	6.16
Nd	33.78	31.73	28.15
Sm	9.24	7.38	7.38
Eu	2.96	2.40	2.5
Gd	10.07	7.51	8.28
Tb	1.70	1.19	1.4
Dy	9.95	7.02	8.35
Ho	2.02	1.38	1.67
Er	4.99	3.46	4.18
Tm	0.67	0.47	0.57
Yb	4.08	2.72	3.4
Lu	0.62	0.41	0.53
Ba	137.88	220.88	111
Th	2.59	2.99	2.33
Nb	23.05	21.77	19.46
Y	47.82	33.35	40.19
Hf	6.72	5.42	5.47
Ta	1.63	1.47	1.36
U	0.63	0.67	0.55
Pb	2.32	3.20	2.09
Rb	15.55	17.41	4.1
Sr	226.47	331.25	237.2
Zr	253.45	210.70	210

Major elements in wt%, trace elements in ppm. Ni, Cr, Sc, V XRF data, all other trace elements ICP-MS data. FeO_t, total iron; LOI, loss on ignition. Initial isotopic data are recalculated to an age of 66 Ma. Number in brackets for the measured isotopic compositions refer to the 2-sigma analytical uncertainty.

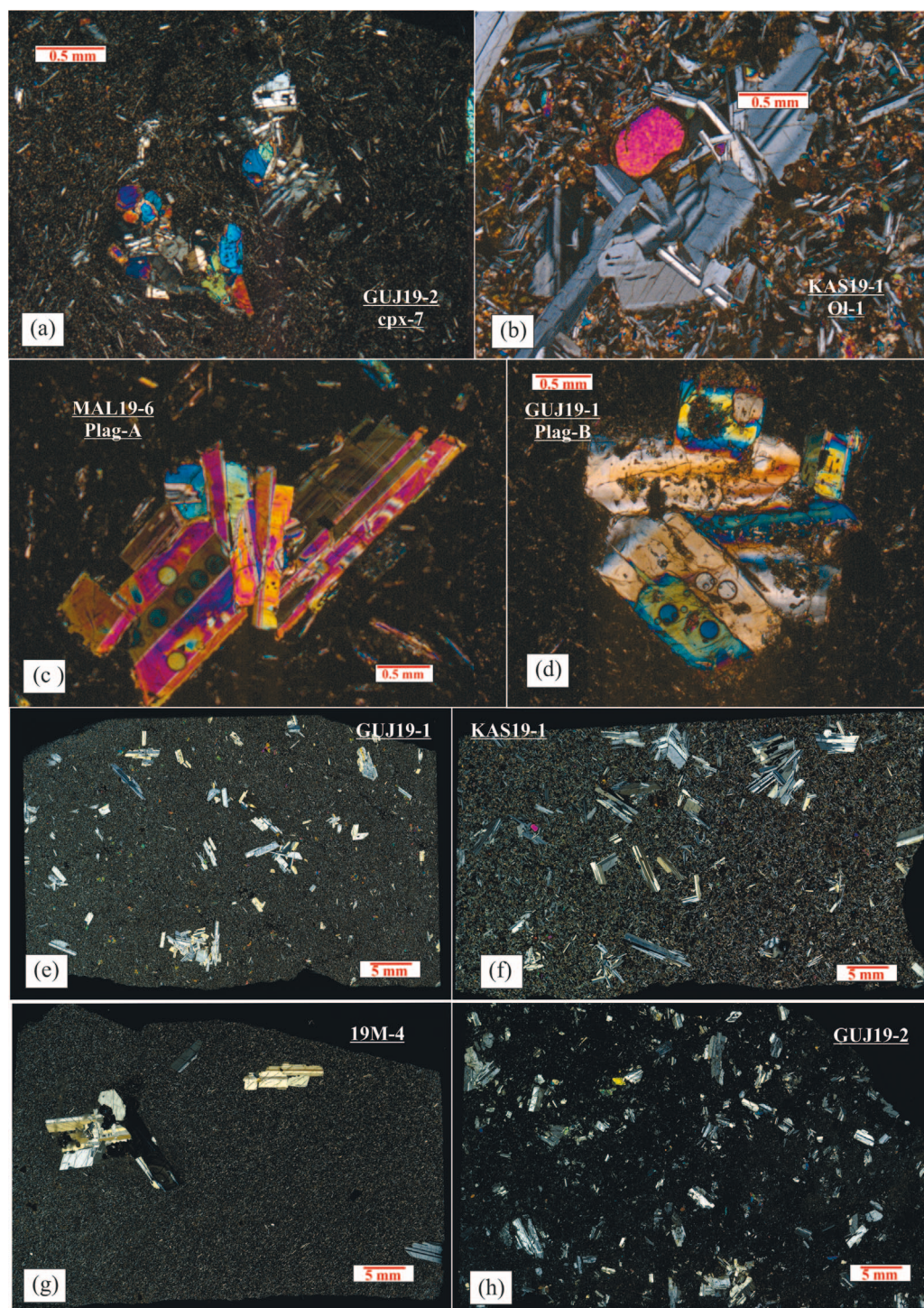


Fig. 3. Cross-polarized thin section images from the studied Deccan basalts. (a) Small clinopyroxene crystal aggregate from GUJ19-2. (b) A relatively large olivine crystal from sample KAS19-1. (c, d) Cross-polarized images of 100 micron thick sections of samples MAL19-6 (Plag-A) and GUJ19-1 (Plag-B); note that small and large circles are due to laser ablations for trace element and Sr-isotope analyses, respectively. (e–h) Cross-polarized scans of entire thin sections of samples GUJ19-1, KAS19-1, 19M-4, and GUJ19-2.

then picking out the plagioclase grains. On seven of the matrix samples and on one whole rock (MAT14-2) we obtained Sr–Nd–Pb isotopic compositions. The whole-rock and matrix compositions are reported in Table 1.

According to the total-alkali silica diagram (Le Bas *et al.*, 1986; Electronic Appendix 1, Fig. S1) the whole rocks are basalts (SiO_2 48.0–51.0 wt%), except GUJ19-2 (SiO_2 54.5 wt%), which is a basaltic andesite. The MgO of all samples is relatively low (6.0–3.5 wt%),

while FeO_t (total iron) and TiO_2 are high (11.5–15.7 wt% and 2.3–4.2 wt%, respectively) except in GUJ19-2 and GUJ19-4 (TiO_2 1.2–1.4 wt%) (Fig. 4). The FeO_t/MgO ratio (>2.0) of all GPBs, including data from previous studies (e.g. Beane *et al.*, 1986) are among the highest of all Deccan rocks (Fig. 4e). Most of the whole rocks have major element compositions, which overlap with evolved Deccan basalts from the Kalsubai or Wai subgroups, which are Fe and Ti-rich, whereas GUJ19-2 resembles the low-Ti composition of

Table 2: Considered plagioclase-melt partition coefficients (Ds) for An_{70–65} plagioclase compositions

Ti ¹	Fe ²	K ³	Rb ³	Mg ³	Sr ³	Ba ³	La ³	Ce ³	Eu ⁴
0.038	0.045	0.24	0.05	0.34	2.1	0.18	0.05	0.045	0.3

¹From Aigner-Torres *et al.* (2007). ²Calculated after Laubier *et al.* (2014). ³Calculated after Sun *et al.* (2017) for An₇₀. ⁴Calculated after Dygert *et al.* (2020). Plagioclase/melt Ds were experimentally obtained in several recent studies (Aigner-Torres *et al.*, 2007; Tepley *et al.*, 2010; Laubier *et al.*, 2014; Sun *et al.*, 2017; Dygert *et al.*, 2020). As the Ds may significantly depend on the plagioclase composition and on crystallization temperature and considering that the cited studies obtained significantly different results for Ds of some elements, we considered partition coefficients appropriate for the studied plagioclase crystals. Sr, Ba, Mg, and K partition coefficients vary with An. Although most experimental studies indicate that Sr and Ba partition coefficients increase at decreasing An, for Mg and K there are contradictory results. For example, Bindeman *et al.* (1998) measured a decreased incompatibility of Mg and K at decreasing An, Sun *et al.* (2017) obtained opposite trends. However, in general all studies agree that for these elements the change in Ds is 20–30% from An₇₈ to An₆₀, i.e. for the range of the plagioclase crystals analyzed here. The Eu and Fe Ds are strongly controlled by the fO₂ and are here calculated according to Dygert *et al.* (2020) and Laubier *et al.*, 2014) for fO₂ in the range QFM to QFM-1 at a temperature of 1150°C. Plagioclase/basalt partition coefficients.

evolved Lonavala subgroup basalts, from the Bushe formation in particular.

Compared with whole-rock samples, matrix samples are enriched in FeO_t (by 1.0–5.4 wt%, mean 1.9 wt% enrichment) and TiO₂ (up to 2.0 wt%, mean 0.5 wt%) and depleted in Al₂O₃ (0.9–3.6 wt%, mean 1.9 wt% depletion), CaO (mean 0.4 wt%) and Na₂O (mean 0.13 wt%). The FeO_t (13.8–17.8 wt%) and TiO₂ (2.5–4.2 wt%) contents of most matrices are among the highest of Deccan samples. The difference between whole-rock and matrix compositions can be used to calculate by mass balance the amount of plagioclase megacrysts, which ranges from 6 to 26 wt% (mean 11 wt%) and is broadly consistent with petrographic observations.

The trace element contents of whole rocks are generally slightly depleted compared with matrix samples, except for Sr, which is enriched in whole-rock samples. Trace element ratios vary relatively little between matrix and whole rocks, except for those ratios involving elements that are compatible (Sr, crystal/melt partition coefficient = $D > 1.0$) or moderately incompatible in plagioclase (Ba, Eu, partition coefficient $D = 0.1$ – 1.0 ; see Table 2 for plagioclase/melt partition coefficients used).

The trace element contents and ratios display a relatively large variation among the studied samples (Figs 4 and 5). For example, La/Yb varies from 4.4 (GUJ19-4) to 11.3 (GUJ19-2), Zr/Nb from 6.5 (GUJ19-4) to 17.3 (KAS19-1), Zr/Y from 2.8 (GUJ19-4) to 6.8 (GUJ19-2), and Nb concentration from 10 (GUJ19-4) to 31 ppm (GUJ19-6). Several of the studied rocks and matrix samples yield higher Nb contents than those of previously analyzed Deccan basalts (Fig. 4f). On the primitive-mantle normalized multi-element diagram, all samples display broadly similar patterns and are enriched in very incompatible elements, compared with moderately incompatible ones. The most depleted sample for almost all elements is GUJ19-4, which shows marked negative anomalies for Rb, K, Ta, Pb, Zr and Hf, and the lowest Nb, FeO_t/MgO and Zr/Y of all GPBs (Figs 4e,f and 5). Its trace element pattern is relatively little enriched in very to moderately incompatible trace elements. This is confirmed also by the Rare Earth Element (REE) pattern (chondrite-normalized values; Fig. 5e), which for GUJ19-4 is moderately enriched in light/middle REE (La/Sm_{CN} 2.3) and nearly flat from middle to heavy REE (Sm/Yb_{CN} 1.3) and shows a positive Eu anomaly ($(Eu_{CN}/(Sm_{CN} \times Gd_{CN})^{0.5} = Eu/Eu^* = 1.18$ for the whole-rock sample and 1.08 for the matrix sample). On the other hand, the sample that is most enriched in highly incompatible elements is GUJ19-2 (La/Yb_{CN} = 7.7; Ba/Y = 11.7), whose trace element pattern is characterized by marked negative anomalies for Ba, Nb-Ta, Sr, while its Pb shows a slightly positive anomaly. The REE pattern of GUJ19-2 is characterized by high La/Sm_{CN} (3.1) combined with by Sm/Yb_{CN} (2.3) that is slightly lower than most other samples (2.3–3.0), and by a clear negative Eu anomaly ($Eu/Eu^* = 0.83$ for the GUJ19-2 whole-rock sample and 0.85 for

the matrix sample). All other samples show similar REE patterns, which are moderately enriched in light vs. middle and heavy REE. However, these samples are clearly different in their high field strength elements and large ion lithophile elements. For example, Nb/La_N and Ce/Pb_N vary from high values in GUJ19-6 (1.1 and 2.2, respectively), to intermediate values for NAS19-6, MAL19-3, MAL19-6, GUJ19-4 and 19M-4 (Nb/La_N 0.85–0.93, Ce/Pb_N 1.4–1.7) to low values for MAL19-4, GUJ19-1, GUJ19-2, GUJ19-5, KAS19-1 (Nb/La_N 0.46–0.65, Ce/Pb_N 0.7–1.5).

Sr-Nd-Pb isotopic data of matrix samples recalculated to an eruption age of 66 Ma show generally correlated variations for the seven analyzed samples (Fig. 6). GUJ19-6 shows the lowest ⁸⁷Sr/⁸⁶Sr_i (0.7048) and highest ¹⁴³Nd/¹⁴⁴Nd_i (0.51278, εNd +4.7). On the enriched end of the Sr-Nd isotopic spectrum lies GUJ19-2, which has very high Sr isotope ratio (0.7157) and low Nd isotopic compositions (εNd_i –13.9). Samples 19M-4, MAL19-3, MAL19-6 plot at relatively low ⁸⁷Sr/⁸⁶Sr_i and high ¹⁴³Nd/¹⁴⁴Nd_i, while GUJ19-1 and KAS19-1 are high in ⁸⁷Sr/⁸⁶Sr_i and low in εNd_i. ²⁰⁶Pb/²⁰⁴Pb_i, ²⁰⁷Pb/²⁰⁴Pb_i, ²⁰⁸Pb/²⁰⁴Pb_i isotopic compositions are correlated, with 19 M-4 plotting at the depleted end and GUJ19-2 being the most enriched sample. The correlation of Pb isotopic ratios with ⁸⁷Sr/⁸⁶Sr_i or εNd_i is in general poor. In particular, GUJ19-6, the most depleted sample in Sr-Nd isotopic space is slightly higher in ²⁰⁶Pb/²⁰⁴Pb_i than samples 19 M-4 and KAS19-1 and just slightly lower than GUJ19-1. Sr-Nd isotopic compositions are generally well correlated with incompatible element ratios such as Nb/La or Ce/Pb (not shown), while these correlations are very scattered for Pb isotopic compositions.

Mineral compositions

Plagioclase

Plagioclase megacrysts from 14 samples were analyzed by EMP. Among these, a total of 33 megacrysts from 11 samples were analyzed for detailed core-rim crystal traverses (Fig. 8; Electronic Appendix 2, Table S2, S3). The EMP traverses are 1.9–0.25 mm long, with a pacing between analysis spots of around 10 μm in most crystals and c. 20 μm in a few. Plagioclase major element compositions are reported in the Electronic Appendix 2, Supplementary Table S3.

Figure 7 shows the measured compositional ranges for all samples analyzed including traverses and spot analyses of cores (samples GUJ19-1, GUJ19-2, GUJ19-5, MAL19-4, KAS15-3, KHK15-1, 19M4, and 19P5) and the traverses. All samples except GUJ19-4 overlap the averaged core compositions of megacrysts from six GPBs in the Kalsubai subgroup (Hooper *et al.*, 1988). Anorthite contents (An) range from 53 to 82 (mol%); most plagioclase crystals are labradorite (An_{60–70}), while bytownite is also present in six samples. In five samples (GUJ19-2, GUJ19-4, GUJ19-5, MAL19-4, 19M-4) the plagioclase crystals are nearly unzoned, i.e. with less than 5 mol% An variations for crystals showing

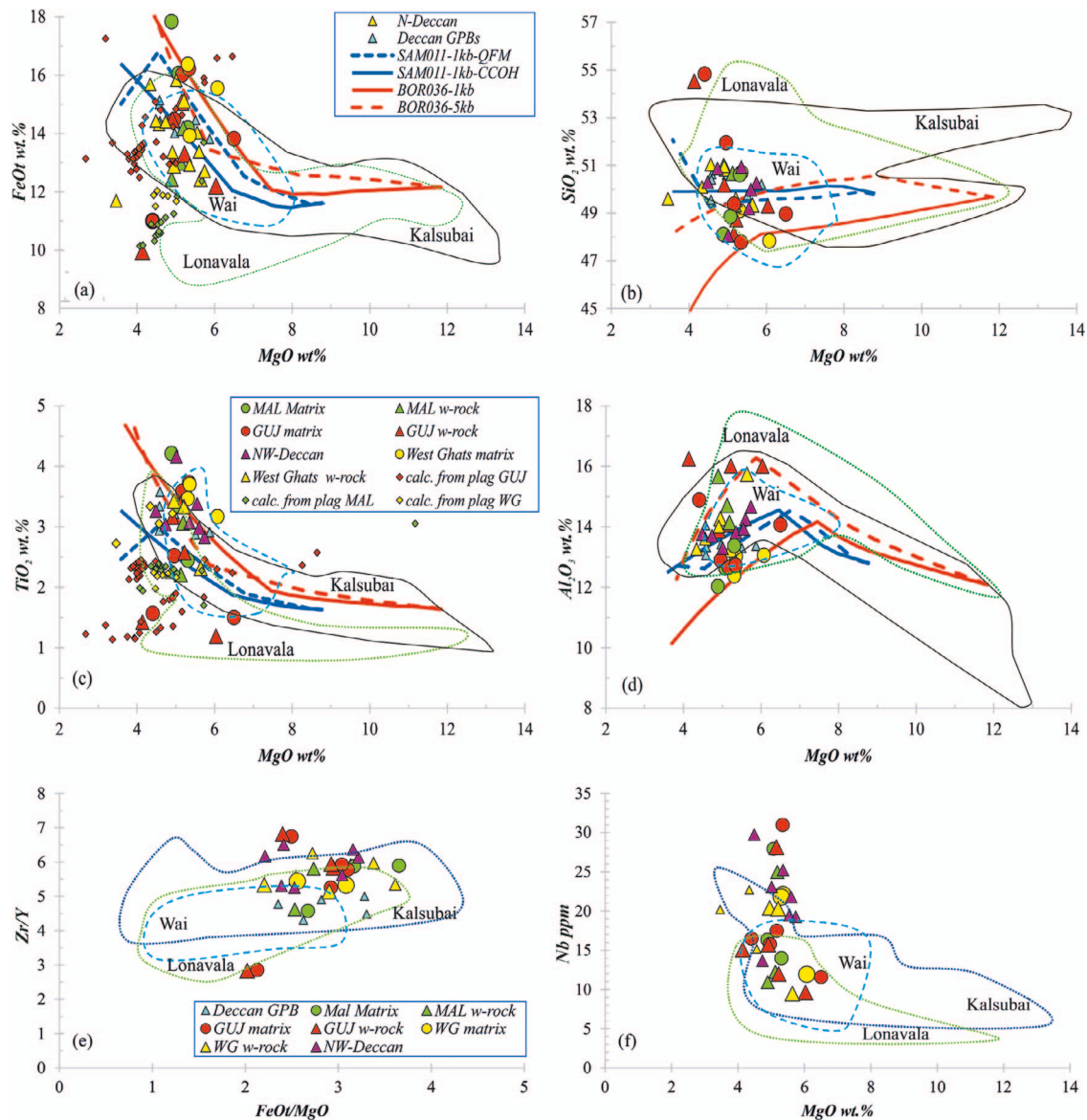


Fig. 4. Major and trace element variations of the studied Deccan samples and of previously analyzed basalts (GEOROC database) of the Kalsubai (lower Fms., black dotted contour), Lonavala (middle Fms., green dotted contour), and Wai subgroup (upper Fms., blue dashed contour). Presently studied samples include whole rocks (large triangles) and matrix (large circles) from Gujarat-Saurashtra (GUJ samples, red symbols), the Malwa Plateau (MAL samples, green symbols), the WG (KAS19-1, 19 M-4 and other samples listed in Table 1; yellow symbols), and the north-western Deccan (purple triangles). Also plotted are previously analyzed GPB samples (blue triangles) from Beane *et al.* (1986). Rhyolite-MELTS liquid lines of descent calculated starting from SAM011 and BOR036 (BOR036) at 0.1 and 0.5 GPa (SAM011 only at 0.1 GPa), f_{O_2} at QFM or COH buffer (SAM011) or unbuffered (BOR036), all run anhydrous. Also reported are compositions calculated to be in equilibrium with plagioclase megacrysts (LA-ICP-MS Mg, Fe, Ti data; Table 3; Ds are reported in Table 2).

optical evidence of oscillatory zoning (e.g. crystals from 19 M-4, Fig. 2e). However, in six samples (GUJ19-1, GUJ19-2, GUJ19-6, MAL19-3, MAL19-6, KAS19-1; Fig. 8) all analyzed crystals show a significant zoning in terms of An. This zoning is generally normal (i.e. rimward decrease of An; e.g. GUJ19-1, GUJ19-6, MAL19-6, KAS19-1; Fig. 8a, I, m, q) and occasionally reverse (e.g. GUJ19-2; Fig. 8e). An decreases of 5–10 mol% near the rim are seen in about half of the analyzed crystals, whereas An remains near-constant in the others. In a few samples, the An contents vary either near the core (MAL19-6, Plag-3) or near the rim (GUJ19-1, plag-1) or throughout the crystal (GUJ19-4, Plag-1; Electronic Appendix 2, Table S2). In five samples, at least one plagioclase crystal shows a resorbed inner core with >5 mol% An higher than the adjacent regions.

Minor element (K, Mg, Fe; Fig. 8) variations tend to be consistent with An variations. K₂O displays core-rim variations that are roughly anticorrelated to those of An, e.g. low K₂O corresponds to high An. High-An resorbed cores tend to be depleted in K₂O compared with the rest of the crystal. Plagioclase crystals of some samples (GUJ19-4, MAL19-3, 19M-4, and NAS19-6; Electronic Appendix 2, Table S2) are depleted in K₂O compared with crystals with similar An in other samples. In contrast, sample GUJ19-2 shows the highest K₂O in plagioclase for a given An. The MgO contents in plagioclase range between about 0.05 and 0.25 wt% and are not correlated with An. Within crystal variations are generally negligible, i.e. the MgO profiles are nearly flat. Although the MgO contents are low and thus close to detection limit (c. 0.05 for EMP analysis), we could expect a detectable change at

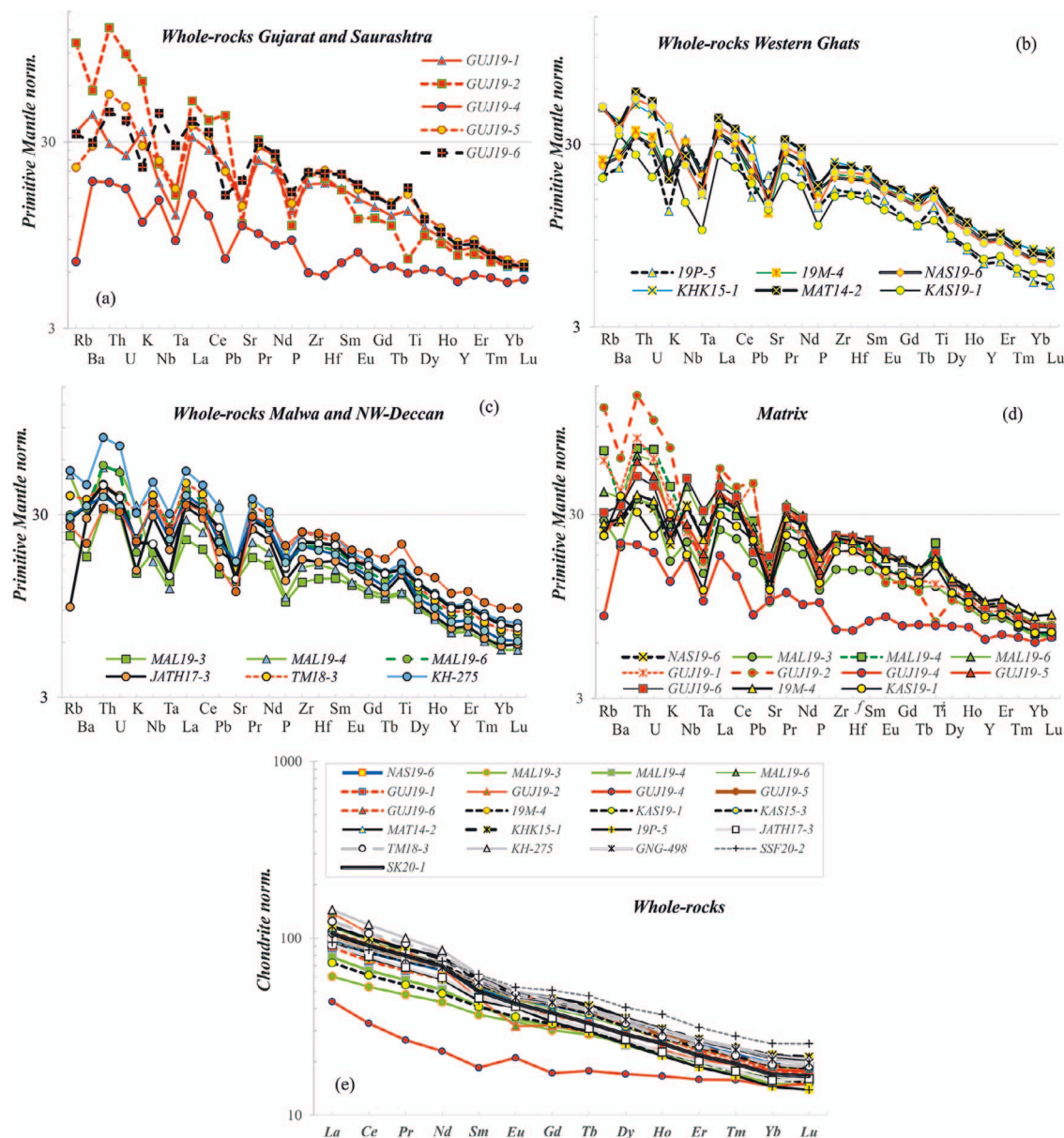


Fig. 5. (a–d) Primitive mantle-normalized (McDonough & Sun, 1995) trace element contents of analyzed whole rocks (a–c) and matrix samples (d). (e) Chondrite-normalized (McDonough & Sun, 1995) REE pattern of analyzed whole rocks. Matrix compositions are not plotted for REE as they are quite similar to those of whole rocks, except for Eu, which is on average c. 5% depleted in matrix vs whole-rock composition.

least when An varies by more than 10 mol%. FeO_t contents range from about 0.40 to 0.90 wt% for all crystals and are generally not correlated with An. However, FeO_t contents increase significantly (by 0.10–0.30 wt%, i.e. by about 30–100% relative) in the last 50–100 μm near the crystal rims in 13/33 of the analyzed crystals from most of the samples analyzed in detail (8/11).

Trace elements were collected in five samples and nine plagioclase crystals by LA-ICP-MS (Fig. 9; Electronic Appendix 2, Supplementary Table S4) along core-rim traverses close to those analyzed by EMP. Images of analyzed crystals with laser spots are shown in Fig. 3c,d and in the Electronic Appendix 1, Supplementary Figs S2, S3. Due to the c. 40- μm -diameter analytical spot size, we could not analyze the outermost rims as in EMP analyses. The spacing between consecutive spots is not constant as we tried to avoid altered or fractured areas. In two sieved-textured plagioclase crystals, a few analysis spots involved parts of the melt or matrix replacing the dissolved plagioclase, and were discarded.

In general, trace elements that yielded values close to detection limit were also discarded. We focused on the concentrations of Sr, Ba, Ce, La, Eu, Li, Y, and Rb (the latter three elements not shown in Fig. 9). Minor elements like K, Mg, Fe, and Ti were also analyzed by LA-ICP-MS and yielded results that are generally consistent with those obtained by EMP.

The trace element contents in plagioclase megacrysts are broadly correlated with their whole-rock and matrix compositions. However, the plagioclase crystals of GUJ19-1 are relatively poor in Ba and Sr even though the matrix and whole rock of this sample are relatively rich in these elements.

The trace element contents generally show small core-rim variations and small differences between crystals from the same rock. However, sample GUJ19-1 again shows an anomalous behavior; its plagioclase crystals have cores with Ti close to 250–300 ppm and K c. 1200 ppm, while Ti increases to c. 380 ppm and K to c. 1700 ppm in one crystal's outer half. The Mg content of GUJ19-

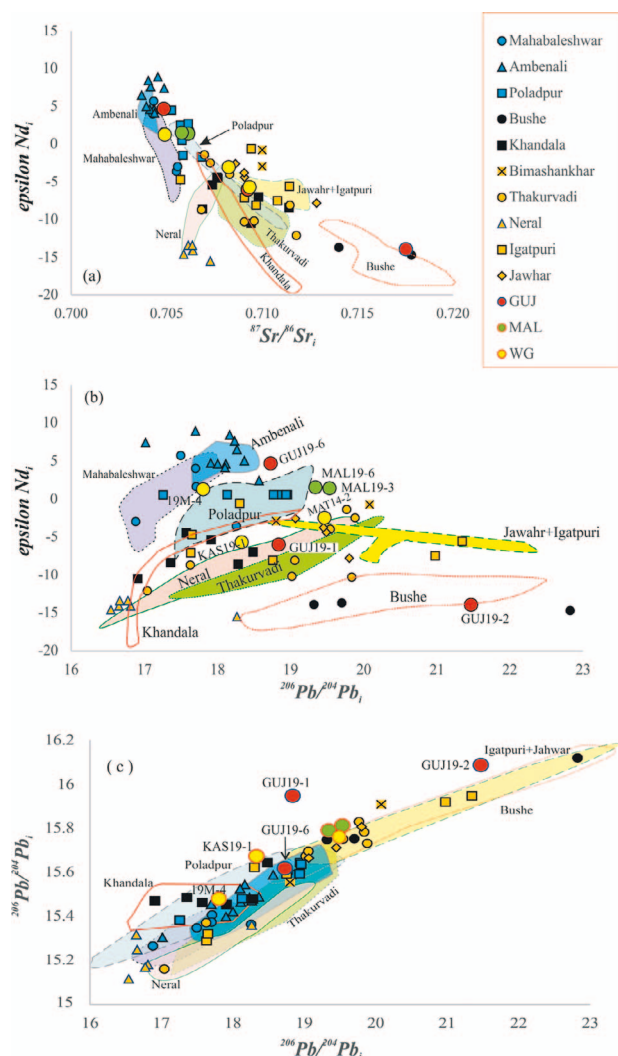


Fig. 6. Initial (at 66 Ma) Sr-Nd-Pb isotopic compositions of the studied rocks (larger symbols with label) and of Deccan basalts from the WG (smaller symbols, data from Basu et al., 2020a). GUJ samples are GUJ19-1, GUJ19-2 (most radiogenic Sr-Pb isotopic values), and GUJ19-6 (less radiogenic values); MAL samples are MAL19-3 and MAL19-6; WG samples are KAS19-1 (higher Sr-Pb) and 19 M-4 (lower Sr-Pb). Fields plotted in diagrams are from Peng et al. (1994, 2014), Vanderkluyzen et al. (2011), and Basu et al. (2020a).

1 Plag-A shows a marked decrease from core to rim, which is paralleled by a drop in An from c. 76 to 65. Plagioclase data for this same sample show significant differences in terms of Ba, La, Ce, Eu, and Mg between the two analyzed crystals.

$^{87}\text{Sr}/^{86}\text{Sr}$ isotopic compositions in plagioclase were analyzed for five rock samples on a total of nine plagioclase crystals (Fig. 10; Table 3). Each of the 51 analyzed spots has a diameter of 154 μm ; therefore, two analyses of a sieve-textured core (in GUJ19-1) are a mixture of the plagioclase with its dissolved, glassy parts. Due to the relatively large spot size, the outermost rim could not be analyzed (Fig. 3c,d; Electronic Appendix 1, Supplementary Figs S2 and S3).

In general, the initial isotopic compositions (recalculated to an age of 66 Ma) of the five samples are correlated with the isotopic composition of the matrix samples (Fig. 10f), i.e. the $^{87}\text{Sr}/^{86}\text{Sr}_i$ of plagioclase from GUJ19-6 and 19 M-4 are relatively low (c. 0.7043–0.7050), those from MAL19-6 are intermediate (c. 0.7056) and those from KAS19-1 and GUJ19-1 are high (0.7092–0.7107).

In detail, however, all analyzed plagioclase spots from GUJ19-6 are significantly lower than the matrix composition (considering 2 sigma uncertainty on the LA-ICP-MS and matrix analyses). Likewise, most plagioclase spots of MAL19-6 have $^{87}\text{Sr}/^{86}\text{Sr}_i$ lower than the respective matrix while most of GUJ19-1 have higher $^{87}\text{Sr}/^{86}\text{Sr}_i$ than the respective matrix. Core-rim or inter-crystal variations of $^{87}\text{Sr}/^{86}\text{Sr}_i$ are negligible in GUJ19-6 and in KAS19-1, but are significant in GUJ19-1, MAL19-6, and 19M-4. In particular, GUJ19-1 shows significantly different $^{87}\text{Sr}/^{86}\text{Sr}_i$ in the two analyzed crystals. In its Plag-B, the two apparently inner analysis spots have lower $^{87}\text{Sr}/^{86}\text{Sr}_i$ than the two outer spots. However, the portion of the crystal that yielded the highest $^{87}\text{Sr}/^{86}\text{Sr}_i$ seems to be part of a plagioclase core region, which was partially resorbed and then included in a plagioclase aggregate. Therefore, for this crystal the early crystallized parts have higher $^{87}\text{Sr}/^{86}\text{Sr}_i$ than the later crystallized ones. Sample 19 M-4 shows a significant core-rim increase of $^{87}\text{Sr}/^{86}\text{Sr}_i$, while the opposite is apparent for Plag-A of GUJ19-1, which has a rim with relatively low $^{87}\text{Sr}/^{86}\text{Sr}_i$ indistinguishable from the matrix composition. Plag-A of MAL19-6 shows also a rimward decrease of $^{87}\text{Sr}/^{86}\text{Sr}_i$; however, for this plagioclase crystal the rim isotopic composition is significantly lower than that of the matrix.

Clinopyroxene, olivine, and Fe-Ti oxides

Clinopyroxene and olivine were analyzed in a few samples as these crystals are rare and generally small (<400 μm). Clinopyroxene and olivine compositions are reported in the Electronic Appendix 2, Supplementary Table S5 and Table S6. Clinopyroxene was measured in 10 samples where it occurs as monocrystals (e.g. single crystals surrounded by the groundmass), glomerocrystic clots, or as inclusions in plagioclase megacrysts (cf., Figs 3a and 2f, respectively).

Clinopyroxenes are augite to pigeonite (Fig. 11). The low-Ca clinopyroxene is present in half of the samples and usually occurs as microcrysts or groundmass crystals. In some samples (e.g. GUJ19-1, KAS15-3) clinopyroxene inclusions in plagioclase megacrysts tend to be enriched in Fe compared with the other analyzed crystals, i.e. these two groups of clinopyroxenes are not in equilibrium.

The augitic crystals have quite variable compositions (Fig. 12) with Mg# varying from 82 to 40 (Mg# = 100 (Mg/(Mg + Fe²⁺)), where Fe²⁺ is calculated based on stoichiometry; Papke et al., 1974). The highest Mg# is observed in augites from samples GUJ19-2 (Mg# c. 80), while the lowest is those of augite inclusions in large plagioclase from MAL19-4 (Mg# c. 50) and in phenocrysts or microcrysts from GUJ19-5 (Mg# c. 40–50). The variable Mg# of the augites is not correlated with that of the host rocks, which all yield similar Mg# (41–45). In particular, GUJ19-2 augites are Mg-rich, even if this rock is fairly evolved. It should also be noted that some samples have relatively homogeneous clinopyroxene compositions (e.g. GUJ19-2; Fig. 12a, b), while others have strongly variable compositions (Fig. 12a–d). For example, samples 19 M-4, 19P-5, and GUJ19-1 have clinopyroxenes with significantly different TiO₂ contents (e.g. in 19 M-4 TiO₂ varies from c. 1.0 to c. 2.5 wt%, at similar Mg#). A significant variability of augite compositions has been also observed between phenocrysts and augite included in plagioclase megacrysts in some samples (e.g. in 19P-5, MAL19-4, and GUJ19-1).

Most augite macro- or micro-crysts (maximum axis: >100 and <100 μm , respectively) analyzed in detailed core-rim traverses (Fig. 12) show a clear drop of Mg# at the rim of the crystals in the contact with the groundmass (this is particularly strong in GUJ19-1). Only augites from GUJ19-2 are essentially unzoned in Mg#. In general, TiO₂ is correlated with that of the matrix compositions,

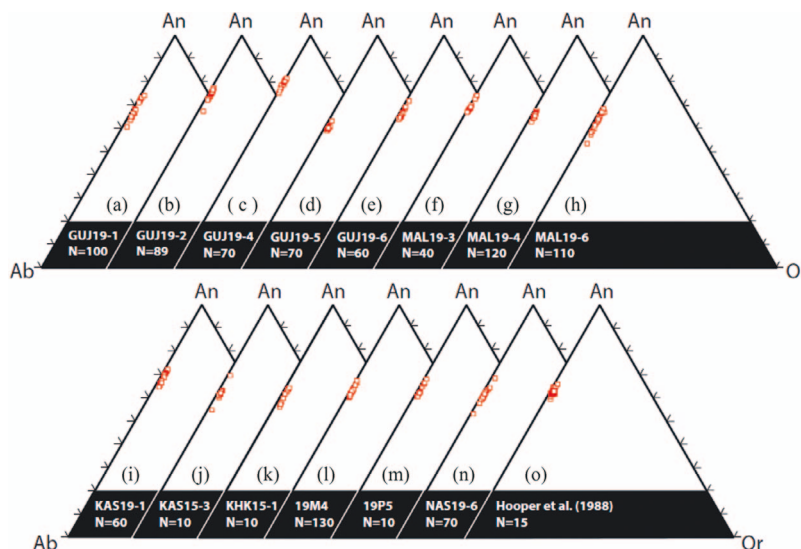


Fig. 7. Plagioclase triangular classification diagrams. An, anorthite; Ab, albite; Or, orthoclase. All components are in mol%. (o): giant plagioclase compositions from the WG (Hooper *et al.*, 1988) are plotted for comparison.

being low in augites from GJ19-2 (0.5 wt%) and in most of GJ19-1 (c. 0.6–1.0 wt%), while it is high in GJ19-6 (0.9–1.4 wt%) and MAL19-6 (0.9–1.9 wt%). One augite crystal from GJ19-1 is zoned in TiO_2 , with the central portion showing relatively high TiO_2 (c. 1.1 wt%). Similarly, a few microcrysts from GJ19-1, included in plagioclase aggregates show high TiO_2 up to 1.4 wt% (Fig. 12e). The two MAL19-4 augites included in plagioclase megacrysts show markedly different compositions, for example in terms of Mg# (c. 50 vs c. 70) and TiO_2 (c. 0.8 vs c. 1.2 wt% for the two crystals).

Olivine crystals or their pseudomorphs larger than 100 μm are present in about half the samples. Fresh olivine was detected and analyzed in four samples (MAL19-4, MAL19-6, KAS19-1, GJ19-1; Fig. 12f). In general, the forsterite content (Fo, mol%) varies from 74 to 51 in all analyzed samples, except in MAL19-4 where it can be as low as 25. Of the analyzed olivine compositions, only the phenocryst core of KAS19-1 is in equilibrium with its host-rock assuming a mineral/melt K_D for (Fe/Mg) of 0.30 ± 0.03 (Roeder & Emslie, 1970). The relatively large olivine from KAS19-1 shows a constant core composition (c. Fo₇₄) and then a clear decrease to Fo₅₈ in the outermost c. 50 μm . Olivine phenocrysts from MAL19-6 and MAL19-4 show Fo compositions of c. 61–51 and 71–59 and are significantly depleted in Mg/Fe compared with their whole rocks (Fig. 12; Table S6). On the contrary, the olivine included in large plagioclase crystals from MAL19-4 are slightly enriched in Mg/Fe compared with equilibrium conditions with the matrix.

Most analyzed Fe-Ti oxides are magnetite (Tables S7). Rare ilmenite has been found both as inclusions in plagioclase megacrysts and as microphenocrysts in MAL19-4, MAL19-5, and GJ19-3.

EBSD data

EBSD data were obtained to determine if the optical deformation microstructures observed under the petrographic microscope are due to crystal plasticity, as suggested by lobate boundaries separating parts with different optical extinction. A plagioclase clot from sample KAS19-1 (Plag-4) was selected as it shows clear undulatory extinction (Fig. 2h). Chemical traverses across the plagioclase grains constituting this aggregate show near-constant major element compositions, with An contents (c. 60–65 mol%)

comparable to those of other plagioclase crystals from this same rock (Fig. 8q).

The EBSD ‘Texture Components’ (TC) maps of Fig. 13 highlight the existence of internal microstructures within the plagioclase clot. Growth twins, with mostly straight boundaries and disorientations between neighbor grains $>170^\circ$ (Fig. 13 d), coexist along with lobate grain boundaries. This is consistent with deformation and recrystallization microstructures, traced by high angle grain boundaries (disorientation between neighbor grains $>30^\circ$; see Fig. 13d) and by sub-grain boundaries (disorientation $<10^\circ$), as well as by deformation twins, whose twin boundaries terminate with a cusped along twin-, grain-, and sub-grain boundaries (definition of subgrain boundaries and grain boundaries as in Passchier & Trouw, 2005).

A chemical map (Fig. 14) was acquired by EDS-SEM analysis of the portion of deformed plagioclase of KAS19-1 where the above-mentioned fracture evolved. The map shows that the fractures between plagioclase grains are filled by Mg-Fe-rich and Na-Al-poor material, which most likely is infiltrated basaltic magma.

DISCUSSION

Comparison with the WG lava flow compositions

The basalt compositions reported here are compared with those from the WG based on their geochemical composition. The comparison is mainly based on the isotopic compositions (Fig. 6), on trace element ratios, and on the discriminant functions (Fig. 15a, b) as defined by Mahoney *et al.* (2000). The latter have been widely used to assign Deccan basalt samples to WG lava flow formations, which show only subtle geochemical differences (e.g. Vanderkluyzen *et al.*, 2011 and references therein).

Several samples including KAS19-1, MAT14-2, and 19M-4 were obtained from the WG, i.e. their stratigraphic position is well known. KAS19-1 was sampled on top of the Jawhar formation (corresponding to the so-called Thalghat GPB; Beane *et al.*, 1986). Its trace element ratios and contents as well as its Sr-Nd isotopic composition are consistent with lower Kalsubai affinity, but in particular its Pb isotopic composition overlaps Igatpuri rather than Jawhar basalt compositions (age-corrected data from Basu *et al.*, 2020a). Interestingly, the Sr-Nd-Pb isotopic data of KAS19-1 are

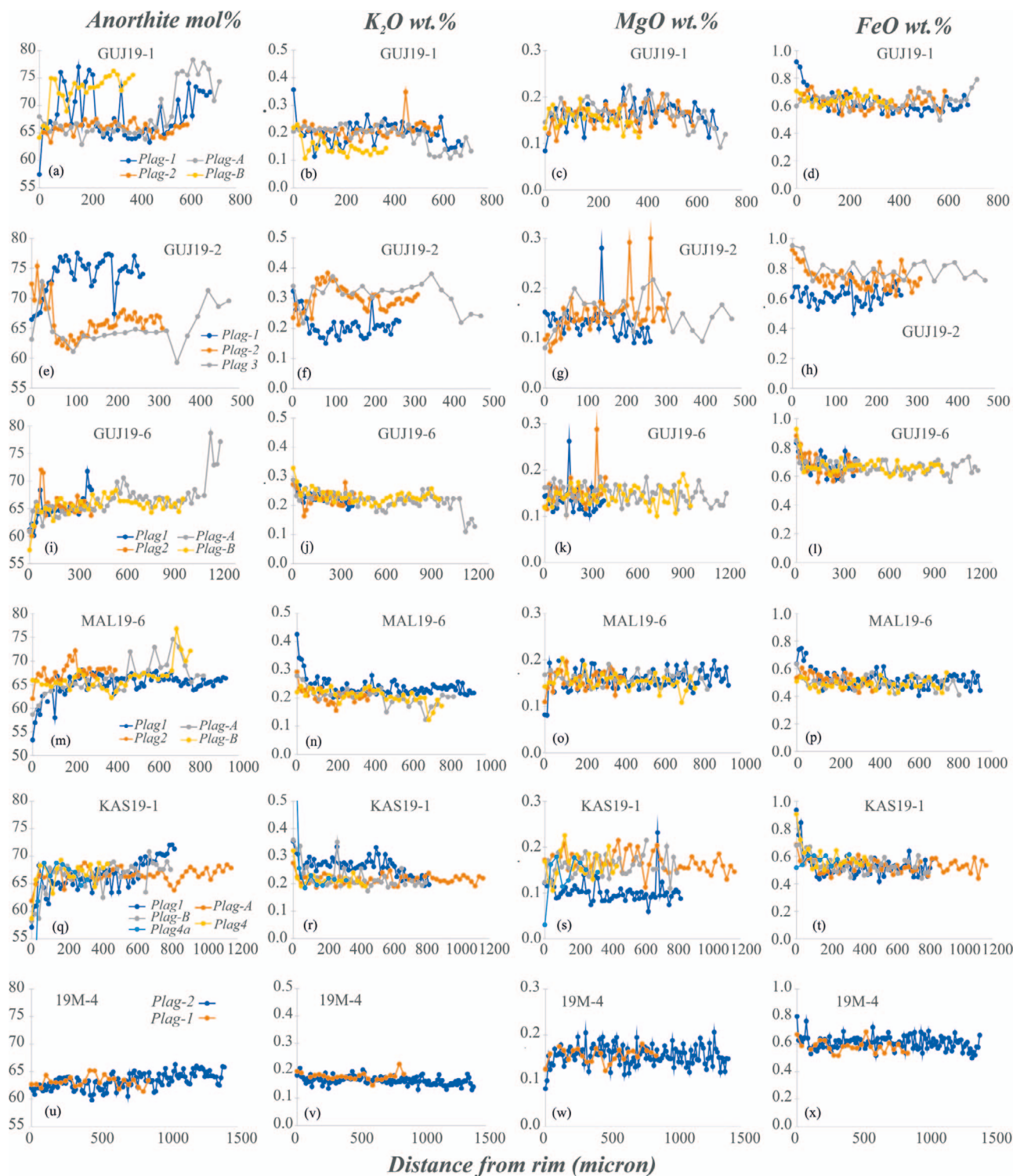


Fig. 8. Major and minor element core-rim variations of analyzed plagioclase, EMP data. Each point on the traverses represents an analysis point. Distance is in microns, Anorthite is defined as mol%. Occasionally, single analysis points may have been deleted when these were affected by altered zones or by micro-inclusions of other mineral species. For each sample 2–4 crystals were analyzed (shown by different symbols). Plag 4 and 4a from KAS19-1 were also analyzed by EBSD. The complete data set is reported in the Electronic Appendix 2, Tables S3.

significantly different (generally less enriched) than the isotopic data published in Peng et al. (1994) and Borges et al. (2014) for the same Thalghat GPB, implying that this GPB flow was formed from slightly distinct and not completely mixed magma batches. The Tunnel-5 sample MAT14-2 (GPB flow between the Neral and Thakurvadi fms.) has isotopic and trace element ratios similar to

those published by Beane et al. (1986) and Peng et al. (1994) for the same GPB. Its isotopic compositions overlap those of Thakurvadi (isotopic data from Basu et al., 2020a), but not of Neral basalts. Sample 19M-4 comes from high in the WG near the base of the Mahabaleshwar formation (Rajgad GPB; Shandilya et al., 2021) and has trace element and isotopic composition similar to those of

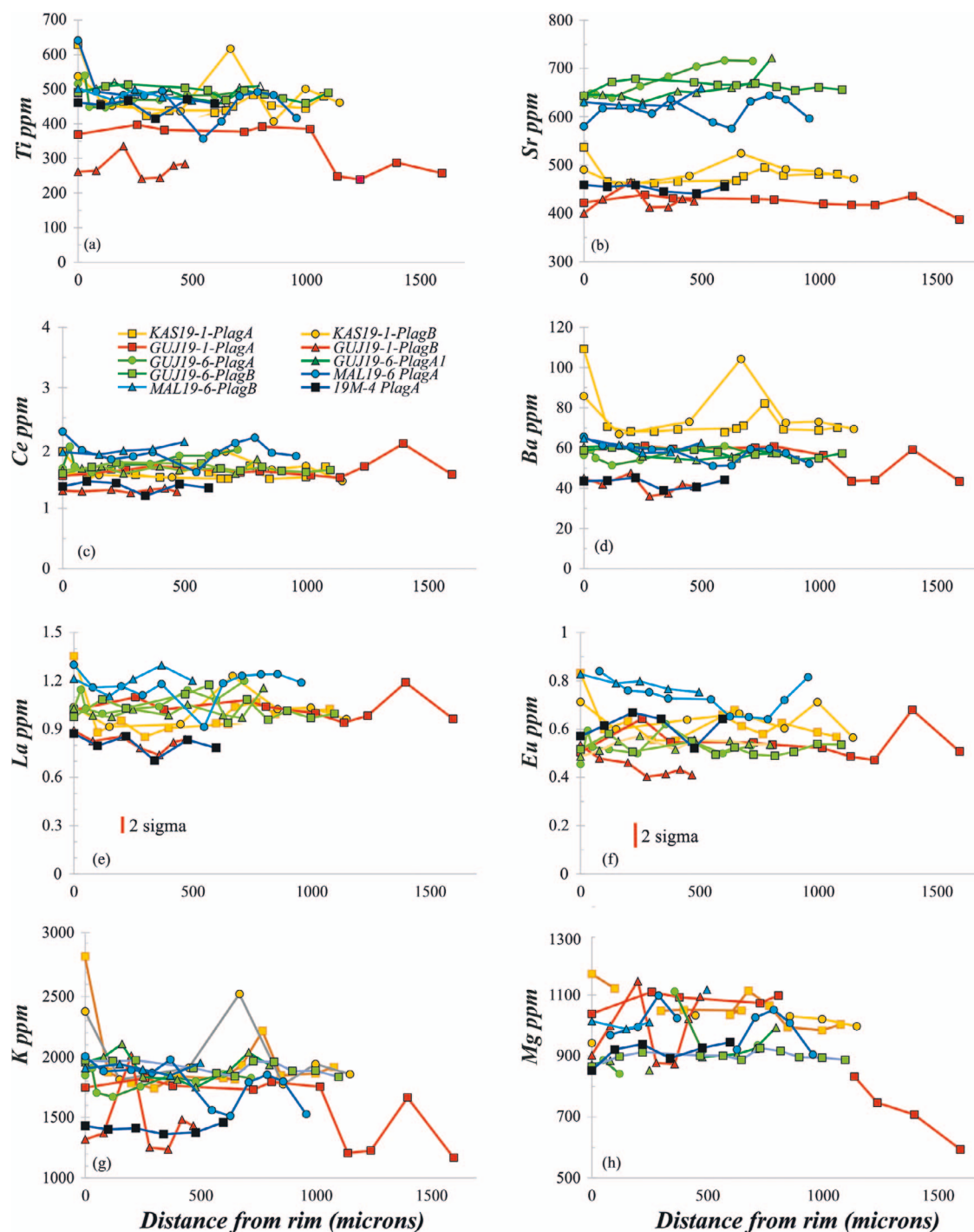


Fig. 9. Core-rim minor and trace element variations of plagioclase megacrysts, LA-ICP-MS data. Analytical uncertainties (2 sigma) are shown for La and Eu; for the other elements the uncertainty is smaller than the data symbol. Data are reported in the Electronic Appendix 2, Table S4. The Electronic Appendix 1, Supplementary Figures S2 and S3 show the analyzed plagioclase crystals and analysis spots.

Mahabaleshwar basalts, partially overlapping the Ambenali field (Figs 6 and 15). Notably, the composition of 19M-4 is quite different in terms of trace element ratios from that of sample 19P-5, which has been assigned to the same GPB flow field sampled at another locality (Shandilya *et al.*, 2021).

Sample GUJ19-2 shows clear similarities with the Bushe chemical-type in terms of major and trace element compositions (Figs. 4, 5, 15). However, compared to the WG Bushe flows, GUJ19-2 shows slight differences, for example in Sr-Nd-Pb isotopic composition (Fig. 6) and slightly more enriched trace element

ratios (e.g. Ba/Y; Fig. 15) as in other Saurashtra Bushe-like basalts (Melluso *et al.*, 1995; Cucciniello *et al.*, 2020).

Sample GUJ19-6 has major and trace element composition (Fig. 4, 5, 15) and Sr-Nd-Pb isotopic composition (Fig. 6), which overlap with the Ambenali and Mahabaleshwar basalts (Basu *et al.*, 2020a) and the northern Deccan basalts (Peng & Mahoney, 1995; Peng *et al.*, 1998). However, GUJ19-6 is enriched in U and Th ($U/La_N = 1.0$) and depleted in Zr/Nb (6.5) compared with most WG Ambenali and Mahabaleshwar basalts ($U/La_N < 1.0$; $Zr/Nb > 8$), while its Ba/Y is similar to those of Mahabaleshwar

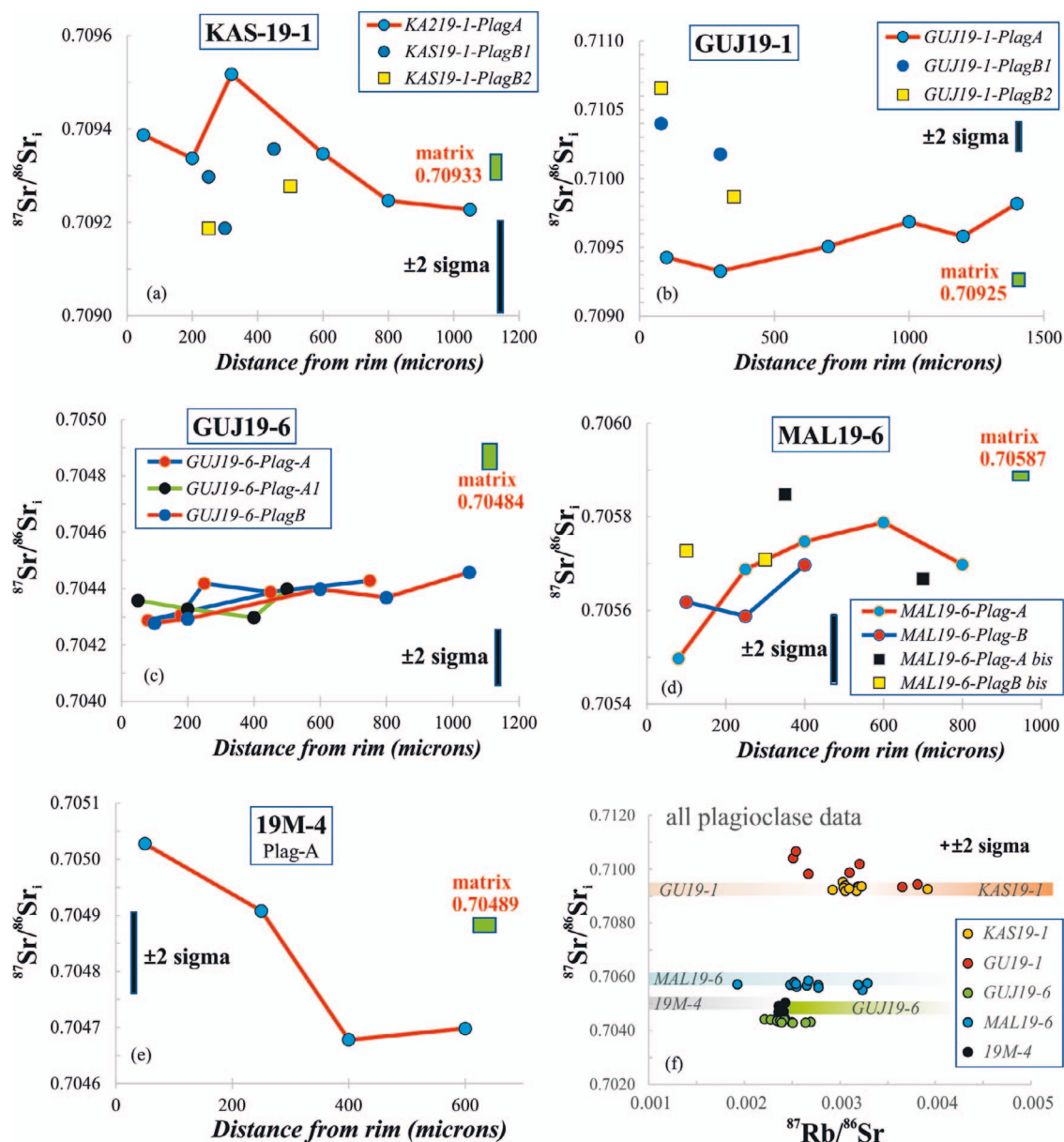


Fig. 10. (a–e) Initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic compositions, recalculated to 66 Ma, of the plagioclase crystals analyzed by LA-ICP-MS (Table 4). Lines indicate successive analysis points obtained along a core-rim traverse. Other points are from other crystals of the same sample. The 2-sigma bars are average uncertainty values for each sample, but are quite consistent for all analyses (c. 0.0015–0.0020). Green box shows composition of matrix samples (bulk analysis), for which errors are less than 0.00002 (i.e. c. 10 times smaller than for laser spot data). Laser analysis spots have a diameter of 154 microns. The Electronic Appendix Figs S2 and S3 show the analyzed plagioclase crystals and analysis spots. (f) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{87}\text{Rb}/^{86}\text{Sr}$ of all analyzed plagioclase samples; bars indicate $^{87}\text{Sr}/^{86}\text{Sr}$ of matrix (however, consider that $^{87}\text{Rb}/^{86}\text{Sr}$ of matrices is out of scale, being in the range 0.16–0.22).

but higher than for Ambenali basalts (Fig. 15). While it does not perfectly match with either Mahabaleshwar or Ambenali basalts, we can confidently compare the composition of GUJ19-6 to those of the basalts from the upper parts of the Wai subgroup in general. A similar conclusion can be reached for GUJ19-4 and NAS19-6, despite lacking isotopic compositions for these samples, which hinders a precise comparison with WG formations. GUJ19-4 is characterized by a whole-rock and matrix REE pattern resembling that of an enriched MORB, with nearly flat intermediate to heavy REE chondrite-normalized values (Fig. 5). Such a pattern is not common in WG Deccan basalts. In the case of NAS19-6, sampled at the southeastern margin of the central Deccan plateau, an attribution to the Wai subgroup and probably the Mahabaleshwar

Fm. is consistent with its composition and with previous geochemical studies for this area (Jay & Widdowson, 2008; Wilson Mantilla *et al.*, 2022). However, the $^{40}\text{Ar}/^{39}\text{Ar}$ age recently obtained for NAS19-6 (65.976 ± 0.065 Ma; Wilson Mantilla *et al.*, 2022) is substantially older than those of $^{40}\text{Ar}/^{39}\text{Ar}$ dated Mahabaleshwar basalts from the WG (65.521 ± 0.065 to 65.422 ± 0.103 Ma; Renne *et al.*, 2015; Sprain *et al.*, 2019).

GUJ19-1 and GUJ19-5 are similar to basalts from the Kalsubai subgroup in terms of trace element ratios (e.g. Zr/Nb, Nb/La), discriminant functions and isotopic compositions (available for GUJ19-1 only; Fig. 4, 5, 15). The best fit for GUJ19-1 is obtained with basalts from the Thakurvadi Fm., as it does not overlap the Jawhar-Igatpuri field nor the Neral basalt field, e.g. in Fig. 6 (isotopic compositions) and in Fig. 15.

Table 3: Rb-Sr isotopic compositions of the analyzed plagioclase megacrysts from samples KAS19-1, GUJ19-1, GUJ19-6, MAL19-6, 19M-4

Sample	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}_i$
KAS19-1					
KAS19-1-plgA-1	0.002924	3.60E-05	0.70923	0.00020	0.709227
KAS19-1-plgA-2	0.003918	8.30E-05	0.70925	0.00020	0.709246
KAS19-1-plgA-3	0.003187	3.70E-05	0.70935	0.00019	0.709347
KAS19-1-plgA-4	0.003030	3.70E-05	0.70952	0.00020	0.709517
KAS19-1-plgA-5	0.003200	4.30E-05	0.70934	0.00022	0.709337
KAS19-1-plgA-6	0.003055	3.70E-05	0.70939	0.00018	0.709387
KAS19-1-plgB-1	0.003173	9.40E-05	0.70919	0.00020	0.709187
KAS19-1-plgB-2	0.003226	5.30E-05	0.70936	0.00020	0.709357
KAS19-1-plgB-3	0.003040	1.30E-04	0.70930	0.00016	0.709297
KAS19-1-plgB-4	0.003057	4.00E-05	0.70919	0.00023	0.709187
KAS19-1-plgB-5	0.003096	4.20E-05	0.70928	0.00017	0.709277
GUJ19-1					
GUJ19-1-plAgA-1	0.002670	1.10E-04	0.70982	0.00021	0.709817
GUJ19-1-plAgA-2	0.043400	6.70E-03	0.70962	0.00022	0.709579
GUJ19-1-plAgA-3	0.015540	7.10E-04	0.70970	0.00020	0.709685
GUJ19-1-plAgA-4	0.005311	7.00E-05	0.70951	0.00019	0.709505
GUJ19-1-plAgA-5	0.003652	3.80E-05	0.70933	0.00020	0.709327
GUJ19-1-plAgA-6	0.003811	3.70E-05	0.70943	0.00017	0.709426
GUJ19-1-plg-B-1	0.003205	6.80E-05	0.71018	0.00022	0.710177
GUJ19-1-plg-B-2	0.003100	1.80E-04	0.70987	0.00020	0.709867
GUJ19-1-plg-B-3	0.002511	4.80E-05	0.71040	0.00021	0.710398
GUJ19-1-plg-B-4	0.002540	2.10E-04	0.71066	0.00020	0.710658
GUJ19-6					
GUJ19-6-plg-A-2	0.002333	2.80E-05	0.70443	0.00014	0.704428
GUJ19-6-plg-A-3	0.002420	2.30E-05	0.70439	0.00014	0.704388
GUJ19-6-plg-A-4	0.002211	2.60E-05	0.70442	0.00013	0.704418
GUJ19-6-plg-A-5	0.002694	2.60E-05	0.70431	0.00013	0.704307
GUJ19-6-plg-A-6	0.002640	2.40E-05	0.70429	0.00012	0.704288
GUJ19-6-plg-A-1	0.002275	2.90E-05	0.70440	0.00016	0.704398
GUJ19-6-plg-A-7	0.002497	2.90E-05	0.70430	0.00012	0.704298
GUJ19-6-plg-A-8	0.002365	2.20E-05	0.70433	0.00014	0.704328
GUJ19-6-plg-A-9	0.002341	2.80E-05	0.70436	0.00012	0.704358
GUJ19-6-plg-B-1	0.002424	7.50E-05	0.70446	0.00014	0.704458
GUJ19-6-plg-B-2	0.002374	2.40E-05	0.70437	0.00013	0.704368
GUJ19-6-plg-B-3	0.002417	2.70E-05	0.70440	0.00014	0.704398
GUJ19-6-plg-B-4	0.002391	2.30E-05	0.70430	0.00010	0.704293
GUJ19-6-plg-B-5	0.002505	2.10E-05	0.70428	0.00012	0.704278
MAL19-6					
MAL19-6-plg-A-1	0.002480	2.70E-05	0.70570	0.00016	0.705698
MAL19-6-plg-A-2	0.002522	2.80E-05	0.70579	0.00014	0.705788
MAL19-6-plg-A-3	0.003288	6.30E-05	0.70575	0.00014	0.705747
MAL19-6-plg-A-4	0.002773	2.20E-05	0.70569	0.00013	0.705687
MAL19-6-plg-A-5	0.003235	3.50E-05	0.70550	0.00014	0.705497
MAL19-6-plg-A-6	0.002654	3.30E-05	0.70567	0.00012	0.705668
MAL19-6-plg-A-7	0.002671	3.50E-05	0.70585	0.00011	0.705847
MAL19-6-plag-B-1	0.003190	3.00E-04	0.70570	0.00014	0.705697
MAL19-6-plag-B-2	0.002774	2.20E-05	0.70559	0.00015	0.705587
MAL19-6-plag-B-3	0.002548	2.20E-05	0.70562	0.00014	0.705618
MAL19-6-plag-B-1	0.001927	3.00E-05	0.70571	0.00015	0.705708
MAL19-6-plag-B-2	0.002541	2.40E-05	0.70573	0.00014	0.705728
19M-4					
19M-4-plAg-A-1	0.002412	5.60E-05	0.70470	0.00018	0.704698
19M-4-plAg-A-2	0.002359	4.10E-05	0.70468	0.00015	0.704678
19M-4-plAg-A-3	0.002360	3.90E-05	0.70491	0.00016	0.704908
19M-4-plAg-A-4	0.002429	3.80E-05	0.70503	0.00017	0.705028

2-sigma analytical uncertainties are reported. Initial isotopic data ($^{87}\text{Sr}/^{86}\text{Sr}_i$) are recalculated to 66 Ma.

The composition of samples from the Malwa Plateau MAL19-3, MAL19-4, and MAL19-6 are difficult to assign to a specific WG chemical type. While Sr-Nd isotopic compositions of MAL19-3 and MAL19-6 are similar to those of the Poladpur formation, their Pb isotopic ratios are slightly higher than those of Wai basalts. Trace element compositions of these Malwa samples resemble those of

Wai (for MAL19-3 and MAL19-6) or Lonavala (Khandala) basalts (for MAL19-4). In detail, MAL19-6 has low Zr/Nb and Ba/Y, which is compatible with Ambenali basalts (Fig. 15a) and it overlaps that formation also on the discriminant function diagram (Fig. 15b). Nonetheless, the isotopic compositions of MAL19-6 are significantly more enriched than those of Ambenali basalts.

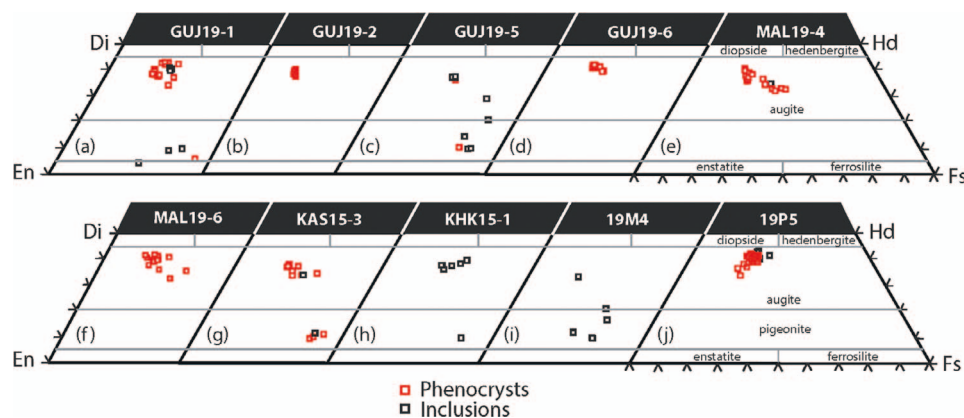


Fig. 11. Clinopyroxene triangular classification diagrams. En, enstatite; Di, diopside; Hd, hedenbergite; Fs, ferrosilite. All components are in mol%.

A general conclusion that arises is that the compositions of the lava samples from the northern Deccan (Malwa, Saurashtra) studied herein only partially overlap those of WG lava flow formations. Subtle differences between northern vs. southern (e.g. WG) Deccan suggest a slight North–South change in mantle and crustal components. We also note that geochemical similarity does not necessarily imply a synchronous emplacement, which needs to be confirmed by geochronological data. For example, sample NAS19-6 shares geochemical characteristics of the Mahabaleshwar Fm., but has been shown (Wilson Mantilla *et al.*, 2022) to be significantly older than this formation where it is defined in the WG (e.g. Sprain *et al.*, 2019).

Magma differentiation

A general observation is that our samples are quite evolved, i.e. low in MgO (5.6–4.1 wt%) with only GUJ19-4 having MgO higher than 6.0 wt%. Such evolved compositions are not rare in the Deccan, and several formations are dominated by basalts with MgO in the range 6–4 wt%. Most of our samples are also rich in FeO_T (12–15 wt%; except GUJ19-2), FeO_T/MgO (2.0–5.9), and TiO₂ (2.2–3.5 wt%, except GUJ19-2 and GUJ19-4), as other evolved Deccan basalts (Beane *et al.*, 1986; Basu *et al.*, 2020a). However, our basalt whole-rock and, in particular, matrix compositions plot among the most Ti- and Fe-rich Deccan basalts. The Ti-enriched composition is further highlighted by multi-element diagrams (Fig. 5) in which both whole-rock and matrix (not shown) samples show a positive Ti anomaly for most samples (except GUJ19-2 and GUJ19-4), which is not common among most other Deccan basalts.

*f*O₂–*T*–*P* conditions and mineralogical constraints

Ilmenite-magnetite pairs were found only in MAL19-4 and MAL19-6. In the former sample, the oxides were re-equilibrated at sub-solidus conditions as confirmed by reflected-light microscope observation, while in MAL19-6 they seem to be in mutual equilibrium (considering the Mg/Mn ratio of magnetite and ilmenite; Table S7, Electronic Appendix 2; Bacon & Hirschmann, 1988) and yield a temperature of 1030–1050°C and log *f*O₂ of –10.8 to –10.9 corresponding to about 0.4 log units below the QFM buffer (using Sauerzapf *et al.*, 2008).

The oxidation state can be further constrained by the minor and trace element content of the plagioclase crystals. Dygert *et al.* (2020) and Laubier *et al.* (2014) investigated the control of *f*O₂ on the Eu and Fe plagioclase/basalt partition coefficients,

while Lundgaard & Tegner (2004) highlighted the importance of melt SiO₂ in controlling the *D* of Fe³⁺ and Fe²⁺. In order to be in equilibrium with the matrix, the relatively low Fe of the plagioclase cores would require Fe to be quite incompatible, a condition that is attained at low *f*O₂ (Fe³⁺ is less incompatible than Fe²⁺; Laubier *et al.*, 2014). On the contrary, at moderate *f*O₂ close to the QFM buffer, the melt in equilibrium with the plagioclase cores would be depleted in Fe compared with the matrix samples, but would still be similar to typical evolved Deccan basalts. The increasing Fe at the plagioclase rims would either suggest crystallization at progressively more oxidizing conditions (>QFM) or crystallization from a progressively more Fe-rich magma (e.g. Ruprecht & Wörner, 2007). On the other hand, the Eu partition coefficient increases at decreasing *f*O₂ (Eu²⁺ is more compatible than Eu³⁺; Dygert *et al.*, 2020). Therefore, Eu contents of the analyzed plagioclase would be in equilibrium with most Deccan magmas for a *D* calculated for QFM or QFM-1 conditions, while for QFM-2 or QFM+1 the calculated equilibrium melt would be different (lower and higher in Eu, respectively) from any Deccan basalt in terms of its Eu concentration (Electronic Appendix 1, Supplementary Fig. S4). In summary, the most likely interpretation of Fe and Eu contents, combined with the available oxide mineral compositions suggest that the analyzed plagioclase crystallized from a melt at QFM or QFM-1.

Clinopyroxene and olivine compositions can be used to calculate crystallization pressure and temperature (Neave & Putirka, 2017). The clinopyroxene-equilibrium melt geo-thermobarometer yields uncertainties of about 0.14 GPa and about 50°C (Neave & Putirka, 2017). For clinopyroxene phenocrysts, i.e. those crystals being in contact and in textural and chemical equilibrium with the matrix composition, calculated pressures are lower than 0.4 GPa (Fig. 16). The highest values, c. 0.3 GPa, are yielded by GUJ19-6, while GUJ19-1, GUJ19-2, and MAL19-6 yield pressures generally lower than 0.2 GPa. Clinopyroxene included in large plagioclase crystals gives <0.3 GPa in sample MAL19-4, and <0.2 GPa for sample MAL19-6 (calculated from clinopyroxene composition only, i.e. not considering an equilibrium magma). Calculated temperatures are about 1160–1130°C in sample for GUJ19-6, about 1120–1100°C in GUJ19-2 and about 1140–1120°C for the other samples. Olivine temperatures (Putirka, 2008, equation 22) are about 1160°C in sample KAS19-1, while for the other samples olivine and matrix are not in equilibrium hindering application of the geothermometer. In conclusion, the analyzed samples dominantly evolved at low pressure (0.1–0.3 GPa) and moderate temperature (1170–1100°C).

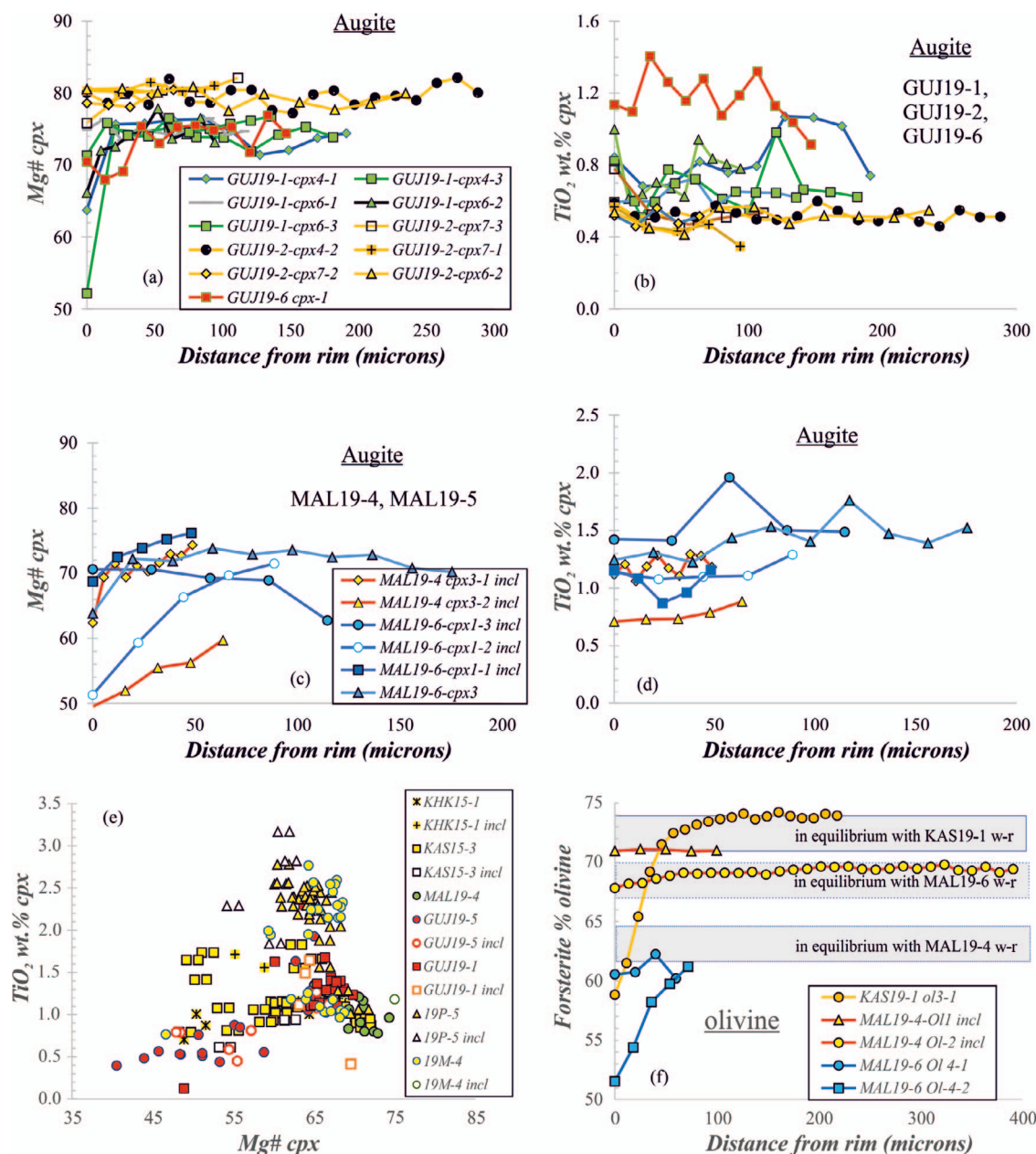


Fig. 12. Clinopyroxene and olivine compositions of the analyzed samples. (a–d) Mg# (= 100 (Mg/(Mg + Fe²⁺)), where Fe²⁺ is calculated according to Papike *et al.* (1974) and TiO₂ wt% core-rim traverses of augites from samples GJ19-1, GJ19-2, GJ19-6 (a, b) and MAL19-4, MAL19-6 (c, d). All analyzed GJ and MAL19-6 cpx3 clinopyroxenes are phenocrysts, while the remaining MAL clinopyroxenes are inclusions in plagioclase megacrysts. Augite data plotted in (a–d) and olivine data were obtained at the University of Milano. (e) Mg# vs TiO₂ wt% for core and rim of augitic clinopyroxenes analyzed at the USGS. Incl = augite inclusion in plagioclase megacrysts. (f) Olivine core-rim traverses, forsterite contents (Fo = mol% Mg/(Mg + Fe); Milano University analyses). Olivine from KAS19-1 is part of a plagioclase-dominated crystal aggregate, but the olivine rim is in contact with the groundmass; olivine from MAL19-4 are inclusions in plagioclase megacrysts, while those from MAL19-6 are small phenocrysts. The rectangles show compositions in equilibrium with the whole rocks of KAS19-1, MAL19-6, and MAL19-4 assuming a mineral/melt K_D for (Fe/Mg) of 0.30 ± 0.03 (Roeder & Emslie, 1970).

Closed-system differentiation and MELTS modeling

We tested the possible evolution of magma compositions with Rhyolite-MELTS (Gualda *et al.*, 2012) considering equilibrium crystallization, low to intermediate pressure (0.1 and 0.5 GPa), dry or moderately hydrous conditions (H₂O = 0.5 wt%), and low to moderate oxygen fugacity (f_{O_2} close to the COH and QFM buffers). These parameters were chosen based on the experimental and mineralogical studies on Deccan basalts (Sano *et al.*, 2001; Gangopadhyay *et al.*, 2003; Melluso & Sethna, 2011) and on results discussed in the previous sections.

Starting from the whole-rock compositions, Rhyolite-MELTS equilibrium crystallization modeling indicates that for hydrous magmas and pressure higher than 0.1 GPa clinopyroxene or olivine crystallize along with plagioclase in about equal amounts, i.e. the calculated compositions fail to reproduce the observed mineralogy of the rocks. For low-pressure (0.1 GPa) and anhydrous conditions, the match between calculated and observed compositions improves. This is shown in Fig. 17 for the whole-rock composition of GJ19-4. Rhyolite-MELTS modeling has been done starting from little evolved Deccan basalts with

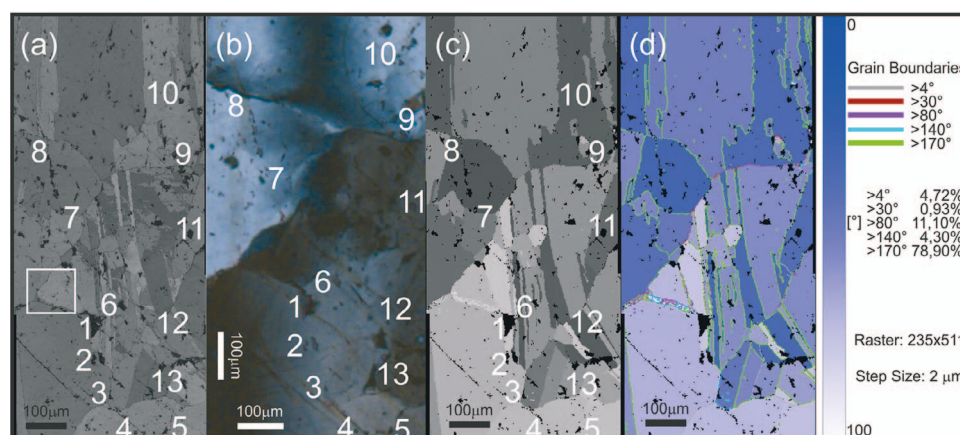


Fig. 13. EBSD maps and cross-polarized light image for sample KAS19-1. The white rectangle in Fig. 2h is the area ($470 \times 1022 \mu\text{m}$) mapped with EBSD ($2 \mu\text{m}$ step size). (a) EBSD 'Band Contrast' map (BC-map). (b) Cross-polarized light (XPL) image. (c) EBSD 'Texture Components' map (TC-map) highlighting the microstructures of the plagioclase clots shown in Fig. 2h. (d) EBSD 'Texture Components' map defined by blue to white color shades reflecting the crystallographic disorientation of each pixel of the map within a 0° to 100° range from a chosen reference orientation (expressed in Euler angles). In (a), (b), and (c), numbered marker points are shown for a better comparison between the images, since a one-to-one comparison of XPL images and EBSD maps is not straightforward. XPL images are indeed influenced by the interference of light crossing a $30\text{-}\mu\text{m}$ -thick polished thin section, whereas EBSD maps gain their information just from the uppermost few nanometers of the same rockslide. An important impingement microstructure is preserved in the central part of the analyzed area (from No. 9 to No. 7) and in the lower part (from points 3 to 13), where twinned plagioclase crystals impinge with an un-twinned one and subgrain boundaries radiate (Fig. 13d). A noteworthy microstructure occurs in the lower left, where an about $16\text{-}\mu\text{m}$ -large bright zone extends from No. 1 toward the left border in the TC map (Fig. 13c). This area is characterized by a complex configuration of tangled boundaries (Fig. 13d).

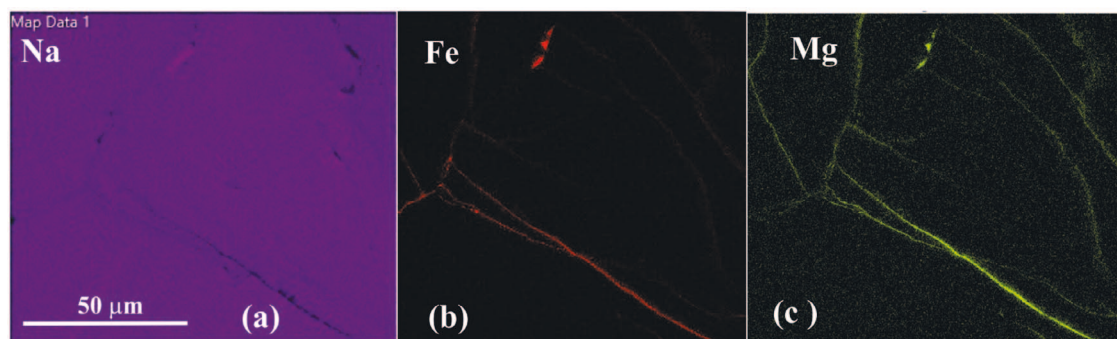


Fig. 14. Na, Fe, Mg chemical maps of a c. 100×100 micron area from the deformed plagioclase grains in KAS19-1 (see Fig. 13 for location of the map). The dark colors in (a), bright red in (b) and bright green-yellow in (c) mark low Na and high Fe-Mg areas along fractures, which are probably filled by matrix of basaltic composition.

about 8 and 12 wt% MgO in order to check if these would represent suitable parental magmas for the observed whole-rock and matrix compositions. The considered parental magmas are samples SAM011 and BOR036 from Beane *et al.* (1986), which respectively belong to the Igatpuri and Thakurvadi Formations (Kalsubai subgroup). The modeling was run at 0.1 and 0.5 GPa, 0, 0.5, 1.0 wt% H_2O , and with QFM- or COH-buffered or unbuffered f_{O_2} . Starting from SAM011 the best fit with the observed matrix compositions (except for GUJ19-2 and GUJ19-4) is obtained for low P, QFM and anhydrous conditions. High-pressure (0.5 GPa) conditions yielded less satisfactory results. Starting from BOR036 (c. 12 wt% MgO), matrix compositions are reached both for low pressure (0.1 and 0.5 GPa), at QFM or unbuffered f_{O_2} , and anhydrous conditions. Starting from the BOR036 magma composition, after about 58% fractionation the evolved magmas reach up to 16–18 wt% FeO, similar to the matrix compositions. Such calculated evolved melts would be in equilibrium with plagioclase (An_{61}) similar to most observed rim compositions. Fractionated minerals are olivine (8 wt%), clinopyroxene (30 wt%) and plagioclase (19 wt%, average An_{68}).

An important conclusion that can be drawn from MELTS modeling is that only dry and low-pressure conditions are compatible with the observed compositions (Fig. 18). Hydrous conditions and high pressure would delay plagioclase saturation, favoring instead mafic minerals, and would slightly reduce the density of the calculated melts. Considering SAM011 and BOR036 as starting melt compositions, at 0.1 GPa the density of evolved melts similar to the matrix compositions ranges between 2.64 and 2.61 g/cm^3 for hydrous conditions, while it would range from 2.76 to 2.79 g/cm^3 for dry conditions (density values calculated with Rhyolite-MELTS). At the same low pressure, the density of a plagioclase with An_{75-60} composition ranges from 2.67 to 2.64 g/cm^3 . It should be considered that melt densities calculated with Rhyolite-MELTS are about 2% higher than those obtained in a recent experimental study (Krättli & Schmidt, 2021). Accounting for this correction, plagioclase is clearly buoyant in dry, low pressure, Fe-rich ($\text{FeO} > 15 \text{ wt\%}$) melts (melt minus plagioclase densities are $>0.10 \text{ g/cm}^3$). Considering that the melt density is largely controlled by the melt Fe content, it is interesting to notice that very Fe-rich samples (e.g. MAL19-4, KAS19-1) are also very rich

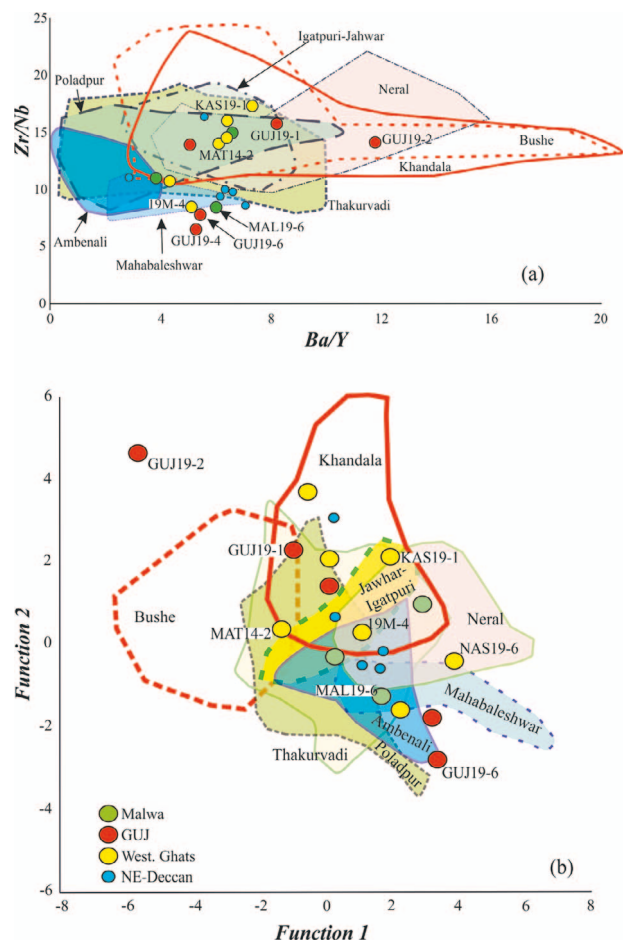


Fig. 15. Ba/Y vs Zr/Nb (a) and discriminant function diagram of the analyzed basaltic whole rocks. The fields for WG Deccan formations are from Vanderkluyzen *et al.* (2011) and references therein. Discriminant functions are defined as in Mahoney *et al.* (2000): Function 1 = $-0.48 \text{ SiO}_2 - 0.155 \text{ Al}_2\text{O}_3 + 1.289 \text{ TiO}_2 + 0.157 \text{ CaO} + 0.097 \text{ K}_2\text{O} + 1.397 \text{ P}_2\text{O}_5 - 0.048 \text{ Ni} + 0.462 \text{ Ba} + 0.301 \text{ Sr} - 1.707 \text{ Zr} - 0.744 \text{ Y} - 0.002 \text{ Nb}$; Function 2 = $0.145 \text{ SiO}_2 + 0.135 \text{ Al}_2\text{O}_3 - 0.141 \text{ TiO}_2 - 0.251 \text{ CaO} - 0.286 \text{ K}_2\text{O} + 0.439 \text{ P}_2\text{O}_5 + 0.058 \text{ Ni} + 0.953 \text{ Ba} - 0.247 \text{ Sr} + 0.815 \text{ Zr} + 0.039 \text{ Y} - 1.215 \text{ Nb}$.

in plagioclase megacrysts (up to c. 15–20%). On the other hand, the quite evolved and relatively low-Fe sample GUJ19-2 yields a relatively low calculated density (c. 2.69 g/cm³ with Rhyolite-MELTS, or c. 2.64 g/cm³ considering Krättili & Schmidt, 2021) close to that of plagioclase. Although this sample is rich in plagioclase crystals (c. 9 vol%), all its plagioclase crystals are relatively small (<1 mm).

Deformed plagioclase megacrysts from crystal mush

Plagioclase deformation

Plagioclase deformation features include high angle lobate grain boundaries (Fig. 13) that point to impingement of different plagioclase crystals into one another. The microstructures shown in Fig. 13 suggest that impingement was accommodated not only by crystal plasticity (formation of subgrain and high angle grain boundaries), but also by fracture formation. Such fracturing must have been localized along pre-existing twin boundaries and became progressively dissected into fragments, rotating up to disorientations of 80–90° (red boundaries). Fractures are probably filled by basaltic melt as suggested by the chemical map (Fig. 14).

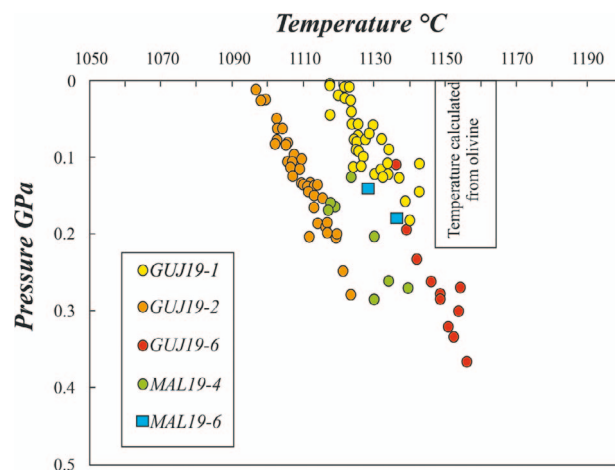


Fig. 16. Clinopyroxene crystallization pressure (GPa) and temperature (°C) calculated after Neave & Putirka (2017). Plotted data refer to clinopyroxene composition in chemical equilibrium with the matrix composition considered as representative of the equilibrium melt (Neave & Putirka, 2017). Note that uncertainties in temperature ($\pm 28^\circ\text{C}$) and pressure (c. ± 0.1 GPa; Neave & Putirka, 2017) are quite large. Plotted data refer to clinopyroxene composition in chemical equilibrium with the matrix composition considered as representative of the equilibrium melt (criteria for equilibrium as defined in Neave & Putirka, 2017). The vertical rectangle shows the temperature calculated from the olivine composition of KAS19-1 (Figs 3b and 11f), which is close to chemical equilibrium with its whole rock and matrix (temperature calculated after Putirka, 2008, equation 22).

The disorientation angle distribution between neighbor pairs (Fig. 19) calculated for the EBSD map shows that the data are clustered and depart from a random distribution. The largest cluster forms disorientation angles between 170° and 180° and is related to twin boundaries of Albite-, Carlsbad-, and Albite-Carlsbad twins in the analyzed plagioclase clots (see also Electronic Appendix 1, Figs S5, S6, S7). A second cluster with low disorientation angles (<30°) relates to a deformation process characterized by recovery and recrystallization during impingement (Passchier & Trouw, 2005). The cluster defined by disorientations between 80° and 90° probably refers to the opening and sealing of the above-mentioned fracture (Fig. 13), which also happened during plagioclase impingement.

A major implication of the EBSD data (Figs 13 and 19) is that impingement occurred at high temperature causing slip along the <100> (001) system with simultaneous fracturing. Fracture formation during ductile deformation has also been shown in high strain rate torsion experiments by Rybacki *et al.* (2008, 2010), who deformed anorthite aggregates at 1100°C and 400 MPa. Cavities nucleate mostly at grain triple junctions and along grain boundaries and coalesce to micro-fissures, micro-fractures and shear bands under such deformation conditions (e.g. Spiess *et al.*, 2012). These dynamically evolving microstructural sites are associated with pressure drops that cause melt infiltration from the surroundings. This would explain healing of the fracture in the impinged plagioclase agglomerate and the presence of basaltic matrix between the deformed plagioclase grains (Fig. 14). Notably, other samples contain plagioclase clots, which show textures similar to the analyzed Plag-4 clots from KAS19-1, for example, Plag-2 from GUJ19-6 (Fig. 2d) as well as crystal from GUJ19-1 and GUJ19-4 (not shown). The plagioclase clots from GUJ19-2 (Fig. 2i) also shows evidence of recrystallization during deformation.

High-temperature deformation in the presence of melt suggests that the plagioclase clots from several samples probably

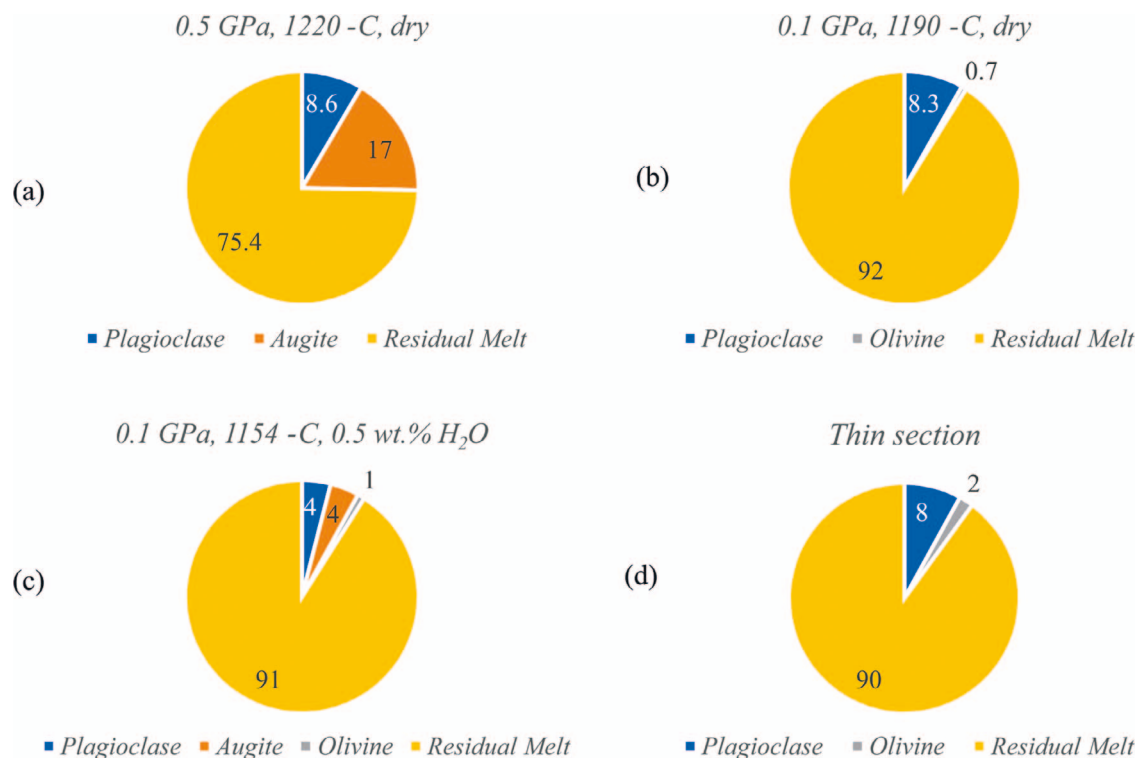


Fig. 17. (a–c) Crystallized mineral phases and residual melt wt% obtained from Rhyolite-MELTS modeling (Gualda et al., 2012) starting from the whole-rock composition of GUJ19-4 and considering crystallization at equilibrium. Reported are the results for 0.5 and 0.1 GPa pressure, for dry or slightly hydrated conditions. All models done for QFM-buffered fO_2 . (d) Modal analysis of the thin section of GU19-4.

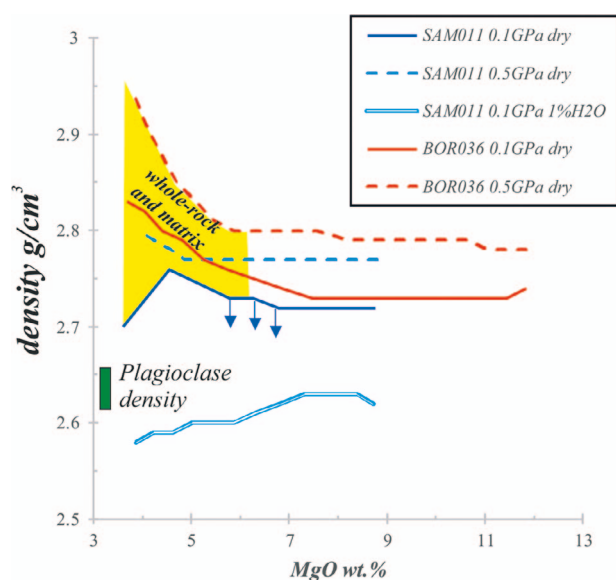


Fig. 18. MgO vs. melt density (g/cm^3) as calculated with Rhyolite-MELTS (Gualda et al., 2012) starting from the same magmas as in Fig. 4, at 0.1 and 0.5 GPa, dry and hydrous conditions. The green rectangle shows the density of plagioclase, which ranges from c. 2.65 to 2.62 g/cm^3 for An_{70-60} . The yellow field shows MgO and density calculated for whole rocks and matrices. Note that following Krättli & Schmidt (2021) melt densities would be 2% lower than calculated by Rhyolite-MELTS, cf. blue arrows.

originated in a crystal mush. Melt-assisted dislocation creep is the most likely process and is compatible with a viscous crystalline mush, with some interstitial melt between the plagioclase crystals (Sparks et al., 2019). Dislocation creep has been documented in

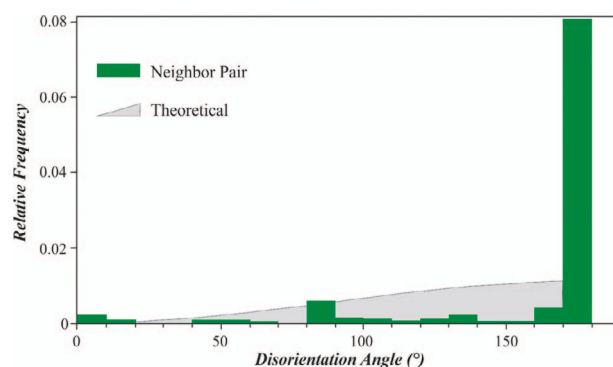


Fig. 19. The disorientation angle distribution between neighbor pairs calculated for the EBSD map of the plagioclase from KAS19-1. The histogram shows that data are clustered and depart from a random orientation (gray line). The largest cluster between 170° and 180° is related to twin boundaries; the cluster between 80° and 90° refers to the data next to the fracture to the left of point #1 (Fig. 2). Low disorientation angles ($<30^\circ$) and disorientation angles 120–130° relate to deformation, recovery and recrystallization processes during impingement.

large mafic intrusions like the Bushveld or Skaergaard (Holness et al., 2017, 2022), but never, to our knowledge, in volcanic rocks from LIPs. The differential stress necessary to deform plagioclase crystals from a crystal mush is lower than that required to deform plagioclase in gabbros (which is c. 10–20 MPa) and could be provided by arrival of new hot magma rising from the deeper crust and fluxing the crystalline mush (Spiess et al., 2017). The fracture recognized in the plagioclase clot analyzed here could suggest high rates of deformation related to rapid magma ascent through a pre-existing crystal mush (Sparks et al., 2019). If this latter hypothesis is correct, it suggests that deformation of the

analyzed plagioclase occurred during rise of new magma into the shallow-crust crystal mush, either during a replenishing event of the shallow plumbing system, and/or shortly before eruption of the magma.

(Dis-)equilibrium between plagioclase and magmas

Plagioclase crystallized in equilibrium with anhydrous or H_2O -poor magmas should have the An content close to the Ca# ($= \text{Ca}/(\text{Ca} + \text{Na})$) of the equilibrium melt since the $K_D(\text{Ca}/\text{Na})$ is about 1.0 (Kohut & Nielsen, 2003; Feig et al., 2006). We found that the Ca# of whole rock and matrix are similar to the An of most plagioclase crystals zones. The range of An contents never exceeds 20 mol% in all analyzed plagioclase crystals, suggesting that the plumbing system of the analyzed lava flows was formed by relatively uniform, similarly evolved magmas. This is in accord with the data from augite and olivine, which are typically low in Mg/Fe, and with the rather uniform major element composition of Deccan basalts, in particular the low-MgO samples studied here. Such homogeneous compositions point to an efficient homogenization of the magmas in large magma chambers (Ernst et al., 2019). However, a detailed look at minor and trace element contents and Sr isotopic compositions of the plagioclase megacrysts of many samples suggests a more dynamic and complex scenario, which we will discuss below.

Four samples (MAL19-6, GUJ19-1, GUJ19-2, GUJ19-6) show rounded, partially resorbed high-An cores (c. An_{75}), which are quite different from their rim compositions, which are in equilibrium with the matrix. Such high-An cores may reflect crystallization from significantly more primitive (with higher Ca/Na) or more hydrous melt (as An increases with H_2O ; Feig et al., 2006) compared with the melt in equilibrium with the low-An rims.

The plagioclase Mg, Sr, Ba, and REE (La, Ce, Eu) concentrations (EMP and ICP-MS data) are at or close to equilibrium with whole-rock and matrix compositions for most samples. The only exceptions are one plagioclase of KAS19-1 significantly depleted in MgO, the high-An plagioclase of GUJ19-1, which is significantly depleted in Ba and REE, and the high-An plagioclase core of GUJ19-6, which is enriched in Sr and depleted in REE compared with equilibrium compositions.

The K and Fe equilibrium between plagioclase (EMP and ICP-MS data) and matrix or whole rock is observed only for about half the analyzed samples (NAS19-6, MAL19-3, GUJ19-4, GUJ19-5, 19M-4). In contrast, the equilibrium melts for the analyzed plagioclase crystals of GUJ19-6 and MAL19-6 and for one (of 4) crystals of KAS19-1 are enriched in K compared to the matrix. High-An plagioclase cores of GUJ19-1 and GUJ19-2 are significantly depleted in K. Such differences are only partially explained by a major element dependence of the partition coefficients for K in plagioclase (see next section). For Fe, equilibrium melts calculated from the plagioclase cores of GUJ19-1, MAL19-6, and KAS19-1 are depleted in Fe compared with the matrix and whole rock. Notably, the high-Fe contents observed in many plagioclase crystal rims from most samples would require an equilibrium melt slightly more Fe enriched than whole rock and matrix, at least considering the D_{Fe} of 0.045 that we used. However, as the Fe partitioning depends also on the plagioclase and melt composition (cf. Lundgaard & Tegner, 2004) the D_{Fe} may be lower for evolved melts and An-poor plagioclase, pointing to a possible equilibrium between the matrix and the crystal rims.

While EMP data for Ti in plagioclase are scattered, ICP-MS Ti data are much less so and indicate significant disequilibrium for

the samples GUJ19-6, MAL19-6, 19M-4 and for the high-An plagioclase of GUJ19-1. For all these plagioclase crystals, the matrix and whole-rock contain almost double the Ti compared with the equilibrium melts calculated from plagioclase core compositions for $D=0.04$ (Fig. 4c). This discrepancy is probably not related to the considered Ti partition coefficient, as this value is consistent with several experimental studies (Bindeman et al., 1998; Bédard, 2006; Aigner-Torres et al., 2007; Tepley et al., 2010; Laubier et al., 2014; Sun et al., 2017). On the contrary, it suggests that several plagioclase crystals were in equilibrium with relatively low-Ti melts compared with the whole rock and in particular to the generally Ti-rich matrix.

$^{87}\text{Sr}/^{86}\text{Sr}_i$ of most plagioclase crystals is generally similar to that of the respective matrix compositions (Fig. 10f). Nonetheless, the high-An plagioclase of GUJ19-1 has significantly higher $^{87}\text{Sr}/^{86}\text{Sr}_i$ than its matrix, while the plagioclase crystals of GUJ19-6 and most plagioclase analyses of MAL19-6 are significantly depleted in $^{87}\text{Sr}/^{86}\text{Sr}_i$ compared with their matrix (Fig. 10). Three of the five analyzed samples show $^{87}\text{Sr}/^{86}\text{Sr}_i$ variations from core to rim or among distinct crystals, which significantly exceed the analytical uncertainty and indicate a hybrid origin for at least some of the studied GPB basalts.

In summary, chemical disequilibrium between plagioclase and matrix or whole-rock compositions is observed for about half the investigated samples. Those showing the strongest disequilibrium for most elements and for $^{87}\text{Sr}/^{86}\text{Sr}_i$ are the three samples containing high-An cores, i.e. GUJ19-1, GUJ19-6, and MAL19-6.

Some constraints on melt compositions and residence times

The range of Sr isotopic composition and trace element zoning of the plagioclase megacrysts reflects a combination of crystal growth and diffusive equilibration with a range of melt compositions. It is not straightforward to separate the two effects, because trace element partitioning depends on An content and temperature (e.g. Bindeman et al., 1998), and the diffusive re-equilibration of several elements can occur on timescales of years to centuries (e.g. Costa et al., 2003; Zellmer et al., 2003; Costa, 2021). Thus, the trace element zoning of the plagioclase that we report is a combination of crystallization and diffusion that it is hard to deconvolve with the types of analytical data that we have collected. Nonetheless, we have assessed the likely range of compositions of the melt and degrees of equilibration for some elements with different diffusivities and partitioning relations, and used the Sr isotope zoning to provide maximum residence times at a given temperature.

The variation of An with minor and trace elements in our crystals is complex, but K and Mg show a distinct behavior. Mg is poorly zoned in most crystals, including for example the low- and high-An plagioclase from GUJ19-1, GUJ19-2, GUJ19-6, and MAL19-6 perhaps pointing to an almost complete re-equilibration of this element. The only exception is Plag-1 in KAS19-1 (Fig. 8s). On the contrary, K shows a significant correlation with the An content, which may in part be due to the dependence on An of the K partition coefficient (e.g. Bindeman et al., 1998). In GUJ19-1, GUJ19-6, and MAL19-6 the differences in K content from high- and low-An plagioclase may be almost entirely due to a significant increase in the partition coefficient from An_{75} to An_{60} plagioclase (Bindeman et al., 1998). For example, in GUJ19-1 (Fig. 8a, b), low- and high-An crystals may all be in equilibrium with a magma having c. 1.5–2.0 wt% K_2O . On the contrary, low- and high-An crystals of GUJ19-2 yield strongly different K_2O (Fig. 8e, f), which may be only partially explained by a change in the partition

coefficient. We found that the low- and high-An plagioclase cores of GUJ19-2 would be in equilibrium with a magma having c. 3 and c. 2 wt% K₂O, respectively. Using the partition coefficient parametrization of Sun *et al.* (2017), the difference would be even larger (1.0 vs 2.5 wt% K₂O in the equilibrium magma, respectively). Therefore, in this case we expect that high- and low-K plagioclase crystals from GUJ19-2 were entrained by the same magma a short time before the eruption (see below). In KAS19-1, the An contents of all analyzed crystals are similar (except for a high-An core). Nonetheless, one crystal shows significantly higher K and lower Mg than the others (Fig. 8r, s) and neither K nor Mg seem equilibrated, pointing to very short residence times.

Constraints on timescales

Diffusion modeling of plagioclase megacrysts from Deccan GPBs (Borges *et al.*, 2014) suggests that significant Sr isotopic core-rim zoning are compatible with residence times of a few centuries (200–700 years). Here, we did not attempt detailed diffusion modeling since our LA-ICP-MS isotopic and trace element data are not detailed enough. Moreover, the presence of deformation features of the plagioclase implies that re-equilibration would not only occur simply by volume diffusion, but also via grain boundary diffusion (Dohmen & Milke, 2010), a process that is much more difficult to model. Thus, we have instead calculated the time that it would take to equilibrate a plagioclase crystal in three dimensions and obtained the maximum time of residence at a given temperature and plagioclase composition (Fig. 20). The observation of the zoning in trace elements and Sr isotopes would thus indicate that the residence times should be less than those required to reach a high percentage of equilibration (e.g. 90%). We find that the ⁸⁷Sr/⁸⁶Sr zoning observed in several of the plagioclase crystals analyzed here would suggest maximum residence times of about 1–8 centuries, depending on the temperature (1100°C–1000°C). For Mg and K complete equilibration could occur much earlier, in a few years to a few decades. It is worth emphasizing that these calculations are maximum residence times at the calculated temperatures and that models are for a fixed composition at the boundary. This means that if for example Mg and K concentration of the liquid changed over time faster than that of the Sr isotopes, it is possible that some processes recorded by Mg and K occurred a few years before eruption. This is consistent with the zoned olivine profile of sample KAS19-1 (Fig. 12f). This was modeled for Fe-Mg diffusion and yielded maximum residence times of about 5 years (Electronic Appendix 1, Fig. S8).

Thus, these estimations of timescales indicate that mixing of distinct magma batches occurred a few years to a few centuries before eruption, attesting to quite rapidly evolving magmatic systems. This is consistent with Deccan and LIP lava flow fields in general erupting as relatively short-lived pulses, each lasting a few centuries (Knight *et al.*, 2004; Chenet *et al.*, 2008).

A CONCEPTUAL MODEL FOR THE ORIGIN OF PLAGIOCLASE-RICH MAGMA

Textural and EBSD analyses indicate that at least part of the plagioclase megacrysts we studied were formed in crystal mushes (Fig. 21). The strong oscillatory zoning of several large plagioclase crystals (e.g. in 19 M-4) may reflect degassing pulses and consequent undercooling in a dynamic system being at least partially surrounded by magma (cf. Higgins & Chandrasekharam, 2007). However, several plagioclase crystals lack oscillatory zoning and some others show petrographic or EBSD evidence of deformation that point to residence in a relatively melt-poor, highly viscous

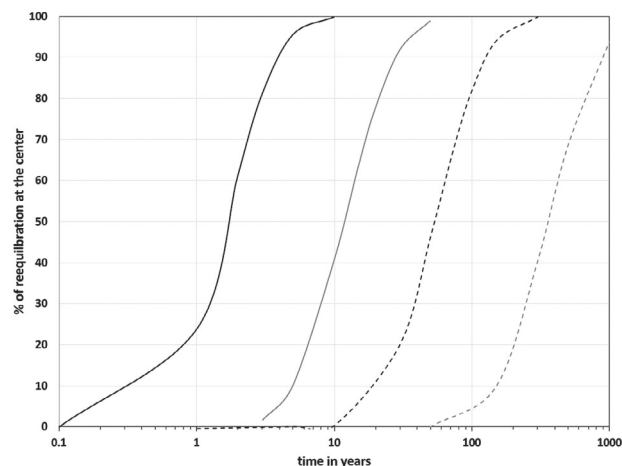


Fig. 20. Model of the degree of equilibration of Mg and Sr concentration (C) in plagioclase An₇₅ at 1000°C and 1100°C as a function of time. Equilibration % = $100 - 100 \times [(C - C_{\text{Equilibrium}}) / (C_{\text{Initial}} - C_{\text{Equilibrium}})]$. Curves show diffusion calculations for the equilibration of the concentration at the center of the plagioclase crystal using the 3D analytical solution for a parallelepiped (Crank, 1975) of a size $1 \times 0.25 \times 0.25$ mm. Diffusion coefficient of Mg from Van Orman *et al.* (2014) and that of Sr from Giletti & Casserly (1994).

environment such as expected in a crystal mush. Chemical data on plagioclase megacrysts, Rhyolite-MELTS modeling, pressure-temperature estimates on clinopyroxene and olivine, and literature data for GPBs from other LIPs (e.g. Krans *et al.*, 2018; Moore *et al.*, 2018) suggest that the plagioclase formed in the shallow crust from largely degassed, evolved basaltic magmas. In general, c. 1-cm-large plagioclase crystals as those investigated here would require several centuries to grow from a basaltic magma (Higgins & Chandrasekharam, 2007). However, shallow pressure conditions, volatile degassing, and significant undercooling may significantly enhance plagioclase crystallization rates (McCarthy *et al.*, 2020). Such conditions are consistent with a shallow-depth crystal mush, which was occasionally flushed by hot, Fe-rich basaltic magma.

Considering the multiple lines of evidence for chemical zoning and disequilibrium between the plagioclase and matrix compositions, particularly for Sr isotopic compositions, it seems likely that plagioclase crystals from some samples were in contact with and crystallized from chemically distinct basaltic melts. In a crystal-mush scenario, we can envision continuous growth of the plagioclase over decades or centuries and several pulses of magmas flushing through the crystal mush. In other cases, plagioclase crystals show a much more homogeneous, unzoned composition pointing to a magmatic system with relatively constant composition. It should also be noted that single GPBs sometimes show significantly heterogeneous compositions, as highlighted for example by Thalghat (Borges *et al.*, 2014 and this study) and by Tunnel-5 GPB samples (Beane *et al.*, 1986; Basu *et al.*, 2020a; this study).

Assuming that plagioclase megacrysts formed primarily in crystal mushes, the question arises as to how these highly viscous systems were remobilized during Deccan eruptions. The disruption of the crystal mush can occur by arrival of magmas rising from the deep crust and these magmas would be quite dense if they were as Fe-rich as the matrix of the samples analyzed herein. In such Fe-rich magmas, the buoyancy of plagioclase would be significant (>0.1 g/cm³; Fig. 18) enough to contribute to an effective fluxing of the crystal mush and uptake of large

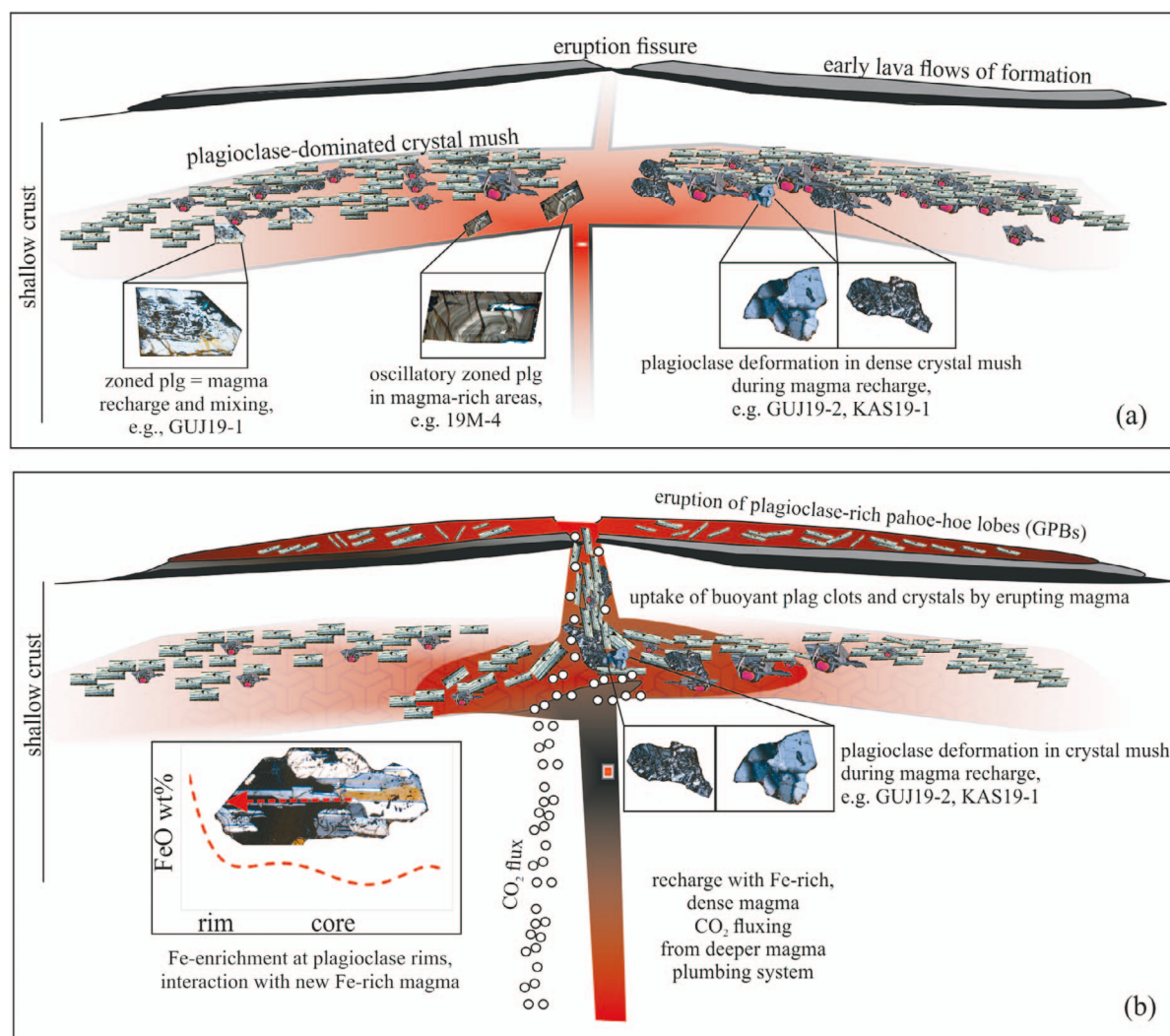


Fig. 21. Schematic representation of the proposed scenario for (a) the formation of plagioclase-rich crystal mushes in the shallow crust and (b) their eruption due to arrival of new Fe-rich magma rising from the deeper crust. In (a), the plagioclase-dominated crystal mush forms from a homogeneous melt (as shown by, e.g., samples GUJ19-4 or NAS19-6) or from a hybrid magma (as shown by the zoned plagioclase crystal from, e.g. GUJ19-1). Oscillatory zoning may develop in magma-rich regions. Deformation of plagioclase crystals by dislocation creep can occur in the crystal mush, when this mush is fluxed by rapidly rising magma (Spiess *et al.*, 2017). (b) Shows the arrival of Fe-rich magma, which is suggested by the Fe-rich plagioclase rims. Further plagioclase deformation may occur in this phase, shortly prior to the eruption. Erupted GPB flows are highly heterogeneous as they may be constituted by magmas with different composition (i.e. the magma residing within the crystal mush and the magma rising from the deeper crust), as well as by variable amounts of plagioclase megacrysts from the pre-existing crystal mush or plagioclase phenocrysts. Furthermore, mafic minerals may be part of the crystal mush (e.g. clinopyroxene and olivine inclusions in plagioclase megacrysts) or phenocrysts crystallized from the rising magma. Possible fluxing by CO_2 is shown in (b) and may enhance flushing of the magma plumbing system and eruption of GPB flows.

plagioclase crystals and aggregates in a rapidly rising magma plume (Bergantz *et al.*, 2015). The heterogeneous distribution of extremely coarsely crystalline zones within GPB suggests that the rheological threshold for eruptibility (e.g. Marsh, 1981) was lowered by the flux of Fe-rich mobilizing melts. Evidence for a late arrival of Fe-rich melts comes from matrix and plagioclase rim compositions, which are significantly enriched in Fe compared with the plagioclase cores, even considering a major element control on the Fe partition coefficient (Bindeman *et al.*, 1998). The matrix samples are among the most Fe-rich samples of the Deccan and are in (or close to) equilibrium with plagioclase rims. The late magma in equilibrium with plagioclase rims was most likely an evolved basalt with relatively high Fe and Na/Ca (and high K for a few samples, e.g., MAL19-6), but it generally was slightly different from magma in equilibrium with plagioclase cores, for example in terms of Sr isotopic composition.

Such Fe-rich basaltic magmas probably differentiate from common Deccan basalts. Considering the Rhyolite-MELTS modeling starting from a Kalsubai MgO-rich basalt (e.g. SAM011, BOR036, MgO c. 8 and 12 wt%, respectively; Beane *et al.*, 1986), FeO enrichment up to 17 wt% can be reached at low pressure (0.1 GPa) in particular for dry conditions (Fig. 4a). Even higher FeO (up to 20 wt%, for c. 4 wt% MgO) can be attained at 0.5 GPa, dry and unbuffered f_{O_2} conditions (Rhyolite-MELTS modeling). Therefore, the most likely interpretation for the late Fe-rich melt is that it derived from mid- or deep-crustal depths and was essentially anhydrous. However, such melt would have a high density (c. 2.9 at 0.5 GPa) and thus a low buoyancy relative to the middle-shallow crust, i.e. it would normally not rise up to the shallow crust, despite its low viscosity (c. 2.0 poise). Such high-density magma would also encounter difficulties in crossing the low-density, plagioclase-rich shallow-crust crystal mush. A possible

scenario, which could explain the mobilization of the Fe-rich melt and its ascent through the plagioclase-rich mush in the shallow crust would be a fluxing of the plumbing system by volatiles, CO₂ in particular, rising from the deep plumbing system. Notably, recent melt inclusion analyses have shown that at least some Deccan basalts are quite rich in CO₂ (Hernandez Nava *et al.*, 2021). Moreover, several of the samples analyzed here yield high Nb, up to 50% higher than all other previously analyzed Deccan basalts at similar MgO (Fig. 4f). Hernandez Nava *et al.* (2021) and Boscaini *et al.* (2022) use Nb as a proxy for CO₂ contents in basalts with MgO > 7 wt%. Even considering that the studied samples are quite evolved and that the CO₂/Nb ratios may be partially modified during fractional crystallization, it may be suggested that the studied samples were derived from Nb and thus CO₂-rich parental magmas.

It is noteworthy that GPB flows tend to occur at the transition between successive basalt formations of the WG lava pile. A similar situation is described for GPBs from the Ethiopian LIP, which erupted after a period of volcanic rest (Krans *et al.*, 2018). Therefore, we may speculate that volatile fluxes were enhanced by arrival of new magma in the plumbing system, during transition from the waning extrusion of one basalt formation to the inception of extrusion of the next one. In this scenario, CO₂ exsolved from the deep plumbing system, possibly at depths in excess of 15–20 km (Black & Manga, 2017; Caricchi *et al.*, 2018; Capriolo *et al.*, 2020; Black *et al.*, 2021) could have significantly decreased the water fugacity of the system and promoted plagioclase crystallization (e.g. Caricchi *et al.*, 2018). Incorporation of low-density plagioclase from the crystal mush significantly increased the buoyancy and eruptibility of magmas of the upper part of the magmatic plumbing system (Cashman *et al.*, 2017).

CONCLUSIONS AND GENERAL IMPLICATIONS ON DECCAN MAGMA PLUMBING SYSTEMS

Most of the samples show some evidence for textural and/or chemical disequilibrium. The chemical zoning of plagioclase crystals indicates residence times, which range from a few years to a few centuries (as also found by Borges *et al.*, 2014). The presence of deformed plagioclase crystals suggests that their megacrysts formed in crystal mushes in a shallow magmatic system and dislocation creep could have occurred when the crystal mush was fluxed by new magma intrusions. The presence of shallow crystal mushes also suggests that the magma plumbing system of at least part of the Deccan, and thus of LIPs in general, may not be fundamentally different from that of subduction-related and of some ocean island magmatic systems (Neave *et al.*, 2017; Sparks *et al.*, 2019; Black *et al.*, 2021). Our data on plagioclase megacrysts shed light only on the shallowest differentiation of Deccan magmas, and the general picture that emerges is that of a dynamic, rapidly changing magmatic plumbing system, with a complex evolution in a transcrustal system. Fluxing of CO₂ fluids from the deep to the shallow parts of the magmatic plumbing system could have played a major role in decreasing the water content of the shallow magmas, promoting crystallization of plagioclase and the creation of crystal-rich mushes. The interaction of evolved but Fe-rich magmas with the plagioclase mushes allowed to reach density and viscosity values that facilitated the eruption of GPB. This proposition is consistent with recent interpretation of Deccan magmatism as resulting from a complex network of magma chambers (Mittal *et al.*, 2021), rather than from a simple large

magma chamber (Ernst *et al.*, 2019) with a homogenous magma composition.

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