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Are flood basalt eruptions monogenetic or polygenetic?

Hetu C. Sheth · Edgardo Cañón-Tapia

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Abstract A fundamental classification of volcanoes divides them into “monogenetic” and “polygenetic.” We discuss whether flood basalt fields, the largest volcanic provinces, are monogenetic or polygenetic. A polygenetic volcano, whether a shield volcano or a stratovolcano, erupts from the same dominant conduit for millions of years (excepting volumetrically small flank eruptions). A flood basalt province, built from different eruptive fissures dispersed over wide areas, can be considered a polygenetic volcano without any dominant vent. However, in the same characteristic, a flood basalt province resembles a monogenetic volcanic field, with only the difference that individual eruptions in the latter are much smaller. This leads to the question how a flood basalt province can be two very different phenomena at the same time. Individual flood basalt eruptions have previously been considered monogenetic, contrasted by only their high magma output (and lava fluidity) with typical “small-volume monogenetic” volcanoes. Field data from Hawaiian shield volcanoes, Iceland, and the Deccan Traps show that whereas many feeder dykes were single magma injections, and the eruptions can be considered “large monogenetic” eruptions, multiple dykes are equally abundant. They indicate that the same dyke fissure repeatedly transported separate magma batches, feeding an eruption which was thus polygenetic by even the restricted definition (the same magma conduit). This recognition helps in understanding the volcanological, stratigraphic, and geochemical complexity of flood basalts. The need for clear concepts and terminology is, however, strong. We give reasons for replacing “monogenetic volcanic fields” with “diffuse volcanic fields” and for dropping the term “polygenetic” and describing such volcanoes simply and specifically as “shield volcanoes,” “stratovolcanoes,” and “flood basalt fields.”

Keywords Volcanism · Monogenetic · Polygenetic · Flood basalt · Hawaii · Iceland · Deccan Traps

Introduction: monogenetic and polygenetic volcanism

A well-known classification of volcanoes divides them into “monogenetic” and “polygenetic” (e.g., Walker 2000). A monogenetic volcano is one which erupts only once, a classic example being the scoria cone of Parícutin (active 1943–1952) in the central Mexican volcanic belt (Luhr and Simkin 1993). Parícutin is one of the several hundred similar volcanoes in the Michoacán-Guanajuato “monogenetic volcanic field.” Though the individual volcanoes are short-lived, such fields themselves are active for millions of years and have total volumes comparable to those of polygenetic volcanoes (e.g., Condit et al. 1989; Connor and Conway 2000; Németh 2010). A “polygenetic” volcano is one which erupts many times, mainly from the same conduit or vent, though satellite vents (producing flank eruptions) are not excluded. Well-known shield volcanoes (e.g., Mauna Loa) and stratovolcanoes (e.g., Etna, Fuji) are all polygenetic edifices.

Distinction between these two categories is not always sharp. For example, monogenetic and polygenetic volcanoes can be intimately associated in the same volcanic

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H. C. Sheth (✉)
Department of Earth Sciences, Indian Institute of Technology Bombay (IITB), Powai, Mumbai 400076, India
e-mail: hcsheth@iitb.ac.in

E. Cañón-Tapia
Earth Sciences Division, Centro de Investigación Cientifica y de Educación Superior de Ensenada (CICESE), CP. 22860 Ensenada, Baja California, Mexico

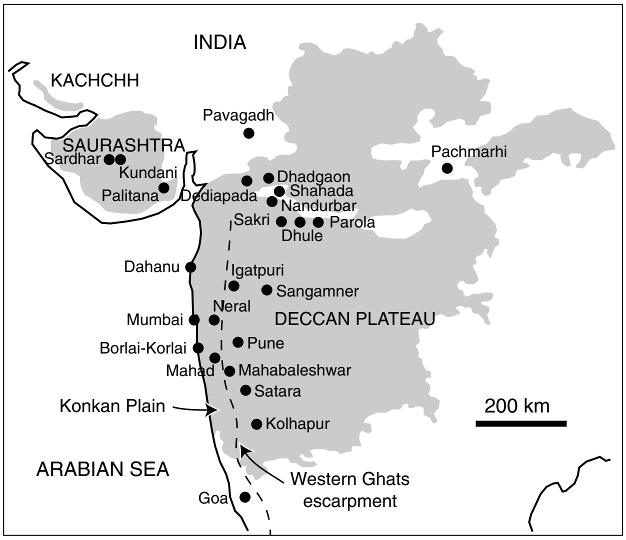

Fig. 1 Map of the Deccan Traps volcanic province (*gray*), with localities discussed in the text and some other localities marked

field, as in the San Francisco volcanic field in Arizona, with the Mount Humphreys stratovolcano at its center (e.g., Duffield 2005). Large polygenetic volcanoes such as Mauna Loa or Etna can contain hundreds of small monogenetic volcanoes on their slopes, produced by flank eruptions. Flood basalt provinces may also contain monogenetic volcanic fields (Camp et al. 1991; Németh et al. 2003, 2007; Németh 2004; Kshirsagar et al. 2011). Besides, many small, "monogenetic"-looking volcanoes with simple morphology have complex internal architectures and polygenetic histories (e.g., Schmincke 2004; Németh 2010; Sheth 2012).

The focus of this contribution is on flood basalts, which form the largest volcanic provinces on Earth. The question of whether flood basalt volcanism is monogenetic or polygenetic is essentially unaddressed in the large literature on flood basalts, but is important for achieving a correct physical volcanological and conceptual understanding of them. For the younger and still active flood basalt provinces like Iceland, the question also has important volcanic hazard implications (Galindo and Gudmundsson 2012). We present and build on field observations of our own, as well as of others, in Hawaii, Iceland, and larger flood basalt provinces, with a focus on the Deccan Traps (Fig. 1).

Models for monogenetic versus polygenetic volcanism

Many models for monogenetic versus polygenetic volcanism consider that the rate of magma generation in the mantle is a key factor determining the style of volcanism at the surface. For example, Fedotov (1981) considered that a low regional magma generation rate results in monogenetic volcanism, because the small associated thermal input promotes extensive magma solidification therefore restricting the ability of magma to reach the surface. He considered that as the rate of regional magma supply increases, polygenetic volcanism would be favored. Similarly, Wadge (1982) also visualized polygenetic volcanoes as receiving a continuous influx of magma from the mantle.

Walker (1993) showed that magma supply rate is not simply related to the type of volcanism at the surface. He pointed out that the time-averaged magma supply rate for flood basalt fields is at least as large as that of the most productive polygenetic shield volcanoes like those of Hawaii, Galápagos, or Réunion. Because he envisaged flood basalt eruptions as monogenetic, he concluded that a distinction between monogenetic and polygenetic volcanism based solely on the average magma supply rate was inadequate. Walker (1993) therefore suggested a parameter, the "modulation frequency" of the magma supply, to distinguish the two categories of volcanism. This parameter essentially means eruption frequency and postulates a mechanism, not clearly described by him, for partly preventing magma in the mantle from reaching the surface.

Takada (1994a, b), following Nakamura (1977), recognized the influence of lithospheric stress in controlling the type of volcanism in a given region. Differential stress in the lithosphere provides a physical explanation for the modulation mechanism postulated by Walker (1993). Nevertheless, Takada (1994a) envisaged the role of the lithospheric stress in a different form, as controlling the interaction of fluid-filled cracks during magma ascent in the lithosphere. He suggested that polygenetic volcanoes form in places where the differential stress at depth is relatively small, and preferably compressive, as these conditions favor the convergence of batches of magma to form a single conduit. In contrast, monogenetic volcanism develops in places where the differential stress is large, and preferably extensional. On his output-stress (more properly, output-strain rate) diagram, monogenetic volcanic fields follow a rift-trend while many polygenetic volcanoes indicate larger magma input rates but smaller deformation rates.

Despite its appeal, Takada's (1994a, b) crack-interaction model may have limited geological application, because typical time periods between two successive magma injection events and eruptions in a polygenetic volcano (>200 years) may exceed the time period of magma solidification in a dyke (a few months, Delaney and Pollard 1982; Cañón-Tapia and Walker 2004), and if two magma batches are likely to interact during ascent, they must occur almost simultaneously in time and very close in space. Thus, even if the Takada (1994a, b) model may provide a simple explanation for large-volume eruptive events, it does not explain the formation of a polygenetic volcano unless a relatively high magma supply rate, keeping a single conduit open, is invoked (Fedotov 1981). Cañón-Tapia and Walker (2004) suggest that the occurrence of monogenetic and polygenetic volcanism has more to do with the degree of melt connectivity in the source region, with monogenetic volcanism occurring where lateral melt connectivity in the mantle is poor. Favorable stress conditions are important as well. In any case, the mechanism determining the type of volcanism in a given region remains insufficiently understood.

Flood basalts

Flood basalt provinces like the Deccan Traps of India have total volumes of millions of cubic kilometers of basaltic lava typically erupted in short time intervals of one million years or so (e.g., Baksi 2014). They are formed by hundreds of large to very large eruptions, some of which may have individual volumes of >2,000 km^3 (e.g., Self et al. 1997; Bryan et al. 2010). Flood basalt lava flows have been classified into "simple" and "compound" types (Walker 1971). "Simple" flows are tabular, cover considerable areas, and typically show well-developed columnar jointing throughout their thickness, indicating that they are single cooling units. "Compound" flows can also be voluminous, but are made up of many small-scale (meter-scale or Hawaiian-size) flow units or lobes, usually without columnar jointing (Keszthelyi et al. 1999; Bondre et al. 2004; Sheth 2006). Walker (1971) considered that all flows are compound, at some scale or another, and Self et al. (1997) show that the simple flows of the Columbia River province are simply very large (kilometer-size) lava lobes, which they describe as "sheet lobes." However, Bondre et al. (2004) do not find evidence for lateral contacts in many large simple lava flows of the Deccan Traps and mention an example near Pune (see Fig. 1 for all Deccan localities mentioned in the text) that can be traced continuously for 80 km without lateral variation in thickness. The stacking of flood basalt lavas can produce complex patterns (e.g., Jerram 2002; Vye-Brown et al. 2013a).

Thordarson and Self (1998) and Self et al. (1997) calculated an eruption rate of 4,000 m^3/s for the huge Roza Member of the Columbia River flood basalt province, estimated to have formed in ~10 years from a linear eruptive vent-fissure system 150 km long. This rate is the same as the peak eruption rate of the 1783–1784 Laki eruption in Iceland, world's largest historic eruption that had severe environmental effects. The larger of the Icelandic flood basalt eruptions (15–20 km^3), such as the Laki and Eldgjá (935–940) eruptions, are the link between the small-volume Hawaiian basaltic eruptions (~1 km^3) and the very large (hundreds to thousands of km^3) flood basalt eruptions such as those of the Deccan Traps (Th. Thordarson, pers. comm., 2006; A. Gudmundsson, official review).

Walker (1993, 1999, 2000) briefly mentioned flood basalt eruptions to be monogenetic; we suggest that many individual flood basalt eruptions are polygenetic, that evidence for this is found in their feeder dykes, and that this recognition of the polygenetic nature of many individual flood basalt eruptions helps to understand the complexities of flood basalt volcanology and stratigraphy.

Dykes and sills, feeders and non-feeders

Dykes form as hydraulic (magma-driven) extension fractures and transport magma from the magma generation zone to a shallower-level magma chamber and from the magma chamber to the surface (e.g., Gudmundsson 1990, 1995a, b; Gudmundsson and Marinoni 2002; Galindo and Gudmundsson 2012). Dykes that terminate at depth and fail to reach the surface are called arrested dykes, and those that reach the surface are feeder dykes. Dykes advect hot fluid (magma) through much cooler country rock, and many dykes display glassy selvages formed by chilling of the magma against the country rock at the dyke margin (Fig. 2a). On some occasions, dykes cause partial melting of country rock (Grunder and Taubeneck 1997; Petcovic and Dufek 2005), and any chilled margins may represent a late stage of magma flow. Dykes also often exhibit columnar jointing across their widths (Fig. 2a, b).

Individual dykes can be the end result of one or numerous separate magma injections. Dykes in which magma flowed only once would be represented by a single set of margin-perpendicular joint columns (Fig. 2b). Because such dykes are analogous to the so-called simple flood basalt flows, we could call them simple dykes, but we prefer the slightly longer-term "single-injection" dykes because of its clarity and accuracy. If a dyke is the end product of several magma injections, all of the same composition, the dyke is said to be "multiple," whereas if the successive magma injections are of different compositions (e.g., basalt and rhyolite), the dyke is said to be "composite." A multiple dyke can be best identified from multiple sets of margin-perpendicular columnar joints and internal chilled margins between the constituent injections. In their absence, fine-scale textural or compositional variations are helpful (Hooper 1985; Reidel and Fetch 1987; Reidel 1998; Cañón-Tapia and Herrero-Bervera 2009).

In the Deccan (Fig. 1) and the Columbia River flood basalt provinces, dykes are abundant and sills are rare (e.g., Swanson et al. 1975). In comparison, sills are abundant in the Karoo province (Polteau et al. 2008) and in Iceland (Gudmundsson 2012). Like dykes, sills can be simple, multiple, or composite. The Mahad tholeiitic sill in the southwestern Deccan Traps is a single ~22-m-thick saucer-shaped intrusion (Duraiswami and Shaikh 2013), whereas the

Fig. 2 Deccan tholeiitic dykes. **a** Chilled margin of dyke against Mesozoic sandstone. This is dyke PMD11 near Pachmarhi (Sheth et al. 2009). Note the large columns. The whole dyke is multiple, with at least seven or eight rows and a total thickness varying from 28 to 34 m. Geologist is Partha Das. **b** Dyke at Borlai-Korlai. Dyke trends roughly north–south and is ~60 cm wide

Fig. 3 A nearly horizontal picritic multiple sill intruded within older sedimentary rocks (not seen in this photo) on the north shore of the Isle of Skye, Scottish Hebrides. People for scale

200-meter-thick Chakhla-Delakhari tholeiitic sill near Pachmarhi, in the northeastern Deccan Traps, is a multiple intrusion and is known to have fed a local lava flow (Crookshank 1936; Sen 1980; Sheth et al. 2009). Gudmundsson (2012) has illustrated multiple sills in Iceland, and Fig. 3 shows a picritic multiple sill in the Scottish Hebrides, which may have fed some of the associated flood basalt lavas (Emeleus and Bell 2005). Below, we describe dykes in monogenetic and polygenetic volcanoes, in Iceland and in the Deccan Traps, and discuss their significance.

Dykes in monogenetic volcanoes

Because magma ascends through the lithosphere primarily in dykes (Wilson and Head 1981), even small monogenetic volcanoes (scoria cones, tuff cones and rings, and maars) must have an underlying feeder dyke. In some cases, feeder dykes join monogenetic vents separated by a few hundreds of meters and probably form a thicker dyke at depth, as envisaged by Reches and Fink (1988). Dykes associated with a single cone display complex local arrangements that seem to have evolved throughout the eruptive episode of the volcano and serve to distribute the magma from the central conduit to the boccas that may form around the main crater. Occasional cone breaching and structural collapse around the dykes influence the evolution of the eruption and may even lead to the formation of small cryptodomes, as described for the Lemptegy volcano (Petronis et al. 2013). In general, dykes associated with monogenetic edifices have irregular shapes, are segmented or consist of sets of short parallel intrusions, and tend to radiate from a central area (Valentine and Krogh 2006; Keating et al. 2008; Hintz and Valentine 2012; Petronis et al. 2013). The dykes tend to be relatively thin (typically <2 m), but locally can be as wide as 5 m. Although these dykes occasionally show evidence for multiple injections, most are single injections.

Dykes in polygenetic volcanoes

Although polygenetic volcanoes repeatedly erupt from the same main vent or conduit, which is usually circular or elliptical in plan, dykes play an important role in the development of polygenetic volcanoes. Dykes often form a radiating pattern around the central vent (Odé 1957; Nakamura 1977). They are up to a few kilometers long and commonly <5 m wide. Because these dykes divert magma from the central conduit and lead to flank eruptions, they can be considered analogous to the dykes observed in the shallow substructures of monogenetic volcanoes. Nevertheless, the deeper levels of at least some polygenetic volcanoes reveal "coherent dyke complexes," the type example of which is found on the eroded Hawaiian shield volcano Ko'olau (Walker 1986). They have been documented in the other Hawaiian shield volcanoes (e.g., Fig. 4a) and in American Samoa, Ponape, and Madeira (Walker 1992). They are composed of parallel and tightly packed (forming >40 % of total rock) dykes. Many of these are single-injection dykes (Fig. 4a), but many are multiple dykes identifiable by numerous internal chilled margins (see Fig. 4.17 in Parfitt and Wilson 2008 for a multiple dyke in the Ko'olau volcano). Although individual injections are typically ~2 m thick, the thickness of the multiple dykes can reach >10 m.

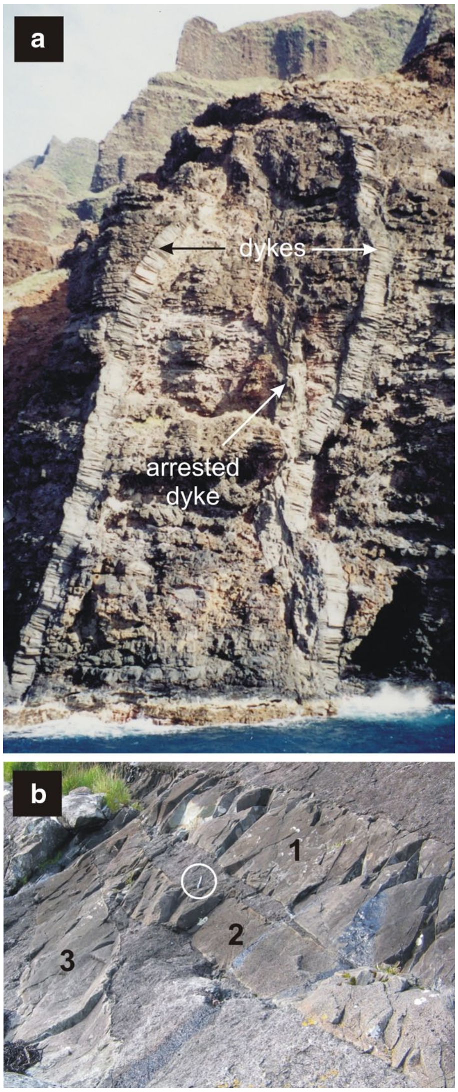

Fig. 4 **a** Dykes cutting lavas forming the high cliffs of the Na Pali coast on Kauai, Hawaii. The two dykes in the cliff in the foreground are ~2 m thick, and each shows a single set of columnar jointing. A third has been arrested halfway up the cliff. **b** Oblique outcrop view of mafic cone sheets (marked 1–3) in the Cuillin plutonic complex, Isle of Skye, Scotland. Pen near center of photo (within *white circle*) is 15 cm long

Coherent dyke complexes form when a volcano is able to spread and widen, so as to accommodate the incoming dykes. If the volcano is unable to do so, as when it is buttressed by an adjacent, older volcano, then the volcano swells and a "coherent intrusive sheet complex" (Walker 1993) forms. Sheets are tabular intrusions dipping at moderately steep angles and are thus a separate category from both dykes and sills (e.g., Gudmundsson and Brenner 2005). Examples of such sheet complexes, containing hundreds of individual tabular intrusions striking and dipping in various directions, are found in the eroded plutonic centers of the Scottish Hebrides (Fig. 4b) or in central volcanoes in the rift zones of Iceland (Walker 1992; Walker et al. 1995; Emeleus and Bell 2005; Gudmundsson and Brenner 2005). Dyke complexes and sheet complexes both play an important role by distributing magma into different parts of a large polygenetic volcano.

Repeated use of the same fissure, suggested by the multiple dykes seen in the older and exposed Hawaiian dyke complexes, is supported by geophysical observations of ongoing intrusive activity on the active Hawaiian volcanoes. Periodically emplaced intrusions under the East Rift Zone of Kilauea volcano can be grouped into two types (Epp et al. 1983; Hardee 1987). One group is defined by large-volume (100–1,000 m^3/s) magma movements accompanied by shallow seismic swarms. The second group is associated with smaller magma volumes (1–10 m^3/s) being emplaced aseismically. The former type opens new conduits through fracturing, whereas the latter type reutilizes a previous, open or partially open conduit, thus not requiring new fracturing. It has been noted (Epp et al. 1983; Hardee 1987) that the seismic dykes are more common in the lower parts of the rift zones, whereas the aseismic dykes are more common in the upper parts of the rift zones nearest to the summit caldera.

Dykes in Iceland

Regional tholeiitic dyke swarms in the rift zones of Iceland are about 50 km long, 5–10 km wide, and contain several hundred dykes, with the average dyke thickness being ~4 m (Gudmundsson 1990). The dykes are almost parallel and vertical, with power law length size distributions and positive length–width correlations. Crustal dilation due to them is computed at 1–2 % to as high as 28 % along partial profiles, the average being 5–6 % (Gudmundsson 1995b).

Gudmundsson (1990, 1995a, b) has provided extensive field observations on dykes and feeder dykes in Iceland and noted the difficulty of finding feeder dykes even in this young terrain. Gudmundsson (1995a) has described many dykes in Iceland composed of many columnar rows (see, e.g., his Fig. 8) and suggests that the final dyke is an aggregate of several magma intrusion events at intervals of hundreds, possibly thousands, of years. A new magma injection in a cooling but still partially molten dyke would preferentially occur along a weak zone, typically the median plane, and when this is repeated several times, a multiple dyke with many columnar rows is the end result. Gudmundsson (1995a) makes a fine distinction between “dykes with multiple columnar rows,” produced by numerous magma injections in the same fissure separated by months to years, and “multiple dykes,” in which the time periods between the successive magma injections are long enough (tens or hundreds of years) that later magma injections develop chilled margins against the earlier ones. In the present work, this distinction is unimportant and both types are designated “multiple dykes.”

Gudmundsson (1995a) states that the feeder dyke of the 1975–1984 Krafla Fires eruptions in the Northern Volcanic Zone of Iceland was emplaced in nine eruptions and monitored with geophysical methods and field observations. The feeder dyke increased in width and length during the nine eruptions, over nearly 10 years. It reached a maximum thickness of 9 m and length of 11 km in the area of the Krafla caldera, though surface deformation occurred over the much larger (100 km long) area of the Krafla volcanic system. Gudmundsson (1995a) noted that the Krafla Fires feeder dyke largely coincided with the feeder dyke emplaced in the previous rifting episode of the Krafla volcanic system, namely the Mývatn Fires eruptions (1724–1729). He interprets this as showing that the Krafla Fires feeder dyke is a multiple dyke formed over about 250 years. Another example of a multiple feeder dyke, in the Eastern Rift Zone of Iceland, is that which reactivates and feeds the 5.5-km-long summit fissure Heklugja during all eruptions of the highly active stratovolcano Hekla (Gudmundsson et al. 1992).

The 1783–84 Laki eruption (the largest flood basalt eruption on Earth in historic time) and the even larger 935–940 Eldgjá eruption (Thordarson and Larsen 2007; Scarth and Tanguy 2001) both occurred in the Eastern Rift Zone. The 17-km-long Eldgjá fissure, which extended northeastwards from the Katla volcanic system, and the 27-km-long Laki fissure, which extended southwestwards from the Grímsvötn volcanic system, are parallel and only 5 km apart (Thordarson and Self 1993; Scarth and Tanguy 2001). Each is segmented, as is commonly the case for all regional-length dykes and eruptive fissures (e.g., Gudmundsson 1995a, b), but both feeder dykes were single injections (A. Gudmundsson, official review).

Dykes in the Deccan Traps

There has been considerable recent interest in mafic dyke swarms and their correlations to the lava flows in the Deccan Traps (e.g., Bhattacharji et al. 1996; Bondre et al. 2006; Ray et al. 2007; Sheth et al. 2009; Vanderkluysen et al. 2009). Of hundreds of tholeiitic dykes, we have observed over a large area of the Deccan Traps, many are clearly single-injection dykes. A good example near Igatpuri on the Western Ghats escarpment is shown in Fig. 5a. This dyke shows a single set of corded columns throughout its exposed height, separated from the country rock by a thin, finely jointed, glassy margin on either side. Two other dykes with a single set of columnar joints, exposed

Fig. 5 Tholeiitic single-injection dykes in the Deccan Traps. **a** Dyke in road cut near Igatpuri, Western Ghats, Deccan Traps. Dyke is ~1.3 m thick. Geologist is Loÿc Vanderkluysen. **b** Dyke at Borlai-Korlai, trending roughly north–south and slightly sinuous in plan. Dyke is ~0.7 m wide. Note small parallel dykelet (only a few centimeters thick) nearby. Geologist is T. K. Biswal. **c** Thicker dyke (2 m) at Borlai-Korlai trending roughly east–west, perpendicular to the general trend. Geologist is Steve Ruff. **d** The Kundani dyke CSD3 in central Saurashtra, with thin, platy jointing across much of its width. Dyke trends N80° locally and is a few meters wide. Person for scale

at Borlai-Korlai on the coastline, are shown in Fig. 5b, c. Another single-injection dyke with close-spaced and continuous platy jointing across its width is the Kundani dyke in Saurashtra, in the northwestern Deccan Traps (Fig. 5d). However, multiple dykes seem at least as common as the single-injection ones. A good example from the Western Ghats west of Satara is shown in Fig. 6a. This dyke shows at least three sets of horizontal columnar rows. Another example formed by four injections, exposed near Neral on the Konkan Plain, is shown in Fig. 6b.

The well-developed Nandurbar-Dhule tholeiitic dyke swarm in the central Deccan Traps intrudes highly weathered compound pahehoe flows. The swarm contains several hundred dykes, including 210 dykes >1 km in length,

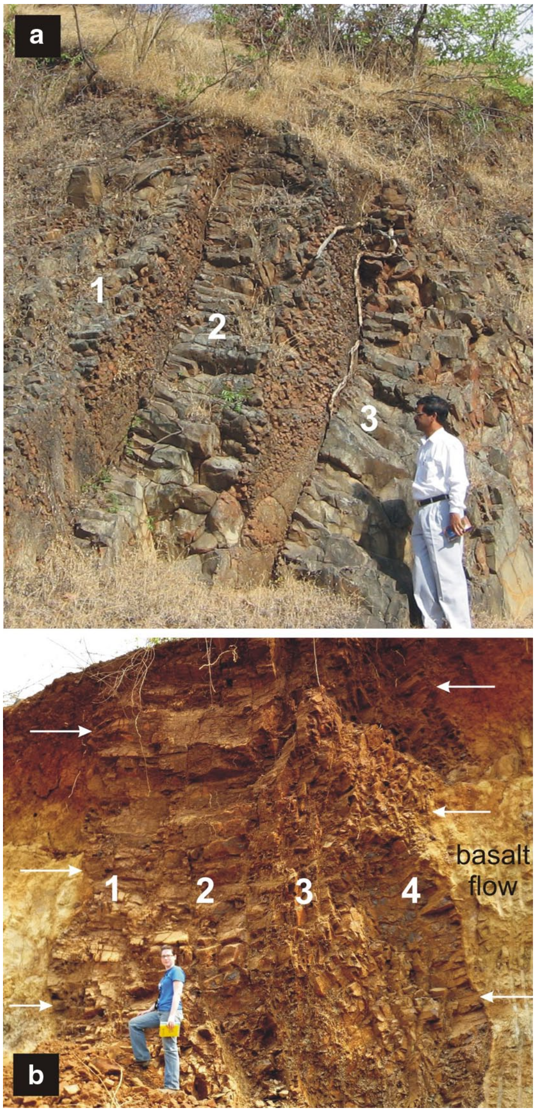

Fig. 6 Tholeiitic multiple dykes in the Deccan Traps. **a** Spectacular multiple dyke exposure in a road cut about 25 km SW of Satara, Deccan Traps. Three columnar-jointed sets in the dyke are identified by numbers 1, 2, and 3, and the cross-sections of the individual columns can be observed on the eroded faces. The total thickness is not determinable. Geologist is Vilas Bhonsle, 2007 photo. As seen on a visit in early 2013, the dyke still exists but the exposure is much disintegrated. **b** Dyke near Neral. Dyke is *vertical*, trends N25°, is 16 km in length, and made up of four columnar-jointed rows with a total thickness of 5 m. The country rock basalt flow is very highly weathered, and the dyke margins are shown by *white arrows*. Geologist is Courtney Sprain

the longest being the 79-km-long Sakri-Dhule-Parola dyke (Ray et al. 2007). Dyke thicknesses range from 3 to 62 m with a mean of 17 m and median of 10 m. The swarm shows a strong preferred orientation with an average N88° strike. Ray et al. (2007) computed about 5 % (and locally higher) crustal extension for the Nandurbar-Dhule dykes, similar to the Icelandic values. They noted that the Nandurbar-Dhule dykes mimic the Icelandic regional dykes in their great lengths, regionally consistent orientations, verticality, and power law length size distribution. However, whereas Icelandic regional dykes show regular (power law or log-normal) thickness size distributions and good dyke length–width correlations, the Nandurbar-Dhule dykes show an irregular thickness size distribution and no correlation between dyke length and thickness. This may be a result of incomplete along-strike and across-strike exposure, or wall-rock thermal erosion due to turbulent magma flow (Fialko and Rubin 1999; Petcovic and Dufek 2005), a mechanism considered insignificant for Icelandic dykes (Gudmundsson and Marinoni 2002).

Many of the long and thick dykes in the Nandurbar-Dhule swarm show multiple columnar-jointed rows (Fig. 7a–d), suggesting that each is the end product of several injections of basaltic magma. Another thick multiple dyke (SH43) in the same swarm, exposed near Shahada and at least 35 km long, shows three columnar rows, each 6 m wide (Chandrasekharam et al. 1999). Even the 79-km-long Sakri-Dhule-Parola dyke, though only 7 m wide over its entire length, is multiple in part (Keshav et al. 1998). This dyke is segmented, with the individual segments in en echelon arrangement, like the regional-length feeder dykes in Iceland.

There is another argument for the thicker Nandurbar-Dhule dykes being multiple injections. Gudmundsson (1995a, b) finds that several of the Icelandic regional dyke swarms have power law thickness size distributions, meaning that the arithmetic average (mean) and the most common (mode) thicknesses are not the same. The mode thickness is <2 m (representing one-third of all dykes), and Gudmundsson (1995a) makes the reasonable argument that all dykes much thicker than 2 m must be multiple injections. In the Nandurbar-Dhule dyke swarm, the thicknesses of only 27 dykes (out of 210 dykes >1 km long) could be measured in the field, and the thickness size distribution is irregular (see Fig. 4a of Ray et al. 2007). However, the mode thickness is 8 m (five out of 27 dykes), and by the same argument as for Icelandic dykes, Nandurbar-Dhule dykes >8 m thick (14 of the 27 dykes) must be multiple dykes. Of course, dykes ≤8 m thick may also be multiple dykes. Thus, a large proportion of the Nandurbar-Dhule dykes are multiple dykes.

Three more thick multiple dykes, and from widely dispersed localities in the Deccan Traps, are shown in Fig. 8. A N40° trending dyke at Vikhroli in Mumbai, on the western Indian coast, shows at least four sets with well-formed joint columns (Fig. 8a). Sheth et al. (2009) mentioned a N75° trending multiple dyke (PMD6) >20 m thick, from the Pachmarhi area of the Mesozoic Satpura Gondwana Basin of central India, and another very thick dyke PMD11 in this area of the northeastern Deccan Traps, with seven to eight jointed rows of a total thickness of 28–34 m, is shown

Fig. 7 Tholeiitic multiple dykes in the Nandurbar-Dhule dyke swarm, central Deccan Traps (Ray et al. 2007). All four views are looking approximately along strike, with people for scale. **a** Dyke NBD9 near Thanepada. Dyke strikes N75°, dips steeply north (*right*), is >23 m thick and covers the whole width of the photo, and shows some ten columnar-jointed rows, each ~2 m wide and indicated by *black arrows*. The southern end of the dyke is eroded away, so the dyke may have been originally thicker. Geologist is Jyotirmoy Mallik. **b** Dyke NBD25 near Hatti. Dyke strikes N83°, dips 85°, is 15.9 km long and 7 m wide, and shows platy jointing. *Arrows* indicate the dyke margins. **c** Dyke NBD41 south of Saitale, with two very clear margins shown by arrows. Dyke trends E-W and is 23.3 km long and 7 m wide. Geologist is Hetu Sheth. **d** *Vertical* dyke with multiple columnar rows. One margin with highly weathered basalt flow is shown by *arrows*. Geologist is Loÿc Vanderkluysen

in Fig. 8b. The chilled margin and thick columns shown in Fig. 2a represent only a part of the northernmost columnar set of this E-W-trending multiple dyke. The N87° trending Sardhar dyke (Fig. 8c), the longest dyke in Saurashtra in the northwestern Deccan (>40 km), also shows many columnar rows.

Thus, multiple dykes are common and abundant in the Deccan Traps. The thinner dykes of the Deccan (say up to 2 m), such as shown in Figs. 2b, 4, are all generally single injections. The thicker dykes in the Deccan (say 5 m or greater), such as those shown in Figs. 6, 7 and 8, are all multiple dykes.

Timescales

Several lines of evidence, summarized by Hardee (1987), indicate that an average magma intrusion rate of 1×10^{-3} km^3/yr will generally suffice to keep a conduit open. A more precise idea about the timescale of formation of a flood basalt multiple dyke can be obtained by considering the solidification time for each magma injection.

Consider a thick multiple dyke like that shown in Fig. 9a, made up of ten 2-m-wide columnar rows. This multiple dyke is a result of five separate dyke injections, each 4 m wide and along the median plane of the existing dyke, as shown in Fig. 9a–e. A heat conduction equation that gives the temperature of intruded dyke magma at a particular distance from its contact at a particular time after intrusion is given by Carslaw and Jaeger (1959):

$$T/T_o = {}^1\!/\!_2 + {}^1\!/\!_2 \,\mathrm{erf}\,[(x)/(2\sqrt{kt})] \qquad (1)$$

where T is the achieved temperature, T_o is the initial temperature, x is the distance of the dyke magma from the contact of the dyke with the wall rock, k is the thermal diffusivity,

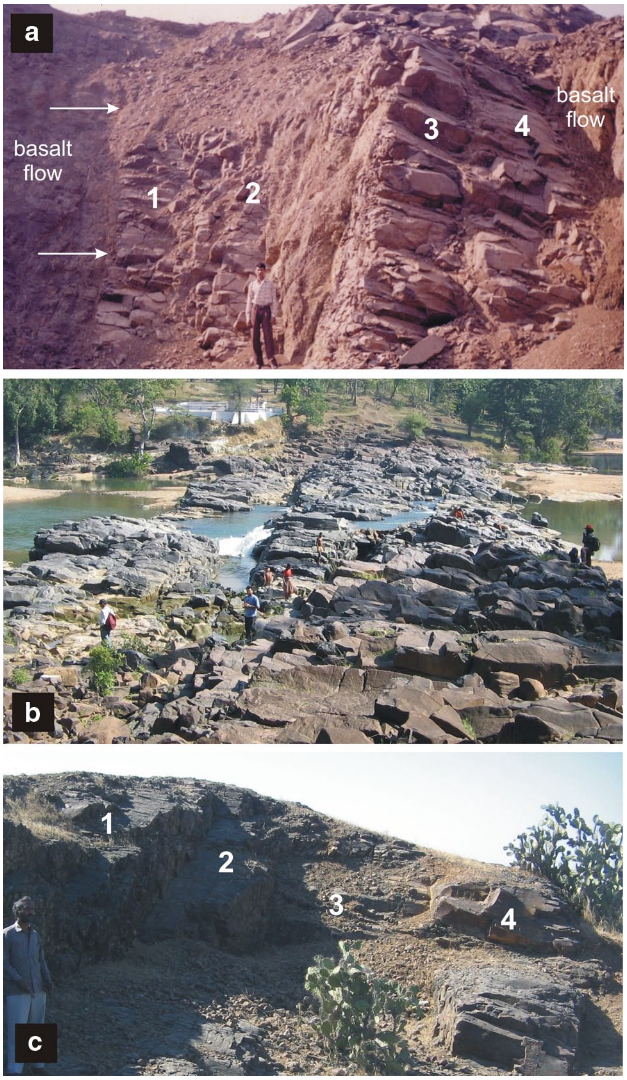

Fig. 8 Tholeiitic multiple dykes in the Deccan Traps. **a** Large dyke with at least four columnar rows, marked 1–4, in the Vikhroli quarry, Mumbai. Person for scale. *Arrows* indicate one of the margins. Dyke trends N40°, dips 83° east (toward the person) and the basalt flow dips 17° west (toward *right*). 1998 photo by Sheth. A much smaller remnant now exists and is the dyke MMD1 of Sheth et al. (2014). **b** Very thick Satdhara multiple dyke PMD11, damming the Denwa River 15 km NNE of Pachmarhi (Sheth et al. 2009). Dyke trends E-W, dips 85°N, and is 28 m wide near the photographer but 34 m wide at the farther end (east), with seven or eight columnar rows. People for scale. **c** The Sardhar dyke in central Saurashtra. Dyke trends nearly E–W, is *vertical*, is several meters wide, and distinctly shows multiple columnar rows, four of which seen in this photo are marked 1–4. Person for scale. This is the longest dyke in Saurashtra, at least 40 km long and possibly >62 km long, if the Kundani dyke (see Fig. 5d) is its lateral extension. If so, the simple Kundani dyke exposes only a single columnar-jointed zone of the multiple Sardhar dyke, giving a feel for the along-strike and across-strike complexities of incompletely exposed dykes

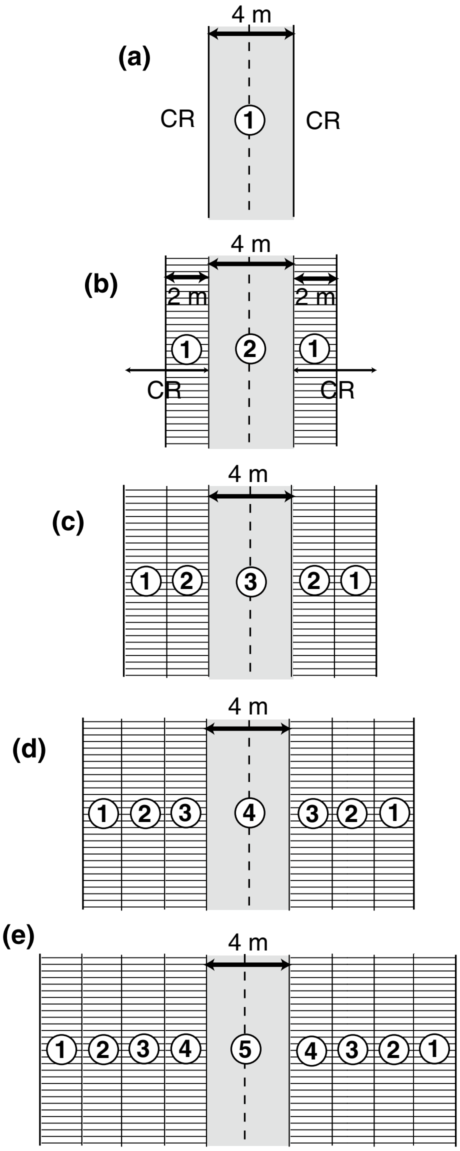

Fig. 9 **a–e** Stages of formation of a multiple dyke, made up of ten columnar rows, emplaced in country rock (CR). The multiple dyke was formed in five separate stages of magma intrusion (marked by numbers *1–5*). Each addition was 4 m wide and split into two by the intrusion of the next one. Columnar joints are shown by *horizontal striped pattern*, and the median plane of each new dyke emplaced by a *dashed vertical line*

and t is time in seconds. The term "erf" represents error function, explained in Philpotts and Ague (2009), and easy to compute using MS-Excel. The thermal diffusivity of basalt (and most rock types) is about 10^{-6} m^2 s^{-1} (Gundmundsson 1995a; Philpotts and Ague 2009).

Solution of Eq. 1 for five injections requires an iterative calculation, but an order of magnitude result can be achieved easily and will suffice for present purposes. Consider that the initial dyke containing basalt magma at its liquidus temperature (~1200 °C at near-surface levels) is emplaced in country rock with a temperature of 25 °C. The dyke starts to develop columnar joints when the magma temperature has fallen to ~800 °C (Gudmundsson 1995a), and columnar joints stop forming when the dyke cools to the glass transition temperature (Budkewitsch and Robin 1994), which for basalt is 725 ± 25 °C (Ryan and Sammis 1981). Because columnar joints grow inward from both dyke margins to the center, the median plane of the dyke in Fig. 9a is the last part of the dyke to solidify and develop columnar joints. All points on the median plane are 2 m away from the contacts of the 4-m-wide dyke, and it is along this plane that the next magma injection occurs. Adjusting the temperature scale so that the country rock is at zero, and using $T_0 = 1175$ °C, $T = 700$ °C, $x = 2$ m and $k = 10^{-6}$ m^2 s^{-1} in the above equation yields $t = 33{,}802{,}000$ s, or about 390 days. Note that using $T_0 = 1200$ °C and $T = 725$ °C does not alter the time estimation significantly.

Assuming that each new magma injection in the multiple dyke is at 1200 °C and is emplaced along the median plane of the former injection, we can estimate the total time of emplacement of the dyke. As the dyke as a whole is widening with repeated injections, the time required for cooling the median planes of the latest injection to 700 °C (the new set country rock temperature) increases because of more effective insulation. Thus, a multiple dyke containing five injections each 4 m wide would take at least 1,950 days, or about 5 years and 4 months for its emplacement.

This time must represent a *minimum* because: (1) the successive injections were taking longer to cool to a given temperature as the dyke was widening, (2) it was assumed that consecutive magma batches were available and emplaced immediately as the previous magma batches had cooled to 700 °C, (3) the calculation takes into account only the last volume of magma that solidified in situ after each injection and does not account for the volume of magma that may have flowed in the dyke fracture, potentially for months to several years, associated with each separate magma injection event, and (4) the latent heat of crystallization of the dyke magma is not easy to incorporate in the model, but will further retard the cooling of the dyke. Nevertheless, the simple calculation shows that a large multiple dyke (20-m-thick and ten columnar rows) would form over several years and possibly a few decades (noting the observations in Iceland).

Discussion

Individual flood basalt eruptions: monogenetic or polygenetic?

Apart from brief statements by Walker (1993, 1999, 2000) that flood basalts are monogenetic eruptions, the question of the monogenetic or polygenetic nature of flood basalt volcanism has not been addressed in the literature. Walker (1993) described "flood basalt fields" in the following manner: "These consist of monogenetic volcanoes erupted from widely scattered vents, but their lava flows cover wider areas than in monogenetic volcano fields, overlap or are superposed to form parallel-stratified successions, and have much greater volumes." Walker (1999) wrote: "Flood basalt fields are also monogenetic in character, but their lavas tend to flood the landscape and are volumetrically larger," and Walker (2000) wrote about "flood basalt fields" that "These consist of voluminous and extensive spreads of lava flows erupted from scattered monogenetic fissure vents." His statements make it clear that he considered individual flood basalt eruptions to be produced by single feeder dyke intrusion events and as "large monogenetic" (our term) eruptions, contrasted only in their high fluidity and very high time-integrated magma output with typical "small monogenetic" (our term) volcanoes.

We have shown here that multiple dykes are common in flood basalt provinces, and therefore, eruptions produced by them were polygenetic eruptions. A key issue is whether the dykes illustrated here (either single-injection or multiple) were indeed feeders. The tops of these dykes are truncated by the present erosion level, so it cannot be determined whether they did feed eruptions at higher levels or were arrested in the crust. However, as suggested by geochemical and isotopic correlations, some of the Nandurbar-Dhule dykes may have fed the lower to middle stratigraphic levels of the >2-km-thick Western Ghats lava sequence, and some Borlai-Korlai dykes (Figs. 2b, 5b, c) may have fed the upper levels of the Western Ghats sequence (Dessai et al. 2008; Vanderkluysen et al. 2011). Thus, both single-injection and multiple injection dykes may have been feeders.

Theoretical considerations of the mechanisms of dyke arrest also lead us to expect a large number of feeders among the surviving remnants of the Deccan dykes. Briefly put, dykes tend to become arrested when they encounter unfavorable stress fields in the country rock, commonly associated with the effects of mechanical layering produced when strata with low stiffness (such as ash or scoria layers) are interbedded with lava flows, or when weak bedding contacts open up (e.g., Gudmundsson 2002; Gudmundsson and Marinoni 2002). Galindo and Gudmundsson (2012) suggest that only ~10 % of the dykes injected into stratovolcanoes and ~30 % of the dykes injected into shield volcanoes become feeders, reflecting the importance of stratification and heterogenous mechanical properties. For an essentially uniform flood basalt sequence (like the Deccan, with almost no pyroclastic beds in between), the ratio of feeder to non-feeder dykes should be considerably higher. An additional consideration is that observed dyke tips (terminations of arrested dykes in vertical sections) are extremely rare in the Deccan.

Therefore, a 50:50 ratio of feeder to non-feeder dykes in flood basalt provinces such as the Deccan is a conservative and reasonable figure. Although many Deccan eruptions, associated with single-injection dykes, would classify as monogenetic as Walker (1993, 1999, 2000) envisaged, the large number of multiple dykes illustrated here suggests that many Deccan eruptions were polygenetic by even the restricted definition (repeated use of the same dyke conduit).

Implications of polygenetic flood basalt eruptions

The recognition of many flood basalt eruptions as polygenetic helps to understand some of the hitherto unexplained problems of the associated tectonics, volcanology, and stratigraphy. Flood basalts are now viewed by some (e.g., Silver et al. 2006) as rapid magma drainage events rather than instantaneous mantle melting events, rendering thermal anomalies (plumes) unnecessary. Nevertheless, in the new scenario, the question of storage of the huge (say 1,000 km^3) magma volume represented by individual flood basalt eruptions is still formidable (see Bryan et al. 2010). The multiple nature of the flood basalt feeder dykes can solve this problem at least to a degree: If the feeder dyke of a 1,000 km^3 lava flow involved five separate magma injections, the magma volume having to be stored at a time would be on the order of 200 km^3. The reduced volume of magma is also compatible with independent reservoirs that may lie at a relatively short distance from one another in the magma production zone, therefore increasing the zone of influence of each flood eruption tapping the magma. The main idea here is that a flood basalt eruption initiated by the extrusion of magma from one of those reservoirs eventually leads to the tapping of an adjacent reservoir, due to the interaction of magma batches at depth. This interaction would be similar to that proposed by Takada (1994a, b), except that even when the initial magma batches came from two different reservoirs (and therefore required two different dykes to rise initially), dyke convergence before reaching the surface would explain the occurrence of multiple dykes at shallower depths.

Polygenetic flood basalt eruptions are more likely to produce compound flows than simple flows, at different scales (meters to kilometers). We mean that breaks in a single eruption, ended by new magma injection every few years in the same multiple feeder dyke, will produce a flow or flow field with internal contacts, i.e., a compound flow. Whether later magma injections in the same feeder dyke would erupt lava in vent-proximal or distal locations would, of course, depend on the lava distribution network developing in the erupting and growing lava flow (Self et al. 1997).

Much recent effort has gone into identifying the feeder dykes of the Deccan flood basalts and building eruptive models for the province, using field and geochemical-isotopic data for dykes and flows (Bondre et al. 2006; Sheth et al. 2009; Vanderkluysen et al. 2011). However, dyke-flow correlations in the Deccan have not been overly successful, because of: (1) common and often extensive alteration and weathering, (2) small but significant differences in chemical and even isotopic composition sometimes observed between dykes and flows, which cannot be ascribed to weathering (see, e.g., Bondre et al. 2006 on the Sangamner dykes). The isotopic differences cannot arise by in situ fractional crystallization, crystal accumulation, or similar processes. Such observations may mean that the flows or the dykes, more probably both, are internally heterogenous (see also Vye-Brown et al. 2013b), and the sampling has been inadequate and nonrepresentative. If the feeder dykes were multiple, it is of clearly necessary to correlate the appropriate magma injection to a particular eruptive unit.

We think that some of the drastic geochemical changes observed through the Deccan stratigraphy may be a result of multiple dykes. Mahoney (1988) noted that the pronounced geochemical shift from the highly crust-contaminated Bushe Formation in the middle of the Deccan sequence, to the overlying, moderately contaminated Poladpur Formation in the upper part, may reflect coating of the wall rocks by chilled rinds of the earlier magmas, thus preventing later magmas from coming in contact with the wall rocks. This scenario is very similar to the multiple feeder dyke explanation we offer in this paper, with the corollary that the youngest Bushe magmas and the earliest Poladpur magmas may have been erupted from the same multiple dyke. On a still smaller temporal scale, two successive, compositionally similar (though not identical) lava flows of a single stratigraphic formation may have been erupted from multiple injections in the same feeder dyke, rather than from two separate dykes. If so, a relatively small number of multiple dykes may have fed the Deccan lavas.

Later magma injections in a multiple dyke may also have a different magnetic polarity than earlier injections. Rapid magnetic polarity changes identified in individual flood basalt lava flows (see Coe et al. 1995 on the Columbia River province) should be recorded in their multiple feeder dykes. Even in the absence of visually identifiable multiple injections within dykes, magnetic studies could detect cryptic multiple injection events (Cañón-Tapia and Herrero-Bervera 2009; Cañón-Tapia and Coe 2002).

Many large (long and thick) multiple Deccan dykes, such as the >40-km-long Sardhar dyke, remain to be analyzed for geochemistry. Even for the dykes well studied in terms of their structure, petrology and geochemistry, such as the Nandurbar-Dhule dykes (Melluso et al. 1999; Ray et al. 2007; Vanderkluysen et al. 2011), isotopic data are scarce. Where field and extensive geochemical data (including Sr–Nd isotopic ratios) exist, as for dykes from Mumbai and Pachmarhi (Fig. 8a, b, Sheth et al. 2009, 2014), multiple zones of the dykes have not been sampled and analyzed. To test the possibilities mentioned above, future geochemical and magnetic polarity studies should sample large dykes not only along their length, but also across their thickness.

Flood basalts provinces: monogenetic or polygenetic?

A flood basalt field might be considered as a polygenetic volcano with widely scattered vents. However, the wide geographic separation between eruptive vents, and the lack of a dominant single vent, makes flood basalt provinces akin to monogenetic volcanic fields, with only the difference that the volumes of the individual constituent eruptions are vastly larger in the former. This creates a conceptual contradiction, because a flood basalt field cannot be simultaneously a polygenetic volcano, and its very opposite, a monogenetic volcanic field. An additional complication is that many individual flood basalt eruptions can be considered polygenetic events.

For this reason, we suggest that the so-called “monogenetic volcanic fields” are much better described by the term “diffuse volcanic fields” which gives their accurate description and which is non-commital about how many eruptions may have produced the individual volcanic centers. If the term “monogenetic” is dropped, then “polygenetic” should be dropped as well, and the latter volcanoes are best described by the more specific “shield volcanoes,” “stratovolcanoes,” and “flood basalt fields.” We do not recommend the term “central volcanoes” commonly applied to stratovolcanoes, as that would also include most small, short-lived, “monogenetic” volcanic centers.

Concluding remarks

We show that a flood basalt province like the Deccan Traps can, within the framework of current definitions and concepts, be equated with a polygenetic volcano (but lacking a dominant vent), as well as with a monogenetic volcanic field (with each eruption being “large-volume monogenetic,” unlike typical “small-volume monogenetic” eruptions). However, all these terms have problems, and better ones are needed. If we use current terminology, individual flood basalt eruptions are not all monogenetic, as Walker (1993, 1999, 2000) suggested, but many are polygenetic eruptions, in which the same feeder dyke fissure was used repeatedly by multiple magma batches. This recognition helps to understand the volcanological, stratigraphic, and geochemical complexity of flood basalts, which is increasingly apparent as our knowledge and techniques improve.

While data-gathering and data-reporting are important, conceptual developments should keep pace with them. In this sense, although Walker (1993, 1999, 2000) was only partly correct when he briefly mentioned flood basalt eruptions as monogenetic, he should be credited for at least thinking about an issue which has been little discussed by others. Our work follows on the lines of Szakács (1994, 2010), Sheth (2007), Cañón-Tapia (2010), and several others in Szakács and Cañón-Tapia (2010), and emphasizes a need for clear concepts and correct terminology and definitions. Some of the existing terms, though often used incorrectly and inappropriately, are popular because they are catchy and can be turned into catchier acronyms. A good example is “Large Igneous Provinces” (LIPs), which, as defined by Coffin and Eldholm (1993), include mafic provinces formed by processes other than sea-floor spreading and plate tectonics. Sheth (2007) argued that the term ought to include many more igneous provinces besides flood basalts, of all compositions, emplacement depths, origins, and tectonic settings. The “revised LIP definition” (Bryan and Ernst 2008) has improved little over the original in that an intraplate setting and “intraplate geochemical affinity” (whatever that means) of the volcanic rocks—ironically the most debatable aspects—are considered essential characteristics (see Cañon-Tapia and Szakács 2010 for a detailed discussion). A recent invited review of large igneous provinces (Bryan and Ferrari 2013), claiming to present the “progress in our understanding over the last 25 years,” maintains the Bryan and Ernst (2008) definition and does not even mention Sheth (2007) or Cañón-Tapia (2010).

We suggest that volcanic fields typically described as monogenetic volcanic fields (many of which contain individual centers with polygenetic histories) should be described as “diffuse volcanic fields,” and the term “polygenetic” should be similarly dropped. We emphasize that “monogenetic” and “polygenetic” are interpretative terms, whereas “shield volcanoes,” “stratovolcanoes,” and “flood basalt fields” are descriptive terms, providing good physical descriptions of these features. With this contribution, we start a discussion which we hope will involve a large number of researchers and thinkers from the volcanological community.

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