Scientific Research Publishing

Open Journal of Geology, 2023, 13, 221-268
https://www.scirp.org/journal/ojg
ISSN Online: 2161-7589
ISSN Print: 2161-7570

Genetic Classification of Pyroclastic Ejecta Based on Physical Volcanology of Possible Large Cauldron in Bombay Volcanic Complex, Western Deccan Trap Province, India

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How to cite this paper: Sharma, R.K. (2023) Genetic Classification of Pyroclastic Ejecta Based on Physical Volcanology of Possible Large Cauldron in Bombay Volcanic Complex, Western Deccan Trap Province, India. *Open Journal of Geology*, **13**, 221-268.
https://doi.org/10.4236/ojg.2023.133011

Received: January 20, 2023
Accepted: March 28, 2023
Published: March 31, 2023

Abstract

Many Propositions are made about the mechanism of emplacement of volcanoclastic material in the Bombay volcanic complex. The present paper deals exclusively with the physical features of the deposits laid by a complex tectono-magmatic process by making detailed inventory of the different kind of volcanic ejecta exposed in the Bomay Volcanic Complex (BVC), and an attempt has been made to classify the deposits genetically. A subsidenace which was hinted at earlier, may be a possible cauldron in BVC has been proposed, which might be responsible for producing such a varied and complex lithology.

Keywords

Bombay Volcanic Complex, Western Deccan Province, Physical Volacanology, Genetic Classification, Pyroclastic Ejecta, Cauldron

1. Introduction

Indian Plate motion over the Reunion Hotspot resulted in extrusion of the end-Cretaceous voluminous basalt lavas of the Deccan Flood Basalt Province (DFPB) that presently cover 500,000 km^2 in western India (**Figure 1**) (Krishnan, 1968 [1]; Subbarao 1981 [2]). This Large Igneous Province (LIP), popularly known as Deccan Traps, is regarded as the second-largest flood basalt province in the world, next to the Karoo (Hooper, 1990) [3], although the lava flows are estimated to have originally covered approximately 1.5 × 10^6 Km^2 (Aswathnarayan, 1971) [4]. In the geographic context, the DFPB has been subdivided into four major domains, namely the Malwa Plateau (north of Narmada River), Main Deccan (south of Narmada), Mandla Lobe (north-eastern part), and Saurashtra Plateau (north-western part) (**Figure 1**). The flows are sub horizontal (<1˚ dips)

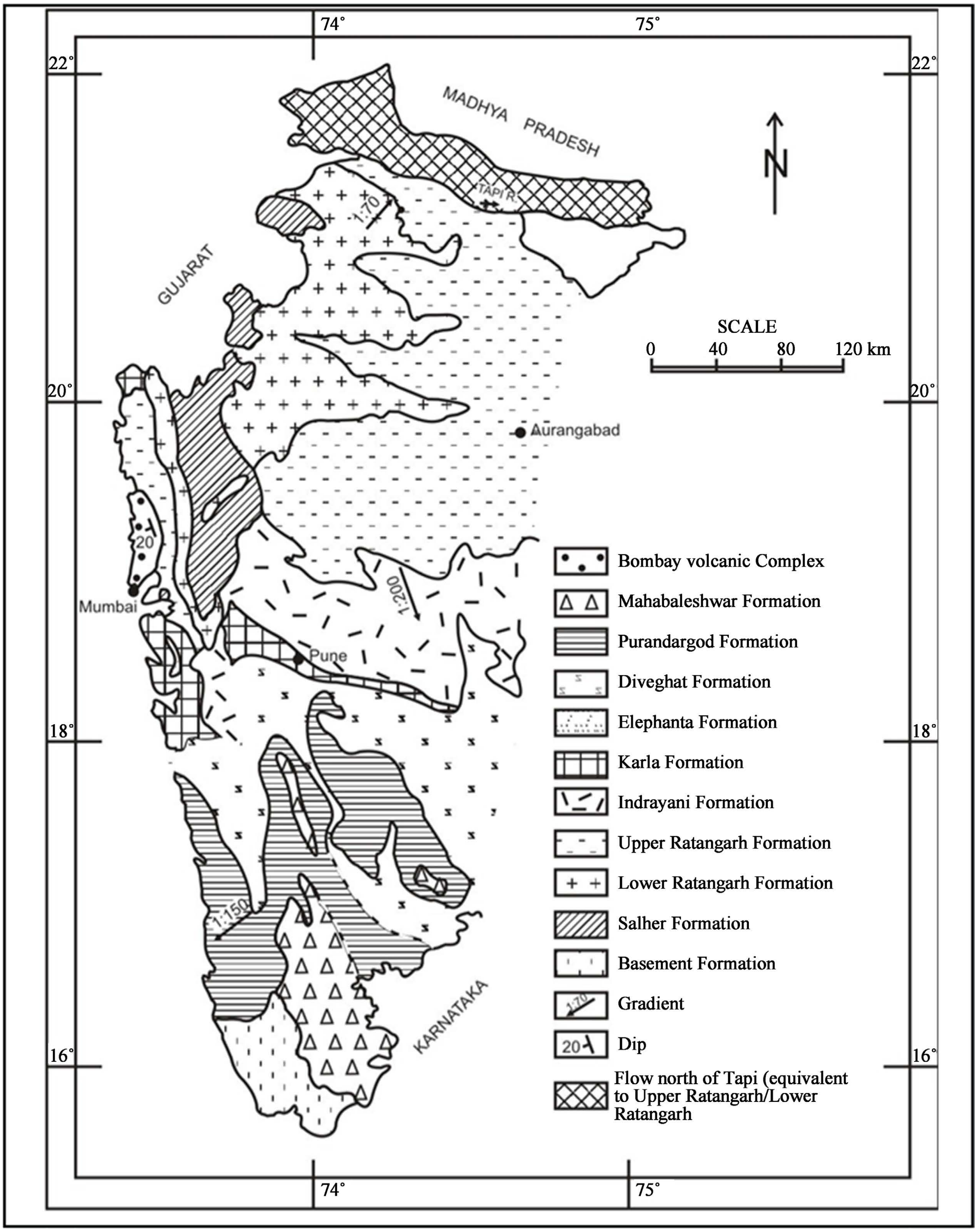


Figure 1. Sketch map of western Maharashtra exhibiting distribution of lava Formations of DVFB, (Godbole *et al.*, 1996).

and "marker flows" are traceable over several km, therefore, used in regional correlation and flow stratigraphy (West, 1958 [5], Raja Rao, *et al.* 1978 [6]). However, steeper southerly dips (up to 20˚) have been noted in some flows along the west coast (Godbole, 1988 [7], Sharma, 1992 [8]). On account of its vast expanse, excellent exposures, and a key position in understanding the Cretaceous-Neogene transition and climate change and Indian plate dynamics, the DVFB has been the focus of continued geoscientific attention that have provided useful information on extrusion mechanism (Aghashe and Gupte, 1971) [9], petrogenesis, paleomagnetism, geochemistry and flow stratigraphy (Beane, *et al.* 1986, [10], Bodas, et al. 1988, [11], Cox, and Hawkesworth, 1985 [12]). These studies have identified a largely monotonous, Fe-tholeiitic nature of Deccan basalts while some minor alkaline suites (Girnar, Pavagarh, and Kutchchh have also been studied (Bose, 1980, [13], Krishnamurthy, *et al.* 1999, [14], Greenough *et al.*, 1998 [15]). In stark contrast to the tholeiitic characteristics sustained throughout the Deccan province, a suite of volcanic rocks exposed in a small region to the west and north of Mumbai metro characterizes a heterogeneous volcaniclastic assemblage comprising felsic lavas (Sheth and Pande, 2014) [16], and pyroclastic rocks (agglomerates, tuffs, etc.), plutonic and subvolcanic intrusive bodies (**Figure 1**). Ghosh, 2022 [17], has described pyroclastic rocks of india in time nd space but detailed account of pyroclasts of the BVC did not find a place, Sheth, 2018, [18], published photographic atlas of field features of flood basalt but details of pyroclasts from BVC is not included. The diversity and complexity of this suite indicate a unique volcano-tectonic environment, distinct from the main Deccan Flood Basalt volcanism. This region is separated from the main Deccan Province by an arcuate fault in the east and any correlation between the two seems unlikely on account of an abrupt change in the volcanic facies and absence of tuffs, agglomerates, and felsic volcanics in the mainland Deccan Traps.

Despite offering an interesting setting and a variety of pyroclastic rocks, the region has not received due geoscientific attention, probably on account of its minuscule extent compared to the main Deccan Traps. Krishnamurty (1981) [19] and Powar (1982) [20], attributed the origin of these rocks to a failed rift along the coast from Cambay to Mumbai (Bombay) as one of the arms of the Cambay triple junction, Sears and Hyndman 1988, assigened origin of LiP' s like DVP to terrestrial maria, Sheth, (2007) [21], suggested pre eruption uplifting in the area, based on the presence of mafic dyke swarms (Deshmukh, S.S. and Sehgal, 1980 [22]), agglomerates & felsic tuffs (Raman, 1979) [23], alkaline plugs, hot springs, and steep dips, Godbole, 1988 designated these rocks as the Bombay Volcanic Complex (BVC). The same nomenclature has been followed in this communication. Earlier, Clark (1869) [24], had noted tilted flows in the Mumbai (erstwhile Bombay) region and observed that the hills of Seleste Island have peaks and moderate slopes while those in the Konkan area are flat-topped, and suggested that the flows in the Bombay area originated in the adjacent Konkan coast. Auden (1949) [25], recognized flexuring of the flows in the Panvel area in Mumbai while agglomerates in the vicinity of Borivali National Park as the probable locales of effusive vents. Raman (1979) [23], also observed that some of the felsic flows may be reworked pyroclasts. Sears and Hyndman (1988) [26], proposed a terrestrial Maria, analogous to the Lunar Maria, and suggested the development of a crater due to the impact of an extra-terrestrial body. The overflow or spillover of this crater/Lava Lake was responsible for the spread of the Deccan basalts. Although the crater suggested by them corroborates with the arcuate fault in the coastal arean (the eastern boundary on land, as the western half of the proposed crater lies in the Arabian sea, which cannot be verified), this hypothesis fails to explain the non-correlation between BVC lithologies and basaltic flows in the Deccan mainland, to the west and east of the arcuate fault, respectively. The plume origin of Deccan basalt volcanism associated with the Indian plate movement over the Reuinion Hotspot has been the largely accepted explanation (Peng and Mahoney, 1995) [27], Sheth (2005) [28], postulated the development of such a LIP by Ocean floor spreading. On the other hand, Chatterjee and Rudra (1996) [29], argue for origin through impact catering and have identified a submerged impact crater on the passive western Indian shelf that they named "Shiva Crater" located west of Bombay in the Arabian Sea (Chatterjee, *et al.* 2006 [30]. Their model is based entirely on the borehole data from oil exploration drilling in Bombay High and adjacent oil fields, however, they remain largely silent about the features on the land and have hardly given any details of the crater on land. A 500 km diameter crater, as proposed by these authors, would have generated gigantic scale volcanism and the products are expected to have homogeneity over large areas. This is in contrast to the miniscule volume and complex and diverse lithologies encountered in the BVC. The proposed models on the evolution of DVFB are based on the data from basic volcanic rocks and considerations on lithosphere configuration and the dynamics of the Indian plate. Although volumetrically negligible, the lithologically unique BVC is significant in providing additional constraints helpful in understanding the geological evolution of the DFB province, not much is known in terms of the lithological characteristics, geological relationships, depositional features of the BVC. This paper is the first attempt to provide a comprehensive account of the geology of the BVC comprising the lithological diversity of pyroclastic deposits and hybrid flows, field relations, megascopic and petrographic characteristics. The effusive setting and depositional environment indicators, textural characters of the acid, and basic tephra have been discussed to work out a non-genetic classification of these rocks and infer the volcanic setting resulting in such a diverse assemblage of volcaniclastic rocks within a small area.

1.1. Geological Overview

The Deccan Volcanic Province (DVP), one of the best-preserved and most extensive continental flood basalt provinces in the world, which erupted during the Cretaceous-Paleogene period and is linked to the mass extinction. These are also referred to as Deccan Traps in geological literature. The term "Deccan Trap" was coined by W.H. Sykes in 1833, [31] and is derived from a Sanskrit word Dakshin meaning south or southern and a Swedish word Trapp/Trappa meaning Stair, to describe the step like or terrace like topography characteristic of this terrain. This volcanic province covers half a million square kilometers in aerial extent, covering a major part of western and central India; the estimated extent prior to erosion being 1,500,000 sq.km, with a volume of approximately 1.3×10^6 cubic km.

Geographically, the DVP has been divided into various sub-provinces-Main Deccan Province, Malwa Traps, Saurashtra and Kutch Traps and Mandla Traps. It is thickest in the western ghats, thickness varying from 400 m to 1650 m. The DVP is dominantly made up of sub aerial tholeiitic basalts with subordinate picrites, picritic basalts and alkaline basalts. The basalts are quartz and hypersthene normative, low-K tholeiites; plagioclase, (labradorite-bytownite) augite, occasional olivine and secondary zeolites being the main mineral constituents. Volcano plutonic complexes (acidic to alkaline flows, gabbros, lamprophyres, carbonatites, dolerites, ne-syenites, etc.) exposed in Saurashtra, Khambat graben, Narmada rift and West coast show considerable diversity of rock types.

In the last four decades lot of research has been done on DVP, which has resulted in a wealth of information on stratigraphy, geochemistry, paleomagnetism, biotic assemblages, tectonics etc. Lithostratigraphic classification has been established by Geological survey of India (GSI), separately for Main Deccan Province (Western Maharashtra) and Eastern Deccan Province separately, based on extensive field studies with emphasis on litho logical characters. This is based on observable criteria like, flow type, flow gradient, marker horizons like Megacryst (Giant Plagioclase Basalt). DVP was assigned Supergroup status, with Sahyadri Group, divided into three Subgroups (Kalsubai, Lonavala, Mahabaleshwar), which comprise nine Formations (Salher, Lower Ratangad, Upper Ratangad, Indrayani, Karla, Diveghat, Purandargad, Mahabaleshwar) and four members, marker horizons (M1, M2, M3, M4). Based on geochemical work, a Chemostratigraphic classification (was established by a different groups from India, USA and UK, for the MDP (Western Maharashtra). As per this classification, the Deccan basalt Group comprised of three Subgroups (Kalsubai, Lonavala,Wai)and twelve Formations (Jawahar, Igatpuri, Neral, Thakurwadi, Bhimashankar, Khandala, Bhuse, Poladpur, Ambenali, Mahabaleshwar, Panhala, Desur). The Lithostratigraphic and Chemo-stratigraphic classification show sound correlation. Attempts have been made to correlate the flows across other subprovinces, the validity of such a correlation has been doubted because of the structure, tectonics and the crustal contamination.

Intrusive bodies like sills, dykes and plugs form an important component of flood basalt provinces. These show a large variation in their geographic distribution, mineralogy and geochemical characters. The dykes display uniformity in their trend in Narmada-Tapi region (ENE-WSW), along the west coast (NNW-SSE to N-S) and Maharashtra Plateau (NE-SW), thus exhibiting three trends on a regional scale. The Narmada-Tapi dyke Swarm and the West Coast dyke swarm constitute dykes having tholeiitic as well as alkaline composition. The dykes of

Maharashtra plateau (upland) are generally tholeiitic. Some of these dykes host a variety of xenoliths of crustal and mantle origin. Recent studies show that some of the east-west dykes from Narmada-Tapi area and a few of the N_S trending dykes show chemical affinities to the lower and middle formations of Kalsubai and Lonavala Subgroup (Krishnamurthy, 2020) [32].

Absolute age data, based on Ar-Ar and U-Pb indicate the period of volcanological cycle from 69.5 to 62 Ma. Krishnamurthy (2020) [33] which included three pulses. The earliest eruptions were along the rift valleys (Narmada, Cambay) and also the Malwa sub province; the main pulse (Kale and Pande, 2022) [34]. Paleomagnetic studies in MDP, has resulted in a 30N-29R-29N magnetostatigaphy, wherein the main pulse constituting most of the lava pile, coincides with 29R. The boundary between Purandargad (Ambenali) and Mahabaleshwar Formations corresponds to the 29R/29N transition (Verma and Khosla, 2019) [35]. This main pulse was almost continuous volcanic event that straddled the Cretaceous Paleogene boundary (KPB), with ~1.3×10^6 cubic km of flood basalt outpouring. This could have substantially affected the Late Maastrichtian environmental crisis (Keller *et al.*, 2016) [36]. The third pulse is represented by the volcanics around Bombay/Mumbai, which continued upto 61Ma (Kale and Pande, 2022) [34]. Jain *et al.* (2020) [37] have reported significant volumes of lava erupted during the late pulse underlying the petroliferous sediments in the Bombay Offshore complex (Jain *et al.* in, Kale and Pande, 2022) [34].

1.2. Regional Geology

The target terrain of the present study, the region towards the west of the Panvel Flexure, designated as Bombay Volcanic Complex (BVC) Godbole, 1988 [7] is described as the youngest phase of the Deccan volcanism. The rhyolitic flows from Dongari area have yielded 62.6 ± 0.6 to 62.9 ± 0.2 Ma ages ($^{39}Ar/^{40}Ar$ method) by Sheth and Pande (2014) [16]. In contrast to the monotonous and largely homogenous Fe-tholeiitic flows of main Deccan Traps (porphyritic to aphyric basalts) of the DFBP, the BVC is characterized by a heterogeneous association of unclassified basalts, acidic flows, interbedded basaltic flows and agglomerates, volcanic breccias, acidic and basic tuffs, etc. The area also exposes some gabbro and diorite plutons (**Figure 2**). The BVC extends from Mumbai in the south to Akkarpatti in the North, westward it continues offshore into the Arabian Sea. An arcuate fault defines its eastern and northern limit and directly juxtaposes these rocks with the mainland Deccan basalt flows. This fault is traceable from Danda Creek (Mahim-Kelve) in the North to Paye-Kharbao in the south through Parol with a break in the Mumbai region where it is concealed under the alluvium (Godbole *et al.* 1996) [38]. This fault is convex towards the east and separates a thick pile of pahoehoe flows towards north and east of it, from the hybrid basalt and interlayered sequence of basaltic flows and volcanic tephra and plutonic rocks belonging to the BVC, exposed to the west of the fault. The rocks exposed within the BVC are characterized either by a very steep gradient or gentle westerly dips (10^0 to 20^0) in the coastal region. This pile of hybrid basalt and volcaniclastic rocks represents the violent phase of volcanism, post-dating the main phase of Deccan volcanism (Devey & Lightfoot 1986, [39], Duncan and Pyle 1988 [40], Hopper 1994 [41] & Hooper *et al.*, 2010, [42], Sheth, *et al.* 2001) [43]. The complexity of rock types and their mutual relations make it difficult to classify these rocks, however, large-scale mapping has helped in determining the gradient of flows and mutual relations, while physical depositional features have helped develop the stratigraphic succession of BVC. The stratigraphic succession of the BVC erected by Godbole (1988) [7] is given here under.

Alluvium and beach sand deposits.
Karal Rocks.
Basic and acidic intrusive.
Acidic flows and Acidic tuffs.
Agglomerates with interbedded basalts.
Fine-grained, plagioclase phyric and non-porphyritic basalt.
Crystalline basalt with bands of agglomerate.

The basaltic flows exposed within the BVC are aphyric to plagioclase phyric. However, the flow-top determination criteria, such as the presence of red/green bole, Fragmentary tops, clinker at the base, and vesicular horizons are conspicuously absent, making flow demarcation difficult. (Godbole, *et al.* 1977 [44], Ghodke, *et al.* 1984 [45], Godbole *et al.* 1996 [38], Godbole, 1988 [7] and Godbole and Ray 1996 [46]. The flows are massive, hard, non-vesicular and at places, possible magmatic lapilli or immiscible globules can be seen as spherical droplet-like features. The spherical bodies are extenuated on weathering and appear as few mm (an ink drop size) to tens of cm diameter pendants on the weathered rock surfaces. Such features are best developed at the Tungar hill. Another peculiar feature observed is the nearly baked/charred bodies of lava, enclosed within the basaltic flows. Volcanic agglomerates and other volcaniclastic deposits including acidic flows and tuffs (welded and non-welded), mudflows, reworked pyroclasts and tuffs exhibiting banding and lamination, pyroclastic surge deposits, possible lava fountain deposits and lahar type deposits can be seen at various places. Acidic flows with spatter features occur along the Bhuigaon coast. The intrusive phases in BVC are basaltic, dolerite, diorite, rhyolite and gabbro dykes,. The Tertiary sedimentary deposits comprising sand derived from basalts, pyroclastic rocks and dykes, and embedded indurated calcareous cement and sea-shells are locally designated as Karal rocks. These occur as patchy outliers restricted to the shore region and display variable thickness and shallow westerly dips.

2. Lithology and Nomenclature: (The Present Contributions Based on the Large Scale Mapping of the Pyroclasts of BVC)

A fairly good preservation factor of the rocks of BVP allows a systematic inventory of megascopic characteristics and depositional features useful in modeling the emplacement history. The following parameters have been used to document these aspects.

1) Clast composition, shape, size, and mutual cohesion; 2) Depositional features; 3) The geometry of the deposit; 4) Vesicularity of the rock type (5). Basaltic rocks and their relationship with the pyroclastic ejecta. These rocks being indurated pyroclastic ejecta, non-genetic classification has been attempted by utilizing their lithological characteristics and facies evaluation. However, this scheme of non-genetic classification has not been embodied in the IUGS sub-commission on the Systematics of Igneous Rocks on the descriptive nomenclature and classification of pyroclastic deposits (Schmid, 1981) [47]. Although Schmid (1981) [47] professed that this scheme used is descriptive rather than genetic. The lithological classification is the most important nongenetic classification, based on characteristics of constituent fragments and the degree and type of welding, grain size variation and the overall size distribution within the deposit. Using these parameters, Fisher (1960 [48], 1961 [49], 1966) [50] has proposed the grain size limits of various pyroclastic fragments, subsequently modified by Schmid (1981) [47], to include a granulometric classification for various pyroclastic deposits into two main categories. Wright & Mutti (1981) [51] have grouped all pyroclastic deposits into two major types, *i.e.* pyroclastic flow and surge deposits, and pyroclastic fall deposits.

Pyroclastic deposits with 50% or more ash size fractions are named "ash flow" deposits (Fisher and Schmincke, 1984) [52], while the terms "Block" and "Ash flow" are used for coarse-grained deposits with <50% juvenile and ash size fragments (Perret, 1937) [53]. The term "Pumice Flow" is used for deposits containing less than 50% blocks and lapilli and "Welded tuff" is used when the features of welding are observed. In the following section, the afore mentioned criteria have been utilized to attempt a non-genetic classification of pyroclastic deposits of BVC. For this purpose, the study area has been subdivided into various sectors characterized by a common field and depopsitional characteristics. The pyroclastic ejecta in the area has been grouped in various sub groups based on clastsize, type of the clasts, and depositional features/structures associated with them (R.K. Sharma, 2000 [54], 2020 [55], 2022 [56] and Sharma 1992 [8], 2018 [57], Sharma and Pandit 1998 [58]). The main categories identified are

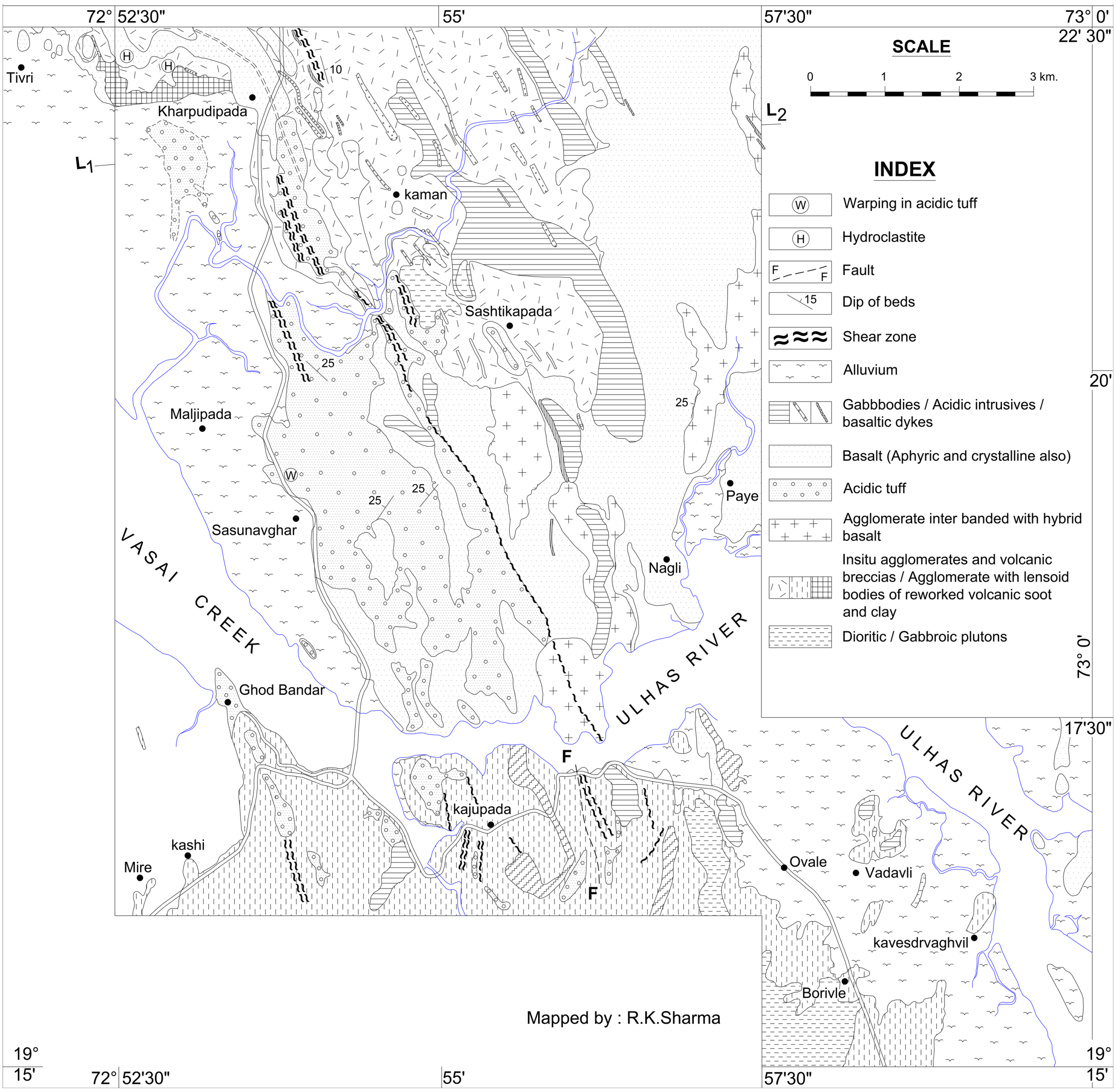
1) The coarse grained deposits including volcanic breccias and agglomerates.

2) Ejecta with finer clasts and tuffaceous nature.

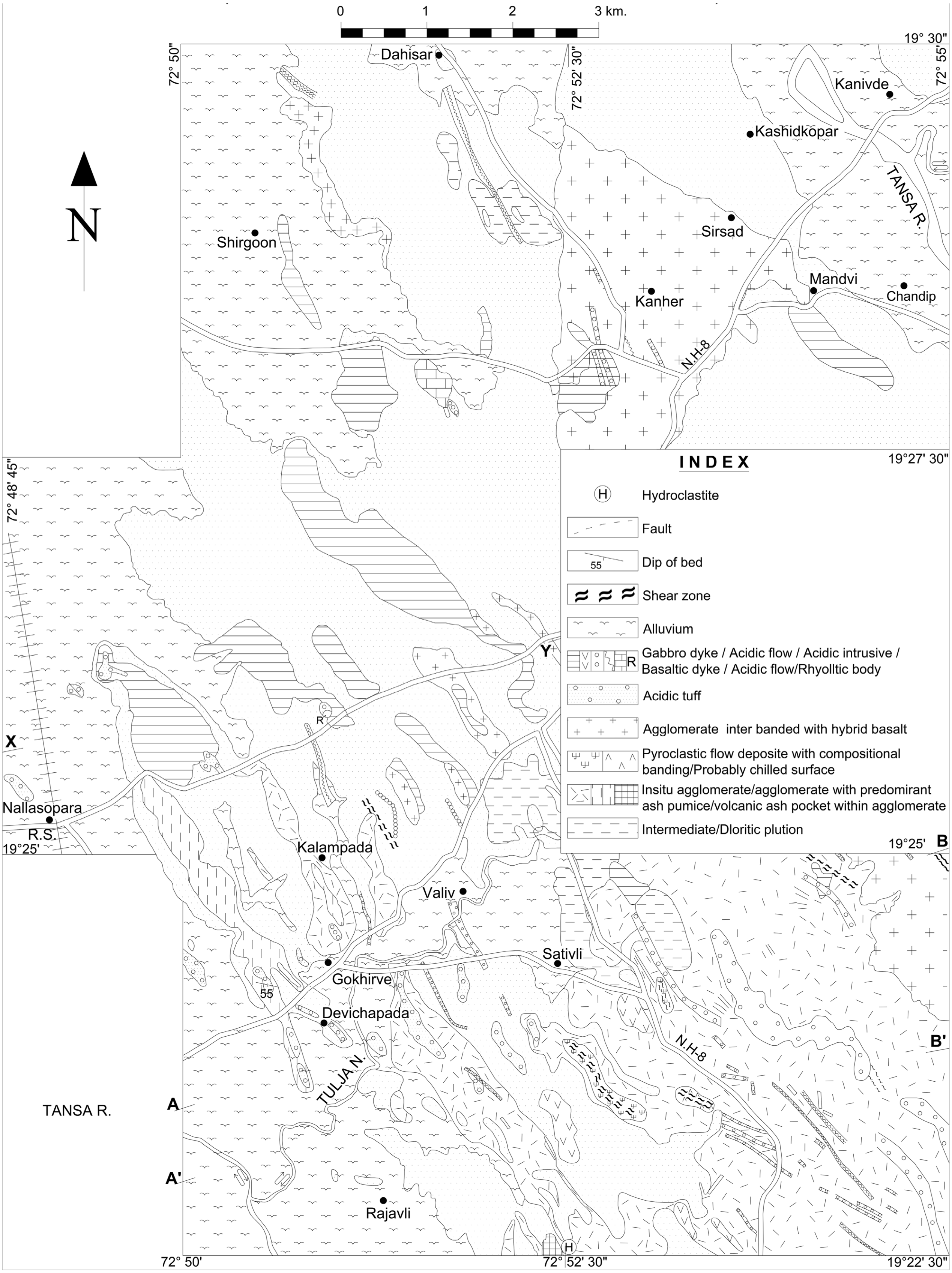
3) Bedded Pyroclasts.

2.1. The Coarse Grained Pyroclasts

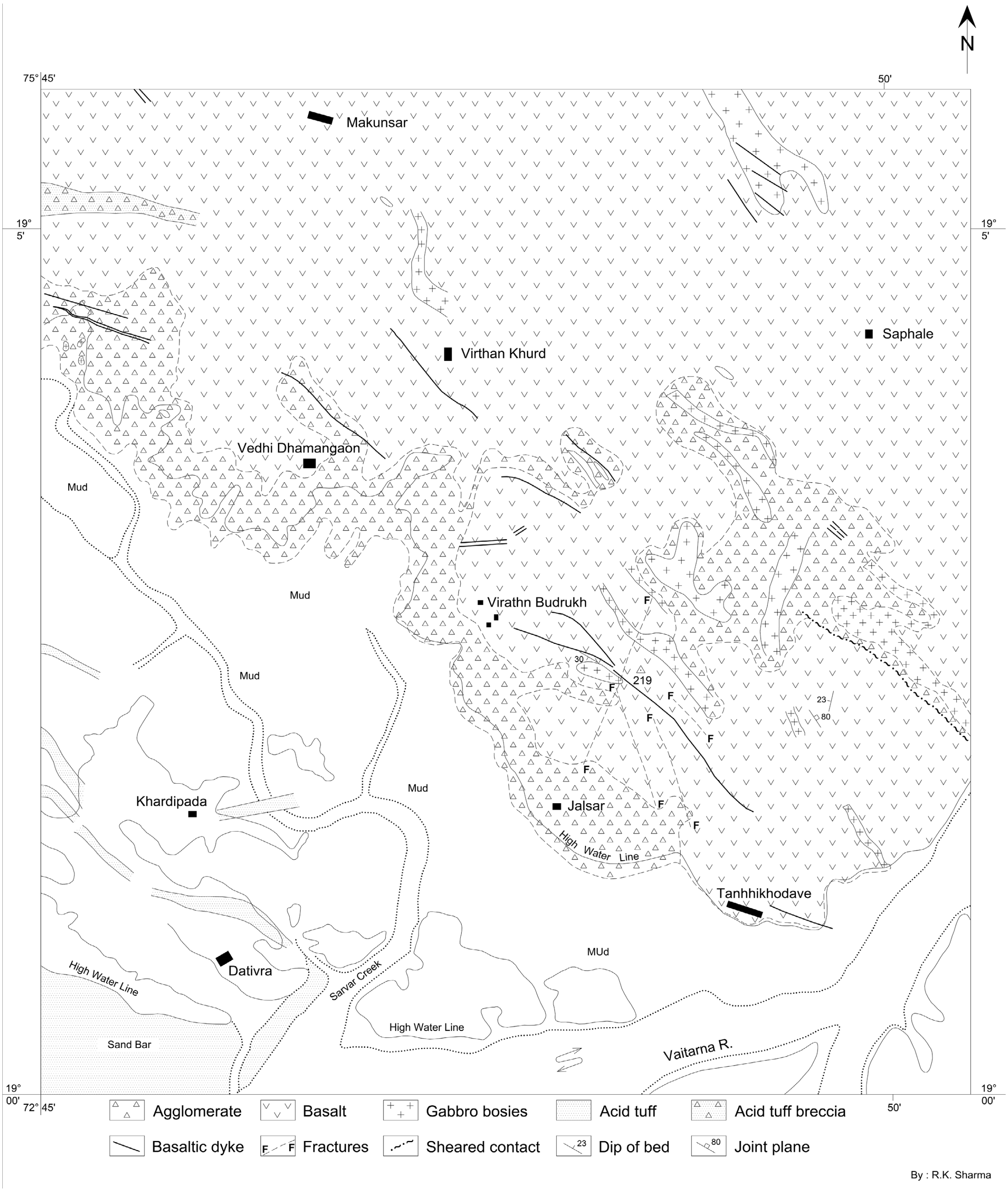
The volcanic agglomerate and breccias is the second most abundant unit in the volcanic ejecta after basalt exposed in the BVC. The basalt comprise more than nearly 90% of the exposed rocks. The type sections of the agglomerate and breccias are concentrated in the eastern and south eastern part of the study area. The important transects are Kaman-Shilloter transect, (Figure 2(a)) Sativli Dhaniv belt, Gopkhivre-194 hill, Brahamnipada section, (Figure 2(b)) and Saphale-Figure 2(c). Murba and Kore-Nandgaon section. Figures 3-12 depict the various features associated to coarser mafic ejecta.) The agglomerates consist of a wide range of fragments in composition and size. The size of the embedded fragments vary between <4 mm to >1 m in dimention and shape varies rom irregular to rounded and sub rounded and angular to subbgular. Fragments of lapilli, bomb and other siliceopus fragments. Besides these, juvenile soot fragments, epiclastic tuffaceous clasts also occur. The relative abundance of clast is highly variable in different parts. The agglomerate of Gokhivre-Nalasopara saction are rich



(a)


0
1
2
3 km.
19° 30"
72° 50"
72° 52' 30"
72° 55'
Dahisar
Kanivde
Kashidkopar
TANSA R.
Shirgoon
Sirsad
Mandvi
Chandip
Kanher
N.H-8
19°27' 30"
INDEX
Hydroclastite
Fault
Dip of bed
Shear zone
Alluvium
Gabbro dyke / Acidic flow / Acidic intrusive / Basaltic dyke / Acidic flow/Rhyolltic body
Acidic tuff
Agglomerate inter banded with hybrid basalt
Pyroclastic flow deposite with compositional banding/Probably chilled surface
Insitu agglomerate/agglomerate with predomirant ash pumice/volcanic ash pocket within agglomerate
Intermediate/Dloritic plution
72° 48' 45"
X
Y
R
Nallasopara
R.S.
19°25'
B
Kalampada
Valiv
Sativli
Gokhirve
55
Devichapada
B'
TULJA N.
TANSA R.
A
A'
Rajavli
H
72° 50'
72° 52' 30"
19°22' 30"

(b)



(c)

Figure 2. (a) Geological amp of Kaman Shilloter area, showing distribution of various types of volcanic ejecta; (b) Map of Gokhivre-sativli area depicting disposition of volcanic ejecta; (c) Map depicting distribution of pyroclastic rock in Saphale area.

in ash pumice fragments and large cherty fragments, while the agglomerates of Kaman-Shilotter transect are rich in basaltic fragments of lapilli to boulder size.

Figure 3. The Agglomerate with aligned boulders of basalt, along the flow surface, also grading of clasts suggestive of some reworking and flow of the ejecta by the process of volcanism (Location.-Kohli Nalla section.)

Figure 4. Debri flow/Ash flow with assorted basaltic boulders and clasts aligned parallel to the flow surface. Dips suggest draping down/flowing of pyroclastic material down a slope. (Note the normal grading of clast in flow unit from bottom to top) Location—Kohli Nala section.

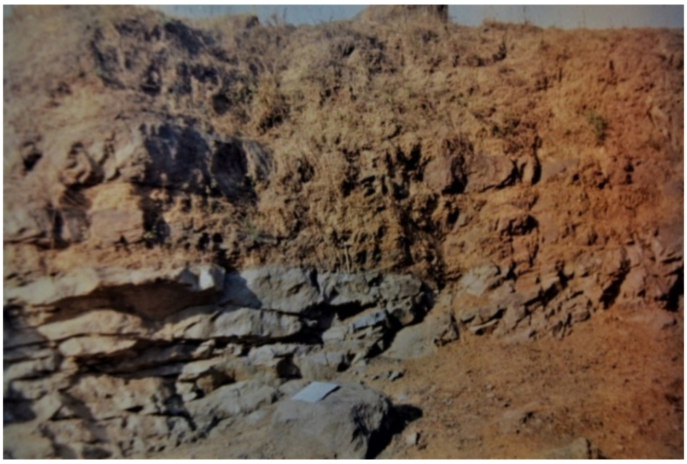


Figure 5. Crudely bedded proclastic deposit at Devkinpada section intercalated with basalt flows, with felsic tuff pockets and hydroclastites.

Figure 6. Bombs with chilled margins suggestive of sub aerial deposit. Vadrai area. Spindle shaped bomb embedded in the pyroclastic agglomerate of basaltic composition. depicting a violent effusive phase, where ejecta was thrown in the air, resulting in chilling of margins of the lump, which subsequently fell on pyroclastic flow material and got embedded in it.

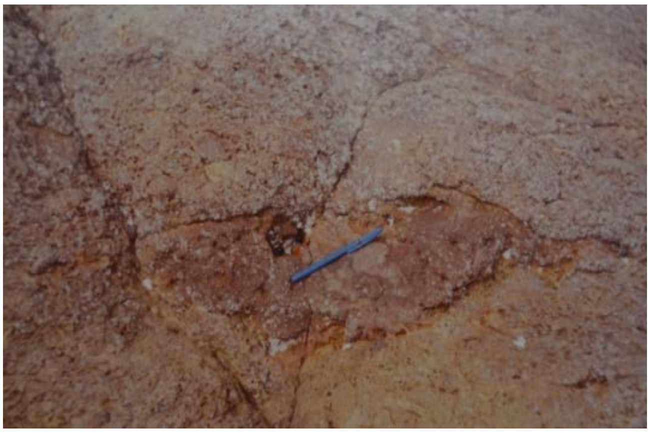


Figure 7. Spindle shaped bombs embedded in basaltic composition tuffaceous material. Vadrai area.

Figure 8. Abundance of block size fragments in Debri flow indicating down the slope draping of the ejecta, under the influence of gravity along natural slope. Hence no banding or flow structures (194 hill section).

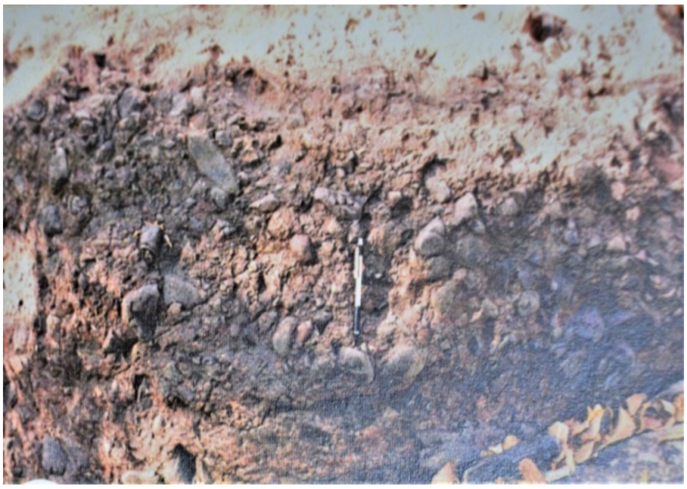


Figure 9. Debri flow in 194 hill section.

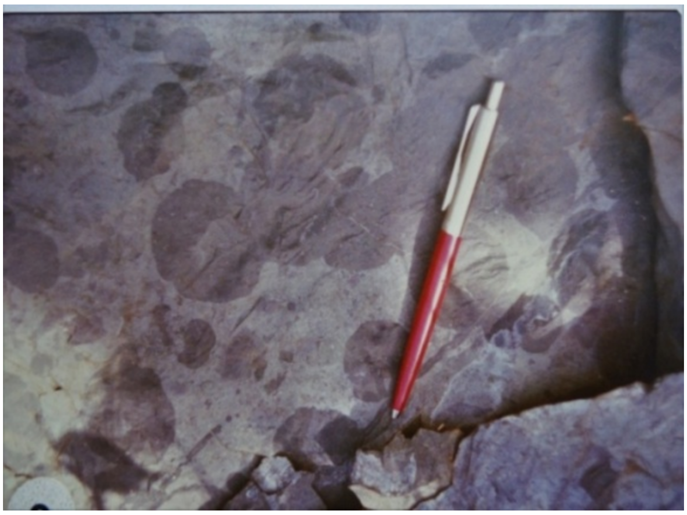


Figure 10. Possible mixing of magma, observed in Shilloter area.

Similarly colour of the deposit/ejecta varies from brownish grey in Kaman area to greenish grey in Devkinpada-Brahmanpada section, while the agglomerate deposits in Dhaniv-Sativli-Gokhivre-Nalasopara are ash grey in colour. Crude stratification in agglomerate is recorded from Borivalli national park area. Here the ejecta is mudflow/ash flow type and is rich in bombs and smaller lailli sized fragments of andesitic material.

The Kaman-Shilotter belt

This is about 10 km long transect with brown to grey coloured agglomerate deposit exposed on the ground level containing sub angular boulder to pebble size clasts and fragments of basalt, basaltic scoria, and pumice besides epiclastic and cognate basalt fragments (Figure 2(a)). Average size of such clasts varies between 2 to 64 mm, with large blocks of 1 × 1 m, larger ones are more angular as compared to subrounded smaller one, embedded in tuffaceous matrix. The rounded boulder sized clasts aligned parallel to the flow surface indicate flowage of the ejecta under the influence of gravity, after being saturated with water, facilitating crude bedding in the agglomerate as observed near Kohli nala. This type of bedding is suggestive of flow of the agglomerate like a debri flow, and such unit acts as a base for the successive pyroclastic flow (Fisher, 1964) [59]. Generally massive with open framework, gradation in fragment size, fluidity of the fragments. Sheet/tabular occurrence, three-dimensional geometry could not be ascertained because the base is not exposed Gradation from agglomerate to pumiceous flow (observed at Bapane village) associated with fine-grained aphanitic basalt flows, with acidic and basic tuff pockets.

The coarser fractions of the deposits along Kaman belt have semicircular to oval outline with restricted dimensions. The major part of volcanoclastic unit is a massive flow. Using the nongenetic criteria, this unit can be classified as the "*block and ash flow deposit with localized coarser deposits of volcanic breccias*".

Dhaniv-Sativli and 194 hill section

This section is the type locality for volcaniclastic deposits in the area (Figure 2(b)). The salient characteristics of the deposit here include size of the clasts varies between 2 mm and 64 mm, with occasional boulder and block size (up to 256 mm), embedded in a strongly welded, grayish glassy tuffaceous matrix. Type of clast include: Basaltic bombs (crescent and spindle-shaped to irregular shapes). dolerite, gabbro, diorite and pumice. Angular fragments have chilled margins and probable magma rinds can be seen. Depositional characteristics include mainly massive, crudely -bedded, with slump structures evidenced by a gradual decrease in size from top of the hill to bottom Associated with thinly bedded and compositionally banded pyroclastic deposit. Essentially fine-grained basic tuffs.

Devkinpada-Brahmanpada section

This lies in extension of Kaman shilotter transect but agglomerates are greenish grey in colour and contain abundant cherty fragments. The matrix is basaltic and exceeds the clasts proportion. The basaltic fragments are lapilli to block size along with bomb fragnents (Figure 11 & Figure 12).

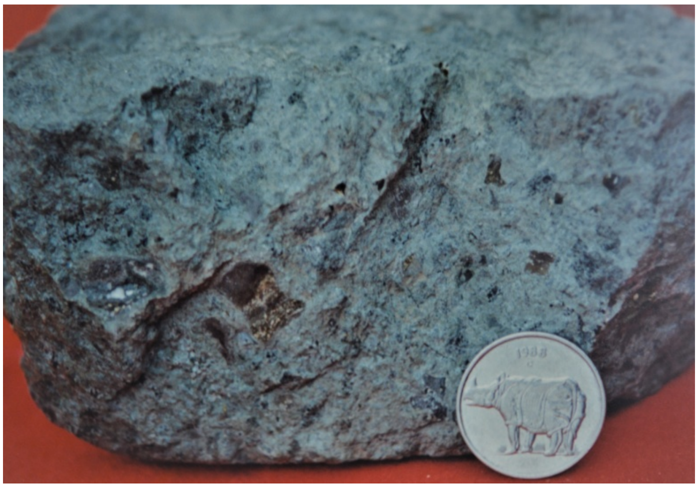


Figure 11. Lumps and fragments of basaltic material embedded in the dark tuffaceous mafic pyroclastic flow/ash flow. The chilling of the margins of the fragments and embedded material is evident.

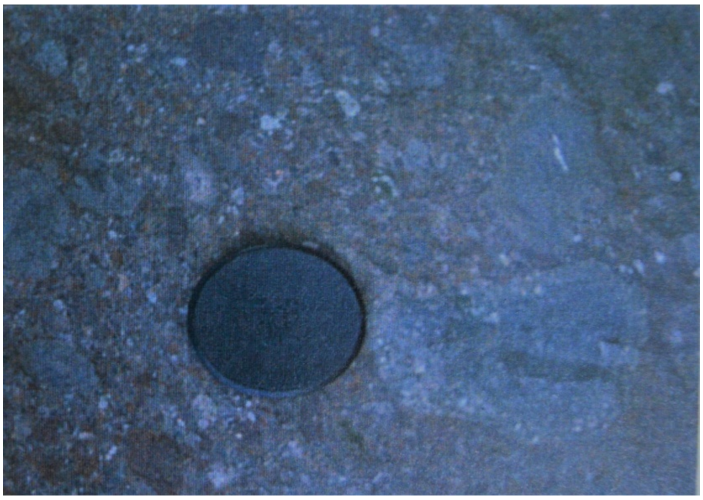


Figure 12. Ash flow with pumice and juvenile glass shards and accidental clasts of congealed magma.

Tungar nala section is the thickest section exposed but the agglomerates here are inter layered with basalt and are of ash flow/bed type the clasts are predominantly basalt with lapilli as common size but block size asalt fragments also recorded as large as 3 × 3 m. and such blocks contain multiple basaltic vein like features within these blocks occuring as intrusive. There are plug like bodies of basalt contained in these agglomerate/ash beds. The matrix and clasts are of the similar composition and dykes of basic and acidic composition are found intersecting in these agglomerate and basalt section. The top and bottom of this alternately bedded succession are composed of hybrid basalt flows. Which contain circular ink like material within these fows suggesting either mixing of magma during eruption or else they represent magmetic lapillies (Figure 10).

Above mentioned features indicate that these "volcanic agglomerate and pyroclastic flow" deposits are of sub-aerial extrusion. The volcaniclastic ejecta exposed in Chinchoti, Devkinpada, Bamanipada, Saphale and TungarNala section exhibit similar characteristics and associations. Therefore, all these deposits can also be grouped under Pyroclastic agglomerate/volcanic breccia and flows.

The coarser fragment deposits, (Figures 3-9) which exhibit a gradational fragment arrangement and show graded bedding and alignment of fragments/blocks along the bedding surface, occurring within the ash flows of vitric matrix and basaltic matrix, can be classified as the pyroclastic fall type of deposits. Here reworking of fall tephra has taken place which resulted in gradation and various flow structures. The coarser component of these deposits represents the violent phase of the eruptive process, where as compositionally banded and thinly bedded tuffaceous deposits of andesitic to basaltic composition can be grouped as pyroclastic flow (Pyroclastic surge deposit Figures 13-16) as it contains bedding sags and planar bedding.

2.2. The Finer Grain Size Ejecta

The Volcanic ejecta that shows the development of flow structures and bedding,

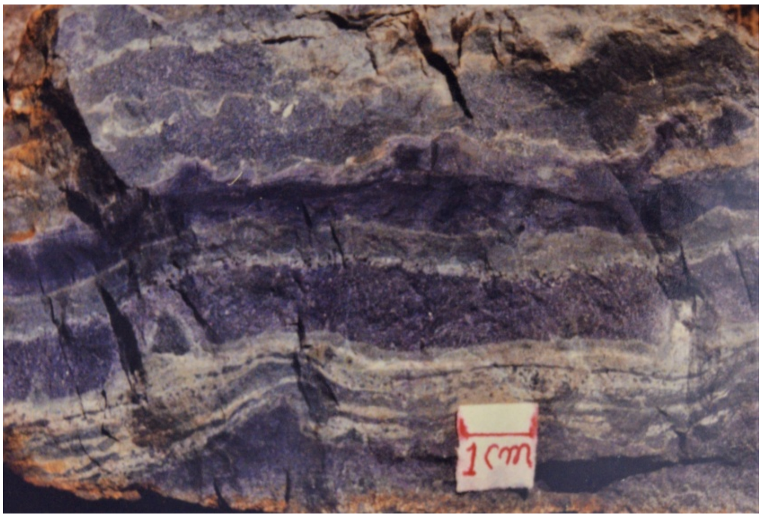


Figure 13. Pyroclastic flow with well-preserved. Pyroclastic surge deposit).

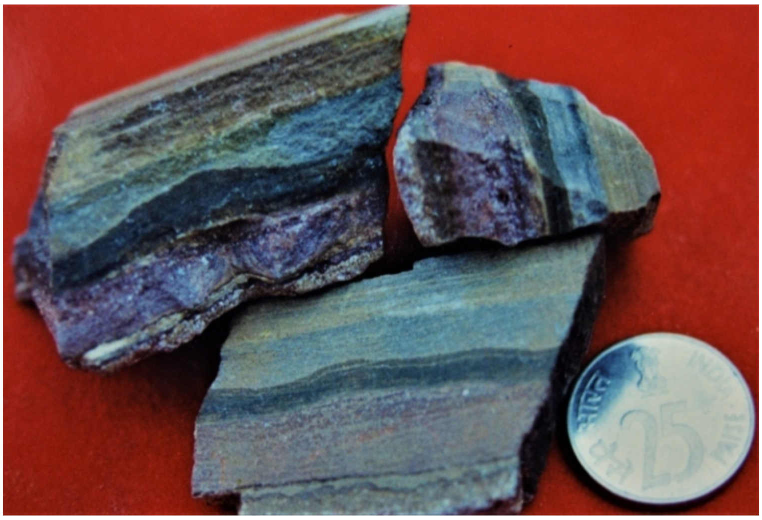


Figure 14. Well-bedded Compositionally banded, possible pyroclastic surge deposit.

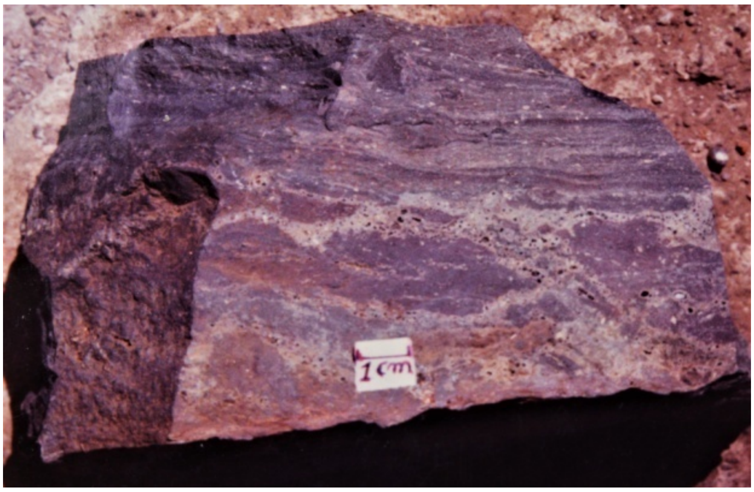


Figure 15. Frothgy mass on top layer of pyroclastic flow, a type of pyroclastic surge deposit, indicating turbulent flow of the volcanic ejecta.

Figure 16. Flowage marks on top of pyroclastic flow extentuated due to erosion, (proclastic surge deposit, turbulent flow indicators).

represents the later phase of the eruptive process where the pressure got reduced and a high particle deposition took place, which in turn gave way to the low particle turbulent deposit, represented by pyroclastic surge deposit of the compositionally banded nature (Figures 13-16). The inter-fingering nature and the localized occurrence of breccia indicate simultaneous eruption from multiple sources within proximity. The source vents were small and could produce only small dimension agglomerate deposits of basaltic and intermediate composition.

The grain size-based classification and correlation of isolated coarse and fine volcaniclastic deposits has been attempted by preparing a thematic map of the study area (Figure 17). Four different size groups have been identified. It was observed that the coarsest fragment pyroclasts are scanty and have limited aerial distribution, indicating possible effusive vent locales. Further, the coarser fragment deposits are concentrated in the northern and north-eastern parts, whereas southern and south-western parts show increasing predominance of finer size pyroclastics, suggesting an overall decrease in fragment size from east to west and north to south.

Lithostratigraphic columns at various locations, has been prepared to depict the distribution of pyroclastic material with respect to fragment size, space, composition and stratigraphic position (Figure 18). The diagram shows that the pumiceous material (ignimbrite) occupy the present-day tops of hills in most of the cases, and concentrated towards western and south-western parts of the study area. Besides, the coarse fragment pyroclastic deposits are concentrated towards northern and north-eastern parts and there is a progressive decrease in size from north-east to south-west and from east to west. Further this is also observed that the agglomerate occupies different stratigraphic positions in different locations. These observations are in agreement with the inferences derived from Figure 17.

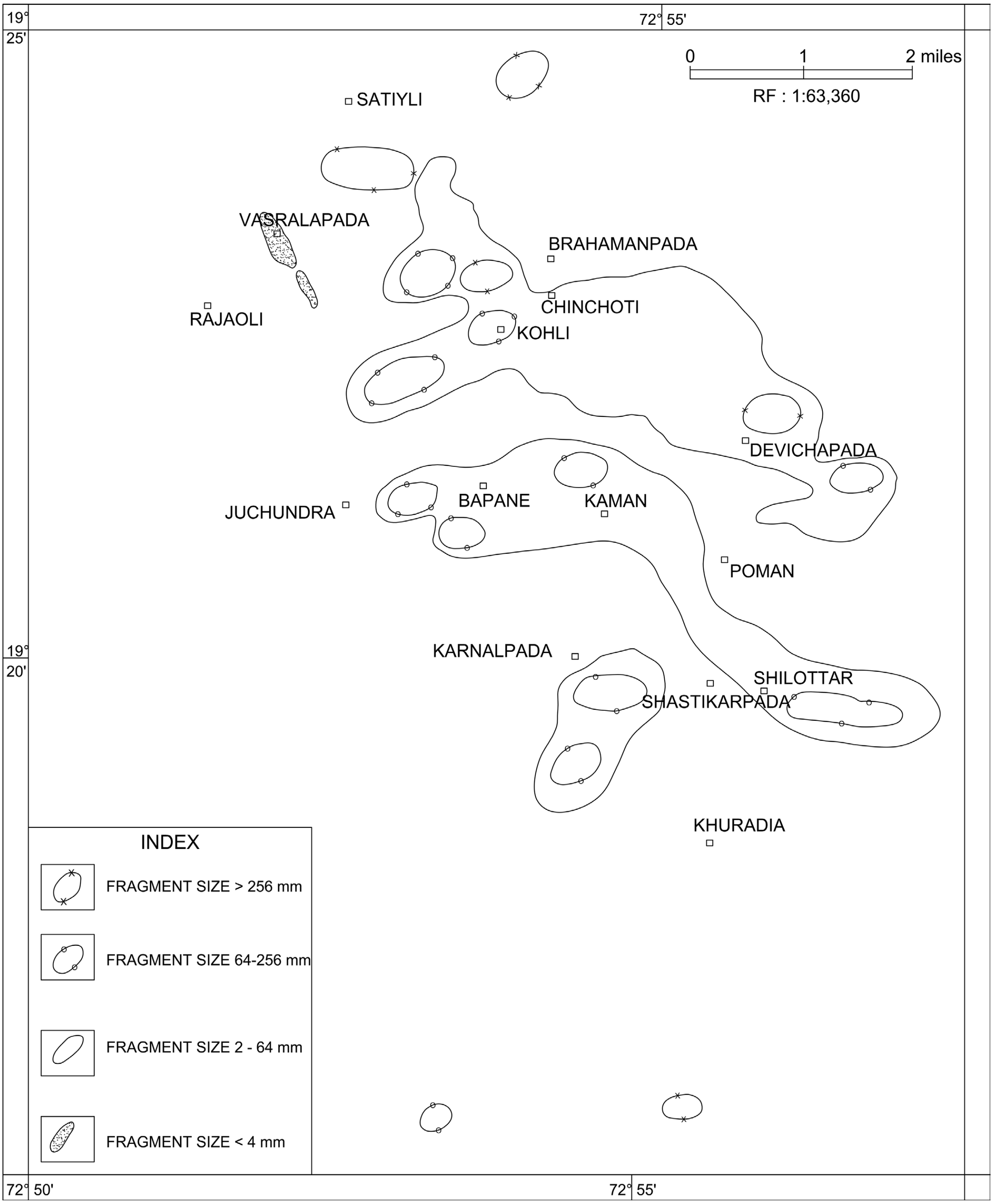


Figure 17. Thematic map depicting distribution of various grain sized pyroclastic deposits in the studied area (Sharma, 2000).

The agglomerates of Saphale, Murba, Nandgaon: The size of clast in these areas vary between 2 to 64 mm, rarely >64 mm. The common size is lapilli in Murba. In Nandgaon larger fragments, up to block size are present and compositionally include, Basalt, GPB, (Giant Pbenocryst basalt) dolerite, gabbro, diorite,

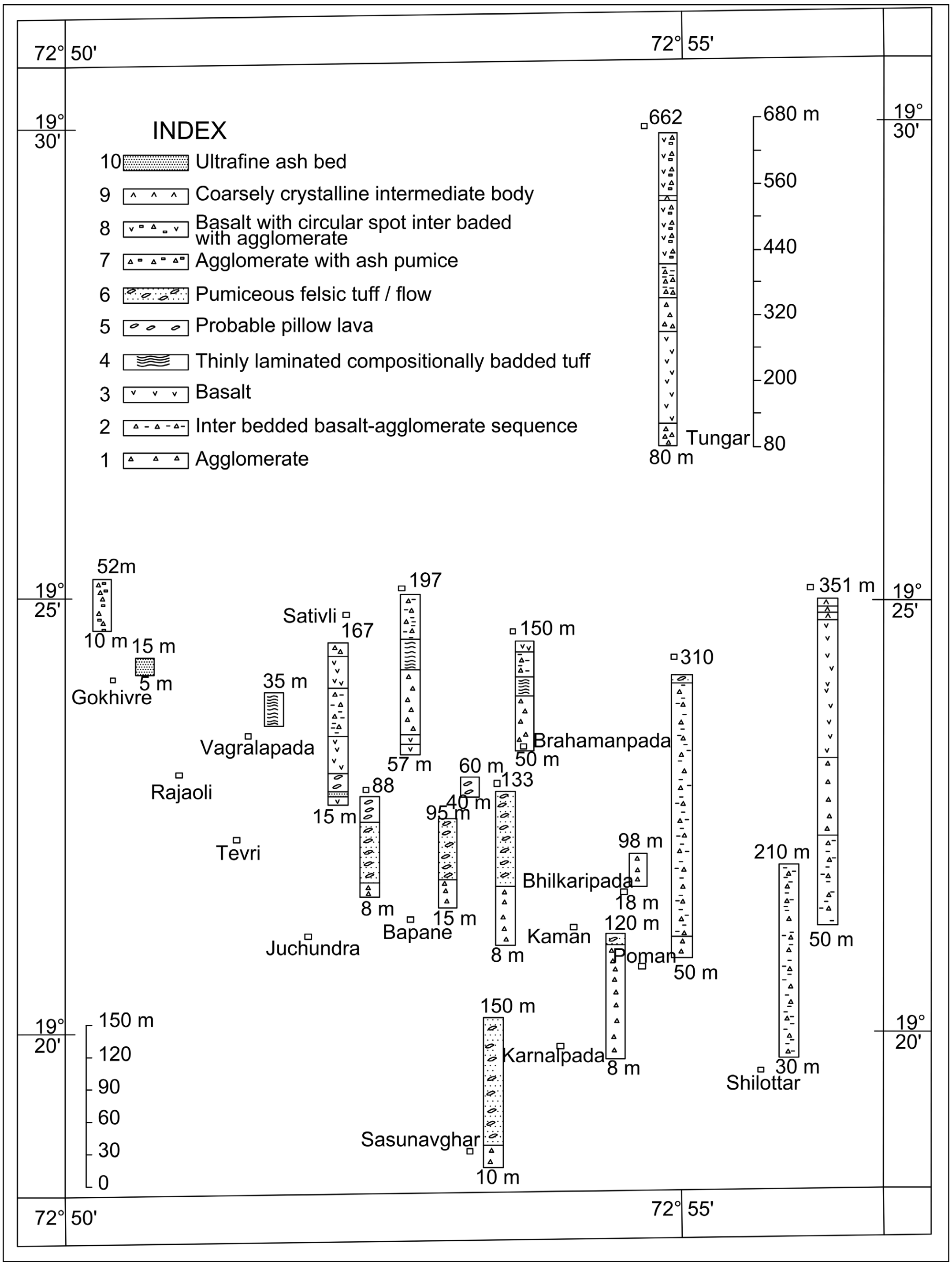


Figure 18. Thematic map depicting disposition of the various types of ejecta and its stratigraphic position. (Sharma, 2000).

juvenile clasts, pumice fragments, /reddish consolidated soot, cherty mass, gabbro, greenish basic rock clasts. Rounded to sub angular fragments, scoriaceous at places. Ribbon bombs, spindle bombs, spherical bombsand are massive and non-bedded. The matrix is Clayey and muddy in certain areas (Makunsar and Tembhikhodave), basalt matrix at other places. Associated with basaltic flows.

The agglomerate bodies are lenticular to lensoid in plan.

Vadrai-Murba section: The coast from Dativre to Nandgaon is characterized by the occurrence of agglomerate bands, which run discontinuously all along the the coast except at Satpati where they are covered under thick beach sand. The best developed section is exposed between Vadrai-Murba-Nandgaon. The agglomerates are interbedded with basaltric flows and occur as lenticular bodies running parallel lto the coast. The Vadrai agglomerate runs sinuously for kilometers together and range in width from 2 m to more than 15 m. The ribbon bomb, spindle, and spatter type are commonly found embedded in the juvenile glassy material. Circular basaltic lapillus are most common besides bomb fragments.

3. The Bedded Pyroclastic Deposits

The bedded pyroclastic deposits are the second largest exposed lithounit in the area. The bedded sequence of pyroclastic flows ash beds tuffs and thinly bedded, compositionally banded vitric tuffs along with agglomerates of varying thickness and proportion dot the entire area. Felsic rocks including the compositionally banded (light and gray) tuffs together with andesitic and acidic flows as well as pumiceous flows of the acidic nature (Sharma and Pandit, 1998) [58], constitute an important litho unit in the area and forms parts of this category of deposit. The banded and pumiceous nature has a significant bearing on the mechanism of deposition. The salient characters of these rocks exposed in various areas are summarized for attempting a non-genetic classification.

The pyrolcasts of Juchundra area contain juvenile clasts of lapilli size. Pumice, juvenile clasts, cognate basalt, epiclastic tuff rafts are also found embedded less than 4 mm size matrix with occasional rafts of tuffs of 50 cm. The depositional features associated are repetitive graded bedding, cyclic deposit with cross-bedded nature (**Figure 19** & **Figure 20**). Thickeness varies up to 20 m. Welded, with an unconsolidated pumiceous layer. Associated with agglomerate and basalt flows. The ejecta at Sasunvghar are essentially consists of pumice, (4 mm size) with occasional epiclasts. Thinly bedded, fine internal laminations thickness up to >100 m. are welded. Certain sections have thin encrustation of Fe-Mg minerals (**Figure 21**) inner parts friable and unconsolidated. Inter-bedded with basalt. The Ghodbander pyroclasts have less <4 mm sized pumice. Moderately bedded with 1/2 to 1 m thick beds. 10 to 20 m. thick. Well consolidated with pumice aligned parallel to the bedding. deposited over basaltic flows.

Characteristic features of felsic rocks Graded bedding, pumice aligned parallel to bedding surface, internal stratification, cross bedding in upper section, long rafts aligned parallel to bedding surface Very thinly bedded, internal stratification..Veisculating holes and cavities on the surface) Moderately bedded, basal layer contains cherty balls, lumps cored oraccretionary lapilli. Thinly bedded with compositional banding, bedding sags reverse and normal grading of pumice and lithic fragments, pumice stretched along bedding surface (all these features are depicted in **Figures 22-24**).

Figure 19. Banded Ignimbrite deposit at Juchundra, exhibiting various flow layers.

Figure 20. A Basal unit of acidic tuff resting over basaltic agglomerate exhibiting balls and lumps might suggest reworking of the tuffaceous material and re-depositing.

Figure 21. Thinly laminated felsic tuff welded in nature, pumice fragments aligned along bedding plane, note jasperisation along weak planes. Loc-Sasunavghar.

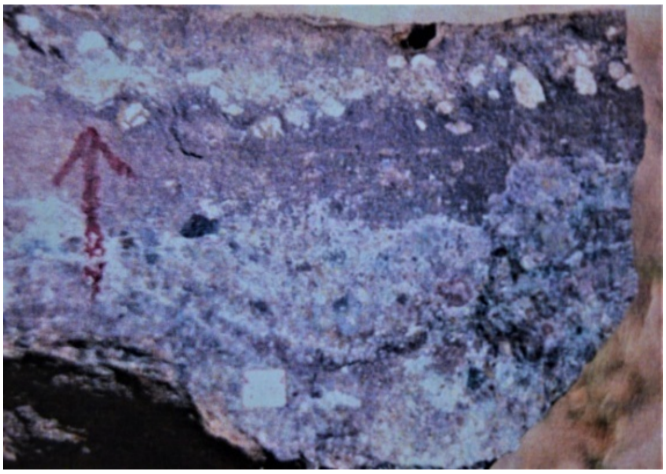


Figure 22. Reworked bedded volcanoclastic deposit exhibiting reverse grading of pumice fragments.

Figure 23. Thick acidic tuff deposit, thickly bedded and thinly laminated, lacking any significant depositional structure, could result from air fall deposit. Loc-Ghodbandar.

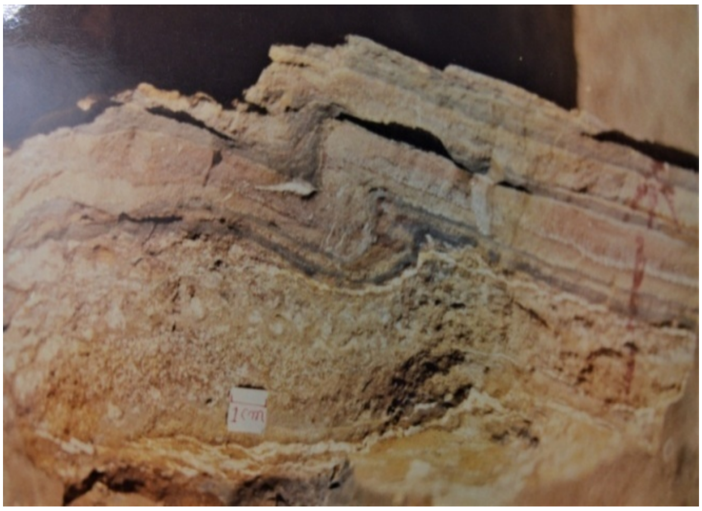


Figure 24. Compositionally banded tuffaceous rock exhibiting possible bedding sag and a pumice rich layer.

The presence of all the above dpositional features indicate the deposits to be either pyroclastic surge or pyroclastic flow type of deposits. The accretionary lapilli and lumps of the chert (**Figure 20**) in the basal layer may indicate a base surge tuffaceous deposit. Besides the type localities mentioned above, these rocks also occur at some small isolated outcrops. Based on empirical classification criteria, these can be termed fall or flow deposits, hydroclastites and pillows. Besides the depositional features described above, significant reworking of the volcanic ejecta during the process and after the eruption and related structures are exhibited in **Figures 25-29**. These features depict exclusively the pyroclastic flow deposits. The depopsitional features like dune bedding and possible soft sediment deformation (**Figure 30(a)**, **Figure 30(b)**) imdicate reworking of the pyroclastic material before deposition.

4. Genetic Classification of Pyroclastic Deposits

Genetic classification is an important objective of such studies. The genetic

Figure 25. Flow folding in Rhyoliic/felsic flows, depicting effusion of viscous lava through a narrow edifice under pressure producing these flow folds. Location (Usarni Bhuigaon coast).

Figure 26. Thick acidic flow depicting randomly oriented flow folding at Kore.

Figure 27. Multiple felsic flow layers exhibiting clinker nature exposed at Bhuigaon/ Coast.

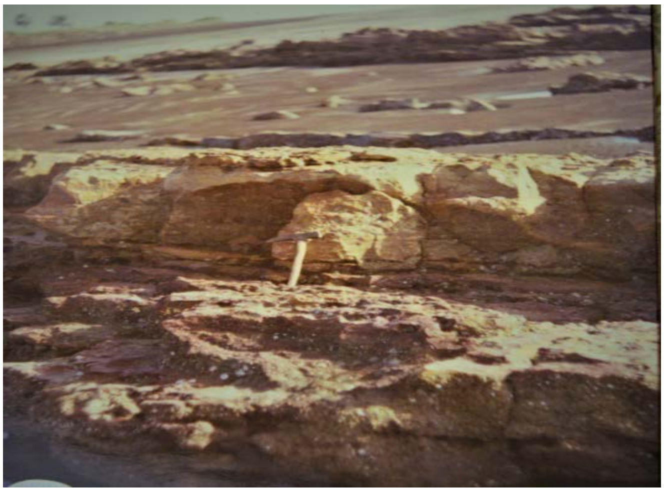
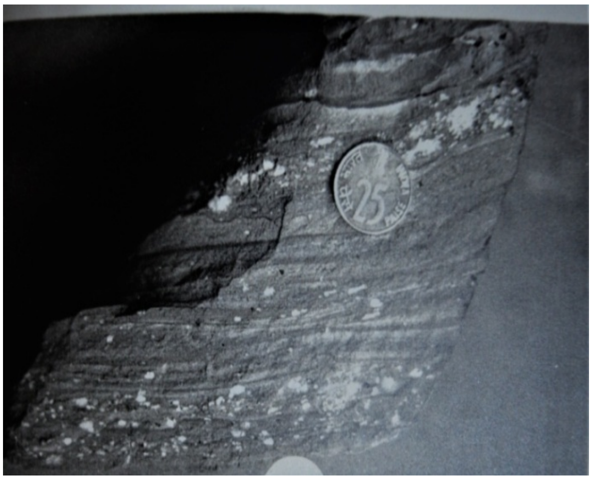


Figure 28. Interlayered sequence of felsic and mafic flows. Mafic flows on top in phorto-graph. Loc-Bhuigaon coast.

Figure 29. Acidic breccia/tuffaceous dyke disposed in sinous out crop pattern might suggest deep seated origin. Location at Mathana-Usarni coast.

(a)



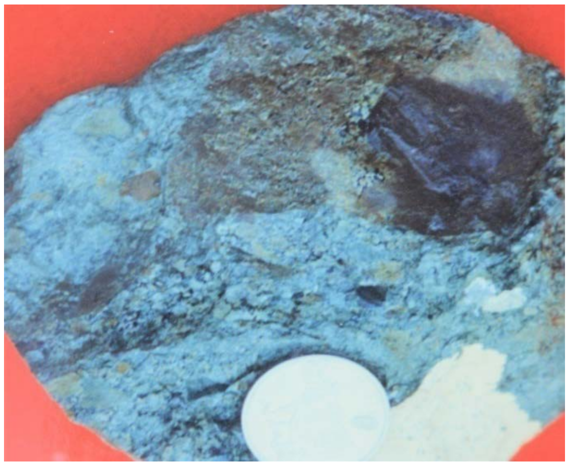
(b)

Figure 30. (a) Reworked bedded acidc tuff exhibiting soft sediment deformation or PCD, South of Bassein creek; (b) Acidic tuff bedded in nature exhibiting alignment of pumice fragments and possible dune bedding suggesting reworking. Location-South of Vagralapada.

classification uses the locality name of the volcanic eruption where the particular deposit was first observed, and several classifications have been proposed (Lacroix 1930, [60], Escher 1933, [61], Fenner 1937, [62], Van Benmelen 1949, [63], Macgregor 1952, [64], Aramaki 1957, [65], Murai 1961, [66], Fisher 1961, [49], 1966 [50]). Many of these classifications have been modified by Wright *et al.*, (1980) [67], Smith and Roobal (1982) [68], who named the flows and their deposits according to the field criteria, such as the relative abundance of pumice, scoria, poorly vesiculated blocks, and ash.

In most cases, the pyroclastic flow and pyroclastic surge, deposits of the same flow, become separated by gravity segregation (Fisher, 1983) [69] Cas and Wright (1987) [70], have used pyroclastic fall, pyroclastic flow and pyroclastic surge deposits as genetic classification criteria for pyroclastic deposits. Pyroclastic fall has further been classified by various authors depending upon the degree of fragmentation, dispersal and type of fragments present, and the type of fall involved. Some special features associated with the pyoclastic ejcta and mafic flows are depicted in (**Figure 31**, **Figure 32**).

(a)



(b)

Figure 31. (a) Composite lapilli containing embedded in mafic ash flow, suggesting felsic/andesitic eruption before the mafic volcanism; (b) Similar type of composite lapilli containing lapillus and fragments of consolidated volcanic soot embedded in mafic ash flow, suggesting multiple eruption pulses.

(a)

(b)

Figure 32. (a) Tongue like bodies of lava intruding in top another lava flow. Loc. Tiveri/Taveri; (b) Possible partially developed pillows or hydroclastic deposit resulted due to lava flowing over wet sediments or in to a shallow water body.

The genetic classification is best applied to the recent pyroclastic rocks because of the often observable definitive context to vent or volcanic center (not always), or at least inferable for modern successions. Such features are lacking in older volcaniclastic rocks, further, induration, lithification, welding, metamorphism and alteration etc. modify these rocks to an extent that the rock could be speculated to be of volcaniclastic origin. The factors complicating this aspect are devitrification and recrystallization and growth of new minerals during diagenesis and low-grade metamorphism. All these factors lead to alteration and modification of the original texture of the rock e.g. the devitrification of originally glassy lava can produce an equigranular mosaic or spherulitic texture, to give megascopic pseudo-granularity. Therefore, genetic classification of lithified volcanic rocks should be well supported by detailed lithological characterization and evaluation of all other relevant characters.

Here in the present case the deposits have been classified genetically based on field criteria, and supported by the petrographic studies. The depositional fetures, size and type of the fragments and association. As the Block and ash flow deposits of Kohli nala, (**Figure 3** & **Figure 4**) volcanic agglomerates and ash flows of Kaman shilotter belt, (**Figure 2(a)**, **Figure 8**, **Figure 9**, **Figure 11** & **Figure 12**) volcanic breccias of Vadrai Nandgaon and Murba section (**Figure 6** & **Figure 7**) Besides the bedded deposits of pyroclastic nature having evidences of reworking involved during and after it was erupted, have benen grouped under pyroclastic bedded deposit once again based on depositional fetures like dune bedding, presence of bedding sags, grading of clasts alignment of clasts along the flow surfaces, normal and reverse grading of pumice and lithic fragments and lastly by occurrence of soft sediment deformation and presence of internal stratification.

The basaltic and felsic flow deposits of pyroclastic origin from Kore, Usarni, Bhuigaon suggest that they have been erupted from different vents/source as there are repetitive or alternate sequence of felsic and mafic flows as witnessed in

Bhuigaon. The flow folding at Kore indicates that the eruption of viscous felsic lava through a very narrow fissure opening under pressure resulted in bulging of felsic lava in to randomly oriented folds. Further the embedded fragments of stony rhyolite on the top surface of felsic flow suggests violent nature of the acidic erution through either a lava fountain or a fissure causing brecciation and falling of the sub aerial material on the flowing lava. This is also supported by the clinkary nature of the multiple felsic flow layers exposed at Bhuigaon. The repetitive nature of the volcanic effusion or in other words the pulsatory nature of the effusuion is very well documented in depositional and physical features in the form of composite lapilli (**Figure 31(a)**, **Figure 32(b)**).

The summarized account of the detailed lithlogical and depositional characters (**Table 1** & **Table 2**) has enabled the author to place various types of deposits under the different genetic classes. The compositionally banded and thinly bedded tuffaceous deposit of andesitic to basaltic composition can be grouped as pyroclastic flow (Pyroclastic surge deposit) as it contains bedding sags and planar bedding.

Similarly, the coarser fragment deposits, which exhibit gradational fragment arrangement and show graded bedding, and also alignment of fragment blocks along the bedding surface, occurring within the ash flows of vitric matrix and basaltic matrix, can be classified as the pyroclastic fall type of deposit, where, reworking by the processes of volcanism has taken place and has caused the gradation and various flow structures. The coarser component of these deposits represents the violent phase of the eruptive process, whereas the finer part, which shows the development of flow structures and bedding, represents the later phase of the eruptive process where the pressure got reduced and a high particle deposition took place which in turn gave way to the low particle turbulent deposit, represented by pyroclastic surge deposit of the compositionally banded nature.

The interfingering nature and the localized occurrence of breccia indicate different sources for simultaneous eruption within a close proximity. The dimensions of the source vent were small to produce the small dimension agglomerate deposits of basaltic and intermediate composition.

Similar procedure has been adopted to summarize the characters of the felsic deposits, as under *Genetic classification as applied to the felsic rocks of the area.*

Besides the type localities represented above, a number of other insignificant locations have also been studied. Applying the established criteria these can be named as fall or flow deposits, hydroclastites and pillows.

A similar pocket of white ash occurs within the basaltic flow and agglomerate on Kaman-Shilotter road. This is about 2 m thick bed and has <4 mm grainsize. A lensoid pocket of such deposit exposed to the south of the Bassein Creek is also an evidence of pyroclastic fall deposit.

5. Salient Microscopic Evidences Suggesting Fragmentary Nature of Ejecta

Beisdes these field and depositional features there are very salient features and pertinent observations which could be made from the photomicrographs of the mafic and felsic ejecta from the area. The salient features and textural attributes directly could be related to the genitic aspect of the ejecta (Figures 33-44).

Table 1. Summary of the field characters of basic volcanic ejecta and associated basalt.

Characters	Kaman-Shilotter	Sativli 194 hill	Saphale	Nandgaon Murba
Clast/fragment size	Average size 2 to 64 mm 10% to 15% > 64 mm, maximum lm	2 to 64 mm	Upto 64 mm	Murba, mainly lapilli size max. 64 mm
Composition of clast	Basalt, dolerite gabbro, subordinate cherty, siliceous.	Basalt, dolerite, gabbro, diorite, cherty, pumice	Basalt, GPB, gabbro, diorite, dolerite.	Tuffaceous lapilli, basalt, subordinate gabbro,
Shape of Pyroclasts	Sub-angular to angular, bigger ones are more angular, chilled margms	Bombs of various shapes, fragments of bombs, smaller fragments angular.	Subangular to blocky, basaltic blocks	Various shaped bombs, ribbon, spherical and spindle.
Matrix	Basaltic, gray with angular clasts of cherty and soot material, size gradation at places	Tuffaceous glassy, small lapilli of siliceous material with chilled margins	Basaltic, occasional radish clayey muddy.	Basaltic, occasionally muddy.
Welding, compaction, cohesiveness	Cohesive with magmatic character, finer flows have tuffaceous matrix.	Very well welded glassy nature, coarser parts are magmatic and cohesive.	Well consolidated, open framework.	Vitreous nature, magmatic with patches of muddy matrix, less welded
Depositional structures	Massive with occasional gravity bedded, basalt boulders aligned parallel to beds, vitreous tuff beds	Massive, small sectors contain compositionally banded tuffs with planar bedding, bedding sags	Non bedded massive	Massive non bedded
Geometry of the deposit	Sheet, with localized circular to semicircular out crop.	Sheet, inter-layered with tuffs	Wedge shaped with circular out crops	Lenticular, lensoid.
Associated facies	Basalticflows, pumiceous layer on top, pockets of tuff present, interlayered with basic vitric tuff bands, acidic dykes	Thinly bedded compositionally banded tuffs, basalt flows, acidic dykes.	Basaltic flows, gabbro intrusives.	Basaltic flows, plugs of basaltic nature dyke swarm.
Vesicularity of clasts	Scoraceous basalt, pumice, vesiculated tuffaceous clasts, non-vesicular blocks of dolerite, gabbro, and acidic rocks and vein quartz.	Vesicular basalt fragments., small pumice fragments, vesiculated acidic tuff fragments with non vesicular blocks and smaller fragments of all.	Scoraceous fragments of basalt and soot material occasional pumice fragments along with non vesicular fragments.	Scoraceous basalt fragments and scoraceous lava soot material, occasional pumice fragments Besides non vesicular fragments of all.
Relation with the associated facies.	Gradational, conformable and interfingering relation with the associated rocks	Conformable but not gradational, interlayerd with compositionally banded and felsic/flows	Gradational with basalt. Housed within the basaltic pile.	Gradational with the basalt flows, encompassed within the flows itself.

Table 2. Description of various parameters of different clasts.

Characters observed	Juchundra	Sasunavhgar Navsinghdwar	Gokhivre	Ghodbander
Size oftlze clast	2 to 64 mm (max. 50 cm) rafts of tuffs	Essentially < 4 mm lower parts contain 4 - 64 mm	Essentially < 4 mm lower layer contains cored lapilli (2 - 64 mm)	<4 mm
Type ofclast	Pumice, juvenile and epiclastic fragments.	Oxidized tuff fragments, pumice, consolidated soot.	Essentially pumice fragments.	Pumice epiclastic fragments.
Shape of clasts	Circular, elliptical pumice, lithics are angular. Rafts aligned parallel to bed.	Circular pumice, other fragments subangular to angular.	Spherical, elongated, gray ash pumice smaller clasts angular.	Spherical to elongate pumice.
Cohesiveness welding	Vitreous, brittle, well defined pumiceous zone lithified.	Well consolidated, glassy fracture, with brittle unconsolidated layers in between shale like fissility	Well indurated welded, with cherty balls, upper part loose and vesicular	Consolidated but friable
Cystals	Contains feldspar crystals	Certain sections contain crystal tuff, rest vitric	No crystals observed, in hand specimen	No crystal observed.
Structure (Depositional)	Cyclic deposit with graded bedding, reverse grading of pumice, normal grading of lithics, tongues observed, cross bedding in upper parts.	Moderately bedded, internal cross stratification and dune structure developed.	Thinly bedded bedding sags, reverse and normal grading of pumice and rock fragments.	Thickly bedded with no internal bedding
Association	Lying over an agglomerate, interbedded with non welded crystalline felsic tuff.	Overlying basalt flow, has intrusive relation at one place with associated basalt.	Interbedded with basalt, and agglomerate	Lying conformably over basalt
Thickness	about 20 m	>l00 m	10 - 15 m	10 m
Geometry of the deposit	Sheet, layered	Sheet, layered	Layered limited dimensions	Small fill type.
Bedform and other salient feature	Contains planer beds, with tongues of one sub layer protruding into other, margins of such tongues are chilled	Planar beds dune structure	Planar beds bedding sags, cherty lumps, cherty balls and cored/accretionary lapilli, upper beds contain only ash pumice.	Planar beds, thick bedding, surface has cavities of various sizes.

6. Possible Tectonomagmatic Model Explaining the Heteroginity of Rocks of BVC

With the foregoing evidences and features associated with the volcanic deposits, a reasonable genetic explaination for the process responsible for generating such a varied and complex clastic volcanic litho assemblage can be deduced at least in terms of mechanism of deposition of the pyroclastic ejecta. There are certain very striking features in the area which help in building up of the volcanic history of the ejecta deposition and can help explain the very complex nature of the

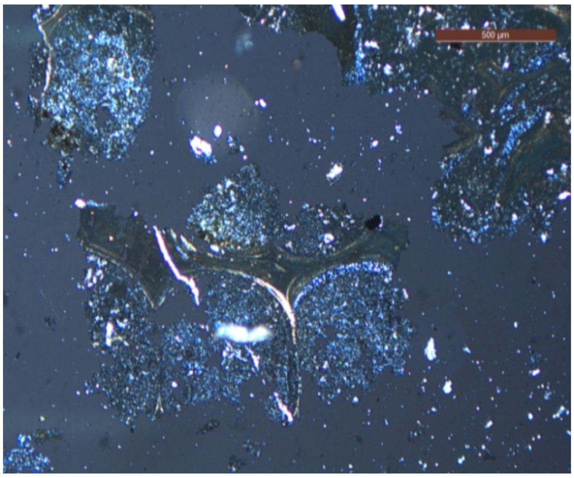


Figure 33. Pohotomicrograph of a vatic tuff depicting various shapes of glass shards. These shards are the walls of the bubble which get shattered either due to hot magma entering the wet sediment or in to a waterbody, or the shattering could take place due to subaerial bursting of these bobbles due to increasing gas pressure exerted by the moving magma.

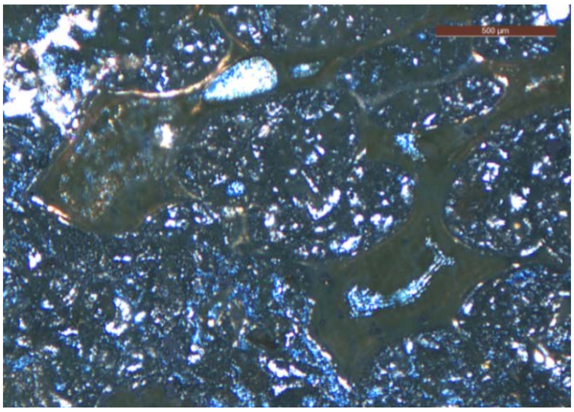


Figure 34. Mafic flow having glass shards with devitrified centre. The devrtific.

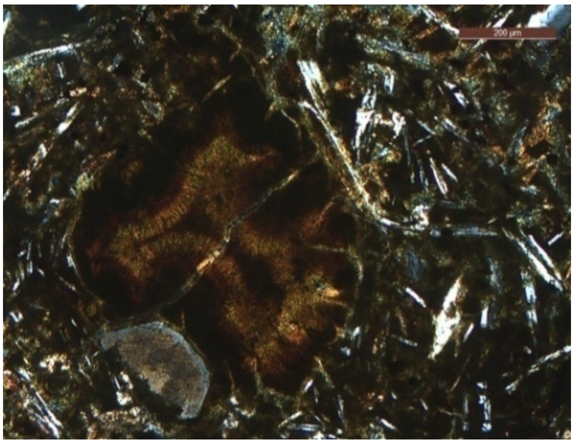


Figure 35. Photomicrograph depicting a typical sub aerial glass shard having thick dark skin developed along the margin due to chiiling of glass in the air. The desiccation crake in the glass shard suggests post its deposition healing of the crack due by the basaltic melt which is exhibiting microlites in the ground mass.

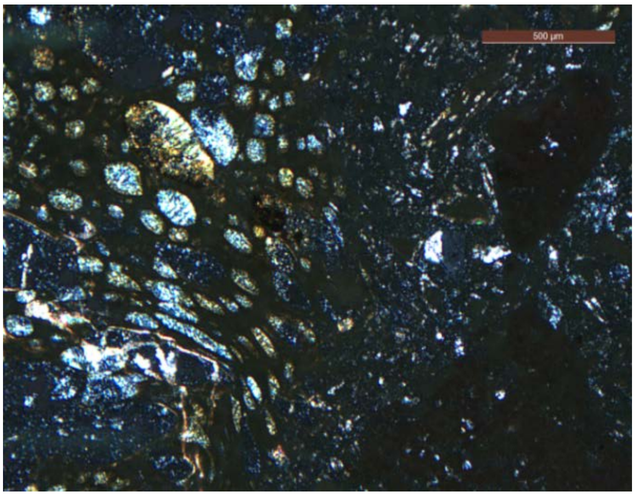


Figure 36. The glass pumice section depiting stetching of the vesicles and devitrification of the same. Glass shard and lithic fragment could also be seen in the photo (NE and SE part).

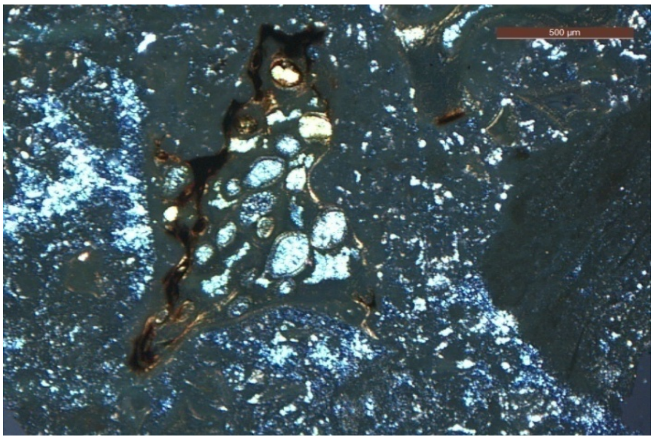


Figure 37. Glass pumice with stretched vesicles and bent structure. The bending might represent some tectonic disturbance post deposition.

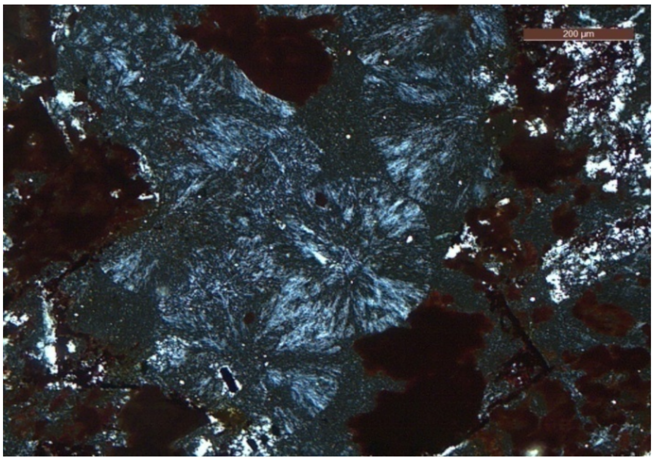


Figure 38. Typical glass spherulites exhibiting devitrification, the ground mass also depicts ferruginisation and devitrification. An ideal representation of status of alteration of mafic ejecta in the area.

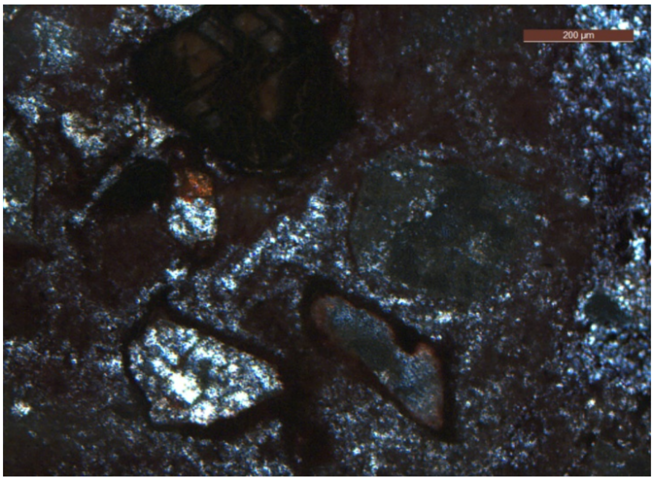


Figure 39. Glass pumice with stretched vesicles and complete devitrification of these glass vesicles. These vesicles are separated from each other by well defined thick dark skin composed of chilled glass/magmatic melt.

Figure 40. Portion of a mafic tuff exhibiting devitrification of glass shard and development of thick dark brown skin depicting chilled magmatic melt.

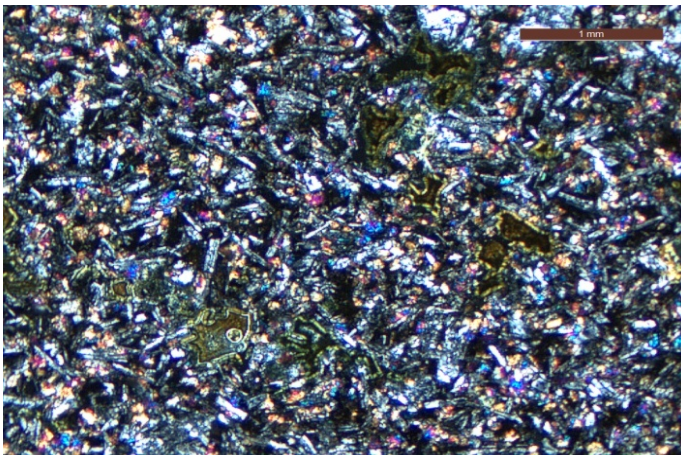


Figure 41. The crystalline basaltic flow containing glass shards suggests pyroclastic nature of the basaltic flows in the area.

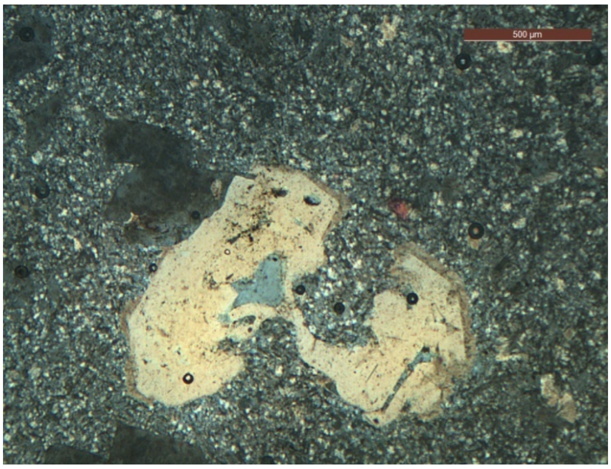


Figure 42. The photomicrograph depicts post emplacement magma activity in the area. The part digestion/or embayment of the potash feldspar crystal suggests emplacement of the pre-crystallized melt and post emplacement turbulence in magma is depicted by embayment.

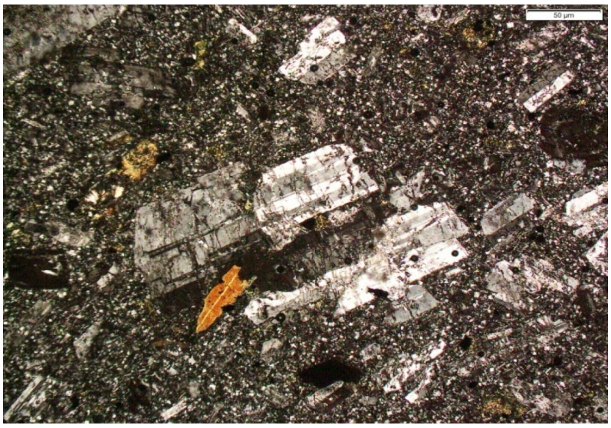


Figure 43. Photograph depicts microscopic shifting in the plagioclase crystal. This is the result of adjustment/equilibrium mechanism of growing crystals with the magma turbulence.

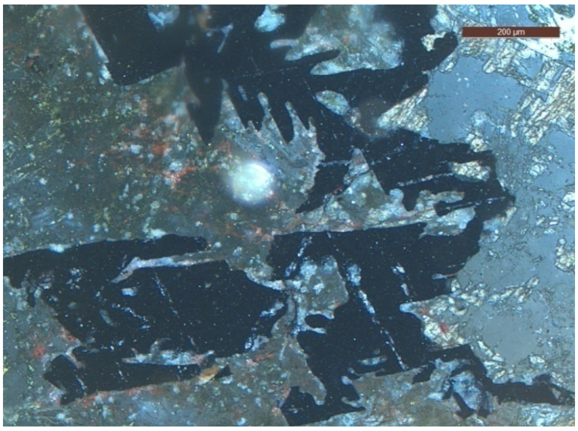


Figure 44. Photomicrograph exhibits completely pseudo-morphed pyroxene porphyroblast by metallic mineral, appearing as opaque in a basaltic rock. The gel like siliceous material occupying cleavage planes of pyroxene is the hydrothermal fluid generated and emplaced along structurally favourable locales, during tectonic activity a post consolidation of pyroclastic flow.

rocks exposed in the area. The features were observed during the large-scale mapping of the area that revealed detailed characteristics of the bimodal tephra. Salient observations relevant in adopting a sequential approach in developing a tectono-magmatic genetic model are listed below.

1) The presence of an arcuate fault running for a distance of nearly 110 km in the western part of DFBP, can be named as Mahim-Kharbao-Paye-Matunga fault, marks the eastern boundary of the BVC and the main Deccan volcanics. Such setting is quite peculiar to this area and has not been seen elsewhere. This fault is crowded with enechlon disposition of acidic and basaltic dykes and a sill beside a large gabbroic pluton (Godbole, 1988) [7].

2) A 450m thick sequence of alternating ash flow, agglomerate, and hybrid basalts in Tungar Hill section is intruded by several acidic, basaltic and andesitic dykes. The fragments of rocks embedded in the agglomerates are the largest in this section among agglomerates of the area. There is a gradual reduction in size of the fragments from east to west as could be depicted in **Figure 17** suggesting it to be a probable eruption edifice.

3) The felsic intrusive body exposed near Pelhar dam contains large xenoliths of gabbroic rocks in the central and granitic on the peripheral parts, suggesting possible evolution and differentiation of gabbroic magma (Godbole, 1988) [7].

4) Large plutonic bodies near Tungar Fata, Valiv and various other places are traversed by basaltic dykes and aplitic veins containing gabbroic xenoliths, possibly representing the fringe of a larger pluton below, indicating evolution through differentiation of an original gabbroic magma or multiple intrusive activity induced due to different pulsatory nature of errupions of Deccan lava. Envisaged by Godbole 1988 [7].

5) Basalt flows are characterized by the occurrence of spherical to irregular droplet/bleb like bodies, as seen in the Shillotter area (**Figure 10**); however, such features attain much larger size and get extentuated on weathering in Tungar Hill section, and appear like discs and pendants on the weathered surface. In Tiveri area tongue like bodies of mafic material, are intrusive into basaltic flows, (**Figure 31**) while in Valive irregularly disposed bodies of bsalt within the flows suggest during or post erupting disturbances or the evidence of mixing has been recorded along the eastern-most margin to the coast, all through the study area.

6) The layered sequence of basaltic and acidic flows in Dongari-Manori (Kandivali) area, southeast of Ghodbander, and a repetitive sequence of basaltic and acidic flows at Bhuigaon can be inferred in terms of a pool of bimodal magma (Sukeshwala & Poldervaart, 1958) [71], (Ghose, 1976) [72] argued for the occurrence of two parent magmas to explain the absence of intermediate composition rocks in the area.

7) Agglomerates and acidic and basaltic tuffs are generally lenticular in shape and discontinuous in disposition, suggesting that these bodies may represent remnants of feeder fissures developed parallel to the main fault bordering the BVC on the east.

8) The clastic/fragmentary nature of rhyolitic/acidic flows in Bhuigaon area and the occurrence of bombs of rhyolitic/acidic composition suggest violent pulse of volcanism. The limited extent of acidic flows might indicate that these flows were originated and deposited from fissure fountains.

9) Alignment of hot springs along the arcuate fault indicates a higher thermal gradient indicating the deep-seated nature of this fault. These springs have a higher sulphur content and temperature ranges up to 66˚C (Ganeshpuri 19˚58'N - 72˚59'E; Sativli Koknere 19˚41'N - 72˚51'E and Haloli 19˚41'N - 72˚44'E (Godbole, 1988) [7].

10) The breccia dykes in Mathana and Gokhivre area can be attributed to the exumation of the deep seated consolidated remnant of vent. Their exhumation to the surface might be due to the re-adjustment during the susidence of the crustal block.

11) The occurrence of coarse-grained doleritic material without any features of intrusion, in Saphale area, and along the Mathana-Usarni coast indicate that these rocks are not true flows and may have exited as small pools of differentiated magma brought to the surface by exhumation.

12) The entire coastline is dotted with basaltic dykes that range in thickness from pencil thin dykelets to as thick as 100 m. Such dyke swarms are more prominent near Saphale, Akkarpatti and Murba. The agglomerate bands exposed in these areas contain spherical bombs of lapilli to pebble and even boulder size, indicating an effusive vent along the coastal tract in this part. These agglomerates are lenticular in shape and discontinuous in occurrence. All these features indicate proximity to a fissure zone.

The above features underline a complex tectono magmatic environment of eruption and deposition which cannot be explained through the process of mafic volcanism associated to a LIP. The diversity in rock types and complexity in their textural attributes suggest their exhumation to the surface through a process of collapse of the upper crustal blocks within the upper parts of the magma chamber after the significant volume of the magma was withdrawn from the chammer, which can be termed as Cauldron subsidence process that was also hinted at by Godbole (1988) [7].

Geophysical and Other Characteristics of BVC

The occurrence of dyke swarms all along the coast from Dahanu in the north to Mumbai in the south (Shirgaon, Akkarpatti, Saphale, etc.) suggests the presence of a fissure zone along this tract. Kailasam (1972) [73] interpreted the positive gravity anomaly below Mumbai (Bombay) region related to a shallow magma chamber just below the trap cover. Biswas (1988) [74] suggested cyclic rifting in the west coast region. Auden (1975) [75] postulated congealed basalt and ultrabasic lava bodies between 18˚30'N and 21˚30'N latitudes while SubbaRao and Sukeshwala (1981) [2]. And Sears & Hyndman (1988) [26] conjectured the presence of peridotite or troctolite bodies below the Mumbai (Bombay) region. Takin, 1966 [76], Qureshi (1981) [77] had attributed the positive gravity anomaly below this region to the shallow level emplacement of a high-density rock, possibly olivine gabbro. This shallow level high gravity "frozen" magma chamber and all the acidic and intermediate dykes present west of the arcuate fault, are restricted to the BVC terrain. These do not have any direct relation to the basic dykes of the area and deviate from the general trend; however these dykes appear to be a product of some magmatic activity near or within the fissure zone (Godbole *et al.* 1996) [46]. Deshmukh and Sehgal (1988) [22] and Sheth, *et al.* (2009) [78], inferred that all the dykes in the western part of DCFB and in Narmada region were emplaced along the dilatory tension cracks.

Pyroclstic nature of the rocks and petrographic characteristics such as an abundance of Y shaped and crescent shaped shards, magmatic lapillus, devitrification of glass, presence of scoriaceous pumice, the occurrence of soot-like material within flows, embayed quartz, zoned plagioclase and micro scale displacement of the feldspar porphyroblasts in flows in the BVC are characteristics of the violent nature of the volcanism and post magmatic turbulence in the magma.

Sethna and Battiwala (1980) [79], Lightfoot (1985) [80] suggested that the acidic intrusive and the rhyolitic flows of Mumbai area have chemical signatures that favour a late-stage derivation relative to the fractionation of a gabbroic/basaltic magma that produced the Deccan volcanism. Cox (1988) [81] also noted similarities in geochemical signatures between rhyolites of Mumbai and Karoo; however, the minuscule volume of the former and occurrence of basaltic ejecta in the Mumbai area calls for some alternative mechanism. Godbole (1988) [7] has also reported olivine cumulates from some differentiated intrusive bodies. The occurrence of composite lapilli, a large variety ofvolcanic bomb shapes and a wide size range of fragments in volcanic and volcaniclastic ejecta, the limited aerial extent of the tephra, and their gradational amalgamation with the basaltic flows indicate a short-lived violent eruptive phase. These features point towards a fissure eruption and lava fountain deposits further supported by the occurrence of acidic crystal tuff resulting from a fissure-type feeder under pressure resulting in the flow folding.

7. Proposed Eruptive Mechanism and Discussion

The interpretation of facies of volcanic deposition is a very difficult question to be answered in case of older volcanic sediments like the present one, for the reasons explained already. Though a detailed field inventory has been made and genetic classification has been applied to the tephra, yet it is very difficult to ascertain the actual magmatic/tectonomagmatic process involved in laying these deposits. The various features recorded indicate a certain environment of deposition of the volcanic material but the same feature can be produced by the other process of the deposition in different environment. The inward dipping margins of the possible caldera at moderate angle and defined by the country rock breccias that grades into the intercalated rocks within the complex is a strong evidence in the favour of proposed structure. The litho units exposed, include massive, polymict lapilli tuff, tuff breccias >150 m thick with intercalated lava and minor bedded volcaniclastic rocks, possible pillows lava >50 thick and thinly bedded inferred reworked deposits in general capping the mounds of pyclastic/volaniclastic rocks in the complex succession and are in turn covered by basalts. Beyond the proposed cauldron area, the succession of fine grained bedded volcaniclastic succession are not recorded. The volcaniclastic deposits of LIP eruptions are important fundamentally for the volcanic landforms that form during these eruptions, are larger than and differ in other ways from the volcanic clastic basaltic volcanos. These large fragmental eruptions must have dramatic impacts of flora, fauna and sedimentary system and such eruptions potentially provide an efficient vehicle for injecting particulate debries and aerosols such as sulphur and chlorine in to the atmosphere, so it is important that we attempt reconstruction of fragmentation mechanism, eruptive volume and eruption duration to add to our growing understanding of its impact on the climate (McClintock, *et al.*, 2008) [82]. But here the authors are using physical volcanology to interpret the possible volcano-tectonic or magmato-tectonic environment within the BVC, while the other aspects are not being discussed. The intra complex (BVC) rock assemblage are dominated by massive hybrid mafic pyroclastic and effusive rocks followed by polymict lapilli tuffs, ash flows, volcanic breccias, bedded and assorted agglomerates interlayered with lava flows and minor bedded volcaniclastic and pyroclastic rocks. The thickness of such a succession in Tungar hill section is enormous, exceeds 400 m. Possible pillow lava is around 50 m in thickness, thinly bedded reworked pyroclasts and tuffs probably deposited (thickness are plotted in respective column diagrams in respect of various sections **Figure 18**) as lacustrine sediments after reworking of the volcanic vitric tuffs of acidic nature. At places these finely laminated and thinly bedded deposits from the present day top. The notion that major dykes might have acted as feeders to the Deccan Trap flows, initially propounded by Auden (1948) [25] was supported by some later workers such as RajaRao *et al.* (1974 [83], 1978 [6]). Agashe and Gupte (1972) [9] and Sethna (1981) [84] observed that the thicker dykes are located either close to the present-day coast or offshore. Mahoney (1988) [85] suggested that magmatic egress passes from somewhere in the west indicating feeders in the coastal area. Kaila (1981) [86] reported thinning of the trap pile towards the coast suggesting block faulting along the west coast. Mahoney (1988) [85] also observed features of rifting and subsidence associated with Deccan volcanism at some places. Hooper (1990) [3] suggested crustal extension as the major cause of Deccan volcanism. Sears and Hyndman (1988) [26] proposed a terrestrial Maria, the over flow of such a lunar lake generated the Deccan trp flows. But the overflowing of a magma will involve uniform spread of the monotonous composition for kilometers together, but here in the BVC the homogeneity or the monotony of the tholeiitic flows is not recorded, rather a very heterogenous assemblage is exposed. Sheth 2005 [87] & 2007 [21] did not agree with the plume-related origin of Deccan volcanism and suggested a pre eruption rifting and ocean floor spreading as the mechanism for extrusion of voluminous basalt lavas. White and Mckenzie, 1995 [88] suggested mantle plume derived magmaetism for DVP, Chatterjee and Rudra (1996) [29] and Chatterjee (2006) [30] argue and propose an impact catering to the generation of DVFB, but their postulation is based on the off shore drilling data and they speak about the geology offshore, on land complexities are not taken care by them. These propositions cannot explain the complexity of volcanism and diversity in rock types encountered west of the arcuate fault depicted in **Figure 1** and **Figure 2(a)** (Mahim-Paye-Matunga fault) that shows features typical n of a normal eruption. The subsidence in the uppermost part of the brittle lithosphere could be triggered by the withdrawal of massive volumes of magma, which in the present case seems sequential extrusion of basic flows in quick succession. A mechanism of listric fault has been proposed by Sheth 1998, [89], for pavel flexure, which is far east of this coastal arcuate fault. Somewhat similar but different mechanism is proposed by the current worker based on the detailed physical volanological studies carried out along with an exhaustive details of the grain size, mutual relation of the volcanoclastic rocks with the volcaniclastic and other reworked component of the volcanic assemblages exposed. Based on the field occurrence and petrographic features, subsidence resulting in to a large cauldron' in the BVC is suggested. Mahoney and Coffin (1997) [90], suggested that the initial eruption of basalt in deccan volcanism were partly explosive in nature that disperse ash and volcanic aerosols differently then effusive eruption of lava. The LIP' s which are best known for effusion of huge volumes of mafic lava also include volcaniclastic eruptions of significant volume (Ross *et al.* 2005) [91]. Studies of the effusive products of the LIP's magmetism point to a relatively passive eruption style dominated by emplacement of pahoehoe lava and construction of shield volcanoes accompanying injection of huge volumes of magma into the crust to form extensive sheet like dyke swarm (Self *et al.* 1997, [92], Chevallier and Woodford, 1999) [93]. Large volume volcaniclastic eruptions during the early stage of Ferrer-Karoo, and Green land flood basalt, Sieberian Traps and possibly Deccan Traps are recorded by wide spread exceptionally thick vocaniclastic deposits of mainly basaltic composition. (Ross *et al.*, 2005) [91]. The pyroclastic and volcaniclastic deposits thin distally and that appears a pattern within the complex. Magma emplaced over a broad area through a network of feeder dikes and sheets created many small vents, these features could be observed in terms of plug like bodies in saphale area, dyke swarm in Akarpatti area within the BVC. These deposits overlap within the complex. An abrupt end to eruption that formed the volcaniclastic deposits is evidenced by occurrence of thick succession of hybrid mafic lava that filled the cauldron part, first by water, than lava subsequently. Information is lacking concerning the intensity and the nature of eruption that produced them, the nature of the vents from which these thick deposits derive or the detailed temporal relationship between early explosive eruptions and the main phase of flood basalt eruption.

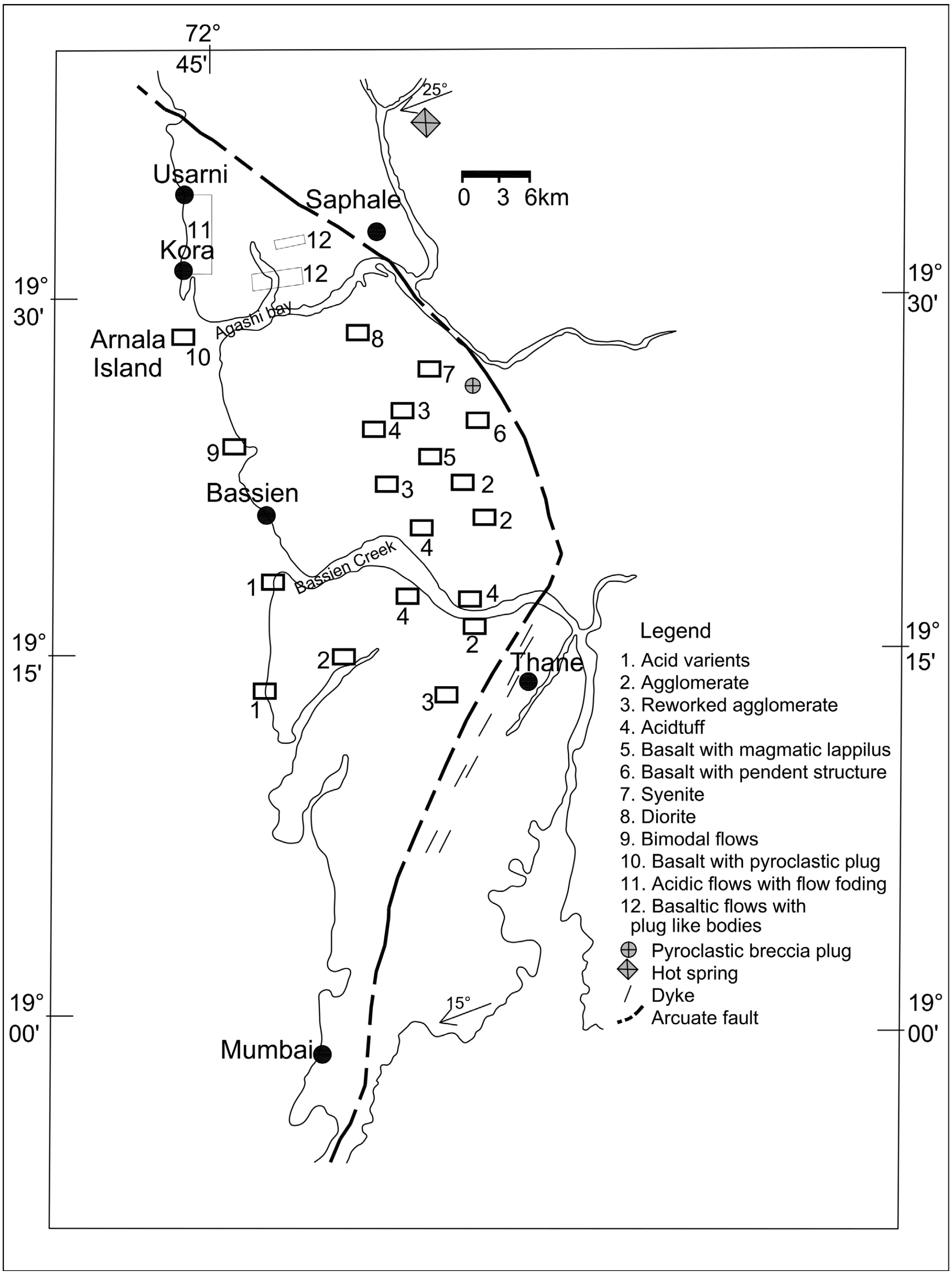


Figure 45. The proposed Cauldron area depicting various lithotypes and other features.

The possible mechanism of the subsidence is conjectured as The subterranean withdrawal of the magma from shallow magma chambers to the eruption site elsewhere would cause a sudden fall in pressure and the disequilibrium would result in the development of tensional cracks in the upper part of the crustal block, which could initiate collapse along some major planes of structural weakness. The collapse would result in a tensional regime and consequent tearing off of the surface would take place, leading to the development of sympathetic cracks/fractures parallel to the main failure surface. These fractures and faults acted as feeders for the clastic deposits resulting from the initial strombolian nature of the lava fountain. The Large-scale collapse resulted in the mixing of already erupted volcanic flows with the new batch of high-temperature magma from below, producing hybrid basaltic flows. Some plutonic bodies also got emplaced due to the stoping process. Some of the deep-seated fractures which could reach the magma chamber could tap the parent magma of lamprophyric plugs and dykes. Only emanations were left during the final stages that facilitated the welding of pipe rocks through fluidization.

As the cauldron region was under a high tensile strain, voluminous mass was eroded at a rapid pace to expose the plutonic bodies that were possibly partially exhumed during the collapse of an enormous mass of the crustal rocks as slip surface has a through of nearly 600 m. The clastic effusive rocks were largely digested and assimilated by the lava, therefore, the remanents are seen as isolated occurrences. **Figure 45**, where in the various locations dominated by the particular volcaniclastic and volcanoclastic assemblage is depicted, indicates as much as 14 variants of the volcanic assemblages of rocks. Now no single eruptive mechanism seems to explain this complex and hybrid lito assemblage.

The arguments and observations put forth above, converge towards "cauldron subsidence" as a plausible phenomenon to explain the complex volcanic history, lithological heterogeneity, field and petrographic observations of BVC rocks. The reported gravity anomaly below the Mumbai region (Kailasam *et al.*, 1972) [73] can be interpreted as a shallow magma chamber just below the trap cover, further supporting the cauldron subsidence theory. Such an origin for BVC was also indicated by Godbole (1998) [7] this should await substantiation through independent lines of evidence.

Acknowledgements

The author is indebted to late Dr. Godbole (from Geological Survey of India, Pune) who was a pioneer worker in the area and exposed the undersigned to the geology of BVC. The Author is highly thankful to Dr. M.K. Pandit, Professor retired University of Rajasthan Jaipur for his kind support and guidance during the course of research work, as this write up pertains to the research work carried out under his supervision. The author is also thankful to Dr. (MS) Sudha Vaddadi for her constant support and help in providing inputs to this write up.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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