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Primary volcanic structures from Nakora area of Malani Igneous Suite, Western Rajasthan: implications for cooling and emplacement of volcanic flows

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This communication reports field observations and petrographical studies of 44 volcanic flows in the Nakora ring complex. They are characterized into three different zones, viz. A, B and C, based upon the patterns of lava flows, cooling joints, vesicular nature and relative stratigraphic position observable in the field. Differences in the thicknesses of the flows have been related to total cooling time of the lava flows. Using the temperature–depth/thickness–time diagram, the total cooling time of these volcanic flows (40 flows are acidic and 4 flows are basic) with total thickness of 1776 m has been calculated and found to be 534.108–610.661 years. Flows in zone A in Nakora are more perfect, suggesting slow cooling and farther location from the volcanic vent, as compared to zone C, where flows are thicker as observed at locations closer to the vent.

Keywords: Cooling time, lava flows, Nakora, Rajasthan, thicknesses.

IGNEOUS rock complexes generally preserve many primary and secondary structures such as flows, vesicles and columnar cooling joints. The primary features are formed immediately after the magma is exposed on the surface and provide information about the physical conditions of the volcanoes. Secondary features such as the vertical columnar joints are useful in analysing the tectonic history of an area[1–5]. In this communication, we present the primary volcanic structures embedded in the volcanic flows in the Nakora area of Western Rajasthan.

The rocks of Nakora area (25°45′–25°50′N, 72°05′–72°15′E) are a part of Malani Igneous Suite (MIS) which spreads over an area of 51,000 sq. km in northwestern Indian shield and shows bimodal volcanism. MIS consists mainly of volcanic, plutonic and dyke phases. In Rajasthan, the rocks of MIS are spread from south of Sirohi to north of Pokaran and from east of Jodhpur to the edge of the Thar desert. Earlier studies[6–10] of MIS pertain to petromineralogical and geochemical aspects whereas the present studies describe flow zonation based on the physical features of the flows and evaluate the cooling time of lavas based on the thicknesses of the flows. The

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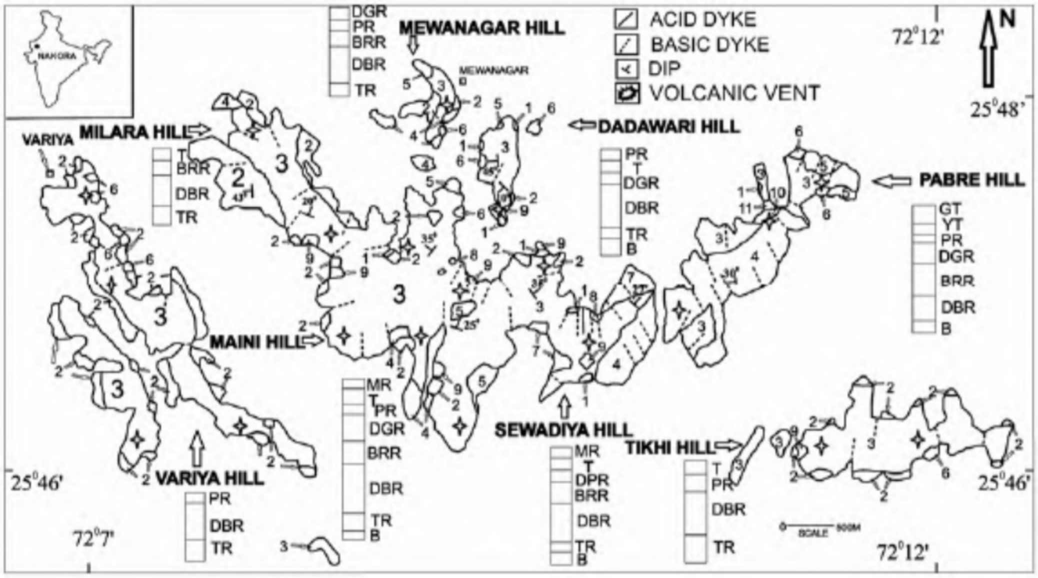

Figure 1. Flow stratigraphy map with lithological logs of Nakora area, Rajasthan. B, Basalt (1); TR, Trachyte (2); DBR, Dark brown rhyolite (3); BRR, Brick red rhyolite (4); DGR, Dark grey rhyolite (5); PR, Purple rhyolite (6); DPR, Dark pink rhyolite (7); MR, Mineralized rhyolite (8); T, Tuff (9); YT, Yellow tuff (10); GR, Grey tuff (11); (✧) represents the observatory points of primary volcanic structures, viz. flows, vesicular structures and cooling joints.

rocks exposed in Nakora area comprise granite, rhyolite, trachyte, basalt, gabbro and dolerite. A volcanic vent[11] and 44 volcanic flows[12] are reported in the study area.

On the basis of detailed geological field work, measurement of thickness and attitude of individual flows, vesicles, joints and petrography, 44 volcanic flows in Nakora area (Tikhi hill – 4, Sewadiya hill – 7, Maini hill – 8, Variya hill – 3, Pabre hill – 7, Dadawari hill – 6, Mewanagar hill – 5, Milara hill – 4 flows) are identified. Field criteria adopted to mark individual flows are: (i) identification of the volcanic assemblages; (ii) observation of the presence/absence of pyroclasts; (iii) systematically noting down the colour, form, structure, minerals – type, occurrence, association, alteration, ratio of phenocrysts/groundmass in the rocks; (iv) study of any sudden change in the given characters of a particular flow; (v) order of superposition of volcanic flows in different hills. These volcanic flows of Nakora area can be utilized for information on stratigraphic set up and different structural features in a particular hill (Figure 1 and Table 1).

The primary volcanic structures in basalt flows of Deccan[4,13] and Ireland[2,14] are classified into three tiers, viz. lower colonnade zone, entablature zone and the upper colonnade zone. For convenience, we have simplified these zones as A, B and C here for Nakora lava flows which are based on the primary volcanic structures like flows, vesicular structures and cooling joints mapped in the area. Zone A is exposed at few places but most of the area is covered by zone C. Zone A is characterized by well-developed columns (Figure 2 *a*; less than 1 m height) with fewer number of vesicles, but as compared to other zones larger sized vesicles (2–3 cm diameter) are observed here, which indicate that there was a time gap in lava solidification before the subsequent eruption. Zone C is characterized by fewer well-developed joints with >1 m columns height (Figure 2 *b*) and small-sized vesicles (<1 cm diameter), but the number of vesicles are more as compared to zone A. Zone B has mixed properties of A and C and shows irregular joints (Figure 2 *c*). Soil cover and growth of vegetation are observed in zone C (Figure 2 *d*). Zone B manifests more irregularity helping to identify the individual characteristics from one flow to another. All three zones show different thicknesses but zone C shows more thickness compared to others.

Columnar jointing is a common feature in this volcanic terrain which is visible as parallel, prismatic columns in these flows due to differential cooling. The study of primary volcanic structures is necessary and a useful tool for identification and comparison of lava flows in the field[5]. This generally occurs as sills, dykes and lava flows with basaltic composition. Chevron pattern, fan-shaped columns, inclined columns (Figure 2 *c*), rosettes, etc. are the other distinctions of cooling joints. Fan-shaped columns can be easily identified from top view of joints (Figure 2 *e*). Most columns tend to have five or six sides but we observed up to seven sides from top side of the columns (Figure 2 *f*). This suggests a shallow intrusive or extrusive environment in their formation[5,14]. Columnar jointing cracks are spread up to bottom surface of the cooling and their direction is normal to the solidified top surface[1]. The perfectness in joint pattern of zone A (Figure 2 *a*) is

Table 1. Physical characters of primary volcanic structures in Nakora area, Rajasthan, India

Rock	Zone, thickness (m)	Phenocrysts	Diagnostic properties
Tikhi hill			
Tuff	Zone B, 8	Q	Tuff shows shades, viz. light yellow to light grey, at few places shows glassy material in it, small vesicles observed, quartz as phenocrysts is distributed in the entire rock, P : G ratio is 4 : 96.
Purple rhyolite	Zone B, 10	Q + F	Purple rhyolite is observed in small area having P : G ratio 7 : 93 with very small amount of vesicles. This portion lies in southern side of the hill and difficult to identify joint pattern here.
Dark brown rhyolite	Zone C, 110	Q + F	Dark brown rhyolite occupy large areas, shows phenocrysts of quartz and feldspar, P : G ratio is 10 : 90; contains coffee brown rhyolite also, mostly rhyolite is enveloped by trachyte. This zone contains 2–4 facies joints with 1–2 m height.
Trachyte	Zone B, 15	F + Q	Light grey and blue colour, non-phorphyritic to phorphyritic nature with very small number of vesicles, P : G ratio is 3 : 97, middle zone exposed mainly in outer portion of Tikhi hill consists mainly of vertical joints having 0.5–1 m height.
Pabre hill			
Grey tuff	Zone B, 10	Q	After tracing some distance from south to north direction yellow tuff becomes into grey tuff, P : G ratio is 4 : 96.
Yellow tuff	Zone B, 8	Q	Tuff shows yellow colour but rarely green colour, having P : G ratio 4 : 96
Purple rhyolite	Zone B, 4	Q + F	Purple rhyolite occupies very small area, quartz and feldspar are present as phenocrysts having P : G ratio 9 : 91, in few places very small vesicles noted.
Dark grey rhyolite	Zone B, 50	F + Q	Eastern end of Pabre hill is exposed with dark grey rhyolite; feldspar and quartz are phenocrysts but quartz in less amount, P : G ratio is 5 : 95.
Brick red rhyolite	Zone C, 90	F + Q	Brick red rhyolite with small amount of quartz having P : G ratio 8 : 92, 4–5 facies joints developed, western part of the hill showing radiating and inclined joints with caves (2 * 5 m dimensions) and spheroidal weathering also exposed.
Dark brown rhyolite	Zone B, 60	F + Q	Mostly outer part of Pabre hill is covered by DBR rhyolite with phenocrysts of feldspar (pink) and quartz, P : G ratio is 15 : 85, small tubes/caves (up to 5 * 10 m dimensions) are exposed.
Basalt	Zone B, 10	Q	Grey colour; occur as a small flow (at northern side of the hill) with phenocryst of quartz, P : G ratio is 2 : 98.
Sewadiya hill			
Mineralized rhyolite	Zone B, 5	F+Q	Mineralized rhyolite is enriched with quartz veins and vugs (few cm to 5 cm size) P : G ratio is 10 : 90, at few places phenocrysts covers more than 30% of rock.
Tuff	Zone B, 10	Q	Light green tuff consists of quartz as a phenocrysts, P : G ratio is 5 : 95 and this occurs as smaller area as patch like structure in Sewadiya hill, spheroidal weathering also exposed.
Dark pink rhyolite	Zone B, 50	F + Q	Orthoclase feldspar as phenocrysts shows 1–5 mm size, P : G ratio is 15 : 85, at places number of phenocrysts occupy 40%. Small tubes/caves also exposed.
Brick red rhyolite	Zone C, 80	F + Q	Phenocrysts of orthoclase feldspar gives rise brick red colour to rock; P : G ratio is 20 : 80, phenocrysts (1–3 mm) size varies with distance, at few places flow bands are present in the rock, small tubes/caves (2 * 5 m dimensions) also exposed.
Dark brown rhyolite	Zone C, 200	F + Q	Rhyolite flows are mostly porphyritic in nature having feldspar and quartz as a phenocrysts, P : G ratio is 12 : 88, DBR occupy 70% area of Sewadiya hill, middle portion of this flow contains horizontal flow, upper part shows well developed joints with more height (up to 10 m), caves (5 * 10 m) and tubes exposed.
Trachyte	Zone B, 8	F	Trachyte shows blue colour and look like rhyolite but less vitreous with orthoclase as phenocrysts, P : G ratio is 12 : 88.
Basalt	Zone B, 10	Q	Basalt underlies tuff and shows light grey to dark grey colour; having quartz phenocrysts, vesicles filled by calcite, P : G ratio is 5 : 95, spheroidal weathering also exposed.
Maini hill			
Mineralized rhyolite	Zone B, 10	F + Q	Pink mineralized rhyolite is close to vent having quartz veins and vugs and also shows calcite veins, P : G ratio is 25 : 75, it contains geod rhyolite which shows spheroidal weathering.
Tuff	Zone B, 5	Q	Flow bands are easily recognizable in yellow to green tuff; quartz occurs as phenocryst, P : G ratio 7 : 93, this is highly fractured tuff with multiple nucleus and exposed spheroidal weathering also.
Purple rhyolite	Zone B, 5	Q + F	At few places purple rhyolite shows very less vesicles, quartz is more dominant than feldspar, P : G ratio is 8 : 92.
Dark grey rhyolite	Zone B, 20	F + Q	Feldspar and quartz are phenocrysts, P : G ratio is 6 : 94.

(*Contd*)

Table 1. (*Contd*)

Rock	Zone, thickness (m)	Phenocrysts	Diagnostic properties
Brick red rhyolite	Zone B, 30	F + Q	Brick red non-porphyritic rhyolite also exposed and shows flow bands, feldspar and quartz as phenocrysts and P : G ratio is 7 : 93.
Dark brown rhyolite	Zone B, 200	F + Q	Dark brown rhyolite having feldspar and quartz as phenocrysts, exposed 70% area of Maini hill, P : G ratio is 12 : 88, back of temple a small outcrop (50 * 100 m dimensions) contained inclined joints (20–30° dipping towards west), northern flank of this hill shows spheroidal weathering also.
Trachyte	Zone C, 20	F + Q	Light blue colour trachyte exposed at lower end of the hill, feldspar and quartz as phenocrysts, P : G ratio 30 : 70, Maini is covered by small-2 outcrop of this hill.
Basalt	Zone A, 5	Q	Basalt underlies dark brown rhyolite, shows dark grey to black colour having quartz as a phenocrysts and P : G ratio is 5 : 95.
Milara hill			
Tuff	Zone B, 15	Q	Occurs as small patches and has quartz as phenocryst, P : G ratio is 7 : 93.
Brick red rhyolite	Zone B, 30	F + Q	Brick red rhyolite is exposed at lower end of Milara hill, feldspar and quartz as phenocrysts shows P : G ratio 6 : 94.
Dark brown rhyolite	Zone C, 150	F + Q	Dark brown rhyolite is maximum dominant, almost 60% of Milara hill, P : G ratio 9 : 91
Trachyte	Zone B, 50	F + Q	Dark blue porphyritic trachyte covers almost 30% of Milara hill; feldspar and quartz as phenocrysts and shows P : G ratio 25 : 75, alternating layers of trachyte are common here.
Mewanagar hill			
Dark grey rhyolite	Zone B, 25	F + Q	Dark grey rhyolite is mostly concentrated in northern end of Mewanagar hill, feldspar and quartz occurs as phenocrysts, P : G ratio is 15 : 85.
Purple rhyolite	Zone B, 15	Q + F	In purple rhyolite, quartz is more dominant than feldspar, feldspar size is from 1 to 5 mm, P : G ratio is 12 : 88.
Brick red rhyolite	Zone B, 30	F + Q	Brick red rhyolite is mostly concentrated in two patches near Mewanagar hill, P : G ratio is 12 : 88
Dark brown rhyolite	Zone C, 70	F + Q	Dark brown rhyolite lies in central portion of Mewanagar hill and shows 70 m thickness, feldspar and quartz are phenocrysts, P : G ratio is 20 : 80.
Trachyte	Zone A, 15	F + Q	Flow bands are easily recognizable in dark blue trachyte of Mewanagar hill, feldspar and quartz are phenocrysts, P : G ratio is 25 : 75, vesicles are small, feldspar % varies from place to place.
Variya hill			
Purple rhyolite	Zone B, 20	F + Q	Purple rhyolite is observed near Variya village, also exposed as small outcrops in the scattered pattern, feldspar and quartz occur as phenocrysts; P : G ratio is 5 : 95, vesicles are observed at few places.
Drak brown rhyolite	Zone C, 100	F + Q	Porphyritic nature of rhyolite decreases in Variya hill as compared to other hills, P : G ratio 10 : 90, non-porphyritic nature also observed.
Trachyte	Zone B, 30	F + Q	Trachyte is exposed along the fringes of Variya hill, feldspar and quartz are scattered homogeneously, P : G ratio is 10 : 90.
Dadawari hill			
Purple rhyolite	Zone A, 10	Q + F	Quartz content is slightly more than feldspar, both are scattered uniformly, P : G ratio is 13 : 87.
Tuff	Zone B, 20	F	Tuff overlies the basalt, presence of orthoclase feldspar as a phenocryst, P : G ratio is 7 : 93.
Dark grey rhyolite	Zone B, 25	Q + F	Dark grey rhyolite contains quartz and feldspar as a phenocrysts, DGR is located in small area towards northern end of Mewanagar, P : G ratio is 7 : 93.
Dark brown rhyolite	Zone C, 125	F + Q	Almost in the all area it is exposed, feldspar and quartz are phenocrysts, P : G ratio is 18 : 82, feldspar and quartz are almost in equal amount and uniformly distributed, as compared to all Nakora ring complex this flow contained more perfecticity with sharp facies having up to 8 m height.
Trachyte	Zone A, 5	F + Q	Trachyte is observed at few places, P : G ratio is 10 : 90
Basalt	Zone B, 8	Q	Outcrop of basalt is exposed up to main road of Nakora temple, basalt has sharp contact with dark brown rhyolite, it consists mainly quartz as phenocryst, P : G ratio is 5 : 95, few and large size vesicles present, spheroidal weathering also exposed.

Figure 2. Field photographs (***a***, ***b***, ***c***, ***d***, ***e***, ***f***) and photomicrographs (***g***, ***h***). ***a***, Well-developed joint columns observed in zone A. ***b***, Natural volcanic caves exposed in zone C at different levels of the volcanic flows. ***c***, Inclined joints in zone B of Nakora area. ***d***, Soil cover and growth of vegetation observed in zone C. Dolerite dyke cuts the flow. ***e***, Fan-shaped columns observed from top view of the joints. ***f***, Top view of joint exposed seven sides. ***g***, Phenocrysts of orthoclase, quartz, arfvedsonite as essential minerals in the quartzo-feldspathic groundmass of porphyritic rhyolite. ***h***, Rhyolite shows flow bands of different colours.

the result of slow cooling and suggests larger distances from the probable source of lava flow whereas zone C with less perfectness is located near the vent. On the other hand, fractures in zone B have formed as a result of rapid cooling[2].

Nakora area mainly consists of felsic volcanic rocks (rhyolite/trachyte having mainly dark brown, light brown and pink shades, etc.) and tuff (with green and yellow colours). Rhyolite is dominant in the Nakora area and shows columnar joints with vesicles. Trachyte is very similar to rhyolite and exposed during association with rhyolite. Xenolith of basalt in rhyolite and trachyte shows that basalt is the earliest flow. Basalt is fine grained and black and dark brown colour with 4–6 mm size vesicles. It may be mentioned here that there are no weathering and erosional features due to surfacial process, viz. laterization, silicification, kaolinization except spheroidal weathering in the Nakora lava flows are observed. Hence the thickness of the lava flows remains the same since its eruption and this can be related to cooling time of the lava. Maximum variation in vesicular shape and geode density is observed in the volcanic flows of Maini hill where the volcanic vent is located (Figure 1). Here the size and number of vesicles, geode and flow density are similar to the bottom most part of the hill and oriented towards the vent. Natural volcanic tubes/caves are also observed in different flows (Figure 2 *b*). Mostly these flows are horizontal but at places they are cut by dolerite dyke (Figure 2 *d*). In Maini hill, the dolerite dykes contain calcite veins and show spheroidal weathering.

Distinct mineralogical and textural features are observed in each lava flow. Rhyolite consists of phenocrysts of orthoclase, quartz, arfvedsonite as essential minerals in the quartzo-feldspathic groundmass (Figure 2 *g*). Arfvedsonite occurs as large prismatic crystals (length 2 mm and width 0.5 mm), dark green colour (X = dark bluish green, Y = bluish green, Z = yellowish green; extinction angle X^C 13°–15°). It shows flow bands (Figure 2 *h*), porphyritic, aphyritic and perlitic textures. Black colour haematite and brown colour magnetite are scattered in fine-grained groundmass. Trachyte shows trachytic texture and same mineralogical characters except less amount of quartz as in rhyolite. Labradorite and augite are essential minerals in basalt. Basalt shows ophitic and sub-ophitic textures and consists of quartz, haematite and magnetite as accessory minerals. Dolerite consists of untwinned plagioclase feldspar (labradorite) and augite. It consists of haematite and magnetite as accessory minerals. The above petromineralogical observations suggest comagmatic nature of the source in their genesis. Under a microscope, large number of small crystals (groundmass crystals) are observed in Nakora magma which has a strong effect on its rheology. Magma degassing and magma cooling are the processes under which groundmass crystallization takes place. The groundmass crystallization effects the eruptive style of magma[15–18] and lava surface morphology is also related to its groundmass crystallization[19–21]. Rate of groundmass crystallization can be increased due to radiative heat loss from the lava surface[19,23–24]. Hence the concentration of magma, distribution of crystals in fluid lava, amount of gases present in the magma, lava rheology and surface morphology are strongly linked to each other. Intensity of groundmass crystallization is also governed by eruptive dynamics at the vent. Perfectness of zone A as compared to zone C and fractures in zone B supports the discussed view in Nakora area.

The variable flow thicknesses in different flows are used for comparison and measurement of total cooling time of Nakora lava flows with the help of temperature–depth–time diagram[1]. The cooling time of lava flows can be calculated by individual cooling time of different flows. The difference in rate of cooling within the flows is considered as the change in the isotherms[2,14]. The isotherms are parallel to the surfaces of equal stress and hence the distribution of isotherms can be measured using temperature–depth–time curve[1]. Stratigraphic column explains the relationship between flow thicknesses and zones (A, B and C) and it is used for hill-wise comparison and identification of flows (Figure 3). Zone A with total thickness of 35 m consists of Maini, Dadawari and Mewanagar hills (Table 1). These hills constitute the inner circle of Nakora area (Figure 1). Zone C (total thickness 945 m) and zone B (total thickness 796 m) are observed at the outer parts of different hills in scattered form. Maximum measured thickness of the flow is 200 m from Maini and Sewadiya hills and minimum thickness is 4 m at Pabre hill (Table 1 and Figure 1). Thicknesses of different flows are directly related to the cooling history of the lava[25]. The solidification of different flows is the linear function of square root of times ($\sqrt{t}$ days). In 1965, Kilanea Volcano at Hawaii erupted (Makaopuhi lava lake) and a relationship has been established between depth of lava pond and elapsed time[1]. During a Kilanea eruption in 1963, in Alae lava lake, the same type of relationships are observed[3] and suggested[3] that these relationships may be used to indicate the cooling history of (temperature–depth–time curve) the lava flows. The heat loss from upper part of the flow indicates the sloping nature of the isotherms. In the beginning, disturbance is observed in sloping nature of the isotherms but later on it becomes linear. These studies are applied in the present study area and are discussed here. The relationship diagram[1] between cooling time of the lava flows and their respective thicknesses (Figure 4) have been utilized. Considering the fact that the Deccan basalts have crystallized at temperatures between 900°C and 1000°C (ref. 25), assuming the same, the cooling time of different basaltic flows can be determined from slopes of 900°C and 1000°C isotherms. Basaltic flows which have thicknesses of 5 and 10 m have solidified in 225–306 days and 870–992 days respectively. On the other hand, the cooling time of different rhyolitic flows can be determined from slopes of 700°C and 800°C isotherms. Rhyolitic flows having thicknesses of 5 and 10 m have solidified in 449–640 days and 1102–1260 days respectively. Assuming the linearity of isotherms for the lava flows with >10 m thickness, we can say that their cooling time also will be multiple of corresponding cooling time of 10 m thickness. After calculating the thickness of all flows of Nakora area, we are able to calculate the total cooling time

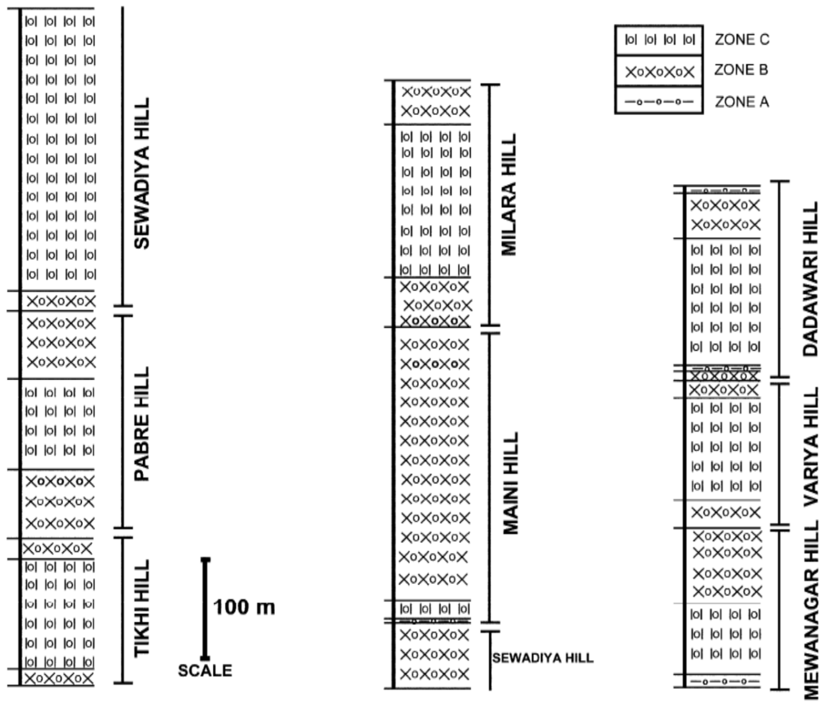

Figure 3. Various zones and volcanic flows.

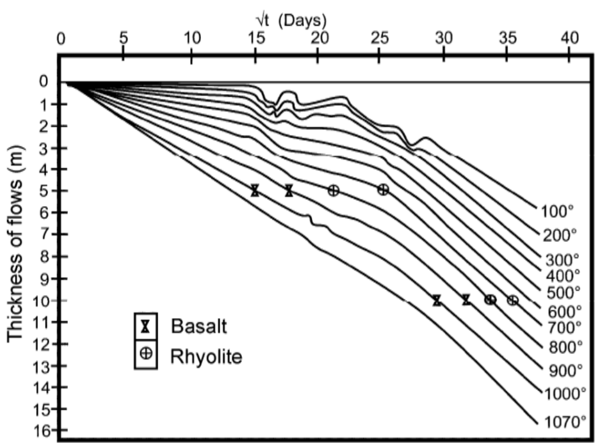

Figure 4. Cooling time against thickness of basalt and rhyolite (having 5 and 10 m thickness); Wright and Okamura[1].

of the particular area. Out of 44 volcanic flows (total thickness 1776 m), four are of basaltic composition with 33 m thickness and have solidified in 2871–3273.6 days, and other 40 rhyolitic flows with 1743 m thickness have solidified in 192,078.6–219,618 days. Total solidified time is from 194,949.6 to 222,891.6 days or 534.108 to 610.661 years for 44 volcanic flows (4 basic and 40 rhyolitic). The calculated and actual cooling times of Nakora area may not be the same because the flow thickness is more and there is variation in lithology also but we have made an approximate estimate of the cooling time of the lava flow. More details about these rocks can be obtained if we have total information of the pattern of isotherms up to the end point of the flow.

Detailed geological field work, measurement of thickness and attitude of individual flows, vesicles and joints and petrography have suggested that Nakora volcanic episodes were initiated with minor basic flows, developed later as voluminous rhyolite comprising all 44 flows. In volcanic vent area (Maini hill), almost all volcanic vent characteristics, viz. lava channels (tunnels), volcanic caves, flows, perlite, breccia, agglomerates, geode, veins, vugs, vesicles and basic dykes are observable[11]. From bottom to top of the vent hill, the size and number of vesicles increase with height indicating the presence of volcanic source area. Geode density also increases in the same manner. Veins and flows are oriented towards the source area. In the present study, we have calculated approximately total cooling time of volcanic flows of Nakora area as 534.108–610.661 years which comprised four basaltic flows with 33 m thickness and all other 40 flows are rhyolitic in composition having 1743 m thickness (total thickness 1776 m).

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Female-biased sex ratio in a protandrous moth: challenging the mate opportunity hypothesis for explaining protandry

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Asynchrony among sexes in arrival/emergence timings is common in animals with distinct breeding periods. Scramble competition among males for virgin females is generally attributed to select for protandry among monandrous mating systems, especially in insects. This is classified as the 'mate opportunity hypothesis', or sexual selection for early male emergence. Sex ratio can influence reproductive asynchrony, and protandry is known to be favoured when sex ratio is male-biased. However, in the present communication, empirical evidence demonstrates female-biased pre-adult, adult and operational sex ratios in the monandrous, protandrous moth *Opisina arenosella*. It appears that males of *Opisina* need not compete among themselves for virgin mates, and that, males, irrespective of the time of emergence, have sufficient mating opportunities. These throw serious questions at the sexual selection theory for explaining protandry in *Opisina*. Additionally, data proved that the last arriving females died as virgins, which support models that predict loss of mating opportunities for females due to protandry.

Keywords: Mate opportunity hypothesis, mateless females, *Opisina arenosella*, protandry, reproductive asynchrony, sexual selection.

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