New approaches towards measuring cupule volume for empirical analysis: an experimental study from Brahmagiri, Southern India

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Cupules (cup marks) are found across the world ranging in age from Palaeolithic to recent in different archaeological contexts. Cupules sites at Brahmagiri, Southern India are rock shelter, mortuary and settlement in context of Iron Age (1200–300 BCE) and Early History (300 BCE–500 CE) evidences. The emphasis of this research is on developing an advanced approach for measuring cupule volume from one of the sites at Brahmagiri through $V = \pi \times d \times (R^2 + r^2 + R \times r)/3$. In order to test the accuracy of the volume values obtained from this formula, a simple experiment was conducted by filling premeasured water into cupules through 5 and 60 ml volume matrix glass and this showed close results validating the above formula with a minimal error margin.

Keywords: Brahmagiri, cupule volume, late Prehistory, rock art, South India.

CUPULES or cup marks are rock art petroglyphs involving a range of workmanship in forming cup-like hemispherical depression over rock surfaces by a hammer stone. They are one of the known categories in world rock art, ranging in age from Palaeolithic to recent. Their functionalities are largely debatable and ethnographic studies have provided a ritual and symbolic phenomenon[1–3]. Apart from this, they also fall within the categories of astronomy, games and sonic production[4–9].

Like elsewhere in the Indian subcontinent, we have recorded cupule sites mainly associated with three major archaeological contexts – painted rock shelters, open sir settlements and megaliths (Figure 1). For example Bhimbetka[10], Mahurjuhari[5], Badami complex[11], Kadebakele[9], Sangankallu-Kupgal[7,12], Vitragal-Devapura[1], etc. The scope of this paper is not on recording of the cupules and sites, as a majority of publications have already focused on them by employing a common two-dimensional measuring method through diameter and depth. Rather, this research emphasizes on measuring the cupules itself, proposing to express their size by volumetric values using systematic quantification methods than through centimetres or millimetres of diameter and depth. This should inform us by how much unit cupule differs in their volumes (size) than by merely knowing their vertical or horizontal lengths.

Since the very beginning of cupule studies, in India and elsewhere, though we have advanced in various aspects of cupules studies like dating, microerosion analysis, residue analysis and replication of cupules themselves yet, we have retained our traditional measuring method of length × breadth × depth and rim diameter. For latest examples, see ref. 13. Attempts are also made on the lines of terms like horizontal and vertical dimensions of cupules[10]. Novel approaches for measuring cupules further suggest that systematic quantification of cupules is in vague. For example, at an Indian cupule site of Kurshiburu[14], researchers attempted to express the dimension of cupules by ratio of diameter and depth which still relied on the consideration of rim diameter length and depth. Lack of considering triple angles of cupules, technically fails to express the individual values.

During the present study at Brahmagiri, a couple of shortcomings were observed while measuring the length, breadth and depth of the cupule. How does one determine the length and breadth of a round or semi-circular, elliptical or spherical object? Traditional measuring method lemmatizes more towards typological and dimensional understanding of cupules despite their composite metrical values. For example, cupule A measures 2 × 2 × 1.7 cm (length × breadth × depth) and cupule B 2 × 1.7 × 2 cm (length × breadth × depth). Now, which one of these is larger in dimension and what is the metrical difference.

Cupule replication project at Daraki-Chattan (Madhya Pradesh) brought to light three important aspects in cupule production technology[15,16]: (i) As the cupule takes its depth and circumference, morphological changes occur on the striking surface of the hammer stone. The hammer platform experiences erosion on its periphery and turns smoother on its radii, and ultimately this process results in shrinking of the hammer surface; (ii) Broad and deep cupules are executed by using multiple hammer stones; (iii) As the cupules achieve certain amount of diameter and depth, further pounding affects only its inner portion (i.e. inner lower portion) and therefore the outer diameter (i.e. the rim diameter) generally remains the same.

The lower portion of the cupule is one of the notable features that Bednarik and Kumar have observed in their various cupule replication projects[17–20]. They reported variations in the geometric rim centre and deepest point of the cupule, and opined that such differences occur because of biomechanics in the cupule production. Bednarik[19] comprehends the shape of cupule resembling spherical cap and attempted to measure volume through spherical segment formula

$$V = \pi d/6\ (3r^2 + d^2),$$

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where V is the volume, r the radius at rim and d is the depth. However, so far, he has not provided any practical demonstration of this formula on any cupules. The formula represents the spherical part of the spherical cap, also called as 'zone', comprehending the major part of the cap and excludes the base portion[21–23]. However, the volume of lower portion of the cupule, i.e. the portion below the spherical segment or zone that is not in consideration is not known.

Therefore, we can achieve a higher level of accuracy in measuring cupule volume by considering its lower portion. The rim portion of the cupule is a round or circular or oval or spherical cap in resemblance but its lower portion does not always end exactly as such. As the cupule takes its depth, the lower portion gets a slight sudden and slight narrow shallow curve or roughly shallow conical or shallow concave lower inner surface. Hence on these empirical grounds, after studying various mensuration volume formulas (for example Bronshtein *et al.*[24]), the truncated cone formula $V = \pi \times d \times (R^2 + r^2 + R \times r)/3$ representing the frustum of the cone is chosen. The actual cupules are neither or either of the basic geometrical shape. The rim surface of the cone is the rim surface of the cupule, the other circular end of the frustum is the lower portion of the cupule (i.e. 0.5 cm radius as default) and the actual slant height of the cone is the actual depth of the cupule. Therefore, it accommodates all the three physical sections of the cupules, i.e. top, lower and depth, and more importantly, it provides no provision for non-spherical segment zone (Figure 2).

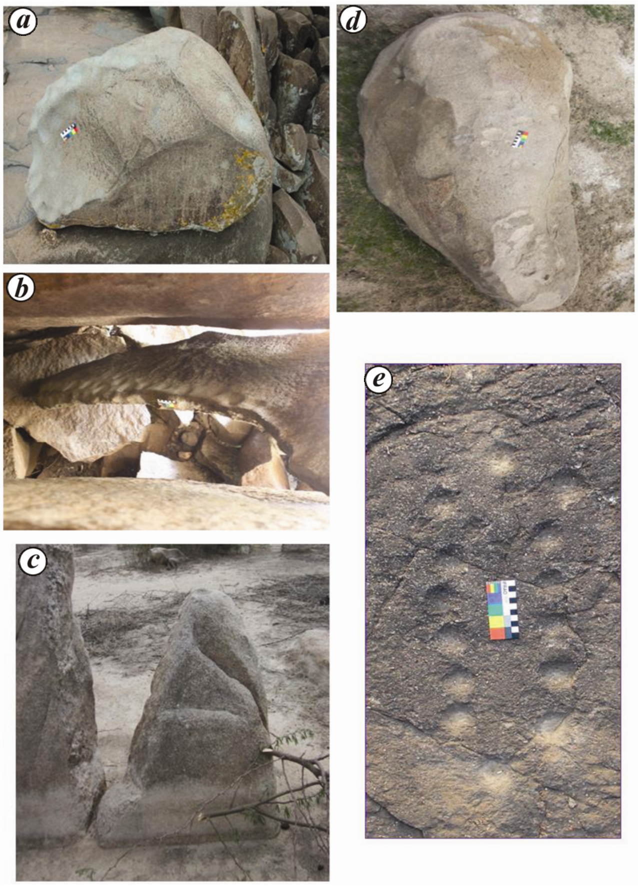

Figure 1. Cupules from different archaeological sites. ***a***, Advi-Rampura hilltop (Raichur); ***b***, vertical lithophone at Dodda damali (Bagalkote)[11]; ***c***, cupule on menhir (Brahmagiri); ***d***, cupule on field boulder (Brahmagiri); ***e***, game board cupule set on basalt (Deccan College campus). Sites 1 to 4 are in Karnataka and site 5 is from Pune.

The volume of a round or circular cupule can be measured by the following formula (Figure 3)

$$V = \pi \times d \times (R^2 + r^2 + R \times r)/3,$$

where V = volume, π = 3.1415927, d = depth, r = radius of cupule top (half the total length/breadth), R = radius of lower portion of cupule (half the total length/breadth).

For example: Cupule A measures 0.5 cm lower portion radius × 3 cm top radius × 4 cm depth and Cupule B measures 0.5 cm lower portion radius × 3.5 cm top radius × 3.5 cm depth.

$$V = \pi \times d \times (R^2 + r^2 + R \times r)/3,$$

$$\text{Cupule A: } V = 3.1415927 \times 4 \times (0.5^2 + 3^2 + 0.5 \times 3)/3 = 45.$$

$$\text{Cupule B: } V = 3.1415927 \times 3.5 \times (0.5^2 + 3.5^2 + 0.5 \times 3.5)/3 = 52.$$

Therefore, though the dimensions of both cupules are slightly different, the differential value is 7 cm^3.

This research initiated a simple experiment to verify the accuracy of the proposed formula by filling water in the cupule and measuring the volume of water it

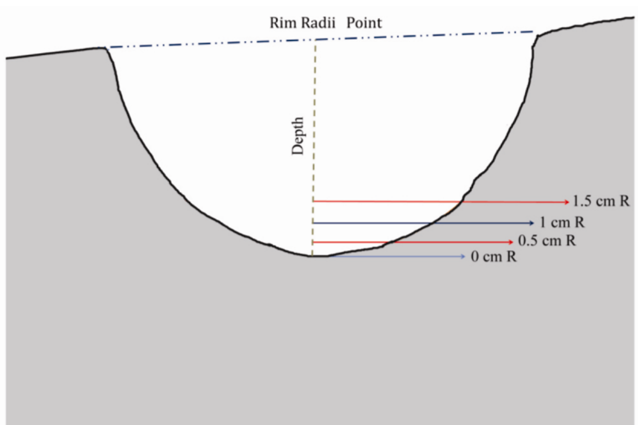

Figure 2. Schematic vertical cross-section of a cupule. As the cupule takes its depth its lower portion measurements gradually reduces and reaches to 0 cm at base point, therefore the lower radius (R) is considered at 0.5 cm as default. The position between 0 and 0.5 cm does have a good share in determining the actual volume of the cupule. Note: Figure not to scale.

accommodates. This resulted in a reasonable amount of water loss even before sucking through pipette and dropping into volumetric glass; because any rock in such instances, e.g. granite, absorb water faster and the daylight temperature in semi-arid sites also add to further loss. Therefore, this process was found impractical, non-progressive and waste of time. Hence, we first measured water in 5 and 60 ml volumetric glasses and then filled the cupules (Figures 4 and 5). The volume values obtained using the formula and the corresponding volumetric glass measured are given in Table 1. Accordingly, the results are closely differing in the range of –1 to –7 and +1 to +20 (1 cm^3 = 1 ml).

Brahmagiri is a multicultural period-type site with immense archaeological importance from Microlithic/ Mesolithic (9000–3000 BCE), Neolithic (3000–1200 BCE), Iron Age (1200–300 BCE), Early History (300 BCE–500 CE) to modern times[25–29]. The ongoing transect survey at

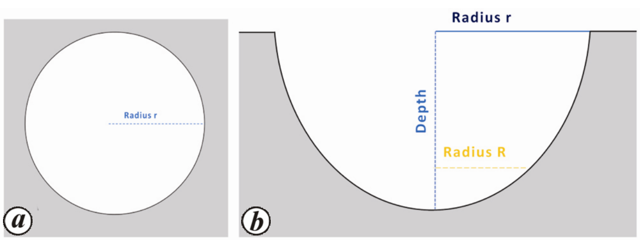

Figure 3. ***a***, Horizontal section; ***b***, Vertical sections of a round or spherical shape cupule illustrated to measure its volume by considering top radius, default lower radius of 0.5 cm and depth. Note: This is a schematic illustration and either of the actual cupules is not strictly geometrical in shape.

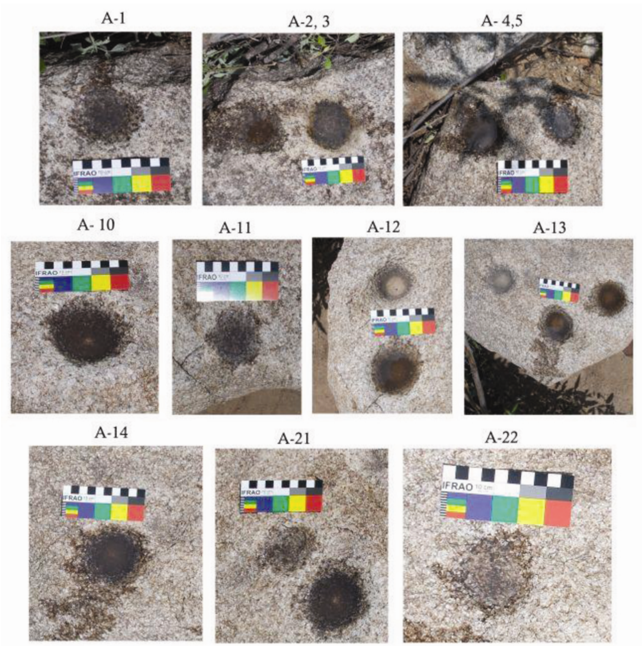

Figure 4. Cupule volume measured by filling premeasured water through volumemetric glass/beaker. Inset are cupules on Boulder A, Brahmagiri.

Brahmagiri[27] has located four cupule sites in different contexts (Figure 6). They are human occupied painted rock shelter; one site on flattop of the menhirs and two sites of field boulders amidst settlement-mortuary space. The rock shelter site and its significance in landscapes of Brahmagiri is reported by the author elsewhere[27] and the latter three are now presented in this communication (Figures 1 and 7). The common phenomenon in functioning of the cupules is the 'sound'. Sound is made not only for rituals, it could also be for domestic as well as political annotations. Rock shelter containing cultural material depository, characters of multi-layered painted images with differing forms and pigment shades, more particularly the images of horse in early style and anthropomorphs in commanding postures have contextually placed a primary occupation of the shelter during the Iron Age and reoccupation during Early History[27]. This shelter bears a cupule on its entrance, alleged to function on political annotations. The burial site of six menhirs is located over the old flooding terrace (Figure 7 *c*) of Vedavati/Chikka Hagari (tributary of Thungabhadra). Among them, one of the menhir bears a prominent cupule on its top surface (Figure 1 *c*) which attests a ritual association. The other two sites are on field boulders where there is no cultural material evidence and located amidst the habitation and clusters of megaliths. The cupule site, which is of a core concern in this experimental study is 2 A, B and C (Figures 7–9).

The cupule sites found within 50% of the study area is so far non-repetitive in their associated contexts. Suggesting spatially and sonically prominent landmarks, and not necessarily limited to being ritualistic at Brahmagiri. Transect survey covering the northern half of the study areas suggests Iron Age and Early History cultural materials occupying a major extent of overall site space. Cupule production might have belonged to these periods when there were high-density anthropoid activities in the Brahmagiri landscape. On the other hand, cupules in southern Neolithic sites, especially in North Karnataka, are rock gongs in context of rock bruising localities

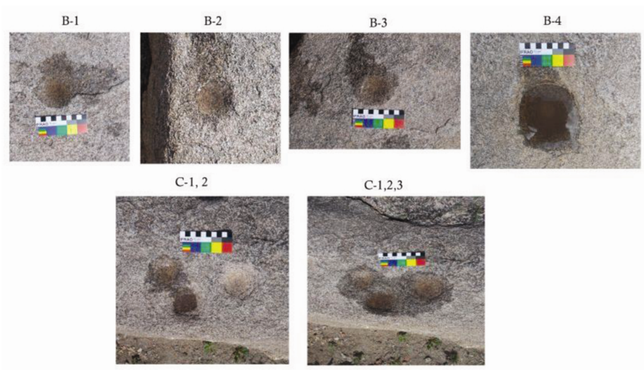

Figure 5. Cupules of boulder B and C, measured through volumetric beaker by filling water, site 2B and C, Brahmagiri.

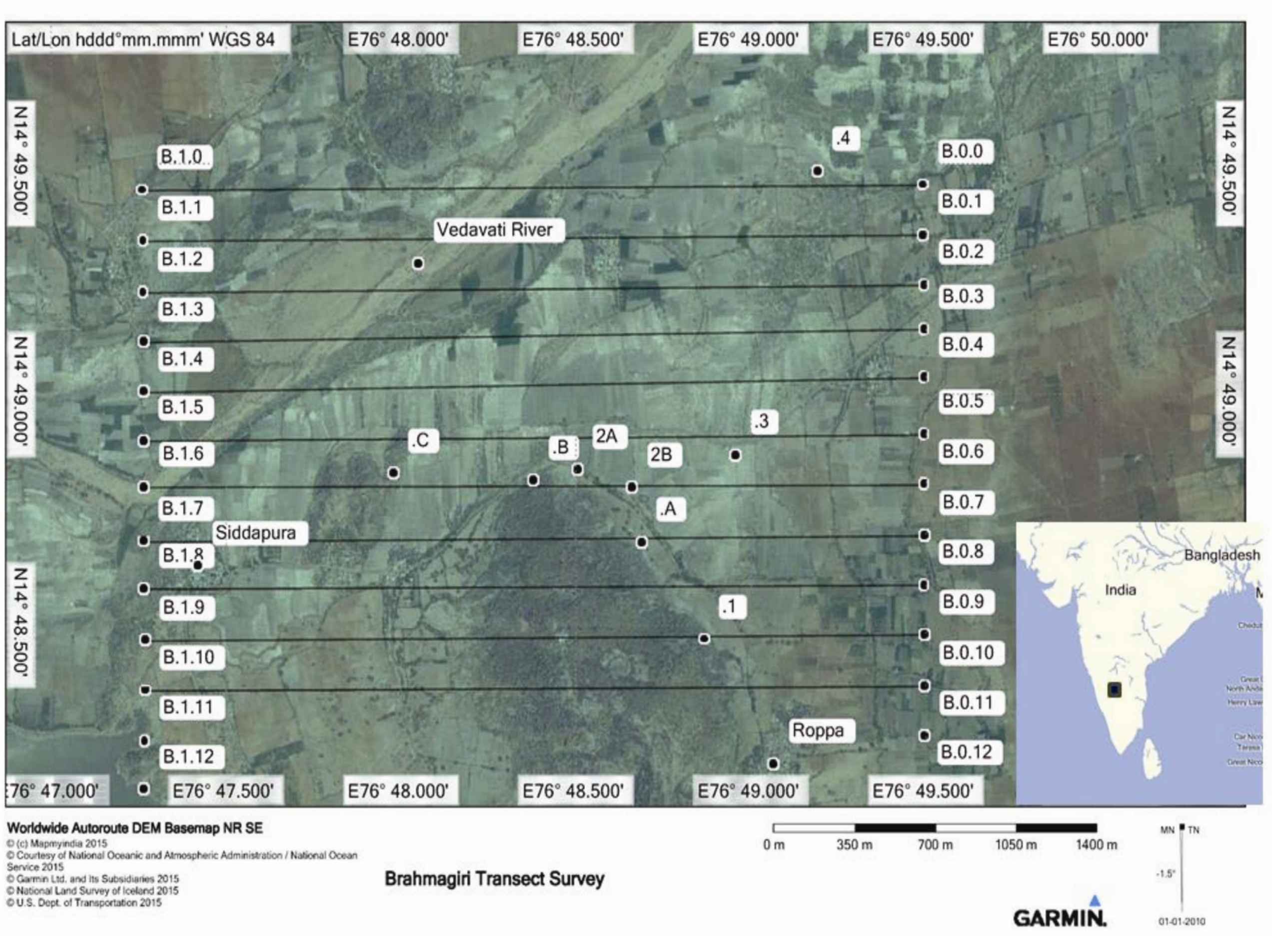

Figure 6. Brahmagiri transect survey plan covering 50% of the study area (surveyed lines are of northern portion, and southern area is not shown). (1) Painted rock shelter with a cupules. (2A and 2B) cupules site where experiment conducted, (3) cupules on a field boulder and (4) cupules on flat top of menhirs (megalithic site). (A) Wheeler's excavated settlement area, (B) and (C) location of Asoka rock edicts.

on the hill summits[7,30]. However, none of the previous and present studies on Brahmagiri had encountered rock bruisings. The transect survey anticipates a least possibility in finding rock bruisings at Brahmagiri. Based on our observations at a number of inselberg centred sites at Raichur Doab (particularly Raichur district, Karnataka), Neolithic artist looked for dark coloured boulders like granodiorite and dyke at the middle and upper terraces of the hills, and not the white-pinkish coloured granites, like the Clospete granites of Brahmagiri inselberg.

A total of 25 cupules, all in relatively round shape, were noticed on a flat surfaced boulder (2A) (Figure 8). Placement of cupules on the surface is in a circular manner. The cupules range from 1.5 cm radius in top × 0.5 cm depth with 2 cm^3 and 2 ml to 5 cm radius in top × 2.5 cm depth with 73 cm^3 and 70 ml (Table 1). The cutting marks on the outer surface of the boulder and the partial damage of cupules number 6–9 amply comprehend that the cupule platform is a flake of a large rocky fracture which happened during the striking of cupules and later on secluded in quarry activity in the nearest past. Cupules numbers 11 and 20 are interesting, as they contain cracks (Figure 4: A11 and 20).

A total of seven cupules are pounded on two flat surfaced cupule boulders B and C respectively, which are foot apart (Figure 9). Four round-shaped cupules on boulder B are oriented towards four coordinal directions at an uniform distance of 18 cm. The cupules size ranges from 3 cm radius in top × 1.5 cm depth with 17 cm^3 and 3 ml to 7.5 cm radius in top × 4.5 cm depth with a 284 cm^3 and 264 ml (Table 1). On boulder C, three cupules are placed in a triangular format. All the three cupules are round in shape, measuring from 3 cm radius in top × 1.5 cm depth with 17 cm^3 and 14 ml to 4 cm radius in top × 2.5 cm depth with a 48 cm^3 and 50 ml respectively (Table 1).

We now discuss as to how the above proposed volumetric method of measuring cupules enables higher level of examinations and influences new empirical perspectives in the cupule studies.

On the cupule boulder 2A, 25 cupules are pounded in a rough circular pattern (Figure 8). The inner space of the

Table 1. Dimension of the cupules and experimented results through cubic volume formula and water volume on the cupules of Boulder 2A, B and C, Brahmagiri

Cupule no.	Dimension $R \times r \times d$ (cm)	Cubic volume unit (cm^3) $V = \pi \times d \times (R^2 + r^2 + R \times r)/3$	Water volume (WV). (one cm^3 = one ml)	Difference with cm^3 and WV
Boulder A				
1	0.5 × 3 × 1.5	17	15	–2
2	0.5 × 3.5 × 1	15	18	+3
3	0.5 × 4 × 3	57	50	–7
4	0.5 × 3.5 × 1.5	22	19	–3
5	0.5 × 3 × 1	11	9	–2
6	Damage	–	–	–
7	Damage	–	–	–
8	Damage	–	–	–
9	0.5 × 2 × 0.5	3	5	+2
10	0.5 × 4 × 3.5	67	57	–10
11	0.5 × 2.25 × 1.5	10	15	+5
20	0.5 × 4.25 × 3	64	60	+4
13	0.5 × 5 × 2.5	73	70	–3
14	0.5 × 3.5 × 2	30	33	+3
15	Damage	–	–	–
16	0.5 × 2.25 × 1	7	9	+2
17	0.5 × 1.75 × 0.5	2	3	+1
18	0.5 × 1.5 × 0.5	2	2	0
19	0.5 × 2.5 × 1	8	8	0
20	0.5 × 2.75 × 1	10	9	–1
21	0.5 × 2.5 × 1	8	8	0
22	0.5 × 2.25 × 1	7	8	+1
23	0.5 × 2.5 × 1.5	20	20	0
24	0.5 × 1.75 × 0.5	2	3	+1
25	0.5 × 2 × 0.5	3	3	0
Boulder B				
1	0.5 × 3.5 × 1.5	22	15	–7
2	0.5 × 3 × 1.5	17	13	–4
3	0.5 × 3 × 1.5	17	13	–4
4	0.5 × 7.5 × 4.5	284	264	–20
Boulder C				
1	0.5 × 3 × 1.5	17	14	–3
2	0.5 × 3 × 2.5	28	30	+2
3	0.5 × 4 × 2.5	48	52	+4

circular circumference and the location of the cupule boulder in an open field infer that the cupules might have been pounded by the pounder sitting in the middle of the boulder and turning his/her position. They all appear to be round, but are not uniform in their volume, because they are invariably determined by lower portion radius in reference to the rim radius and the depth achieved. For example, cupules A 2, 4 and 14 have a rim radius of 3.5 cm but the depth difference is 1, 1.5 and 2 cm respectively with a differing volume capacity of 15, 11, 30 cm^3 and 18, 19, 33 ml respectively. The depth of cupules A 2, 16, 20 and 21 is uniformly 1 cm with differing rim radius of 3.5, 2.5, 2.8 and 2.5 cm resulting in 15, 7, 10, 8 cm^3 and 18, 9, 8, 9 ml respectively. Volume suggests unevenness in cupule dimensions (Table 1). In this case a number of pounders might have employed a wide range of hammer stones of non-uniform surface dimensions. The pounders seem to be free from any sort of action plan or pattern in mind, and pound the cupules of different dimensions, one after the other or at the same time.

Unlike the cupules on boulder A, some sort of control is apparent in pounding of seven cupules on boulders 2B and C (Figure 9). As the cupules are placed on the edge and on flat surface, closely, at equal distance, there is some uniformity in their dimensions. They look almost spherical, as though they have been made with conscious efforts (Table 1 and Figure 9). On boulder B, the cupules are placed towards four cordial directions each at a distance of 18 cm. On boulder C, the cupules are concentrated on the surface edge, with 2–4 cm spacing between them. When water was poured into C1 or C2, it overflowed into C3 (Figure 5: C1–3). Except cupules number B 4 (r-7.5, V-284), C1 (r-3, V-14) and C3 (r-4, V-48), the rest of them are uniform in their top radius of 3 cm but slightly differ in volume. Cupule B3 is conspicuous with largest dimensions of rim radius 7.5 cm, depth 4 cm and volume 284 cm^3 and 264 ml.

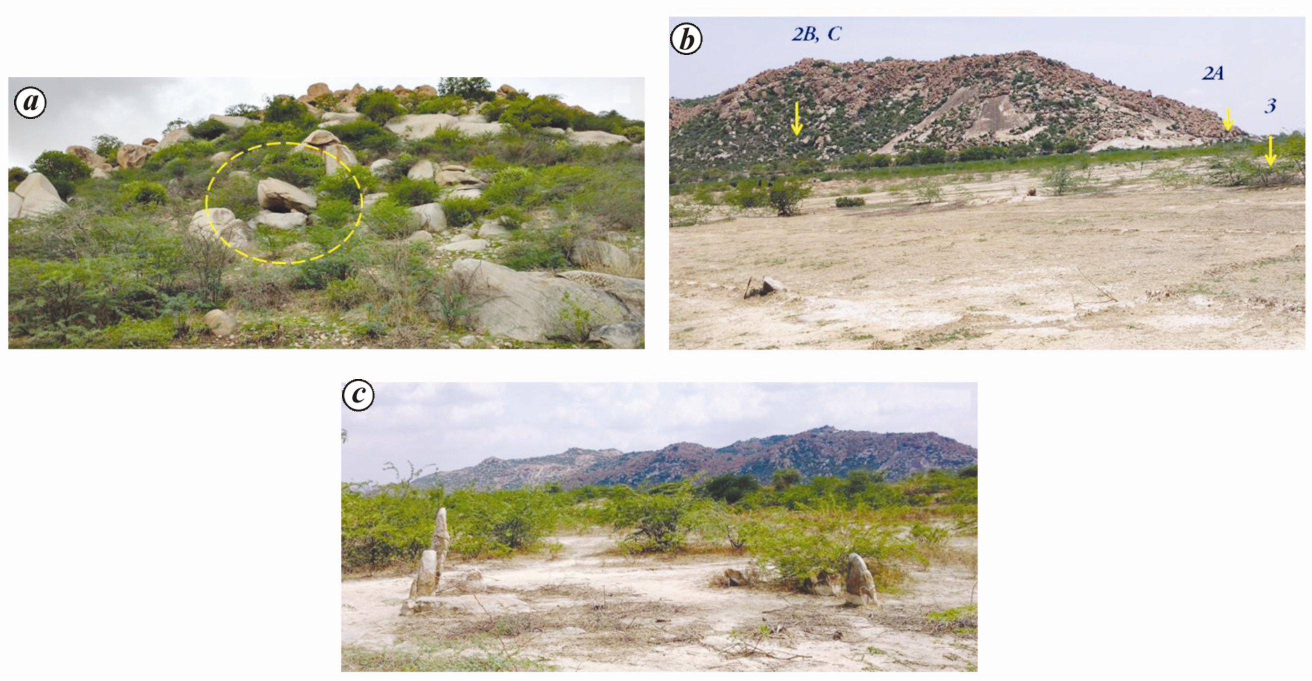

Figure 7. Landscape view of Brahmagiri hills. ***a***, Cupule in the painted rock shelter (site 1); ***b***, Pointed locations are sites 2 and 3; ***c***, Cupule on menhirs (site 4).

Figure 8. Cupule boulder 2A, Brahmagiri.

Figure 9. Cupule boulders 2B and C, Brahmagiri.

Thus the above empirical observations on the morphological features of cupules were possible, as the dimensions of various sections or angles and their cubic volumes were easily determined using the discussed formula. This formula is three-dimensional in approach representing all the different angles or sections of the cupule i.e. top portion, lower portion and the depth. As a result, the cubic (cm^3) values obtained through the formula closely differ with the water volume (ml) by –1 to –7 and +1 to +20, tallying with few cupules. Since both are systematic in their methods, the error is also systematic and exceptionally has a modest effect on the result. Thus, the use of this method for knowing cupule volume should be considered as an alternative for high cost effective digital morphometric scanners.

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M 6.7, 4 January 2016 Imphal earthquake: dismal performance of publicly-funded buildings

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The *M* 6.7 Imphal Earthquake of 4 January 2016 caused devastation in Manipur state and adjoining areas. This event presented another opportunity to understand the earthquake risk of the affected region as well as of the North-Eastern Himalayan region, which have similar patterns of seismicity, built environment and construction practices. Many dramatic collapses and damages, especially to publicly-funded buildings were disproportionate to the observed intensity of shaking. This was primarily due to poor compliance with seismic codes, inferior quality of raw materials and shoddy workmanship. Consequently, the seismic risk in the region is growing at an alarming pace with increasing inventory of vulnerable construction. This article discusses seismic performance

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