New insights on the corrosion of the Delhi iron pillar based on historical and dimensional analysis

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The history of the Delhi iron pillar has been critically reviewed to show that the pillar has been exposed to the environment of Delhi for only the last 800 years. Dimensional and historical analysis of the pillar indicates that it was originally buried up to the start of the smooth surface section. The changes in the burial level of the pillar over the centuries has been explained. Reasons for the severe soil-line corrosion occurring at a distance of 1.5′ from the bottom of the pillar have been addressed.

THE iron pillar currently situated in the Quwwat-ul-Islam mosque (Figure 1) near the Qutub Minar at New Delhi has attracted the attention of metallurgists and archaeologists for its excellent resistance to corrosion. The theories which have been proposed to explain its superior corrosion resistance can broadly be classified into two categories: the environmental[1–3] and material[4–7] theories. According to the proponents of the environment theory, the mild climate of Delhi is responsible for the corrosion resistance of the Delhi iron pillar as it is known that the relative humidity at Delhi does not exceed 70% for significant periods of time in the year[3], which therefore results in very mild corrosion of the pillar. On the other hand, several investigators have stressed the importance of the material of construction as the primary cause for its corrosion resistance. The ideas proposed in this regard are the relatively pure composition of the iron used[4], presence of phosphorus and absence of S/Mn in the iron[5], its slag enveloped metal grain structure[3], and passivity enhancement in the presence of slag particles[6,7]. Other theories to explain the corrosion resistance are also to be found in the literature like the mass metal effect[3], initial exposure to an alkaline and ammonical environment[2], and surface coatings provided to the pillar after manufacture (barfing[8] and slag coating[9]) and during use (coating with clarified butter[3]). That the material of construction may be the important factor in determining the corrosion resistance of ancient Indian iron is attested by the presence of ancient massive iron objects located in areas where the relative humidity is high for significant periods in the year (for example, the iron pillar at Dhar in Madhya Pradesh, the iron beams in the Surya temple at Konarak in coastal Orissa and the iron pillar at the Mookambika Temple at Kollur situated in the Kodachadri Hills in the Western Ghats).

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The Delhi iron pillar is a classic product of the forge welding technique that was employed by ancient Indians to manufacture large iron objects[10]. The iron required for fabrication was received in the form of lumps

Figure 1. The Delhi iron pillar located at the Qutub Minar complex in New Delhi.

which were obtained by the solid state reduction of iron ore in the presence of charcoal[11,12]. The iron lumps were later forged together and the large mass of the pillar was thus produced. In order to clear the controversy regarding the probable method (i.e., the vertical or horizontal forge welding technique) used to forge such a large piece of iron, the various aspects of the forge welding technology employed to construct the main body of the Delhi iron pillar has been critically analysed, recently[10]. The analysis reveals that the main body of the pillar must have been manufactured by the vertical forging technique while the finishing operations on the pillar (to produce an even surface) must have been performed with the pillar in the horizontal position. It is really a wonder how the main body of the pillar of such large dimensions could have been produced at a very early date which would have demanded immense planning as to the processing and handling of such a large iron object. Incidentally, forging of such large iron objects could be performed in the West only from the 19th century onwards[13,14] and therefore the manufacture of the Delhi iron pillar is an engineering marvel.

There are several studies reported in the literature on the corrosion resistance of the Delhi iron pillar where it is generally stated that the pillar has withstood corrosion for 1600 years. The analysis of the time period of exposure of the pillar to the environment and the original burial conditions of the pillar have not been critically addressed while discussing the corrosion aspects. These two factors are expected to influence the corrosion of the pillar. The aim of the present communication is to provide new insights on the corrosion of the Delhi iron pillar, addressing specifically the exposure conditions and the burial aspects of the pillar by analysing its history and dimensions. The secondary aim of the present communication is to elucidate the engineering skill possessed by the ancient Indian blacksmiths in the art of working iron and their vision as regards planning, execution and construction of large iron objects. It must be constantly remembered that the construction of such a large iron object is a marvelous engineering achievement. The communication would outline some of the issues that need to be addressed in future studies on the corrosion of the pillar, with specific reference to the buried regions of the pillar.

History

Among the several inscriptions that appear on the iron pillar, the oldest is the three-stanza Sanskrit inscription which covers an area about 2′9″ broad and 10″ high at a level of about 7′ from the stone platform (Figure 2). The inscriptions are distinct showing minimal corrosion damage, but for slight rounding of the sharp edges. This six-line inscription states that the pillar was set up as a

Figure 2. Clearly discernible Sanskrit inscriptions on the pillar.

lofty standard of the divine Vishnu (in a temple dedicated to Vishnu) on a hill called *Vishnupadagiri*, by a king having the name of *Chandra* on his demitting his office as king, after a very long rule (*suciram*), and his taking to retirement[15]. It was the practice in ancient India for the king to relinquish his kingdom to a worthy successor and then spend the last years of his life in seclusion like a hermit. Various theories have been advanced about the identity of Chandra and he has been identified with Chandragupta I, Samudragupta, Chandragupta Vikramaditya II (all the above of the imperial Gupta dynasty), Chandravarman of the Susunia rock inscription and, finally, Kanishka[16–20]. The inscription, moreover, states that Chandra is said to have vanquished a combination of enemies in Vanga (Bengal), perfumed the southern ocean by the 'breezes of his prowess' and overcame the Vahalikas traversing the seven mouths of the river *Sindhu*. It is quite probable that this Chandra mentioned is Chandragupta Vikramaditya II (375–414 AD) because there are concrete historical evidences to establish that this Gupta monarch firmly established his supremacy over Bengal and destroyed the remnants of the powers in the north-west, a task which his father Samudragupta (who, incidentally, is referred to as the 'Napoleon of India' by western historians whereas it should have been Napoleon who must have been called the 'Samudragupta of Europe!!!') could only accomplish partially[18]. Convincing proof that the iron pillar must have been erected by Chandragupta Vikramaditya II is available from numismatic evidences.

What has been stated in verse on the iron pillar was shown on a unique coin-type (known to numismatists as *Apratigha* coin-type which, earlier was mistakenly identified as *Sripratapah*) of Kumaragupta I (414–455 AD), the son of Chandragupta Vikramaditya II, in which Chandragupta and his wife are depicted blessing their son who is seen with his hands folded saluting his parents. The verses on the coin refer to Kumaragupta's parents and mention them to be of the iron pillar fame[15]. It has also been reported that the complete legend on the *Apratigha* coin-type has not been fully deciphered[16]. Moreover, the title Chandra appears written vertically under the king's arms in most of the coins struck during the time of Chandragupta Vikramaditya II (ref. 16). Interestingly, the *garuda* standard is also a regular feature in these coins[16]. Moreover, the fact that Chandragupta II reigned for a very long time (*suciram*) is amply proved by the existence of a wide variety of his coins[16].

The three-versed inscriptions are in the Sanskrit script, whose alphabetical characters belong to the reign of Chandragupta II, his son (Kumaragupta) and grandson (Skandagupta)[17]. The Guptas ruled northern India from the first half of the 4th century (when Chandragupta I was proclaimed the emperor in 319 AD) to the later part of the 6th century AD[18]. The Gupta king that consolidated the empire was Samudragupta who reigned between 335 and 375 AD[18]. Samudragupta's rule was followed by Chandragupta Vikramaditya II. There are recorded instances of the wealth and prosperity of India under his reign which have been documented by the Chinese traveler Fa-hien who visited India totally during the reign of Chandragupta Vikramaditya II (ref. 19). Therefore, it is reasonable to conclude that the iron pillar had been manufactured sometime in the beginning of the 5th century and this implies that the pillar is at least about 1600 years of age, as of today.

The inscription clearly indicates that the iron pillar was originally located as a *garudstambh* (or *garudadhvaja*, a pillar or standard topped with the figure of the bird *garuda*) in a Vishnu temple somewhere in North India, the probable places mentioned as Mathura[17], Kashmir[20], Hardwar[20] and Ambala[12]. Mathura seems the likely place as Fa-hien, the Buddhist Chinese pilgrim who visited India between 399 and 410 AD (wholly within the limits of reign of Chandragupta II), mentions that it was a place of great religious activities[19]. As Vincent Smith has lucidly argued[17], *Vishnupadagiri* must have been a well-known Vaishnava pilgrim center within the Gupta empire and not very far from Delhi. These conditions are satisfied by Mathura which is less than eighty miles from the Qutub Minar, well within the Gupta dominion, contains many hills and mounds in the regions surrounding the present city, is an ancient city of India and has been the site of famous Vishnu temples and Vaishnava worship from time immemorial. The Guptas were ardent devotees of Vishnu as attested by the legends inscribed on their coins[16] and temples[18]. Inscriptions dated to Chandragupta II and Kumaragupta have also been found in Mathura[17]. Smith further ventures to propose that the Katra mound where the magnificent temple of Vishnu, under the name of Kesava, once stood may probably be the *Vishnupadagiri* mentioned in the inscription[17]. This temple, according to contemporary evidences[19], 'was larger and finer than the rest, which can neither be described nor painted. The idols included five of red gold each five yards high, with eyes formed of priceless jewels', and was plundered by Mahmud of Ghazni during his seventeenth raid on 2 December 1018 AD and levelled to the ground[19]. The pillar must have been saved from the ravages of Mahmud of Ghazni. The pillar was later transported and erected in the main temple at Dehali (Delhi) when it was developed around 1050 AD by the Tomar king Anangapala[17]. A contemporary inscription (*'Samvat Dihali 1109 Ang Pal bahi'*) of Anangapala is recorded on the iron pillar itself which states that 'in Samvat 1109 (1052–53 AD) Ang Pal peopled (founded) Dehali'[17]. The pillar currently stands in the Quwwat-ul-Islam mosque, situated in the Qutub Minar complex, the first mosque to be built in Delhi. The mosque was built on the base of a temple that once occupied the site[21] and it is probable that the iron pillar would have been located in that original temple. Inscriptions on the east wall of the mosque state the construction of the original temple by Anangapala in 1052 AD[21]. In the process of re-assembling the iron pillar after the destruction of the temple, the part of the pillar which was initially buried underground (identified by the presence of round-shaped hammered cavities in the base of pillar provided for better gripping of the pillar to the ground, and deep corrosion pits) has been placed above the ground level (Figure 3).

Archaeological evidences[22] and facts based on temple architecture[21] indicate that the current location of the pillar in the mosque may not be exactly the same location at which the iron pillar must have been located in the original temple in Dehali. However, the iron pillar could have been situated in the same temple as one of the pillars in the colonnade bears the date 1124 Vikrama Saka (1067–68 AD). The Quwwat-ul-Islam mosque was constructed on the location of the main temple of that area, the base of which is still clearly discernible. It was a well-established practice of the muslim invaders in India to destroy the places of worship of the conquered and use the materials of construction of the temples in the construction of mosques. In this process, the original temple function and the nature of the Hindu temple objects was distorted, as attested by the large number of such existing structures in India. In this regard, the significance of the Quwwat-ul-Islam mosque should be appreciated. Historically, the first muslim city in India was the one near the Qutub Minar called by the muslim

Figure 3. Hammer marks clearly visible where the rough region comes in contact with the smooth region.

historians as Qila-i-Rai Pithaura, which was originally Prithvi Raj Chauhan's capital[21]. After the second battle of Taraori (near modern Thanesar) in 1191 AD, Prithvi Raj's fortress-city came into the hands of the muslims. The invaders generally built their first mosque on the site of the largest temple in the city that had been conquered. Therefore, the pillar would have been located at the main temple which originally occupied the site of the Quwwat-ul-Islam mosque. The Persian inscription (incidentally, the first on any building in India[21]) over the inner east gateway of the mosque describes the demolition of the temples[21]. Later historical events have been well recorded in the numerous inscriptions found in the mosque, which have been published and translated by Banerjee[21]. It is interesting to note that the Qutub Minar complex at Delhi, where the iron pillar is located, is the first recorded instance of Indo-Islamic architecture in that the construction materials for the Islamic structure were obtained from earlier existing Hindu structures[21]. The pillar has been ever since lying in this location.

Dimensions

There was a lot of speculation about the depth of the pillar below the ground before Beglar measured the same in the last century. The detailed dimensions of the pillar, have been quoted by Hadfield[14] to be:

Total length	23′8″
Height above the ground	22′
Height below the ground	1′8″
The upper diameter (below decoration)	12.5″
The lower diameter	16.5″
Total weight	6 tons

The dimensions of various portions of the Delhi iron pillar were also recorded in detail by Ghosh[5] who studied the pillar with the assistance of the Archaeological Survey of India (ASI) in the late 1950s and early 1960s. He provided the following dimensions:

Distance from bottom of the pillar to the level of the yard	1′7″
Height from the yard level to the raised platform	1′6″
Height of cylindrical portion above ground level	17′
Height of the decorated portion	3′5″
Total length	23′6″
Diameter at bottom above ground level	16.7″
Diameter at top, below decoration	11.85″
Diameter of the topmost bulging portion (underground)	19.09″
Diameter of the base (underground)	24.59″
Topmost square surface of the decoration	1′ × 1′
Diameter of the iron cylinder fitted at the top	8″
Length of the slot for flag staff	6″
Depth of the flag staff slot	1′3″

The tapering cylindrical main body of the pillar stands 17′ from the platform level out of which the bottom 2′ surface is rough in nature, showing visible hammer marks (see Figure 3)[5].

On analysing the dimensions of the pillar provided by Beglar and Ghosh, it is amply clear that the stone platform that is currently seen around the Delhi iron pillar was not present when Beglar made his measurements, as he reports that the total length below the ground level is only 1′8″, whereas Ghosh mentions that this is the distance from the bottom of the pillar to the level of the courtyard (1′7″, which can be taken as accurate since it is a recent measurement). This is because the stone platform surrounding the pillar base was constructed by Beglar in 1871. The pillar was completely removed from its base by Beglar, an assistant of the noted archaeologist Alexander Cunnigham, when he studied the buried underground structure of the Quwwat-ul-Islam mosque's courtyard and pillared areas in 1871 (ref. 22). The stone platform seems to have been assembled by him after the pillar was removed from the base. This is also attested by Hadfield[13] who mentions that, on perusal of earlier photographs of the pillar, he did not notice the stone platform and that it had been put in place after Beglar's investigations. The absence of the stone platform before 1871 has also been mentioned by Smith[17]. Interestingly, when the Committee of the Iron and Steel Institute, made some special inquiries with regard to this pillar in

1872, one Lieutenant Spratt, of the Royal Engineers stationed at Delhi, replied that the depth of the pillar below the ground was 3′ (ref. 23). It is therefore clear that the stone platform was in place by the time Spratt made his observation sometime in 1872. Visual evidence for the absence of the stone platform is also available from a published photograph[24] and drawing[25] of the pillar taken before the construction of the stone platform. Therefore, it is first established that the body of the pillar was buried under the ground for only 1′7″ of its length, from the time it was placed in the mosque courtyard till 1871.

Analysis of dimensions

The dimensions of the main body of the pillar were critically analysed in order to understand the original burial level of the pillar and also to appreciate the pillar's symmetrical design. The design symmetry of the Delhi iron pillar is not clearly revealed by the reported dimensions. The analysis of the overall dimensions of the pillar is discussed below.

If the start of the smooth surface section is taken as the original burial level, the relative dimensions of the pillar are as provided in Figure 4. It is seen that the buried base is one fourth of the total length of the main body of the pillar, excluding the decorative top. The rough surface occupies one-fourth (60 U) and the smooth surface three-fourths (180 U) of the pillar main body length. The burial of the pillar body to one-fourth of its height would have provided the necessary stability to the structure. Moreover, the relative dimensions do not resemble any pattern if the burial level is taken as the present one. Therefore, it can be firmly concluded from the analysis of the pillar's relative dimensions that the pillar was originally buried to the start of the smooth surface region.

The decorative capital of the pillar is currently 40 U in length, i.e. one-sixth of the pillar's main body height. However, this would not be the appropriate way to view this. The decorative bell capital has been described in detail elsewhere[26]. The capital was originally topped with an idol. This would have, most likely, been that of *garuda* as Gupta *garudstambhs* (literally meaning 'pillar topped with *garuda*'), placed in front of the *garbh grihah* (sanctum sanctorum) in the main temple courtyard, generally were topped with an idol of *garuda*, as proven by the only existing Gupta *garudstambh* in the ruined Vishnu temple at Eran (*Erakina*) in Madhya Pradesh (Figure 5). Inscriptions on the Eran pillar indicate that it was constructed around 480 AD during Gupta rule[18]. An artistic construction of the idol atop the Delhi iron pillar, based on the Gupta *garudstambh* at Eran, is provided in Figure 6. Note the figures of lions located at the corners of the top box-shaped pedestal. The remnants of the rods, used for holding these figures, can still be seen in the corners of the lower side of the top face and upper side of the bottom face of the box-shaped pedestal[26]. It must also be mentioned that the *garudstambh* standard is noticed in nearly all the Gupta coins dating from Samudragupta[16]. The total length of the decorative column including the Garuda idol must occur at a certain fixed ratio to the main body of the pillar, especially to its length above the ground. It is reasonable to assume that the idol would have been approximately 20 U in length, thereby providing the total length of the decorative top as 60 U. It immediately becomes obvious that the length of the decorative capital (60 U) would now be exactly one-fourth of the total pillar height exposed above the ground level (240 U). Moreover, the depth of burial below the ground level would be equal to the height of the decorative capital of the Delhi iron pillar, indicative of the engineering design of the pillar.

A short comment is in order on the base unit U. The relative dimensions of the pillar were provided in

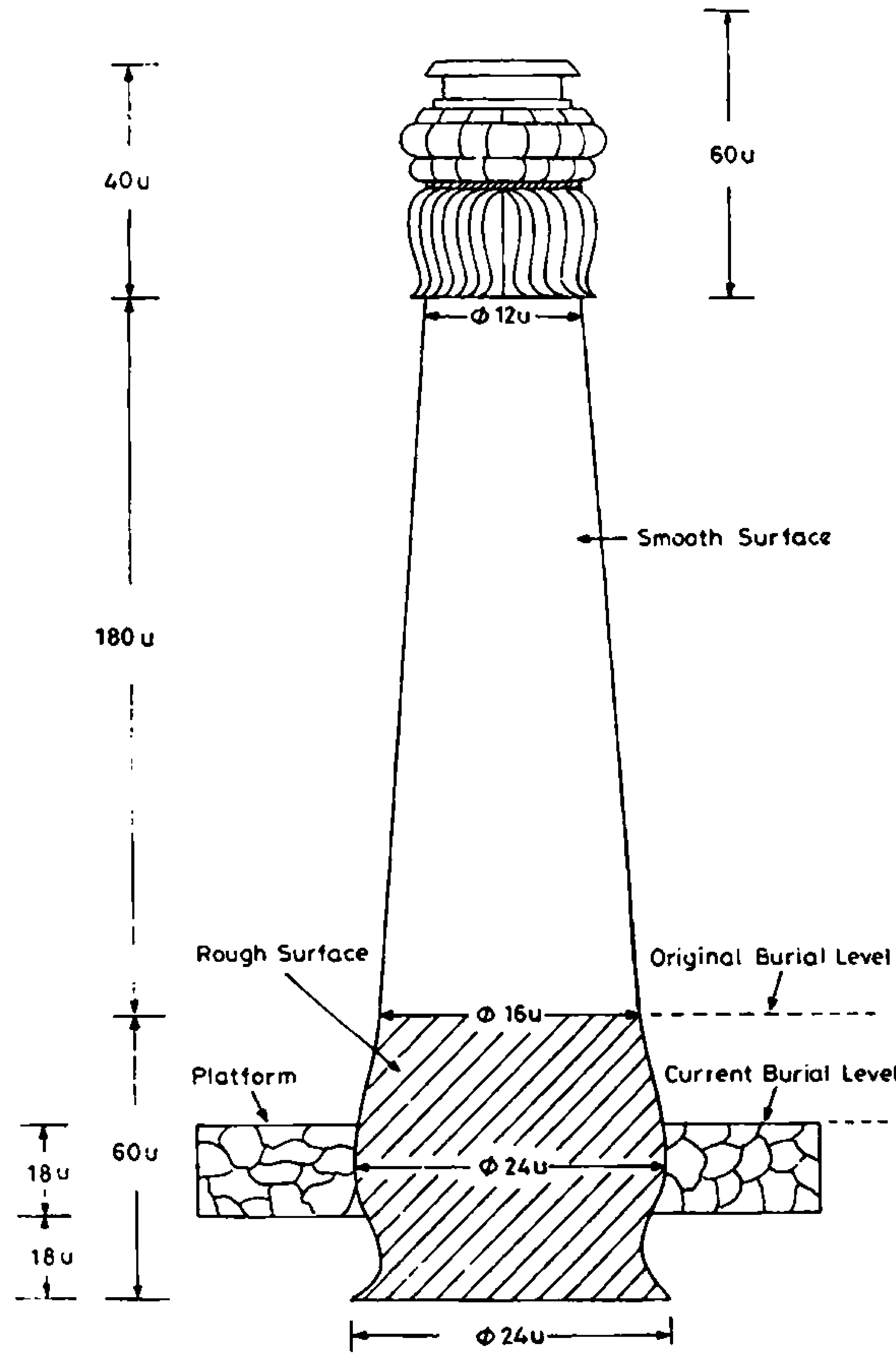

Figure 4. Relative dimensions of the Delhi iron pillar. The unit U measures 1″ and is equal to 1 *angulam*.

Figure 5. Gupta *garudstambh* from the ruined temple at Eran, Madhya Pradesh.

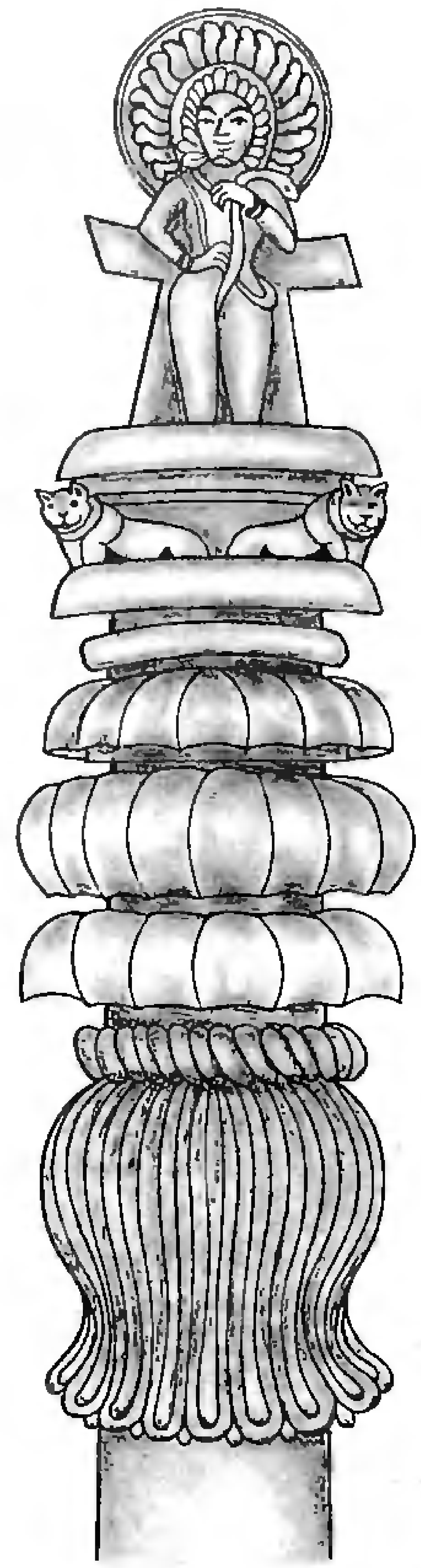

Figure 6. An artistic recreation of the figures originally present on top of the Delhi iron pillar capital. The recreation is based on the only existing Gupta *garudstambh* at Eran, Madhya Pradesh.

Figure 4 in terms of the unit U. This unit corresponds to 1 inch. It is further interesting to note that the top square surface of the pillar's pedestal measures exactly 12″ × 12″. The ancient Indian measure of length, omitting microscopic measurements, was the *angulam* which measured to 1″. This was divided into 8 *yavas*. On the higher side, 12 *angulams* equalled 1 *vitasti* (12″ or 1′) and 2 *vitastis* to 1 *hasta* or *aratni*. Further, 4 *hastas* resulted in 1 *danda*[27]. Therefore, the ancient Indian measure unit could have been adopted by the British and the conclusive proof of the same is the above analysis of the dimensions of the Delhi iron pillar. This aspect needs further elucidation by concerned authorities.

Original burial level

The above dimensional analysis of the pillar indicates that the current burial level of the pillar was not the original burial level of the pillar when it formed a part of the temple. There are further evidences to support this conclusion. First, the rough portions of the pillar which are visible in the bottom regions of the pillar (Figure 3), as it currently stands, is not a result of imperfection during the time of manufacture (as erroneously stated by some previous investigators[2,3]) but rather was provided for the specific purpose of gripping the pillar to the ground. This can be easily seen by observing the hammer-marked cavities that are still visible on the surface of the pillar in the rough region just below the smooth surface finish region (Figure 3). The rough portion of the pillar was originally buried in the courtyard of the temple and later was left exposed outside when the iron pillar was displaced from its original position. Further support to this idea is provided by the observation that if one were to stand at the level of the start of the smooth section of the pillar, the person would directly face the inscriptions. Therefore, the pillar must have been buried at this level as the inscriptions would be otherwise too high for a person standing at the base of the pillar to read. This is shown in Figure 7 where the author had placed a perch to reach the level of the start of the smooth surface. It can be noticed that the inscriptions now appear at face level. The well-polished sur-

Figure 7. The original burial level was the start of the smooth section as the inscriptions in this case would appear at face level.

face currently visible on the iron pillar (at a distance of approximately 4′ from the platform level) is due to the habit of visitors trying to clasp their hands behind their backs which, folklore states, if successfully completed would bring luck to the person. On careful observation of the pillar's surface, it is noted that there is a region in the pillar which appears to have a different hue from the rest of the surface and this region occurs at exactly the same height had people clasped their hands around the pillar when it was originally buried in the temple. The belief of clasping the hand around the pillar 'for good luck' appears to be a very old tradition. The appearance of the band at this level is proof that the original burial level in the temple was at the start of the smooth section.

Moreover, the custom of clasping the hands around the pillar also existed when the pillar was buried in the mosque courtyard even before the stone platform was constructed by Beglar in 1871. This can be seen in the drawing of the pillar (without the stone platform) by an artist named Mirza Shah Rukh Beg for publication in Syed Ahmed Khan's Urdu work *Athar'al-Sanadid* in 1846, where a bearded man is seen embracing the pillar[25]. In such a case, it must have resulted in a polished band just at the start of the smooth section and this is the reason why the region just at the start of the smooth section (the region above the indicating scale in Figure 3) appears polished and even surfaced.

Interestingly, a grill iron cage has been recently constructed by the Archaeological Survey of India along the perimeter of the stone platform (Figure 1) in order to prevent people from clasping their hands on the pillar. The bright polished band of material, currently seen at a height of 4′ from the stone platform, would henceforth not come in contact with peoples' hands. Therefore, the passive film (that is responsible for the pillar's excellent corrosion resistance[6,7]) would grow unhindered at this location. At this juncture, it is important to monitor the growth of the passive film on the surface of this polished region by accurately measuring its thickness and visually following its growth by photography. The author hopes that such a study on the pillar would be initiated on a long-term basis involving the active cooperation of the ASI and metallurgists.

Pillar bottom

Beglar reported that the floor of the mosque 'consisted of two layers of well-dressed stone close set, nine and ten inches thick respectively, resting on a basis of rubble-stone of enormous dimensions and indefinite depth, the excavation having been carried down over fourteen feet without coming to the bottom of the layers of rubble-stone. These two layers of dressed stone extend throughout the entire area of the mosque courtyard, and cloisters of inner enclosure. In the courtyard, however, these layers are overlaid by another layer of stones of irregular shape and size, and evidently belonging to various portions of some ruined structure; the consequence of this is that the level of the courtyard is higher than the level of the floor of the mosque and cloister'[22]. Therefore, the beautifully constructed double flooring resting on the massive foundation was left intact by the muslims and they placed a superficial layer of broken material over the dressed stone in the courtyard. The pillar is supported by the upper layer of the old Hindu floor and surrounded by the superficial layer of broken stones laid down by the muslims. This can be seen in the plan and section of the pillar's base which was provided by Beglar (reproduced in Figure 8). It is presently stabilized by another stone platform constructed around the base, on the surface of the courtyard floor, by Beglar in 1871.

Ghosh excavated the region around the pillar[5] and observed the bottom portion of the pillar. Ghosh has provided a picture of the underground portion of the pillar below the ground level which is reproduced in Figure 9. Ghosh observed that the 'base of the pillar was flat and eight small projections shaped as toes of an elephant were seen at equal intervals'[5]. These projections were inserted into a sheet of almost pure lead. A heavy slab of stone was found placed horizontally on the original upper layer of the temple floor on which the lead sheet was found. It can be noticed from Figure 9 that the pillar is in the upright position when the observations were recorded by Ghosh, thereby implying that the pillar

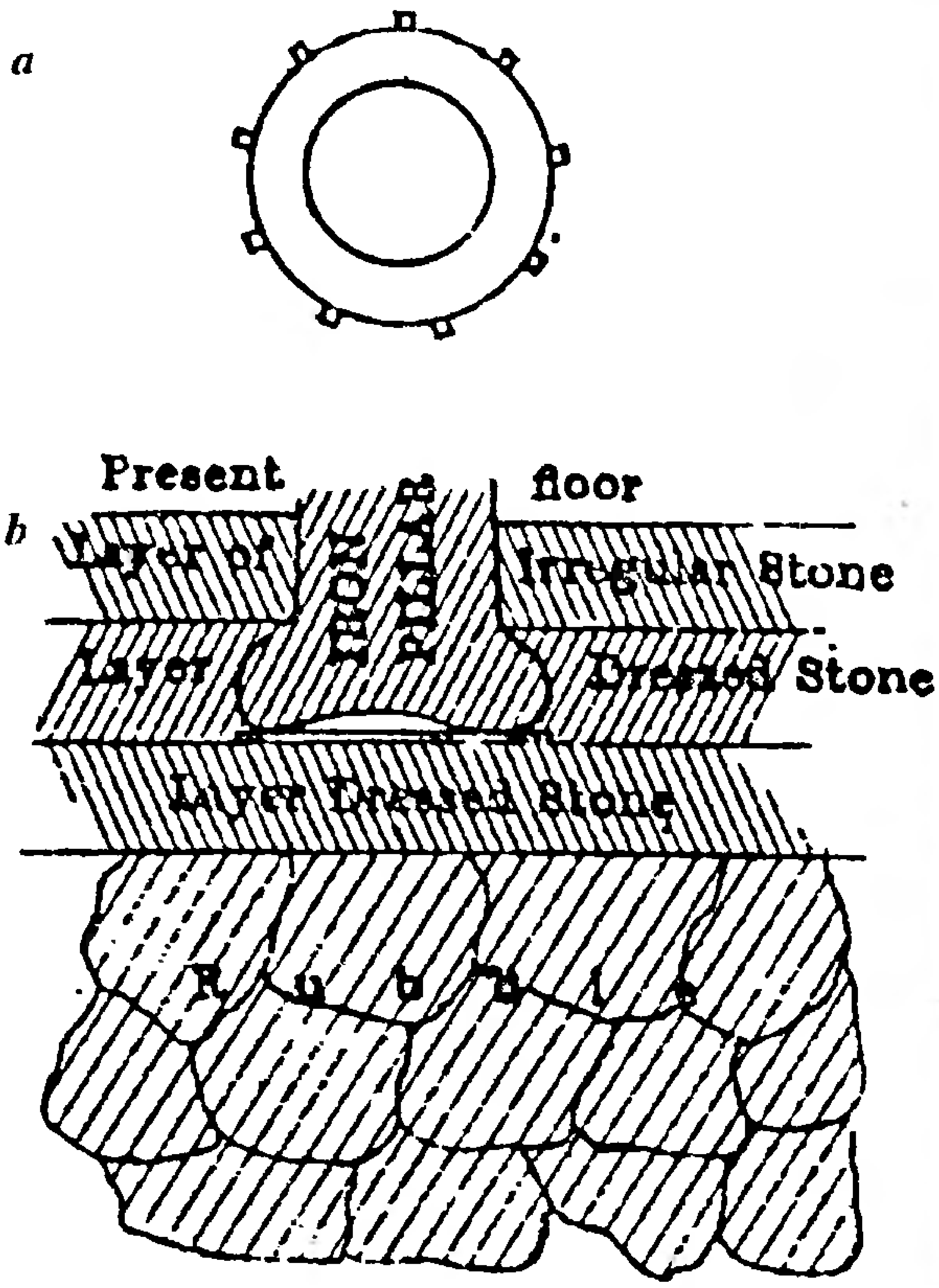

Figure 8. Reproduction of the plan (*a*) and section of iron pillar's base (*b*), as reported by Beglar[22].

Figure 9. Underground portion of the Delhi iron pillar[5].

was supported firmly upright while a portion of earth was removed from its base. Spratt comments that 'the pillar ended in a bulb like an onion, which is held in place by eight short thick rods of iron and which at their lower extremity are let into a block of stone, in which they are secured by lead'[25]. The presence of small iron rods projecting from the bottom perimeter of the pillar has also been reported by Beglar[22]. He states that 'the iron lat or pillar was found resting on the second layer of dressed stones composing the floor; its total height from the top of the capital to the bottom of its base is 23 feet 8 inches. The base of the pillar is an irregular knob in shape, resting on several little pieces like bits of bar iron, let into the stone underneath and secured with lead'[22]. Smith also quotes the presence of 'the grid iron of iron bars, soldered with lead onto the upper layer of the dressed stone'[16]. Curiously, the plan of the pillar's base, reported by Beglar (Figure 8), shows that there are nine projections emanating from the base of the pillar. This could be due to a mistake during the publication of the report from the notes taken in the field by Beglar, as Spratt[23] and Ghosh[5] both confirm the presence of 8 iron rod projections. It is certain that the pillar was disturbed from its upright position by Beglar in 1871. It is reasonable to assume that the stability of the pillar must have been suspect when it was reburied by Beglar. The additional stone platform must therefore have been constructed by Beglar in order to provide further support and stability to the pillar. Surprisingly, Beglar does not provide any reference to the erection of the stone platform in his report[22].

Implications for corrosion of pillar

Historical analysis of the pillar has revealed that the pillar was located at a different place prior to its current location in Delhi. The most likely place where the pillar was situated, before it was bought to Delhi around 1050 by Anangapala, is Mathura. Therefore, the climatic conditions of Mathura (like the relative humidity, temperature and rain statistics), averaged over several decades, should also be analysed to understand the environment to which the iron pillar was exposed before it was brought to Delhi. The climatic conditions of Delhi have already been analysed and related to the pillar's corrosion resistance[2]. Such a study would provide further insights on the role of environmental conditions (atmospheric exposure) in influencing the corrosion of the pillar, before its location at Delhi.

Dimensional analysis of the pillar has revealed that the region in contact with the soil line has changed over the years. The pillar was initially buried up to the start of the smooth section while it was present in the temple and later buried up to a different depth when it was placed in the mosque courtyard. The addition of the stone platform further modified the burial line. In view of these changes in the burial line, it is interesting to analyse the nature of corrosion of the pillar's surface in contact with soil. It is expected that the corrosion of the pillar's regions buried in soil would be more severe than the regions exposed to the environment.

It is well known that the corrosion of metallic objects partially buried in soil exhibit maximum corrosion damage just below the ground level due to the differential aeration cell effect. The soil provides a humid environment if water is retained in the soil due to poor drainage. Water contains dissolved oxygen which is essential for atmospheric corrosion to proceed as the reduction of oxygen is the cathodic reaction that supports the oxidation (i.e. corrosion) of metal. Corrosion depletes the environment of dissolved oxygen which is readily replaced in the soil region exposed to the atmosphere. However, oxygen cannot be replenished in the soil located at a depth under the ground. Depleted oxygen leads to the creation of an anode supported by the cathode (formed at the soil-line by reduction of excess dissolved oxygen). This is a typical example of a differential aeration cell. Corrosion damage is, therefore, maximum just below the soil-line, where dissolved oxygen is less accessible and soil resistance between the cathode and anode areas is minimal. This situation is akin to the corrosion of metallic objects half-immersed in water wherein the corrosion damage is maximum just below the waterline for similar reasons as outlined above[28]. Keeping the above factor in mind and returning to the Delhi iron pillar, it is to be noticed that there is very little corrosion damage in the region where the smooth surface contacts the rough surface, the location of the original burial level (Figure 3). The reason for the dull polished smooth finish of this region is due to the habit of travelers clasping their hands around the pillar in the mosque courtyard, even before the stone platform was erected. This is also seen in an old drawing of the Delhi iron pillar[25] in which a person is seen embracing the pillar at the location where the rough surface changes to the smooth surface. The lack of corrosion at this location indicates that the pillar was not in long-term direct contact with a water-containing environment (i.e., soil) at its base when it was consecrated in the temple. The moisture in the soil is relatively non-corrosive in the short term, but the residence time of moisture on the metal surface will control the degree of corrosion in soil in the long term[28]. This implies that the pillar must have been originally gripped by a stone platform, with coarse gravel as the filling material, which would have provided the necessary drainage.

The location of the pillar in the temple would also have to be considered while addressing soil corrosion. In the original Gupta temple, the iron *garudstambh* must have been placed in the main temple courtyard, in front of the sanctum sanctorum (*garbh grihah*). Such an arrangement is noticed in the temple ruins at Eran. The pillar must have been exposed to the atmosphere as the courtyards in Gupta temples were not roofed at the top. The construction of roofed pillared hall (*mandapa*) in front of the sanctum sanctorum in the Hindu temple was developed around 700 AD[29], much after the Gupta period. (In the earlier temples (for example, the Shore temple at Mahabalipuram and the Kailasanatha temple at Kanjeevaram, both built around 700 AD[29]), the *mandapa* was isolated from the sanctum sanctorum by an open space. Later, the custom of uniting the two by an intermediate chamber (*antarala*) was established. Leading up to the *mandapa* was a roofed porch (*ardha-mandapa*) and there may be a transept on each side of this central hall called *maha-mandapa*. One of the first temples to combine all these attributes was the Vaikuntanatha Perumal temple at Kanjeevaram.) The Gupta temples, at the most contained a small roofed porch in front of the entrance (for example, Temple No. 17 at Sanchi and the beautiful Deogarh temple[29]). Therefore, the iron pillar must have originally been placed in a courtyard exposed to the environment in the original Gupta temple. This is schematically depicted in Figure 10 where the iron pillar topped with a statue of *garuda* (according to Gupta conventions) is shown standing in the uncovered platform in front of a temple. The temple shown in this figure is modeled after the Gupta temple at

Figure 10. An artistic recreation of the iron pillar in its original location in the temple courtyard. The temple is modeled after the Gupta temple at Deogarh.

Deogarh. Although the pillar could have been later enclosed in a closed courtyard when the temple must have been renovated or extended during later times, it must have been still exposed to the atmosphere, as this is dictated by the rules of temple architecture[29]. *Dhvajastambhs* exposed to the atmosphere can still be seen in temples constructed according to strict temple architecture canons.

In spite of direct exposure to the atmosphere, the lack of corrosion at the original burial level indicates that accumulation of water at the base would have been minimal when the pillar was located in the Gupta temple, and later in the temple at Delhi. Non-accumulation of water is likely as the constructed temples were strictly provided with an intricate drainage system whereby the water collected in the main temple area was drained out of the area in a particular direction. Therefore, it is concluded that water would not have been retained on the body at the base of the pillar when it was originally consecrated in the temple, although it was exposed to the environment. The designers of the pillar had ensured that water will not accumulate at the base of the pillar.

The above analysis implies that the buried section of the pillar was not exposed to a corrosive atmosphere at its base for the first 800 years of its existence till about 1200 AD. It was only when the pillar was uprooted from its location in the temple and placed in the Quwwat-ul-Islam mosque that the buried portion of the pillar was directly exposed to a humid soil environment. Interestingly, the rough underground portion was exposed outside in order to reveal the 'imperfection' of Hindu art. Therefore, it is expected that the corrosion damage would be significant at the burial level when the pillar was placed in the mosque as drainage facilities were not provided (from the base of the pillar) and moreover, the pillar was also exposed directly to the atmosphere. This hypothesis is verified by critically observing the current underground section of the pillar which shows significant reduction in the section thickness at just below the level it was buried in the mosque originally, i.e. 1′6″ from the bottom of the pillar (Figure 8). It has been stated by Ghosh[5] that this area is severely corroded, showing the presence of deep corrosion pits. The iron pillar in this region is covered with a thick adherent coating of rust which Ghosh had to chisel out for cleaning. He states that 'the rust appeared laminated and its maximum thickness was 1.5 cm. Under the rusted portion, the pillar showed a rough surface pitted at places. In some of the pits, water poured into them flowed out through the base'[5]. Therefore, the region of the pillar where corrosion damage is maximum occurs at a height of approximately 1′6″ from the bottom of the pillar. Future studies on the corrosion aspects of the pillar should also address this location. Valuable information on the nature and process of passive scale formation (that is responsible for the pillar's corrosion resistance[6,7]) could be obtained by analysing the cross-sectional microstructure and composition of the rust located in this region.

Conclusions

Historical and dimensional analyses of the Delhi iron pillar reveal that although it was exposed to the atmospheric environment for 1600 years, it was exposed to the environment of Delhi for only about 800 years. The stone platform currently seen around the pillar was erected in 1871 by Beglar. Dimensional analysis provides that the start of the smooth section was the original burial level of the pillar in its original location in a Hindu temple. The soil-line corrosion damage was minimal when the pillar was located in the temple indicating the provision of drainage facility around the pillar. Soil-line corrosion was accelerated when the pillar was relocated in the mosque courtyard. It is also concluded that the surface region where maximum corrosion has taken place occurs at a distance of approximately 1′6″ from the bottom of the pillar. Future studies should focus specific attention on the rust formed in this region, which is expected to provide valuable information regarding the nature of the passive film formation on the exposed surface of the pillar.

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REVIEW ARTICLE

Stereochemistry of peptides and polypeptides containing omega amino acids

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The omega amino acids have a larger degree of conformational variability than the alpha amino acids, leading to a greater diversity of backbone structures in peptides and polypeptides. The synthetic accessibility of chiral β-amino acids and the recent observation of novel helical folds in oligomers of cyclic β-amino acids has led to renewed interest in the stereochemistry of ω-amino acid containing peptides. This review focuses on the conformational characteristics of the polymethylene chain in ω-amino acid segments and surveys structural features in peptides established by X-ray diffraction. The literature on polymers of achiral ω-amino acids (nylon derivatives) and chiral, substituted derivatives derived from trifunctional α-amino acids, reveals that while sheet-like, intermolecular hydrogen bonded structures are formed by the former, folded helices appear favoured by the latter. ω-Amino acids promise to expand the repertoire of peptide folds.

THE genetic code determines the translation of nucleic acid sequences in genes into amino acid sequences in proteins. The alphabet of amino acids specified by the genetic code is generally limited to twenty. The genetically coded amino acids are all α-amino acids, structures in which the carboxyl and the amino groups are linked to a common tetrahedral carbon centre, the α-carbon atom. Variants of the α-amino acids are found in nature in which the amino and the carboxyl groups are placed on different carbon atoms. In ω-amino acids, the two functional groups are separated by polymethylene units of variable length (Figure 1). The introduction of additional C–C bonds into the polyamide (polypeptide)* backbone introduces additional degrees of conformational freedom, which can, in principle, have profound effects on structural and functional properties of peptides containing ω-amino acids. Recent studies have established convenient synthetic routes to chiral β-amino acids[1–3]. The observation of novel helical folds in peptide oligomers of acyclic[1] and cyclic β-amino acids[4,5], the characterization of α-helical structures in peptides incorporating β-Ala–γ-Abu segments[6] and the demonstration of proteolytic stability of a model β-hexapeptide[7] have provided a dramatic new impetus for the use of ω-amino acids in peptide and protein design. This report presents a brief overview of the structural features established in peptides containing ω-amino acids.

*We shall use the term peptide to describe amide linkages involving ω- amino acids in oligomeric sequences. We use the broad definition of a peptide bond as the linkage between amino acids, not necessarily restricted to α-amino acids[8]. The term polyamide is confined to the descriptions of polymeric sequences involving ω-amino acids encompassing the entire range of nylons[9]. The term isopeptide has been used in the literature to describe peptide bonds formed by side chain carboxyl or amino group in trifunctional amino acids like Asp, Glu and Lys. In the present review, the term β-peptide is adopted for homooligomeric sequences containing β-amino acids. The nomenclature used follows the current literature[1].