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THE IRON PILLAR AT DELHI*

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ABSTRACT

The massive Iron Pillar located in South Delhi has been an object of considerable interest to modern scientists and technologists for two main reasons viz., the amazing technology by which a metallic object weighing nearly seven tons could be fabricated over fifteen centuries ago and the phenomenal corrosion resistance displayed by this ancient monument despite exposure to sun, rain, wind and dust for so long. In this paper all available material on this metallurgical marvel is examined scientifically and systematically and an attempt made to answer such questions as are likely to arise in the minds of discerning visitors to this impressive monument. The following important conclusions are arrived at: (1) Date of Erection : 370-375 A.D., (2) Date of the Inscription : 380–385 A.D., (3) Mode of Fabrication : Hammer forging and welding ball of hot pasty iron in many steps, and (4) Reasons for Restlessness : Many viz., unusual chemical composition, protective oxide film, favourable Delhi climate and slag particles at grain boundaries.

Keywords: Delhi iron pillar, Fabrication of iron pillar, Corrosion resistance, Palaeography of Delhi pillar, The rustless wonder.

INTRODUCTION

It is now generally accepted by scholars and scientists alike that the famous Iron Pillar (Fig. 1) located at Mehrauli village in the Southern outskirts of Delhi and not far from Qutab Minar (or Kutab Minar), another well-known monument and tourist attraction today, has been in existence for over 1500 years and that it was fabricated during the Gupta Period (320 A.D. to 495 A.D.), when Indian civilization reached one of its zeniths and recorded some extraordinary literary, artistic scientific and technological achievements. Known as "Lohe-ki-Lat" *i.e.*, Iron Pillar, in local language and connected with numerous legends, this metal-

*This paper draws heavily from the author's recent monograph entitled *"The Rustless Wonder: A Study of the Iron Pillar at Delhi"* (Vigyan Prasar, New Delhi, 1996).

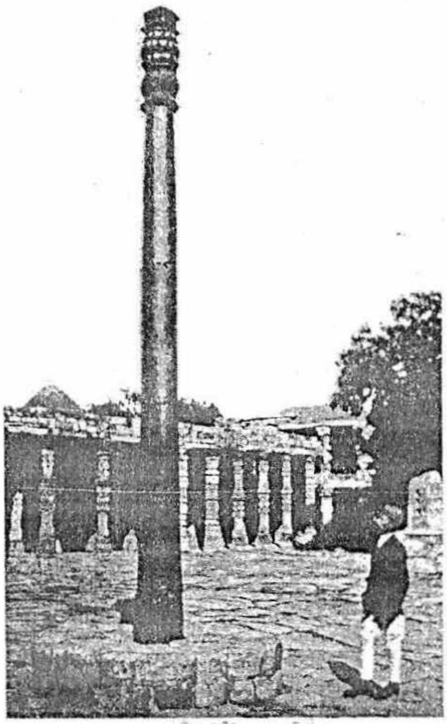

Fig. 1 : A photograph of the famous Iron Pillar at Delhi.

lurgical marvel of ancient India does not seem to have attracted the serious attention of researchers in the fields of either history and archaeology or science and technology till the second quarter of the 19th century. One need not be surprised by this almost unbelievable fact since the Age of Modern Science and Scholarship began only in the 18th century and had its first blossoming in Europe, even as India languished in a shocking state of slavery disarray and apathy during this period.

The first reports [1] on the Iron Pillar emanate, not surprisingly, from British soldiers and travellers who were already moving around in the Indian sub-continent in gradually increasing number during early 19th century. As recorded by Stephen [6] and Fleet [9] in 1876 and 1888 respectively one Captain Archer, who accompanied Lord Combermere in 1828 on his tour of North-West India, reported on the Delhi Pillar, describing the inscription on it as 'of unknown antiquity' and which 'nobody can read'. In 1831 Lieutenant William Elliot of the 27th Regiment N. I. made a fascimile of this inscription at the request of Dr. Mill of Bishop's College, but the work was "so ingeniously mismanaged that no a single word could be made out !" A few years later [2] Captain T. S. Burt of the

Engineers made a reliable ink impression of the inscription and passed it on to Mr. James Prinsep, one of the greatest Indian Antiquaries of the 19th century. This provided the impetus for the first important paper on the Delhi Pillar. It was authored by Prinsep [3] and published in 1838 in the *Journal of the Asiatic Society of Bengal* with a lithograph of the inscription, his reading of its Sanskrit text in ancient *Nagari* script, a modern *Nargari* transliteration of the same and his own English translation of it.

Following Prinsep's pioneering efforts, General A. (later Sir Alexander) Cunningham [4] and Dr. Bhau Daji [5] of Bombay threw more light on the six-line Sanskrit inscription on the Pillar. The former thought that the inscription belonged to the 3rd or 4th century A.D., while the later opined that it should be assigned a somewhat later date. Daji read a paper on this subject on April 13, 1871 at Bombay before members of the Asiatic Society and the same was published in 1875 in the *Society's Journal.* Daji's important paper contained a revised version of the text of the poetic inscription and its translation, including the correct reading of the king's name as Chandra. In his famous Reports, published in 1871 but covering the years 1862 to 1865, Cunningham has drawn attention to other inscriptions on the Pillar, mentioning, quite correctly, that "they are more numerous than important."

Stephen [6] recorded in 1876 that "we have no trust-worthy account of the original location of this Pillar or its age, but tradition, silent as to its maker, attributes its erection to Anang Pal I and places it in the temple of Rai Pithora." When the temple was converted to a mosque by Qutb-ud-din Iback (around 1190 A.D.), the Pillar was permitted to stand where it was, but neither tradition nor history discloses the name of its maker or his purpose in making it. Daji was of the view that in the Mosque and buildings around, there are stones which originally belonged to Jain, Saiva and Vaishnava temples of the 10th or 11th century A.D. As Stephen has further noted, the inscription by Anang Pal II about the erection of the Pillar is brief and has the date 1109 'Samvat' *i.e.,* 1052 A.D.

DESCRIPTIONS OF THE PILLAR

Stephen [6] has also described the Pillar, quite unerringly even in 1876, as "a solid shaft of wrought iron" although most travellers around that period described its material as "mixed metal", "brass", "bronze", "soft iron" and "cast iron". Even Daji was emphatic around this time about his statement that "iron forms no portion of this monument, and it is a compound (alloy) of several metals". However, Stephen had the advantage of knowing that one Dr. Murray Thompson had analysed a small bit of the Pillar for General Cunningham and thus was quite certain that the metal was "pure malleable iron with 7.66 specific gravity".

Both Stephen [6] and Smith [11] agree on the location and dimensions of the Pillar in their writings. Smith's detailed description in this regard deserves reproduction, at least in extracts:

"The great mosque built by Qutb-ud-din Iback in 1191 A.D., and subsequently enlarged by his successors, as well as its minaret, the celebrated Qutb Minar, stands on the site of Hindu temples, and within the limits of the fortifications known as the Fort of Rai Pithaura, which were erected in the middle or latter part of the twelfth century to protect the Hindu city of Delhi from the attacks of the Mussalmans, who finally captured it in 1191 A.D. These buildings are situated about nine miles south of modern Delhi, or Shahjahanabad, and lie partly within the lands attached to the village of Mihirauli (Mehrauli, as it is known today), an evident corruption for Mihirapuri".

"The Iron Pillar stands in the courtyard of the mosque at a distance of about ten yards outside its great arches. The total length of the Pillar from the top of the capital to the bottom of the base is 23 feet 8 inches, Twenty-two feet are above ground, and only 1 foot 8 inches are below ground. The weight is estimated to exceed six tons. The lower diameter of the shaft is 16.4 inches, and the upper diameter is 12.05 inches, the diminuation being 0.29 inch per foot. The capital, which is of the bell pattern, is 3.5 feet high".

"The base is a knob or bulb, slightly irregular in shape, 2 feet 4 inches in diameter, resting on a gridiron of iron bars, soldered with lead into the upper layer of dressed stone of the pavement. The bulb does not penetrate the lower layer of dressed stone. The column is, therefore, supported by the upper layer of the old Hindu floor, and the superficial layer of broken stone laid down by the Mussalmans. It is now further steadied by a small stone bench or platform, which has been recently built round the base on the surface of the floor".

"The capital (Fig. 2) consists of seven parts, namely, a reeded bell, like that of Budha Gupta's monolith at Eran, a thin plain disc, three discs with serrated edges, another thin plain disc, and a square block. Judging from the analogy of the Eran monument, where a similar square block serves as pedestal to a statue, it is probable that the iron Pillar was originally surmounted by an image of Vishnu, the God to whom it is dedicated".

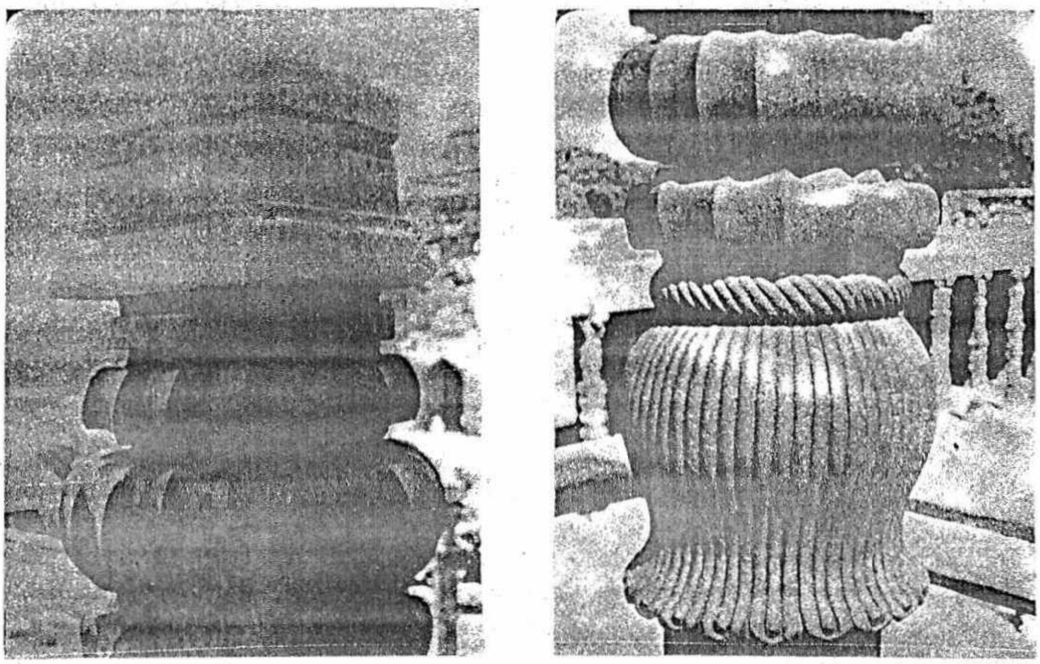

Fig. 2 : Two views of the impressive capital of the Delhi Iron Pillar.

"The style of the Pillar and the form of the characters of the inscription, considered together, permit no doubt that the monument was erected in the Gupta period. As Dr. Fleet has pointed out, the characters of the inscription closely resemble those of the panegyric on Samudra Gupta on the Allahabad Pillar. The well-marked top lines of the letters on the Iron Pillar, which were once supposed to mark a later date, are also found in Kumara Gupta's Bilsad inscription".

RECENT DATA ON THE PILLAR

Scientific studies on the Pillar may be considered to have made a beginning with the classical paper [20] of the distinguished metallurgist Sir Robert Hadfield in 1912. During the last 80 years both Western and Indian scientists have undertaken a number of investigations to probe the nature (composition, structure *etc.,*) of this fascinating monument, often referred to as a "metallurgical enigma".

In our country apart from the Archaeological Survey of India and the Tata Iron and Steel Works, two Laboratories of the Council of Scientific and Industrial Research (CSIR) *viz.,* the National Metallurgical Laboratory, Jamshedpur, and the National Physical Laboratory, New Delhi, have made significant contributions in this area.

The dimensions of the Pillar, as first measured by one Miss Cummings for the paper by Hadfield in 1912 are as under :

Total length	23 ft 8 in	(7.21 m)
Portion above ground level	22 ft	(6.71 m)
Portion below ground level	1 ft 8 in	(50.8 cm)
Upper diameter (below the decoration)	12.5 in	(31.8 cm)
Lower diameter	16.5 in	(41.9 cm)

Neogy's measurements of 1914 agree well with the above [22].

In 1961, on the eve of the centenary of the Archaeological Survey of India, the Pillar was dug out for chemical treatment and preservation, and reinstallation by embedding the underground part in a newly constructed masonry pedestal. Following the excavation a detailed examination of the entire Pillar (exposed portion, buried portion and the capital at the top) was carried out by Dr. B.B. Lal, Chief Chemist, and measurements of different parts of the Pillar were taken in detail [91]. The state of the Pillar in general and the condition of the corroded and rusted areas in particular were photographically documented. The measurements then recorded by the Archaeological Survey of India are as under:

Total length of the Pillar	23 ft 6 in	(7.16 m)
Portion below ground upto the height of the raised pedestal	3 ft 1 in	(94.0 cm)
Cylindrical portion of the Pillar exposed to view	17 ft	(5.18 m)
Height of the capital with decoration	3 ft 5 in	(1.04 m)
Diameter at the base of the pedestal	16.7 in	(42.4 cm)
Diameter at the top below the capital	11.85 in	(30.1 cm)
Diameter at the base (underground)	24.59 in	(62.5 cm)
Topmost square, flat surface of the capital	1 x 1 ft	(30.5 x 30.5 cm)
Diameter of the iron cylinder fitted at the top	8 in	(20.3 cm)
Length of slot or groove for flagstaff	6 in	(15.2 cm)
Depth of slot or groove for flagstaff	1 ft 3 in	(38.1 cm)

The capital of the Pillar was found to be made up of a solid cylinder of iron fitted into a deep groove at the top end. The upper end of the cylinder has a flat square base with a rectangular slot about 15.2 cm long at the centre, evidently provided for holding a flagstaff. Since the slot, about 38 cm deep, is exposed to atmosphere, much rain water accumulates into it along with rain-washed and win-blown dust. The weight of the pillar was well over 6 tonnes.

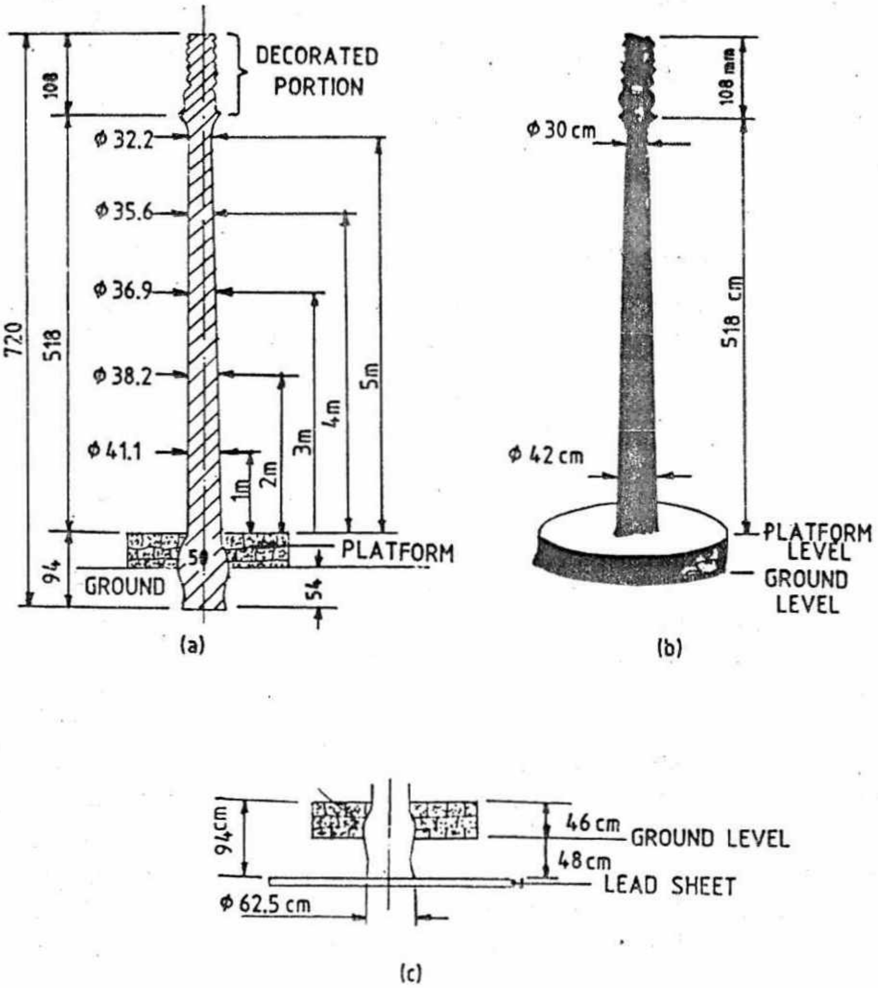

Fig. 3 : The Delhi Iron pillar physical diensions (a) Sketch of the pillar, (b) visible portion,and (c) portion hidden belwo the platform level.

The latest, and perhaps the most exhaustive, measurements of the Pillar [92,93] were made in 1989 by Bindal *et al.,* of the National Physical Laboratory, New Delhi, while subjecting it to ultrasonic non-destructive testing studies. Fig. 3 gives its dimensions comprehensively.

The chemical analysis of small samples taken from the Iron Pillar has been carried out several times, starting from the earliest analysis reported by Hadfield in 1912. the Chief Archaeological Chemist (Dr. B.B. Lal) associated with the Archaeological Survey of India, carried out an analysis in 1945 at the Laboratories of the Chief Metallurgical Inspector, Government of India, Jamshedpur, and found that his values were quite close to those reported by Hadfield some 30 years earlier. Around 1963, thanks to the initiatives of Dr. B.R. Nijhawan, Director, National Metallurgical Laboratory, Jamshedpur, chemical, spectrochemical and electron-probe analyses [60,63] were undertaken on a piece weighing about 4 grams taken from another location in the Pillar. Although there were minor variations in the percentage of carbon, silicon and phosphorus, as shown in Table 1, it was clear that the iron of the Pillar is astonishingly pure *i.e.*, low in carbon in particular, *vis-a-vis* commercial irons of today.

Table 1 : Chemical analysis of samples taken from lower portion of the Iron Pillar

Element	Hadfield (1912)	Lal (1945)	Ghosh (1963)	Lahiri (1963)
Carbon (%)	0.08	0.09	0.23	0.28
Silicon (%)	0.046	0.048	0.026	0.056
Phosphorus (%)	0.114	0.174	0.180	0.155
Manganese (%)	Nil	Nil	Nil	Nil
Sulphur (%)	0.006	0.007	trace	0.003
Nitrogen (%)	0.032	—	0.007	—
Copper (%)	0.034	—	—	—
Total Fe (%)	99.72	99.67	99.77	—
Specific Gravity	7.81	7.75	7.67	7.50

THE MAIN INSCRIPTION ON THE PILLAR

There are many inscriptions on the Iron Pillar at Delhi, but by far the most significant and earliest of them is the six-line Sanskrit inscription in archaic Gupta Brahmi script on its upper portion (Fig. 4). Although it could be deciphered and translated in the very first and seminal paper [3] on the Pillar by Prinsep in 1838, many aspects of it have been shrouded in mystery and dogged by controversy. The inscription is not dated, but refers to the conquests of a powerful king named 'Chandra'. As the dynastic particulars of the great Ruler are not recorded in the inscription, there has been no unanimity amongst scholars about the exact identity and precise historical context in terms of his period or specific data. On grounds of palaeography, content, language, style of execution *etc.*, the Pillar is considered by most scholars to belong to the early Gupta period *i.e.*, later 4th or early 5th century A.D. It may not be out of place to refer here to the equally significant, but less mysterious, inscription on the Allahadad Stone Pillar devoted entirely and unambiguously to a recital of the glory, pedigree, and conquests of the early Gupta King, Samudragupta (Table 2).

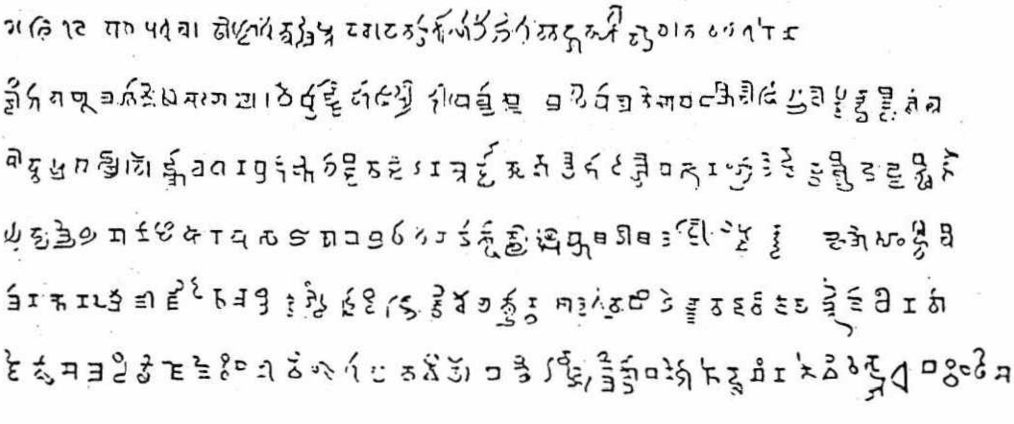

Fig. 4 : The Sanskrit inscription in Gupta–Brahami script on the Iron pillar as prepared for the study of James Prinsep in 1838.

Table 2 : Genealogy of the important Gupta Kings

Chandragupta I
Vikrama I or Vikramaditya I
Mahārājādhirāja
Married to Kumāradevī of the Lichchāvi family
(320-340 A.D.)

Samudragupta
(Kācha)
Mahārājādhirāja
Married to Dattadevī
(340-376 A.D.)

Chandragupta II
(Vikrama II, Vikramāditya II or Vikramānka)
Paramabhattāraka and Mahārājādhirāja
Married to Dhruvadevī
(376-414 A.D.)

Kumāragupta
(Mahendra or Mahendrāditya)
Mahārājādhirāja
Married to Anantadevi
(414-455 A.D.)

Skandagupta
(Kramāditya)
Paramabhaṭṭāraka and Mahārājādhirāja
(455-467 A.D.)

The round monolith sandstone column on which this long 33-line 'Prasasti' (Eulogy) has been engraved is 35 feet in height, dates from the 3rd century B.C. (as shown by the famous edicts of Emperor Ashoka on it) and now stands in a conspicuous position inside the Fort of Allahabad in Uttar Pradesh. Although the upper portions of this inscription have suffered considerable damage, the really important part of the inscription dealing with significant historical and genealogical facts (from line 19 to 30) is fortunately in a state of excellent preservation and is decipherable without the slightest doubt from beginning to end. It is also in 'Gupta Brahmi' script and the writing resembles in many respects that on the Iron Pillar at Delhi. This similarity acquires considerable importance in the light of the ongoing controversy on whether Samudragupta or his son Chandragupta II is the king referred to in the inscription on the Iron Pillar.

As has been remarked by practically all scholars [3-11] who have examined the main inscription on the Delhi Pillar, its writing is in excellent condition throughout, owing, of course, to the nature of the substance *viz.*, rustless, smooth iron, on which it is engraved. The six lines of the inscription cover a space of about 2 feet 9.5 inches broad by 10.5 inches high. The bottom line is about 7 feet 2 inches above the stone platform round the lower part of the column. The size of the letters varies from 0.3 to 0.5 inch and the engraving is on the whole very good. However, the metal has closed up over some of the strokes and this has in turn led to a rather imperfect appearance of a few letters in the lithograph (Fig. 4).

As early as in 1888 Fleet noted [9] that the characters on this inscription belong to the northern class of alphabets and, allowing for the stiffness resulting from engraving on so hard a substance like iron of this column, they approximate in many respects and rather closely to the Allahabad posthumous pillar inscription on Samudragupta. As a distinguishing feature between the two, one has to take note of the very marked 'matras' or horizontal top strokes of the letters, which seems to correspond to the Bilsad pillar inscription of Kumaragupta (Table 2) in Etwa District of Uttar Pradesh, which is generally assigned the date 415-416 A.D.

EVIDENCE OF PALAEOGRAPHY

Palaeography is the modern science dealing with the study of ancient writings and inscriptions. It has now developed to such an extent that its evidence can well be clinching and final. In the earliest paper [3] on this subject published in 1838, an authority as distinguished as Prinsep allotted this inscription to the 3rd or 4th century A.D. In 1875 Daji was inclined to assign it to a period later than the time of the Guptas [5]. In his important contribution of 1887 Fleet commented [9] on the closeness in regard to the characters of the inscriptions between the Iron Pillar at Delhi, the Pillar describing Samudragupta's heroic exploits at Allahabad and the Kumaragupta Pillar at Bilsad. His first impression was to identify King Chandra of the Iron Pillar with Chandragupta I, the first 'Maharajadhiraja' of the Gupta dynasty.

The views of many Indian researchers on this subject have been recorded in the 1989 book on "King Chandra and the Mahrauli Pillar" edited by Joshi and Gupta [96]. A careful perusal of these leads to the conclusion that most scholars are inclined to place this insription, on palaeographic grounds alone, along with those of Samudragupta and Chandragupta II. The assertion of Sharma in 1945, as quoted in his book, is worth reproducing :

> "... The evidence of palaeography is conclusive. I have compared the Mehrauli Pillar inscription with the Kushana inscriptions on the one hand and with the Gupta inscriptions on the other ... Even a glance at them reveals a wide gulf between the Kushana and Mehrauli characters and a corresponding similarity between Mehrauli and Gupta ... Therefore the Mehrauli Pillar inscription must be placed on paleographic grounds in the first half of the fifth century."

This book also informs us that Daji had no doubt that the Mehrauli Prasasti was written in early 5th century A.D. Another vital fact in the present discussion concerns the posthumous character of the inscription. Though a few scholars have tried to controvert the observation of Fleet that it is a "posthumous eulogy", a careful scrutiny of the text does not leave any scope for doubt. Verse 2 of the inscription makes a double reference to this fact : firstly, the King has gone to the other world in bodily form and secondly, the king remains in this world in the form of his fame. Thus it follows from the text of the inscription itself that though the "dhvaja-stambha" or "flag-staff" for Lord Vishnu was set up by King Chandra, the inscription on it could not have been engraved during his life time. In all likelihood the inscription was composed and engraved during the reign of his successor. To sum up, the evidence of palaeographic studies seems to point to Chandragupta II or Samudragupta as the King referred to in the inscription on the Delhi pillar. Consequentially, the monarch who got the inscription composed and engraved, eulogizing his father's exploits, has to be Kumaragupta or Chandragupta II respectively.

EVIDENCE OF THE KING'S EXPLOITS

It is obvious that whomsoever the historians may identify as King Chandra of the inscription on the Iron Pillar, that King has to live up to the many heroic exploits and achievements mentioned in the Prasasti (Eulogy) on the Pillar. Most early historians have tended to give more importance to the name rather than to the achievements of this King and thus we have a surprisingly wide cleavage in the recorded views on this question. Every early monarch, big or medium or small, whose name contained the word "Chandra" (meaning the moon) as a component, has been seized upon by one historian or the other. So we have this rather confusing state of affairs [96] wherein King Chandra has been identified even with Chandragupta Maurya (315 B.C.-295 B.C.), and Kanishka (Chandra 75 A.D. - 110 A.D.).

During the period 1962-67, while engaged in preparing his doctorate thesis entitled "A History of the Imperial Guptas", Goyal [95] came forward with the interesting and original proposition that King Chandra of the Iron Pillar inscription is best identified with Chandraprakasa, which is another name of the Gupta emperor Samudragupta. He has summarized his views in the earlier-referred book [96] edited by Joshi and Gupta. To start with, he points out, in agreement with Fleet, that the relevant portion of the inscription does by no means asserts that the original name of the king was Chandra, the expression being "Chandrahvena *i.e.,* called Chandra". He then suggests that no king known to history of this period by the name Chandra can be given credit for the notable achievements mentioned in the inscription. We should, therefore, reverse the process of enquiry, start with the analysis of the facts recorded about him and try to identify the king who answers the description best, without getting unduly obsessed about the name.

The inscription (Fig. 4) supplies us the following facts about the eulogized monarch:

i) He defeated his enemies in the Venga countries.

ii) He crossed 'the seven mouths of the river Indus' *i.e.,* the Indus delta, and conquered the Vahlikas.

iii) The breezes of his prowess were still "perfuming" the regions of the Southern Ocean.

iv) He established sole and supreme sovereignty on the earth by "the force of his own arm".

v) He ruled for a long time.

vi) He was a devout Vaishnava and put up this Pillar as a "Dhvaja-Stambha" (Flag Staff) for Lord Vishnu.

vii) His fame lingered on the earth even after his death.

Agreeing with earlier scholars on the possible date of the inscription, Goyal notes that this monarch flourished either in the second half of the 4th century or in the early decades of the 5th century A.D., was simultaneously a mighty conqueror, empire builder and devotee of Lord Vishnu and acquired sole and supreme sovereignty by his own prowess and not as a sequel to the power and prestige of his predecessor. "There is only one king who answers this description and he is Samudragupta, the real founder of the Gupta empire." Goyal is on very strong grounds in this last assertion because historians generally identify Samudragupta alone as "the most able soldier in a line of fighting kings", "one of the greatest Rulers India has known", "hero of a hundred fights" and "the ablest and most versatile of the Guptas".

As Goyal points out rather sarcastically, Chandragupta II was an empire builder only in the sense that he acquired an empire by killing his brother Ramagupta. His only notable military achievement was the conquest of the Saka kingdom of Western India, which, incidentally, had shrunk to a rather small size by the time he conquered it. All the same, it is extremely significant that this victory over the Sakas has not even been hinted at in the inscription on the Iron Pillar. Goyal has further unearthed the fact that Samudragupta was probably known by the name Chandraprakasa, as brought out in a Sanskrit verse quoted by Vamana in his Kavyalankarasut ravrtti (Circa 800 A.D.).

The reference here is to Vasubandhu, the famous Buddhist scholar, who was the minister of "Chandraprakasa, the sone of Chandragputa". As much is not known of any patronage extended by Kumaragupta, son of Chandragupta II, it seems reasonable to conclude that the expression Chandraprakasa in the above verse refers to Samudragupta, who was himself a poet, apart from being the son of Chandragupta I.

In his conclusion Goyal has conceded that a few points mentioned in regard to King Chandra in the inscription on the iron Pillar fit both Samudragupta and Chandragupta II. Both were Vaishnavas by faith, and both ruled for a long period. However, the military feats, as noted in the inscription, are quite distinctive and leave no room to doubt that they fit only Samudragupta, the indomitable warrior who performed rare feats of valour in that general period. "Actually the Mehrauli *prasasti* neither records nor omits any significant fact which requires a laboured interpretation in the case of Samudragupta, as it does in the case of Chandragupta II. It merely described *mutaties* mutandis in three brief verses what the Allahabad *prasasti* says in 33 long lines".

It is clear from the foregoing that historical evidence definitely narrows down the identification of the King eulogised in the inscription on the Delhi iron Pillar to either of the two great monarchs of the Gupta period *viz.,* Samudragupta and Chandragupta II. Until about 30 years ago, the so-called Chandra-Chandragupta II equation was accepted, by and large, by historians, but Goyal's thesis proposing the Chandra-Samudragupta equation was accepted, by the large, by historians, but Goyal's thesis proposing the Chandra-Samudaragupta equation has been increasingly favoured in the last two decades by scholars and researchers in the field. Since the inscription constitutes obviously a posthumous eulogy, another monarch, possibly the son *i.e.,* either Chandragupta II or Kumaragupta, got the inscription incised on the Pillar.

On internal evidence, the Iron Pillar is neither a "*Vijaya-Stambha*" (Pillar of Victory) nor a "*Kirti-Stambha*" (Pillar of Fame). It is actually a "*Dhvaja-Stambha*" (Symbolic Flagstaff) of Lord Vishnu and hence, in all likelihood, got installed originally in a Vishnu Temple and, as per general tradition, without any inscription. As Smith surmises [11] the *Visnupada-Giri* (Mount of Vishnu's Feet) referred to as the location for the Pillar in the inscription could well have been in Mathura, the city presently just eighty miles from Delhi and well-known as a site for Vishnu temples from time immemorial. This ancient pilgrim centre has many hills and mounds in or adjoining the city precincts, was well within the boundary of the Gupta empire and has also thrown up some stone inscriptions of the Gupta period. The choice of Iron and not the traditional stone for the Pillar strongly suggests a tough soldier and warrior behind it, not so much a great Patron of Arts and Letters. On this ground also Samudragupta has a clear edge over Chandragupta II as the builder of the Pillar. The three Sanskrit *Slokas* of the inscription can definitely be associated quite naturally with Chandragupta II, the grateful son of a great warrior-father and acknowledged Patron of great Sanskrit poets. Thus the date of erection of the Pillar can be narrowed down to 370-375 A.D., while the main inscription can be assigned the date of 380-385 A.D.

MODE OF FABRICATION OF THE PILLAR

On the basis of available information [88, 90, 97, 101, 102] on iron technology in ancient India, it is now possible to tackle effectively the problem of fabrication of this unusual Pillar. In this connection, special mention deserves to be made of the laudable initiative of the Metals Research Committee, Council of Scientific & Industrial Research (CSIR), New Delhi, in sponsoring some Research Projects during the sixties on the iron pillar and the so called Adivasi Iron still produced by age-old processes in the jungles of Bihar, Orissa and Madhya Pradesh. Thus Indian scientists and technologists could enter into a field of research that was until then, by and large, the exclusive preserve of Western investigators.

In 1963 the British scientists Bardgett and Stanners came to the conclusion[61,62] that the Iron of the Pillar was never in a molten state, nor subjected to any heat treatment. The construction of such a large piece of iron at that date would almost certainly have consisted in hammerforging balls of hot iron and in continuous hammering to create a smooth surface. During the reasonable time needed to complete this process, an oxide film would have been forming and got hammered into the surface. Slag too would have been incorporated in the scale. In the same year, following elaborate chemical and metallographic studies of the Pillar iron, as also ancient iron relics from Konarak in Orissa, Sultanganj near Delhi and Sinhabad in Maharashtra, Ghosh [60] came to many interesting conclusions. He found that the chemical composition and general microstructure of the Pillar Iron and the primitive. *Adivasi* iron are quite similar, rather like a modern low-carbon steel, but the mechanical properties of the former are some what different, obviously due to heavy hammering. The Pillar looked to have been very effectively forge-welded. Another paper of the same year [63] by Lahiri *et al.*, confirmed these finding.

A few year later the Swedish scientist Wranglen wrote two review articles[72,73] on the Delhi Pillar and agreed with the earlier investigators that the material of the Pillar was wrought (*i.e.*, worked) iron and had never been molten. He was of the view that the iron ore was perhaps weathered magnetite, obtained by surface quarrying, and was bedded intermittently with charcoal in a small charcoal-fired furnace with a foot-driven hide-bellow. The hot lumps of iron sponge thus obtained were hammer-forged in order to squeeze out most of the slag. Judging from the weld-lines visible on the surface, the Delhi Pillar seems to have been built up from a great many lumps, weighing 20-30 kg, successfully forge-welded together under firing with a charcoal blast. The surface of the Pillar still retains marks of hammer blows.

In 1984 Tylecote of the Historical Metallurgy Society, Great Britain, reported how the black-smiths of Aligarh had replied confidently to a question put to them by a British traveller in 1924 on the making of the Delhi Pillar. This reply is worth quoting in full :

> "Having procured an immense quantity of exceedingly pure Gwalior ore, which could be reduced to pure iron or mild steel by simply heating the blocks of ore in the presence of charcoal and hammering them into billets, they would have proceeded to the site chosen for the Pillar. Having made a hole in the ground, they would have piled in a quantity of ore and placed a mass of kindled charcoal fire over it directing the blast on to it by placing 6 to 8 pairs of native bellows with the nozzles converging on to the centre of the

mass. A few feet away on one side they would then have prepared a similar hole and repeated the process so that there were two masses of white-hot native iron close to one another. When these were at the welding temperature the surface charcoal would have been swept away. By levers the second mass would have been turned over on top of the first mass and then hammered down until it welded itself on to it".

"More 'pancakes' having been welded on in the same manner, they would have trimmed the rough exterior with chisels and then fitted the earth again upto the level of the large mass so obtained. Thus, they would have continued to forge and weld on these thin sheets, raising after each addition the level of the earth so that the new 'pancake' was a little above the level of the forged mass. Thus would the Pillar have been built up eventually, as we now know it. Finally the whole of the outside would have been pared down with cold chisels to a true cylindrical surface".

The long review of Lal [91] on the Delhi Pillar, published in 1989, but largely based on his studies during the early sixties in the Archeological Survey of India, also comes to the conclusion that the massive Pillar was not cast, but fabricated by forging and hammer-welding lumps or balls of hot pasty iron in a step-by-step process.

Making use of recent research data on reduction of magnetite (Fe_3O_4). Dube has suggested in his 1990 paper [98] that sponge iron pieces obtained by charcoal reduction of iron ore would in fact be agglomerates of reduced iron particles with high porosity. He considers it reasonable to conclude that the Delhi Pillar was made by successive hot forging of directly reduced sponge iron blocks in a die.

This procedure is rather similar to modern power-forging techniques, with the difference that the later is not usually used to make long products by joining many pieces together. One may even say that ancient Indians combined in one process the three modern steps of powder production, consolidation and sintering through "preform" directly from the iron ore. In a long review Biswas agrees [102] with earlier investigators and concludes that forge welding was indeed the technique used to fabricate the Iron Pillar.

The mode of fabrication by forge welding, as suggested by most researchers in this field, seems plansible in every way and had, in fact, been proposed in Great Britain for the Chedworth, Catterick and Corbridge beams. In 1991, Rao illustrated his article on the Pillar [101] with an artist's impression of this mode of fabrication. The same is reproduced in Fig. 5 with a few minor alterations.

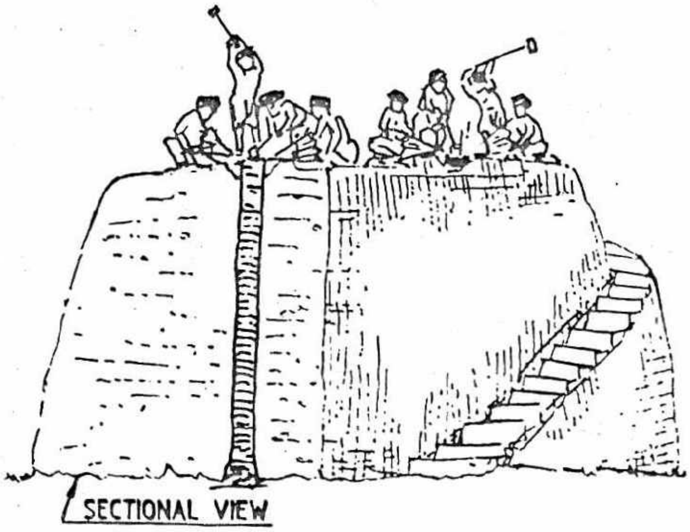

Fig. 5 : Forging of the Delhi iron Pillar – An artist's impression

The question has been raised by many as to how long it would have taken the blacksmiths of those days to forge this massive and magnificent Pillar. Assuming that the furnaces of that age could produce only 20-30 kg of pasty sponge iron in one heat lasting a few hours, some 250-300 heats would have been necessary to produce the iron needed for hot forging and shaping the Pillar. With 10 furnaces operating in tandem and each producing 2 heats every working day, it would have taken at least 2 weeks to obtain required iron. At 10 workers per furnace and at least 12 labourers for hammering, over 120 craftsmen and labourers would well have been on the job for a fortnight and more to complete this unusual, daunting and pioneering project led undoubtedly by a highly gifted master blacksmith.

CORROSION RESISTANCE OF THE PILLAR

Although the astonishing corrosion resistance of the main, exposed, cylindrical part of the massive Iron Pillar has rightly attracted worldwide attention, it is relevant to record here that the bulbous base as well as the grooved capital of the Pillar has, in fact, been subjected to corrosion effects like normal varieties of wrought iron. This fact has often not been highlighted in accounts and articles devoted to the iron Pillar.

It was only in 1961 that the famous Pillar was dug out for chemical treatment, preservation and reinstallation on the eve of the Centenary Celebrations of the Archaeological Survey of India. Dr. B.B. Lal, Chief Chemist of this Organisation at that time, was in charge of these operations and has recorded the following conclusion in his Report: "An examination of the buried part of the Pillar and the hollow capital surmounting it has amply demonstrated that the iron of the Pillar is vulnerable to rusting like any other specimen of wrought iron".

Corrosion Effects Recorded in 1961

The first impression in 1961 was that the portion of the Pillar below the earth was "superficially rusted". However, on detailed examination, the buried portion of the Pillar was found covered with thick crusts of rust and, in fact, copious rust scales could be collected, ranging in thickness from a few millimeters (mm) to no less than 15mm in some portions. Further, the bulbous base of the Pillar was found riddled with numerous cavities and hollows caused by deep corrosion and mineralization of the iron. The samples of rust scales collected from the corroded base of the Pillar and the samples of soil adhering to it were subjected to chemical analysis. The composition of the iron sample drawn from the pillar base was nearly the same as reported earlier for samples taken from the cylindrical, exposed portions of the Pillar. The soil portions were found, not unexpectedly, to be loaded with appreciable quantities of soluble sulphates and chlorides.

An interesting feature revealed for the first time during the 1961 investigations was the presence of a sheet of metallic lead, 99.37% pure and 3mm thick, wrapped around the bulbous end of the Pillar to a height of about 80 cm. The lead sheet was found to be in an excellent state of preservation and, barring a superficial whitish layer, was almost completely free from corrosion. It was rightly concluded by Dr. Lal during his 1961-1962 studies that most of the damage to the buried part of the Pillar was due to prolonged galvanic action and corrosion, induced by the juxtaposition of lead and iron of the Pillar, the latter serving as the sacrificial anode and the former as the cathode. The marked corrosion of the iron pillar base and the well-preserved survival of the lead sheet are both according to expectations of scientists, since iron stands nearer to the base/active end than lead in the Galvanic Series.

It is appropriate to record here in passing that if a zinc sheet had been used in place of the lead sheet, the former would have become the sacrificial anode and corroded, saving the iron of the Pillar from electrolytic corrosion, even though the rusting of iron would have gone on in the ambient environment characterised by moisture containing dissolved oxygen.

Incidentally, the excavation of 1961 also revealed that the Iron Pillar had a flat circular base with 8 thick projections sticking out uniformly around its circumference and overlay an iron grid laid horizontally on a heavy slab of stone resting on a stone foundation. The lead sheet was wrapped all around the foundation and to a height of about 80cms, coming upto just below the pillar base. The visible lower portion of the Pillar presents a somewhat rough, unfinished and pitted surface and could well have been embedded in the ground at its original locations.

In 1961 the capital of the Pillar with its deep rectangular groove or slot, presumably meant for holding the flagstaff on an image of Garuda the vrhicle of Lord *Vishnu*, was also examined to assess its state of preservation. It was found that thick laminated rust scales mixed with earthy matter had accumulated at the base of the groove, indicating considerable corrosion. Evidently, accumulation of rain water as well as sand, dust and clay brought by the winds had contributed to marked rusting here over the years. Since the rain water could accumulate to a depth of over a foot in the slot along with dust, the wetted portions provided rather ideal conditions for corrosion over long spells.

The Rustless Wonder

The excellent state of preservation of the massive shaft of the Iron Pillar despite exposure for over 15 centuries to sun, rain, wind and dust has naturally attracted the attention and admiration of metallurgists, materials scientists and corrosion technologists during this century. Among the numerous publications dealing with this fascinating and intriguing phenomenon the research papers from the sixties [60-102] have been the most helpful, the Indian scientists rubbing shoulders during these the decades with their Western counterparts on a footing of equality and cooperation, in throwing light on this challenging area of metals research.

The foremost point to be kept in mind here is the extra-ordinary inhomogenity of the Iron Pillar from many points of view. The pillar was obviously forge-welded from a great many sponge iron lumps of different composition, so that the chemical analysis and consequently microstructure as well as mechanical properties are variable from layer to layer of the Pillar. In the unetched condition *i.e.*, before etching by acidic solution to reveal the metallic grain and phase structure, microscopic examination of the pillar iron reveals slag particles distributed irregularly. In the etched condition the microstructure shows polyhedral grains of ferrite (*i.e.*, almost pure iron) with some slip bands and varying, but small amounts of pearlite (the well -known and intimate mechanical mixture of ferrite and iron carbide. Fe_3C, known as cementite in metallurgical circles). The carbon content thus varies from very low ($<0.1\%$) to 0.3%, while the microhardness varies on the Brinell Scale all the way from 80 for pure ferrite to 180 for pure pearlite.

Effects of Chemical Composition

The variation in carbon content in the Pillar iron has been referred to earlier (see Table 2) but a related point to be stressed again is that the carbon percentage is not particularly low, as often taken for granted in earlier publications. The carbon content and the volume of pearlite are both lower in the surface layers and increase inwards in the direction of the pillar axis, apparently as a result of surface decarburization (loss of carbon) during hammer-forging of the hot, pasty iron.

The phosphorus content in the pillar iron is definitely quite high and less varying than the carbon content. It occurs partly as a solid solution (*i.e.*, dissolved) in ferrite and partly as slag inclusions of iron phosphate ($FePO_4$). Further, the strongly oxidized parts and the surface layers, depleted of carbon, tend to be richer in phosphorus than the interior parts of the Pillar. In a sample containing 0.8% P, careful analysis showed that 0.18% was dissolved as elemental P in ferrite, whereas the remainder appeared as phosphate slag. It is generally agreed that this high phosphorus content in the pillar iron checks its corrosion and makes its own distinct contribution to the corrosion resistance of the Pillar. The view of experts has been that in oxygen-consuming corrosion phenomena, as in water and humid atmospheres, phosphorus in ferrite exerts a beneficial influence through oxidation to phosphate which as an inhibitor promotes the formation of protective, impervious oxide films on the pillar surface.

The sulphur content of the Delhi Pillar is very low, according to all determinations, probably because charcoal was used in reducing the ore. Coupled with the fact that the manganese content of the Pillar is also very low. The very low percentage of sulphur means that there are very few centres of iron-rich manganese sulphide (MnS) to initiate pit corrosion by serving as effective local cathodes. In fact, the sulphur printing technique has rarely revealed in the pillar iron any microscopically visible inclusions of sulphides. Thus the low sulphur and magnanese contents are expected to make some contribution to the increase in corrosion resistance of the Delhi Pillar.

Effects of Protection Films

As any visitor to the famous Pillar will immediately note, there is a prominent band of the circumference of the pillar at a height of about 1.0 to 1.5 meters above the stone platform, which is exceptionally bright and smooth, as if specially polished. This is due to the custom of visitors standing with their backs towards the Pillar and trying to clasp their hands around it "for luck". As in the case of the 200 year old iron chain in a shrine on Adam's Peak in Sri Lanka, contact with human hands with consequent repeated polishing and greasing, has practically prevented rusting of this portion of the Pillar.

In fact, various studies have established beyond doubt that the Iron Pillar is coated by a protective film varying in thickness from 60 to 600 microns. According to magnetic measurements this predominantly oxide film is less than 50 microns thick in the bright, polished section referred to above; it increases to 500-600 microns away from this section. If the oxide film is scraped off, the exposed iron starts to rust, and after a few years the newly formed oxide film cannot be distinguished from the main oxide of the Pillar. There is thus strong support for the theory that the good state of preservation of the Pillar is mainly, if not solely, due to a protective film of corrosion products.

According to optical, X-ray and chemical investigations, the protective film on the Delhi Pillar seems to consist mainly of Fe_3O_4, which is magnetic as opposed to the non-magnetic $Fe_2O_3.nH_2O$. One analysis gives the following break-up of oxides : Fe_3O_4-67.0%, FeO-13.1%, H_2O-14.8%, $FePO_4$-1.7%, SiO_2-3.19%, MgO-0.2%, CaO-0.1%. The much larger proportion of the magnetic fraction in the rust of the Pillar, as compared to the non-magnetic fraction is an unique feature. In the commonly encountered rust of ordinary mild steel, there is a much greater portion of the non-magnetic oxide over the magnetic variety. Evidently under the atmospheric conditions prevailing in Delhi, the rust of the Pillar has not fully undergone the further oxidation from the Fe_3O_4 to the Fe_2O_3 stage. It is noteworthy here that the thick rust layers obtained below the ground display compositions closer to $Fe_2O_3.nH_2O$.

The content of phosphate in the surface oxide film corresponds to 0.35% P in the iron, which is within the variation limits for the analytical P values. However, there is a general enrichment of P in the rust, as compared to the substrate. Experts believe that the portion of P of the basic material which is evenly distributed in solid solution in ferrite contributes probably more to the formation of the protective surface film than the heterogeneously distributed inclusions of phosphate slags.

The SiO_2 (silica) content of the surface oxide film is much higher than the corresponding silicon content in the pillar iron. Since, furthermore, X-ray studies of the surface oxide reveal the presence of quartz (another form of silica), it is fairly obvious that the SiO_2 content is mainly derived from occluded dust, a direct consequence of the sand storms quite common in and around Delhi. The small quantities of magnesium and calcium oxides (MgO and CaO) on the surface may be traceed to the same cause.

Incidentally, it is well known that the thickness of protective films increases according to the parabolic law. At the first growth rate of 5 microns/year, the growth in 1600 years works out to be around 200 microns, in good agreement with the average of measured values.

Environmental Effects

According to some experts the deciding factor behind the rustlessness of the Iron Pillar at Delhi has been the comparatively dry and unpolluted climate of the Delhi area, particularly during the 15 centuries upto the beginning of this century. As noted by many scientists the climatic conditions at Delhi have some special features contributing to low corrosion rates for irons and steels. The most important of them is the low relative humidity (r.h.) of the air at Delhi, as at many other hot and dry places in the world. It is only in morning hours during the monsoon rains in July, August and September and also in January that the r.h., exceeds the critical value of 70%, above which noticeable rusting starts. In the afternoons the r.h., never exceeds this critical limit. In fact, the r.h., is very low (20-40%) except in the monsoon period.

Delhi is no desert. In fact, the rainfall is considerable, amounting to about 700 mm per annum, as in many parts of Europe, even though this amount of rain may be considered relatively small for a country like India. This rainfall in conjunction with the generally high temperatures, going above 40°C at times, contributes to the dry climate, in which moisture readily evaporates. This is particularly true of a large, freely-exposed object of considerable heat capacity such as the six-tonne Iron pillar. As can be appreciated even by laymen, the heavy Pillar absorbs large quantities of solar radiated heat. This counteracts dew precipitation during the night and results in rapid drying after rainfall. It is also to be noted here in passing that the heavy monsoon rains exert a rinsing and cleansing effect on the Pillar.

In such a discussion on the influence of climatic factors on corrosion phenomena, the pollution of the atmosphere cannot be forgotten. Due to small industrialisation and little use of fossil fuels, the concentration of corroding gases like sulphur dioxide (SO_2) is rather low in most parts of India. Accumulation of waste products from animals and men, generating ammonia, will presumably mean for a hot and densely populated country like India that the atmosphere is generally 'alkaline' rather than 'acidic' and hence conducive to good corrosion resistance in irons and steels. Conditions have been changing fast in India since independence in 1947 and particularly through the rapid industrialization of the last three decades, but the conditions outlined here have been true for the last 15 centuries for areas in and around Delhi.

Effects of Heterogeneities

The lack of homogeneity in chemical composition and microstructure, as also in the distribution of slag inclusions, oxide particles *etc.*, in the Pillar iron has been referred to earlier. However, the possible favourable role of this multi-faceted heterogeneity in protecting the Pillar from atmospheric corrosion has not yet been given due consideration.

As is well-known, intergranular corrosion is a common type of galvanic corrosion caused by metallic impurities segregating at grain boundaries and serving as cathodic sites in corrosive environments to the detriment of the metal or alloy forming the grains. This phenomenon is labelled as "inter granular" because it proceeds along the continuous network of grain boundaries. In case of the Delhi Pillar, the progress of such inter-granaular corrosion may well be halted effectively by non-metallic barriers such a slag or oxide particles segregated at the grain boundaries.

The above referred non-uniformities, as also imperfections like slip bands, microstrains *etc.*, introduced by heavy hammering, can also contribute in some measure to the remarkable corrosion resistance of the Delhi Pillar. This is because in general terms any metallurgical process proceeds smootly and fast in homogeneous material, but gets halted or hindered by heterogeneities, imperfection and non-metallic obstacles. Even a continuing process like corrosion can thus be stopped effectively at microscopic or even smaller sub-microscopic entities that break the perfect homogenity of the concerned material. To sum up, the results of different scientific studies points to several factors *viz.*, unusual chemical composition, adherent protective film, comparatively dry and unpolluted climatic conditions and microstructural heterogeneities, contributing collectively to the phenomenal corrosion resistance of the cylindrical exposed portion of the Delhi Iron Pillar.

CONCLUSION

In the foregoing sections many interesting and important conclusions could be reached on several fascinating as well as intriguing aspects of the famous Iron

Pillar located in South Delhi. Even though all questions concerning this great tourist attraction have not been answered in this paper, it must be clear to the discerning reader that this celebrated monument need not be looked upon any more as a myth or a mystery or an enigma. It has definitely stood out as a metallurgical marvel of its age from a technological point of view and will remain so for all time to come.

More work needs to be done, no doubt, to fill up the remaining gaps *viz.*, the Pillars original location and its whereabouts for some six centuries before its installation at Mehrauli and the tools used for shaping the Pillar's magnificent capital, as also for engraving the inscription on the Pillar. Perhaps the fabrication process also needs to be proved and attempts may well be made to re-create at least a part of the Pillar in one of our metallurgical laboratories with the help of traditional blacksmiths.

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