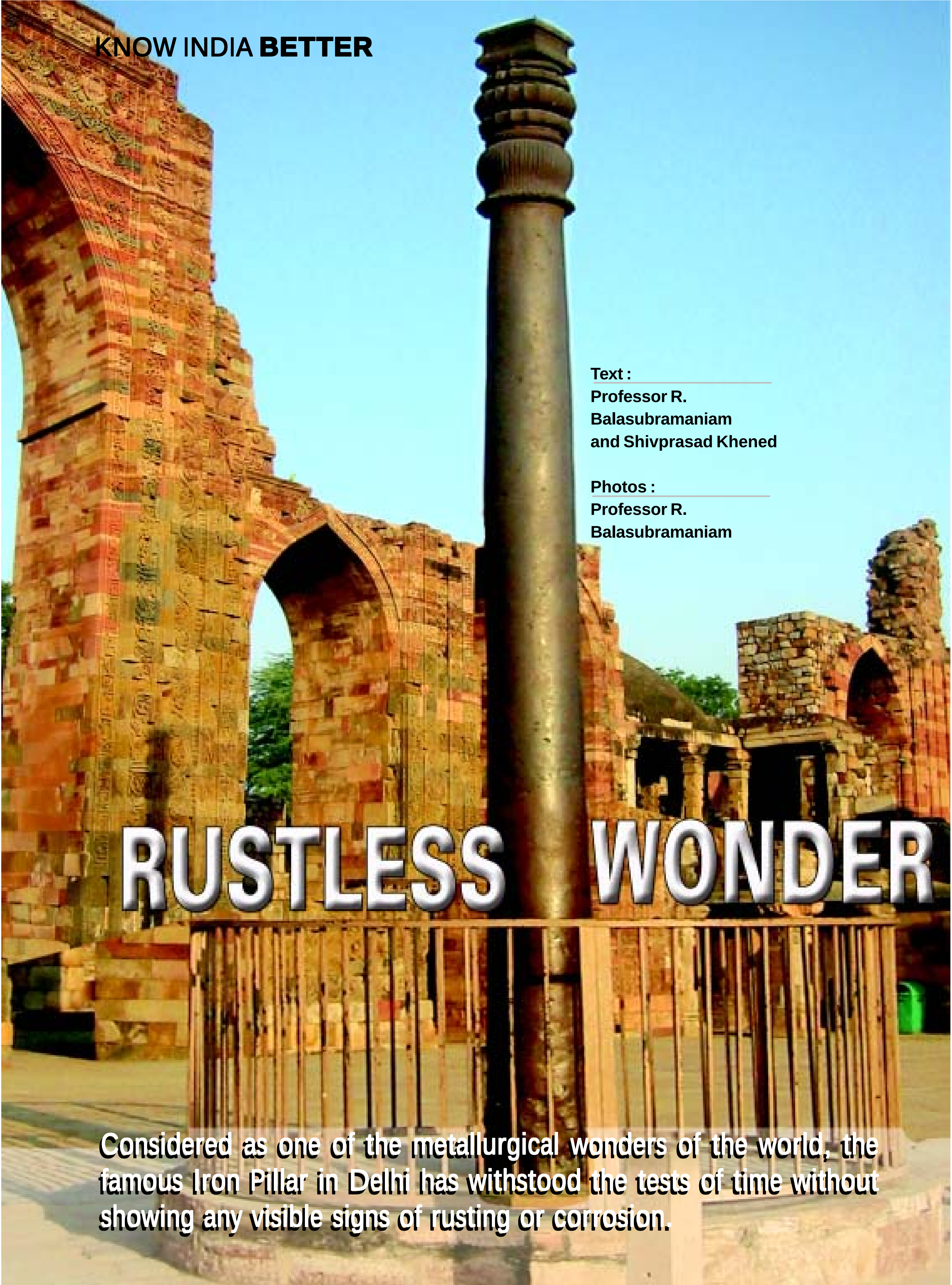

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RUSTLESS WONDER

Considered as one of the metallurgical wonders of the world, the famous Iron Pillar in Delhi has withstood the tests of time without showing any visible signs of rusting or corrosion.

Fig. 1: The Delhi Iron Pillar located in the Quwwat-ul-Islam mosque in the Qutub Complex in New Delhi

Gold for the mistress, silver for the maid
Copper for the craftsman cunning at this trade
"Good," said the Baron, sitting in his hall
"But iron, cold iron, is master of them all."

DELHI, our capital city, has a long and rich heritage. The city has ancient ruins, monuments and contemporary buildings that stand side by side, providing glimpses of its glorious past and tumultuous history. Of all the ancient monuments in the city of Delhi, the Qutub Complex (where the Qutub Minar is located) holds a special attraction. It houses India's unique technological marvel and metallurgical pride, the Delhi Iron Pillar. Its uniqueness in remaining without significant signs of corrosion for more than 1600 years has baffled modern scientists and metallurgists from across the world. Let us explore some historical and scientific matters related to the Iron Pillar, which verily embodies the rich technological achievements of ancient Indian blacksmiths.

The sight of the Iron Pillar standing in the courtyard of the Quwwat-ul-Islam mosque, adjacent to the Qutub Minar, is breathtaking and cannot be missed by any visitor. Visitors hugging the pillar with their backs firmly against it, and trying to make the fingers of their two hands touch while holding the pillar in embrace was all too familiar a scene not until long ago. The belief that such an embrace could fulfill all their desires made every visitor, dignitaries included, to try their luck at the embrace. A barricade has now been built around the pillar to protect it from unending visitors embrace, which was beginning to damage the pillar. A round barricade was put up around the pillar in 1997, which was replaced by a square barricade in 2004. Notwithstanding the barricade, visitors continue to flock to the pillar even today, awe struck that the pillar has withstood nature's fury for such a long period. The pillar is a testimony to the marvellous metallurgical knowledge that existed in ancient India. It should be rightly considered as one of the metallurgical wonders of the world.

Ancient Indian iron

The use of metals and knowledge of metallurgy is inextricably linked to the history of civilisation. Material progress of any country, apart from other things, depends upon mining, metallurgy and metal industries. The credit of providing impetus to material progress, in modern times, no doubt, goes to scientific technology. Even the cursory survey of history of mankind reveals fairly well that people all over the world, specially in India, and much before the dawn of modern scientific age, have been exploring the possibilities conducive to their material progress. Modern metallurgy has witnessed unprecedented growth beginning with the Industrial Revolution. However, many modern concepts in metallurgy owe their genesis to ancient practices that pre-date the Industrial Revolution. Artefacts, tools, objects, etc. made of metals for both artistic and utilitarian purposes have been in vogue ever since antiquity. The commonly used metals, from a historical standpoint, include gold, silver, copper, iron, tin, lead, zinc and mercury.

Iron, however, has its unique place amongst all the metals. Iron stands for power and strength as evidenced from the title given to Sardar Patel, one of the architects of freedom movement in India, who was called the *Loha Purush* - the Iron Man of India. The significance of iron for human kind can best be described in the words of Pliny the Elder (AD 23-79), the Roman naturalist and writer who wrote about iron: "Iron mines bring man a most splendid and most harmful tool. It is by means of this tool that we cut into the ground, plant bushes, cultivate flourishing orchards and make grape vines with grapes. By this same tool we build houses, break stones and use iron for all such purposes. But it is also with the help of iron that we fight and battle and rob. And we do it not only at close quarters, but giving it wings, we hurl it far into the distance, now from embracers, now from powerful human hands, now from bows in the form feathered darts. This, I think, is the most infamous invention of the human brain. For in order to enable death to catch up with man faster, it has given it wings and armed iron with feathers. For that many the blame rests with man and not with the nature."

One of the civilisations that invented iron and refined the technique for extraction from ore was India. The earliest date for iron in the Indian subcontinent is about 1600 BC. Indians further discovered the beneficial aspects of intentionally alloying carbon into iron, thereby producing stronger and tougher steel. Technically, steel is defined as an alloy of carbon and iron. This steeling of iron, which was discovered in the Indian sub-continent sometime in 800 BC, resulted in clearing of dense forests leading to the subsequent second urbanisation of India along the banks of the Ganga and the Yamuna. The first urbanisation of India was the establishment of planned settlements along the once-mighty Saraswati river in the period 3000 BC to 1800 BC - the so-called Indus Valley or Harappan Civilisation. The shifting of feeding river channels away from the Saraswati river (due to tectonic motions), and its subsequent drying up, resulted in the disbursement of the inhabitants of these settlements to other corners of India, by 1500 BC.

It may interest readers that with the advent of carburisation of iron, a special type of high carbon steel was produced in India from as early as the fourth century BC. This steel was known as *wootz* steel and it was much prized by warriors due to tough swords that could be wrought from *wootz* steel. This wonder material of the Orient was held in great esteem by the medieval warriors and European scientists in the nineteenth century. Studies conducted by eminent scientists like Michael Faraday for understanding the mystery of *wootz* steel laid the foundation of modern metallurgy. Given this rich metallurgical tradition in iron and steel making, it was but natural that the Indian sub-continent was home to the creation of marvellous objects. It must be mentioned here that ancient Indian iron was extracted in small furnaces by solid state reduction of the ore. The end product was an iron lump which was later forged together in white heat to produce different objects. This method of working with iron was practised for a long time in Indian history, all the way up to the British period. One marvellous example of a wrought iron product is a gilded wrought iron image of Buddha, now in the Lucknow State Museum (Figure 2). This 18 centimetres high image was discovered from Azamgarh and dated to the Gupta period (320-600 AD).

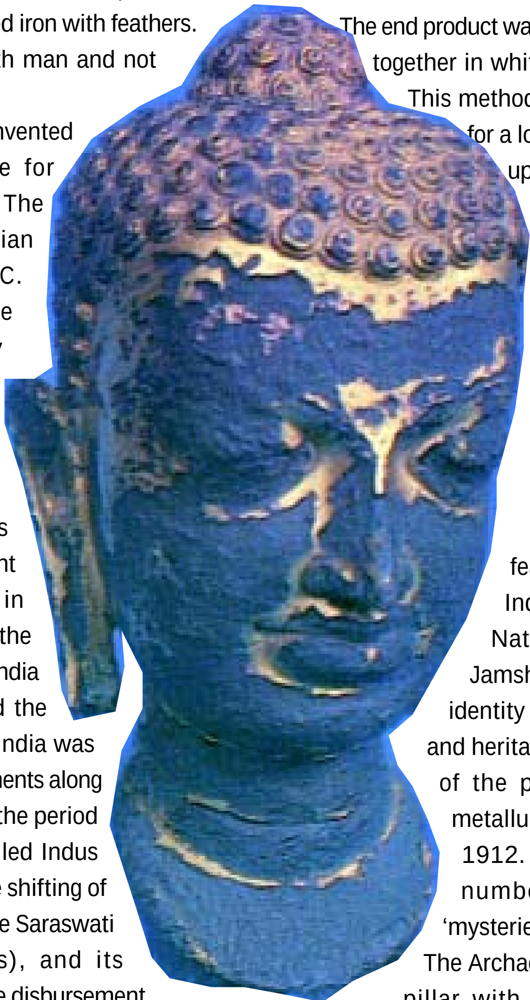


Fig. 2: Gilded wrought iron image of Buddha, belonging to the Gupta period (320-600 AD), now in the Lucknow State Museum.

Early studies

The Delhi Iron Pillar is singularly featured on the emblems of several Indian institutions (for example, the National Metallurgical Laboratory at Jamshedpur), thereby signifying its prime identity as the country's metallurgical pride and heritage. The first detailed scientific study of the pillar was by an eminent British metallurgist, named Hadfield, in the year 1912. Ever since, there have been a growing number of studies in which several 'mysteries' of the pillar have been unravelled. The Archaeological Survey of India studied the pillar with the cooperation of the National Metallurgical Laboratory (NML) in 1961. The results of these scientific studies were summarised in a special issue of the *NML Technical Journal* (Volume 5, 1963). A review of the pillar's corrosion resistance appeared in 1970. Professor Anantharaman, one of the doyens of modern metallurgy in India, has published the known scientific facts about the pillar in a book titled *The Rustless Wonder – A Study of the Iron Pillar at Delhi* in 1996.

Fig.3: The 6-line 3-stanza Brahmi-Sanskrit inscription on the pillar, the oldest and largest of all the inscriptions on the pillar. This inscription is at a level of about 7 feet from the stone platform.

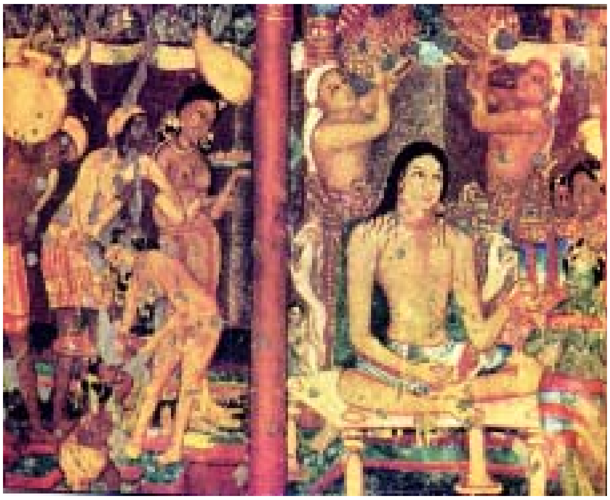


Fig.4: Ajanta painting showing king having the royal bath. It is reasonable to assume that Chandragupta II Vikramaditya must have appeared similar to this image of the king in this painting, which was executed during the Gupta period.

Pillar's history

Among the several inscriptions on the pillar, the oldest (and also the largest) is a three-stanza six-line Sanskrit-Brahmi inscription, at a level of about seven feet from the stone platform (Figure 3). This inscription records that the pillar was set up by *Chandra* as a standard of Vishnu at *Vishnupadagiri*. The monarch's conquests have also been poetically described in the inscription. Based on the nature of the characters, the inscription can be dated to the period between 400 and 450 AD. This inscription appears to have been provided using specially prepared dies (i.e. by die-striking operations). Specific die shapes were used for making the inscription. The monarch *Chandra* has been identified unambiguously with Chandragupta II Vikramaditya (375 AD-414 AD), based on careful analysis of archer type Gupta gold coins. A possible image of how Chandragupta II Vikramaditya would have looked like can be hypothesised. The Ajanta cave paintings were executed during the Gupta period. In one of the Ajanta paintings, the king is seen having his royal bath (Figure 4) and this would be the appearance of a monarch of this period.

The original location of the pillar, *Vishnupadagiri* (meaning "Vishnu-footprint-hill") has been identified as modern Udayagiri, situated in the close vicinity of Besnagar, Vidisha and Sanchi. These towns are located about 50 kilometres east of Bhopal, in central India. There are several aspects to the original erection site of the pillar at Udayagiri. It must be worth noting that *Vishnupadagiri* is located on the Tropic of Cancer and, therefore, was a centre of astronomical studies during the Gupta period. The Iron Pillar served an important astronomical function, when it was originally at *Vishnupadagiri.* The early morning shadow of the Iron Pillar fell in the direction of the foot of *Anantasayain Vishnu* (in one of the panels at Udayagiri) only in the time around summer solstice (June 21). The creation and development of the Udayagiri site appears to have been clearly guided by a highly developed astronomical knowledge. Therefore, the Udayagiri site, in general, and the Iron Pillar location in particular, provide firm evidence for the astronomical knowledge that existed in ancient India around 400 AD. The flowering of astronomical knowledge under prominent astronomers like Aryabhatta, Varahamihira and Brahmagupta during the Gupta period is well-known.

Based on careful study of history of the Qutub Complex, it can be reasonably concluded that the pillar was erected at its current location in the Quwwat-ul-Islam mosque by Iltutmish (1210-1235 AD). Iltutmish was the first Delhi Sultan to invade Malwa in 1233 AD. After his capture of *Vishnupadagiri,* several objects were carried to Delhi and the pillar was one such object. In fact, the Quwwat-ul-Islam mosque was completed by Iltutmish and it is certain that he planted the wonderful Iron Pillar in the centre of the mosque

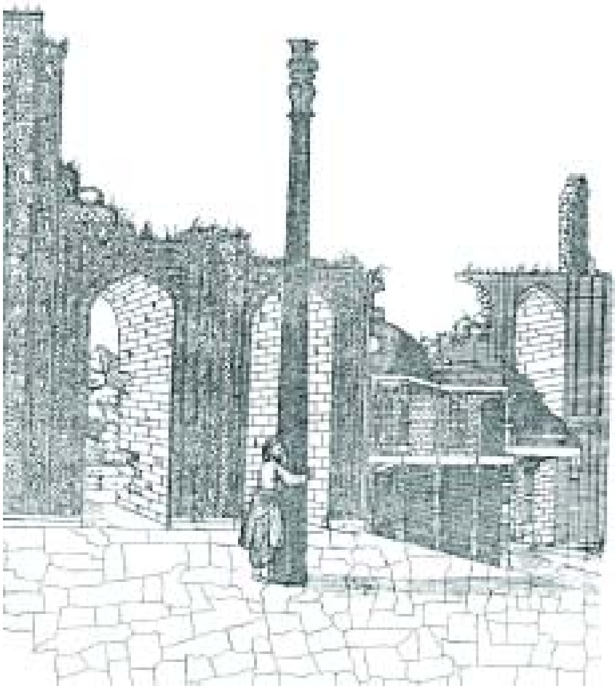


Fig.5: Free hand sketch of the pillar by an artist Mirza Shah Rukh Beg for publication in Syed Ahmed Khan's Urdu work *Athar'al-Sanadid* in 1846. In this illustration, a bearded person is seen clasping the pillar (without the stone platform) at the top of the rough section.

Fig.6: Bottom region of the iron pillar. The rough portion was originally buried in the ground.

courtyard. Ever since, the pillar has remained at this location.

Engineering feat

Let us explore some engineering aspects of the pillar. We first realise that current burial level of the pillar was not the original burial level of the pillar when it was located at Udayagiri. The rough portion of the pillar was originally buried in the courtyard of the temple and later left exposed outside when the iron pillar was displaced from its original position. Notice the hammer-marked cavities, which are visible on the surface of the pillar in the rough region just below the smooth surface-finish region (Figure 6). This rough surface was the as-manufactured condition of the pillar. It was left rough in order to aid gripping of the pillar to the buried underground region in Udayagiri.

There is a stone platform currently seen surrounding the pillar base was set by Beglar in 1861. Early sketches and published photographs of the pillar, before the construction of the stone platform, attest to the absence of the stone platform before Beglar's excavations. One example is the free hand sketch of the pillar by an artist named Mirza Shah Rukh Beg, commissioned for publication in Syed Ahmed Khan's Urdu work *Athar'al-Sanadid* in 1846 (Figure 5).

A critical analysis of the dimensions of the main body of the pillar provides conclusive evidence for the original burial level of the pillar and also an appreciation of the pillar's symmetrical design. Considering the basic unit as U, the rough surface occupies one-fourth (60U) and the smooth surface three-fourths (180U) of the pillar main body length, excluding the decorative top. The burial of the pillar body to one-fourth of its height would have provided the necessary stability to the structure. The unit U is

Fig.7: The underground portion of the pillar below the ground level before conservation treatment.

equal to one modern inch. The *angulam*, the ancient Indian unit of measurement, equals 0.75 of the modern one inch.

The buried underground region was excavated in 1961 (Figure 7). The base of the pillar was flat. Eight small projections were seen at equal intervals. These projections appeared from the sheet of almost pure lead, placed at the bottom of the pillar. A heavy slab of stone was found placed horizontally on the original upper layer of the temple floor on which the lead sheet rested. It appears that the two iron rods were placed parallel to each other and another two iron rods were placed above these such that they were perpendicular to the initial rods. This provided a grid-like structure. These iron rods were placed on a lead sheet. The iron pillar base was then fixed atop this iron grid structure thereby providing the necessary support at the bottom. The lead sheet would have acted like a cushion in case of seismic disturbances. However, the main purpose of the lead sheet appears to be to grip the pillar to the supporting stone underneath.

A coating of lead was present when the underground regions were excavated. In 1961, the surface was cleaned and the cracks were consolidated. A new lead coating was provided on the pillar in the buried underground region and the pillar again buried under the ground (Figure 8). This coating needs to be replaced as this is causing enhanced damage of the buried underground portion of the pillar due to galvanic corrosion.

Fig.9: The mark of a cannon ball shot can be seen in the southern face of the pillar half way up the height of the pillar. The Qutub Minar is seen in the background.

Fig.8: The underground portion of the pillar below the ground level after provision of a new lead coating before being buried again in 1961.

Chemical composition

The underlying metal of the pillar would be discussed briefly in order to elucidate its characteristic features. Incidentally, these features are also characteristics of ancient Indian irons.

Several composition analysis of the iron of Delhi Pillar is available. The average composition of the pillar iron is 0.15 per cent C, 0.25 per cent P, 0.005 per cent S, 0.05 per cent Si, 0.02 per cent N, 0.05 per cent Mn, 0.03 per cent Cu, 0.05 per cent Ni and balance Fe. The high phosphorus (P) content of the pillar iron must be particularly noted. Careful compositional analysis near surface regions proved that there was no surface coating provided specifically for enhancing the corrosion resistance of the pillar. The pillar is a solid body with good mechanical strength. In fact, a cannon ball fired at the Delhi Iron Pillar in the 18th century (either by Nadir Shah in 1739 AD or Ghulam Quadir in 1787) failed to break the pillar. The marks of this cannon ball shot can be seen in the southern face of the pillar half way up the height of the pillar (Figure 9).

The presence of phosphorus is crucial to the corrosion resistance of Iron Pillar. In ancient iron making practice, limestone was not added. The absence of lime resulted in a higher amount of phosphorus in the metal. It must also be noted that there are indications that phosphorous addition may also have been intentional. We have some evidence for this based on observations recorded during the detailed travels of an early British explorer by the name of Buchanan. In his detailed description of steel making at Devaraya Durga in Karnataka in the eighteenth century, Buchanan describes an Indian *wootz* steel making furnace. According to Buchanan, conical clay crucibles were filled with a specific amount of wood, from the barks of a plant *cassia auriculata*, pieces of wrought iron, then sealed and fired. Interestingly, the bark of this plant contains a high content of phosphorus, extracted by osmosis from the ground.

Manufacturing methodology

The Iron Pillar weighs almost six tons! It is even now a real challenge to manufacture such a large object. Therefore, given the time period of manufacture of the Iron Pillar, its construction must be considered a real engineering feat. Based on careful analysis of several aspects of manufacturing methodology gleaned from careful observation of the surface of the pillar, the following conclusions can be reached.

The starting material was iron lumps obtained from bloomery furnaces. They weighed between 20 and 40 kilograms. They were joined together by forge welding. This was the method used in ancient and medieval India to manufacture large iron objects. Forge welding is an operation in which iron lumps are joined together by forging them in the hot state (high temperature of about 700ºC to 900ºC) so that they fuse together. This process initially involves heating of the lumps to a relatively high temperature in a bed of charcoal in order to make them soft and amenable for deformation. One iron lump is then placed on top of another and force is applied in order to weld them in the solid state. As the force is dynamic in nature, it is called forge welding.

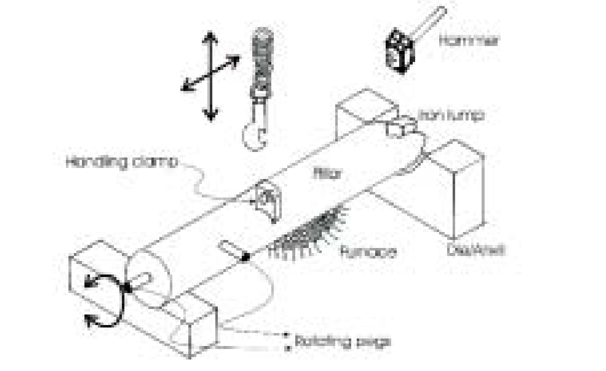


Fig.10: The side-way horizontal forge welding methodology of the Delhi Iron Pillar. The heated iron lumps were placed on the side surface of the pillar and hammered on to the same. The addition of metal would have been sideways with the pillar in the horizontal direction.

Fig.11:Decorative bell capital of the Delhi Iron Pillar: top

For manufacturing the pillar, the heated iron lumps were placed on the side surface of the pillar and hammered on to the same by the use of hand-held hammers. The addition of metal was sideways with the pillar placed in the horizontal direction. This is shown schematically in Figure 10. The pillar's vertical and horizontal movements would have been aided by handling clamps provided on the surface of the pillar, the protruding portion of which must have been chiseled away during the surface finishing operations. Visual proof for the presence of these clamps is available at two locations on the pillar. Finally, the surface of the pillar (that was supposed to be exposed) must have been smoothened by chiselling and burnishing the surface of the pillar, thereby providing it a smooth tapered cylindrical appearance. Finally, the Sanskrit words might have been inscribed on to the surface of the pillar using cold dies possibly heating the metal surface locally before inscribing on it. The decorative bell capital must have been finally fit on to the top portion of the Delhi Iron Pillar before its erection, possibly in the royal presence of *Chandra*.

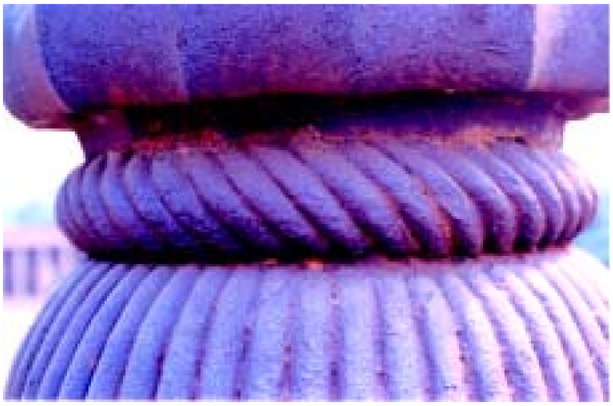


Fig.13: Details of the slanted rod structure above the reeded bell structure. Notice the presence of a black filling in between the joints.

Fig.14: The top of the pillar presently contains a hollow slot in which an image of *Chakra* must have been originally present. The presence of a circular cylinder of diameter 8", intersecting the surface, is evident.

Decorative Bell Capital

The top decorative capital of the Iron Pillar is a wonderful engineered structure. Notice its beauty and symmetry in Figure 11. The decorative bell capital consists of seven distinct parts. The bottom-most part is the reeded bell structure which has been manufactured by utilising iron rods of uniform diameter (Figure 12). Atop this comes the slanted rod structure. The presence of a black filling in between the joints can be noted (Figure 13). This filling has been identified as a lead-based solder. The next three members are rounded structures, with the top one being only half rounded because when the pillar is viewed from the bottom, this part would appear curved when viewed in perspective from the bottom. A round disc comes above this and finally the box pedestal is placed on the top of the capital. The box capital contains holes that are empty at the four corners and these could have been originally utilised for holding different animal figures, depending upon the season of the year. The top of the pillar presently contains a hollow slot (Figure 14) in which a *chakra* (discus) image must have been originally fit. Interestingly, the image of the Delhi Iron Pillar capital's box pedestal along with the *chakra* image is depicted in one of the Vishnu panels in cave 6 at Udayagiri (Figure 15) itself and this is the most forceful argument for the *chakra* image atop the Delhi Iron Pillar capital. The circular disc is also in tune with the cut that is seen on the top surface of the capital.

Fig.12: Decorative bell capital of the Delhi Iron Pillar: bottom

Corrosion resistance

The real fascination of the Delhi Iron Pillar is its remarkable characteristics of corrosion resistance in the atmospheric environment. We know that the pillar is at least 1600 years old based on the identification of Chandra of the Gupta-Brahmi inscription on the Iron Pillar with Chandragupta II Vikramaditya (375-414 AD).

Corrosion is a common menace, which eats away and eventually destroys metals and alloys by electrochemical attack. The rusting of ordinary iron and steel is the most common form of corrosion. Rusting takes place in moist air, when iron combines with oxygen and water to form a coating of brown-orange deposit, which in common parlance is termed as rust (hydrated iron oxide). The rate of corrosion increases where the atmosphere is polluted with sulphur dioxide. We come across the menace of rust in our day to day lives. Even modern cars and other gadgets are not spared from this menace. Salty road and air conditions accelerate the rusting of car bodies. It may be noted here that because of oxidation the extant articles made of iron in antiquity are extremely rare. We tend to live with rust even in modern times and take rusting for granted as a natural phenomenon. However it is baffling to note that the Iron Pillar has largely remained rustless for all these long years. Several theories have been proposed to explain the pillar's excellent corrosion resistance. They can be broadly classified into two categories: environmental and material theories.

The proponents of the environment theory state that the mild climate of Delhi is responsible for the corrosion resistance. It is known that atmospheric rusting of iron is not significant for humidity levels less than 70 per cent.

That the environmental theory may not be important is attested by the presence of ancient massive iron objects

Fig. 15: Vishnu of cave 6 at Udayagiri. (Photo: Ellen M. Raven)

Fig.16: Iron beams in Konarak Sun temple placed on supports in the courtyard.

Fig.19: The forge welded iron cannon at Thanjavur, called *Rajagopala*

located in areas where the relative humidity is high all round the year. Good examples for this case are the iron beams in the Jagannath temple at Puri, the Sun temple at Konarak (Figure 16) and the iron pillar at Adi-Mookambika temple at the Kodachadri Hills (Figure 17). Puri and Konarak are situated on the western coast of India while Kodachadri is on the eastern coast. The distance from the location of these massive iron objects to the actual seacoast is less than 20 kilometres, thereby implying that these iron objects are constantly subjected to a saline environment due to proximity to the seacoast. There are other examples of massive iron objects in several other parts of the Indian sub-continent that have successfully withstood atmospheric corrosion. These

Fig.17.: Iron pillar at Kodachadri Hills

include the iron pillar at Dhar (Figure 18) and the numerous large forge-welded iron cannons scattered all over the Indian sub-continent. Two examples are the 22 ton Rajagopala cannon at Thanjavur in Tamil Nadu (Figure 19) and the 20 ton Dalmardan cannon at Bishnupur in West Bengal (Figure 20).

Advocates of the materials theory stress the construction material's role in determining corrosion resistance. The ideas proposed in this regard are the relatively pure composition of the iron used, presence of phosphorus, and absence of sulphur and manganese in the iron, its slag particles, and formation of a protective passive film. There are also less-widely held theories about the pillar's corrosion resistance. These suppositions include: the mass metal effect, initial exposure to an alkaline and ammoniacal environment; residual stresses resulting from the surface finishing (hammering) operation; freedom from sulphur contamination both in the metal and in the air; the "cinder theory", which holds that layers of cinder in the metal stop corrosion from advancing; and that surface treatments of steam, and slag and coatings of clarified butter were applied to the pillar after manufacture and during use, respectively. The use of surface coatings is readily discounted because a freshly exposed surface attains the colour of the rest of the pillar in about three years time.

Scientific research by the writer has revealed that the

Fig.20: The forge welded iron cannon at Bishnupur, called *Dalmardan*

excellent atmospheric corrosion resistance of the Delhi Iron Pillar is due to the formation of a protective passive film on the surface of the pillar. In other words, the Iron Pillar does rust, but the passive rust is protective and thin such that significant rusting is not realised. Philosophically, this is very akin to the protective clothing that one wears in the cold season. The jacket or sweater, that one wears when the mercury dips down, "prevents" the body heat from being dissipated and, therefore, keeps the person warm. In a similar manner, the protective passive film on the surface of the pillar does not allow corrosion of the underlying metal of the iron pillar, by preventing moisture from contacting the bare metal surface. The relatively high phosphorus content of the Delhi Iron Pillar plays a major role in aiding the formation of the protective passive film.

The rust layer becomes increasingly protective—and the rate of corrosion decreases—as its composition changes. In the initial stages, the rust comprises lepidocrocite and goethite. These forms of rust do not offer excellent protection and, therefore, the rate of corrosion is still maintained on the high side. Conversion of part of this rust to magnetite does result in lower corrosion rates. However, cracks and pores in the rust allow oxygen to diffuse and complementary corrosion reactions to occur. Moreover, reduction of lepidocrocite also contributes to the corrosion mechanism in atmospheric rusting.

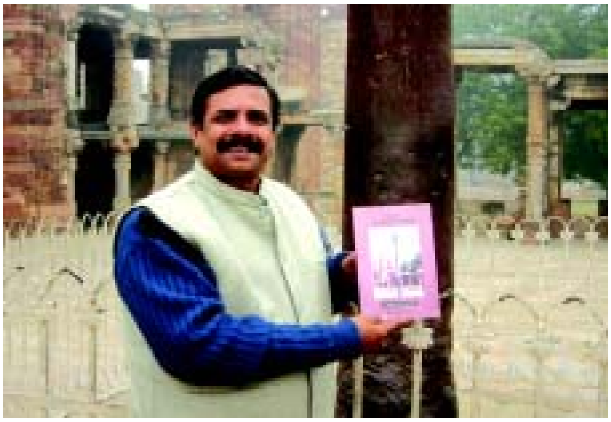
When viewed from a nonscientific standpoint, the Delhi Iron Pillar's ability to resist corrosion has often been called a "mystery". This notion must be dismissed. There is nothing mysterious about the Iron Pillar. The remarkable corrosion resistance can be understood by applying the basic principles of corrosion research. The direct reduction technique used to produce the iron is no mystery, either. The established scientific facts notwithstanding, there is one aspect that is not well understood and this may be called a mystery, in one sense. This is the method by

Fig.18: Dhar iron pillar

which the iron lumps were forge-welded to produce the massive six tonne structure.

On to the future

India is again on the forefront of steel making as is very much evident by the stellar rise of the Indian steel magnate - Laxmi Mittal. It is time that we also paid more careful attention to the Delhi Iron Pillar, which serves as a guidepost for metallurgists in the twenty-first century and beyond. It is hoped that research on the Iron Pillar will motivate others to explore the potential uses of phosphorus containing iron. There are so many wonderful options available with phosphoric irons. The iron-phosphorus alloys deserve as much attention as the more popular iron-carbon alloys (steels). There is an exciting future in developing phosphoric irons, particularly for corrosion scientists and engineers. The beacon of light showing the way to the future is the Delhi Iron Pillar, with its tested proof of corrosion resistance.■



Professor R. Balasubramaniam holding a copy of his book on the Iron Pillar

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