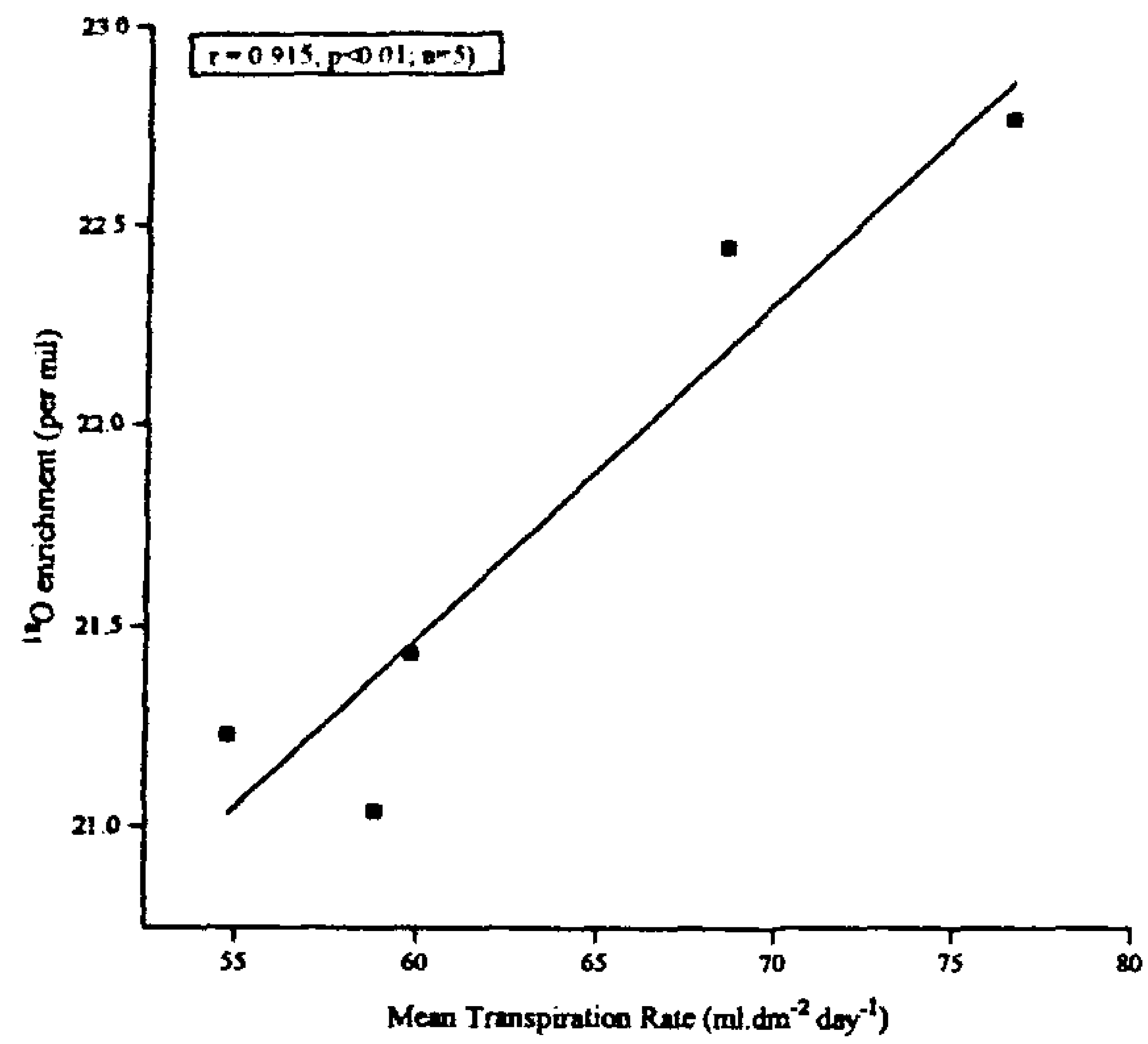

Figure 2. Relationship between ^{18}O enrichment in leaf biomass and mean transpiration rate in contrasting cowpea genotypes. The daily water loss over a period of 25 days (30–55 DAS) was summated to arrive at the total water loss. The MTR was computed from the ratio of the total water transpired to the total functional leaf area retained during the experimental period. Each value is an average of at least three replicates.

oxygen isotopic enrichment occurs in leaf water due to g_s (Figure 1). The mean transpiration rate (MTR) derived based on gravimetry on the day of leaf water extraction also recorded a similar linear relationship with leaf water ^{18}O ($r = 0.83$; $p < 0.005$; $n = 7$). The enriched ^{18}O finds its path into the cellulose through a metabolism leading to its synthesis[7]. Therefore, the ^{18}O composition in leaf biomass can be considered as a reflection of the ^{18}O enrichment that occurred over an extended period of time.

Dried leaf powder of the cowpea genotypes was analysed for the ^{18}O composition by on-line pyrolysis at the PDZ-Europa, UK, using an IRMS (*Geo 20-20*). The ^{18}O composition in biomass also showed a significant positive relationship with mean transpiration rate (Figure 2). These results clearly suggest that, the variations in the ^{18}O enrichment that occur in leaf water are due to differences in T and ^{18}O in leaf biomass can be effectively used as a powerful surrogate for the time integrated estimation of transpiration rate and g_s. Although an increase in ^{18}O in leaf water as influenced by environmental variables like vapour pressure difference (VPD) has been reported[8], our results suggest that despite such confounding factors, this technique can be employed for the determination of T and g_s. Further, we show here, for the first time, that the mean transpiration rate is related to the ^{18}O enrichment in leaf biomass and the genetic variability in T and g_s can be quantified by the ^{18}O enrichment technique. Besides this, the observed differences in ^{18}O enrichment can also be used to ascertain whether stomatal factors or the mesophyll capacity brings about the genetic variability in WUE[2]. This could significantly help efforts to improve WUE.

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The iron pillar at Kodachadri in Karnataka

The historical iron pillars at Mehrauli, Delhi, and at Dhar, in Madhya Pradesh, have attracted the attention of scientists for over a century and have been the subject matter of many publications (e.g.)[1–4]. However, a third iron pillar located in *Ādi-Mookāmbikā* temple at Kodachadri village in a remote forest area of the Western Ghats in Karnataka has not received much scientific attention so far, partly because the concerned village is difficult to reach and partly because the pillar itself is not as massive and imposing as the Delhi and Dhar monuments. Even the Dhar pillar too has not been subjected to systematic scientific and archaeo-historical studies like the Delhi pillar. In fact, two books have already appeared[5,6] on this pillar, dated to mid-Gupta period (~ 375 A.D.) and located in the vicinity of the still more famous Kutub Minar.

Propelled by scientific curiosity as well as deep interest in India's glorious metallurgical heritage, the present author embarked on the adventurous journey to Kodachadri twice during the last eighteen

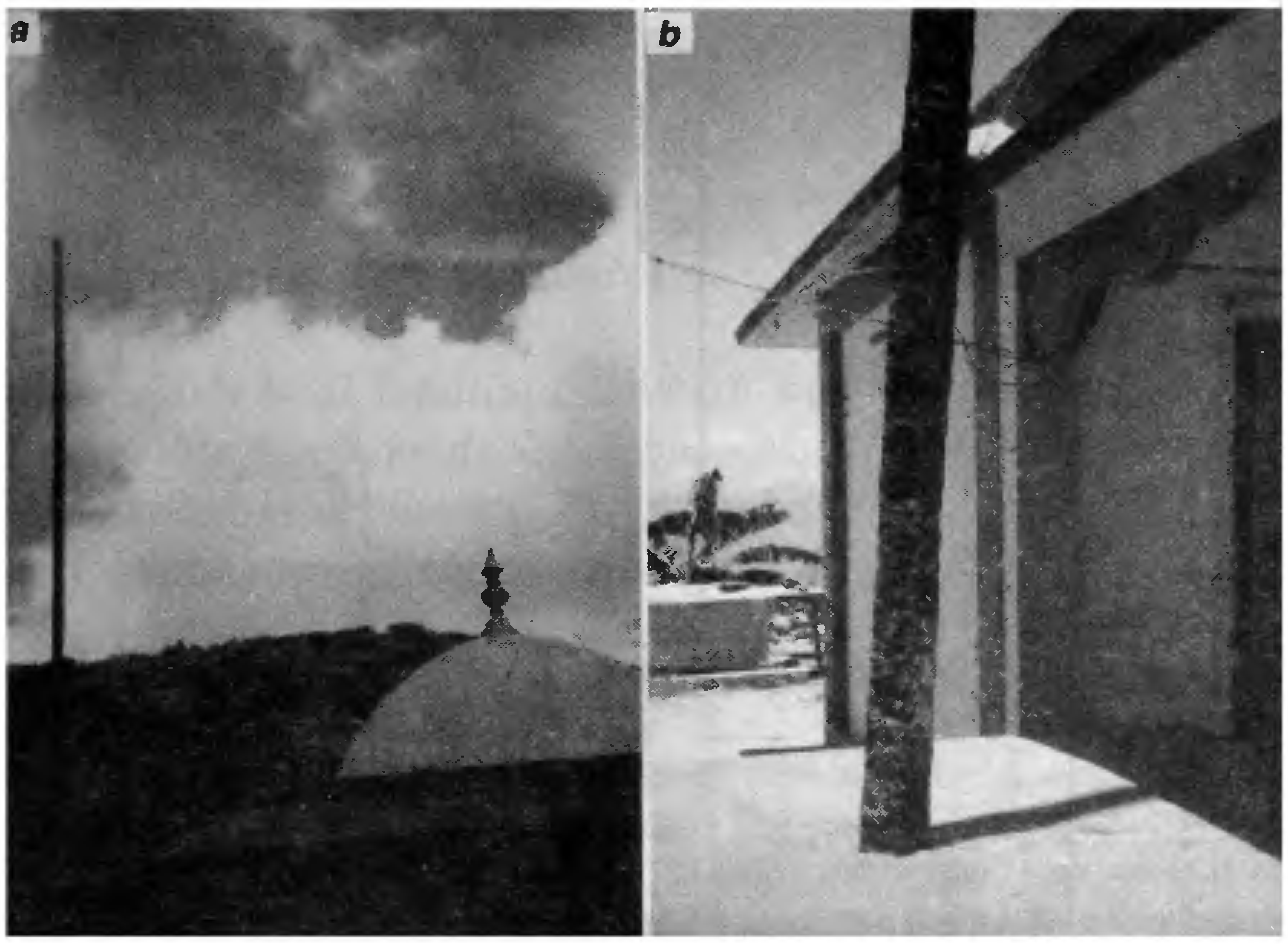

Figure 1. Different views of the Kodachadri pillar. ***a***, View of *Ādi-Mookāmbikā* temple's top from afar, with the iron flag-staff (*Dwaja-Sthamba*) towering above, the lush forest providing the backdrop. ***b***, View of the rugged surface of the pillar, highlighting the rectangular cross-section with serrated appearance above the platform.

months and undertook some preliminary studies on the material constituting this long-neglected pillar with assistance from fellow-metallurgists at the Karnataka Regional Engineering College, Surathkal; and the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam. Results of these studies, as presented here, confirm the unanimous view of the local residents that this pillar is a product of an earlier period in indigenous iron making, and therefore deserves a detailed and serious study by scientists and technologists devoted to India's metallurgical heritage.

Popularly referred to as the *Dwaja-Sthamba* (flag-staff) of the *Mookāmbikā* temple, the Kodachadri iron mast or pillar has long been associated in the minds of most scientists, particularly metallurgists, with the pilgrim centre of Kollur, a town located in the plains, about 120 km north of the well-known port city of Mangalore in South Canara District of Karnataka. This temple with claims to be the *original Mookāmbikā* temple is associated with the killing of the dumb (*mooka*) demon *Mookāsura* by the lion-riding Mother Goddess *Ambikā* in the adjoining forests, where the demon was disturbing the penance of sages and holy men devoted to the Goddess. Today Kodachadri can be reached from Kollur by jeep on a 40 km long winding and slippery mud road with many hairpin bends, often submerged in water during the rainy season lasting from April to November. The iron flag-staff towers above the small temple (Figure 1 *a*) and can be sighted a few kilometers away on the road, while approaching Kodachadri. If local lore is to be believed, this flag-staff is actually the top portion of the *Tri-Shūla* (trident) with which the Mother Goddess nailed down the wicked demon into the bowels of the earth!

The temple top has been recently renovated, somewhat on modern lines with brick, cement and distemper (Figure 1 *a*, *b*), and a platform has been added ostensibly to stabilize the pillar, but with possible un-thought-of and undesirable interactions in due course between the cement of the platform and the iron of the pillar. Rising not less than 10 m above the ground level, with a rectangular cross-section of 8.5 cm × 5.8 cm and characterized by rough, serrated and slightly reddish surface (Figure 1 *b*) the pillar displays evidence on top for local melting, flow of melt and solidification, caused by lightning during the monsoon period. Allowing for a total height of 14 m, including the hidden portions in the platform and below the earth, the weight of this flag-staff can be estimated as about 500 kg.

A very small piece weighing a few grams only was extracted from the projecting rough surface of the pillar with the consent and cooperation of the temple priest and was later subjected to a series of modern metallographic tests at the Materials Characterization Laboratories of the Indira Gandhi Centre for Atomic Research, Kalpakkam. To the author's surprise, the X-ray examination could not reveal definite presence of any element or compound besides pure iron (Figure 2 *c*), while the microscopic study revealed only grains of iron (Figure 2 *b*) with very little pearlite (eutectoid of iron and Fe_3C, i.e. iron carbide generally referred to as cementite). However, a few greyish and many rather large dark inclusions (Figure 2 *a* and *b*) were noticed and could be subjected to microhardness testing and electron microprobe analysis. While the small globular inclusions could be identified as iron silicate containing some calcium (Ca) and phosphorus (P), the bigger irregular-shaped ones consisted of only iron oxide (Fe_2O_3) with traces of other elements like silicon (Si), calcium (Ca) and phosphorus (P). The VHN microhardness numbers were around 140 for the iron grains, about 155 in the pearlite-cum-matrix areas, and around 165 in the dark inclusions. From image analysis, the volume fraction of all the inclusions was estimated as less than 2.0%. It was not possible to arrive at the exact volume fraction of the greyish pearlitic area, but assuming it to be around 1.0%, the carbon content of the pillar iron can be estimated as definitely less than 0.05%.

It is obvious from these preliminary investigations that the Kodachadri iron pillar is *not* a product of modern iron making processes. The composition of the material of the pillar, viz. less than 0.05% carbon in what looks like almost pure iron, without the usual silicon, manganese and sulphur contents one associates with modern iron and steel, and with inclusions of only iron oxide and silicate, strongly suggests age-old indigenous methods for making the so-called *Ādi-vāsi* (tribal) iron with pure iron ore and wood charcoal. The fact that this pillar has withstood the onslaught of the sun, wind and rain in living memory,

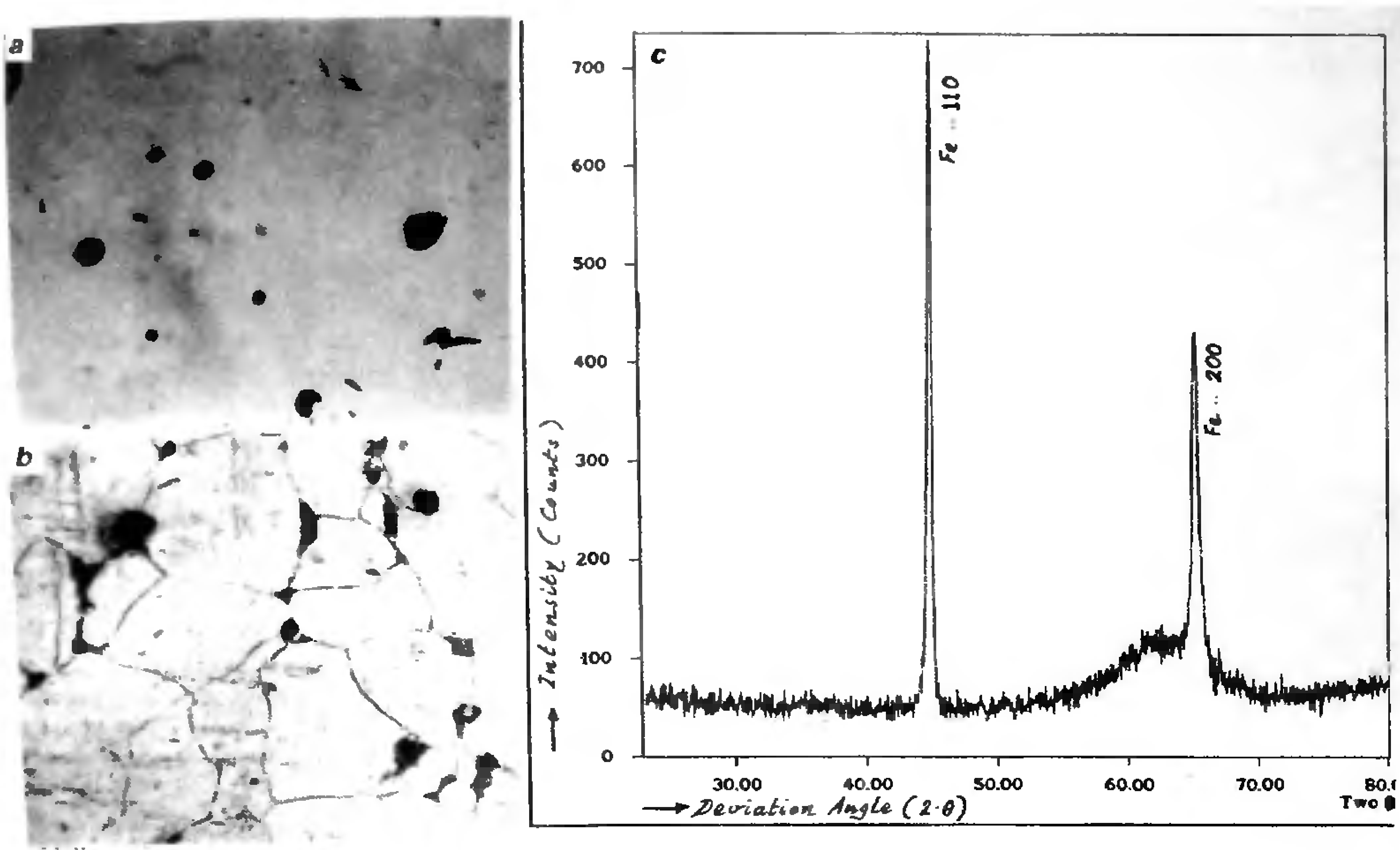

Figure 2. Results of metallographic studies on a small piece from the pillar. Photomicrographs ***a*** (× 150) and ***b*** (× 700) showing presence of only grains of iron with very little pearlite. A few greyish and many rather large dark inclusions are noticed as well. ***c***, X-ray diffractometer record showing the strong 110 and 200 reflections from iron.

and perhaps also of marine air with the Arabian Sea only 40–50 km away, is proof of its high corrosion resistance, even though its surface is not as smooth and clear as that of the Delhi pillar. Acting as a lightning arrester during the rainy season, the top of the pillar seems to have melted frequently and perhaps *rapidly* solidified through removal of heat by iron from the pillar itself. A metallographic study of this part of the pillar is bound to yield some interesting results.

The data reported here, although from a very small piece of the pillar, point to the need for a more thorough and systematic scientific, technological and archaeo-historical study of this iron mast, towering alone in its majesty in a remote hilly and forest area of Karnataka.

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