2.5 m/s, 12.5 m/s, 230 kW, 10 m/s and 140 kW, *n* is calculated to be 2.13. The wind speed data presented in Figure 8 are at 10 m height and the WEG machine rotor is at 48 m and the data are only at lower wind speeds compared to the rated wind speed.

In conclusion, the performance of the wind farm of 18 WEGs near Chitradurga, Karnataka is analysed using field data from the farm. The period considered is from April 2005 to March 2012. The average plant load factor for the period under study is 34.68. The monsoon season seems good for electricity generation from the wind farm. From April 2005 to March 2012, roughly 86.7 GWh of electricity is generated in this farm and supplied to the grid. Assuming that 1000 g of CO_2 is liberated from a coal thermal plant during production of 1 kWh of electricity, roughly 86.7 kilo tonnes of CO_2 is prevented from entering the atmosphere. Our study shows that Chitradurga has high potential for generation of power from wind energy.

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ACKNOWLEDGEMENT. A.C. thanks DST, ISRO and MoES for funding this research.

Received 4 September 2012; revised accepted 6 February 2013

Two thousand years of iron smelting in the Khasi Hills, Meghalaya, North East India

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Radiocarbon dating of charcoal from iron slag revealed evidence of continuous iron smelting in the Khasi Hills, Meghalaya, NE India spanning the last two millennia. The slag layer, which is dated to 2040 ± 80 years BP (353 BC–AD 128), is the earliest iron smelting site studied in the entire region of NE India. The presence of wüstite, fayalite, glass and metal iron, together with spinels such as hercynite in the slag, indicates that it was an acid product of a bloomery iron-making process. The relative isolation of the Khasi people, who inhabited a highly elevated plateau, is evidence of the indigenous origin of this manufacturing technology, although diffusion of knowledge through cultural and technical contacts or population migration cannot be excluded.

Keywords: Ancient metallurgy, furnace, iron slag, radiocarbon dating.

THE discussion on the early development of iron metallurgy in India has been shaped by two primary concepts. The first assumed a diffusive spread of iron smelting technology related to the migration of the Aryans, an Indo-European speaking people, who entered the Indian subcontinent from the northwest[1–3]. The second concept postulates that there was an independent origin and development of iron-ore mining, extraction and manufacturing technology, founded on the raw materials that were contemporaneously available in India[4–7].

However, in both cases, North East (NE) India was not taken into consideration. The reason for this was the difficulties involved in archaeological exploration of areas of hilly terrain with frequent heavy rain and dense vegetation cover, as well as evidence of the strong material, linguistic and genetic connection of the region with cultures of East Asia and Southeast Asia, at least from the Neolithic period[8–10]. These are clearly visible in the case of the central part of Meghalaya, which is inhabited by the Khasi, an Austro-Asiatic speaking people, representing the remnants of an ancient migration from Southeast Asia[11,12].

No demonstrable archaeological evidence of the Iron Age in Meghalaya has yet been found, although the first

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British naturalists who visited Meghalaya in the early 19th century described the iron industry that had developed in the upper part of the Khasi Hills[13–17]. The remnants of former iron-ore excavation and iron manufacturing, visible today in the landscape of the Khasi Hills, indicate that it could be the result of prolonged occupation by the Meghalaya inhabitants. Metallurgical tradition was also accompanied by the erecting of megalithic memorial monuments, bearing similarities to other megalithic sites in India frequently associated with the Copper–Bronze or Iron Age[18,19].

The aim of this communication is to estimate the temporal extent of iron smelting in the Khasi Hills and to present an analysis of the technological process of iron production development during that time. This study integrates field observations with laboratory analysis of samples from the raw materials and products, supplemented by reconstructions based on historical reports of iron smelting given by eye witnesses from the early 19th century.

Meghalaya is one of the rainiest inhabited environments on earth, with more than 11,000 mm of precipitation recorded annually in Cherrapunji[20,21]. This small state is a hilly plateau uplifted to about 1900 m above the Bengal Plain in the south and the Brahmaputra valley in the north (Figure 1). The basement of the plateau is formed by gneisses and quartzites with granite intrusions representing a source of iron-ore[22–24]. The upper part of the plateau in the Khasi Hills, 1000 m asl, is deforested, severely eroded and overgrown by grass[25]. Only the small patches of broadleaved hill forest (sacred groves) that remain, protected through the ages by the people for religious and cultural reasons, are evidence that the plateau must once have been covered by forest in the past[26].

Historical reports from the British administration of the Khasi Hills were used as sources of information concerning the spatial distribution of iron metallurgy sites in the

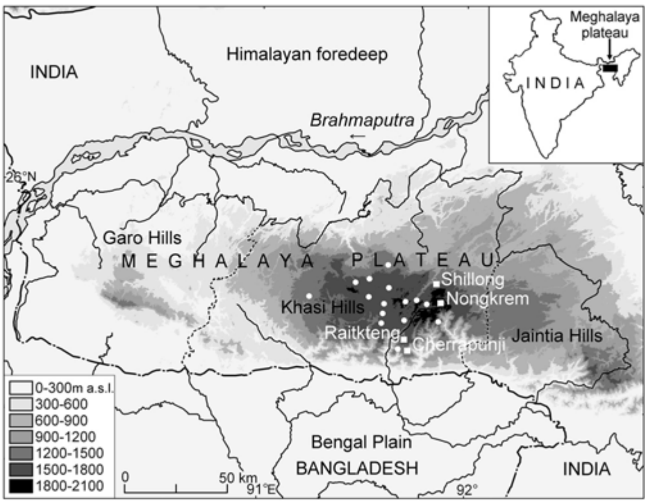

Figure 1. Location of the Khasi Hills in Meghalaya. Distribution of sampling sites (white squares) and other sites of iron smelting (white dots) is indicated on the basis of reports from the 19th century[13–17].

early part of the 19th century[15–17]. Sediments containing ferruginous sand, clay tuyeres and iron slags were collected from four sites at different depths, either from exposed sections or by digging trenches, during extensive fieldwork covering about 1000 km^2 and carried out between 2007 and 2010 (Figure 2).

The absolute grain size composition of the sediment was determined using the combined sieving method and a Fritsch Laser Particle Sizer Analysette 22. Charcoal was extracted from some iron slags for dating at the Poznan AMS Radiocarbon Laboratory and conventionally at the Absolute Dating Radiocarbon Laboratory in Krakow, Poland. Calibration of the radiocarbon dates (expressed as cal years BC/AD time intervals with a probability of 95%) was carried out using the calibration dataset IntCal09 and OxCal (version 4.1) calibration program[27].

The wet chemistry method was used for chemical composition analysis of iron-ore deposits. In order to study the microstructure of the slags, polished sections were prepared and the microstructure of the samples was examined using an Axio Carl Zeiss optical metallographic microscope. Compositional analyses were performed on a Hitachi S-3500N scanning electron microscope with an energy dispersive spectroscopy (EDS) Noran microanalytical device and X-ray diffractometer PANalytical EMPYREAN 2.

The principal source of iron-ore in the Khasi Hills were the granite outcrops. The ore, primarily titaniferous magnetic oxide ($Fe^{2+}(Fe^{3+},Ti)_2O_4$), is a colluvial sand that results from the weathering of granite. Wet chemical analysis of colluvial sand from the granite area in Nonkgrem, the most important centre of iron-ore extraction[15], indicates that it contained 10–12% by weight of iron oxides (FeO, Fe_2O_3). The operation of washing the decomposed granite in local streams enriched the content of iron oxides up to 35% by weight. About 65% by weight constituted gangue silicate minerals, which were mainly quartz and potassium feldspar.

The only fuel used for smelting was charcoal. The best charcoal was produced from local oak species, but in cases where there was a lack of a hardwood other kinds of trees were used for carbonization[16]. The smelting was performed in above-ground bloomery furnaces that could hold 0.3–0.5 m^3 of ore and charcoal in alternate layers. The fire inside was blown by large bellows, from which the air was conducted by kaolin clay tuyeres. The temperature inside the furnace was controlled by regulating the rate of operation of the bellows.

Most interesting from the technological point of view was the intentional preparation and use of slag-ore lumps. Analysis of sections indicates that it contained slag core wrapped up with a mixture of iron-ore and charcoal, which was heated before smelting in the furnace. The slag core additionally favoured the scorification of the gangue, thereby increasing the efficiency of the metallurgical process.

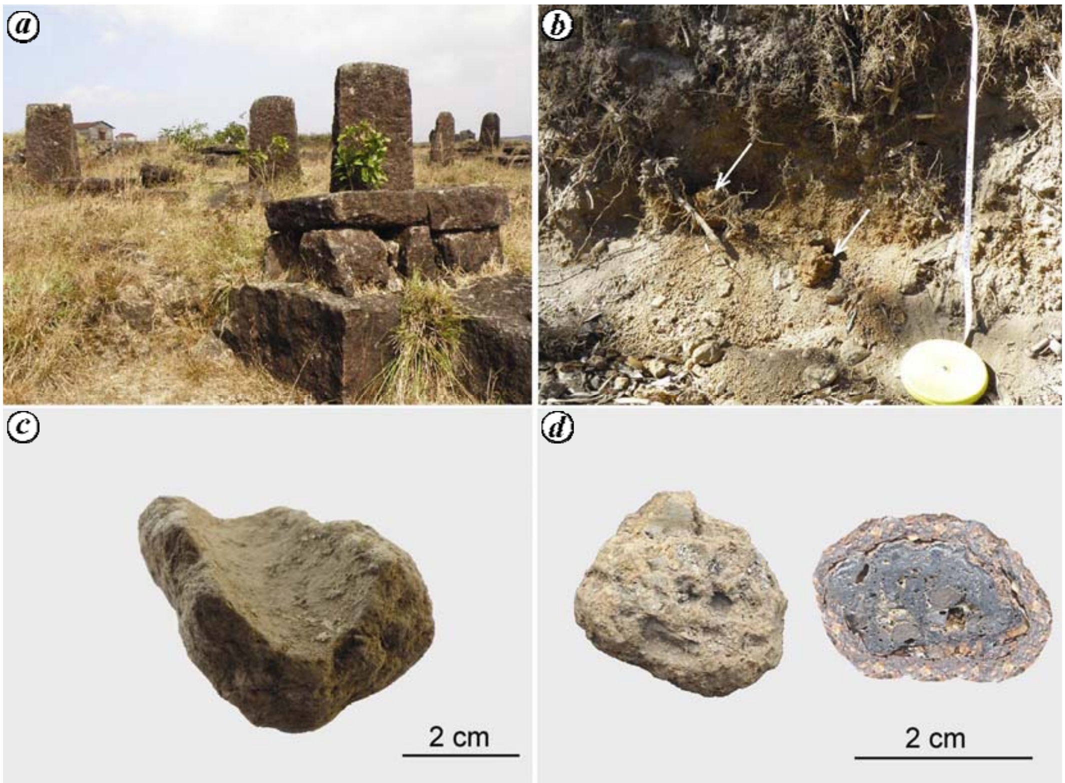

Figure 2. Components of iron smelting in the Khasi Hills during the Iron Age: ***a***, megaliths; ***b***, iron slag (indicated by arrows); ***c***, tuyere; ***d***, slag-iron-ore lump and its section.

The hot porous mass of iron, extracted from the furnace, was immediately shaped into circular lumps and then split into two with an axe. The split was opened by a couple of wedges and the hot mass was inserted into a trough full of pounded dross to cool. The weight of the lump obtained during a single smelt reached about 6.5 kg. The technology applied permitted up to 15 smelts daily from the same furnace[15,17]. In most cases, the crude iron, as obtained from the smelting furnaces, was taken to market or carried to other villages, where it was manufactured into tools. The lumps were placed in the fire and after eight re-heatings and beats, a new tool was formed. The loss of weight arising from impurities of the iron as it comes from the smelting reached about 43% (ref. 17). The manufacturing of iron by the bloomery process generates substantial quantities of waste products in the form of slag.

Traces of the iron industry are still visible in the Khasi Hills as deposits of washed sand with charcoal, clay tuyeres and slag. Lithological analysis of deposits containing iron slag, combined with radiocarbon dating of charcoal from four sites scattered in the upper part of the plateau, helped determine the temporal range of iron smelting (Figure 3, Table 1). However, it is important to note that because of the effects of high rainfall, settlement development and road construction, most of the originally deposited remnants of former iron smelting have been destroyed or re-deposited. Therefore, only a few sites located in areas with less rainfall, mainly between Shillong and Nongkrem, are valuable for continuous reconstruction of metallurgy development in the Khasi Hills.

The Shillong site (27°37′09″N, 91°53′49″E, 1500 m asl) is located within the quartzite area on the top of an elongated hill. Several slags up to 20 cm in size were scattered on the surface of a cultivated field over an area of tens of square metres. Remains of a broken quartzite megalith were visible near the investigated site. Excavation up to the quartzite bedrock did not reveal any traces of iron smelting below ground level.

The Nongkrem site (25°29′34″N, 91°52′54″E, 1750 m asl) is located within the granite area in the valley bottom. This is the main centre of the former iron-ore excavation[15,17]. The section cut by an adjacent road exposed washed sandy deposits containing charcoal and several layers of slag with broken clay tuyeres. The upper part of the section has a well-developed soil horizon about 50 cm thick. The middle part of the section, up to a depth of 240 cm, is loamy sand with gravels and layers of slag with diameter between 1 and 10 cm. The charcoal extracted from the slag layer at a depth of 80 cm was dated at 245 ± 25 years BP. The lower part is a coarse-grained weathered cover *in situ* along with partially weathered granite boulders. Several iron slags reaching

Table 1. Radiocarbon dates of charcoal extracted from iron slag and sandy colluvial deposits at the Nongkrem and Raitkteng sites in the Khasi Hills

Site	Sample	Depth (cm)	Age ^{14}C (years BP)	Calendar age 2σ (BC/AD)	Dating context
Nongkrem	N6/1	80	245 ± 25	AD 1527–1552 AD 1633–1673 AD 1777–1800 AD 1941–1954	Charcoal from iron slag layer covered by soil and colluvial sand
	N6/3	270	2040 ± 80	353–295 BC 229–220 BC 211 BC–AD 128	Charcoal from iron slag layer located within *in situ* weathered cover
Raitkteng	R4/2	12	240 ± 60	AD 1480–1698 AD 1725–1815 AD 1835–1878 AD 1916–1955	Charcoal from the top of the extensive slag layer covered by skeletal soil
	R4/4	55	1110 ± 30	AD 880–1014	Horizon of charcoal indicating phase of deforestation

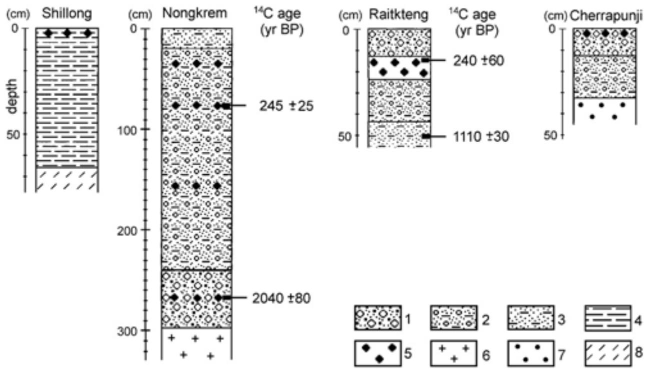

Figure 3. Lithostratigraphy of profiles with iron slag at four sampled sites in the Khasi Hills. 1, Sand with gravel; 2, Loamy sand with gravel; 3, Loamy sand; 4, Loam; 5, Iron slag; 6, Granite bedrock; 7, Sandstone bedrock; 8, Quartzite bedrock.

15–20 cm in diameter were found at a depth of 270 cm. Charcoal extracted from one of these slags was dated at 2040 ± 80 years BP.

The Raitkteng site (25°18′00″N, 91°42′40″E, 1450 m amsl) is located within a sandstone area at the base of a small hill overgrown by grasses. A section is exposed by a local sand–clay quarry. The skeletal soil covers a 10 cm thick slag layer, stretching over an area of at least several hundreds of square metres. The radiocarbon age of charcoal extracted from the top of this layer was determined to be 240 ± 60 years BP. The bottom of the profile presents loamy sand with a horizon of charcoal dated at 1110 ± 30 years BP. Relatively large charcoal particles up to 0.5 cm in size probably indicate the main phase of deforestation.

The Cherrapunji site (25°16′12″N, 91°44′15″E, 1300 m amsl) is located within a sandstone area at the base of a small hill overgrown by grasses. Several sandstone megaliths are scattered in the neighbourhood. Many slags up to 20 cm in size were found over an area covering tens of square metres. Excavation up to the sandstone bedrock did not yield traces of iron smelting below ground level. The Cherrapunji location, similar to the Raitkteng site, was probably one of the main iron smelting centres in this region[15,16]. However, in the 19th century, slag deposits from both sites were used as material for construction of the Cherrapunji–Shillong road.

Slags are the most abundant and best-preserved product of traditional iron smelting and thus are a staple of archaeometallurgical research in the Khasi Hills. Their composition and structure are closely related to the materials used and the conditions of the metallurgical process.

The samples from the Shillong and Raitkteng sites represent tap slags, as indicated by the smooth surfaces and pronounced flow structures, composed of multiple fingers of tap slag welded together (Figure 4); evidently, it was very fluid.

The samples from Nongkrem and Cherrapunji are from the lower part of the furnace and are extremely inhomogeneous, incorporating numerous inclusions of unreduced or partially reduced ore. Evidently, it was not very fluid at furnace temperatures, because the surfaces are rough and broken surfaces show many cavities from entrapped gas. The slag was rapidly chilled producing very fine structure throughout.

In a thin section, slags from Shillong, Raitkteng and Cherrapunji are almost entirely composed of fayalite (Fe_2SiO_4) in a glass matrix, with dendrites of wüstite (FeO). Wüstite dendrites differ in size reflecting local diversity of slag crystallization. Within the fayalite, hercynite ($FeAl_2O_4$), fusible eutectics ($FeO–Fe_2SiO_4$), mullite ($Al_6Si_2O_{13}$) and occasional iron droplets were also crystallized. As the slags contain abundant hercynite, the ore must also have contained alumina or aluminosilicate clay minerals in particles too small to be visible in a thin section. Analysis shows that tuyeres were produced from kaolin clay with quartz sand and heated at low temperatures, making possible the poor transition of kaolinite into mullite.

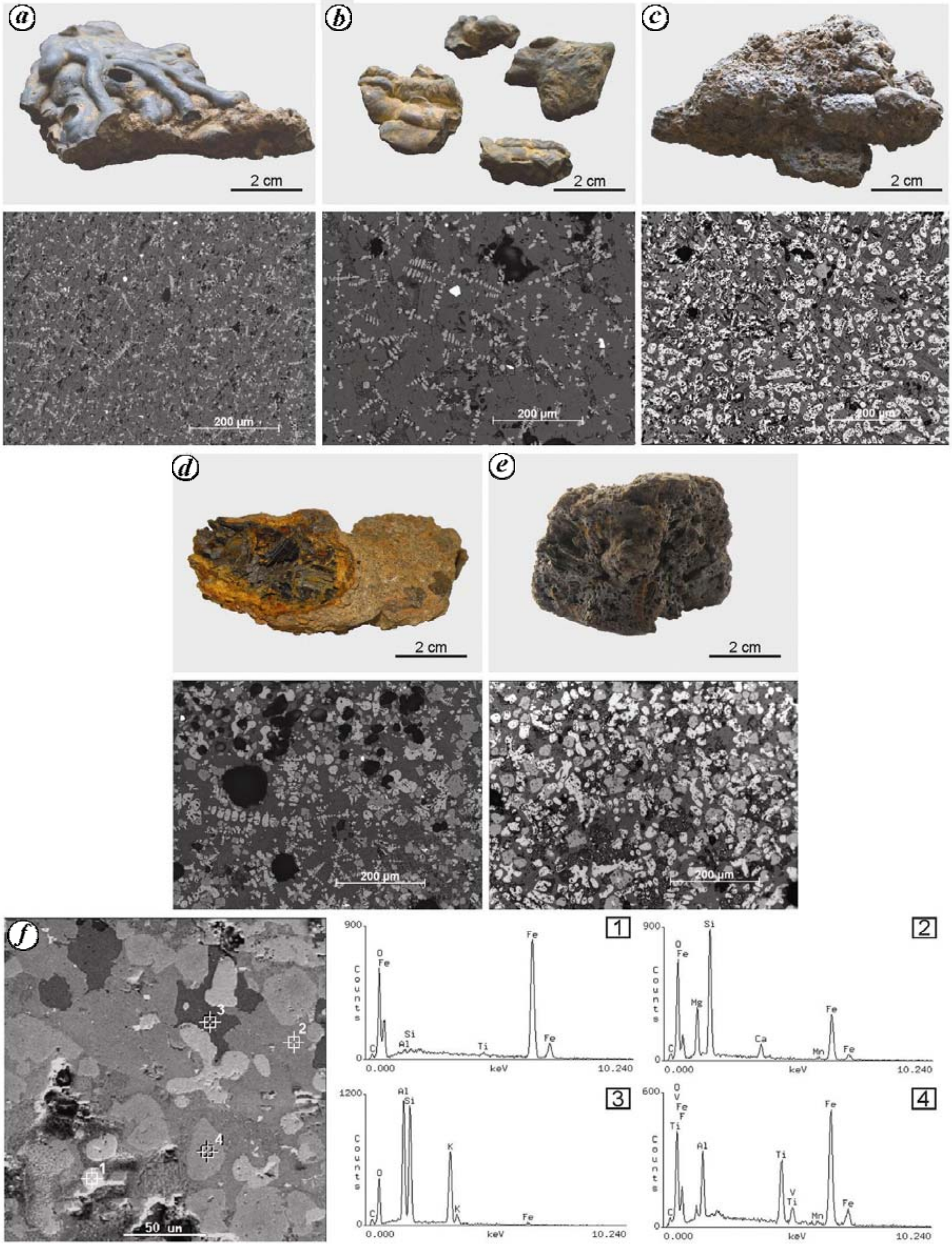

Figure 4. Iron slag (upper photographs) and its microstructure (lower sections) at four sampled sites: ***a***, Shillong; ***b***, Raitkteng; ***c***, Cherrapunji; ***d***, Nongkrem (N6/3 sample dated at 2040 ± 80 years BP); ***e***, Nongkrem (N6/1 sample dated at 245 ± 25 years BP); ***f***, SEM image of Nongkrem sample N6/1 and its EDS spectra (1–4). Microstructures: pores–black, fayalite–light grey, silica–glossy areas in fayalite, wüstite–bright dendrites, mullite and hercynite–dark grey and white structure–metallic iron.

The slag from the Nongkrem site has a more complicated microstructure. Iron oxide (56–67% FeO) and silicon oxide (up to 20% SiO_2) are predominant in all the slags with an increased contribution of titanium (TiO_2) in the presence of other phases (Figure 4*f*: 1–4; Table 2). Apart from fayalite and dendrites of wüstite, visible

Table 2. Energy dispersive spectroscopy compositional data (wt%) for smelting slags from the Nongkrem site

Sample	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Fe_2O_3
N6/1	1.66	9.88	20.42	1.39	3.10	4.15	3.43	55.96
N6/3	–	11.37	19.63	–	1.05	1.19	–	66.75

phases have also been identified using the EDS method as a composition of Ti–Fe–O, Fe–Al–O (Figure 4*f*: 4) and Al–Si–K–O (Figure 4*f*: 3).

Evidence of substantial bloomery smelting has been found in the appearance, microstructure, composition and excavation context of slag, charcoal and tuyeres, as well as in the surviving 19th century descriptions of iron manufacturing in the Khasi Hills. Iron was produced in the Khasi Hills over the last two millennia. The Nongkrem site, one of the main sources of iron-ore, was continuously in use for smelting from early in the 1st century AD to the middle of the 19th century. The continuity of iron production is confirmed by thick deposits of washed sand with several layers of slag, as well as radiocarbon dating of charcoal from the lowermost and uppermost layers of the slag. Similar features of sedimentation continuity reveal all deposits of colluvial sands with charcoal in this part of the Khasi Hills[24]. The location of the lower layer of slag almost on the granite boulders in Nongkrem, was dated at 2040 ± 80 years BP (353 BC–AD 128), making it the earliest studied iron smelting site in the Khasi Hills and consequently, in the whole of NE India. The direct reduction process of iron smelting declined after the advent of processes for making liquid steel on a large scale in the 19th century[28]. Official statistics shows that iron was the main export article from the Khasi Hills in 1858 (ref. 29), but it does not appear in the statistics prepared in 1876 (ref. 30). The low ore content in the granite rocks and consequent high cost of obtaining it, were additional factors in the rapid collapse of iron smelting in the plateau. This is also confirmed by radiocarbon dating of charcoal from the top slag layers in Nongkrem and Raitkteng.

The results of a study of chemical and phase composition and the microstructure of iron smelting slags, reveal that they are an acid product of a bloomery iron-making process. The process of iron-ore reduction is governed by objective physical, chemical and thermodynamic rules and cannot be unique by itself. It is carried on in the same material-energetic system: ore + reducer (charcoal, CO, H_2), at a suitable temperature. Therefore, despite covering such a vast expanse of land and spanning two millennia, there was little fundamental variability in the resulting products: bloomery iron and fayalitic slag. Specific to the iron smelters' skills are the materials used, metallurgical devices and the technology of the reduction process that influence the conditions of slag formation.

Metallurgical slag from the Khasi Hills reveals typical heterogeneity for ancient metallurgy, related to incomplete reactions following premature termination of the smelting process or local gradients in oxygen supply in the furnace. Further complications arise from post-process alterations, beginning with rapid oxidation and the rate of crystallization during the removal of liquid slag from the furnace (tapping)[31,32].

The microstructure and phase composition show that fayalite and fine wüstite dendrites are dominant components of iron slag. The presence of wüstite shows that an ideal operation was not attained and that more metal that could have been recovered in the smelting process[33]. Additional constituents such as hercynite and identified phases Ti–Fe–O, Fe–Al–O and Al–Si–K–O are derived from aluminium and titanium minerals in the ore. This kind of slag constitutes strong evidence for the practice of bloomery iron smelting in the Khasi Hills[34].

The study reveals that both the oldest and youngest analysed slags have high iron content of above 55% (Table 2), similar to slags from furnaces found in many parts of Eurasia[35]. We have no indication that any great changes in technology occurred during the 2000 years of Khasi iron-making. As long as supplies of charcoal and ore remained abundant and bloomery iron was the superior market product, it is possible that producers had no motivation to seek change. However, it is important to mention that as slag from previous blooms had high iron content, it was recycled in the form of slag-ore lumps into the furnace with new ore. This technological innovation has not been described in other areas of India so far.

Only a small portion of smelted iron was manufactured into tools, such hoes, hammers and arrow heads for the local market. The larger portion was transported in the form of impure lumps and sold in the Bengal Plain (today Bangladesh). There, in the villages along the rivers, iron was used for the production of nails for fastening the planks of boats[17]. Allen[29], using calculations from custom gates, estimated that the quantity of exported iron from the Khasi Hills was about 1700–2400 tonnes annually.

The smelting of iron in the Khasi Hills, which exceeded considerably the needs of the local inhabitants, shows standardization of manufacturing related to mass production in a seemingly efficient technological system. Standardization may be a sign of more established technologies, when the main engineering parameters have been locally modified and accepted by both producers and consumers[36].

The above evidence for bloomery smelting in the ancient Khasi Hills, throughout the last two millennia, raises important questions regarding its origin. Meghalaya is inhabited by two ethnic groups representing the remnants of Neolithic migration. It is assumed that the Khasi and Jaintia groups, belonging to the Austro-Asiatic language family, migrated from Southeast Asia and spread up to the lower Ganges around 3000 BC (ref. 11). Later on, the present-day population of the Garo group, belonging to the Sino-Tibetan language family, migrated southwards from their original homeland in China[37]. The archaeological record of this period and specifically, the shouldered celts and the cord-impressed potteries found in Meghalaya, confirm close affinity with the materials found in South China and Southeast Asia. However, there was no evidence of Copper–Bronze or Iron Age in Meghalaya, or any relationship to subsequent migration or cultural contacts with East Asia. In contrast, the Khasi and Jaintia groups had occasional contacts with the Indo-European speaking people living in the Bengal lowlands.

Iron technologies appeared in Southeast Asia around the 5th century BC (refs 38, 39). The production of iron by the bloomery process has led to suggestions that iron technologies were transferred by some means from the west or north[38,40]. Recent evidence shows that bloomeries were used in China, migrating from the West as early as the 8th century BC, before being replaced by the locally developed cast-iron production around the 4th century BC (ref. 41). Therefore, despite Neolithic migration of ancient farmers from the southeast to the Khasi Hills, the iron-making technology was probably invented independently or alternatively, could have been introduced from the West.

The relative isolation of the Khasi people, who inhabited a highly elevated plateau, suggests the indigenous origin of manufacturing technology. On the other hand, given their trade contacts with surrounding lowlands, one cannot exclude the possibility of the diffusion of iron-production knowledge, which is known to have reached the lower Ganges and Brahmaputra, close to the western border of the plateau, about 700 years BC (ref. 42). Diffusion of technological practices does not necessarily imply movement of people. However, several colonization waves in the Early Medieval Period forced local Austro-Asiatic language-speakers to move eastwards from the lower Ganges towards the surrounding Meghalaya lowlands[43].

Radiocarbon dating of charcoal and the results of chemical, microstructure and phase composition of iron-ore and slags, indicate that the smelting of iron in the Khasi Hills was initiated at least 2000 years ago and continued up to the middle of the 19th century. Large-scale metallurgic production was the response to the demand for iron from the adjacent lowlands, which did not have iron-ore resources.

Although we know when iron smelting first began to appear in the Khasi Hills, we do not know how the metal-workers came to possess knowledge of making iron. The relative isolation of the Khasi people, who inhabited a highly elevated plateau, is evidence of the indigenous origin of manufacturing technology. On the other hand, given their trade contacts with the surrounding lowlands, one cannot exclude the possibility of the diffusion of iron-production knowledge from the West.

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ACKNOWLEDGEMENTS. This paper is the outcome of a bilateral project agreed between the Indian National Science Academy and Polish Academy of Sciences. We thank Prof. S. Singh and Dr H. J. Syiemlieh, Department of Geography, North-Eastern Hill University, Shillong for help in organizing our fieldwork.

Received 31 July 2012; revised accepted 6 February 2013

An adaptive system of vigilance in spotted deer (*Axis axis*) herds in response to predation

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Spotted deer or chital (*Axis axis*), a major prey species in southern India, lives in large groups. To understand the benefits of group living, we carried out observations on chital herds under natural conditions. Individual and group vigilance showed a negative correlation with herd size, whereas the latter had a positive correlation with proportion of vigilant individuals. Furthermore, individual vigilance was negatively correlated with proportion of individuals vigilant and positively correlated with group vigilance. These results are explained in the context of a three-phase vigilance system, probably operative in the chital herd, under specified ecological conditions. We surmise that this system allows for adaptation to predation risk and has possibly co-evolved with the optimal hunting strategy of the predator.

Keywords: Chital, co-evolution, dhole, vigilance, predation.

'ANTI-PREDATORY vigilance' behaviour is often exhibited by prey species to decrease predation risk and to increase chances of survival[1]. Prey animals constantly strike a balance between the amount of energy invested in vigilance and activities that enhance growth, reproduction and fitness[2]. Solitary individuals are constrained as foraging and vigilance are mutually exclusive. The need to replenish energy reserves and the risks involved in foraging impose a trade-off on an individual[3]. A trade-off between the two decides where animals forage, the duration of foraging and the amount of time they invest in vigilance behaviour[4].

An alternate strategy adopted by certain species is the formation of groups[5,6]. During congregation, where all the individuals attempt to optimize within the same constraints, collective vigilance gives the individual an advantage of being able to spend more time in feeding without any drastic drop in the probability of survival as the tasks are shared[6]. A number of mechanisms may favour aggregation between conspecifics over solitary existence, including earlier detection of approaching predators (detection effect)[1,7], a greater proportion of time available for feeding because each individual needs to invest less in vigilance ('Many-eyes' hypothesis)[1], 'confusion' of attacking predators[8] and when predators are limited in their ability to capture more than a single prey item per attack and simple numerical 'dilution' of risk[4,9].

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