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COPPER PRODUCTION PROCESS AS DESCRIBED IN AN EARLY FOURTEENTH CENTURY AD PRĀKṚTA TEXT COMPOSED BY ṬHAKKURA PHERŪ

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The paper discusses the integrated copper production process, as described by Ṭhakkura Pherū in his work, *Dhātūtpatti*, composed in the early part of the fourteenth century AD. The scientific and engineering explanation to the various unit operations and processes adopted for the extraction of copper have been described. It has been shown that the stated copper extraction process is basically similar to the modern "Roast-Smelt-Conversion" process. The copper was mechanically worked into thin strip shape. The characterization test for the good quality copper has also been described. The probable location of the copper mine has been discussed.

Key words: Copper mine, Copper production process, *De Re Mettalica*, *Dhātūtpatti*, *Dravyaparīkṣā*, *Ratnaparīkṣā*, Ṭhakkura Pherū.

I. ṬHAKKURA PHERŪ AND HIS LIFE

Ṭhakkura Pherū, born in the later part of the thirteenth century AD in India, was a scholar-cum-administrator, and had a multi-faceted personality. He wrote a number of works on various subjects such as Mathematics, Astrology, Gemology, Metallurgy, Vāstuśāstra and Geology. The titles are as follows: (1) *Yugapradhāna Catuṣpadikā*, (2) *Ratna Parīkṣā*, (3) *Vāstuśāstra*, (4) *Jyotiśasāra*, (5) *Gaṇitasāra Kaumudī*, (6) *Dhātūtpatti*, (7) *Dravya Parīkṣā* and (8) *Bhūgarbha Śāstra*. Except *Yugapradhāna Catuṣpadikā*, which was composed in Apabhraṁśa language, all other works of Ṭhakkura Pherū are in Prākṛta language.

The life-sketch of Ṭhakkura Pherū is known from his works in which he has given vital information in this regard. He was a Royal Treasury Officer of Alauddin Khilaji and was an expert of Gemology, and subsequently wrote his

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Ratna Parīkṣā on this subject in 1315 AD. After the death of Alauddin, he was appointed the Governor of Royal Mint by his successor Sultan Kutubuddin of Bandichoda Birudawale in 1316 AD. He had gained considerable experience on various types of currencies and coins, and composed his *Dravya Parīkṣā* on this subject in 1318 AD. It says,

evaṃ davvaparikkhaṃ disimittaṃ candataṇaya phereṇa /
bhaṇiya suya - baṁdhavatthe teraha paṇahattare varise //
(*Dravya Parīkṣā,* 149)

The above references suggest that the date of birth of Ṭhakkura Pherū can safely be assigned as the later part of the thirteenth century AD.

Dhātūtpatti[1] is an important work of Ṭhakkura Pherū, which contains fifty-seven *gāthās* written in *Prākṛta* language. Its date of composition can safely be assigned as the early part of the fourteenth century AD. There are three *gā thās* in this book, which deals with the metallurgy of copper, as prevalent in India in those times. In the present paper an attempt has been made to discuss the various aspects of the metallurgy of copper, viz.steps deployed for the extraction of copper from its ore, mechanical working of the extracted copper into thin strips, and the characterization test for the good quality of copper, as described by Ṭhakkura Pherū in his *Dhātūtpatti*.

2. Copper Production Process as Described by Ṭhakkura Pherū

The following *gāthās* cited from the *Dhātūtpatti* of Ṭhakkura Pherū describes the process of extraction of copper and its subsequent mechanical working:

babveraya khāṇīo āṇavi kuṭṭijja dhāhu maṭṭīya /
gomaya sahiyaṃ piṇ ḍiya karevi sukkavi ya paiyavvaṃ //
pacchā khuḍḍai khiviyaṃ dhamijja nīsaraī savva malakadaṃ /
jaṃ hiṭṭhe rahai dalaṃ taṃ puṇa; kuṭṭevi dhamiyavvaṃ //
tassāu vahai payaraṃ taṃ tambamiṭṭhyam viyāṇ eha /
vuḍḍaṇ aye puṇ evaṃ guṭṭhaṃ guliyaṃ tao havai //

(*Dhātūtpatti*, 8-10)

[Word meaning: *babveraya* = name of a place, *khāṇī o* = mines, *āṇavi* = brought, *kuṭṭijja* = crushed and ground, *dhāhu* = metal, *maṭṭī* = soil *(dhāhu maṭṭi* means ore of a *metal), ya* = and, *gomaya* = cow-dung, *sahiyaṃ* = mixed with, *piṇḍiya* = balls, *karevi* = formed, *sukkavi* = dried, *ya* = and, *paiyavvaṃ* = burnt, *pacchā* = subsequently, *khuḍḍai* = pit (pit type furnace), *khiviyaṃ* = charged, *dhāmijja* = heated, *nīsarī* = comes out, *savva* = all, *malakadaṃ* = gangue, *jaṃ* = that (charge material) of, *hiṭṭhe* = at the bottom, *rahai* = left behind, *dalaṃ* = part or portion, *taṃ* = it, *puṇa* = refined, *kuṭṭevi* = crushed and ground, *dhamiyavvaṃ* = heated, *tassāu* = mechanically worked, *vahai* = beaten (with a hammer), *payaraṃ* = thin strip, *taṃ* = that, *tamba* = copper, *miṭṭhyaṃ* = good quality, *viyāṇeha* = to be considered of, *vuḍḍaṇaye* = to expand, *puṇevaṃ* = cleaned or refined, *guṭṭhaṃ* = bunched together, *guliyaṃ* = folded or rolled, *tao* = that, *havai* = obtain.]

> Eng. tr.: 'The copper ore brought from the Babveraya mines was crushed and ground, and then mixed with cow dung. Balls were formed from this mixture, which were dried and burnt. Subsequently, it (the calcine) was charged into a pit type furnace and heated. As a result, all the gangue materials separated out from the charge (and were removed). That part of the material, which was left behind at the bottom of the pit type furnace, was crushed, and subsequently heated (for the recovery of copper). The copper thus produced was mechanically worked into thin strip. If the copper can be formed into thin strip by mechanical working (i.e., beating by a hammer), it should be considered to be of good quality. The thin copper strips were cleaned/refined and were bunched together or folded/rolled in to round shape. Such copper should be obtained (for the usage)'.

It is possible to visualize the process and details of the production of copper thin strips from its ore from the above description of Ṭhakkura Pherū. The run of mine copper ore obtained from Babveraya was first crushed to smaller pieces. The impure fraction (rock fragments having no copper) must have been removed simultaneously by hand picking. Subsequently the crushed ore pieces were ground to fine size. Ṭhakkura Pherū has used the word *kuṭṭija.* In the *Prākṛta-Hindi Dictionary,*[2] *"kuṭṭa"* means "kūṭanā". *Kuṭṭa* is actually a Sanskrit word. Monier-Williams[3] defines *kuṭṭa* as "breaking or bruising, grinding". According to Apte[4] it means, "to cut, to divide, to grind or to pound". In the present context, *kuṭṭija* means breaking of ore to very small sizes, and yet not so small that it becomes powdery. Ṭhakkura Pherū has not given the details of the crushing and grinding equipments used. Perhaps these were too common. The word *gomaya* is a Sanskrit word, and Monier-Williams[3] has given its meaning as cow-dung. The ground ore was mixed with cow-dung, and agglomerated to form balls, which were then dried and burnt. Ṭhakkura Pherū further states that the resulting material was then charged into a pit type furnace. All the gangue materials that separated out from the value were removed. The material left behind at the bottom of the furnace was heated in another furnace for the recovery of copper. Liquid copper was cast into a suitable shape, preferably narrow slab shape. These were mechanically worked by beating with hammers in hot and cold condition to produce strips of copper. The copper which could not successfully be converted into strip shape (i.e. the one which fractured during the working operation) was refined.

Copper ores can be classified basically in two groups- sulphide ore, and oxide ore (which include oxide, carbonate, hydroxy carbonate or silicate ores). Chalcopyrite has been the principal ore of copper in India. The Sanskrit name for chalcopyrite has been *mākṣika*, and it has a long history in India. The noted Ayurvedic treatise *Suśruta Saṃhitā* (Cikitsā, 13. 7) has referred to *mākṣika*. According to it, there are two varieties of *mākṣika*-golden and silvery. *Mākṣika* has been widely mentioned in Rasaśāstra texts, such as *Rasārṇava* (tenth century AD), *Rasaratnasammuccaya* (thirteenth century AD) etc. It is not unreasonable to believe that the ore used in Ṭhakkura Pherū's process was chalcopyrite.

It is apparent from the above description that the process of burning of dried balls prepared from the mixture of crushed and ground copper ore and cow-dung is the equivalent to today's roasting practised under oxidizing/semi-oxidizing conditions. The heating of the burnt copper ore in a pit type furnace, wherein all the gangue are removed in the form of slag and the value (*matte*) is left behind at the bottom of the furnace is equivalent to modern day's smelting of roasted copper ore. The subsequent heating of the value (*matte*) in a furnace to produce liquid copper is equivalent to the modern process of conversion of copper *matte* to liquid copper. Thus Ṭhakkura Pherū's copper making process can be considered to be a "Roast-Smelt-Conversion" route, which very closely resembles with the modern day copper making process. In the following paragraphs, the various steps in the extraction and working of copper, as described by Ṭhakkura Pherū are discussed in detail.

Crushing, grinding and agglomeration of chalcopyrite do not require much explanation, as these were simple unit operations. It is important to note that Ṭhakkura Pherū has prescribed crushing and grinding of ore before burning. The reason for it is discussed later.

2.1 Roasting of Chalcopyrite Ore

The burning of balls of chalcopyrite prepared from the mixture of crushed and ground ore and cow dung refers to the roasting process, wherein the sulphide content of the ore was oxidized. As a result, the proportion of sulphur in the charge was reduced, and SO_2 was liberated. Roasting of chalcopyrite is complex in nature, and depending upon the prevailing condition it may lead to partial or complete oxidation, or sulfation of chalcopyrite. Bumazhnov and Lenchev [5] found that chalcopyrite dissociated into bornite (Cu_5FeS_4), pyrrhotite (FeS) and sulphur at 440-780°C. At the dissociation temperature of 440-470°C, bornite and pyrrhotite were observed at the chalcopyrite grain surface. At 780°C, the dissociation proceeds in the entire grain volume. At 750-800°C, small amounts of chalcocite were also formed. Lenchev and Bumazhnov[6] also suggested that a series of solid solution of Cu-Fe-S were present as intermediate phases during the formation of bornite. Gabler et al[7] stated that dissociation of chalcopyrite produces 'bornite-like phase' ($Cu_5Fe_{5-x}S_{8-x}$).

In the present case roasting was carried out in heap(s). Since the chalcopyrite ore was crushed and ground prior to roasting, the kinetics of the process would have been fast. The reaction was limited by the rate at which air can be supplied near the ore particle. Initially the burning of cow-dung would facilitate a reducing atmosphere (hydrocarbon gases) around the ore particle, and subsequently the atmosphere would change to oxidizing one. The chalcopyrite ore would dissociate and partially oxidize. It is expected that roasting would produce a calcine consisting of FeO, Fe_2O_3, Fe_3O_4, FeS, $CuSFeS_4$ (bornite), or $Cu_5Fe_{5-x}S_{8-x}$ (bornite-like phase), unroasted $CuFeS_2$ and some Cu_2S. Volatile matters such as arsenic and antimony (and even cadmium and zinc) also get removed. The oxidation of FeS and sulphur is exothermic in nature and therefore heat is liberated during roasting process.

Another important point to note is that Ṭhakkura Pherū has stated that the copper ore should be crushed and ground before making balls along with cow-dung. This helps in enhancing the kinetics of the roasting reaction. During roasting, a thick film of oxide forms on the surface of the sulphide grains. For oxidation to continue, free access of oxygen at the sulphide-oxide interface and withdrawal of sulphur dioxide away from this interface, are essential. The rate of roasting would be controlled by the inward diffusion of oxygen, and outward (counter current) diffusion of sulphur dioxide through the oxide layer formed on the reacting ore particles. For a given degree of reaction, the time of roasting is proportional to the square of the diameter of the particle to be roasted[8]. Size reduction of ore results in a larger surface area, which is conducive to increased rate of gas/solid reaction. Bumazhnov and Lenchev[5] have found experimentally that the dissociation rate of chalcopyrite decreased linearly with the diameter square of the reacting particles. It is apparent that Ṭhakkura Pherū recognized the importance of size - reduction of chalcopyrite ore by crushing and grinding for promoting the enhancement in the rate of roasting.

Another interesting point in the process described by Ṭhakkura Pherū is that cow-dung was used to make the balls of the crushed and ground copper ore. Roasting of sulphides is an exothermic reaction. Once sulphides are heated to ignition point, only a small amount of heating, sufficient to heat the ore to its ignition point is necessary. This was accomplished by the use of cow-dung. The actual ignition temperature depends on the chemical/mineralogical composition of the minerals. It can vary between 450°C-650°C, which is low enough to be attained by the burning of cow-dung.

During burning of the chalcopyrite balls, the ore particles would decrepitate resulting in the creation of fissures and cracks in the particles. This makes the ore particles more permeable for the passage of air. It is to be noted that the use of cow-dung in the preparation of copper ore balls provides heat in the vicinity of each ore particle. After the roasting is completed the heap of calcine obtained will contain lesser of sulphides, more of iron oxides and ashes of cow-dung.

It would be interesting to compare the process details of the roasting as described by Ṭhakkura Pherū with those described in other historical texts of similar period. Agricola in his famous Latin book *De Re Metallica*, written in 1556 has given the description of roasting of metallic ores as follows[9]:

> "I now come to the methods of roasting, and first of all to that one which is common to all ores. The earth is dug out to the required extent, and thus is made a quadrangular area of fair size, open at the front, and above this, fire wood is laid close together, and on it other wood is laid transversely, likewise close together, for which reason our countrymen call this pile of wood a crate; this is repeated until the pile attains a height of one or two cubits. Then there is placed upon it a quantity of ore that has been broken into small pieces with hammer; first the largest of these pieces, next those of medium size, and lastly the smallest, and thus built up a gently sloping cone. To prevent it from becoming scattered, fine sand of the small ore is soaked with water and smeared over it and beaten with shovels; ... ...In some districts the ore is roasted once, in other twice, in other three times. as its hardness may require ....Very often also, water is put on to the ore which has been roasted, while it is still hot, in order to make it softer and more easily broken; for after fire has dried up the moisture in the ore, it breaks up more easily while it is still hot, of which fact burnt limestone affords the best example." (Book VIII, p. 273)

Agricola has prescribed the usage of wood for supplying heat to start up the reaction of roasting. On the other hand, Ṭhakkura Pherū's process uses cow dung, which must have been much cheaper as compared to wood, Moreover, only a minimum amount of heat is needed during roasting for initiating the reaction, and subsequently the process itself generates heat. From this point of view cow-dung is more economical. Further, the cow-dung was available in the vicinity of each chalcopyrite particle. This would be more efficient in providing initial heat to the particle, as compared to the Agricola's process. Ṭhakkura Pherū has not mentioned two- or three-stage roasting, as stated by Agricola. It is due to the fact that the average size of the copper ore pieces made by prior crushing and grinding was small enough and consequently a single step roasting was adequate. Moreover, another noteworthy difference is that where as the process of roasting described by Agricola combines the process of crushing brought about due to "fire-setting" with the proper "roasting". On the other hand, Ṭhakkura Pherū kept these two processes independent of each other.

2.2 Smelting of Roasted Chalcopyrite Ore

The second step in the extraction process as described by Ṭhakkura Pherū consisted of smelting of the roasted copper ore in a pit type furnace. All the gangue material was separated from the value in the form of slag. The value known as *matte* was left out at the bottom of the furnace and it contained almost all the copper and a part of the iron. The remaining iron was oxidized and combined with the gangue materials and the SiO_2 flux present in the ore to form slag. Ṭhakkura Pherū has not stated whether any flux was added to the furnace during smelting stage. It seems likely that the SiO_2 present in the ore charge acted as flux. In this context, it is interesting to note that most chalcopyrite concentrate contains 3-10% or even as high as 25% silica, 3-8% alumina and up to 2% calcium oxide. Further, the ash formed after the burning of cow dung also contains SiO_2, CaO and Al_2O_3, which would exert a fluxing action.

During this stage, bornite or "bornite-like phase" present in the roasted ore charge would form a *matte*, which is essentially a solution of Cu_2S and FeS with some dissolved impurities originating from the charge. Also, some of the FeS present in the roasted ore would react with oxygen of the air to form FeO. Any unroasted ore present in the charge was also converted to *matte*. FeO would then combine in-situ with silica present in the ore to form an iron silicate (fayalite, $2FeO.SiO_2$) slag. Eventually *matte* (specific gravity = 4.5-5.0) and slag (specific gravity = 3.0-3.2) layers would have formed.

If the ratio of carbon in the fuel used to air supplied during smelting stage was such that stochiometric combustion occurred, i.e. no excess air was used, very little reaction would have occurred between the roasted ore and the combustion gases. The process was mainly a melting process, and liquid *matte* would have formed. On the other hand, if excess air than what required for complete combustion of fuel was blown inside the smelting furnace from the beginning, then the remaining oxygen would have oxidized the FeS, resulting into a higher grade *matte*.

The slag obtained during smelting would have contained some copper, which would be present in the slag in two forms, viz dissolved Cu_2O and entrained droplets of *matte*. The amount of copper in slag would depend upon the viscosity of the slag; higher the slag viscosity more the copper loss in the slag. Inadequate temperature, formation of magnetite during roasting and smelting, and the presence of alumina in the charge contribute to a higher viscosity in slag.

2.3 Conversion of Copper *Matte*

The third step in the extraction of copper from its ore consisted of conversion of copper *matte* into liquid copper. As stated by Ṭhakkura Pherū, the *matte* was crushed, and was heated in a furnace. The air blown to the furnace oxidized the iron sulphide, which was an exothermic reaction. The FeO formed is skimmed or slagged off. When all the FeS has been oxidized, essentially pure Cu_2S is obtained, which is known as "white metal". With further blowing with air, Cu_2S starts getting oxidized to Cu_2O, which subsequently reacts in-situ with Cu_2S to form liquid copper. The resulting copper is termed as "blister copper", which contains about 2wt% impurities. The most important impurities are iron, sulphur and oxygen. Also all the noble metals present in the initial charge would also accumulate in the blister copper. Typically, blister copper prepared from chalcopyrite would contain Au, Ag, Se, Te, Ni, Co, Fe, Zn, Cd, Sn, S, As, Sb, Bi and dissolved oxygen.

2.4 Mechanical Working of Copper

The liquid copper was cast into a suitable shape, which was mechanically worked by beating with a hammer to form thin strips. Ṭhakkura Pherū states that the thin strips were cleaned/ refined. Beating must have been carried out in hot and cold states, i.e. hot and cold working. Oxide films formed on copper strip surface during hot working must have been removed before any cold working was carried out to obtain a better surface finish. An interesting point to note is that Ṭhakkura Pherū has prescribed that copper be stored as strips. This would show that the copper is of good quality, as it is not possible to judge the good quality of copper if it is stored in the ingot/slab shape. This aspect has been dealt with in detail in the next section. Ṭhakkura Pherū advises to use such a copper, i.e. malleable copper strips.

2.5 Refining of Off-Grade Copper

The copper, which cannot be shaped into thin strip, would eventually fracture during mechanical working. This aspect is dealt with in the next section. Although, Ṭhakkura Pherū has not very explicitly stated, his usage of the word *puṇevaṃ* during mechanical working of copper suggests that such impure copper, which can not be worked to thin strip shape, should be further refined. He has not given any details of such a refining process. In all probability it would have been fire refining.

2.6 Characterization Test for Good Quality Copper

Ṭhakkura Pherū states that if the extracted copper is sufficiently malleable so that it can be shaped into thin strip by beating, then the copper should be considered to be of good quality. A similar characterization test has been stated in *Rasārṇava*; an important Rasaśāstra text of the tenth century AD. It states that copper is of two varieties. viz. red and black. The copper, which can withstand the blows of heavy hammer, has smooth surface, is soft, and is of red colour, is considered to be of the best quality:

> *tāmraṃ ca dvividhaṃ proktaṃ raktaṃ kṛṣṇaṃ sureśvarī* /
> *ghanaghātasahaṃ snigdhaṃ raktapatraṃ mṛdūttamam* //
> (*Rasārṇava*,7.105)

The black-variety of copper referred to in *Rasārṇava* is the one containing iron or high amount of oxygen.

The important impurities in the copper obtained by the process described by Ṭhakkura Pherū, would have been iron, sulphur, and oxygen. Sulphur and oxygen form a brittle chemical comound Cu_2S and Cu_2O with copper. These compounds form a thin film on grain boundaries in the form of eutectic. These decrease plasticity in copper and make it prone to cracking during working. Iron makes copper harder and less ductile. Thus, Ṭhakkura Pherū has prescribed the malleability test to determine the quality of copper.

3. Location of the Copper Mine

As stated earlier, Ṭhakkura Pherū has referred to the copper ore obtained from "Babveraya". A pertinent question is as to where is Babveraya located. Nahata[1] in his Hindi translation of the relevant *gāthā*, has translated it as "Baberā", but has not discussed its location. Some possible explanation regarding the location of Babveraya is being given in the following paragraphs.

It seems most likely that he copper mine referred to by Ṭhakkura Pherū was near the Delhi Sultanat. Khetri, Alwar and Lalsot-Khankhera copper belts contain widespread copper mineralization over 150 km by 150 km area of Rajasthan and Harayana [10]. The largest deposits in the Khetri copper belt are at Khetri.

Copper mineralization in Khetri has been well known since a very long time. The ore contains about 1.1-1.7% Cu and 0.5 g/t Au. Geological Survey of India (GSI) has also carried out a number of geological exploration work in the nearby areas of Khetri. In the present context, it is interesting to note that GSI carried out geophysical and geochemical survey for copper ore at Babai-Kishorepura area, Babai east and west blocks of the Khetri-Babai section, and Surhari-Babai-Chinchroli blocks in the Khetri copper belt and has prepared several field reports during 1960s and 1970s [11-14].

GSI and many multinational companies have been carrying out geological mapping work for copper mineralization in the Alwar district of Rajasthan and has compiled several reports. During 1960s and 1970s, the GSI carried out a number of geochemical survey for copper occurrence in areas such as Tatarpur, Nalladeshwar, Kishori Shyampur, Todi-ka-Bas, Pratapgarh-Nagal, and Deota in the Alwar district [15-20]. Kho-Dariba extension area in Alwar district has also shown copper occurrence [21]. Further, abandoned old copper mines in Alwar district have been reported. For example, Goel and Dube[22] have reported the evidence of old copper mines in Pratapgarh belt in Alwar district. These mines are situated in hill feature. Shafts of one meter in cross-section have been discovered. They have been divided into larger rooms occassionaly where the availability of copper ore was extensive. These old copper mines are mostly shallow and are above the water table. At Jodhawas, 4 km from Sariska on the Thanagazi route in Alwar district, ancient copper, lead and tin mines have been located [23].

There are two possible locations, which could be connected with the Babveraya of Ṭhakkura Pherū. Firstly, there are villages named Baberā, Baberi and Babariya in the Bansur tehsil of Alwar district in Rajasthan [24-25]. Bansur tehsil is located near the western boundary of the Alwar district, and is S.E. of Khetri (Fig. 1). It is not only that the names of the above three villages resemble very much with Babveraya of Ṭhakkura Pherū, but also the fact that there has been a tradition of the availability of copper ore deposit in the Alwar district, as discussed above. Thus, any of these three villages could be recognized with Babveraya.

Another possible location, which may be recognized with Babveraya of Ṭhakkura Pherū could be Babai town, located about 36 km south of modern Khetri in Jhunjhunu district (Fig. 1). It might be possible that this area was called as Babveraya, which successively changed to Babai. This place also has the evidence of copper mineralization, as stated earlier.

It must be said that more corroborating evidence are needed before we can identify more conclusively the location of Babveraya of Ṭhakkura Pherū.

4. Summary and Conclusion

Ṭhakkura Pherū has described an integrated route for the production of copper strips from chalcopyrite ore. The process of copper extraction from chalcopyrite ore, as described by Ṭhakkura Pherū, may be summarized as follows. The selected run of mine ore was first crushed to larger pieces and then ground to fine size. Some mineral beneficiation was carried out by hand picking during crushing operation. The ground ore was mixed with cow-dung, and ball shaped pellets were prepared, which were subsequently sun-dried. The heap(s) of dried balls of chalcopyrite were roasted (burnt) in a shallow pit, which resulted in the partial oxidation of ore. The roasted ore was charged in a pit type furnace, which can be considered as the smelting of the roasted ore. All the gangue material was separated as slag. The left out material at the bottom of the furnace was copper *matte*, which is a mixture of copper sulphide and iron sulphide. The resulting copper *matte* was crushed and charged into another furnace, wherein it was converted into liquid copper. The resulting copper was cast into narrow slab shape, which was subsequently subjected to mechanical working by beating with a hammer in hot and cold conditions, to form strips. The copper strips were cleaned/ refined, bunched together, and folded/rolled in to a round shape for storage. The copper, which could not be fabricated into strip shape and fractured during fabrication, was fire refined. Ṭhakkura Pherū has prescribed a characterization test for testing the quality of copper, which basically consisted of testing its malleability. If the copper can be beaten into thin strips, it is considered to be of good quality. Ṭhakkura Pherū advised to buy copper in thin strip shape, as it is of superior quality.

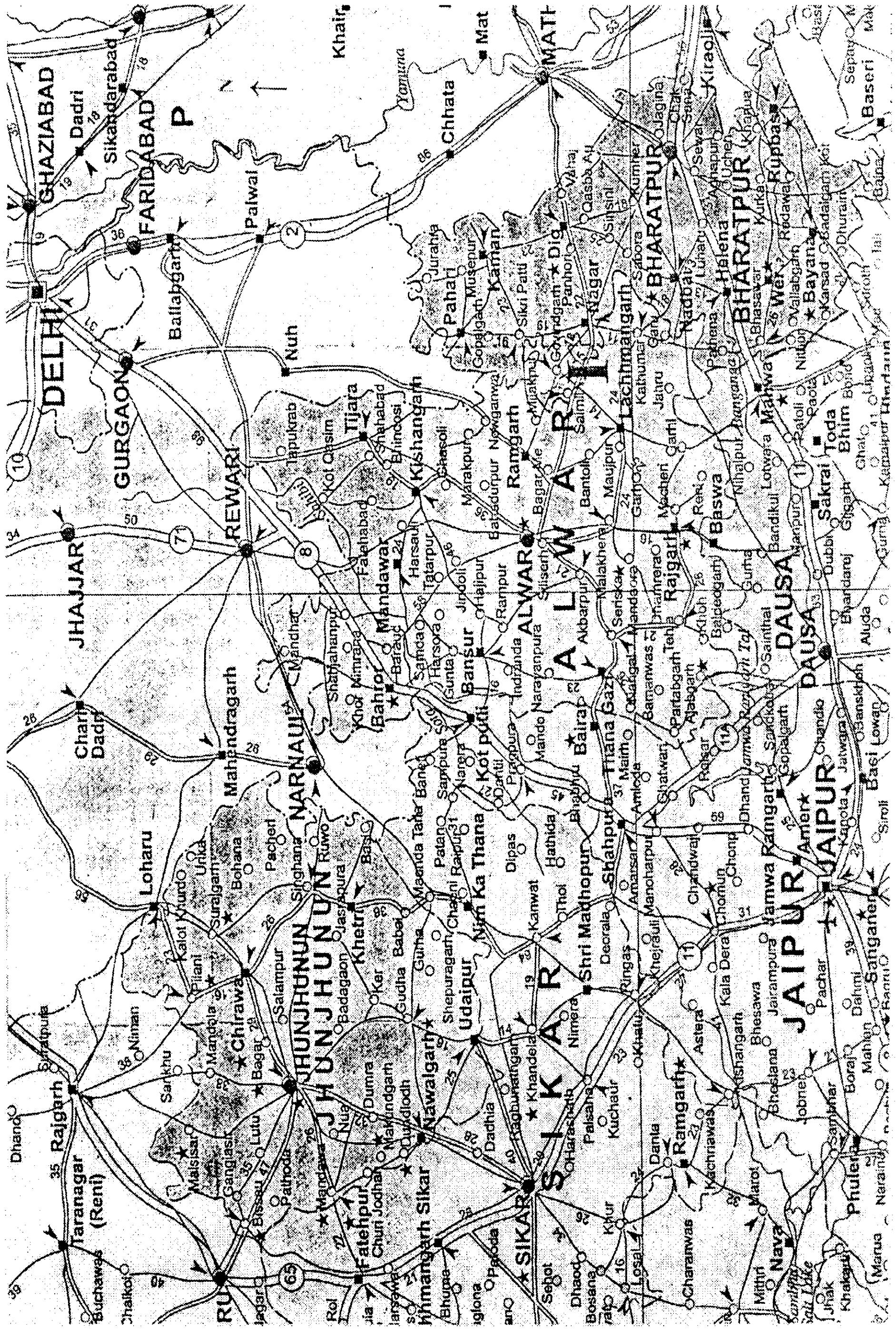

Fig. 1. Geographical map of Alwar and Jhunjhunu districts of Rajasthan

The basic principle of copper extraction process of Ṭhakkura Pherū is very much similar to the modern and pre-modern pyrometallurgical copper extraction process. The important applications of copper strips, where purity was a critical factor, were in utensils and coin making in the times of Ṭhakkura Pherū. The copper extraction process described by Ṭhakkura Pherū was capable of being operated on a relatively large scale. It seems likely that the copper mines of "Babveraya", as stated by Ṭhakkura Pherū, was in the Khetri-Alwar copper belt in Rajasthan. Although, the *gāthās* of Ṭhakkura Pherū describing the process of copper extraction from the ore are dated early part of the fourteenth century AD, it is not unreasonable to assume that this process was in existence even much before than that period in India. The three *gāthās* of Ṭhakkura Pherū discussed in this paper could be considered to be of historical importance in Indian copper metallurgy.

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