ORIGIN OF DALLI-RAJHARA AND ARI DONGRI IRON DEPOSITS OF MADHYA PRADESH, INDIA

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Four processes of origin are suggested for the formation of the Precambrian iron deposits of Dalli-Rajhara and Ari Dongri of Madhya Pradesh.
I. Supergene ores of meteoric origin: (*a*) Leaching of silica and consolidation and reconstitution of the remaining iron portions; (*b*) Leaching of silica and substitution of iron; and (*c*) Deposition of leached iron after migration. II. Syngenetic. III. Metamorphic due to regional metamorphism : (*a*) Leaching of silica by heated ground waters during regional metamorphism and substitution of iron; (*b*) Metasomatic replacement of silica by iron during regional metamorphism; (*c*) Conversion of soft ores resulted by supergene processes into hard ores by mild metamorphism. IV. Hydrothermal.
The recemented ores (Canga) are attributed to a process similar to lateritisation and are, therefore, controlled by physiography, structure, stratigraphy and the groundwater regimen. The massive ores are regarded to have been derived mostly by syngenetic and metamorphic processes. The strongly foliated massive ores are thought to have been derived mostly by metamorphic process and partly by hydrothermal process as at Ari Dongri. The blue dust (powdery ore) is formed either due to supergene processes or due to metasomatism. The blue dust occurring as beds below the compact massive ores is attributed to the groundwater regimen.
It has been concluded that many a time more than one process have worked which complicated the genetic analysis of the ores.

The origins suggested in this paper are based on the study of the Dalli-Rajhara (20°33′—20°35′; 81°—81°7′) and the Ari Dongri (20°23′—20°25′; 81°3′—81°4′) Iron formations of Drug and Bastar districts respectively (Fig. 1) which belong to a group of Precambrian metasedimentary and metavolcanic rocks. Comparisons are made with other deposits of Madhya Pradesh and also with some of those of the world the accent thereof being on deposits related to oxide facies Iron formations. The ores can be classified on the basis of the origin into four types :

I Supergene-Meteoric origin
   a. Leaching of silica and consolidation and reconstitution of the remaining iron portions.
   b. Leaching of silica and substitution of iron.
   c. Deposition of leached iron after migration.

II Syngenetic

III Metamorphic—Mostly due to regional metamorphism.
   a. Leaching of silica by heated ground waters during regional metamorphism and substitution of iron.

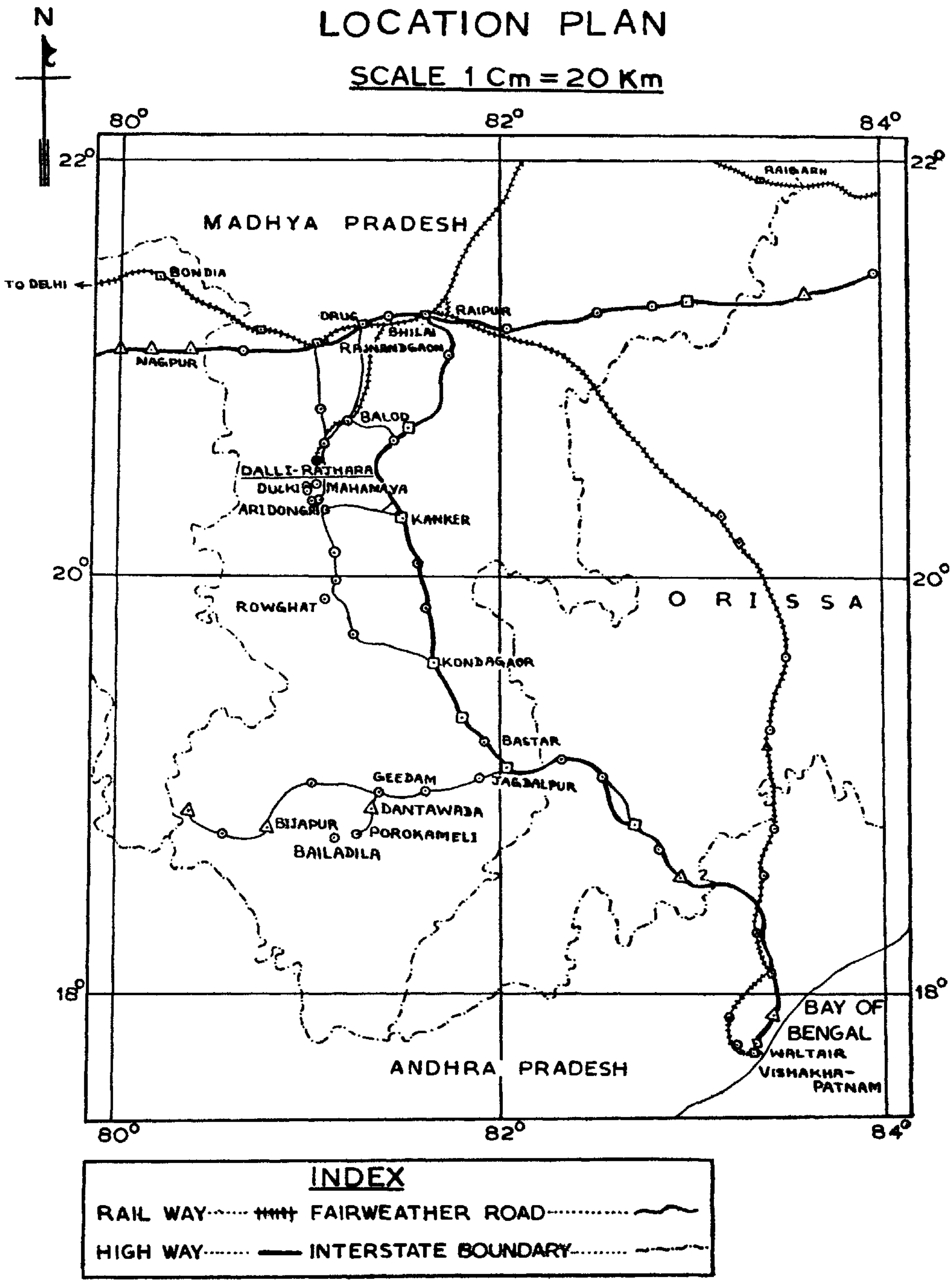
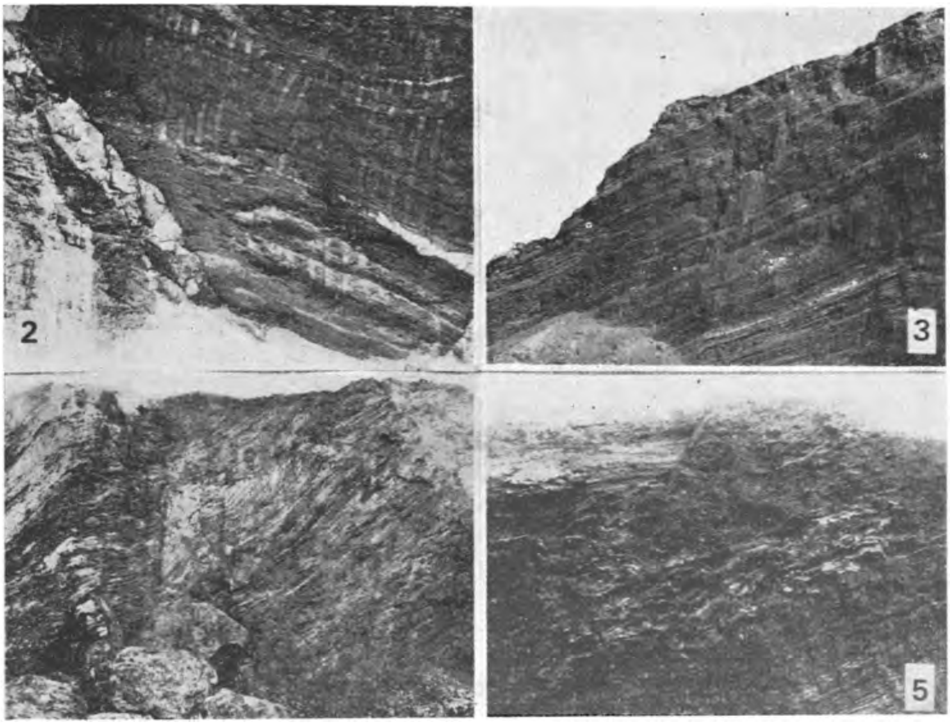


FIG. 1. Location plan.



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FIGS. 2–5. 2. Secondary quartz vein in the soft laminated ore with the blue dust in between the laminations—Rajhara. 3. Blue dust exposure—1680 feet bench at Rajhara. 4. Wavy Banded hematite-quartzite converting into laminated ore—Rajhara. 5. Gradational contact of laminated powdery ore with laminated massive ore—Rajhara.

b. Metasomatic replacement of silica by iron during regional metamorphism.

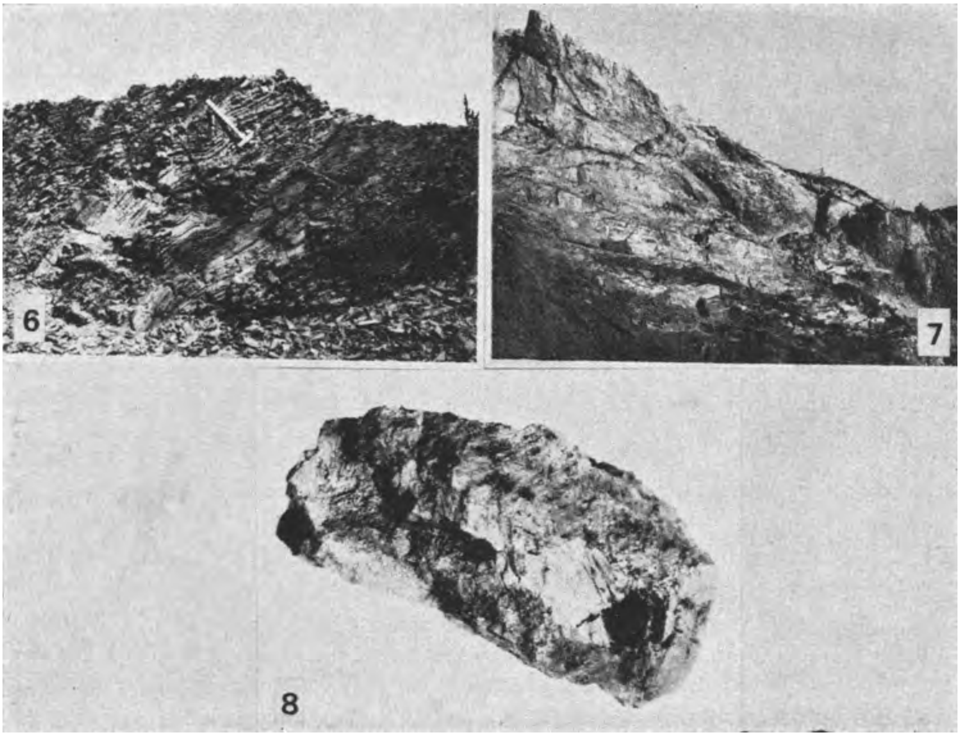
c. Conversion of soft ores resulted by supergene processes into hard ores by mild metamorphism.

IV Hydrothermal

SUPERGENE ORES

The supergene ores of this region are derived mostly from the Banded hematite-quartzites or from the Banded hematite shales. Therefore all gradations are seen from the enriched Iron-formation to the massive ores and from blue dust to massive ores through laminated ores (Figs. 2 to 8). The common sequences observed in this area are as follows :

A	B	C
Enriched Iron-formation	Enriched Iron-formation	Enriched Iron-formation
Laminated ores	Laminated ores	Laminated ores
Laminated massive ores	Recemented ores	Laterites
Massive ores		



FIGS. 6–8. 6. Slumping and crumpling in the laminated ore—Rajhara. 7. The micaceous hematite bands interlayered with the massive ores–Ari Dongri. 8. Phyllitic shale becoming shaly massive ore—Southwest of Dalli.

The enriched Iron-formation with about 30–40 per cent Fe content is mined as 'ore' at Lake Superior. It is formed due to the removal of quartz and other constituents from the banded type rock by the supergene fluids of meteoric origin. This results in disaggregation partly or completely which is also residually enriched in the iron. The author has disagreed that the hard massive compact ores could be developed by this process. The porous laminated ores, slumped laminated ores and the perfect laminated ores could have been developed by this process. These laminated ores are covered by a cap of lateritic or recemented ores. The massive ores resulted from the laminated ores show fine laminations filled with interstitial goethite or hematite of a next generation. When the silica is leached out and could not be substituted by iron the slumped ore is developed due to the breaking of the layers by the superincumbent formation. These, when hydrated and cemented, result in the recemented ores.

The supergene ores normally occur either on the surface or a few feet below the surface. Barring the structural complexities, the high grade ore formed by this process should occur at or near the surface with decrease in grade downwards. This is in relation to the structural position at the time of the supergene ore formation.

Since the leaching phenomenon is the dominant process, the surface ores should have less amount of silica and more amount of phosphorous and alumina due to the residual concentration. The supergene ores have more hydration and the primary ore minerals are rimmed by the second generation hematites guided by mineral cleavage and grain boundaries. The goethitisation and limonitisation is very common in supergene ores.

Origin of the Supergene Ores—The theories which are so far proposed by various geologists rally round three mechanisms—action of meteoric waters, hydrothermal solutions and the eclectic theory. There is also a great controversy with regard to the temperatures of water which leach the silica. Some attributed cold water leaching, and some hot water leaching. It is even proposed by some that the leaching has taken place by cold water near the surface, by warm water at intermediate depth and by hot water at deeper zones. Since the supergene ores are found dominantly at or near the surface, there is no reason why we should ascribe hot water leaching. Gruner (1930) has originally proposed the hydrothermal theory (which he later modified in 1937) due to the action of meteoric waters activated by fluids from magmatic sources. Considering all the existing theories and based on the field observations, the author arrived at the conclusion that the meteoric waters had a high thermal gradient at the peak period of supergene Iron formation.

The fine laminated ores, laminated massive ores, slumped laminated ores, recemented ores are ascribed to the supergene process. The supergene process is confirmed by the fact that the ores are nearer to the surface and concentrate in the synclinal portions signifying downward leaching. Where the benches are opened it is clearly seen that the ores are grading into unleached Iron formation.

One common objection is what had happened to the enormous silica which has been removed. The silica removed is observed to have been concentrated as secondary quartz veins. Most of the silica, however, must have been leached off through the circulating waters. The solubility of quartz is now regarded as quite high (Krauskopf 1956). The solubility increases when there is an increase in temperature and when there is crushing of quartz during tectonism. Kruyt (1952) explained the leaching of silica in colloidal form. According to him the silica in the colloidal form can remain as such for longer periods and therefore is transported effectively. The rate of transport also depends upon the system, confined or unconfined. In a confined system the rate of transport of leached silica is high. It also depends on the paleolatitudes and the inlets and outlets and the permeability of the acquifer. The paleohydraulic gradients are, of course, the main controlling factors in the transportation of the leached out silica. Thus it is visualised that the thermal gradient of meteoric waters was the major factor in the solution of silica and the hydraulic transportation of the leached out silica. James *et al.* (1968) have proposed a complicated process of stagnation of water and their periodic expulsion in the elimination of silica. They suggested the same mechanism for the infiltration of colloidal iron oxides to substitute the leached out silica. Here the possibility of maximum development is at the depth. If the present topography represents the inversion, this process can be visualised to have taken place.

During the process of metamorphism there is generally crystallisation and during deformation there is disaggregation. Both these things can facilitate the leaching mechanism at a faster rate. Due to metamorphism the schistosity is pronounced and this adds in the higher rate of permeability which facilitates the quick transportation. Thus a number of factors must have helped in the leaching mechanism.

Taking leaching as granted, the next problem before us is the enrichment mechanism. The enrichment is related to the present or Precambrian erosion surfaces. It is also related to the premetamorphic or postmetamorphic erosion surfaces. Unless the volume to volume enrichment has taken place the ores could not have been rich enough. This recovery percentage would have been much lower had they not been enriched. Along with the leaching of silica, leaching of iron must have also taken place, though at a different rate. Ruckmich (1963) has calculated for the Cerro Bolivar (Venezula) ores a rate of removal of silica 200 times greater than Fe. Eichler (1968) has also estimated a greater rate of leaching of silica when compared with Fe. Assuming that the present conditions have existed in the past, this explains the greater leaching of silica. At this consideration it is reasonable to assume that the iron ores are being developed even today.

The question arises as to the source of the additional iron to substitute the silica gap. It is presumed that the hydration within must have added in interlocking the bands and grains. The extensive goethitisation at the surface is an indication for this. The goethite at the surface is again dehydrated partly or wholly to give rise to hematite.

The formation of supergene ores can be correlated with the formation of bauxites. In bauxites also there is the complete leaching and removal of silica. The massive iron ores must have resulted by leaching and enrichment along numerous closely spaced fractures across the bedding planes and along the bedding planes also. Where the leaching is predominant along the bedding planes the resultant is the laminated ores. Where the leaching is along and across the bedding planes the resultant is laminated massive ores and massive ores. Where the enrichment is incomplete the resultant is the porous laminated ore. The slumped laminated ores have already been explained before. The recemented ores are broadly derived by the secondary cementation of the slumped laminated ores. The replacements must have added the cementation and enrichment in all the above types of ore.

Similar leaching and enrichment processes must have taken place in case of banded hematite shales. In the banded hematite shales the first stage is the leaching of iron and transportation. In the next stage the silica is migrated with a different mobility altogether. The iron has more mobility than silica. The transported iron has concentrated at the depositing end to give rise to concentrated ore. In the banded hematite shales with silica bands, the silica is removed as described above. In case of non-Banded hematite-quartzites and hematite shales and the leached iron and silica can sometimes be carried away together to long distances. The geochemical separation might then take place. In case of shaly ores the nature of the solvent is also quite important.

Massive and compact-massive and schistose-massive ores were probably formed under oxidising conditions and it appears that there were many phases of such conditions before the formation of hard compact massive ore. The conditions can be visualised to have ranged from highly oxidising to mildly reducing. This analysis is made on the basis of the occurrence of hematite in combination with the limonite and goethite.

In depths, however, the leaching and enrichment mechanisms cannot be so rapid nor simultaneous as they are at the surface due to the lack of sufficient acidity and inadequate oxidation. Oxidising conditions hasten the leaching and precipitation processes. There large scale massive and laminated massive ore formation of the supergene type must have been possible under conditions of intensive simultaneous leaching and enrichment with an abundant supply of acidic solutions. The flaky or schistose massive ores, the recemented and breciated ores and the powdery ores (blue dust) need detailed explaination and therefore are dealt separately in the later pages.

Controls of Supergene Ores—The influence of physiographic environment, the paleolatitudes, the inlets and outlets of the water system, coupled by the intermittent cycles of erosion and uplift are the physiographic criteria which had the genetic control. The changes in the paleoclimates, intensity of rainfall and the thermal gradient are the climatic factors that have controlled the supergene formation. The important control, however, is the planar structures and the fractures across them. These planes and fractures have increased the permeability of the formation to facilitate the faster leaching and transportation. It also depends on the basic composition of the Iron-formation itself as some are more susceptible for leaching and enrichment than others. The grade of metamorphism and the disaggregation of the grains due to deformation increase the development of supergene ores. The grain size, the nature of the quartz grains and the nature and temperature of the solvent are also important factors. Even the facies has its role in he formation of supergene ores. In the oxide facies the development is maximum in view of the oxidising conditions. A number of other factors add to the formation of supergene ores.

The following vertical zoning can be attributed for supergene enrichment process at Ari Dongri ;

1. Massive hard banded rock with alternating bands of quartz and iron-quartz called 'the zone of unweathered Iron-formation.'
2. The quartz grains are dissolved and carried away by secondary solutions called 'the zone of leaching of silica from Iron-formation.' This zone also forms the beginning of martitisation of magnetite.
3. At last, percolating meteoric waters dissolved magnetite, hematite and martite called 'the zone of hydration.'

In case of Ari Dongri deposits there is a zone of martitisation also above the zone of hydration.

SYNGENETIC ORES

From the extensive field studies the author has come to the opinion that most of the high grade ores are syngenetic. The contacts of the syngenetic ores with the enclosing shales or Banded hematite-quartzites are generally quite sharp. The portions where the quartz rich bands or shale rich bands extending into the ore and the iron rich bands extending into them are also considered to be syngenetic.

The hard compact massive ores with no trace of banding, the high Fe content (upto 70 per cent also) and the lack of gradation between these rich bands and the shales (or Banded hematite-quartzites) indicate a syngenetic origin for most part of these ores. Even when the gradation is present the gradation is within a few centimeters to a maximum of few meters.

The geochemistry favours the deposition of iron and silica separately. The mobility of iron is regarded as high and therefore must have been carried faster than silica. The leaching of silica is higher than the leaching of iron and therefore the geochemical separation must have taken place at the source itself. When the shales and cherts could be formed from the argillaceous and siliceous sediments there is no reason why pure massive ores could not be formed. In fact this is the dominant process observed in the Dalli—Rajhara iron deposits. Weld (1915) has also observed a sedimentary facies range from pure quartzites on one hand to pure massive ores on the other hand, with all gradations in between.

Chemically the massive ores resulted by this process have only one or two generations of hematite with very little goethite. In most cases there is only one generation. The uniformity, the granular nature and the uniform optical properties all denote a sedimentary syngenetic origin.

In field there can be seen a fresh Banded hematite-quartzite by the side of crustal massive ore. This is not possible by supergene process as there can not be any selective leaching and enrichment for local patches. The syngenetic theory has been proposed by Percival (1931) and Freyberg (1932) also for the Singhbhum and Brazilian ores respectively.

Some of these syngenetic ores must have been further modified by the later supergene and metamorphic processes. The hydrothermal activity must have further obliterated all the original syngenetic characters. The preservation of the sedimentary structures like the ripple marks etc. is a further indication that most of the high grade ores are syngenetic in origin.

Metamorphic Ores

These ores are similar to the syngenetic ores described above. The massive ores, some of the laminated ores, schistose massive ores and the blue dust have originated this way. Here also there are three processes namely

(*a*) Leaching of silica by heated ground waters during regional metamorphism and substitution of iron.

(*b*) Metasomatic replacement of silica by iron during regional metamorphism.

(*c*) Conversion of soft ores resulted by supergene processes into hard ores by mild metamorphism.

Therefore, the concentration involves mainly either the heated ground waters during metamorphism or the synmetamorphic metasomatism during regional metamorphism.

Neither the supergene processes nor the syngenetic processes cannot satisfactorily explain the formation of high grade deposits at depth. The formations in this area have been subjected to diagenesis and low grade regional metamorphism. During these processes particularly during the later process the ground waters will be heated up which will quicken the leaching phenomenon. There is always metasomatism associated with the regional metamorphism either during or in the waning stage.

Further the close relation of the ores to folded structures and the lack of slump structures in most of the hard ores will point to the possibility of metasomatic replacement. It means that the quartz and other minerals from the Banded hematite-quartzite or shale would be metasomatically replaced by hematite, derived from the Iron formation itself by the fluids emanating from the sedimentary rocks undergoing anatexis or from the younger granitic bodies. These fluids have migrated through the permeable or other favourable structures and replaced the silica at a much faster rate. The migration of iron must have been controlled by stresses set up during tight folding of the rocks. The emanated hot fluids must have carried iron migrated to the relatively low pressure parts. Apparently the metasomatism was complete in the hard compact massive ores and incomplete in the porous or schistose massive types.

Even if the metamorphism had not played a direct replacement role it has definitely helped in the supergene processes. It is also possible that more than one process must have operated in the conversion of the Iron-formation into hard iron ores. Metasomatism has converted the soft ores derived by supergene processes into hard ores. Even some blue dust has been converted into hard blue massive ore by metasomatism.

Hydrothermal Ores

The ores derived by this process are seen mostly at Ari Dongri. The iron ore at Ari Dongri is associated with martite, pyrite and chalcocite which indicates the hydrothermal activity. Here the iron ore itself is flaky type. Even in the Banded hematite-quartzites the hematite has become micaceous which shows that the hydrothermal activity has effected the Banded hematite-quartzites also. In the hydrothermal deposits generally the hematite formed is often so thinly flaked that the ores are not suitable for blast furnaces. But since the scales are strongly compacted at Ari Dongri they are as good as the hard ores. The tectonic movements or the metamorphism also develop thin flakes resulting in the schistose or foliated massive ores. In a place where metasomatism and hydrothermal activity have worked together, it is difficult to judge as to which of the processes have converted them into micaceous type. The mineral assemblage, then, is the best guide. By the association of pyrite and martite it has been shown that these are dominantly hydrothermal ores. Even at Mahamaya the cavities of massive ore are filled by well developed crystals of hematite very similar to the cavity filling deposits. This represents the hydrothermal activity.

Recemented Ores

The recemented ores are also called as consolidate ores, crustal recemented ores, crustal ores, hematite breccia, etc. Canga is a term used in Brazil for these ores. These ores contain both detrital and nondetrital fractions. The recemented ores are formed similar to laterites and are therefore controlled by physiography, structure stratigraphy and the ground water regimen. These are to be distinguished from the brecciated ores. The brecciated ores are formed by the cementing of the slumped laminated ores by hematite or goethite. The recemented ores, on the other hand, are formed by the transportation of leached iron and precipitation at the slopes on evoporation. This is the difference between iron and silica. Silica is not so easily precipitated. The brecciated ores or the brecciated recemented ores either indicate slumping due to overburden or due to the tectonic disturbance. The formation of these ores can be definitely ascribed to the supergene processes.

Massive Ores

The massive ores are regarded to have been derived mostly by syngenetic and metamorphic processes. The laminated ore formed by supergene processes must have been converted into hard massive ores by metamorphic processes. The hard compact massive steel grey ores with almost the theoretical percentage of iron are not ascribed to the supergene process.

Schistose Massive Ores—The strongly foliated massive ores are thought to have been derived mostly by metamorphic processes. The foliation must have also been caused by the hydrothermal process as at Ari Dongri. The foliated or schistose massive ores indicate replacement probably during the rising cycle of orogeny. Part of the schistose massive ores are again cemented and compacted by the unfoliated hematite of later generations.

Blue Dust

The blue dust is generally found at some depth below the surface. Sometimes they also occur as thick beds under the massive ores. They are generally associated with the laminated ores and disaggregated Banded hematite-quartzites. They are not associated with shales. Occasionally there are pockets of blue dust within the massive ores. The original laminations with all the structures like fine banding, minute puckerings, pinching and swelling of bands, are all found well preserved in the blue dust, when it is associated with Banded hematite-quartzites or laminated ores. Sometimes the quartz veinlets often intersect the blue dust as well as the laminated ores. The unleached Banded hematite-quartzite fragments are some times seen within the blue dust.

In chemical composition they are quite similar to the massive ores. Hematite is the predominent constituent. It is fine crystalline and also flaky in habit. They occur as separate granules or as aggregates in parallel growth. The magnetite content is almost negligible. The size analysis of different samples has been carried out and the results are shown in Table 1. It is found that around 60 per cent of the material passes through 120 mesh.

The blue dust associated with schistose massive ores owe their origin to metasomatism where silica has been removed by the metasomatic fluids. Evidently the replacement has not taken place. This could be perhaps the synmetamorphic metasomatic effect. The blue dust associated with the laminated ores and the disaggregated Banded hematite-quartzites is suggested to have been formed by the supergene process. Here also the recementation could not take place after desilication. If magmatic emanations had played any role in the desilication, this also would result in the formation of the blue dust. In both the cases the compaction or replacement of the desilicated Iron-formation could not have taken place.

TABLE I

Screen test results for the blue dust (Rajhara mechanised)

Size of the mesh	Upper horizon	Middle horizon	Lower horizon
>8	23.6	18.6	33.8
>20 to <8	10.8	7.8	12.0
>40 to <20	10.2	5.4	8.4
>60 to <40	7.2	4.2	3.4
>80 to <60	6.4	3.4	2.5
>100 to <80	9.8	2.2	1.4
>100	32.0	58.4	38.5
	100.0	100.0	100.0

The blue dust occurring abruptly below the compact massive ores is attributed to the groundwater regimen. The abrupt contact represents the paleowater table which separated the belt of weathering, oxidation and enrichment, etc. from the underlying belt. Some of the blue dust has again been converted into blue massive ore either by compaction due to metasomatism or by recementation due to hydration.

GENETIC DISCUSSION

The genetic classification given above is quite arbitrary since the formation of the ore is a very complicated process consisting in a consequtive and multistage evaluation-transformation of rocks and ores from the period of sedimentation upto the present time. A historical sequence can be deduced as follows—sedimentation, diagenesis, metamorphism, supergenesis, associated with the paleoweathering conditions and the present supergenesis. The above stages manifested themselves in a number of ways. While syngenetic was the principle process for some deposits, diagenesis was effective for another. Similarly while metamorphism was the principal process of mineralisation for some deposits, supergenesis is a major process for still another group of deposits. There are all modifications and transformations from one type of process into another type of process. Many a time more than one process have worked which complicated the genetic analysis of the ores. Deformation has added to the complexity.

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