SUMMARY AND CONCLUSIONS

About a couple of years after the liberation of Goa from Portugese occupation in 1961, the author started a systematic geological investigation of one of its largest iron ore deposits at Bicholim taluka, in the northern part of Goa, in which Sirigao-Bicholim and Sanquelim are the two important localities having rich deposits of iron ores. Although it was chiefly aimed at the structural and genetic studies of the ore deposits yet considerable attention was paid to deal with their stratigraphy, mineralogy and some important economic aspects. A summary of this study as well as several interesting conclusions arrived at, are given in the following paragraphs.

1. The iron ore deposits of Bicholim are confined to the Precambrian phyllites of North Goa, which are in many respects similar to the well-known Precambrian Dharwar schists of Mysore. Phyllites and banded ferruginous quartzite are the two major rock types in the area under investigation. These banded ferruginous rocks are believed to be the source rock of iron ore deposits and hence, they are treated here as iron formations. The phyllites have also some small lenses of massive quartzites which crop out sporadically in the area. There are a number of basic dykes intruding into the schistose formations of the area. They have a general NNW-SSE to NW-SE trend. Widespread

lateritization have greatly obliterated the true nature of all the rock outcrops except of the basic dykes, which can be easily recognised in the field. On the basis of field survey and mapping, an attempt was made to build up the stratigraphic sequence of the area as follows :

	Recent	....	Alluvium
	Sub-recent	....	Laterite
	Deccan Trap?	....	Dolerite
Precambrian	Intrusive	....	Metadolerite
	Schistose formation	....	Phyllites with banded ferruginous quartzites and some massive quartzites.

The lithological characters and some primary sedimentary structures of the phyllites and banded ferruginous quartzites show that they are low grade metasedimentary rocks.

The strike of the schistose rocks is NW-SE, which is more or less the same as that of the Dharwars of the type area in Mysore. They generally dip northeastwards. Structurally, the area occupies a part of the western limb of a northwesterly plunging regional syncline, the axis of which passes through Zormen, Querim, etc., which fall beyond the area investigated. Both Sirigao-Bicholim and Sanquelim outcrops of the banded ferruginous quartzites represent two northwesterly plunging and northeasterly dipping isoclinal anticlines. The former anticline was further cross-folded due to a drag. The structure and relative position of two anticlines indicate that they are left-handed en echelon folds.

On the basis of their lithology, comparable grade of metamorphism, structural similarity and association of iron ores, the schistose rocks of the area have been correlated with the Middle Dharwars of Northern Mysore.

2. The petro-mineralogical studies of the phyllites confirm the fact that their grade of metamorphism is considerably low and equivalent to the chlorite zone of the greenschist facies. In the absence of iron or any other silicate mineral the metamorphic grade of the ferruginous quartzite also appears to be low. Some of the basic dykes in which the mineral assemblages are somewhat metamorphosed and show preferred orientation, are identified as metadolerites and considered as the older Precambrian intrusives. The younger ones having unaltered pyroxene, plagioclase felspars and olivine may be of the Deccan trap age.

3. The iron ore deposits of Bicholim are mainly confined to the two well-defined ridges, one of which extends from Sirigao to Bicholim and the other occurs near Sanquelim. The iron ores are usually capped by ferruginous laterite and iron ore laterite which more or less grade downwards into the former imperceptibly. The laterites, however, have no economic importance. The bulk of the commercial grade of ores are mined

from the ore lying below the laterite overburden. The ore horizon has been divided into three zones viz., hard, friable and powdery, which can be easily recognised by their nature and physical characters. The hard ore zone, which occurs in the upper part of the deposits gradually passes downwards into a zone of friable ore which in turn becomes powdery further down. Occasionally the hard ores are associated with some manganese ores such as pyrolusite and psilomelane and this variety of iron ore is known locally as ferro-manganese. There are also some small but rich pockets of manganese ores which are occasionally found in the overlying ferruginous laterites.

Analytical results of the iron ores show that the average iron contents in the hard, friable and powdery ores are 62 °/o , 64 °/o and 65 °/o respectively. It is very interesting to note that Fe_2O_3 , FeO and SiO_2 contents gradually increase from the hard to powdery ore while Al_2O_3 and combined water go on decreasing. Mineralogical composition of these ores also show that the quantity of goethite decreases significantly from the hard through friable to powdery ore with a corresponding increase of hematite and magnetite. All these facts regarding the nature and composition of the different types of ore and their field relations indicate that they were largely influenced by several complex supergenic processes in which meteoric water played a dominant role.

An attempt was also made to classify the ore deposits into four types viz., hard, friable, powdery and lateritized ores on the basis of their physical characters, mineralogy and chemical composition.

Economically, the iron ore deposits of Goa and particularly of its northern part, which contribute approximately 75 °/o of the territory's total annual production of iron ores, have a great promise. According to a recent estimate, made by the Geological Survey of India, Goa has a reserve of about 405 million tonnesof iron ores, which include about 94 million tonnes of hard (52 °/o Fe) and about 311 million tonnes of friable and powdery ores (62 °/o Fe). According to the same source, the combined reserves of Bicholim and Sanquelim deposits are about 98 million tons. On account of the locations of most of the important deposits of Goa within a radius of about 30 km from the nearest ports and also excellent waterways for easy inland transportation, the f.o.b of its iron ores is cheap and this may be the main reason as to why the ores are in great demand in several foreign steel-producing countries such as Japan, West Germany, Italy, etc.. Since the iron ores of Goa have been fast attracting the international interest, it is now very necessary to have a stricter quality control than before and also to install another agglomeration plant somewhere near Bicholim town. Moreover, because of the rapid depletion of lumpy ore and the problem of marketing the blue dust and iron ore fines, some important suggestions are given for controlling the quality of the ores and also for improving the economy of this important iron-rich territory of India through modernizing mining operations and proper utilization of its iron resources.

4. Structurally, the Sirigao-Bicholim deposit forms a northwesterly plunging and somewhat overturned isoclinal anticline whose axial trend is NW-SE. The northwestern part of this anticline near Sirigao has been cross-folded into a smaller syncline and a corresponding anticline. The trend of the axes of the cross-folds is NNW- SSE, which makes an angle of about 15° north of the general axial trend of the Sirigao-Bicholim anticline.

The smaller Redeval deposit, which occurs about 400 meters northeast of the southeastern part of the Sirigao-Bicholim deposit also have a general northeasterly dip and NW-SE strike. On the basis of its structure, absence of any fault valley between this and the adjacent Bicholim deposit, and also of its great physical and mineralogical resemblences with the other ores of Bicholim it is logical to believe that the Redeval outcrop represents the northeastern limb of the much eroded anticline whose other limb form the Sirigao-Bicholim deposit.

The Sanquelim deposit reveals that it is also a case of isoclinally folded anticline plunging northwestwards and that its limbs dip northeastwards. The axial trend of the anticline is NW-SE. Due to removal of a greater part of the anticline by erosion its outcrop pattern became V-shaped.

There are also several important evidences to believe that both the primary and secondary structures of the iron formations have made the [illegible] flow and circulation of the metoric water through them easier and due to which the processes of residual concentration and supergene enrichment of the iron ores were very much effective.

5. Mineragraphic study of the iron and the associated manganese ores led to the identification of specular hematite, magnetite, martite and goethite among the iron minerals, and pyrolusite and psilomelane among the manganese minerals. Some of the iron ores developed schistosity due to preferred orientation of the specular variety of hematite and some magnetite, which are generally segregated in alternate bands. The primary nature of the two minerals has been amply justified by their straight boundary relation and the complete absence of any replacement relation and hence, both magnetite and specular hematite are considered to be the earliest of all the iron minerals to appear and contemporaneous in time sequence. Among the supergene iron minerals, the time range of the second generation of hematite, which is actually a pseudomorph of martite after magnetite, is more or less overlapping with that of the goethite, which occurs as pseudomorph after magnetite. There is also another generation of supergene hematite, which

is actually a pseudomorph after goethite. It has overlapping time relation with the second generation of colloform or massive goethite, which is usually a dominant mineral in the hard ores.

Lepidocrocite occurs rather insignificantly in close association with the colloform goethite with which it has an overlapping time relation. Both pyrolusite and psilomelane, associated with the iron ores, are late supergene minerals.

6. Largely guided by the different views regarding the origin of iron formations and the types of ore associated with them and based on the author's own field and laboratory investigations, the genesis of the iron ores of Bicholim is summarised as follows :

i) Weathering and erosion of ancient land masses supplied so much of iron and silica that they served as the primary source of iron formations. Probably iron was transported in solution and precipitated in a ferrous-ferric or ferrous state while silica was deposited in a colloidal state.

ii) Banding in iron formations was due to rhythmic chemical precipation of iron and silica in the Precambrian basin of deposition under a particular set of physico-chemical condition which never repeated in later geological periods.

iii) Probably a restricted marine environment like that of the Dharwar geosynclinal phase was ideally suitable for the deposition of iron formations during the period concerned.

iv) As most of the magnetites and specular hematites in the iron formations are primary, they should be considered as belonging to the oxide facies of James (1954). A mildly oxidising to mildly reducing deep water environment was envisaged for the deposition of these primary iron minerals.

v) The solvent responsible for the mass leaching of silica from the protores, was meteoric and subsurface water and not derived from any hydrothermal source.

vi) Mass residual leaching of silica, oxidation of magnetite to hematite and deposition of some iron hydroxide under certain favourable physiographic, structural and physico-chemical conditions were the most important processes involved in the transformation of the iron formations into hard, friable and powdery iron ores.

vii) The hard ores owe their origin to almost complete removal of silica by leaching from the near-surface protores and the subsequent deposition of goethite in it from the solutions circulating through the intergranular void spaces. On the other hand the protores, occurring at some depth below the surface, were much disaggregated and rendered powdery because of certain physico-chemical conditions under which the meteoric water continued to leach silica but without being able to deposit any more goethite at such a depth. In the case of friable ore, which occur between the hard and powdery ore zone there was a complete leaching of silica but due to inadequate supply of goethite, many of the void intergranular spaces in the leached iron formations could not be filled up. This is the cause of the protores remaining porous and friable just below the hard ore and above the powdery ore zone.

It may now be concluded that at an earlier stage the residual concentration of magnetites occured at all levels in the iron formations due to complete leaching of silica. But the subsequent or even contemporaneous supergene oxidation of magnetite into hematite and their sécondary enrichment with the addition of colloform or massive goethite were most effective in the upper part of the deposit and as a result of which it gave rise to an upper zone of hard and enriched ores consisting dominantly of hematite and goethite.

On the contrary, there was practically no secondary enrichment and a very restricted oxidation of the underlying zone of powdery ores due to which they were left completely loose and thus retained their original state as well as mineral composition. Between the upper hard and the lower powdery ore zones, obviously there should be a transition zone in which the ores would be neither hard nor powdery but friable, and also have small amounts of magnetite and goethite on account of restricted oxidation and enrichment.

The residual concentration and secondary enrichment of the protores, being extremely slow supergenic processes and largely dependent upon the past topographic and climatic conditions of the area, had more likely continued through several geological periods rather than remaining confined to a single one.