CLASSIFICATION OF MANGANESE DEPOSITS

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ABSTRACT

The widely distributed manganese deposits of the world had earlier been classified genetically by PARK [1956]. VARENTSOV [1964] classified principal manganese formations of exogenetic type on the basis of paragenetic associations of rocks. Both the classifications have their limitations. An attempt has been made in this paper to present a genetic-associational classification of manganese deposits. Accordingly the principal manganese deposits of the world can be classified into three broad genetic types e.g. hydrothermal, sedimentary and superficial. The sedimentary type has been genetically subdivided into nonvolcanogenic and volcanogenic types depending upon their source of the metal. Both the nonvolcanogenic and volcanogenic deposits have further been subdivided according to characteristic rock associations. It has been shown, however, that no generalized conclusion can be drawn to relate the associational subdivisions to particular genetic types or any unique tectonic set up, and thus the associational subdivisions have only a descriptive value.

INTRODUCTION

Manganese ore deposits are widely distributed in the continents and on ocean floors all over the world. Even a very conservative estimate indicates the reserve of manganese ores of the world to well over a billion tons, taking into consideration the well known deposits on the continents only. VARENTSOV [1964] estimated that more than 70% of the total manganese deposits of the world are of Cenozoic age. The Mesozoic era is conspicuous for the paucity of manganese ore deposits (only about 0,004% of the world reserve) while the Paleozoic and Precambrian eras share the rest of the known deposits almost equally.

The above estimate does not include the recent deposits of manganese nodules on ocean floors, the potentiality of which has been emphasized by a number of workers including MERO [1965], BONATTI and NAYUDU [1965], STRAKHOV [1966], PRICE [1967], BÖSTROM [1967] and others.

These vast deposits of manganese have originated by diverse processes and are associated with diverse rock types. Systematic attempts of genetic and/or associational classifications are few and are mostly incomprehensive. The author will attempt here to discuss these earlier classifications and put forward a new scheme that may bring into purview most of the well known deposits of the world.

EXISTING CLASSIFICATIONS

PARK [1956] suggested a genetic classification of manganese ores. His scheme is given below in Table 1.

TABLE 1

Genetic classification of manganese ores [PARK, 1956]

MANGANESE ORES

- HYDROTHERMAL DEPOSITS
- SEDIMENTARY DEPOSITS
  - DEPOSITS INDEPENDENT OF VOLCANIC ACTIVITY
  - DEPOSITS ASSOCIATED WITH TUFFS AND CLASTIC SEDIMENTS OF VOLCANIC AFFILIATION
  - DEPOSITS ASSOCIATED WITH IRON FORMATIONS
- LOW TEMPERATURE SILICATE AND HAUSMANNITE DEPOSITS ASSOCIATED WITH SUBMARINE FLOWS
- METAMORPHIC DEPOSITS
- RESIDUAL ACCUMULATIONS LATERITES

This is the first systematic attempt to classify manganese deposits of all genetic types. However, some of the subdivisions proposed by PARK are not entirely acceptable in purely genetic scheme. As for example, within the "Sedimentary Deposits" PARK suggested three subdivisions on the basis of rock association. In a purely genetic classification of this type [cf. PARK, 1956, p. 75] such associational subdivisions should be kept separate to avoid confusion. Attention may particularly be drawn to the two subdivisions, "Deposits independent of volcanic activity" and "Deposits associated with iron formation", both of which are non-volcanogenic chemical sediments. Thus they should not be classed separately in a genetic scheme. Rather, they may be shown as different associational types under the broader genetic class of non-volcanogenic sediments.

Another subdivision, "Deposits associated with submarine flows and composed mainly of low temperature silicates and hausmannite", proposed by PARK, seems to be superfluous. PARK included "Deposits of complex manganese silicates and oxides" which are associated with submarine pillow flows, under this class. He mentioned the Olympic Peninsula deposit, Washington, Franciscan formation, California and the Japanese deposits as examples. Of the above, the Olympic Peninsula deposit and those of the Franciscan formation can be classed appropriately with the volcanogenic-sedimentary deposits. The Japanese deposits may be included under the hydrothermal [LEE, 1955] and/or volcanogenic-sedimentary class which were later thermally metamorphosed [WATANABE, 1959; 1960; WATANABE, KATO and ITO, 1960].

The class, "Metamorphic Deposits" suggested by PARK is also superfluous as a genetic type, as in none of the deposits cited by him (Indian and Brazilian deposits) any effective concentration of manganese took place during metamorphism. In all these cases, only pre-existing sedimentary manganese deposits were later metamorphosed resulting in compaction and reconstitution of mineral phases, but not necessarily producing or improving the quality of the ores. Thus, these orebodies should appropriately be classed under sedimentary deposits, the metamorphism being only a superimposed phenomenon. Moreover, the manganese oxide ore deposits of Brazil are, mostly (with the exception of those associated with itabirites) supergene products formed by oxidation of meta-sedimentary manganese carbonate protore.

VARENTSOV [1964] attempted to classify the principal manganiferous formations as paragenetic associations of rocks in which manganese deposits are characteristic. His classification is given in Table 2.

TABLE 2

Classification of manganese formations as paragenetic association of rocks [VARENTSOV, 1964]

MANGANESE FORMATIONS

NIKOPOL MANGANIFEROUS FORMATION (Orthoquartzite Glauconite-clay)	THE LIMESTONE DOLOMITE GROUP	GONDITE FORMATION	SEDIMENTARY VOLCANIC FORMATIONS OF THE GREENSTONE SERIES	GROUP OF SUPERIMPOSED CHIEFLY LATERITIC FORMATIONS
THE JASPILITE GROUP	SILICEOUS-SHALE-ORTHOQUARTZITE GROUP	SEDIMENTARY-VOLCANIC FORMATIONS OF THE PORPHYRY SERIES	FLYSCH (TUFFACEOUS TERRIGENOUS) FORMATIONS	

In line with the objection raised on assigning the "Metamorphic Deposits" a separate class in PARK'S classification, the author considers that in VARENTSOV'S classification also, the type "Gondite Formation" is superfluous. The type "Flysch Formation" has also been objected to by DZOTSENIDZE [1966] who expressed doubts about their precise nature. In any case, even according to VARENTSOV, the Flysch type manganese formations are extremely rare. VARENTSOV'S classification is also limited in scope as he attempted to classify the manganese formations of exogenic type only and has not dealt with the hydrothermal deposits.

SHATSKIY [1964] considered most of the manganese ore deposits of the world to be volcanogenic and suggested that the ore deposits of this type can broadly be classified into two types: Greenstone-Siliceous Group and Porphyry-Siliceous Group. The details of these two types will be discussed at length later in the paper.

GENETIC TYPES OF MANGANESE FORMATIONS

In this text, the author will follow a broad based, three fold genetic classification of manganese formations of the world, viz. *1*. Deposits formed by hydrothermal process, *2*. Deposits formed by sedimentary process, and *3*. Deposits formed by superficial concentration. These types will be briefly discussed below:

1. Deposits Formed by Hydrothermal Process

Hypogene vein deposits of manganese formed by hydrothermal process have been described from different parts of the world [HARIYA, 1961; HEWETT, 1964; HEWETT and FLEISCHER and CONKLIN, 1963, etc.]. A close genetic correlation of these hypogene veins and recent hot spring apron deposits of U.S.A. and Japan, has been established by the above workers. Recent concentrations of manganese nodules on ocean floors have been suggested to have formed from hydrothermal solutions by VON GUMBEL [1878], WEDEPHOL [1960], CRONAN and TOOMS [1967] and others.

HEWETT and FLEISCHER [1960] showed that in hypogene veins in different parts of the U.S.A., particularly in San Juan region of Southwest Colorado, rhodonite and rhodochrosite follow the deposition of common sulfides of copper, lead, zinc, silver and the less common sulfoarsenides and sulfoantimonides of copper and silver with quartz and barite. They also showed that in many instances, hypogene veins composed of manganese minerals also contain barite, fluorite and huebnerite. Such association of hypogene manganese minerals in veins with barite, fluorite, gold-silver and base metals, has been elaborated by HEWETT [1964]. HEWETT showed that in zoned hypogene veins, manganese is present in manganous state in the minerals rhodochrosite, rhodonite, alabandite and huebnerite in the lowest two zones, in association with base metals and gold-silver minerals, respectively. Manganese is present in a more oxidized state in the higher zones, as oxides in black calcites associated with fluorite and barite and finally as higher oxides of manganese (pyrolusite, cryptomelane, psilomelane, hollandite, manganite) in the uppermost zones.

HEWETT and FLEISCHER [1960] and HARIYA [1961] have demonstrated that the present day hot springs are depositing manganese oxides (cf. Hot Spring No 23, Arkansas; Saline Valley, California; Sodaville, Mineral County, Nevada; Komaga-Dake Cold Spring, Iwao hot spring, Niimi hot spring and Akan hot spring, Japan: Table 3, ROY, 1968) and thus testify to the feasibility of formation of manganese deposits from a hydrothermal source. NIINO [1959] also demonstrated that sea-floor springs off the southeast coast of Japan, empty manganese-rich solutions in the ocean.

In the ancient deposits, paragenetic association of the mineral groups of manganese, barite, fluorite, gold-silver and base metals and the zoning exhibited by them, confirm the hypogene nature of the manganese minerals, formed from ascending hydrothermal solution (Examples: Pioche, Eureka county, Nevada; Leadville, Pitkin County, Colorado; Bisbee, Tombstone, Gila, Graham, Greenlee and Pinal County, Arizona; Silver City, Hidalgo, Luna, Socorro and Dona Ana County, New Mexico; Philipsburg and Butte, Montana; Inakuraishe, Hokkaido, Japan; Dzhedza and Nayzatas, Central Kazakhstan, U.S.S.R. etc.).

HEWETT [1966] proposed that for most of the stratified deposits of manganese containing little or no iron, the metal was supplied by veins and aprons produced by thermal waters with possible volcanic affiliation. He thought that the absence of commensurate iron with the manganese deposits in space and time can only be explained by postulating a source from ascending hot springs, where iron is separated from manganese by precipitating in deeper zones. Thus HEWETT postulated hydrothermal solutions as the ultimate source of manganese and, in his opinion, the veins and aprons formed by thermal waters, after reworking, gave rise to stratified deposits by remobilisation of the metal.

The above contention of HEWETT [1966] is based on the assumption that iron is separated from manganese at depth during precipitation from thermal waters and hence this process alone can explain the lack of commensurate iron in many stratified deposits. The separation of iron from manganese in vertical columns due to differential mobility during diagenesis of sediments has recently been emphasized by LYNN and BONATTI [1965], STRAKHOV [1966] and BÖSTROM [1967] and this concept certainly restricts HEWETT'S hypothesis from universal application [cf. ROY, 1968].

Though the extent of the role of hydrothermal process in the formation of manganese deposits remains controversial, it is evident that deposits formed by this process constitute a recognised genetic type. Deposits of unequivocal hydrothermal origin, however, seems to be few and possibly account for only a minor part of the manganese deposits of the world [BÖSTROM, 1967].

2. *Deposits Formed By Sedimentary Processes*

The deposits formed by sedimentary processes constitute, by far, the majority of the commercial deposits of manganese of the world. Genetically, the sedimentary manganese formations can be subdivided into two broad types: *(a)* Volcanogenic-sedimentary deposits where the metal was supplied from a volcanic source and the precipitation was closely related in time and space to subaqueous volcanic eruptions (exhalative-sedimentary); and *(b)* non-volcanogenic sedimentary deposits where the source and precipitation of manganese was not connected with any volcanic episode and the metal was entirely derived by weathering of continental landmass (pure sedimentary).

The proponents of volcanogenic-sedimentary manganese formation include BOULADON and JOURAVSKY [Morocco deposits; 1952, 1956], GEIJER and MAGNUSSON [Swedish deposits; 1948], ÖDMAN (Swedish deposits; 1950], PARK [Olympic Peninsula deposit, U.S.A. 1946], SERVICE [Nsuta deposit, Ghana; 1943], SUSLOV [Kuznetsky Altai deposit; 1967) and others, who suggested that concentration of manganese in these deposits took place either during direct volcanic activity or by weathering of manganese-bearing volcanic rocks. SHATSKIY [1964] elaborated this concept and considered that most of the important sedimentary manganese deposits of the world are of volcanogenic derivation, excepting only some of those associated with iron formations (cf. Morro do Urucum, Brazil).

The mechanism of formation of the exhalative-sedimentary type of manganese deposits by leaching out of metals from contemporaneous subaqueous eruptions, has been explained by PARK [1946], KRAUSKOPF [1956] and others. This hypothesis of concentration of manganese by leaching from subaqueous volcanic eruptions (hyaloclastites), has been considered to be the operative process, for the formation of recent deep-sea manganese nodules by BONATTI and NAYUDU [1965], BONATTI [1967], HEWETT, FLEISCHER and CONKLIN [1963], SUMMERHAYES [1967] and others.

A number of workers [BETEKHTIN, 1937; DORR *et al*, 1956; ROY, 1966; STRAKHOV, 1966; STRAKHOV and SHTERENBERG, 1966; VARENTSOV, 1964 etc] proposed that many of the important manganese deposits are of "pure sedimentary" type i.e. nonvolcanogenic in source (cf. Chiatura, Nikopol, Bolsh'e Tokmaksk, Labinsk, Maliy Khingan, Usinsk, U.S.S.R; Minas Gerais, Bahia, Morro do Urucum, Matto Grosso, Brazil; Madhya Pradesh — Maharashtra, Gangpur, Srikakulam, India and others). These deposits have been conclusively proved to be unconnected with any volcanic episode. The manganese in these deposits was evidently derived by weathering of continental rocks. A similar conclusion about the formation of deep-sea manganese nodules has been drawn by GOLDBERG [1954] and GOLDBERG and ARRHENIUS [1958].

The evidences suggesting a volcanogenic derivation of manganese for sedimentary deposits are as follows: *(i)* spatial contiguity of volcanic rocks with manganese formation *(ii)* field features of the manganese deposits themselves, such as interlayering and interfingering of manganese formations and volcanic rocks, combination of vein and stratified deposits, association with hydrothermal deposits etc., *(iii)* hypogene alteration of associated rocks and co-precipitation of chemogenic rocks directly related to volcanic activity, and *(iv)* higher content of minor elements.

None of the above evidences, however, is considered to be unequivocal by itself. Thus, the manganese formations associated with volcanic rocks in S. E. Newfoundland [MOHR, 1965], Central Poland [SAMSONOWICZ, 1956] and Usinsk, U.S.S.R. [VARENTSOV, 1964] have been conclusively proved to be nonvolcanogenic. The use of high concentration of minor metals as an evidence for volcanogenic source also has been questioned by STRAKHOV [1966] who suggested that the higher content of minor elements in some manganese deposits may not be the effect of volcanic activity alone but might have been subscribed by both terrigenous and volcanic sources.

Thus it is clear that the occurrence of unequivocal volcanogenic-sedimentary deposits of manganese is not as widespread as it was thought to be and a similar conclusion has been drawn by BÖSTROM [1967] in case of deep-sea manganese concentrations. BÖSTROM has shown that the role of submarine volcanism is relatively minor in the formation of nodules on ocean floors and stated "at 100% leaching efficiency, only 5% of the total excess manganese could be derived from the effused volume of basalts in the Pacific".

The general consensus among most of the workers is that both volcanogenic and non-volcanogenic sedimentary manganese deposits are common [cf. VARENTSOV, 1964; STRAKHOV, 166 etc.]. The dual source of manganese for the oceanic nodules also has been suggested by ARRHENIUS, MERO and KORKISCH [1964], KRAUSKOPF [1967], SKORNYAKOVA, ANDRUSHCHENKO and FOMINA [1962], STRAKHOV [1966] and others.

In any genetic classification of manganese formations, therefore, both volcanogenic and nonvolcanogenic sedimentary deposits should find adequate places, though, admittedly, there may be such transitional cases where the two types can hardly be distinguished.

The effect of diagenetic modification of the manganese sediments has been emphasized by LYNN and BONATTI [1965], STRAKHOV [1966], STRAKHOV and SHTERENBERG [1966] and others and similar ideas have been forwarded in case of iron sediments by LEPP [1968]. It is difficult to determine, at this stage, how far the mineralogy of the sedimentary manganese ores had been controlled by conditions of precipitation or diagenetic processes. In some cases, the sediments have later been subjected to regional or contact metamorphism and thoroughly modified (cf. India, Brazil, Ghana etc.).

3. Deposits Formed By Superficial Concentration

Deposits of manganese oxide, formed by supergene agencies at or near surface, are common in different parts of the world and some of them assume considerable dimensions to be regarded as major commercial deposits. Concentration of manganese oxides in these deposits is effected by alteration and remobilization of either earlier manganese formations or from rocks that initially contained manganese as minor constituent.

The formation of manganese oxides by alteration and remobilisation of earlier formations where manganese was a major constituent, is primarily restricted to the change in oxidation state of the manganese and thereby formation of new phases in low temperature-pressure conditions. The trend of such changes by oxidation and hydration has been shown to be dependent on the source rock and the oxidation gradient [BRICKER, 1965, ROY, 1968]. Thus a manganese carbonate protore (with primarily rhodochrosite) should ultimately be oxidised to pyrolusite (β-MnO_2) and/or cryptomelane (α-MnO_2) depending upon the extent of K-absorption form ground water [cf. Minas Gerais, Brazil, HOREN, 1953, MARVIN and ZWICKER in BRICKER, 1965; Moanda, Gabon, Africa, BAUD, 1956; Philipsburg, Montana, U.S.A., LARSON, 1962, PRINZ, 1967; Butte, Montana, U.S.A., ALLSMAN, 1956, FLEISCHER, RICHMOND and EVANS, 1962; Piedras Negras, Mexico, ZWICKER in BRICKER, 1965; Ghana, Africa, SOREM and CAMERON, 1960, ZWICKER in BRICKER, 1965; Toyoguchi Mine, Iwate Prefecture, Japan, NAMBU and TANIDA, 1961; Úrkút, Hungary, CSEH NEMETH and GRASSELLY, 1966; etc.]. Depending upon, the oxidation gradient, however, such alteration of rhodochrosite may be arrested in intermediate stages giving rise to γ-MnO_2 (nsutite) or δ-MnO_2 (birnessite). A manganese silicate protore (such as gondite), on the other hand, does not yield γ-or δ-MnO_2 at any stage of alteration, even in ideally low oxidation gradient and directly changes over to pyrolusite or cryptomelane. Pre-existing metamorphosed lower oxide ores also show considerable alteration due to oxidation by supergene agencies, but they (chiefly composed of braunite, bixbyite, jacobsite, hausmannite etc.) also change directly to pyrolusite and/or cryptomelane.

Superficial concentration of manganese from country rock containing only a small amount of the metal has been reported from many countries. Limestones and dolomites are well known in this regard and they contain enormous quantity of manganese locked in them, though the distribution is very sparse and the percentage of a metal rarely exceeds 2—3%. Shales, phyllites and quartzites also contain manganese in very low concentration. Thus in U.S.A. in the southeastern states extending from Pennsylvania through Maryland and Virginia to Georgia, Alabama and Arkansas, superficial manganese deposits have formed in residual clays overlying carbonate and other rocks of Paleozoic rocks that originally contained some amount of manganese. In the Piedmont mine, Cambell county, Central Virginia, almost half the thickness of limestone contains from 0.50 to 0.75% manganese and this is considered to be the source of the superficial manganese oxide deposits that are associated with the limestone [HEWETT and FLEISCHER, 1960, p. 16]. Similarly the shaly dolomite from Shady Valley, and Bumpass Cove, Tennessee contain 0.39 to 1.24% and 0.13 to 0.83% manganese respectively, which is responsible for the formation of the associated superficial deposits. Superficial deposits of manganese are also found in cherts and quartzite (Weissner quartzite and Fort Payne Chert, U.S.A.) as also in phyllites and shales (Orissa and Mysore deposits, India) and at present the source of the metal is assumed to be the country rocks.

SUBDIVISIONS OF THE GENETIC TYPES BASED ON ROCK ASSOCIATIONS

Association with particular rocks is not very characteristic with both epigenetic hydrothermal deposits and superficial deposits of manganese. In case of sedimentary deposits, however, association of characteristic rock types sometimes assumes considerable importance. Several workers have tried to interpret such associations in terms of environments during deposition. VARENTSOV [1964] first classified the sedimentary manganese deposits according to rock associations (see Table 2).

A. Sedimentary Manganese Deposits of Nonvolcanogenic Source

Nonvolcanogenic, pure sedimentary deposits of manganese are found to be associated with the following principal rock types:

1. Association with Orthoquartzite — Glauconite — Clay and Orthoquartzite — Carbonate formations.

Vast deposits of syngenetic manganese ores of Cenozoic age, either unmetamorphosed or slightly metamorphosed, are associated with orthoquartzite — glauconite — clay formations at Chiatura, Nikopol, Bols'he Tokmaksk, Labinsk, Mangyshlak and other deposits of U.S.S.R. and Timna Dome, Israel. Generally nonvolcanogenic is envisaged [BETEKHTIN, 1936, 1937, SOKOLOVA, 1964, VARENTSOV, 1964 and others] though DZOTSENIDZE [1966] concluded that the Chiatura deposit is of "remote volcanogenic type" [cf. SHATSKIY 1964]. STRAKHOV and SHTERENBERG [1966] however, proved conclusively that the arguments of DZOTSENIDZE are untenable. The deposits occurring in association with orthoquartzite-glauconite-clay formation are generally developed on a stable platforms or areas close to platforms in stable areas of the crust. The manganese ores generally consist of higher oxides (pyrolusite, cryptomelane etc.) which pass through a mixed type rich in manganite, to manganese carbonate (rhodochrosite). This variation of mineralogy had been explained by BETEKHTIN [1936, 1937] to be due to depositional condition. VARENTSOV [1964], STRAKHOV [1966] and STRAKHOV and SHTERENBERG [1966], however, explained this gradual change in mineralogy from higher oxides to carbonates through manganite, as due to effects of diagenesis. The high terrigenous impurity of the ore is reflected in the high content of SiO_2. The manganese formations of this associational type apparently originated as a result of severe weathering of continental rocks and later deposition of the ore in shallow littoral areas of marine basins or lagoons. The Nikopol and Chiatura deposits were formed in a humid, the Mangyshlak in semi-arid and the Timna Dome deposit, Israel, in arid condition [VARENTSOV, 1964].

The regionally metamorphosed manganese formations of Sausar and Gangpur Groups of Precambrian age in India occur as part of the orthoquartzite-carbonate formation of possibly miogeosynclinal type [NARAYANSWAMI *et al*, 1963]. These have been conclusively proved to be of nonvolcanogenic sedimentary type [ROY, 1966]. The deposits are characterized by high temperature lower oxide assemblages (braunite-bixbyite-jacobsite-hausmannite) in the ores and manganese silicates (spessartite-quartz and manganese amphiboles and pyroxenes) in the associated gondites [ROY, 1966]. ROY and MITRA [1964] ROY [1966] and ROY and PURKAIT [1968] have shown that neither manganese carbonate nor low temperature silicate was present in the original sediments and the entire manganese was deposited as oxides or hydroxides. The lower oxides and silicates now constituting the ores and the gondites respectively are products of transformation and reaction during regional metamorphism.

2. Association with Iron Formation

The universal presence of undifferentiated manganese in varying quantity has been reported from different facies of sedimentary iron formation by JAMES [1954, 1966] and LEPP [1963, 1968]. Concentration of manganese as important ore deposits, characteristically associated with iron formation, have also been described from different countries including Minas Gerais, Bahia and Morro do Urucum (Brazil), Postmasburg and Kalahari (Africa), Maliy Khingan (U.S.S.R) etc. These deposits are unequivocally considered to be nonvolcanogenic by most of the previous workers including PARK [1956] and even by such staunch supporters of volcanogenic origin of manganese deposits as SHATSKIY [1964]. VARENTSOV [1964] has shown that these manganese deposits are situated in different tectonic set up. The eugeosynclinal type is represented by Minas Gerais and Bahia deposits (Brazil) and Postmasburg — Kalahari deposits (Africa). The miogeosynclinal and platform types are represented by Maliy Khingan (U.S.S.R.) and Morro do Urucum (Brazil) deposits respectively.

In Minas Gerais, Brazil, meta-sedimentary manganiferous formations occur in three associations [DORR *et al.*, 1956]:

(i) Manganese silicate-carbonate-sulphide protore.
(ii) Marble-itabirite protore where manganese was deposited as part of the chemical sediments.
(iii) The clastic sediments now represented by phyllite, quartzite etc.

The manganese silicate-carbonate-sulphide protore is represented by rhodochrosite-manganoan calcite-alabandite-spessartite-rhodonite-manganoan cummingtonite-thulite-tephroite-pyroxmangite-neotocite-bementite-graphite assemblage.

DORR *et al* [1956] concluded that the manganese formation was originally syngenetically deposited in negative Eh and pH around 7 in an euxinic environment, resulting in mineral assemblages of manganese carbonate and sulphide. These were later regionally metamorphosed to give rise to the manganese silicate-carbonate-sulphide protore. Any concentration of manganese oxides in these rocks was due to supergene agencies.

In marble-itabirite protore of Minas Gerais, Brazil, manganese is concentrated in both the members independently. The manganese content in itabirite varies from 0,1 to 45% Mn [DORR *et al* 1956]. The distribution of manganiferous itabirite in normal nonmanganiferous member is strictly stratigraphic. The manganiferous itabirite is, in all probability, primary in origin and does not show any indication of previous deposition as carbonates [PARK, DORR, GUILD and BARBOSA, 1951]. In marbles, on the other hand, manganese is considered to be locked up in manganoan calcite and dolomite and up to 4,20% MnO has been reported in the rock. On decomposition due to weathering, this manganese has been concentrated to form oxide orebodies of local importance.

The Postmasburg-Kalahari deposit of the Union of South Africa, considered to be part of a mobile belt that extends northwards into the Kalahari from the Orange river near Prieska [De VILLERS, 1956], provide another example of close association of manganese with banded iron formation. These is, however, considerable controversy about the origin of these deposits. SCHNEIDERHÖHN [1931] considered these deposits to be meta-sedimentary. J. E. DE VILLIERS [1944] concluded that the deposits are hydrothermal in origin, while the more recent workers [cf. J. DE VILLIERS, 1956] agree that the ores have formed by supergene concentration. The mineralogy of the ores (braunite-bixbyite-hausmannite-jacobsite), however, clearly indicates a high temperature origin. The laminated nature of braunite and hausmannite ore, conformable to the banded iron formation in the Smartt area in particular [J. DE VILLIERS, 1956] indicates a syngenetic formation. Thus, the possibility that the manganese formations were sedimentary in origin and later modified by metamorphism, cannot be ruled out. Such syngenetic meta-sedimentary ore deposits have been described from Otjosondu area in Damara System of southwest Africa [ROPER, 1956], where DE VILLIERS [1951] studied the mineralogy in detail. The mineralogy of the ores of Otjosondu and Postmasburg is comparable, though there are minor differences in textural details.

Syngenetic meta-sedimentary manganese deposits are closely associated with iron formations in a a miogeosynclinal sequence of Maliy Khingan area, U.S.S.R. [ILLARINOVA, KAMINSKAYA and NEMRYUK, 1958 cited by VARENTSOV, 1964; CHEBOTAREV, 1960]. The regionally metamorphosed manganese formation is constituted of the following mineral assemblage: braunite, hausmannite, hematite, magnetite, rhodonite, bustamite, tephroite, rhodochrosite, tremolite, actinolite, chlorite, sericite etc. The mineralogy indicates that the manganese was originally deposited in the sediments as oxides and carbonates. CHEBOTAREV [1960] compared these deposits with those at Morro do Urucum, Matto Grosso, Brazil.

Manganese oxide deposits associated with iron formation of platform type have been described from Morro do Urucum, Matto Grosso, Brazil [PARK *et al*, 1951; BARBOSA, 1956; VARENTSOV, 1964; SHATSKIY, 1964]. Here, manganese ores are interbedded with banded iron formation as part of the Banda Alta formation of Jacadigo Series. The ores are composed of higher oxides (mainly cryptomelane) and hydroxides of manganese [BARBOSA, 1956]. It is indicated that the manganese is genetically related to iron and silica. PARK *et al* [1951] showed that above and below each bed and lens of manganese oxide, beds of clastic materials (arkose) are found which suggest an abrupt but very temporary change from chemical to clastic sedimentation. Possibly this temporary change in environment somehow inhibited the precipitation of iron and silica and at the same time encouraged the precipitation of manganese (possibly by incursion of fresh water).

3. Association of Limestone — Dolomite Formation

Association of sedimentary manganese orebodies with limestone-dolomite formation is not uncommon. Such deposits are found in volcanic associations (cf. Morocco) and they may also be essentially nonvolcanogenic in derivation. An example of nonvolcanogenic manganese deposit forming part and parcel of an extensive limestone-dolomite sequence, has been presented by VARENTSOV [1964] at Usinsk, U.S.S.R. (Lower Cambrian). At Usinsk manganese carbonates are associated with limestone-dolomite formation in an eugeosynclinal tectonic set up. The deposits are made up of rhodochrosite, ferroan rhodochrosite, manganoan calcite and manganoan dolomite. The upper Permian deposit of Ulu-Telyaksk (W. Ural, U.S.S.R.) is a stable platform type manganiferous limestone-dolomite formation. The ore deposits are characterized by manganiferous limestones locally enriched to higher oxides by oxidation [BETEKHTIN, 1946].

B. Sedimentary Manganese Deposits of Volcanogenic Source

STRAKHOV [1967] distinguished three lithologic types among volcanogenic-sedimentary formations, viz. *(i)* the volcanic formations proper, including lavas and tuffs with no marked admixture of terrigenous material, and distinctive of ordinary platform segments of the earth: *(ii)* the volcanic-terrigenous formation with lavas, tuffs and sandstone and clay, formed chiefly in the sea; and *(iii)* the volcanic-siliceous formations with lava, tuff, terrigenous rocks and jasper and siliceous shales, developed in central parts of geosynclinal zone. Deposits of volcanogenic manganese, according to STRAKHOV, are associated with the third type of formation.

SHATSKIY [1964] also agreed that most of the known deposits of manganese ores of volcanic-sedimentary type are paragenetically associated with volcanogenic-siliceous facies. As already stated, SHATSKIY showed that the manganese deposits associated with volcanogenic-siliceous facies can broadly be classified into two subdivisions e.g. Greenstone-siliceous group and Porphyry siliceous group, according to the type of the parent volcanic rocks. These two subdivisions can further be classified into different lithologic formations as follows [SHATSKIY, 1964]:

I. GREENSTONE – SILICEOUS GROUP

GREENSTONE FORMATION	JASPEROID FORMATION	SILICEOUS-SHALY FORMATION	REMOTE SILICEOUS FORMATION

II. PORPHYRY – SILICEOUS GROUP

PORPHYRITIC FORMATION	SILICEOUS-SHALY FORMATION	REMOTE SILICEOUS FORMATION

According to SHATSKIY, these groups (excepting the Remote Siliceous formation in both cases) individually form single genetic series and any of the formations grade into others in the field. He, however, put up an word of caution in recognizing 'Remote Siliceous formation' in either of the groups. He observed: "Connections of the Remote Siliceous formations with volcanic ores can only be indirectly ascertained" and " Identification of isolated *Remote Siliceous Formations* within sedimentary series is a very difficult task. Only those of the formations, whose membership in the volcanogenic-siliceous series could be proved, should be assigned to this class". SHATSKIY also admitted that, "In the Remote Siliceous Formation (Porphyry-Siliceous Group) manganese ores, even if they are formed, are scarce and poor". The identity of Remote Siliceous formations has also been challenged by other workers including STRAKHOV and SHTERENBERG [1966]. It is, therefore, evident, in the light of the uncertainties pointed out above, that the Remote Siliceous formation in both the Greenstone-Siliceous Group and the Porphyry-Siliceous Group, is not an well established genetic or associational type and is, therefore, to be treated with caution.

In the Greenstone-Siliceous Group, the Greenstone formation is characterized by spilite, keratophyre, diabase and such other basic volcanic rocks. Volcanogenic manganese deposits in such association have been reported from South Ural, U.S.S.R. [SHATSKIY, 1964], Olympic Peninsula, U.S.A. [PARK, 1946], Oriente Province, Cuba [PARK *et al* 1944; SIMONS & STRACZEK, 1958] the western Alpine and Penine ophiolitic zones in Switzerland and Italy [GEIGER, 1948] Srednegorsk, Pozharevo area, Bulgaria [KOSTOV, 1944; SUSLOV, 1967], and others. The Jasperiod formation is characterized by jasper, tuff, subordinate limestone lenses and locally terrigenous rocks and it merges to Greenstone formation or Siliceous — Shaly formation by facies gradation. The important examples of manganese deposits associated with this formation are: the Parsetten and Faletta deposits of Graubünden Canton, Switzerland, Chevlyanovich deposit, Bosnia, Balkans and the deposits in the Franciscan formation, California, U.S.A. The deposits at Graubünden Canton, Switzerland are interbedded with Upper Jurassic radiolarites with layers of clayey shales, and this Jasperoid formation is underlain by ophiolitic greenstone formation. The manganese ores consist of oxides and carbonates. At the Chevlyanovich deposit also, the ore deposits are interbedded with Jurassic radiolarites. In this deposit braunite is the chief ore mineral [GEIGER, 1948]. In the Franciscan formation, California, U.S.A, manganese deposits are interbedded with radiolarian jaspers which, associated with carbonate rocks, form the top of the formation consisting of arkose, argillite and spilite-keratophyric basic intrusives. The deposits are characterized by manganese carbonate minerals. [TRASK *et al*, 1950].

Deposits of manganese in Siliceous-Shale formation of Greenstone-Siliceous Group, are comparatively rare. Important examples of deposits of this type are Kellerwald and Harz mountain deposits (Elbingerode and Lautenthal), Germany, Huelva Province, Spain, Fortuna Harbour, N. Newfoundland, Machang, Satakhun and Trenggan, Molucca Peninsula, Mazul'skoye deposit, U.S.S.R. and the Nsuta deposit, Birrim System, Ghana. All these deposits are enclosed in siliceous shales or their metamorphosed equivalents which are directly related to Jasperoid or Greenstone formation of Greenstone-Siliceous group.

The Porphyritic formation, represented by such volcanic rocks as quartz porphyry, dacite, rhyolite etc., contain well developed manganese oxide ore deposits, and in contrast to that of the Greenstone-Siliceous series, manganese is more concentrated as ore bodies and less dispersed in other rocks in the Porphyritic formation. The Glib-en-Nam deposit (Morocco) and Kolningsberg and Långban deposits

(Sweden) occur in Porphyritic formation. The Siliceous-Shaly formation in Porphyry-Siliceous Group is represented by the Central Kazakhstan deposits, U.S.S.R. [SHATSKIY, 1964].

SUGGESTED SCHEME OF CLASSIFICATION

The author has already attempted to review critically the earlier classifications of manganese formations and has discussed the broader aspects of the mode of origin of the different manganese formations and the rock types in which they occur. It has been shown that the five-fold genetic classification of manganese deposits [PARK, 1956] can be streamlined and made more broad-based by accepting a three-fold scheme (e.g. hydrothermal, sedimentary and superficial types). In the light of discussions already made on the source of manganese in the sedimentary deposits, the latter should be genetically subdivided into non-volcanogenic and volcanogenic types.

The sedimentary manganese deposits throughout the world have been shown to be characteristically associated with certain rock formations. No characteristic genetic implication of such association could, however, be drawn in all cases. The non-volcanogenic sedimentary manganese deposits occur in either of the three rock associations, viz. orthoquartzite-glauconite-clay and orthoquartzite-carbonate formations, iron formation, limestone-dolomite formation. These rock associations, but for the orthoquartzite-glauconite-clay formation [of Nikopol type; VARENTSOV, 1964] may be either geosynclinal or platform type. Thus, manganese deposits associated with iron formation, has been reported from eugeosynclinal (Minas Gerais, Postmasburg-Kalahari), miogeosynclinal (Maliy Khingan) and platform type (Morro do Urucum) tectonic set up. Non-volcanogenic manganese deposits of limestone-dolomite formation have likewise been reported both from eugeosynclinal (Usinsk and Apalachian deposits) and platform types (Ulu Telyaksk).

The volcanogenic-sedimentary manganese deposits can likewise be subdivided according to the association of rock formations in which they occur. In this subdivision the volcanic-siliceous facies of volcanogenic-sedimentary type of rock formations has only been considered as manganese deposits are reported only from this facies. The volcanogenic manganese desposits of volcanic-siliceous facies may be subdivided (on the basis of rock association), keeping SHATSKIY'S [1964] classification almost in its entirety. Only the "Remote Siliceous Formations" type is SHATSKIY'S classification has not earned the confidence of all workers and even according to SHATSKIY, its identity can only be established with difficulty. So this type should not be included as an unequivocal type in the classification.

Considering all aspects, manganese formations can be classified both on genetic and associational (with characteristic rock formations) basis. It has already been pointed out that the different associational types of manganese deposits cannot always be explained by any common genetic scheme. For example the limestone — dolomite formation contains manganese deposits of both volcanogenic (Morocco) and non-volcanogenic type (Usinsk, Ulu Telyaksk). Tectonic setting is also of little genetic consequence in many places. Though in eugeosynclinal types manganese deposits commonly show volcanic affiliation, unequivocal non-volcanogenic deposits are also contained in them. (cf. Usinsk deposit, U.S.S.R., Minas Gerais, Brazil.) Similarly the platform type deposits are generally non-volcanogenic (cf. Chiatura, Nikopol,. U.S.S.R) though evidences of volcanism and derivations of manganese ores thereform are also found (Marocco).

TABLE 3

Genetic-associational classification of manganese formations

MANGANESE FORMATIONS

ON GENETIC BASIS

- **HYDROTHERMAL**
  - EX.: BUTTE, MONTANA, PIOCHE, NEVADA, LEADVILLE, COLORADO, SILVER CITY, NEW MEXICO (U. S. A). INAKURAISHI, HOKKAIDO (JAPAN). DZHEZDA AND NAYZATAS, CENTRAL KAZAKHSTAN (U. S. S. R).
- **SEDIMENTARY**
  - **NONVOLCANOGENIC**
    - ON THE BASIS OF ROCK ASSOCIATION
      - ASSOCIATION WITH ORTHOQUARTZITE-GLAUCONITE-CLAY & ORTHOQUARTZITE-CARBONATE FORMATION. MAINLY PLATFORM & MIOGEOSYNCLINAL TYPE. EX.: NIKOPOL, BOL'SHE TOKMAKSK, CHIATURA, LABINSK (U. S. S. R.). ORE DEPOSITS ASSOCIATED WITH GONDITE (INDIA).
        - OXIDE-CARBONATE ORES EX.: NIKOPOL, CHIATURA (U. S. S. R.).
        - OXIDE ORES EX.: MADHYA PRADESH, MAHARASHTRA, GANGPUR (INDIA).
      - ASSOCIATION WITH IRON FORMATION. EUGEOSYNCLINAL: EX.: MINAS GERAIS & BAHIA (BRAZIL); POSTMASBURG & KALAHARI (AFRICA). MIOGEOSYNCLINAL: EX.: MALIY KHINGAN (U. S. S. R.); PLATFORM TYPE: EX.: MORRO DO URUCUM, MATTO GROSSO (BRAZIL).
        - CARBONATE-SULFIDE ORES EX.: MINAS GERAIS (BRAZIL).
        - OXIDE-CARBONATE ORES EX.: MALIY KHINGAN (U. S. S. R.)
        - OXIDE ORES EX.: POSTMASBURG (S. AFRICA).
      - ASSOCIATION WITH LIMESTONE-DOLOMITE FORMATION. EX.: USINSK (U. S. S. R.).
        - CARBONATE ORES EX.: USINSK (U. S. S. R.)
  - **VOLCANOGENIC**
    - ON THE BASIS OF ROCK ASSOCIATION
      - GREENSTONE-SILICEOUS GROUP
        - GREENSTONE FORMATION (SPILITE, KERATOPHYRE, DIABASE ETC.). EX.: OLYMPIC PENINSULA (U. S. A.); S. URAL (U. S. S. R.); SREDNEGORSK (BULGARIA); WESTERN ALPINE & PENINE OPHIOLITIC ZONE (ITALY & SWITZERLAND).
        - JASPERIOD FORMATION EX.: S. URAL (U. S. S. R.); PARSETTEN & FALETTA DEPOSITS IN PENINE ZONE; GRAUBÜNDEN CANTON (SWITZERLAND); CHEVLYANOVICH (BOSNIA); FRANCISCAN FORMATION (U. S. A.).
        - SILICEOUS-SHALY FORMATION EX.: KELLERWALD & HARZ MOUNTAINS (GERMANY); HUELVA PROVINCE (SPAIN); FORTUNA HARBOUR (N. NEWFOUNDLAND); MOLUCCA PENINSULA (MALAYA) NSUTA DEPOSIT, BIRRIM SYSTEM, (GHANA).
      - PORPHYRY-SILICEOUS GROUP
        - PORPHYRITIC FORMATION (QUARTZ PORPHYRY, DACITE, ANDESITE AND LAVAS OF INTERMEDIATE COMPOSITION). EX.: GLIB-EN-NAM (MOROCCO); KOLNINGSBERG, LÅNGBAN (SWEDEN).
        - SILICEOUS-SHALY FORMATION. EX.: CENTRAL KAZAKHSTAN (U. S. S. R.).
- **SUPERFICIAL**
  - EX.: SUPERGENE OXIDE ORES OF GHANA, GABON (AFRICA); MINAS GERAIS, (BRAZIL); DONGRI BUZURG (INDIA) ETC.

It is, therefore, necessary to evolve a genetic-associational classification of manganese formations that may include the most important deposits in its folds. It is understood, however, that no individual associational type is a sole representative of an unique genetic class. More than one associational type may characterize a genetic class and some particular associations may be product of any of the different genetic classes.

The classification of manganese formations suggested by the present author is given in Table 3.

CONCLUSION

An attempt has been made in the preceding pages to synthesize the data on the mode of genesis of the principal maganese deposits of the world an their association with characteristic rock formations. The accumulated data under review indicate that a broad-based three-fold genetic classification (hydrothermal, sedimentary and superficial) encompasses most of the important manganese deposits of the world. Of these three genetic types, the sedimentary deposits are, by far, the most important and can, genetically, be further subdivided into non-volcanogenic and volcanogenic types. The non-volcanogenic and volcanogenic-sedimentary deposits are associated with characteristic rock formations. In the case of the latter, clearcut divisions may be made into Greenstone — Siliceous and Porphyry— Siliceous Groups according to the association of characteristic volcanic rocks. The Greenstone — Siliceous Group can further be subdivided into *(i)* Greenstone formation, *(ii)* Jasperoid formation, and *(iii)* Siliceous — Shaly formation and the Prophyry — Siliceous Group into *(i)* Porphyry formation, and *(ii)* Siliceous — Shaly formations. All these formations merge into one another and are genetically related. The non-volcanogenic — sedimentary formations can be subdivided, on the basis of rock association, into *(i)* association with orthoquartzite — glauconite — clay and orthoquartzite — carbonate formations, *(ii)* association with iron formation, and *(iii)* association with limestone — dolomite formation.

The various subdivisions on the basis of rock association cannot always be related by genesis and/or tectonic set up. Thus, the volcanogenic deposits are generally found in geosynclinal and the non-volcanogenic deposits in platform type basins, though there are evidences on the contrary e.g. the platform type deposit at Morocco is volcanogenic whereas the eugeosynclinal deposits at Minas Gerais and Usinsk are non-volcanogenic. Similarly rock associations do not unequivocally characterize a volcanogenic or non-volcanogenic manganese deposit e.g. manganese deposits with limestone dolomite association at Usinsk and Ulu Telyaksk (U.S.S.R.) are non-volcanogenic whereas those at Morocco are volcanogenic. Thus no individual associational type is a sole representative of an unique genetic class. More than one associational type may characterize a genetic class and some particular associations may be product of any of the different genetic classes.

Finally, the sedimentary manganese deposits of different genetic and associational types are characterized by oxide and carbonate and rarely sulphide ores, sometimes exhibiting lateral variation. Such mineralogical — chemical manifestations of the ores may either reflect differences in depositional environments (controlled by Eh and pH) or the post-depositional diagenetic changes.

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