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REGULARITIES IN THE FORMATION OF MANGANESE DEPOSITS ON CONTINENTS

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ABSTRACT

The destructive type of tectonic regimes directly controlled the formation of the larger part of primary manganese deposits. Recurrences of these regimes in the history of the Earth marked the periodicity of the active manganese-forming epochs. The main body of the manganese ores was deposited in as late as the Early Proterozoic, after the protoplatforms have appeared. In the Archean, the formation of the lowermost crust (lithosphere) stimulated the isomorphic dissemination of manganese, thus raising the clark of the metal in basites and ultrabasites. The taphrogenic rifting on cratons was the major ore-forming regime during the thalassocratic periods in the evolution of the Earth. On the contrary, the geocratic accretive period of the Pangaea formation was less favourable for manganese concentration. On the supercontinents, the manganese deposits practically did not appear in the orogenic and trappean magmatic zones and in the regions of hypergenic crustal formation. The latter regions are favourable for bauxite formation, but not for manganese concentration in the original rocks with the clark of the metal. Secondary manganese deposits appear only in the originally specified manganese-bearing formations. The epochs of bauxite formation and of initial manganese concentration are antipathic. The separation of iron from manganese in the formation of deposits occurred mostly under endogenic conditions. The accumulation of ferruginous ores is characterised by tholeiite, spilite-keratophyric magmatism, whereas the manganese deposits require a more acid and alkalic geochemical regime with a higher effect of fluids. The described genetic conception provides ways of elaborating new criteria for prospecting of manganese deposits.

INTRODUCTION

Manganese deposits are found in the rocks of different geological epochs, from the Precambrian to Anthropogene. They occur in geosynclinal and platform rock assemblages, in crusts of weathering, and in metamorphic layers. Though widely scattered, the distribution of the deposits, however, is specific; they are mostly bedded among marine deposits, whereas commercial manganese ores are almost completely absent from the continental series and the facies of largest lakes. Are there general regularities in the formation of manganese deposits on continents and what are the causes of these regularities? The researchers are as yet unable to give a positive answer.

The author believes that manganese orebodies and the periodicity of their appearance is primarily controlled by tectonic events; the formulation of the problem was first advanced by I. M. Varentsov as far back as in 1962 (Varentsov, 1962). The author proposed arguments in favour of the dependence of manganese concentration on destructive endogenous regimes and on their recurrence in the history of the Earth (Mstislavskiy, 1984*a*).

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The pre-Riphean megachrone has two distinct stages of manganese formation: Archean and Early Proterozoic. As universally known, the protocontinents (protoplatforms) appeared about 2600 m.y. ago, between the Archean and Early Proterozoic. The manganese accumulation, very low in the Archean, is mainly dated from that period and is found only in a few locations: gondites of Madagascar, gondites of Andhra-Pradesh in India, the manganese and carbon-bearing formation of Rio das Velhas in Brazil and other smaller manganese deposits (VARENTSOV, 1962; Geology and genesis..., 1972; Geology and minerals..., 1973).

Contrary to manganese, the ferruginous concentration was a common process in the Archean. The jaspilite concentrations of the greenstone belts constitute such deposits. An important conclusion can be derived that as far back as the Archean and actually in the endogenic conditions, the ferruginous concentration was separated from the manganese deposition. Manganese was in a diffused state and enriched vast amounts of basites and ultrabasites. We may therefore state that the Archean cannot be considered as the manganese metallogenic epoch (MSTISLAVSKIY, 1984*a*).

In contrast to that epoch, the Early Proterozoic stage of the pre-Riphean megachrone is one of the most productive in manganese; it is characterised as the **Early Proterozoic epoch of manganese ore formation.** The deposits of the gondite formation are numerous in the Lower Proterozoic (2200 m.y.) geosynclinal Birrimian system of Central and Western Africa: Nsuta, Ansongo, Tambao, etc. (Geology and minerals..., 1973; Explanatory..., 1980). The gondites are found in the Lower Proterozoic Baram and Paramak groups in Guiana, French Guiana and Surinam in South America, and also in India (1700—2000 m.y. old) (Geology and genesis..., 1972; Explanatory..., 1979). But gondites are technologically difficult and manganese is derived from them by the varieties of lateritically oxidised supergenic ores. However, the commercially important Early Proterozoic deposits are composed not of gondites, but of the ores of the itabiritic (dolomite-manganese-jaspilite) formation of the active zones in the old cratons. To these formations belong the ores of Kalahari, Postmasburg, South Africa, and the explored rich (44% Mn) ores with reserves amounting to 311 m.t., the total tonnage of predicted resources of the South African Republic reaching 12.6 billion tons (Discovery..., 1982). In the Kalahari region there are Kuruman, Middelwit, Rooisloot and other deposits which together with Kwarkwe and Ootsi of Botswana belong to the Transvaal system more than 2000 m.y. old (DU TOIT, 1957; Geology and minerals..., 1973). On the Brazilian shield, the Morro do Mina deposit of the itabiritic formation is confined to the Minas rock group 2200—1900 m.y. old, whereas on the Guiana shield the Serra do Navio carbonate-siliceous formation is located in the Amapa group. Its age, after ALMEIDA and J. V. N. DORR II, is 1800 m.y. (Geology and genesis..., 1972). The lateritically enriched Moanda deposit in Gabon, after J. BOULADON, F. WEBER and others, is confined to the sand-siliceous-pelitic volcanogenic-sedimentary Francevillian rock group 1704 m.y. old (Geology and genesis..., 1972) *(Fig. 1)*.

The gondites are characteristic features of greenstone belts, but the manganese-bearing itabirites with large commercial manganese deposits are located in the mature parts of the continental crust within old cratons of the Southern Hemisphere. The tectonic regime of the ore-forming epoch, however, was different from the regime of slow epeirogenic movements of stable platforms. In the Early Proterozoic, a tremendous destruction of the crust of the protocontinents took place and the processes of rifting were extensively manifested with the appearance of structures of the oceanic

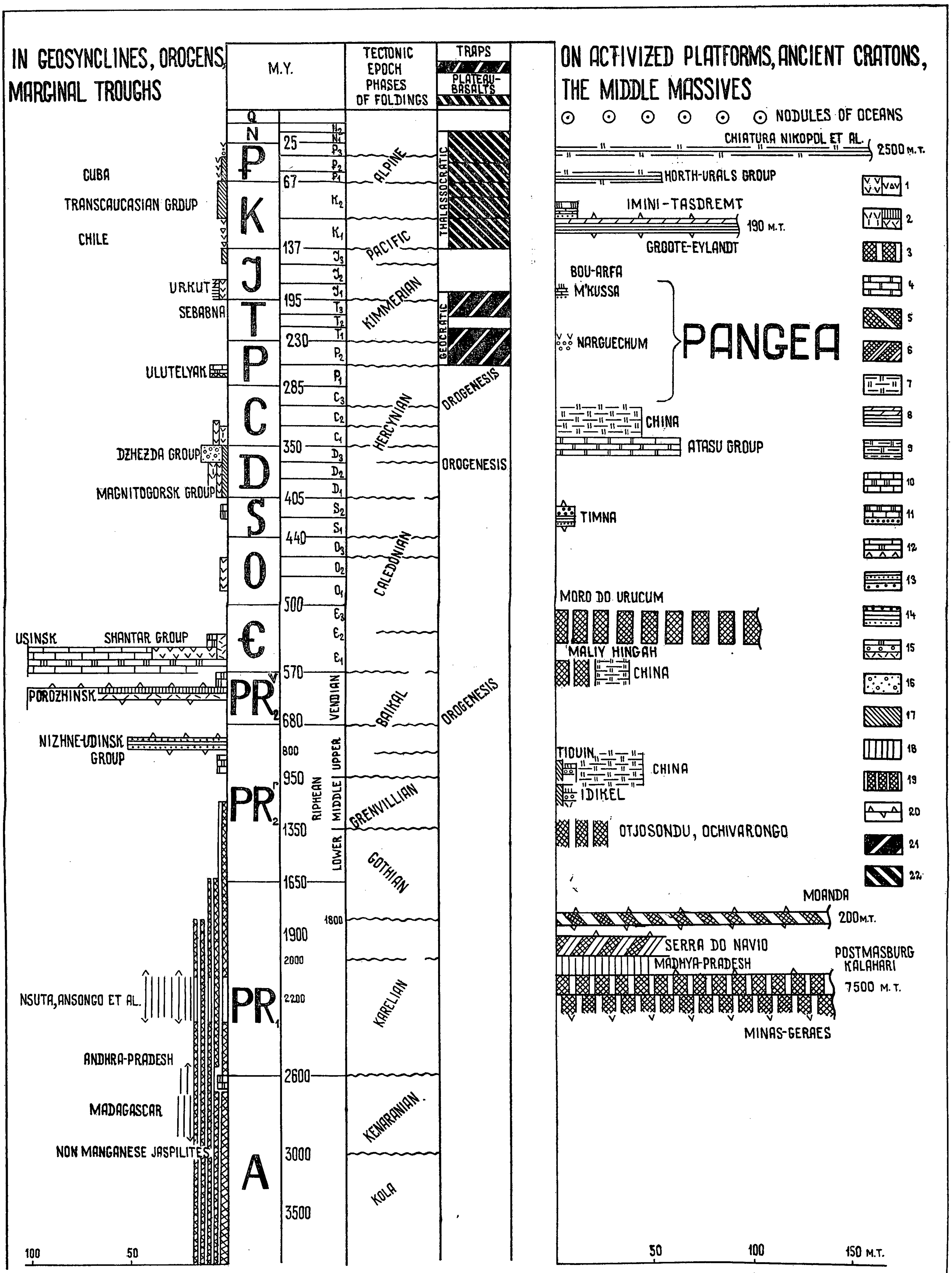

Fig. 1. Diagram of manganese forming epochs, formations and endogenous regimes. Compiled after: Varentsov, 1962; Varentsov and Rakhmanov, 1974; Du Toit, 1957; Peive *et al.*, 1980; Bouladon and Jouravsky, 1952, 1956; Frakes and Bolton, 1984; Ruiz, 1965; Simons and Straczek, 1958; and others, supplemented

Marine manganese formations: volcanogenic-siliceous: 1-spilite-keratophyre-siliceous (a), tholeiite-siliceous-greywacke (b); 2-porphyry-siliceous (a); tuffite-porphyry-siliceous (b). Carbonate-siliceous formations; 3-dolomite-manganese-ferruginous-siliceous (itabiritic); 4-dolomite-siliceous-limestone ferro-manganese (Atasu). Siliceous-shale, siliceous-clay and argillaceous (predominantly) formations; 5-dolomite-siliceous-sandy-argillaceous ferro-manganese; 6-limestone-siliceous-graphitic-shale; 7-siliceous-shale-orthoquartzite; 8-marl-clay; 9-sandy-glauconite-siliceous-clay. Carbonate formations: 10-dolomite-limestone; 11-limestone-dolomite; 12-halogenic-carbonate.

Terrigenous formations: 13-glauconite-quartz sandy-clay; 14-sandy-clay (lagoon).

Continental formations: 15-volcanogenic-carbonate-terrigenous; 16-molassic and volcanogenic-molassic.

Post-magmatic formations: 17-hydrothermal-metasomatic ores in a variety of formations *Metamorphogenic formations:* 18-gondite.

Ferro-manganese formations: 19-jaspilitic (not in scale of ore sources); 20-lateritic-enriched deposits *Stages of manifestation:* 21-traps; 22-oceanic plateaubasalts type (PEIVE *et al.*, 1980) or geosynclinal belts. In the Early Proterozoic, jaspilites were deposited on a gobal scale within the geosynclines, whereas the manganese-bearing itabiritic formations appeared with dolomites in the active taphrogenic structures* and rifts on the old cratons of the Southern Hemisphere *(Fig. 1)*. The distribution of the manganese-bearing itabirites in the Southern Hemisphere is apparently one of the indications of a dissymmetry in the Earth's evolution connected with the breakup of Gondwana and formation of intracraton geosynclines (BOZHKO, 1984). The appearance of manganese-bearing intracraton geosynclines was synchronous with the proto-Thetys opening and has much in common with the phenomenon of reflected tectono-magmatic activisation.

The Riphean is the next manganese forming epoch, which has two stages associated with the initial phases of the Grenvillian and Baikalian epochs of tectogenesis *(Fig. 1)*. In the Riphean, the geosynclinal manganese-bearing formation, which produced gondites in the process of metamorphism, has almost disappeared and the number of manganese-bearing itabirites was sharply reduced. The latter are found in Namibia in the Damara group, the Otjosondu and Ochivarongo deposits (Geology and minerals..., 1973; Explanatory..., 1980). At the same time, the manganese deposits have appeared on the African craton but as constituents of the continental series associated, after G. CHOUBERT, with the acid platform volcanites; such are the Idikel (1,350—900 m.y.), Tiouin, Migouden, Offremt deposits and more than 200 manganese veins pervading the Ouarzazate group927—832 m.y. old (Geology and genesis..., 1972). After J. BOULADON and G. JOURAVSKY (Geology and genesis..., 1972), the Idikel deposit of braunite, psilomelane ores is a metamorphosed hydrothermal sedimentary limnetic formation. On the Chinese platform, the manganese deposits also appeared in the Riphean, whereas in the USSR, there are the Nizhneudinsk group of deposits in the Sayan foredeep and the manganese ores in the geosynclinal units of the Baikal region and the Enisei Range (VARENTSOV, 1962; VARENTSOV, RAKHMANOV, 1978).

The Vendian-Cambrian manganese metallogenic epoch occurred between the Proterozoic and Paleozoic. The Vendian rocks of the Enisei Range contain the Porozhinsk deposit of oxide and carbonate (oxidised in the Meso-Cenozoic) manganese ores in the siliceous tuffites and silicites. To Cambrian time belong the Lower Cambrian Usinsk deposit in the eugeosynclinal zone of the Kuznetsk Alatau, the Gornoshorsk, Arghinsk, Shantarsk groups of deposits and the Durnovsk deposit in Salair *(Fig. 1)*. On active platforms, the Lower Cambrian deposits are located in China, the manganese itabirites in the Maly Khingan median mass, and others (VARENTSOV, 1962; VARENTSOV, RAKHMANOV, 1978). One of the largest regions in the world of manganese-ferro-siliceous formations, situated on the Central Brazilian shield, is characterised by a "typically tectonic position"; the Moro do Urucum deposit located in this region is confined to the lower part of the Jacadigo group of the undifferentiated Cambrian-Ordovician rocks also observed in the geosynclinal complex of the Andes (Explanatory..., 1979). As described by J. V. N. DORR II (Geology and genesis..., 1972), unlike itabirites in other regions, the rocks of the Jacadigo group on the Brazilian shield are only slightly crumpled and unmetamorphosed; the degree of their weathering and hypergenic manganese and iron enrichment is low. This is a positive evidence of the primary nature of commercial manganese ores in jaspilites.

* Taphrogenesis here means contrasting and geologically short-lived subsidences or collapses of crustal blocks along deep ruptures.

The Cambrian epoch of manganese accumulation, the first most productive epoch after the Early Proterozoic one, is coeval with the processes of global destruction during the opening of Proto-Atlantic and in the Vendian-Early Cambrian with the processes of destruction during the formation of the Asian paleo-ocean between the Siberian, East European and Chinese Precambrian continents (PEIVE *et al.*, 1980).

In the Ordovician-Silurian, both oceans closed, which is manifested also in the absence of corresponding epochs of manganese accumulation and in the activity of only secondary manganese metallogenic stages. By the beginning of the Devonian, vast areas of continental crust were formed in these regions, and only in the Urals and Irtysh-Zaisan zone new linear oceanic structures appeared (PEIVE *et al.*, 1980). The geosynclinal manganese deposits of the Mugodzhar Ordovician group and the Magnitogorsk Lower and Middle Devonian group with deposits in the Bugulygyr jasper stratum are actually confined to these structures (GAVRILOV, 1972) *(Fig. 1)*.

The Devonian metallogenic epoch produced the commercial deposits of the active zones. The most important is the Atasu group of ferromanganese deposits of Central Kazakhstan (Karazhal, Ushkatyn, Zhairem, etc.). A. A. ROZHNOV and co-authors (Geology and geochemistry..., 1982; New data..., 1980) indicate, that these afacial deposits were formed at the same time as the basalt-liparite high alkalinity formation during the active tectono-magmatic stage of the Famennian and in the beginning of the Tournaisian. In the adjacent Dzhezda region, the Upper Devonian red limestones are superimposed by the hydrothermal ferro-manganese ores of the Dzhesda Nazaitas and other deposits (KALININ, New data..., 1980). The Atasu and Dzhezda group of deposits reveals the more contrasting **Late Devonian Early Carboniferous epoch.** The Early Carboniferous stage of this epoch is extensively represented in many regions of the world: on the active Chinese platform, in the geosynclines of the Urals (Akkerman) and Morocco (Glib an Nam) (VARENTSOV, 1962). After Said, the Suez graben developed on the African craton in the Upper Devonian-Early Carboniferous and continued in the Red Sea area (MILANOVSKIY, 1976). Along this rift zone in Egypt, the carbonate rocks of Carboniferous age contain the Umm-Bogma and Umm-Rina manganese deposits and the vein manganese ores at Wadi Malik, Agwampt, etc. (Geology and minerals..., 1973) *(Fig. 1)*.

In the middle of Carboniferous age, the continental crust was formed on the vast area of Eurasia. Eurasia and North America composed Laurasia, which at the end of the Paleozoic joined with Gondwana into the Pangaea supercontinent. The geocratic continental regime was now developing on a planetary scale. It should be emphasised, that the geocratic period of formation and the existence of Pangaea from the Middle Carboniferous to the middle of the Early Jurassic was the least favourable for manganese accumulations not only on orogens and the plates themselves, but also in the areas of trapp magmatism and regional hypergenic formation of the crust. For example, in Triassic-Jurassic epoch of the hypergenic formation of the crust the manganese accumulations were not deposited on the territory of the USSR. This was the situation not only in Eurasia, but practically on the entire territory of Pangaea *(Fig. 1)*.

Triassic-Jurassic (particularly T_3-J_1) **and Permian-Triassic** (P_2-T_1) **epochs** experienced intensive trapp magmatism in a number of large regions of the globe, such as the Tungussk syneclise of Siberia (P_2-T_1), the Parana syneclise in South America (T_3) and other structures with the areas of trapp formation over the Gondwana relicts in South Africa (the Karroo syneclise), Antarctica, and Tasmania (T_3-J_1) (BELOUSSOV, 1976). These regions are almost without manganese ores, whereas the ferruginous deposits in trapp formation are fairly numerous.

Therefore, the territory of Pangaea in the Permian-Triassic continental geocratic period of trapp magmatism and in Triassic-Jurassic epoch of regional hypergenic formation of the crust had practically no manganese accumulations (MSTISLAVSKIY, 1984*a*). In Morocco, the Nargeuchum group of deposits in the Permian-Triassic red limestones is associated, after J. BOULADON and G. JOURAVSKY (1956), with distal volcanism (VARENTSOV, 1962) *(Fig. 1)*.

The taphrogenic leptogeosynclinal subsidences of several aquatories in the northern part of Pangaea in the Early Permian, however, caused the activity of the Lower Permian manganese accumulative stage, for example, in the northern continuation of the Urals within the Pay-Khoy and on the Novaya Zemlya. In this region of the Arctic, a new manganese-bearing province of carbonate manganese ores of hydrothermal-sedimentary origin, after V. S. ROGOV and co-authors, is located in the black carbonaceous argillites and aleurolites interbedded with phtanites and limestones (Manganese..., 1984). In *Fig. 1* this Lower Permian ore deposit is not shown, because it can misrepresent the actual absence of manganese deposits on the Pangaea supercontinent itself during the geocratic regime of continental sedimentation and hypergenic formation of the crust inside the continent. The Lower Permian manganese accumulation on Novaya Zemlya and Pay-Khoy was probably associated with the cracks of the rift which penetrated to the northern margin of Pangaea from the Arctic Ocean. The Ulutelyak deposit of manganous limestones with alabandite is described as the sedimentary deposit bedded in the marly-dolomite-anhydrite Lower Permian stratum in the junction zone between the East European platform and the marginal foredeep of the Urals (GRIBOV, 1972).

As soon as Pangaea began to break up, the manganese ores resumed their accumulation in different parts of the globe. For example, in the second half of the Early Jurassic and in the Middle Jurassic the geosynclinal regime is revived in the Alpine belt (BELOUSSOV, 1976) synchronously with the formation of manganese deposits in Hungary (Úrkút), in the northern margin of the African craton in Morocco (Bou Arfa, M'Kussa) (VARENTSOV, 1962), and in the regenerated geosyncline on the southern slope of the Caucasus Major with large pyrite-polymetallic manganese deposits and ores (SMIRNOV, 1982). It is assumed, that in the Late Jurassic the modern Atlantic and Indian oceans started to open, thus predicting the Late Jurassic stage to be a manganese-forming time period. The opening increased in the Cretaceous, when great volumes of plateau-basalts were erupted in the oceans. The available data implies that the initial stages of riftogenesis and taphrogenesis of the oceanic stage of development were productive in manganese accumulation.

The Cretaceous-Paleogene thalassocratic epoch confirms this regularity by accumulating tremendous amounts of manganese in different regions of the world *(Fig. 1)*. For example, the formation of the largest Groote Eylandt Lower Cretaceous (Albian) manganese deposit in Australia (MCINTOSH *et al.*, 1975; FRAKES, BOLTON, 1984) was nearly synchronous with the contrasting block subsidences and basaltic effusions in the eastern part of the Indian Ocean. On the African craton in Morocco, the Imini-Tasdremt deposit in the Cenomanian-Turonian limestone-dolomite stratum was also formed nearly synchronous with a burst of the large Late Cretaceous effusions of oceanic plateau-basalts. This stratified deposit of high-quality oxide ores is occasionally accompanied by manganese veins and, after J. BOULADON and G. JOURAVSKY, has hydrothermal-sedimentary origin.

The numerous small Paleocene deposits of Northern Urals (Polunochnoye, Ivdel, etc.) stretch 200 km along the eastern slope in a narrow intermittent band (RABINOVICH, 1971). In the Paleocene, the rifting and the oceanic plateau-basalt effusions were also manifested, the latter being particularly large in Briton-Arctic province. This province was probably related to the Urals belt through the zones of deep ruptures, which surround in the northeast the epi-Paleozoic East European platform and its northern part, the Barents platform. This is also indicated by the rapid transgression of the Paleocene sea from the Arctic to the south along the eastern slope of the Urals (RABINOVICH, 1971).

Such gigantic deposits of manganese ores as Nikopol and Chiatura (BETEKHTIN, 1946; Nikopol..., 1964; Chiatura..., 1964; AVALIANI, 1982; VARENTSOV, RAKHMANOV, 1974) and other deposits of Southern Ukraine, Western Georgia, the Varna region of Bulgaria and Mangyshlak form a single metallogenic province of the southern part of the USSR and Bulgaria. All these deposits and the entire manganese-bearing province appeared during one short Early Oligocene metallogenic epoch *(Fig. 1)*, when the sub-oceanic Maikop basin of the marginal type appeared in the southern part of the USSR (MSTISLAVSKIY, 1972, 1982). The basin took form in the global epoch of crustal destruction simultaneously with the taphrogenic rifting between the Eocene and Oligocene. At that time, one of the spreading stages of the Red Sea graben occurred (Recent..., 1974), whereas in the south of the USSR the geologically instantaneous taphrogenic subsidence of the Black Sea deepwater basin took place with the amplitude of 4—5 km in the very beginning of the Oligocene (YANSHIN *et al.*, 1980; MSTISLAVSKIY, 1972, 1982).

This vast taphrogenesis coincided in time with the impressive accumulation of manganese ores within one metallogenic province in the time interval of a single metallogenic Early Oligocene epoch. We believe, that this circumstance reflects the unity of the appearance of the manganese metallogenic province and of the manganese metallogenic epoch controlled by one factor, i.e., the endogenous tectonic regime of taphrogenesis.

The endogenous metallogenic regime also controls the endogenous source of manganese in the Early Oligocene sea basin under discussion. G. S. DZOTSENIDZE (1965) and his followers A. I. MAKHARADZE, V. G. GOGISHVILI, N. I. KHAMKHADZE and others (New data..., 1980) for the Chiatura deposit (Chiatura..., 1964), N. I. KHAMKHADZE, G. P. TUMANISHVILI for the Kvirili depression (Manganese..., 1984), B. ALEKSIEV and KR. BOGDANOVA (1974) for the Obrochishte deposit in the Varna ore region of Bulgaria determined the hydrothermal source of manganese and the volcanogenic-sedimentary type of manganese accumulation. These and other data provide grounds to debate the origin of the Chiatura and Nikopol deposits (RAKHMANOV, CHAIKOVSKY, 1983) considered earlier as "classically sedimentary" (STRAKHOV *et al.*, 1968). The solution of the problem shall have a general importance for the understanding of the genesis of manganese deposits on continents.

In this connection we shall discuss the recently obtained observation material of local order on the presence in the past of an ore-supplying hydrothermal channel for the Chiatura manganese deposit formed in the sea basin (MSTISLAVSKIY *et al.*, 1984). On the western slope of the Perevis Highlands, under the Oligocene manganese layer in the zone of the Major Deep Fault, the vein metasomatic-block lenslike manganese ore deposit is bedded in the Upper Cretaceous limestones *(Fig. 2)*. This deposit consists of the oxide-oxidised pyrolusite ores with residual manganite. The ores have higher Mo and V content, and the clarks of concentrations of manganese, the major ore-forming element, and its accessories Ni, Co, Cu, Ba in the ores sharply increase: tenfold for Cu, hundredfold for Ni and Co, and up to three orders for Ba. On the area, the high values of Ni, Co contents from the Upper Cretaceous limestones of the fault zone appear in the field III of the highest Ni and Co concentrations in the

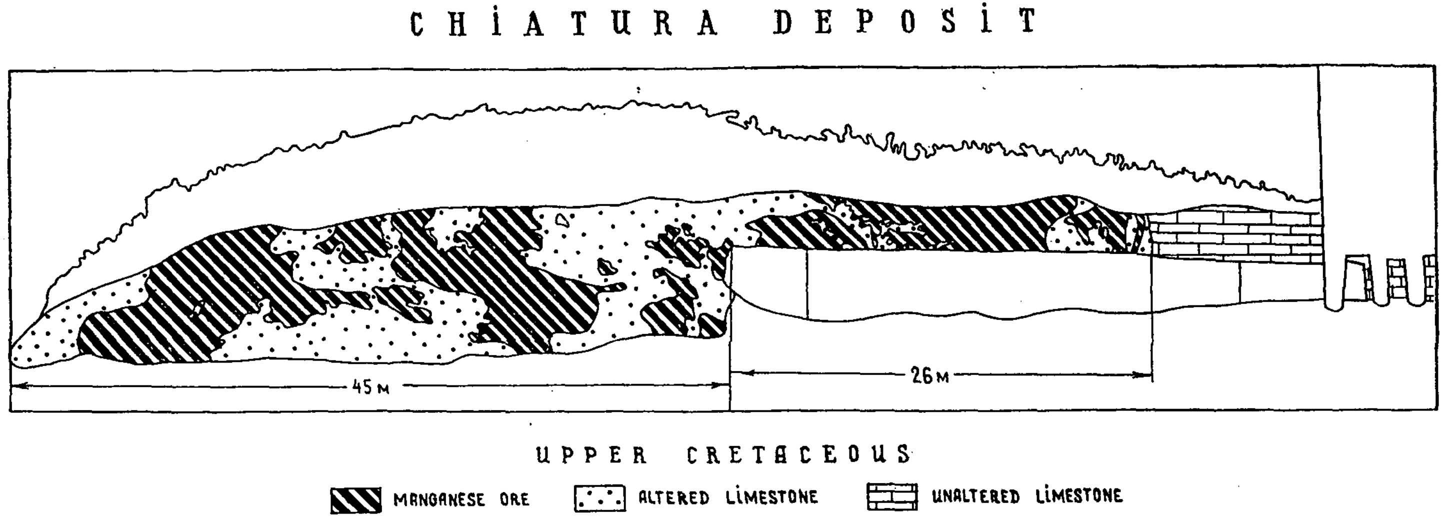

Fig. 2. Denuded fragment of the manganese ore column in the Upper Cretaceous limestones from the Chiatura deposit of the Major Fault on the Perevis Highlands 1-denudation contour; 2-manganese ores and manganised limestones; 3-loose hydrothermally altered limestones, 4-unaltered solid limestones

Oligocene stratified ores (STRAKHOV *et al.*, 1968) confined to the Major Fault *(Fig. 3)*. At the intersections of the fault with the transversal co-sedimentation faults, the mineralizing channels probably appeared; along them the manganese-bearing solutions filtered into the Oligocene sea basin and formed the hydrothermal Chiatura deposit during the period of taphrogenic destruction in the Early Oligocene. The Early Oligocene was the second most important manganese-forming epoch, as also the contrasting metallogenic stages of the Early Proterozoic, when the largest formations, such as Kalahari and Postmasburg, appeared in South Africa *(Fig. 1)*.

Therefore, the available observation material on the Chiatura and Varna groups of deposits implies the hydrothermal source of manganese in the Early Oligocene sea basin. Similar evidence for the Nikopol and Mangyshlak deposits is as yet to be collected. This circumstance still allows certain researchers to classify them as the properly sedimentary type, the more so since at first sight the tectonic position of all these Early Oligocene deposits seems different, i.e., the Nikopol group is deposited in the covering layer of the ancient craton of the Ukrainian shield, the Chiatura deposit is situated within the Alpine fold belt, and the Varna group and the Mangyshlak deposit are confined to the covering layers of the epi-Paleozoic plates, Misian and Turanian. Though the named deposits are confined to different structural blocks, the tectonic causes of their origin were the same. For instance, after tectonic stabilisation in the Late Eocene and the formation on the entire indicated territory of the shallow epi-continental sea basin, where mostly marls and limestones accumulated, a tremendous taphrogenic subsidence of the Black Sea depression took place, as noted above, in the very beginning of the Early Oligocene. These events positively imply a powerful synchronous manganese accumulation in the Early Oligocene in the southern part of the USSR, including the Early Oligocene stage of endogenic destruction of the type of the region's oceanisation. As the result of this process, the synchronous Early Oligocene manganese deposits were bedded in the periphery of the newly formed suboceanic Maikop basin or marginal sea. The author believes that the size of the deposit was actually controlled by the variations in the influence of taphrogenic processes on structurally different blocks. For example, in the regions with a thick platform layer on the epi-Paleozoic plates only small deposits were formed, as in the Varna and Mangyshlak regions, whereas the largest manganese accumulations were deposited in the regions of the denuded (or covered by a thin layer) crystalline basement of the old craton of the Ukrainian shield (Nikopol) or the Dziruli prominence of the median mass (Chiatura) (MSTISLAVSKIY, 1982). V. G. GOGISHVILI, N. I. KHAMKHADZE, V. D. GUNIAVA, from another aspect, discussed the structural confinement of manganese deposits to the Caucasus under effect of hydrothermal processes; the structural location of the Chiatura deposit in the Dziruli region was analysed by G. S. DZOTSENIDZE in the book "Recent data on manganese deposits of the USSR" (1980). All these arguments lead to the conclusion that the processes of endogenous destruction (taphrogenesis, rifting) directly affecting the crystalline basement (or the basement covered by a thin layer) of old cratons and median masses have caused, in the process of sedimentation in these structures, the formation of large and gigantic manganese deposits within the individual cosedimentary depressions *(Fig. 1)*.

Consequently, as already mentioned, the absence of intracontinental manganese accumulations during constructive accretion against the background of geocratic building of Pangaea is symptomatic. Let us note, that the regimes of tectonic stabilisation and cratonisation of the regions, together with climate, control the development of processes of hypergenic crustal and bauxite formation. We should particularly emphasise the circumstance that the manganese-forming epochs, on the one hand,

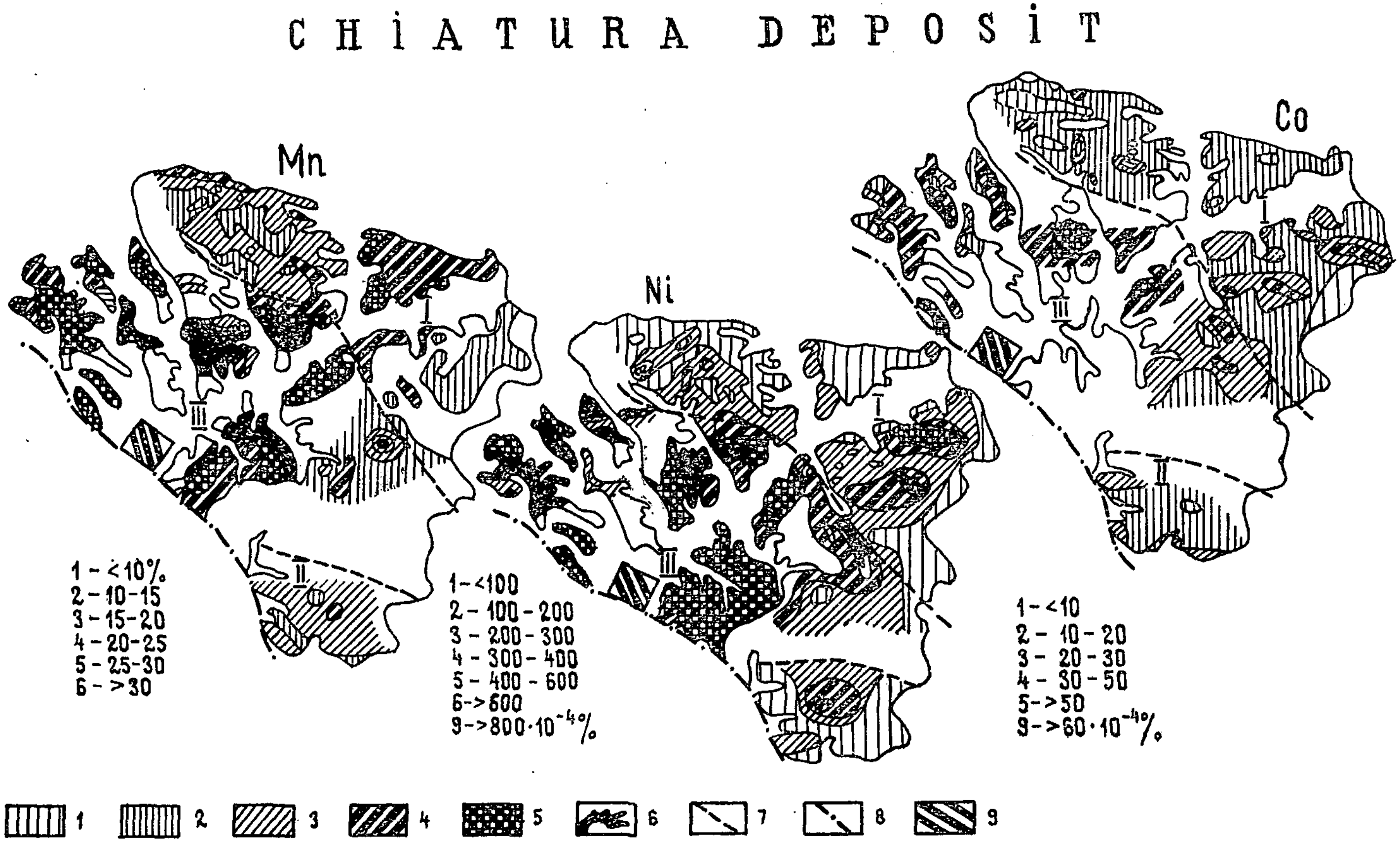

Fig. 3. Distribution of Mn (%), Ni and Co (10^{-4}%) on the Chiatura deposit, after L. E. STERENBERG (STRAKHOV *et al.*, 1968), supplemented: **A** Mn content: 1:up to 10; 2:10—15; 3:15—20; 4:20—25; 5:25—30; 6:>30; **B** Ni content: 1:up to 100; 2:100—200; 3:200—300; 4:300—400; 5:400—600; 6:>600; **C** Co content: 1:up to 10; 2:10—20; 3:20—30; 4:30—50; 5:>50; 7:boundary between the fields of different concentrations of Mn, Ni, Co in the Lower Oligocene Ores; 8:Major Fault; 9:contents of Mn (more than 10%); Ni (more than 800.10^{-4}%), Co (more than 60.10^{-4}%) in the Upper Cretaceous limestones of the Major Fault zone on the western slope of the Perevis Highlands. I, II, III-principal ore fields

and the epochs of hypergenic crustal and bauxite formation, on the other, are essentially antipathic. In the crust of weathering the bauxite and not manganese deposits are bedded in primary oreless rocks. The infiltration residual commercial manganese deposits appear only during the hypergenic enrichment and ennobling of manganese primary deposits of other genetic types formed earlier. This is particularly apparent in the lateritic transformation of technologically unfavourable gondite deposits into the manganese oxide ores of the crust of weathering. Therefore, combined manganese-bauxite deposits, suitable for commercial extraction of manganese, are unknown. Consequently, we presume that the geochemical triad Al-Fe-Mn considered earlier (STRAKHOV *et al.*, 1968), collapses during the formation of deposits (but not of geochemical aureoles) of these metals in the crust of weathering: manganese falls out because it forms neither hypergenic crustal deposits in oreless rocks with the clark of metal (for example, the hypothetical bauxite manganese bodies), nor the sedimentary continental deposits unaffected by volcanism. The manganese ores are more often characterised by a different geochemical triad, i.e., manganese-iron-phosphorus. Its analysis, however, is beyond the scope of this paper.

J. BOULADON, G. JOURAVSKY (1952, 1956), G. CHOUBERT (Geology and genesis..., 1972) have used the typically continental manganese deposits on the African craton (Idikel, Nargeuchum, and others, see *Fig. 1*) to show their hydrothermal-sedimentary and properly sedimentary origin in lake basins associated with manifestations of continental volcanism. Such manganese accumulations on continents are usually spatially connected with the hydrothermal-metasomatic vein manganese ores, for example, in the Quarzazate province (Geology and genesis..., 1972). The Golconda Pleistocene continental volcanogenic-sedimentary manganese deposit is also associated with volcanism. The ores of this deposit have high contents of trace elements: tungsten up to 6.19% WO_3 (average 0.5%), lead up to 5%, and copper up to 0.3% (KERR, 1940).

The unquestionably sedimentary manganese deposits are apparently only those belonging to the type of manganese recent "embryonic" accumulations found in the lakes of Karelia and Finland and in the Baltic and Beloye inner seas; they derive this metal from the crystalline rocks of the Baltic shield (STRAKHOV *et al.*, 1968 SAPOZHNIKOV in: "Geology and geochemistry..., 1982). Other present-day inner seas do not reveal manganese accumulations not being in the zones of volcanism or having no discharge regions for brines. Even the modern Black Sea cannot be regarded, from our viewpoint, as the prototype of the basin, where the sedimentary manganese can accumulate in commercial concentrations. The reason is that during the Neogene-Quaternary, within the drainage area of the Black Sea basin, not only the common rocks with the clark of the metal were eroded, but also the denuded manganese deposits themselves, including those of Nikopol and Chiatura. For example, almost 50% of the Chiatura deposit was eroded and the denudation products were washed out into the Black Sea impounded basin. But new sedimentary manganese accumulations were not re-deposited in the Black Sea in the Neogene-Quaternary, and the submarine deltas of the Rioni and Dnieper rivers, whose tributaries wash out the Chiatura and Nikopol deposits, contain only non-commercial manganese aureoles. Moreover, the waters of the Black Sea, in the hydrogen suplhide zone, have collected up to 100 million tons of dissolved manganese (SAPOZHNIKOV, 1967). In order to obtain 100 million tons of manganese in one deposit, the total volume of the Black Sea water should be somehow "evaporated" and the whole amount of manganese "precipitated" in one locality. It is nonsensical even to suggest this hypothetical "geological process" for the formation of sedimentary manganese deposits, let alone such giants as Nikopol and Chiatura.

All this evidence, we believe, testifies that without volcanism and plutonism the continental basins-lakes and inner seas are genetically unfavourable for the formation of commercial manganese deposits. Proceeding from tectonic conceptions, these deposits are formed in the marginal seas, which appear during taphrogenesis, or in the regions of rifting, when the oceanic crust opens, i.e., in the destruction areas. The cause of the predominance of marine manganese deposits over continental ones is, therefore, apparent if viewed from these concepts. Both taphrogenesis and spreading control the rapid deepening of epi-continental sea basins in the regions of subsidence and of crustal spreading during the formation of deepwater basins. The manganese deposits synchronous with tectonic destruction actually occur in the periphery of these structures, in the intersections of differently oriented cosediment faults within newly formed separate foredeeps or depressions (MSTISLAVSKY, 1982). All Early Oligocene manganese deposits in the south of the USSR and in Bulgaria, the metalliferous sediments of the Red Sea graben, etc., are examples of these accumulations.

How are the processes of destruction manifested in the manganese-bearing regions and in the local parts of the deposits themselves? Besides the mineralising zones of cosedimentary faults with vein and hydrothermal-metasomatic manganese ores, several deposits reveal the lenslike layered sedimentary breccias of tectonic breakup and destruction. They are often thick and contain ore lumps of different size, even blocks. The destruction breccias are observed in the Porozhinsk Vendian deposit of the Enisei Range (MSTISLAVSKIY, 1984*b*), in the Usinsk Lower Cambrian deposit of the Kuznetsk Alatau, after I. M. VARENTSOV (1962), in the itabirites of the Malyi Khingan (Geology and genesis..., 1972), in the Karazhal Famennian deposit of Central Kazakhstan, after A. A. ROZHNOV *et al.* (New data..., 1980), and in other regions. We also tend to classify as the manganese destruction breccias, preceding the supply of hydrothermal ore-bearing solutions into the basin, the Blinkklip Lower Proterozoic basal manganese-bearing breccia of the Postmasburg deposit in South Africa, after A. Du TOIT (1957), the intraformational breccias of the El Cobre Cretaceous-Eocene manganese formation of Cuba, after F. SIMONS and J. STRACZEK (1958), the Imini-Tasdremt breccias, after J. BOULADON and G. JOURAVSKY (1956), V. P. RAKHMANOV, I. K. TCHAIKOVSKY (1980), and other deposits.

The structural position of the breccias is peculiar. They are confined to the roof and near-roof parts in the sides of the anticlinal structures. The comparison of the bedding of the basal manganese-bearing breccias in the Postmasburg deposit, South Africa, and in the Porozhinsk deposit, the Enisei Range, has revealed similar features of their occurrence. Both of them are deposited uncomformably and with washout on the underlying dolomites in the near-roof parts of the structures. The breccias wedge out towards the central parts of the depressions, whereas the angular unconformities and erosions between the two contacting layers disappear (MSTISLAVSKIY, 1984*b*). The analogous bedding of sedimentary breccias is typical of the Karazhal deposits in Central Kazakhstan and probably of other manganese-bearing regions as well. The sedimentary character of breccias with lumps of manganese ores are discussed in detail by F. SIMONS and J. STRACZEK (1958) in terms of evidence of the syngenetic manganese lenslike occurrence in the El Cobre Late Cretaceous-Eocene formation of Cuba.

Besides their stratified lenslike bedding, the manganese-bearing breccias of tectonic destruction in the mentioned deposits are also characterised by other sedimentary features. They are chaotically heaped and without orientation; the ore lumps have different size and habit ranging from several millimeters to decimeters in diameter. The dominating irregular sharply angular habit and the variety of dimensions of lumps of rocks mostly from the enclosing formations, a small amount or absence of gravels of other rocks positively imply the destruction of lithified deposits and intraformational redeposition, chaotic heaping of fragments without remote transportation, rounding or hydrodynamical differentiation.

This kind of breccias is characteristic of volcanogenic-sedimentary deposits with notable domination of pyroclastic and siliceous rocks. The cement of the breccias themselves is mostly composed of the carbonate-siliceous substance, whereas the manganese mineralisation in the non-metamorphosed strata predominantly contains manganite and rhodochrosite with accessory goethite. Manganite also dominates among breccias of redeposited manganese ore lumps, as for example in the Porozhinsk deposit (Mstislavskiy, 1984*b*). At the Porozhinsk deposit, the hydrothermal-metasomatic mineralisation with hausmannite and rarely occurring manganosite was cored at the intersections of faults. These minerals apparently indicate ore shoots, relicts of mineralising channels, which supplied manganese-bearing solutions through the underlying rocks to the basin.

The Porozhinsk deposit in the taphrogenic-siliceous formation, after D. I. Musatov, V. V. Ustalov *et al.,* (New data..., 1980) is located in the Vendian orogenic foredeep of the Enisei Range. It was formed, however, not in the orogenic regime, but during the taphrogenic activity which followed tectonic stabilisation and accumulation of the dolomite layer in the interval between the lower and upper molassic deposits. In a similar manner the hydrothermal-metasomatic ores of the adjacent region were deposited with the formation of the Atasu graben-syncline during the taphrogenic tectono-magmatic activity; these ores are superimposed on the Upper Devonian red limestones of the Dzhesda and Nazaitas deposits (Kalinin, in: "New data...," 1980). The same tectonic position probably occupy the Barremian-Albian manganese stratified deposits of the Arqueros and Quebrada Marquesa formations in the Cocuimbo province, Chile, after C. Ruiz (1965), F. Peebles (1970), E. A. Sokolova (1982).

To emphasise the regularity of confinement of manganese deposits to the regions of crustal destruction, let us recall that manganese-bearing metalliferous sediments of the present-day oceans are found in rifts (the Red Sea grabens, the Gulf of Aden, etc.), in tectonic depressions (the Hess and Bauer depressions), on the slopes of the mid-oceanic ridges, which were formed, as generally acknowledged, by the spreading of the lithospheric plates. The direct observations of the hydrothermal manifestations on the Pacific bottom in the Galapagos active zone and in the Hess depression, after G. Klinkhammer *et al.* (1977), V. V. Gordeev, L. L. Demina (1979), have shown the Mn content to reach 24 mkg/kg at the spouts of the hydrotherms in the bottom water, where the deep isotopes ^{3}He, ^{222}Rn were also detected. All known regions of metalliferous ferro-manganese sediments, with the accessory microelements Ni, Cu, Co, Zn, V are associated with the regions of crustal destruction in the zones of spreading and taphrogenesis. The latter process evidently controls the appearance of large depressions in the ocean bottom several hundreds of kilometers long (the Hess depression and others). The destruction processes in transform faults cause the appearance of zones analogous to the Clarion-Clipperton interrift zone in the Pacific. In this zone, after D. Cronan (1973), M. Bender, I. Dymond (1973), I. M. Varentsov (1976), the ferromanganese concretions are found having high Mn content 22.33% and contents of Fe 9.44%, Ni 1.08%, Cu 0.63%, Co 0.19%.

CONCLUSIONS

By using the available data on the relation between the manganese-bearing capacity and the destruction processes, we classified the manganese deposits according to their confinement to the basic commonly acknowledged tectonic regimes: *1*-platform proper, plate or epeirogenic; *2*-platform with trapp magmatism (geocratic); *3*-geosynclinal; *4*-orogenic; *5*-taphrogenic activisation of platforms and ancient cratons; *6*-oceanic (thalassocratic). The last regime should probably be described as mostly the taphrogenic-rifting endogenous one. The most manganese productive are the oceanic regime and the regime of taphrogenic activity of platforms and particularly of ancient cratons and median masses. Among the geosynclinal regimes, the most favourable is the island arc regime with a sufficiently intensive explosivity. The regime of early geosynclinal large troughs usually produces only small manganese deposits. In the troughs, the ferro-manganese accumulations are normally deposited during the formation of undifferentiated tholeiitic basalts. These deposits are also typical of the trapp formation.

We should emphasise, therefore, the different character of volcanism, during which the iron and manganese ores could accumulate. Manganese ores are often characterised by the differentiated andesite-basalt-liparite series with high alkalinity. For example, as stated by A. A. Rozhnov and A. B. Veimarn, this is typical of cont trasting differentiated subalkaline-basalt—alkaline-liparite formation of the Atasu group of ferro-manganese deposits in Central Kazakhstan; the formation is associated with the potassic metasomatism (New data..., 1980; Geology and geochemistry..., 1982). In Chiatura and Western Georgia, the pronounced alkalic nature of magmatism on the Okribo-Dziruli prominence directly preceded manganese accumulation during the period from the Late Cretaceous to the end of the Late Eocene (Dzotsenidze, 1965). The subalkalic volcanism characterises a number of other manganese-bearing regions.

The genetic positions described above form the basis of systematic classification of criteria for prospecting manganese deposits on continents. Of major importance are the syngenetic criteria on a regional scale and first of all the manganese forming epochs.

The manganese forming epochs, considered as strictly stratigraphical intervals and used as prospecting criteria, still cannot serve as direct indications of manganese accumulations for any territory. We believe, that the epochs are metallogenic for manganese only in the regions, which experienced a special kind of endogenous regime, i.e., taphrogenic or taphrogenic-rifting. Consequently, the stratigraphic indication is combined with the tectonic factor into a single tectono-stratigraphic criterion. The author notes the unity of metallogenic manganese forming epochs and provinces and emphasises their common genetic causes controlled by the manifestations of the taphrogenic-rifting regime. To conclude, the manganese-metallogenic zoning of the territory is based on the specific tectonic properties of the regions derived from the formational and genetic principles controlling ore-prospective areas.

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