1-5 Tectonics of Ni- Cu-PGE Ore Deposit by Continental Flood Basalt

The Ni-Cu-PGE ore deposit is mineralized accompanied by basic to ultrabasic intrusive and / or volcanic rocks. The ore deposit is classified into the following four types by their features and components: (1) ore deposits accompanied by basic sill that is astrobleme origin (Sudbury, Ni : Cu = 1 : 1), (2) ore deposits accompanied by basic sill / dyke which is rift continental flood basalt origin (Noril'sk, Duluth, Crystal Lake, Jinchuan, Ni : Cu = 1 : 1 to 11), (3) ore deposit accompanied with komatiitic volcanic / intrusive rock (Thompson, Langmuir, Kambalda, Pechenga, Shangani, Ni : Cu = 1 : >10), (4) ore deposits accompanied by tholeiitic intrusive rock (Lynn Lake, Giant Mascot, Kotalahti, Selebi-Pikwe, Ni : Cu = 1 : 2 to 3).

In the Ni- Cu- PGE ore deposit accompanied by continental flood basalt, Noril'sk ore deposit in Russia (555 Mt, Ni 2.7 %, Cu 2.06 %) and Jinchuan ore deposit in China (515 Mt, Ni 1.06 %, Cu 0.67 %) have the world second and third ore reserves of nickel. At present, the both ore deposits are in operation as nickel mine. Besides the above two ore deposits, there are Dultuth ore deposit in Minesota, USA (4,000 Mt, Ni 0.2 %, Cu 0.66 %), Great Lake ore deposit in Canada (45.6 Mt, Ni 1.2 %, Cu 0.34 %) and Disko Bugt ore deposit in Greenland as the same origin ore deposits. The development of these three ore deposits have not carried out yet. In this chapter, the outline of the Duluth ore deposit is described, and the geneses of the Duluth and the Noril'sk ore deposits that are concerned to the tectonics are discussed. Finally, the possibility of the Cu-Ni-PGE ore deposit in the Paraná area of Brazil are discussed mainly from the viewpoint of the tectonics of continental rift.

1-5-1 Duluth Ore Deposit

(1) Geology

Midcontinent Rift (MCR) of North America has the extension of 2,300 kilometers from the central Kansas Province through the Lake Superior to the north, and runs through the south of Michigan Province to Ohio Province. The MCR that was formed in the middle of Proterozoic (1,200 to 1,100 Ma) is the world biggest class continental rift. The exposed rocks of the MCR can be observed only around the Lake Superior. In other part, they are overlain by the Paleozoic rocks. The whole feature of the MCR can be only identified by the high gravity anomalies (Fig. II-1-5-1).

The Keweennawan Complex are distributed in the rift around the Lake Superior (Fig. II-1-5-2). They are composed of nepheline-carbonatite of Kapusukasanig tectonic zone in the eastern part of the Lake Superior, gabbro-syenite of Coldwel and Killala Lake in the northern part, flood basalt related to the Mellen Complex and Duluth Complex in the southern and the western part, and sills of small dykes around the Lake Superior. The alkaline rocks in the

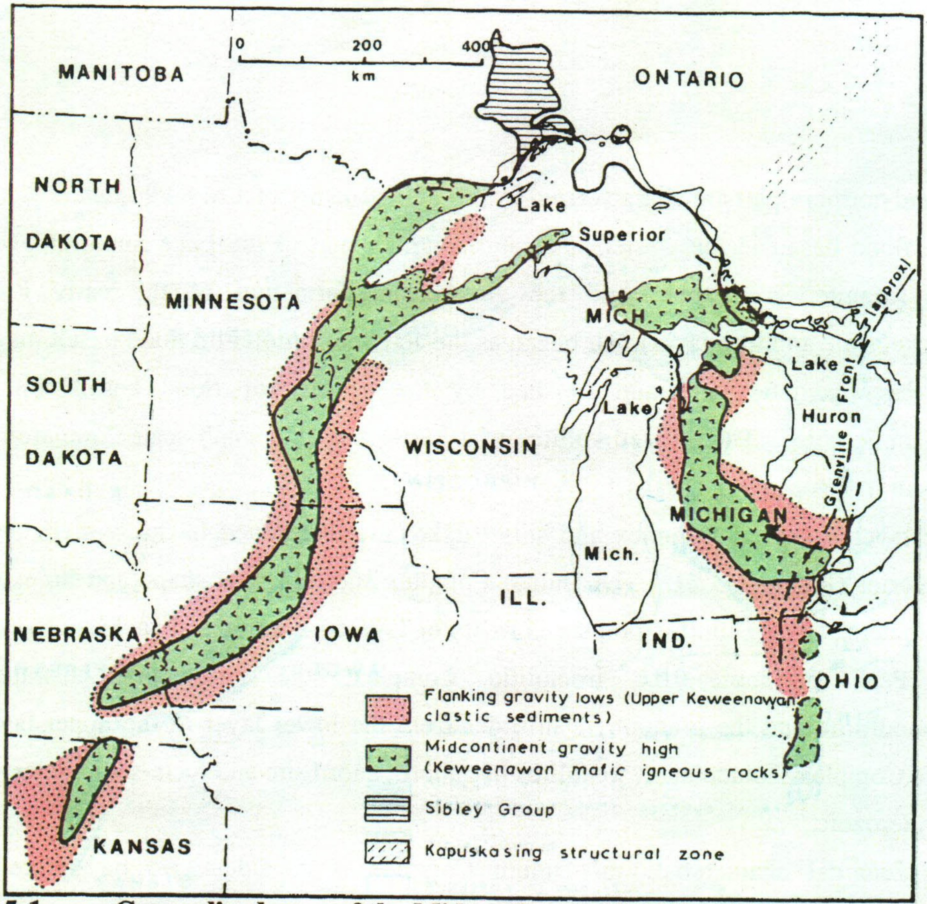


Fig. II-1-5-1 Generalized map of the Midcontinent rift of North America, after P.W. Weiblen (1980)

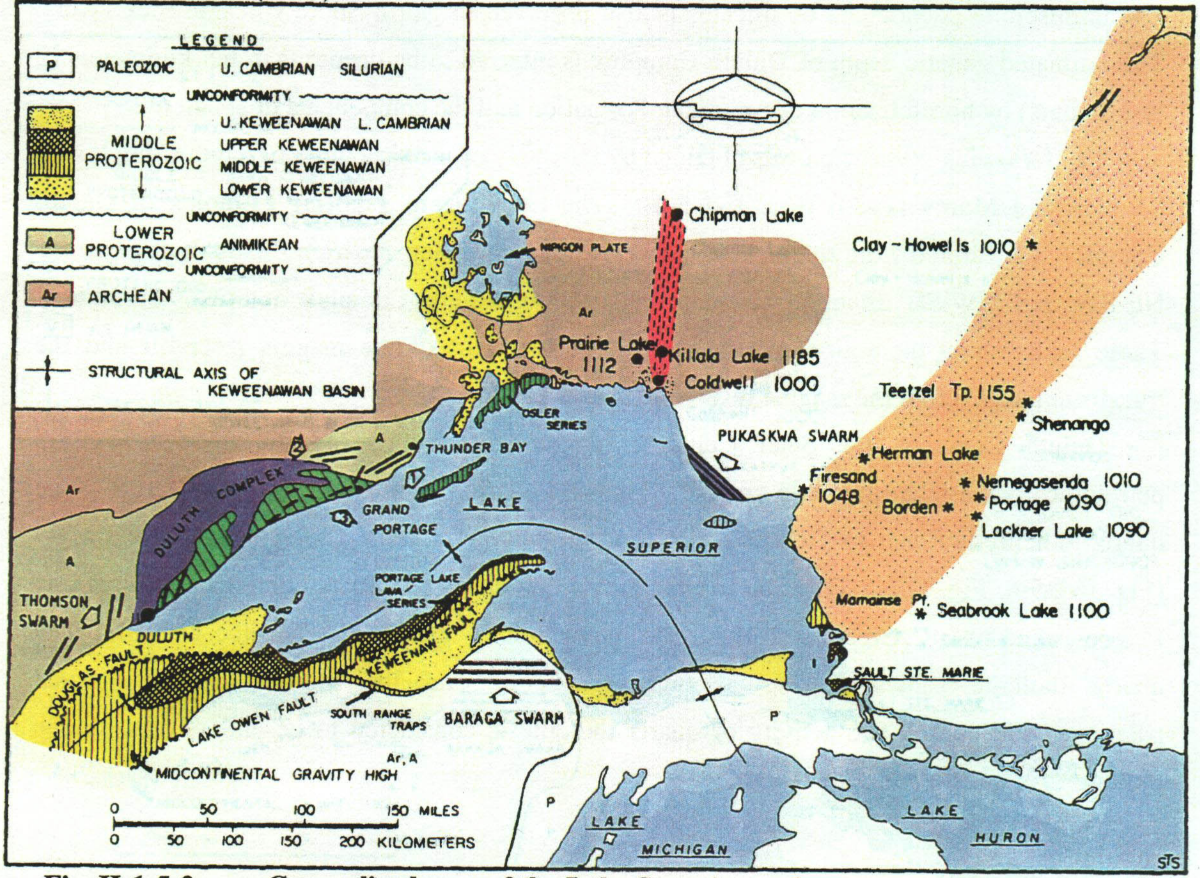


Fig. II-1-5-2 Generalized map of the Lake Superior region

Asterisks, nepheline-carbonatite complexes (K-Ar ages in m. y.) in the Kapuskasing Structural Zone (Gittens and others, 1967: Currie, 1976). Solid dots, alkaline intrusions in the Coldwell Alkaline Province (Currie, 1976). Diagonal lines, North Shore Volcanic Group. The "Nipigon Plate" refers to the patterned areas north of the Osler Series (Card and others, 1972). It includes the Sibley Group (checked pattern) (Franklin and others, 1980) and an extensive area of dip slope explosure of Keweenawan diabase sills (randomly slashed pattern). Keweenawan dike and sill swarms are indicated with heavy parallel lines. One, two, and three refer to the Thunder Bay, Gunflint, and Grand Portage swarms, respectively. The Mellen Complex is located in the area SW of the Keweenaw Fault. (P. W. Weiblen, 1982).

eastern and northern part are characterized by circular structure of 1 to 5 kilometers diameter.

The flood basalt in the western part and southern part of the Lake Superior overlies the Archean (granite, greenstone) and the Animikean Formation of the early Proterozoic (greywacke, slate and iron layer). It began as the activity of tholeiitic flood basalt magma with reverse Paleomagnetic pole and finished by the activity of flood basalt with normal Paleomagnetic pole. The erupted volume of 1 x 106 km^3 is a small scale compared with the flood basalt of Deccan and Paraná.

The layered Duluth Complex and sills / dykes are distributed in the western part of the Lake Superior (Fig. II-1-5-3). The Duluth Complex shows a bow shape and its extension is 225 kilometers. The Duluth Complex consists of layered fractionated rocks. Those are the Bardon Peak peridotite, the troctolitic Complex, the anorthositic Complex, the ferro-granodiorite and the granophyre in order from the lower layer to the upper layer. The troctolitic Complex include many xenoliths of gabbro, anorthsite and meta-sedimentary rocks of lower Proterozoic.

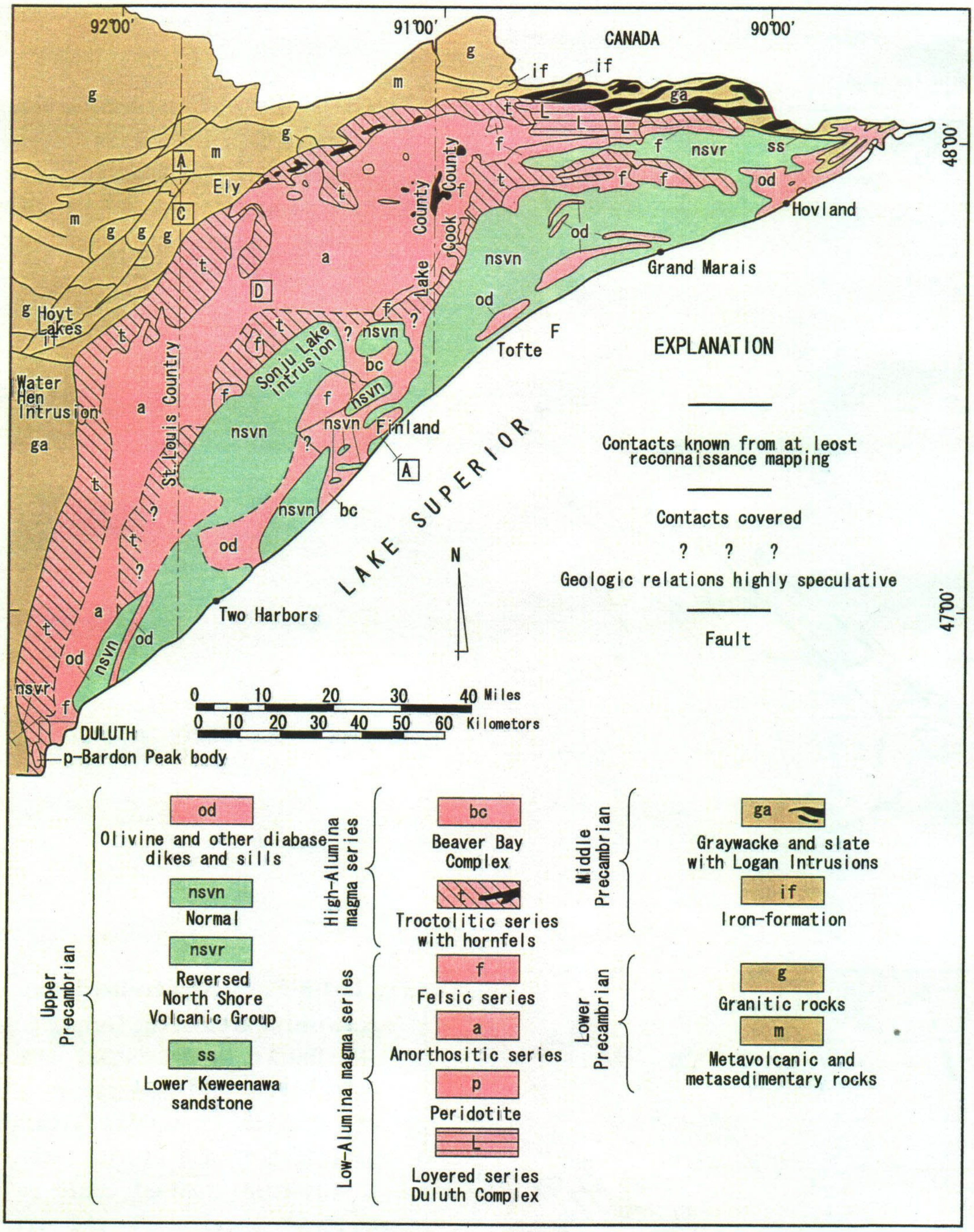
The bimodal characteristic of Duluth Complex is considered to be derived by the immiscibile phenomena of silicates that was experimentally proved in the Skaergaard magma. The immiscibile phenomena of silicates is also observed in North Shore volcanic rock layers. The estimated genetic depth of Duluth Complex is inferred to be deeper than ten kilometers (2 to 2.5 kbars) by hornfelization of Animikan Formation and the components of sphalerite.

The following conclusion was obtained by the study of the structure of Duluth Complex by Weiblen and Morey (1980) (Fig. II-1-5-4). The troctolite to gabbroic Complex of Duluth Complex was formed from the magma reservoir of semi-graben situation. The faults with the NE-SW and NW-SE direction are observed within Duluth Complex and its surrounding. These faults show the stair-step rift in the basement part of the magma reservoir and the transform faults across the magma reservoir (Fig. II-1-5-5).

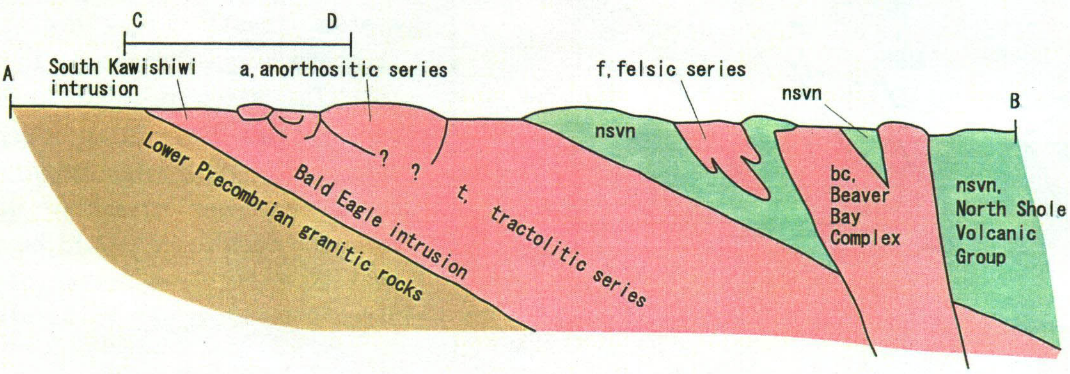
Duluth Complex, the other Complex of the surrounding and the flood basalt are petrologically classified into two groups. They are quartz tholeiite and olivine tholeiite. The quartz tholeiite is richer in TiO_2 and REE, and the olivine tholeiite poorer in Al_2O_3 and MgO (Fig. II-1-5-6, Fig. II-1-5-7). The former shows the similar chemical components to high Ti Faeroe island basalt (Greenland) of mantle plume origin, and the latter to the MORB. The quartz tholeiite shows reverse paleomagnetic pole, and the olivine tholeiite normal paleomagnetic pole. The activity of quartz tholeiite is considered to be earlier than olivine tholeiite.

(2) Mineralization

The initial sulfide minerals are composed of chalcopyrite, cubanite, pentlandite and pyrrhotite. They yield only on the basement of Duluth Complex. Generally the

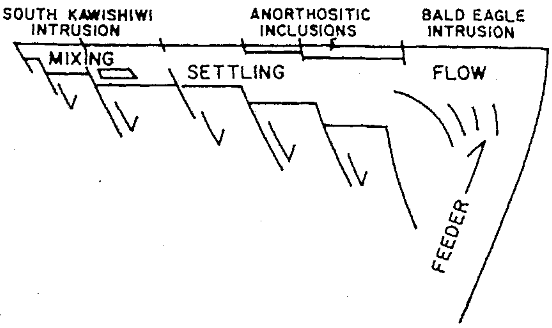


A.

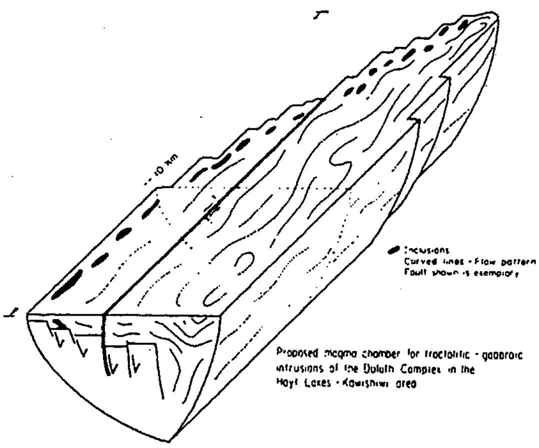


B.

Fig. II-1-5-3 Generalized bedrock geological map (A) and the cross section (B) of the Duluth Complex (P.W. Weiblen, 1982)



A



B

Fig. II-1-5-4 Cross section along Fig. II-1-5-3

1-5-3. C-D indicates crystallization regimes deduced from textures. (B) Three-dimensional view of a proposed magma chamber normal to cross section C-D (P. W. Weiblen, 1982).

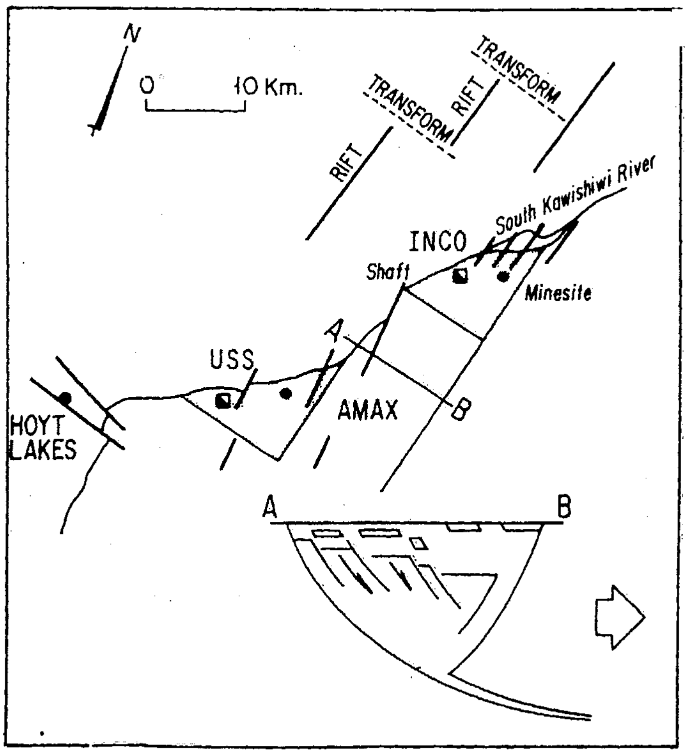


Fig. II-1-5-5 Generalized map view of the Kawishiwi area of the Duluth Complex

The faults (heavy lines) are suggested by coincidence of topographic, aeromagnetic, and gravity lineaments with joint density data (Cooper and others, 1981). The offsets in the basal contact could be generated by a small scale rift and transform fault system (inset) during evolution of magma chambers, as indicated in Fig. II-1-5-4 (B). The sites of most intensive (Cu-Ni exploration by mining companies (USS, AMAX, and INCO) lie within areas that could represent extensive development of offsets. Such areas would be likely places to find a high proportion of country rock mixed with magma (P. W. Weiblen, 1982).

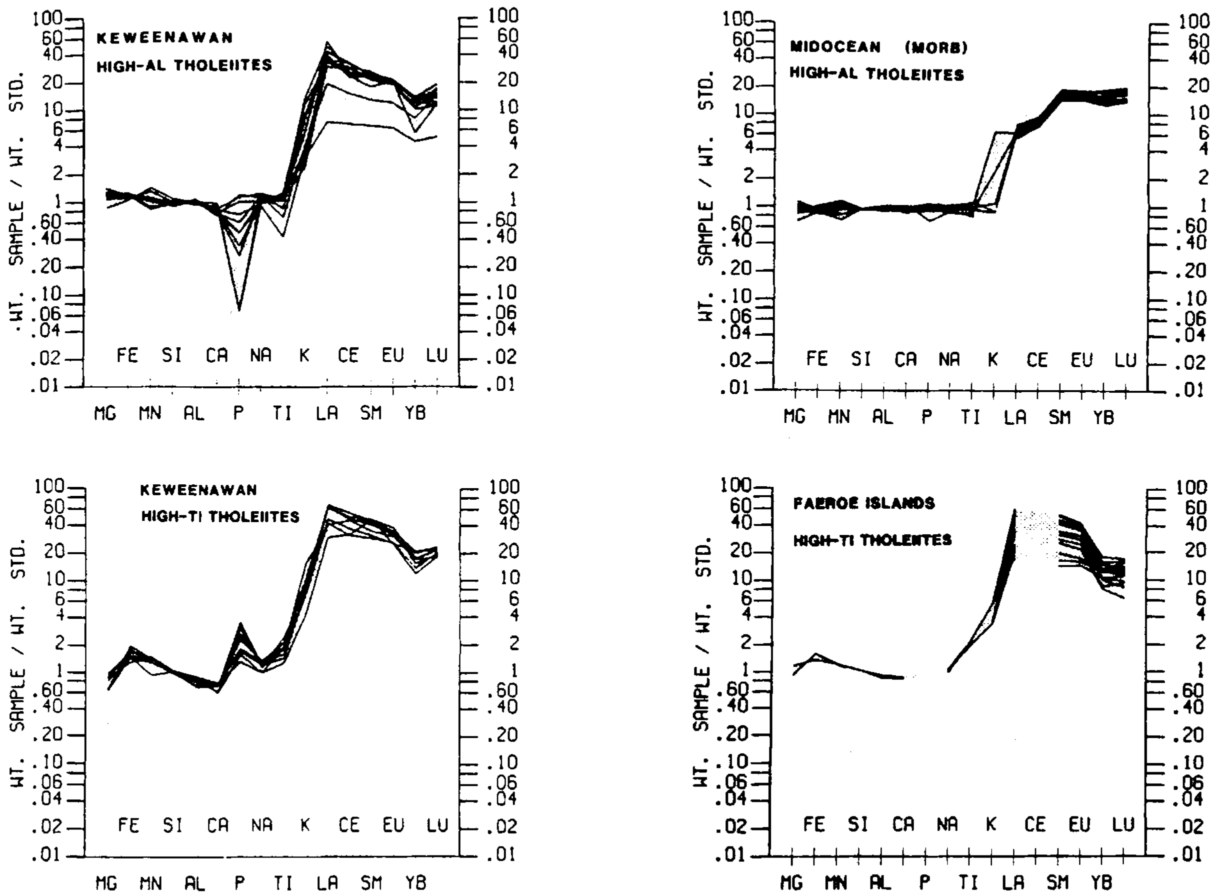


Fig. II-1-5-6 Normalization plots of compositions of Keweenawan dikes and sills; Mid-Ocean Ridge Basalt (MORB), and mantle plume basalt (High-Ti Faeroe Islands basalt)

Data are average, minimum, and maximum values. (Table 6). Data are normalized to an average composition of Midocean ridge basalt (MORB) from Bor-ming Jahn and others (1980). (P. W. Weiblen, 1992).

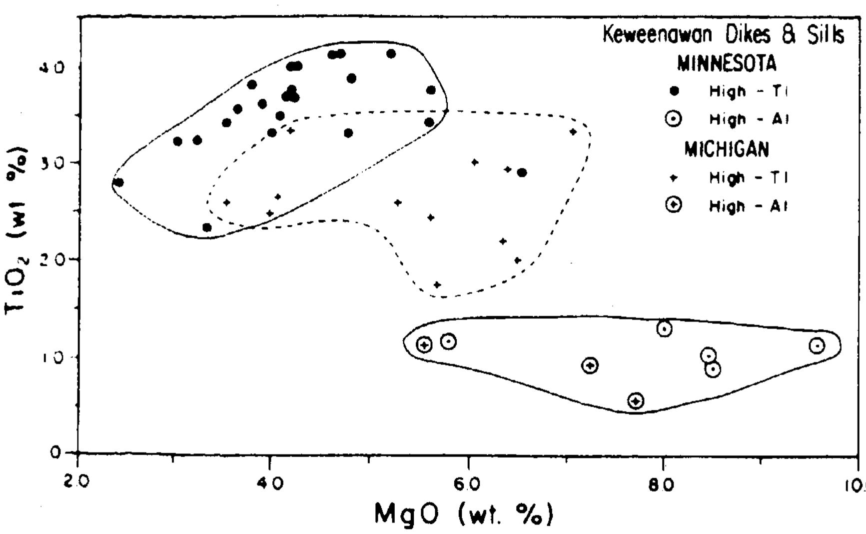


Fig. II-1-5-7 Variation diagram of MgO versus TiO_2 for Keweenawan dikes and sills in Minnesota and Michigan

Michigan. Minnesota data from N. W., Jones (in preparation);Michigan data from Wilband and Wasuwanich (1980). High-Ti refers to quartz tholeiite and high-Al to olivine tholeiite compositions Fractional crystaillization of liquidus phases of olivine, plagioclase, pyroxene, and oxides cannot produce the high-Ti variation from high-Al (Wilband and Wasuwanich, 1980). (P. W. Weiblen, 1982).

mineralization is observed within 100 meters from the basement, however, some of them observed in the range from 300 to 400 meters from the basement. Small amount of sulfide minerals yield as massive ore, other minerals yield as disseminated ore deposit within troctolite. Large amount of xenoliths of meta-sedimentary rocks are observed in the troctolite. The exploration (INCO, USS, AMAX) concentratios in Gunflint region and Kawishiwi-Hoyt Lakes region (Fig. II-1-5-5). The ore reservoir of 4,000 Mt, Cu ore grade of 0.5 wt% and Cu / Ni = 3.33 was confirmed. The chalcopyrite changed to pyrrhotite by the hornfelization in the basement sedimentary rocks. It involved excess sulfur. The sulfur melted into the magma from the sedimentary rocks in the basement of Duluth Complex. As the result, The Cu-Ni-PGE mineralization occurred by immiscibile phenomena. Considering such model, the basement of the semi-graben magma reservoir is considered to be the most potential zone of mineralization of copper, nickel and PGE.

The weak mineralization of Cu- Ni can be observed in Crystal Lake dykes within the Thunder Bay diabase. The extension of Crystal Lake dykes is 700 meters and the shape of the cross section is like a canoe. The fractionation progressed inside the dykes and the layerd structure like trough can be observed. The dykes are composed of gabbro, olivine gabbro, alternation of troctolite and anorthosite and olivine gabbro from the lower to the upper. The sulfide minerals yield within olivine gabbro and the mineral assemblage is the same as the Duluth Complex. Olivine gabbro includes many hornfelized xenoliths of meta-sedimentary rocks like Duluth Complex. The ore grade is low and it is not economical. The reason for the low ore grade is considered that the generation of sulfide melt by immiscibile phenomena was not ssufficient, because the contamination of the country rocks was weak when the dykes intruded.

(3) Tectonics of Midcontinent Rift

a) Triple Junction Model

The model is considered as follows: the hot spot-like doming in several points of the continent initiated the formation of the triple junction. Then, the triple junctions connected to form a rift system and brought about the continental rupture (Fig. II-1-5-8). Moreover, the evolution of magma from CO_2-Alkali rich magma to tholeiitic magma depending on the generated depth, the reaction between the melt and the feeder, and the grade of fractional crystallization is recognized (Bailey, 1978). The examples of the above model are the Red Sea rift of Ethiopia, the North Atlantic rift of the eastern part of Greenland, and the present Mid-Atlantic rift. As the Keweennawan intrusice rocks of MCR are composed of alkaline rock bodies and tholeiitic rock bodies, this model can be applied. Comparing the Keweennawan intrusive rocks with the them of the North Atlantic Rift (the opening in Tertiary), the similar rift

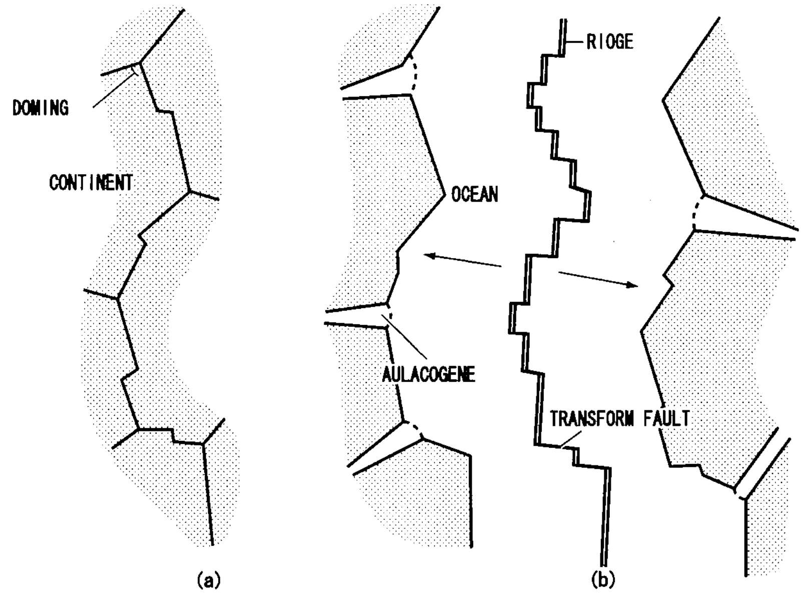


Fig. II-1-5-8 Formation of aulacogene (b) associated with the rupture of the continent (a)

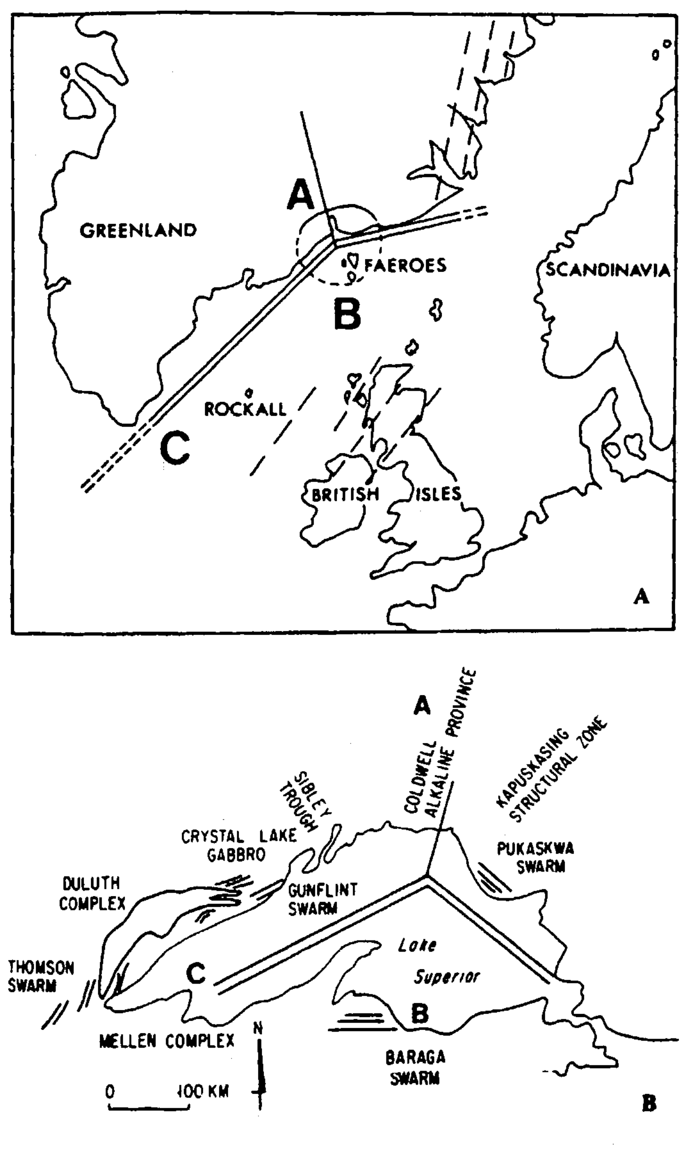


Fig. II-1-5-9 Possible analogies between tl geometry of the igneous rocks associated wi the Tertiary opening of the North Atlantic ε those in the Midcontinent Rift System

(A) Failed arm-rift relations in the North Atlantic (modified from Brooks, 1973); (a) Kangerdlugssuaq alkaline intrusion, (b) high-FeTi quartz tholeiite volcanism. (c) high-Al olivine tholeiite volcanism. (B) Analogous relations to (A) in the Lake Superior region of the Midcontinent Rift System; (a) Coldwell Alkaline Province, (b) quartz tholeiite dikes and sills, (c) olivine tholeiite dikes and sills. (P. W. Weiblen, 1982).

system can be considered (Fig. II-1-5-9). Anyone of Sibley graben, Codwell alkaline rock body or Kangerdlugssuaq alkaline rock body, can become aulacogen (failed arm). The remaining two arms correspond to the direction of the axis of rift and are connected to the other triple junctions. Flood basalt is distributed in the axis of this arm. The Lake Superior and Faeroes are considered to be the triple junction. They were considered to be the center of the magma activities.

b) Transform Fault Model

The transform fault model explains the forming of the rift and the transform fault by lateral movement. The simple shear fracture occurs with lateral movement in isotropic homogeneous medium (Fig. II-1-5-10, A- E). If there are exisiting fractures in the medium, the directions of the shear fractures change (Fig. II-1-5-10, D- E). As the lateral movement progresses, the conjugate shear fractures (R, R') change angles to the direction of the lateral movement. The low angle shear fracture (R) becomes the lower angle shear fracture, and the high angle fracture (R') the higher angle extensional fracture (Fig. II-1-5-10, G). When the lateral movement progresses further, the low angle shear fracture develops to the transform fault and the high angle extensional fracture to the rift (Fig. II-1-5-11).

Norman (1978) says that the distribution of Keweennawan Complex can be explained by the model of transform fault (Fig. II-1-5-12). Chase and Gilmer (1973) presume the transform fault in the rift. For example, the dykes of Gunflint, Thomson, Duluth Complex and MCR can be applied to this model. MCR is divided into several segments estimated by the gravity anomaly (-20 mgal). These segments show the trends of NE-SW and NW-SE directions, which suggest the shear fracture and the transform fault, respectively (Fig. II-1-5-13, A). The airborne magnetic anomaly in the southern part of MCR (Fig. II-1-5-13, B) suggests the shear fracture and the extensional fracture of the same direction. Chase and Gilmer (1973) estimated that the ruputure of the extensional fracture and the width of the rift were approximately 55 kilometers.

1-5-2 Noril'sk Ore Deposit

(1) Paleogeography of the northern Eurasian Continent

Zonnenshain et al. (1990) have reconstructed a paleogeography during the Palaeozoic to the Mesozoic in the northern Eurasian Continent (Fig. II-1-5-14). The early Carboniferous (340Ma) to the late Permian: The plates of Euro-America, Siberia, and Kazakhstan converged into the Ural Sea as a subduction zone. The conversion of the plates involved the Ural orogenic belt, the orogenic movement had finished and formed the Laurasia plate. The conversion movement was linked with the Hercynian orogenic movement.

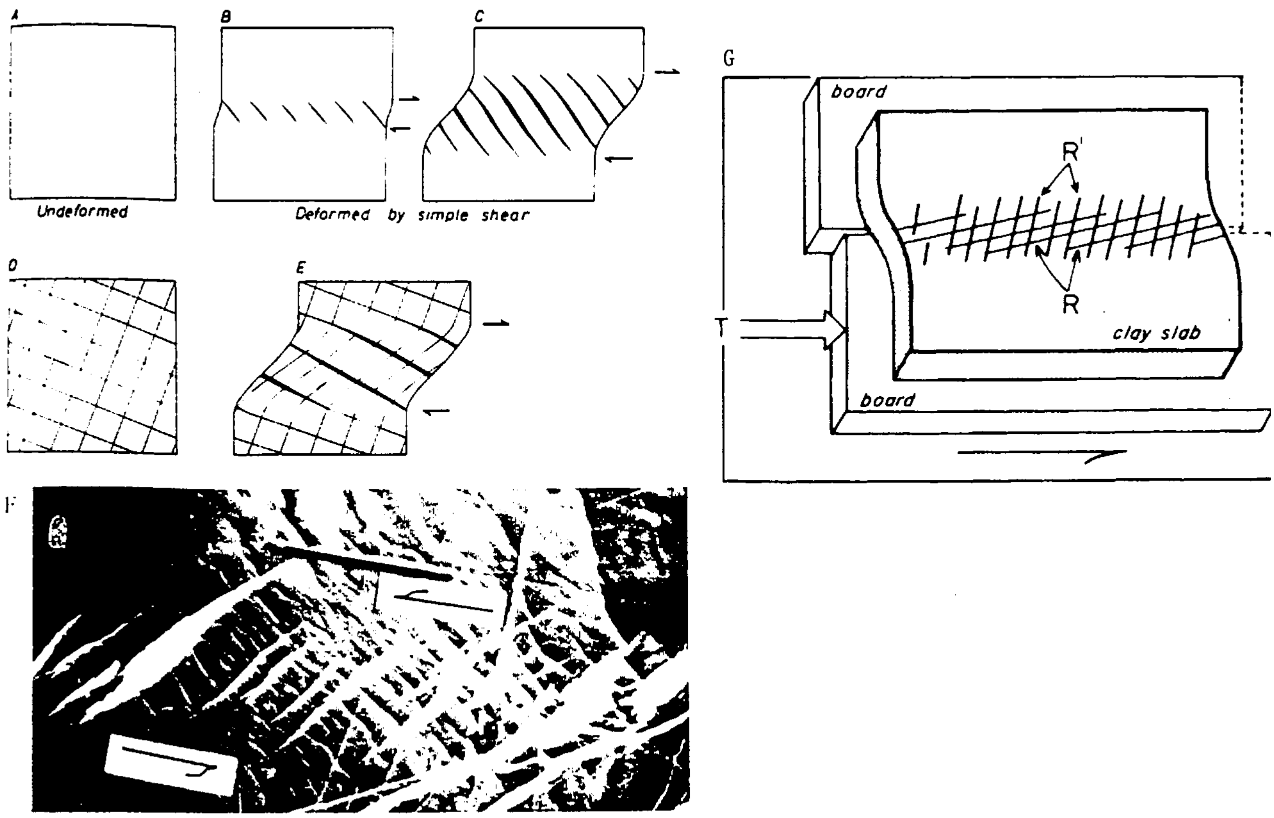


Fig. II-1-5-10 Shear mechanisms for producing extensional features in rocks

A-F, simple shear from Ramsay (1967, p. 88-89). A-C illustrate-structures that are likely t develop with shear in an isotropic rock. Note the curvature in the tension gashes tha develops with progressive shear (B-C). D and E illustrate structures that might form in previously jointed rock. F illustrates zone of en echelon quartz-filled tension gashe produced in graywacke by simple shear, Note the similarity in the shape of the large gash o the left and the map pattern of the Duluth Complex (Fig. II-1-5-2, 3, 9) G, pattern of fracture in the Riedel shear experiment (Tschalenko, 1970). The primary shears (R) rotate to lowe angles to the direction of movement as shearing progresses. The conjugate shears (R') ar essentially the tension gashes in simple shear (B). The two shear directions ar analogous to those depicted by Cloos (1955) for shear with rotation. (P. W. Weiblen, 1982).

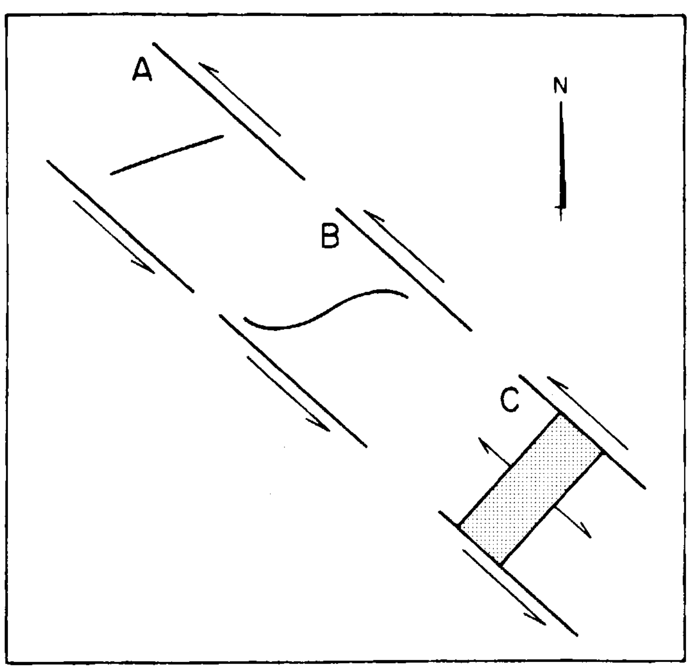


Fig. II-1-5-11 Hypothetical transition in tectonic regimes proposed for the Midcontinent Rift System

(A) In an inirial stage, left lateral wrench faulting would produce simple shear or conjugate Riedel fractures at high angles to the shear directions (Fig. II-1-5-10). Intersection of these directions with preexisting zones of weakness would localize alkaline magmatism as found in the Kapuskasing Structural Zone and the Coldwell Alkaline Province. (B) Progressive shear would produce en echelon fractures as exemplified by the quartz tholeiite and olivine tholeiite dike and sill swarms (Fig. II-1-5-9). (C) The gravity model of Chase and Gilmer (1973) and the half-grabem magma chamber model of Weiblen and Morey (Fig. II-1-5-4) suggest that wrench faulting did progress to actual rifting. (P. W. Weiblen, 1982).

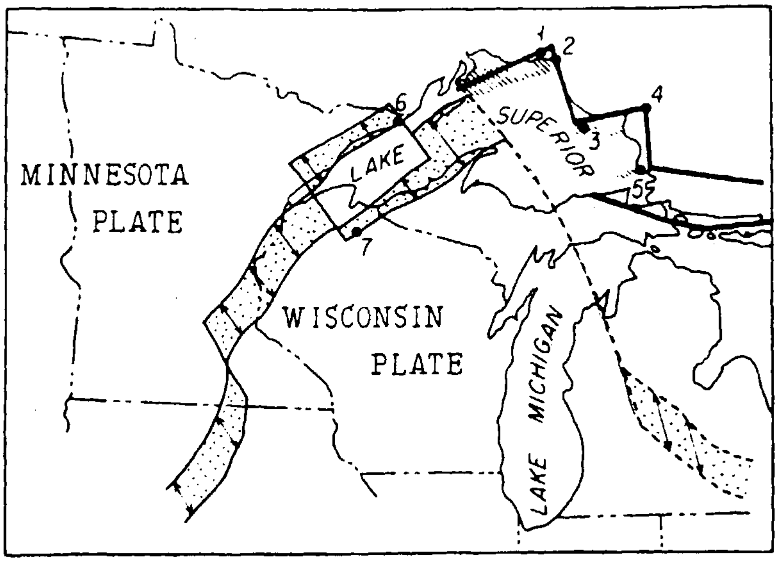


Fig. II-1-5-12 Rifting models for the Midcontinent Rift System (from Norman, 1978)
Shaded area outlines Chase and Gilmer's (1973) model. Heavy lines outline rift and transform intersections proposed by Norman (1978) to explain locus of alkaline complexes and sites of extensive felsic magmatism. 1. Praire Lake Complex; 2. Coldwell Complex; 3. Michipicoten lsland; 4. Firesand River Complex; 5. Batchawana area; 6. Hoveland, Minnesota; and 7. Mellen, Wisconsin. Gravity data do not indicate lithospheric separation north of Lake Superior. (P. W. Weiblen, 1982)

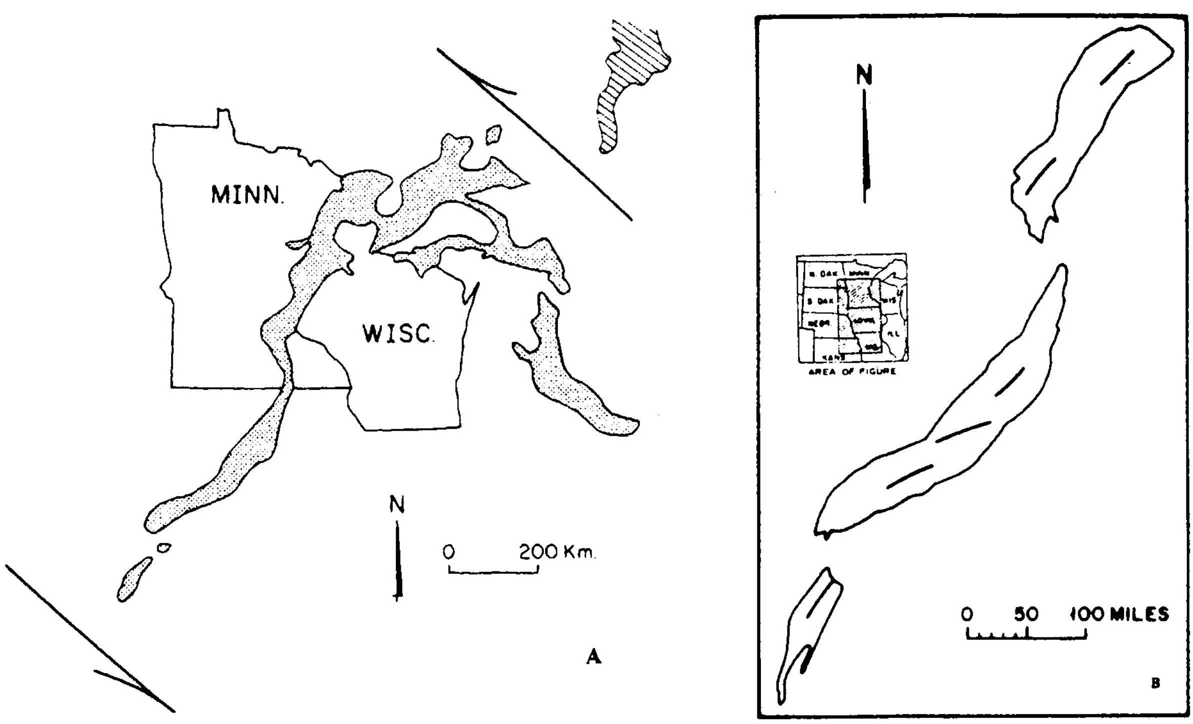


Fig. II-1-5-13 Regional patterns of geophysical anomalies in the Midcontinent Rift System
(A) Outline (stippled area) of the-20 milligal Bouguer gravity anomaly of the Midcontinent Rift System (from Craddock, 1972). Trends of individual segments range from northeast to northwest. Possibly this range in orientation of segments and their sinuous continuity record a change in fracture patterns with time analogous to the two directions shown for a shear couple depicted in Fig. II-1-5-10. and Fig. II-1-5-11. (B) Outline of aeromagnetic anomalies in the southern part of the Midcontinent Rift System (from King and Zietz, 1971). As suggested for the northern part of the rift in (A), the sinuous pattern might also more closely reflect a change in fracture directions due to shear with time rather than a single rift- transform geometry.

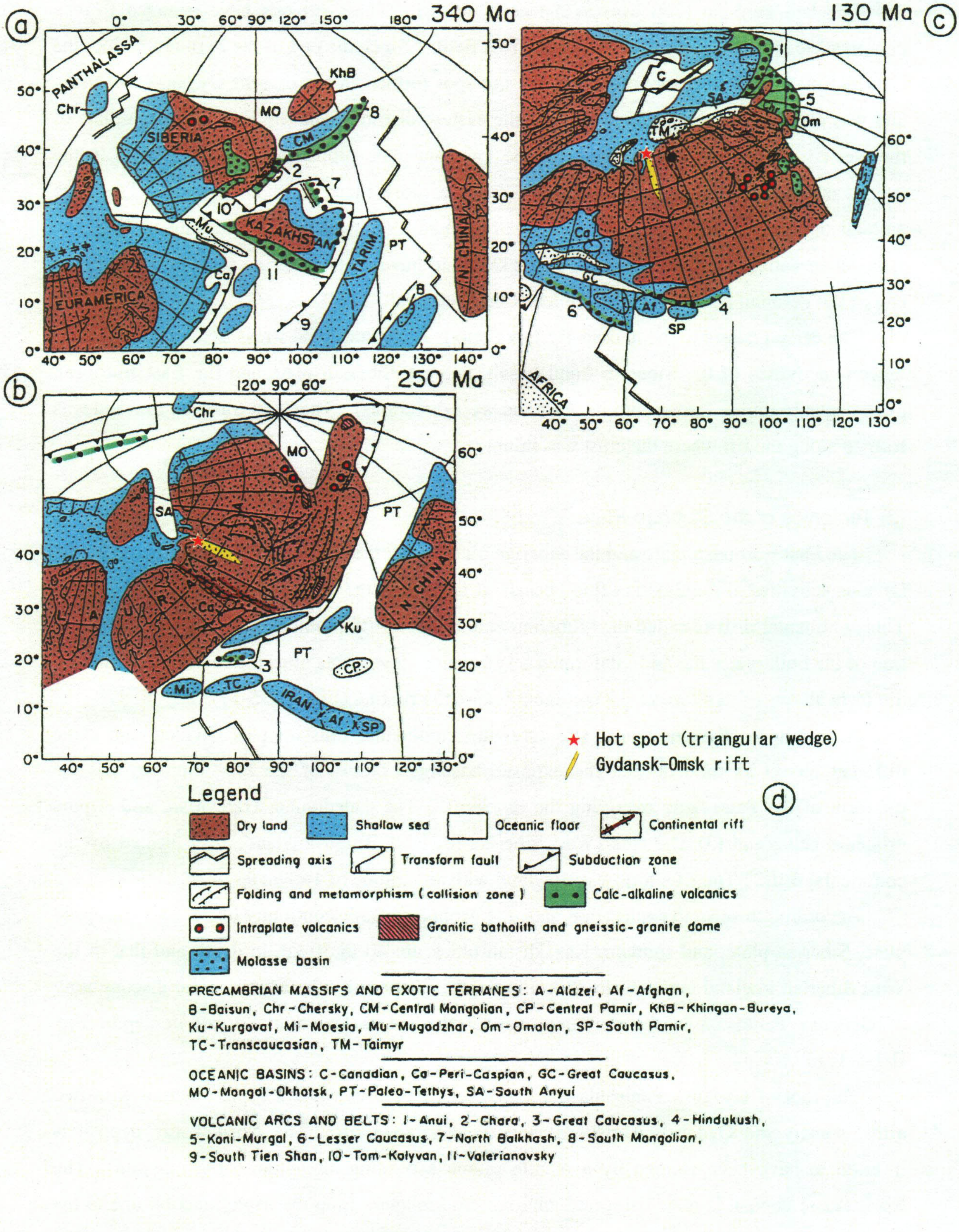


Fig. II-1-5-14　　Reconstruction of the position of the American, European, Siberian, Kazakhstan, north China, and several smaller plates

(a) the early Carboniferous 340 Ma; (b) the Late Permian, 250 Ma; and (c) the Early Cretaceous. Within the larger plates, lines of latitude and longitude refer to their present-day positions. The position of the plates in each diagram refers to their absolute positions during the period in question (drawn after Zonnenshain et al,. 1990).

The late Permian (250 Ma) to the early Triassic: These periods have changed from a compressive stress field to an extensional stress field. Since the end of the Permian period, the Laurasia plate started to ruputure from the hot spot formed in the present Gydansk Peninsula and was divided into the Siberian plate of the eastern direction and the East European plate of the western direction. The ruputure of the Laurasia plate propagated from the north to the south, and formed the Gydansk-Omsk rift with a more than 1,000 km length. The huge amount of the tholeiitic Siberian flood basalt erupted along the rift. According to ^{40}Ar-^{39}Ar radioactive dating, the Siberian flood basalt seems to have erupted during 600,000 years in the end of the Permian period (248.9±2.8 Ma, Campbell et al., 1992).

The early Triassic to the middle Tertiary period: The extensional stress field continued after igneous activities of the Siberian flood basalt, and the Siberian plate and the East European plate began to divide further into the east and west directions. The West Siberian lowland was formed along the rift where the crust was thinnered.

(2) Tectonics of the Siberian Plate

The East European plate and the Siberian plate began the continental drift, triggered by the igneous activities of the Siberian flood basalt, at the end of the Permian period (Fig. II-1-5-15). This continental drift is called the "Siberian continental drift" (Tamrazyan, 1962). The suture line of the both plates has been deformed by structure movements after the rupture. However, the form allows us to re-create the continent before the rupture (Fig. II-1-5-17).

According to the geological structure, the continental crust can be divided into three different blocks as follows: (1) The exposed basement blocks of the Pre-Cambrian and the platform of the Palaeozoic overlying the blocks; (2) The Caledonian, Hercynian, and Alpine orogenic belts; and (3) The rifts (West Siberian lowland, Turan lowland, etc.) formed by the continental drift. The rifts form vast lowland with an altitude of 160 meter or less.

According to seismic exploration data, the Mohorovicic discontinuity of the East European plate, Siberian plate, and southern Kazakhstan block are 40 to 50 km in depth and that of the West Siberian lowland is the 30 to 40 km in depth. Especially the Mohorovicic discontinuity of Gydansk Peninsula in the northern edge of the rift is less than 30 km in depth (Fig. II-1-5-16).

The root of Gydansk Peninsula (N68° N, 85° E) seems to be a triple junction with two arms, namely the Gydansk- Omsk rift and the Khatanga rift. The Noril'sk ore deposit is inferred to have been formed by a mantle plume ascending along the triple junction. The Noril'sk ore deposit is now dislocated approx. 300 km away from the triple junction due to the movement of the plates (Nalrett et al., 1992; D. Schissel, 2001).

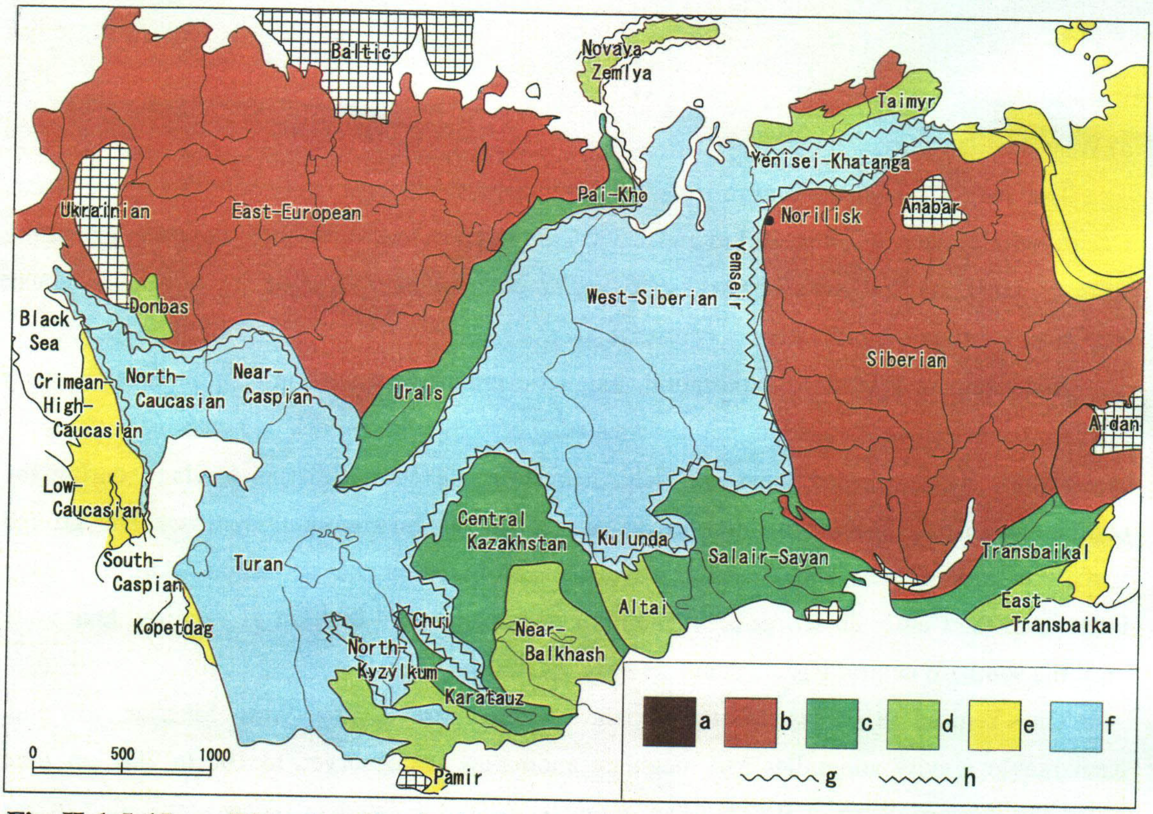


Fig. II-1-5-15 Diagram of geological geotectonic zoning and the Siberian Continental drift

a:ancient shields (archean and proterozoic), b:ancient platforms (Paleozoic), c:regions of Caledonian foldings (Early and Middle Paleozoic), d:regions of Hencynian foldings (Late Paleozoic), e:the Alpine fold regions in the South of the U.S.S.R. (Mesozoic, Cenozoic), f :troughs on the Precambrian folded base (Mesozoic, Cenozoic), g&h:western edge and eastern edge of the Siberian fractural suture. (G.P. Tama ra zyan, 1971).

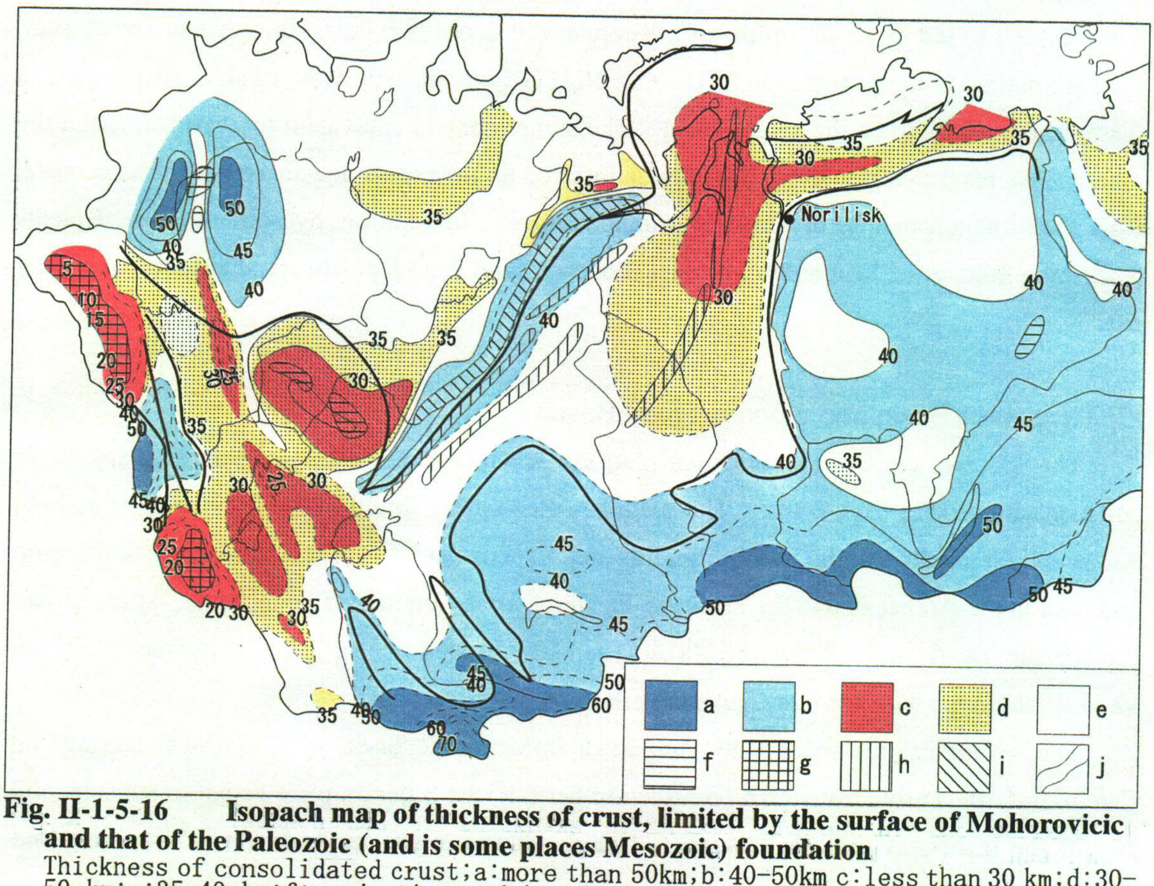


Fig. II-1-5-16 Isopach map of thickness of crust, limited by the surface of Mohorovicic and that of the Paleozoic (and is some places Mesozoic) foundation

Thickness of consolidated crust;a:more than 50km;b:40-50km c:less than 30 km;d:30-50 km;e:35-40 km;f:projections of basalt layer, g:zones of cilandseas with no granite layers (intracratoric basin), h:crushing foundering and down warping bands (bands of positive gravity aromalies and magnetic maxima, i:bands of intensive basalti fication of granite layers in continental crust region (the Urals), j:edges of the Siberian fractural sufure. (G.P.Tamarazyan, 1971).

a) West Siberian Lowland

The West Siberian lowland forms a graben-like subsidence structure belt, facing the Arctic Ocean, with a width of 30 to 50 km and 2,000 km length in the south-north direction extending from Gydansk Bay to southern Omsk City. The collapse belt is called the "Gydansk- Omsk rift," a super giant oil and natural gas reserve area.

According to a seismic exploration, magnetic prospecting, and gravity prospecting, and drilling, the Gydansk- Omsk rift, mainly consisting of sedimentary rock and effusive rock, is the zone where has expanded most and sank lowest in the West Siberian lowland during the continental drift. The sedimentary rocks are 25 km in maximum thickness. The ground surface is covered with the Mesozoic sequence and the Cenozoic sequence. Drillings have intersected the Cambrian sequence. The rift extends approx. 1,000 km as a narrow fault zone until the south, to central Kazakhstan.

The Yenisey River is located in the eastern part of the West Siberian lowland. Remarkable gravity anomalies and magnetic anomalies are observed in 100 to 200 km zone along the western Yenisey River. The anomaly zone is located in the western edge of the Siberian plate and be derived from the basic intrusive rocks.

b) Suture Between Plates and Ni- Cu- PGE Mineralizations

Figure II-1-5-17 shows a plate when the East European plate and the Siberian plate are sutured back to the original. Most of the copper ore deposits (Urals, Kazakhstan, Uzbekistan, etc.) are plotted in the suture zone. The Cu- Ni- PGE ore deposits of Noril'sk is also located in the northernmost part of the suture zone. The suture zone is equivalent to a rift formed in the plate. The magma forming ore deposits, is inferred to have ascended along the rift as an aisle, from the asthenosphere to the crust or ground surface. In addition, hydrothermal ore deposits containing gold, zinc, lead and tungsten, oil deposit, and coal deposits are also found along the rift.

(3) Tungusska Basin and Siberian Flood Basalt

The Siberian plate is a continental platform where is located between the Yenisey River and Lena River (Fig. II-1-5-18). The plate has the Anabar shield in the northern part and the Aldan shield in the south. These shields mainly consist of gneiss, crystalline schist, and quartzite in the Archaean and the Proterozoic, which are overlain by volcanic rocks after the late Proterozoic (K-Ar age: 865-1,195Ma). They are eroded by orogenic movements in the Vendian era (approx. 600 Ma, expansion period) of the Proterozoic.

The geological history of the Tungusska intracratonic basin is as follows: During the Cambrian to the early Ordovician (contraction period), the Siberian plate began to subside, and part of the plate was in a shallow sea. Conglomerate, quartz sandstone, and evaporite, and

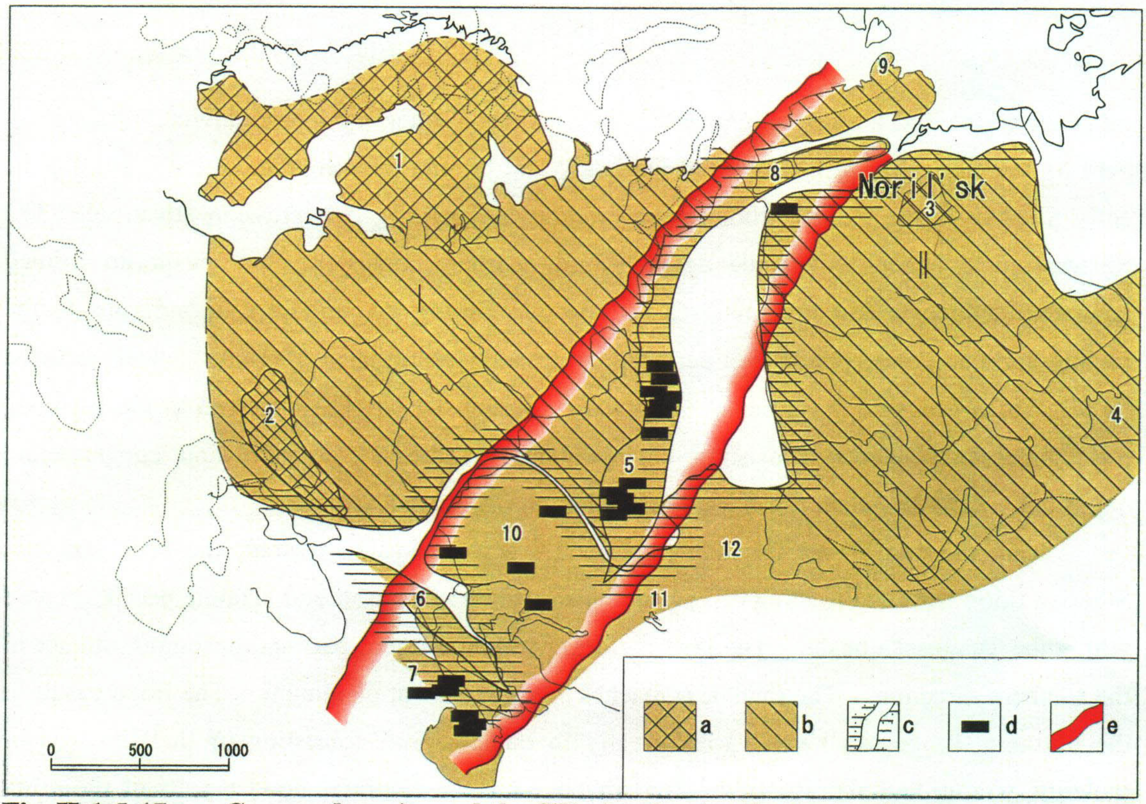


Fig. II-1-5-17 Copper deposits and the Siberian fractural structural suture

a = shields (1 = the Baltic shield, 2 = the Ukrainian shield, 3 = the Anabar shield, 4 = the Aldan shield); h = platforms (I = East-European, II = Siberian); c = edges of the Siberian fractural suture; d = copper deposits; e = concentration zone of main copper deposits

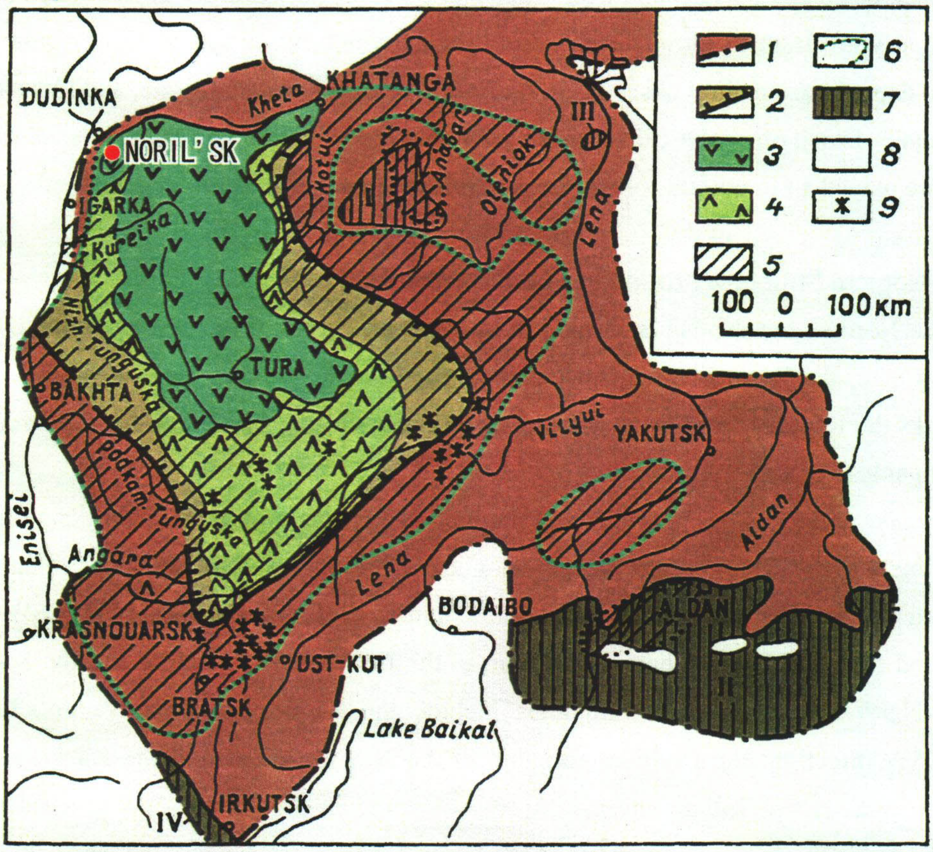


Fig. II-1-5-18 Scheme of distribution of traps on the Siberian platform (from data by Lurje and Masaitis, 1964)

1. Siberian platform boundaries; 2. Boundaries of the Tunguska syneclise; 3. The area of predominant basalt development; 4. The area of distribution of tuffaceous sequences; 5. The areas of intrusive traps development (sills,dikes); 6. Boundaries of development of intrusive traps; 7. Outcrops of the crystalline basement ; 8. Areas of development of the platform cover ; 9. Localities of basalt explosion pipes. (v. v. Zolutuklin, 1988).

other lacustrine and marine sediments have deposited. Since the late Ordovician (expansion period), the Siberia plate had uplifted gradually and terrain sediments deposited. During the early Silurian to the early Carboniferous (contraction period), transgression advanced. The Siberian plate began to subside again. And quartzite, limestone, and evaporite formed lacustrine sediments and marginal sea sediments. During the middle Carboniferous to the middle Permian period (expansion period), deformation and erosion of the sequences occurred by Hercynian orogenic movement. Afterwards, during the late Carboniferou to the Permian, the Tungusska sequence consisting of continental sandstone, siltstone, and conglomerate deposited. Coal and natural gas were formed in the Tungusska sediments.

During the end of the Permian (248.9±2.8 Ma, expansion period), the 1.5×106 km^2 Siberian flood basalt, consisting of vast amounts of tholeiitic basalt and alkaline basalt, erupted within the Tungusska basin. The lava is thicker in the northern part and becoming thinner in the southern direction. The thickness reaches 3,000 meters at maximum. The flood basalt in the northern Tungusska basin varies greatly in composition, consisting of theleiitic basalt, tholeiitic picrite, and alkaline basalt, and so on. On the contrary, flood basalts of the other areas consist of homogeneous tholeiitic basalt.

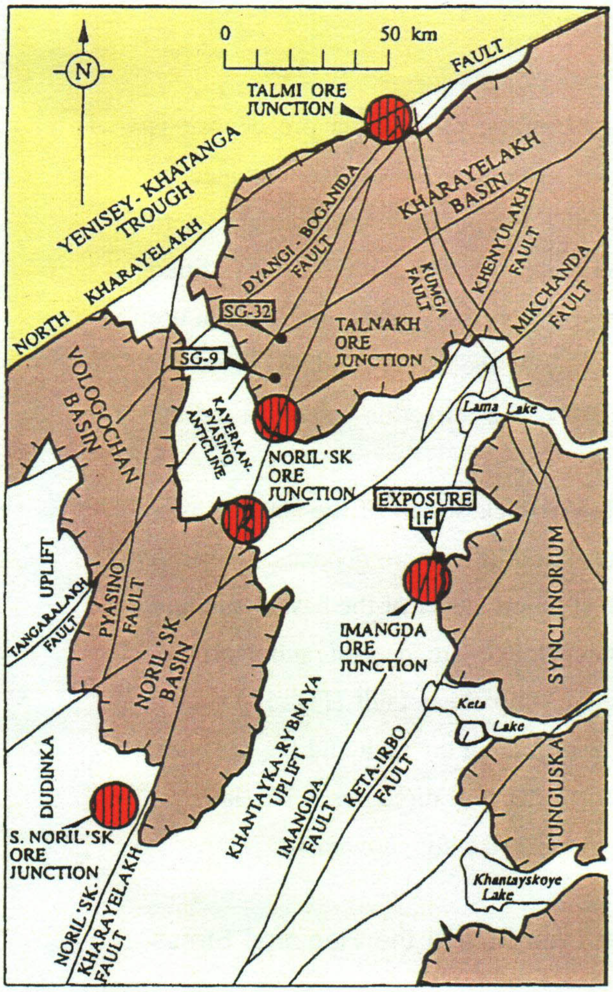
The vast amount of tholeiitic and alkaline dykes, sills, and pipes have intruded inside the Tungussak basin and its surroundings. The Noril'sk Ni- Cu- PGE ore deposit has been formed associated with basic to ultrabasic intrusive rocks, which are a part of the magma activities. The ore deposits are mainly observed in sediments of evaporite, mudstone, and limestone of the Devonian. Based on analytical values of sulfur isotope of sulfide minerals, it is considered that evaporite played an important role in the generation of the Noril'sk ore deposit.

(4) Geological Structure around the Noril'sk Ore Deposit

The Noril'sk ore deposit is located in the northwestern part of the Tungusska basin in the Siberian pate; the West Siberian lowland is located on the western side of the deposit, which overlooks the Khatanga graben, consisting of sediments of the Jurassic to the Cretaceous, in the northern side (Fig. II-1-5-19).

Basins, anticlines (upheavals) and faults are present around the Noril'sk ore deposit. Basins include the Kharayelakh basin, Vologochan basin, and Noril'sk basin. Faults include the Noril'sk- Kharayelakh fault, Imangda fault, and Keta- Irba fault in the NNE-SSW direction; Mikchand fault and North Kharayelakh fault in the ENE-WSW direction; and the Kumga fault in the NNW-SSE direction. Anticlines include the Khantayka- Rybnaya anticline in the NNE-SSW direction; the Dudinka anticline in the N-S direction; and the Kayerkan- Pyasino anticline in the NNW-SSE direction.

The Noril'sk ore deposit consists of the South Noril'sk ore deposit, the Noril'sk ore deposit, the Talnakh ore deposit, and the Talmi ore deposit. All of them exist along the



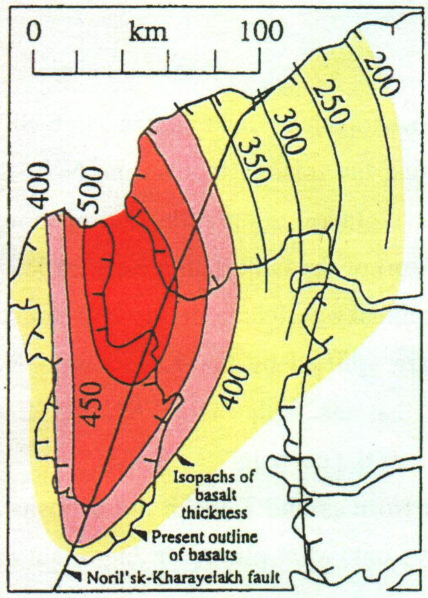


Fig. II-1-5-20 Thickness of the Nadezhinsky formation (lower+middle+upper) suite which illustrates the basin into which lavas were accumulating at the time of eruption (after Naldrett et al, 1992)

Fig. II-1-5-19 Map of the Norilsk region showing the outcrop of the lavas (areas surrounded by lines with attached hatching), main tectonic elements and principal ore junctions (from Naldrett et al, 1992)
Map compiled on the basis of data collected by NKGRE and TsNIGRI.

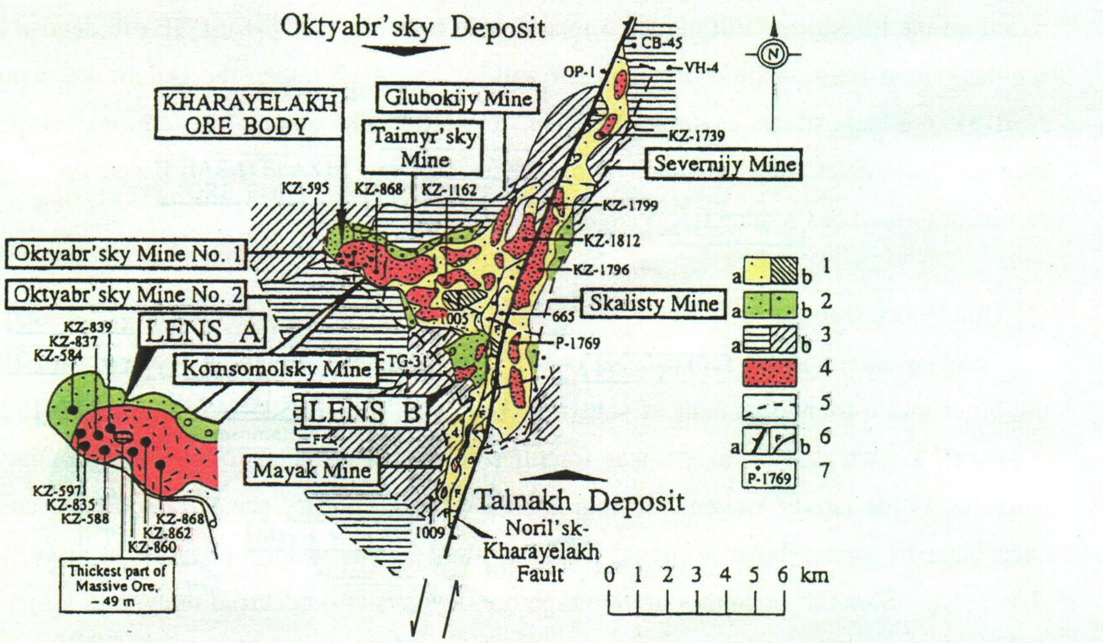


Fig. II-1-5-21 Plan showing the outline of the Northwest Talnakh intrutions, showing the distribution of lenses of massive sulfide

1=outline of ore-bearing intrusions. 2=the instrusions that are thought to represent the intruding mass of magma. 3=Differentiated apophyses(sills)of the ore-bearing intrusions. 4=massive sulfides underlving the intrusions. 5=erosional boundaries of intrusions:6=faults, (a) the Noril'sk Kharayelakh faults; 7=drill holes. (after Naldrett et al.,1996)

Noril'sk-Kharayelakh fault in the NNE-SSW direction. Besides, the Imanga ore deposit is found along the Imanga fault in the NNE-SSW direction. According to the data obtained by seismic exploration in the reflection method, the Mohorovicic discontinuity is deeper at eastern side (50 km) of the fault than western side (45 km). The South Noril'sk ore deposit is uplifted by the Dubinsky anticlcine in the N-S direction, while the Noril'sk ore deposit and Talnakh ore deposit are uplifted by the Kayerkansk- Pyasinsky anticline in the NNW-SSE direction. It suggests that the fault in the NNW-SSE direction and the N-S direction moved after the formation of the deposits.

The Noril'sk and Talnakh ore deposits are located in the thickest part of the Nadezhinsky basalt lava unit what played an important role on the generation of the ore deposits. That to say, both ore deposits are inferred to have occurred at the eruption feeder of the basalt lava unit (Fig. II-1-5-20). A relation between a bonanza of the Talnakh ore deposit and Noril'sk-Karayelakh fault suggests that the fault is a dextral strike- slip shear fault (Fig. II-1-5-21). The ore body in the eastern side of the fault is long and narrow along the fault and the ore body in the western side shows a triangular feature enlongated to the NW direction. The latter is considered to be a tensional fracture zone formed by the dextral strike-slip movement.

1-5-3 Relationship between the Ni- Cu- PGE Ore Deposit and the Regional Stress Field

Two models, a triple junction model and a transform fault model, were proposed to explain the formation of a continental rift and the rupture of a continent (See 1-5-1 (3)). In this section, based on the transform fault model, a relationship between the Ni-Cu-PGE ore deposit and the regional stress field of the continental rift will be discussed, taking the Duluth ore deposit and Noril'sk ore deposit as examples. Then, a relationship among the regional stress field, magmatic activities, and Ni-Cu-PGE ore deposit in the Paraná Basin, based on the survey results described in Chapter 1-5.

(1) Duluth ore deposit

P.W. Weiblen (1982) showed that one of conjugate shear fractures develops into a rift and the other into a transform fault as shearing progresses (See Fig. II-1-5-10 and Fig. II-1-5-11). It is well known that primary shear fractures form many diagonal echelon secondary shear fractures as the lateral movement progresses and the secondary shear fractures are connected each other to form a large tensional fracture called a cymoid loop (Byerlee et al., 1978, Fig. II-1-5-22). Some of bonanzas of vein type ore deposits also occurred in cymoid loops of vein system.

In the Duluth ore deposit, the shape of the midcontinental rift and the location of the

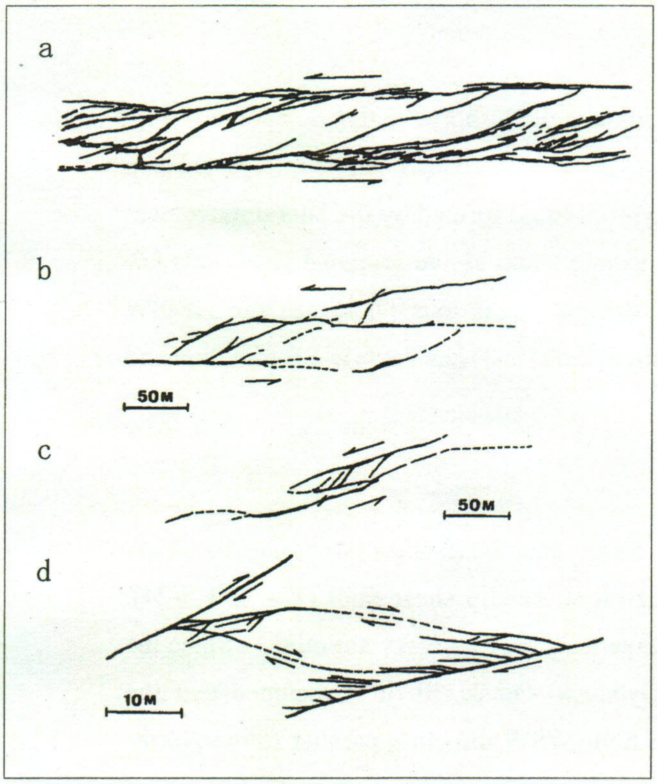


Fig. II-1-5-22 Interior structure of crush zone of the shear fracture formed by rock failure test (a) and those of vein (b～d) (K. Otsuki et al., 1991)

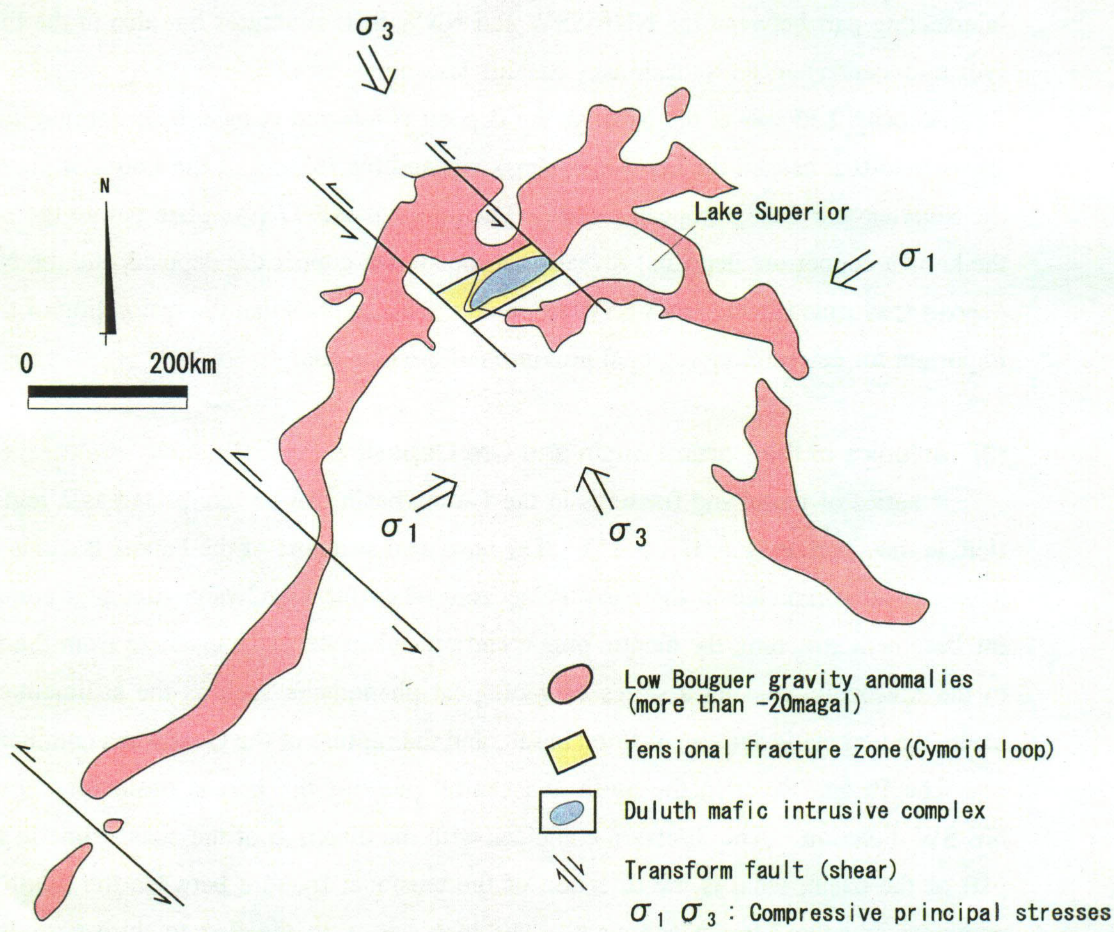


Fig. II-1-5-23 Formation model of Duluth mineralized intrusive complex

transform fault can be determined by the gravity anomaly and airborne magnetic anomaly (Fig. II-1-5-23). The Duluth complex in which the ore deposit is embedded can be interpreted as a rock body that intrudes a tensional fracture zone (cymoid loop) formed by the lateral movement of two transform faults. Assuming that the intermediate compressive principal stress axis (σ 2) is perpendicular, the maximum compressive principal stress axis (σ 1) has the NE-SW direction and the minimum compressive principal stress axis (σ 3) has the NW-SE direction and the tensional fractures are perpendicular to the σ 3.

(2) Noril'sk ore deposit

Noril'sk and Talnakh ore deposits exist along the NNE-SSW trending Noril'sk-Kharayelakh fault. The fault is regarded as a dextral strike-slip shear fault (Fig. II-1-5-24). Both ore deposits are on the NNW-SSE trending Kayerkansky- Pyasinsky anticline. Since the NNW-SSE direction coincides with that of the Gydansk- Omsk rift, it is assumed that the NNW-SSE direction correspond to the σ 1 and the ENE-WSW direction parallel to the North-Kharayelakh fault the σ 3. The Talnakh mineralized zone in the western part of the fault shows a triangular form stretching to the northwest. The mineralized zone may be a kind of tension fracture zone. Both Noril'sk and Talnakh ore deposits are situated not only in the intersecting part between the NNE-SSW and NNW-SSE structures but also in the thickest part (volcano- center) of the Nadezhinsky basaltic lava unit.

As described above, the Noril'sk ore deposit is inferred to have been formed in a regional stress field that caused the Gydansk- Omsk rift and the rupture of the Laurasia plate into both the Siberian and East European plates. Then, Fig. II-1-5-17 (the plate before the rupture and the known copper ore deposits) reveals that the known copper ore deposits and the Noril'sk ore deposit are formed in the NNE-SSW rift zone. This implies that the restoration of the plates is important for determining regional provinces of ore deposits.

(3) Tectonics of the Paraná Basin and Ore Deposit

A series of faults and fractures in the Paraná basin can be interpreted as a regional stress field in the rift zone (Fig. II-1-5-25). The basement structure of the Paraná Basin is inferred to have almost completed in the early Palaeozoic when the Gondwana continent combined. In the basement structure, the mantle plume had moved in the asthenosphere from the Palaeozoic to the Mesozoic, causing a series of geological phenomena such as the sedimentation in the basin, the magmatic activity of flood basalt, and the rupture of the Gondwana continent.

The Paraná River in the north and central parts of the Paraná basin runs almost in the NE-SW direction. The direction coincides with the direction of the coastal line in the eastern part of the basin, what is the direction of the tensional fracture between the South American continent and the African continent. The high ε zone in the first to third periods, the high

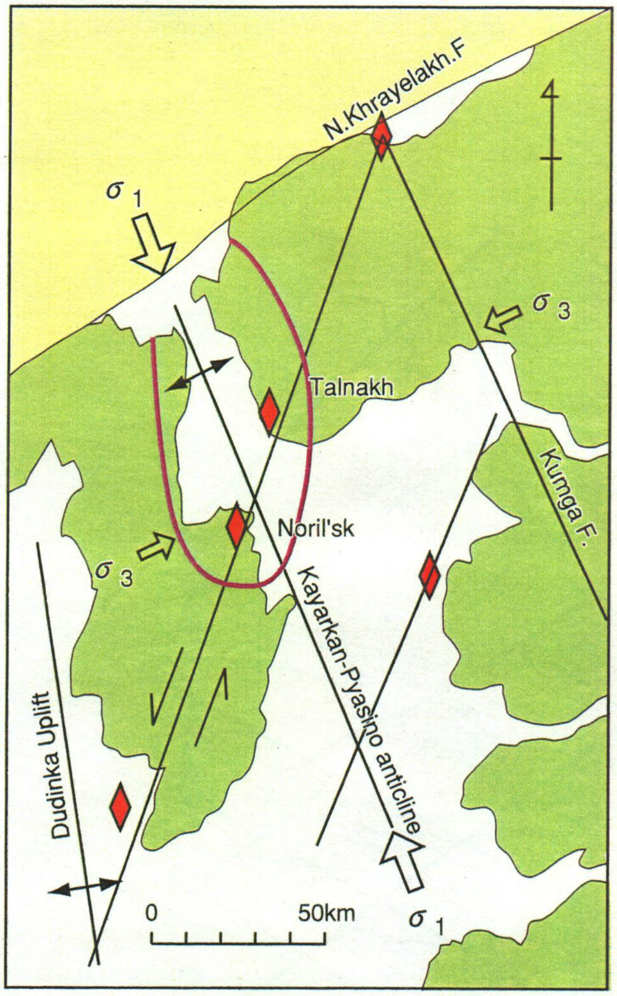


Fig. II-1-5-24 Formation model of Noril'sk ore deposit

Sedimentary rocks of the Jurrasic to the Cretaceous

Siberian flood basalt

Sedimentory rocks of the Paleozoic

Faults and lateral movement

Uplifts

Tensional Fracture Zone(ore deposits)

σ_1, σ_3 Compressive Principal Stresses (σ_1:maximum, σ_3:minimum)

Volcanic center of Nadezhinsky lava unit more than 500meters in thickness.

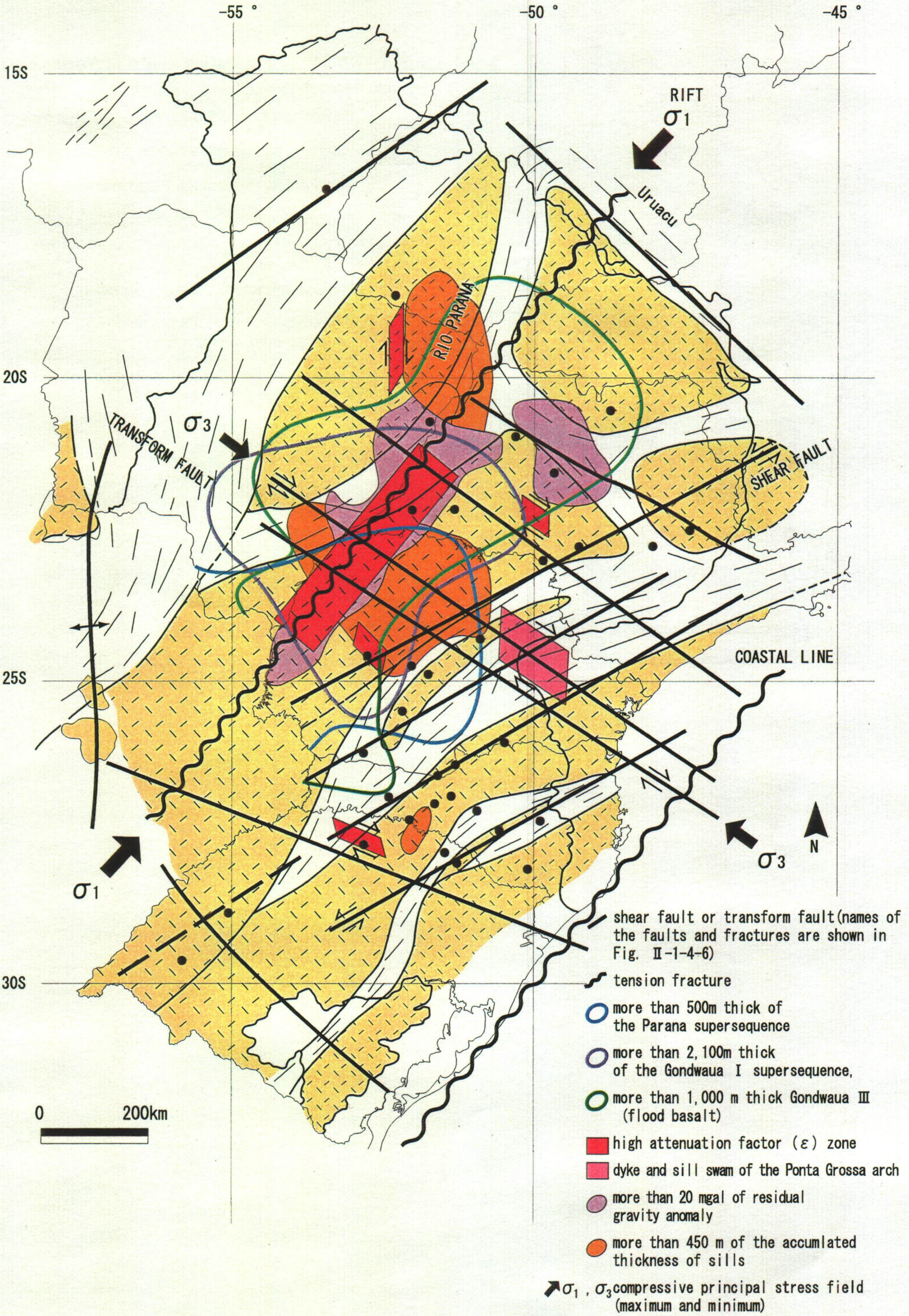


Fig. II-1-5-25 Comprehensive analysis map among the basement structure, basin sediment, gravity anomaly and regional stress field in the Parana basin

gravity anomaly zone, and the thick doleritic sills and dikes are found along the Paraná River. The thick sedimentary sequences and flood basalt lava units are along the Paraná River. Judging from these events, it is inferred that the Paraná River is a great tensional fracture connected to the mantle, i.e. a rift. The plume is considered to have continued to move beneath the rift from the Ordovician to the Cretaceous. Assuming that the rift has the NE-SW direction, the stress axis in the NE-SW direction will be the $\sigma 1$ and the NW-SE direction will be the $\sigma 3$.

The ENE-WSW trending fractures (Transbrasiano, Jacuting, Taxaquara, Lancinha- Cubatao, Blumenau- Soledade) also predominate in the Paraná basin. The fractures divide the cratons of the basement and the Brasilian- Pan African orogenic belts The fracture directions intersect with the $\sigma 1$ axis (NE-SW) at an angle of about 30 degrees. Judging from the secondary shear fracture directions in the basement rocks, the ENE-WSW trending direction is considered to be a sinistral strike- slip shear fracture (Rio Grande do Sur geological map). Although the shear fractures are not accompanied by doleritic sills and dikes, the fracture direction is an important direction that controls the geological structure province of the basement.

Then, the NW-SE trending fractures (Alto Parnaiba, Tiete, Guapiara, Ponta Grossa, Abreu-Mourao, Rio Piquiri, Cacador, Torres Posadas, and Rio Grande) are found in the Paraná basin. The fracture direction is perpendicular to the direction of the rift. The NW-SE trending fracture may be a transform fault. It is accompanied by a large quantity of doleritic sills and dikes along the Paraná River and in Ponta Grossa Arch. As seen in the Duluth ore deposit, the transform fault is the most important fracture direction that brings about ore deposits. Judging from the secondary shear fractures (A.J. Melfi et at., 1988) indicated by the dike swam in the Ponta Grossa arch, the transform fault is inferred to be a dextral strike- slip fault. The sense of the strike- slip direction coincides with the clockwise rotation of the Gondwana continent.

The zone where many fractures such as Ponta Grossa, Abreu- Mourao, and Rio Piquiri concentrate, is the most noteworthy among the NW-SE direction shear fractures. In this zone, a tensional fracture zone is formed as in the Duluth ore deposit by the lateral movement, and it is estimated that a large quantity of sills and dikes intruded in the zone. The tensional fracture zone in the western part of Paraná Province is formed at the intersection between the NE-SW rift and the NW-SE transform fault like the Duluth ore deposit and the tensional fracture zone in Ponta Grossa at the intersection between the ENE-WSW shear fracture and the NW-SE transform fault. As these examples, the intersection between the transform fault and other direction fracture may have played an important role in the formation of a large tensional fracture zone. Moreover, M.S.M. Mantovani et al. (2001) maintained that the feeders of flood basalt lava flows, a rising point of the plume, had gradually shifted to the east from the Paraná River, resulting in the rupture of the continent. The feeders of flood basalt lava flows may have moved from the west to the east along the NW-SE transform faults.

The NW-SE trending Tiete tectonic line is in the northern part of the Paraná basin and the NW-SE trending Torres Posadas tectonic line is in the southern part. The high ε zones and the high gravity anomaly zones are found around each tectonic line. But, both of them are small in scale.

As the fracture concentration zones of the Ponta Grossa arch, Abreu-Mourao, and Rio Piquiri have had stronger magmatic activities in the Paraná basin, the zones are more promising areas for Ni- Cu- PGE ore deposits. In particular, the sills and dikes concentration zone along the Paraná River (the rift zone) is expected as the first priority area for exploration of the ore deposit from the viewpoint of tectonics.