of alkaline basalt and picritic basalt. The chemical component of SiO_2 is generally 53 wt%. That is the transitional component to andesite, and poor in MgO, rich in FeO and TiO_2. It means that flood basalt is differenciated more than MORB.

1-2-3 Genesis of the Flood Basalt

(1) Genesis of Flood Basalt Magma and Mantle Plume

Generally, flood basalt magma was considered to be formed from the high temperature mantle plume that upwelled to the shallow part of the upper mantle and partial melted the homogeneous mantle material on a large scale (McKenzie and Bickle, 1988, etc). For example, Richards et al. (1989) concluded that flood basalt was formed when the mantle plume head reached to lithosphere, and the mantle plume tail corresponded to the following activity of a hotspot.

With regard to the above genesis and activity of high temperature plume, there are two hypotheses. One is based on the traditional plate tectonics and the other is on the plume tectonics that have been suggested recently (Maruyama, 1994). In particular, the hypothesis based on the plume tectonics considers the generation of the plume and its nature from the viewpoint of material circulation of the interior of earth, and considers the activity of a hotspot and LIP.

a) Hypothesis about the Generation Mechanism of Mantle Plume

Based on the traditional plate tectonics hypothesis, the generation and activity of a high temperature mantle plume is considered to be the event on the surface of the earth. By this hypothesis, the mantle plume is a secondary event, the continental breakup and mantle convection occurred because of the conditions of lithosphere and upper mantle, and plate movement (Davies, 1988; Griffiths and Campbell, 1990; Hill, et al., 1992; Anderson, 1994). Some researchers consider that the mantle dose not move relatively from the viewpoint of the whole earth (Griffiths and Campbell, 1990).

On the contrary, the hypothesis that the mantle convection and plume from the deep part of mantle caused the continental breakup and the activity of large volumes of basaltic magma from a hotspot and LIP has been proposed. For example, White and McKenzie (1989) considered that the huge mantle plume that upwelled to the lower continental crust participated in the continental breakup, and the main part of the plume expanded the continental crust, and form from the rift zone to the crust of the marginal part of the continent.

b) Igneous Activity by Mantle Plume (On Hotspot)

Hotspot is known as the igneous activity that is related to mantle plume. Hotspot participates to the forming of almost all flood basalt. The genesis and origin of hotspot are described follows:

1) Forming of Hotspot

A hotspot is considered to form by the upwelling (mantle plume) of a high temperature mantle material from the depth of the mantle. However, there are considerations about the forming of a hotspot that is formed by the ascending current by the small-scale convection within the upper mantle (White and McKenzie, 1995) and is formed by a local hot region within the upper mantle (Miyashiro, 1986; Anderson, 1989). These models are based on two layered mantle convection, and the origin of a hotspot is the boundary of the transitional zone between the upper mantle and lower mantle. The researchers who consider the whole mantle convection suggest that the plume of hotspot is generated from the layer of temperature boundary between the core and mantle. However, verification result of the whole mantle convection and the layered convection has not yet been obtained.

Almost all the active hot spots are considered to erupt basalt lava in the early stage of their activity (White and McKenzie, 1989; Coffin and Eldholm, 1994). Mantle plume is composed of plume head (several hundred to thousand kilometers in diameter) and plume tail (a circle of approximate 100 kilometers in diameter), and the plume head rises up several to several ten centimeters per year by the huge buoyancy. When the plume head reaches lithosphere, basaltic volcanic activity occurs with eruption of a huge volume of lava in a short period of about 1 My. The volcanic activity of the hot spot continues about 100 My by the plume tail to form a ridge and/or line of seamounts. Several low density masses (soliton) with different sizes are assumed within the plume. With regard to the upwelling velocity of soliton, the bigger it is the faster it is. When the plume reaches the shallow part of the upper mantle, since the magma temperature of the first activity is highest, the basalt igneous activity on a huge scale may be considered to occur in the early stage of the hotspot activity.

The style of hotspot activity is considered to markedly depend on the temperature, volume and components of the ascending mantle plume. The size of the temperature anomaly zone (plume head) below the hotspot is almost the same from the study by seismic wave tomography in Iceland and in the Azores, however, each volume of lava at surface differs.

2) Characteristics of the Hawaii Hotspot

The Hawaii hotspot maintains the same petrological characteristics during 70 Ma (K-Ar age of Suiko seamount of Emperor seamounts is 65 Ma). The mantle plume head 100 kilometers in diameter is observed in the shallow part of the upper mantle directly under the Hawaiian Islands. The sea bottom is shallower, being plume located, than that of the surrounding area. This swell is accompanied with plus gravity anomaly (plus Bouguer anomaly) that is supported by the mantle plume. The low velocity layer of seismic wave is existed in the lower mantle under the Hawaii hotspot that is considered to be the mantle plume tail.

As the characteristics of volcanic activity, the chemical component and the effusive rate regularly change according to the development of the volcanic activity. Alkali olivine basalt erupts in the early stage of volcanic activity of the deep sea, and mainly olivine tholeiitic magma erupts on the surface in the same stage. In this stage, picritic magma with many olivine phenocrysts sometimes erupts. The differentiation series is alkali basalt => olivine tholeiite (picrite) => alkali basalt => hyper alkaline rock.

The Nd, Sr isotope component of the Koolau volcano of Oahu Island is closest to that of the primitive mantle. This volcano is tholeiitic basalt with $SiO_2 \geqq 53$ wt% and abundant in SiO_2 (Fig. II-1-2-4).

Hauri (1996) proposed the idea that the melt by partial melting of peridotite that is the main component of the plume and basaltic component generates various magma that of the volcanoes of the Hawaiian Islands according to the mixing rates of volcanoes (Fig. II-1-2-5). It is difficult to explain by the traditional theory of homogeneous mantle plume melt that each magma component varies in spite of the close location of the volcano.

c) The Generational Place of Mantle Plume

There are many opinions about the birthplace of mantle plume.

ε Nd value of much of the oceanic basalt and flood basalt is lower than that of MORB. Some of the primitive mantle shows ε Nd=0. This value means that the source of the oceanic basalt and flood basalt is undifferentiated from that of MORB. The above also means the possibility that the source of the oceanic basalt and flood basalt is primitive materials of the lower mantle. That is, it is possible for the above source to be derived from the plume by upwelling from the upper mantle.

$^3He/^4He$ ratio of the volcanic glass and olivine phenocryst were measured. As the result, the high $^3He/^4He$ ratio of the samples that were derived from the lower mantle is recognized by Kaneoka (1983).

The result of the high pressure experiment concerning the outer core and the lower mantle is shown in Fig. II-1-2-6.

According to Davis, 1990, the partial melted mantle materials in D" layer near the boundary of the lower mantle and the outer core rise as the plume.

According to the high-pressure experiment of Boehler (1996), it was confirmed that the upper mantle does not melt while the outer core melts with the temperature of the boundary of the lower mantle and the outer core (Fig. II-1-2-6(b)).

In the case that a large quantity of hydrogen is contained, it is possible the temperature of

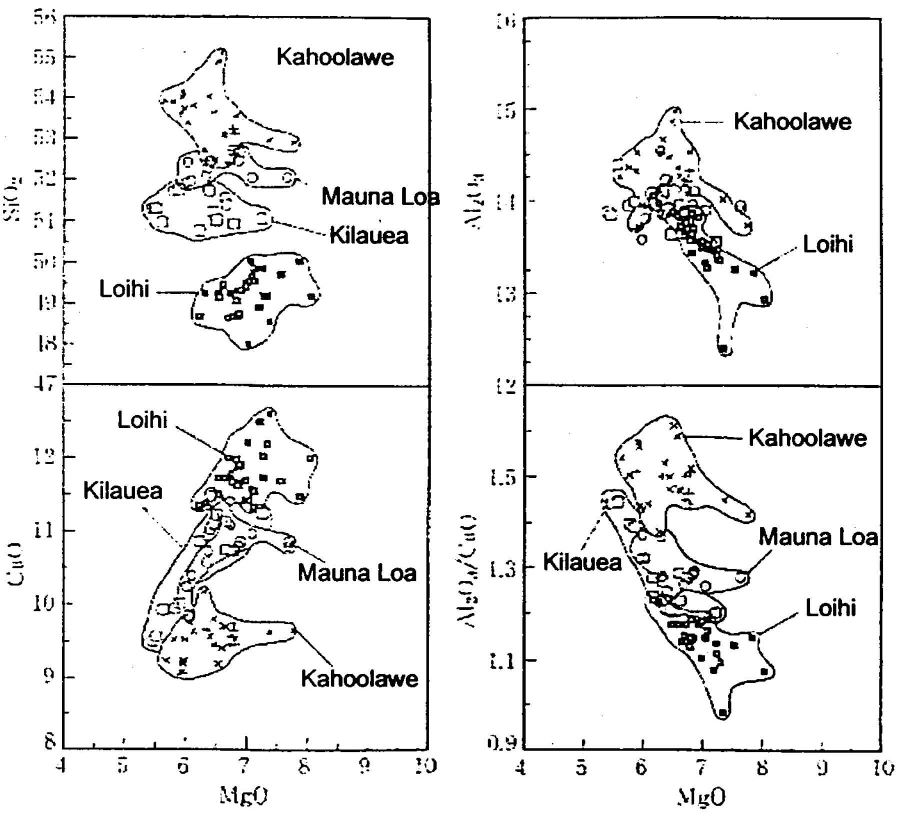


Fig. II-1-2-4 Plots of SiO_2 vs MgO, Al_2O_3 vs MgO, CaO vs MgO and Al_2O_3/CaO ratio vs MgO for Hawaiian lavas (Frey et al., 1994)

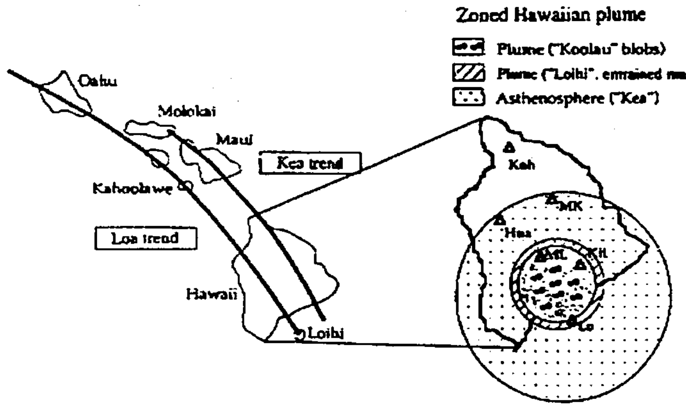


FIG. 4 Schematic model of a zoned mantle plume beneath Hawaii; Loa trend and Kea trend are structural lineaments of volcanic shields identified previously[51]. The plume is zoned owing to the effects of thermal entrainment[79]. The centre of the zoned plume contains quartz eclogite blobs (Koolau component) in a peridotite matrix, while the outer zones consist of heated and entrained lower mantle (Loihi component), surrounded by passively upwelling (not heated) upper-mantle asthenosphere (Kea component). The passage of Loa Trend volcanoes over the plume centre causes them to have larger amounts of the Koolau component, whereas passage of Kea trend volcanoes over the periphery of the plume results in a larger proportion of the upper-mantle Kea component in these volcanoes[53]. Abbreviations for volcano names: Hua, Hualalai; others as in Fig. 3.

Fig. II-1-2-5 Schematic model of a zoned mantle plume beniath Hawaii (Hauri, 1996)

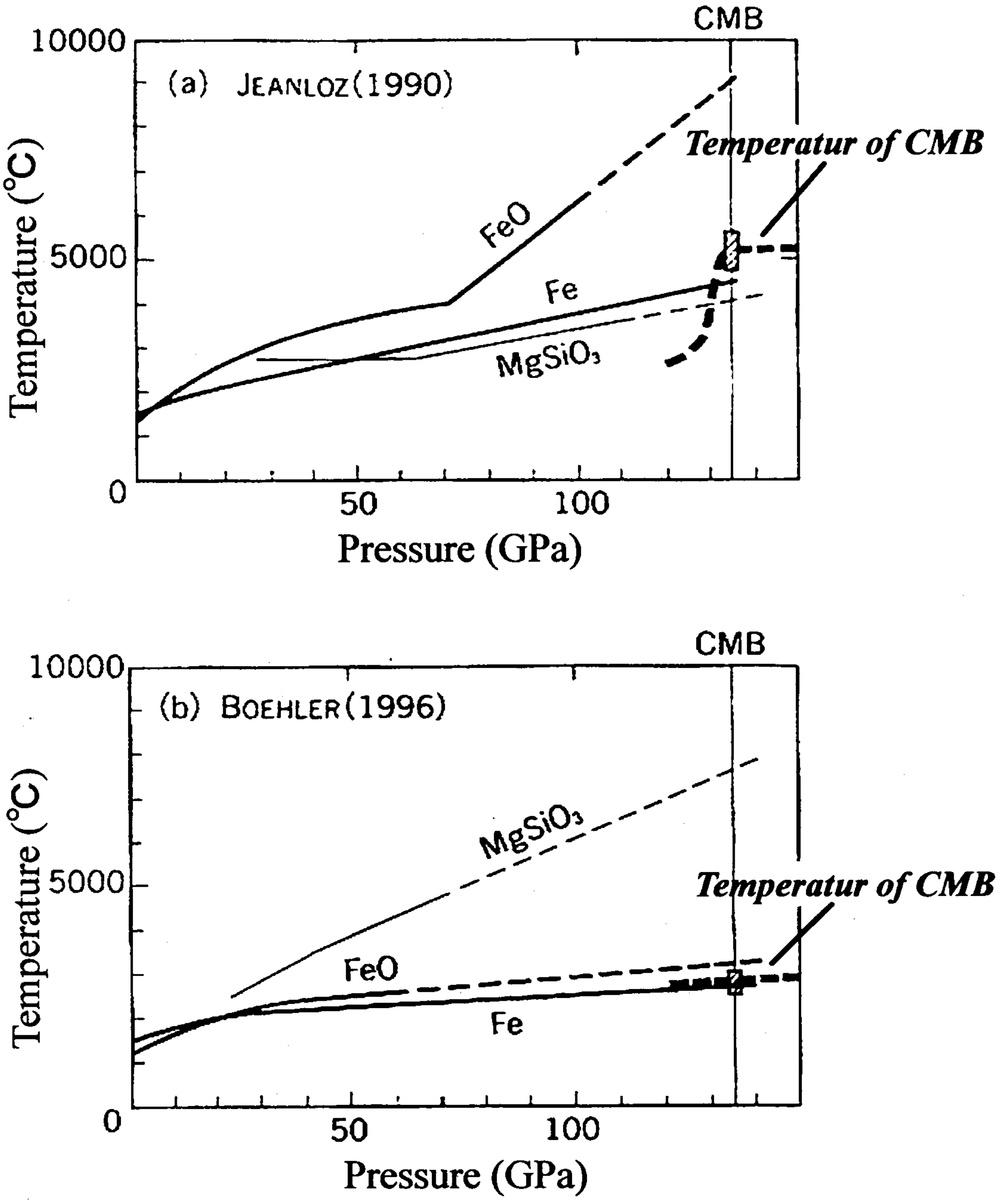


Fig. II-1-2-6 Experimentally determined melting characteristics of core (Fe, FeO) and lower mantle material ($MgSiO_3$: perovskite)
CMB means "border of core and mantle". Broken and slash lines show temperature of the boundary of core and mantle ((a): Jeanloz (1990), (b): Boehler (1995)).

the outer core could be considerably lower than the traditional model (Takahashi et al., 1997). 3,000 to 4,000 degree Celsius appears proper according to a recent experiment.

Therefore, there is no necessity that the mantle plume rises from the border of the outer core and the lower mantle (Takahashi and Nakajima, 1997).

There is a theory that the super-plume upwells from the border of the outer core and the lower mantle and form the flood basalt or ocean plateau. this theory is suggested by the chemical component of HIMU basalt and the characteristics of it's isotope (Tatsumi, 1998).

d) Recycling of Materials in the Interior of Earth

On the contrary to mantle plume, mantle convection is the work to the interior of earth. The oceanic plate is generated in the mid-oceanic ridge and subducts in the margin of the continent (Fig. II-1-2-7(a)).

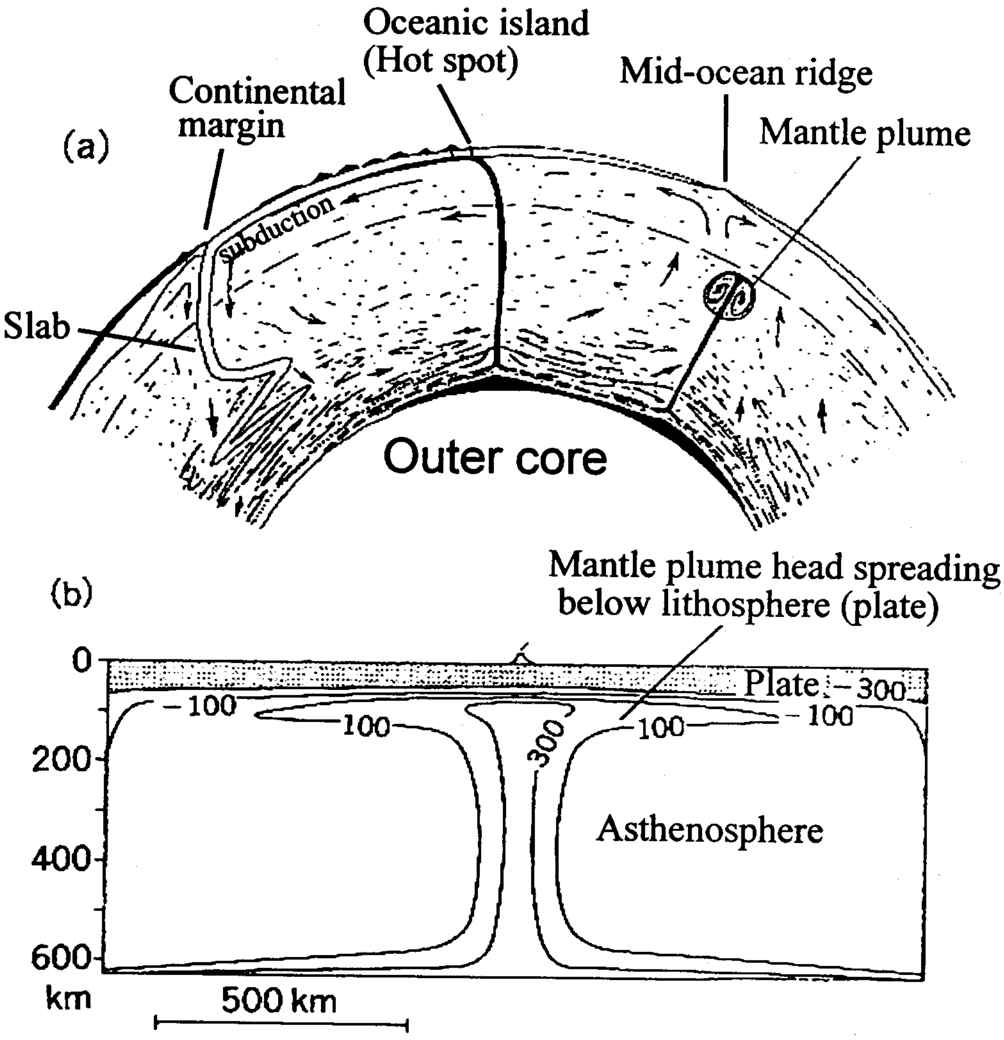
Fukao et al., (1992) confirmed by using a seismic wave that the oceanic plate subducts to the depth of approximately 670 kilometers of Izu/Ogasawara and lies there. At the same time, he also confirmed that a part of the slab subducts into the lower mantle. The mantle convection is temporarily forced to stop by the phase change of peridotite at the discontinuity layer of a seismic wave of 670 kilometers. However, the stayed slab rapidly begins to fall to the boundary of the core and the mantle (Tackley et al., 1993; Honda et al., 1993).

(2) Generation Model of the Flood Basalt by Homogeneous Mantle Plume

The study of the generation process of basalt magma is based on the melting model that is assumed for homogeneous mantle materials (McKenzie and Bickle, 1998 etc). Besides the above model, the generation model from picritic magma by crystallization differentiation is considered to apply to the whole flood basalt (Cox, 1980).

White and McKenzie (1989) considered the generation model of flood basalt magma by using the model of a homogeneous and high temperature mantle plume whose component is like pyrolite. The above model is shown in Fig. II-1-2-8. The explanation of the model is as follows.

- The mantle plume that is generated at the bottom of the upper mantle rises up. The difference of temperature between the plume and surrounding mantle is approximate 300 degrees Celsius at the bottom of the lithosphere. According to the simulation and laboratory experience, the head of the ascending flow appears like a huge mushroom-shaped cloud (Fig. II-1-2-7(b)).
- Picrite magma is generated from peridotite with a high temperature more than 1,500 degrees Celsius within the plume.



(a) Model of convection and plume in the mantle.
(Davies, G.F. (1990))

(b) Temperature variations seen in cross-section through the Cape Verde Swell from the best fitting axisymmentric convection model of Courtney and White (1986). Temperature anomalies are labeled in degrees Celsius with respect to the mean asthenosphere temperature. Note the narrow central rising plume and the broad mushroom-shaped head of hot material deflected laterally by the overlying plate. (White, R. and McKenzie, D. (1989))

Fig. II-1-2-7 **A schematic model of the convection in the mantle**

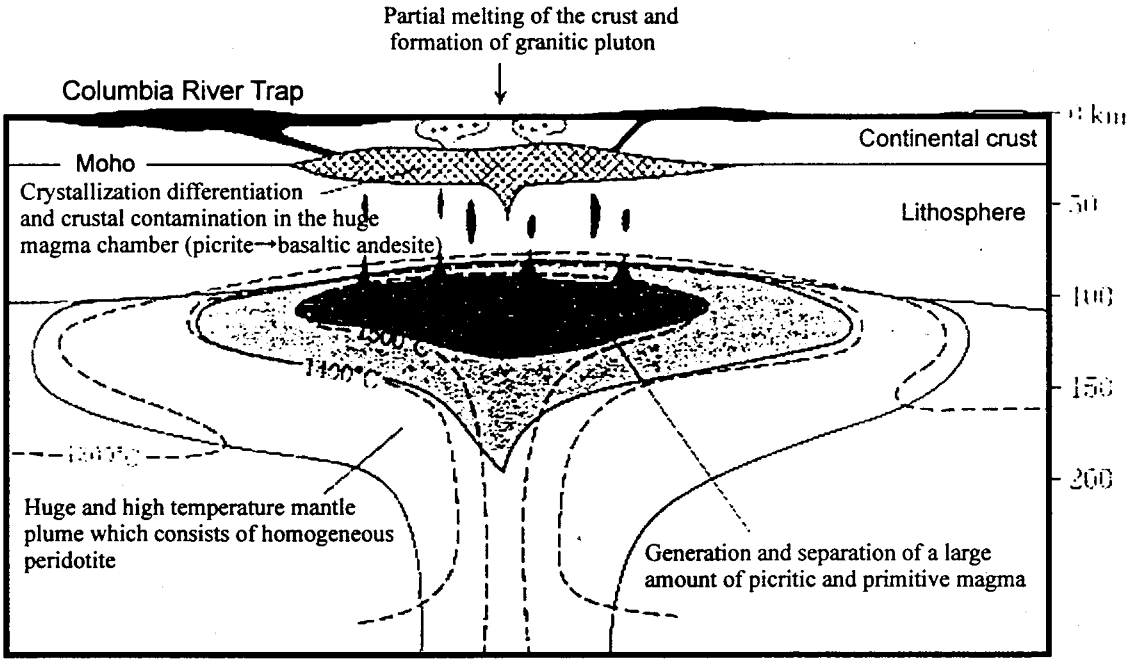


Fig. II-1-2-8 A schematic model of homogeneous plume head for magma genaration through study of the Columbia River flood basalts

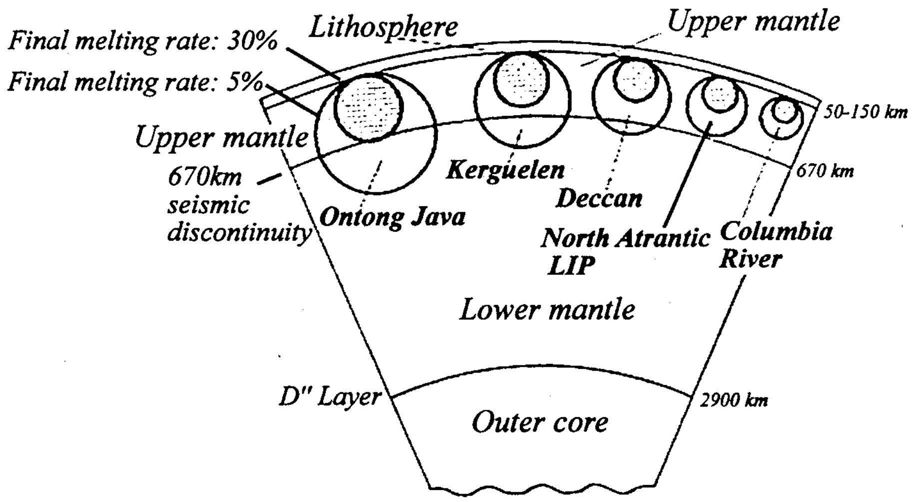


Fig. II-1-2-9 Volume of plume heads calculated on the basis of McKenzie's model (McKenzie and Bickle, 1988)
The volume of them is shown as the section of the sphere before spreading at the bottom of lithosphere (From Coffin and Eldholm, 1994).

- Picrite magma separates and rises up from peridotite to form a huge magma reservoir in the under part of the continental crust (assuming at the depth of Moho discontinuity of the North American continent).
- Fractional crystallization progress within the magma Chamber. And, flood basalt magma is generated by the contamination with a huge volume of the crust materials

(3) Problem of Generation Model of the Flood Basalt by Homogeneous Mantle Plume

Many problems are pointed out in the generation model of flood basalt by homogeneous mantle plume.

The chemical component of a mantle material like pyrolite is assumed in McKenzie and Bickle (1988). In this model, the volume of generated magma and its chemical component is decided by according to obtain initial temperature of the mantle upwelling. However, with application of peridotite melting model to the mantle plume that generate flood basalt on a large scale, it is pointed out that an illogically high temperature plume or unrealistic volume of plume becomes necessary.

For example, the calculated volume of mantle plume head (estimated size of mantle plume that was supplied LIP), that is based on the melting model of a homogeneous mantle with the volume of the existing basalt plateau and oceanic plateau, becomes 1,000 kilometers in diameter. The plume with a 1,000 kilometers diameter within the mantle with thickness of 2,900 kilometers is unnatural (Coffin and Eldholm, 1994: Fig. II-1-2-9).

In the case of the application of the same model to the volcanic activity of the Hawaii hotspot, the potential temperature of the plume is estimated to be approximately 1,560 degrees Celsius (Watson and McKenzie, 1994). The potential temperature of the upper mantle that locats below the mid-oceanic ridge, considering the generation temperature of MORB, is globally approximately 1,280 degree Celsius (McKenzie and Bickle, 1989). The above estimated temperature is higher by approximately 300 degrees Celsius than the potential temperature of the upper mantle. The magma that is generated by partial melting of a very high temperature plume and the partial melting of mantle becomes komatiite (Takahashi, 1996; Fig. II-1-2-10). Picrite magma is generated by the melting of mantle peridotite in the high temperature hotspot, however, almost all the flood basalt is tholeiitic.

It is necessary to remove MgO by crystallization differentiation of olivine and pyroxene for generating from peridotite and erupting MgO poor lava to the surface from the primitive and MgO rich basalt magma. But, a remarkable cumulate layer has not been recognized below the flood basalt by seismic prospecting.

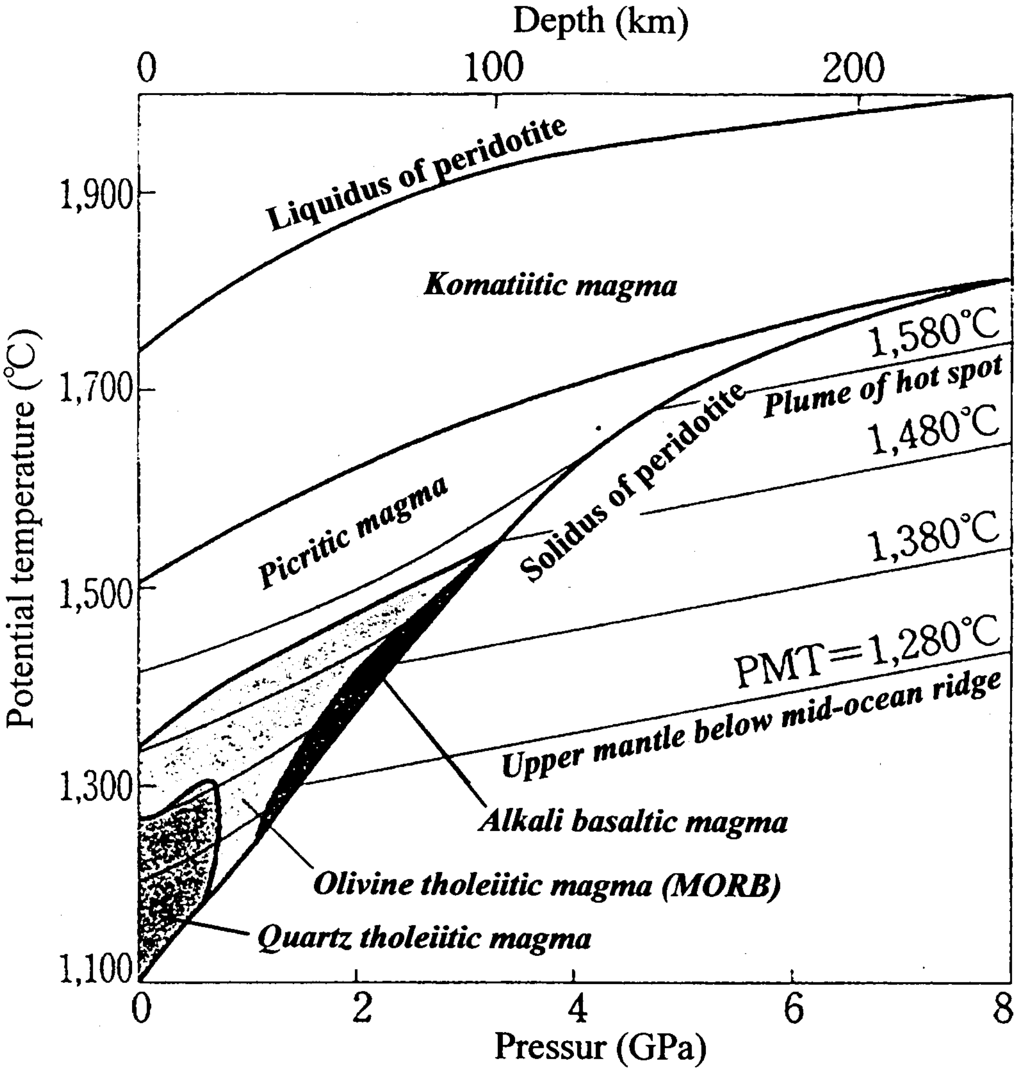


Fig. II-1-2-10 Magma types generated by adiabatic decompression of peridotite (Takahashi, 1996)

PMT means the mantle potential temperature.

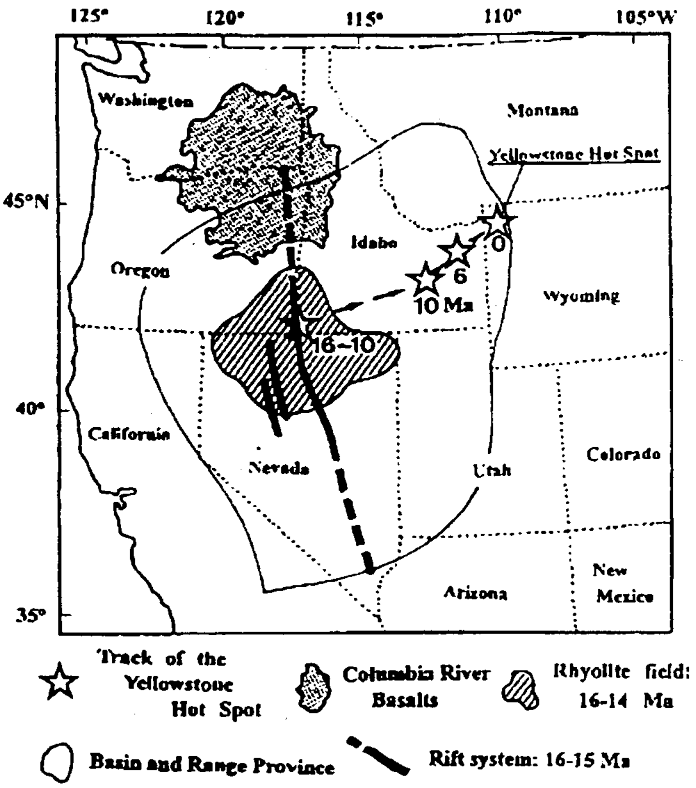


Fig. 1. Map showing the distribution of the Colombia River basalts (CRBs) and track of the Yellowstone hot spot. According to Pierce and Morgan [14], activity of the CRBs started due to the arrival of gigantic plume head of the Yellowstone hot spot ca. 16 Ma ago. The plume hit the boundary between Oregon, Idaho and Nevada where rhyolite volcanism occurred due to crustal anatexsis. Much of the basalt magmas, however, traveled to the north through 1000 km long NS rift system and drained at the boundary between Washington and Oregon States. Simplified after fig. 1 of Pierce and Morgan [14].

Fig. II-1-2-11 **Distribution of the Columbia River basalts and track of the Yellowstone hot spot**

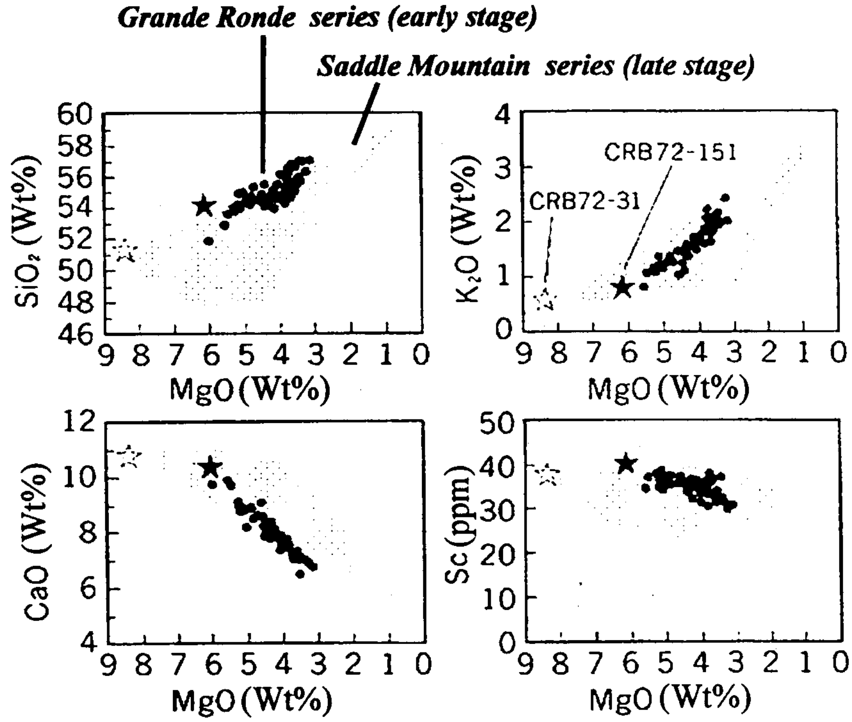


Fig. II-1-2-12 **Feature of geochemical composition of the Columbia River flood basalts**

CRB72-151 is the MgO-rich Grande Ronde series. CRB72-31 is the Saddle Mountain series which show similar geochemical composition of primitive MORB (Wright et al., 1988).

(4) Generation Model of the Flood Basalt by Assuming Heterogeneous Mantle Plume

The traditional model of mantle melting by homogeneous mantle plume cannot explain all the characteristics of flood basalt. Takahashi et al. (1998) proposed the generation model of flood basalt by heterogeneous mantle plume through his study of flood basalt.

a) Characteristics of the Columbia River Flood Basalt

The huge Yellowstone hotspot is considered to have participated in the initial activity to form the Columbia River flood basalt (Pierce and Morgan, 1993). The facies of the initial activity that is the Grande Ronde series basalt occupy 80 vol% of the total amount of eruption (Fig. II-1-2-11). The generated age of the Grande Ronde series basalt is 16-15 Ma and the SiO_2 content is 54-56 wt% that is basaltic andesite. The erupted amount is 2 x 105 km^3 and all the rocks are completely aphyric lava.

The facies of the latter half activity is basalt to dacite of the Saddle Mountain series. The period of the formation of the Saddle Mountain series is after 9 Ma.

The chemical component of the Columbia River flood basalt was described by Wright et al. (1988). The characteristics are as follows (Fig. II-1-2-12):

- More than 80 percent of the volume of the Columbia River flood basalt is basaltic andesite with 54 to 56 wt% of SiO_2 content. Compared to the components of primitive MORB, the average SiO_2 content is 4 wt% higher, the content of MgO is lower and rich in FeO. The chemical component of the Grande Ronde series basalt concentrates in narrow range considering its erupted volume.
- For MgO content, the component alternation trend of major and minor elements shows straight feature. This trend indicates that the chemical component of pre-eruption magma was controlled by crystallization of Al rich clinopyroxene that was stable only under the high pressure (Fig. II-1-2-12).

For the purpose of explanation of the high SiO_2 content in the Grande Ronde series basalt, not only the crystallization differentiation of olivine and pyroxene but also the contamination of the crust must be considered. Therefore, assuming the huge magma reservoir between the mantle plume head and the surface, in the magma reservoir the contamination of crust, including melting of the ceiling of the chamber, must be considered to progress at the same time as the constant crystallization.

Assuming the magma chamber on a large scale, although the magma must contain a large quantity of phenocrysts at the stage of crystallization differentiation, all the lavas are aphyric.

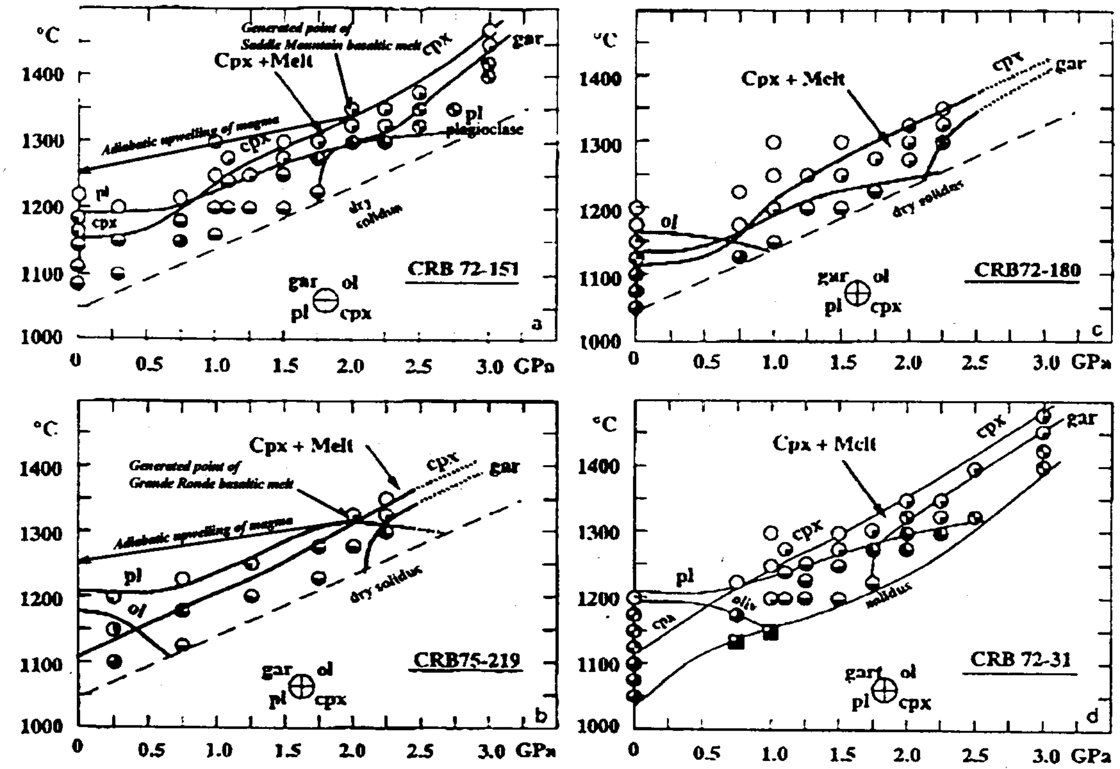


Fig. 3. (a)–(d) Melting phase relations on four representative Columbia River basalts listed in Table 1. Except for CRB75-219, clinopyroxene is the liquidus phase at pressures between 1 and 3 GPa (shaded area). The second liquidus phase changes from plagioclase to garnet at pressures around 2 GPa. Because of the steep dT/dP slope of the clinopyroxene liquidus, magmas formed at high pressures should be considerably superheated if they ascend and erupt rapidly [arrow in (d)]. This is consistent with voluminous eruption of totally aphyric lavas in the Grande Ronde stage of CRBs [42].

Fig. II-1-2-13 Melting phase relations on the Columbia River basalts listed Table II-1-2-3 (Takahashi et al., 1998)

Table II-1-2-3 Composition of starting materials of melting experience (Takahashi et al., 1998)

	CRB72-151 (a) Grande Ronde	CRB75-219 (b) Grande Ronde	CRB72-180 (c) Wanapum	CRB72-31 (d) Saddle Mt.	Av. N-MORB Mid Atlantic 49–52°N	Av. P-MORB Iceland
SiO_2	53.80	51.52	49.17	50.76	50.54	48.83
Al_2O_3	15.19	14.98	14.45	16.02	16.38	14.48
FeO^*	9.40	11.83	13.91	9.52	8.90	12.63
MgO	6.12	5.96	5.70	8.23	7.80	7.57
CaO	10.09	9.71	8.94	10.77	11.62	11.69
Na_2O	2.88	2.76	2.54	2.29	2.79	2.16
K_2O	0.69	0.60	1.01	0.39	0.09	0.17
TiO_2	1.13	1.70	3.15	1.48	1.31	1.71
P_2O_5	0.26	0.32	0.65	0.19	0.13	0.18
MnO	0.16	0.18	0.19	0.14	0.16	0.2
Total	99.72	99.56	99.71	99.79	99.72	99.62

b) Melting Experiment of the Columbia River Flood Basalt

The following knowledge has been obtained by the melting experiment of the Columbia River flood basalt. The result of the experiment by Takahashi et al. (1998) is shown in Fig. II-1-2-13.

The melting experiment under high temperature and high pressure for several kinds of Columbia River flood basalt that were initial materials was carried out. As the result of the experiment, the components of the melts that generated by the partial melting of the initial basaltic materials entered the region of andesite to basaltic andesite components (SiO_2: 54-60 wt%).

In the case that the initial material was almost similar to the primitive MORB (CRB72-151: the Grande Ronde series, CRB72-31: the Saddle Mountain series: Table II-1-2-3), it became obvious that the melt that corresponds to the chemical component and components of the main and trace elements was generated under the conditions of the pressure of approximate 2 GPa (corresponds to the depth of 60 km), the temperature range of 1300 to 1350 degrees Celsius and 30 to 50 vol% of partial melting (Fig. II-1-13).

Wright et al. (1988) considered that the chemical component of the magma of pre-eruption was on the control line of Al rich clinopyroxene from the characteristics of the chemical components of the Grande Ronde series basalt, however, almost all the residual materials of the experiment were Al rich clinopyroxene under the condition (2GPa, 1300-1350 degrees Celsius) that generates a melt similar to the Grande Ronde series basalt. The result of the experiment corresponded to the hypothesis of Wright et al. (1988)

The Grande Ronde series basalt must be generated from remarkably differentiated magma by the traditional model of homogeneous mantle plume. Assuming the initial magma with MgO=20 wt%, the Grande Ronde basalt magma($MgO \leqq 6$ wt%) must be considered the residual liquid after crystallization of 50 vol% of initial magma. Furthermore, the partial melting of mantle on a large scale and generation of a large volume of magma is necessary to generate Grande Ronde series basalt, however, the magma volume is decided by the potential temperature of upwelling mantle materials. The potential temperature must rise approximately 1200 degrees Celsius to 1500 degrees Celsius to increase the final volume of melting of mantle peridotite10 vol% to 30 vol% (Iwamori et al., 1995). The picrite magma with MgO=20 wt% or more, or the MgO rich komatiite magma must be generated within the mantle plume of adiabatic upwelling by approximately 1500 degrees Celsius (Takahashi et al., 1993: Fig. II-1-2-14).

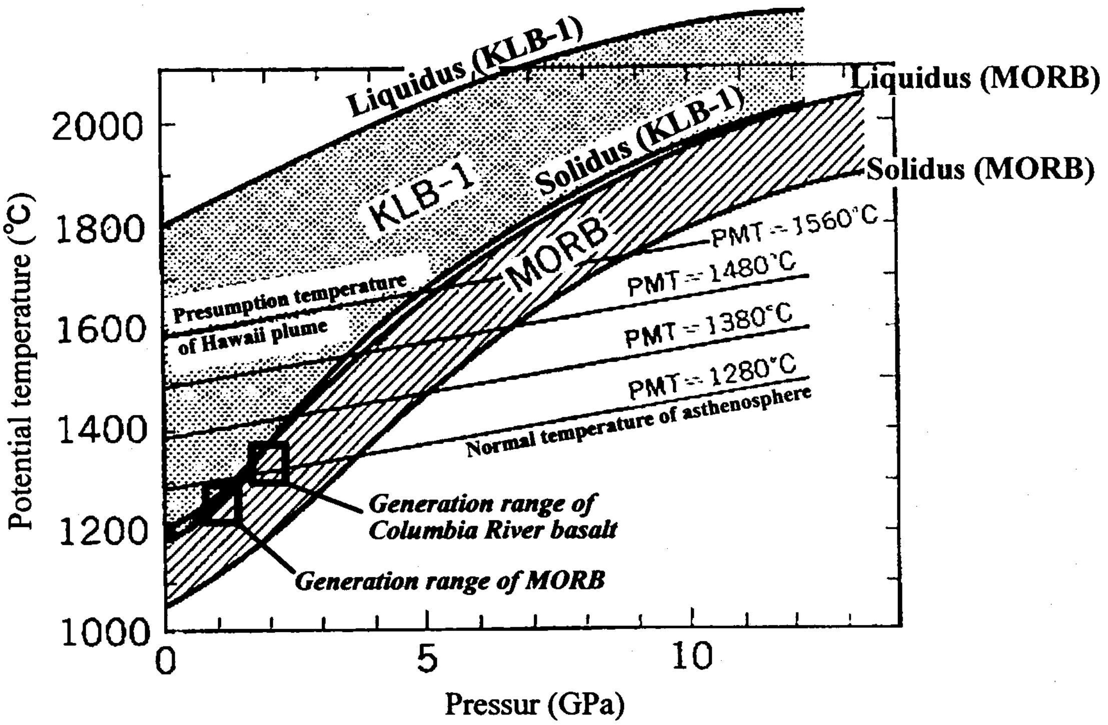


Fig. II-1-2-14 Liquidus and solidus for a fertile peridotite (data: Takahashi, 1986) and primitive MORB (data: Yasuda, et al., 1994; Takahashi et al., 1998) under dry condition
Estimated site for the GR magma genesis (2GPa, 1350°C) is located almost on the avarage asthenospheric mantle adiabat (PMT=1280°C). Even considering the neccessary latent heat the plume temperature for the Columbia River basalt may be PMT-1350°C which is surprisingly lower than current temperature estimate for mantle plume. (Takahashi, 1997)

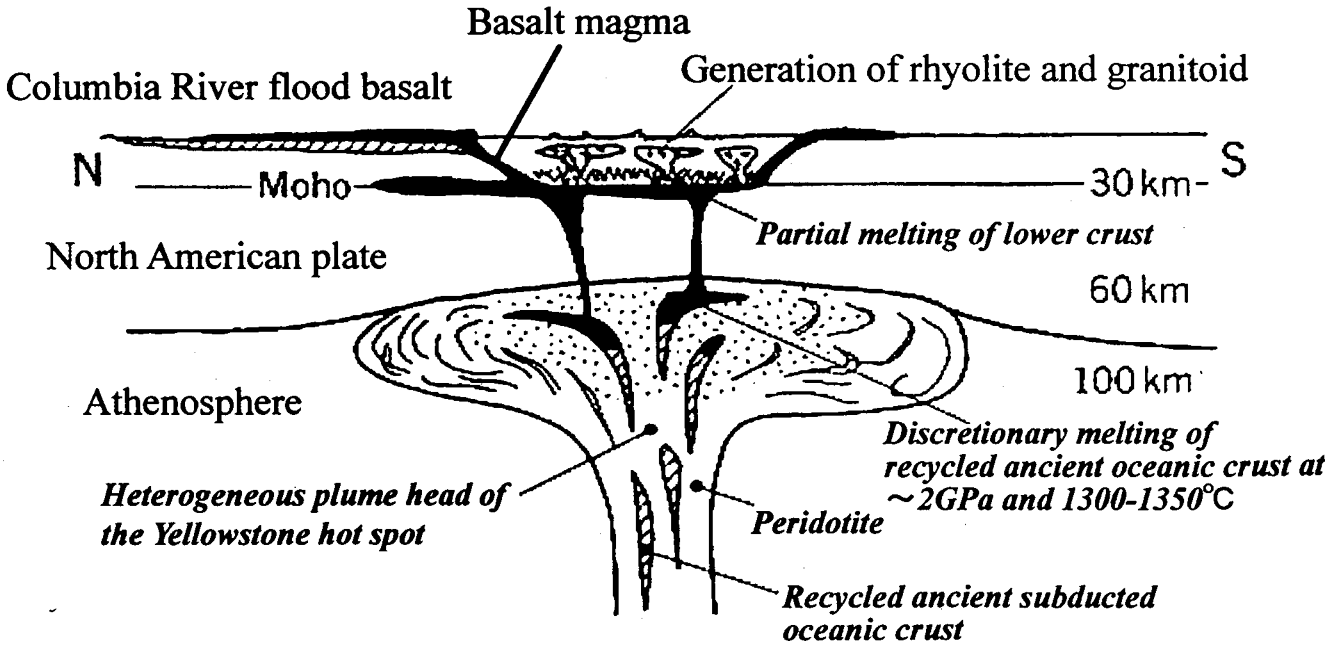


Fig. II-1-2-15 A model for heterogeneous mantle plume head for the initial stage of the Yellowstone hot spot (Takahashi et al., 1998)

(5) Generation Model of the Flood Basalt by Heterogeneous Mantle Plume

a) Application of Heterogeneous Mantle Plume Model to Columbia River Flood Basalt

The picrite magma that is generated by partial melting of mantle peridotite under the conditions of high pressure and high temperature is the original magma of flood basalt by the traditional model of flood basalt generation (Cox, 1980 and so on). However, it is difficult to explain the following two points: why basaltic andesite magma of large volume only erupted and why all of them are aphyric.

A new model for the generation of flood basalt has been proposed (Yasuda et al., 1994: Fig. II-1-2-14). The model is based on the high pressure melting experiment of MORB. Because the melting temperature of MORB (liquidus) is lower than the starting temperature (solidus) of melting of mantle peridotite under any pressure conditions, flood basalt is generated by the selective melting of the basalt component which is included in the mantle plume

Assuming that flood basalt is generated by the melting of the MORB component, the genesis of the Grande Ronde series basalt, that is markedly rich in SiO_2, can be explained, because the melt that is generated by the basalt component contains much more SiO_2 than the melt that is generated by peridotite. Moreover, assuming the adiabatic ascending of the magma that is generated by partial melting of MORB under high pressure that is more than 2 GPa, the magma becomes the superheating condition (more than 1250 degrees Celsius) when the magma reaches the surface, because the viscosity is low and aphyric lava is formed at the time of eruption (Fig. II-1-2-14). This is a reasonable explanation.

As mentioned above, the proposed new model is that the mantle plume of Columbia River flood basalt generation is not the traditional model of the ascending of very high temperature and homogeneous peridotite, but the ascending of peridotite of a comparatively low temperature including a large volume of MORB that is subducted oceanic crust. The model of Columbia River flood basalt generation by heterogeneous mantle plume is shown in Fig. II-1-2-15.

Based on this model, the estimated temperature of the mantle plume is lower than that of the traditional model and approximately 50 degrees Celsius higher than the potential temperature of asthenosphere that is estimated by the conditions of MORB generation. The condition of 1325 degrees Celsius and 2.0 GPa for the generation of Grande Ronde series basalt was obtained. This condition corresponds to the final condition of the place that the magma separated after the adiabatic upwelling of mantle plume forming magma. Therefore, in conclusion, the heterogeneous mantle plume that generated the Columbia River flood basalt stopped upwelling at a depth of approximately 60 kilometers, and selectively melted mainly MORB component to generate tholeiitic basalt magma.

The important factor for the decision of the generation volume is the volume of the oceanic crust component. Therefore, the generation of flood basalt from the low potential temperature mantle plume is considered to be possible.

The original material that is similar to MORB shows an age older than 1 Ga by the isotopic ratios of Sr, Nd and Pb of Grande Ronde series basalt (Hooper and Hawkesworth, 1993). It is considered that the old oceanic crust which had subducted to the interior of earth upwelled by the plume activity accompanied with the beginning of the Yellowstone hotspot activity. In the hypothesis of Ringwood (1994), the subducted oceanic crust is stored in the seismic discontinuity layer at a depth of 670 kilometers, and the oceanic crust is locally heated by the upwelling from the lower mantle, and ascends to the shallow part of the mantle as plume.

If the hotspot participates in the generation of flood basalt, the ascending of the component of the old oceanic crust that is stored within the earth plays an important role. If MORB component itself is conveyed by plume, it is highly possible that plume generates near the seismic wave discontinuity layer at the depth of 670 kilometers that is a lower temperature, not in the boundary between the outer core where the differentiation by melting processes and the lower mantle (Takahashi, 1995).

b) Application Heterogeneous Plume Model to Other LIP and Hotspots

There is a possibility that the activity of heterogeneous mantle plume or a plume with different components participate in the generation of flood basalt, hotspots, ocean ridges and ocean plateaus of the world.

That the basalt of the Hawaii hotspot is richer in FeO and SiO_2 than the partially melted liquid of non-differentiated mantle peridotite which is similar to phyrophanite is pointed out (Hirose and Kushiro, 1993; Kushiro, 1996). The model, in which the tholeiitic basalt magma, that formed the shield volcanoes of Hawaii, is generated by mixing between of SiO_2 rich melt which is formed by the melted oceanic crust included in mantle plume and melt of generated by partial melting of peridotite, is proposed as an example of the activity of heterogeneous mantle plume (Hauri, 1995). There is a report that the recycled slab is included within the Hawaii plume that was generated approximately 1.5 Ga by Pb isotope age (Silver et. al., 1998).

Some believe that the reason for the high La/Sm ratio in the Azorez hotspot where the degree of partial melting must be higher compared to N-MORB, is the effect of subducted continental crust and the components of sedimentary rocks (Schilling et al., 1985; Schilling, 1985). E-MORB that is contaminated by plume component differs from N-MORB in isotopic ratio. The E-MORB of Iceland and the Azores hotspot is higher in $^{87}Sr/^{86}Sr$ ratio than N-MORB. On the contrary, the $^{143}Nd/^{144}Nd$ ratio of it is generally low.

The isotopic characteristics as the example of the activity of mantle plume with the different component of the basalt of Polynesia, and of ocean islands around Africa, whose isotopic components of Pb, etc. has the characteristics of HIMU is explained by recycled slab components (Zindler and Hart, 1986). However, the characteristic of the major elements is that they are rich in Fe, and markedly poor in SiO_2 which is different from Hawaii (Kogiso et al., 1997). These original materials of such HIMU basalt are possibly different from the Hawaii hotspot, and there is the hypotheses that the main composition of the mantle plume that generates HIMU basalt of the ocean islands is meta-peridotite (Super plume). The meta-peridotite was generated by the melting and differentiation of the subducted oceanic crust to the D" layer that is the boundary of the core and mantle (Tatumi, 1995).

The example of the application of the heterogeneous mantle plume model to the LIP of the world by Takahashi et al., (1998) is shown in Table II-1-2-4. Takahashi et al. (1998) explains the LIP generation of the world by the difference of the potential temperature of heterogeneous mantle plume and the final position of stoppage of the plume.

In the case of the Hawaii hotspot, it is considered that the Hawaii basalt is generated by partial melting of not only MORB component but also both the mantle plume and mantle peridotite because of the high potential temperature of the mantle plume and mixing with each other.

Almost all the basalt of the ocean island is alkali basalt. The reason can be explained by the high potential temperature of the plume.

Iceland is an active hotspot volcano the same as Hawaii. Because it is located just above the Mid-Atlantic ridge, mantle plume can upwell adiabatically near the surface. In the case, where the lowest potential temperature (PMT=1280 degrees Celsius: the potential temperature of asthenosphere) is considered, not only the MORB component but also a considerable volume of peridotite melt, and the magma that has a higher content of FeO and elements to concentrate in liquid than the ordinary MORB and similar to E-MORB is generated.

Because of no lithosphere in the axis of the mid-ocean ridge, the whole mantle plume upwells to the surface. Because the mantle plume goes up to a shallower part, the mantle plume becomes a very high temperature by the decompression effect. As a result, the large volume of melt is generated, and a huge ocean plateau is formed. There are some oceanic plateaus that were formed during 20 to 30 Ma, but are not accompanied by a volcanic line that indicates the following volcanic activity, which is different from hotspots (i.e. Manihiki plateau, etc.). This is probably because such oceanic plateaus were formed by the interaction of the high temperature anomaly part in the upper mantle and the mid-oceanic ridge.

1-2-4 Genesis of the Flood Basalt and Mineralization of PGE Ore Deposit

Almost all PGE concentrated within the core in the initial stage of the earth. Moreover, because it fundamentally concentrates in solid phase, it is rarely contained in the continental crust where the differentiation has been progressed (Table II-1-2-5). Therefore, it is reasonable that the PGE in flood basalt is of mantle origin. In the period of the forming of flood basalt, a

Table II-1-2-4 Variety of the magma expected from the heterogeneous mantle plume model

	Shallower ←	**Final depth of plume**	→ Deeper
	0 km ---	--- 50 km ---	--- 100 km
Lower ↑ 1300℃	**MORB** olivine tholeiite	**Columbia River flood basalt** basaltic andesite	**Oceanic island basalt** alkali basalt
Potential temperature of plume			
↓ 1400℃ Higher	**Iceland** Fe rich olivine tholeiite	**Deccan flood basalt** Fe rich olivine tholeiite	**Hawaii shield volcano** Fe, K and Ti rich olivine tholeiite

Table II-1-2-5 Abundance of some transitional metals in earth and planetary materials (Naldrett, 1989)

(ppm)

	Fe	Ni	Pd	Ir	Pt
Carbonaceous chondrites (Planetary system)	270,000	16,000	0.545	0.540	1.02
Total earth (32.4% of core + 67.6% of mantle)	334,000	30,000	1.25	1.14	2.79
Earth's crust	50,000	75	0.001	0.001	0.005
Earth's mantle (Alpine peridotite)	60,000	2,500	0.013	0.006	0.073
Earth's core (Iron meteorites)	907,000	88,000	3.82	3.53	8.45

huge volume of magma was generated compared to the period of ordinary igneous activity. Consequently, melt on a large scale occurred and there is a possibility that PGE, which ordinarily concentrates in the solid phase, may be relatively highly concentrated within the melt.

Therefore, it seems to be most appropriate to consider that the origin of flood basalt with PGE mineralization is the magma that is of mantle plume origin and was generated by large scale partial melting of the plume itself and the surrounding mantle material.

However, the above condition can apply to the general LIP. Factors, such as the supply of silicate component and sulfur, and regional tectonic setting, seems to be more critical for the PGE concentration.

1-3 Noril'sk Cu-Ni-PGE Deposits and Key Factors in Their Exploration

1-3-1 Introduction

The Noril'sk region at the northwest margin of the Siberian Platform hosts several world-class orthomagmatic copper-nickel-PGE sulfide deposits. These deposits were discovered in the 1920's and are an important source of nickel and PGE supply for Russia and also for the world. It is well known that orthomagmatic sulfide deposits are accompanied by mafic to ultramafic magmatic activities and these exist in various geological environments (Table II-1-3-1). In these deposits, the Noril'sk deposits are classified into the type associated with flood basalts. In this type, the deposits are not only the biggest but also the only in operation in the world. Therefore, the deposits give the only model for the copper-nickel-PGE mineralization that is the survey target in the Parana basin area, which has the same geological environment as the Noril'sk region.

The Noril'sk deposits are hosted in the differentiated intrusions which belong to the Siberian flood basalts (Siberian trap), and the probable nickel ore reserves are equal to the deposits at Sudbury (Fig. II-1-3-1). Some 6,200 tons of PGE reserve is next to the Bushveld Complex and the Great Dike (Table II-1-3-2). The ore is characterized by high concentration of palladium, and the ratio of platinum and palladium is almost 1 : 3. The supply of palladium from the Noril'sk deposits reaches 60 % of the world demand, therefore the supply from the deposits is important for the world market.

In this survey, in order to clarify the key factors in the exploration of the "Noril'sk style deposits", documents regarding to the Noril'sk deposits were collected and analyzed, in a part of the existing data analysis.

1-3-2 Outline of Geology

The outline of geology and geological structure of the Noril'sk region are shown in Fig. II-1-3-2 and Fig. II-1-3-3, respectively. The Noril'sk region is located in the northwestern end of the Siberian platform. The geology is characterized by the volcanic sequence belongs to Siberian flood basalts whose thickness exceed 3,500 meters. The volcanic rocks of 2 to 3 x 10^6km^3 erupted in the area of 3.4 x 10^5 km^2. The region is one of the biggest basalt exposed area in the world. These basaltic rocks are overlying the Paleozoic sedimentary rocks whose thickness is approximately 5,000 meters and the Proterozoic basement rocks (granite, granitic gneiss, schist and amphibolite). The Noril'sk deposits are hosted in the sill-like intrusions within the Paleozoic sedimentary rocks. There are two ore junctions, the Noril'sk ore Junction and the Talnakh ore Junction, in the region. These are controlled by the Noril'sk - Kharaelakh

Table II-1-3-1 Classification of mafic and ultramafic bodies (Naldrett, 1989)

Class of Body	Examples
Ⅰ. Synvolcanic Environment	
1. Komatiites	
a. Lava Flows	Barberton(S. Africa)
	Kambalda area(W. Australia)
	Munro(Ontario, Canada)
b. Dunite-Peridotite lenses	W. Australia
	Dumont Sill(Quebec, Canada)
2. Tholeiites	
a. Picritic Bodies	Kakagi Sill(Ontario, Canada)
	Dundonald Sill(Ontario, Canada)
	Centre Hill Complex(Ontario, Canada)
	Kaapmuiden Barberton(S. Africa)
	Kalgoorlie-Norseman(W. Austlaria)
b. Gabbroic bodies	Dore Lake Complex(Quebec, Canada)
	Bell River Complex(Quebec, Canada)
	Big Trout Lake Complex(Ontario, Canada)
	Mulcahy Complec(Ontario, Canada)
	Bird River Sill(Manitoba, Canada)
	Windimurra Intrusion(W. Australia)
Ⅱ. Associated with Rifted Plate Margins and Ocean Basins	
1. Floored by and Closely Associated with Continental Crust	
a. Komatiitic	Cape Smith(Quebec, Canada)
	Thompson Belt(Manitoba, Canada)
b. Largely gabbroic	Fox River Sill(Manitoba, Canada)
	Labrador Trough(Quebec-Labrador, Canada)
	Kemi-Koillismaa Belt(Finland)
	Skaergaard(Thulean Province)
2. Not floored by Continental Crust	
a. Ophiolite complexes	New Caledonia
	Newfoundland
	Cyprus
	Turkey
	USA
	Greece
Ⅲ. Intrusion in Cratonic Areas	
1. Intrusions Related to Flood Basalts	Duluth Complex(Minnesota, U.S.)
	Noril'sk-Talnakh(U.S.S.R.)
	Defek Intrusion(Australia)
	Insizwa-Ingeli Complex(S. Africa)
	Ontario Nipissing Diabase(Ontario, Canada)
2. Large-layered Complexes with no Documented Relation to Flood Basalts	
a. Sheet like	
i) With repetitive layering	Bushveld Complex(S. Africa)
	Stillwater Complex(Montana, U.S.)
	Muskox Complex(Canada)
ii) Without repetitive layering	Sudbury(Canada)
b. Dikelike	Great Dyke(Zimbabwe)
	Jimberlana(W. Australia)
Ⅳ. Bodies Intruded in Orogenic Belts	
1. Synorogenic Intrusions	Aberdeenshire Gabbros(Scotland)
	Rona(Norway)
	Seiland Province(Norway)
	Fongen-Hyllingen Complex(Norway)
2. Alaskan-type Complexes	Duke Island(Alaska, U.S.A.)
	Union Bay(Alaska, U.S.A.)
	Tulameen(British Colombia, Canada)
	Northern California(U.S.A.)
	Urals
	Columbia
	Venezuela
3. Alkalic Bodies	Gardar Province(Greenland)
	Kola Peninsula(U.S.S.R.)
	Numerous Kimberlites and Carbonatites

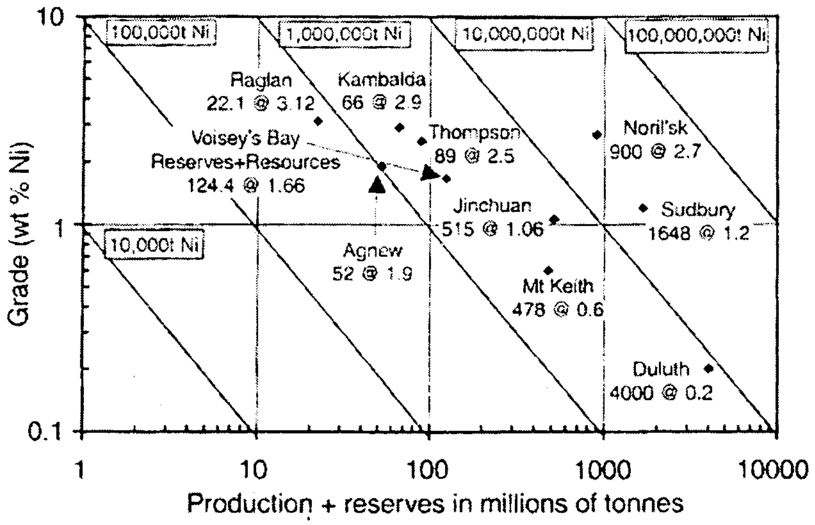


Fig. 1 Plot of grade in wt.% Ni versus production + reserves in millions of tonnes for major Ni sulfide deposits of the world, modified after Naldrett (1994). Data for Sudbury are personal communications from INCO Ltd. and Falconbridge Ltd. (1990); those for Noril'sk are an estimate only; for Duluth are from Listerud and Meineke (1977); for Jinchuan are from Chai and Naldrett (1992a); for Kambalda, Agnew and Mt. Keith are from posters exhibited by Western Mining Corporation at the 13th Australian Geological Convention, Canberra, February (1996); for Thompson are personal communication from, O.R. Eckstrand (1990); for Voisey's Bay are reserves plus indicated and inferred resources announced by Mike Sopko, Chairman, INCO Ltd., in July 1998

Fig. II-1-3-1 Grades versus production + reserves for major Ni sulfide deposits of the world
(Naldrett, 1999)

Table II-1-3-2 Comparison of PGE reserves in the major Ni-Cu-PGE deposits

Data from Buchanan(1979), Naldrett(1981), Robson(1985) and Naldrett(1987)

	Bushveld Complex			Great Dyke *	Sudbury	Noril'sk	Stillwater J-M Reef *
	Merensky Reef *	UG2 *	Platreef *	*			
Million Tonnes	2160	3700	1700	1679	310	1640	49
Grade (Total PGE+Au,g/t)	8.1	8.71	7.27	4.7	0.9	3.8	22.3
Contained PGE+Au (tonnes)	17496	32227	11900	7890	279	6232	1093
Percentage of total	26.8	49.4	18.2	12.1	0.4	9.6	1.7

*: Primary Product

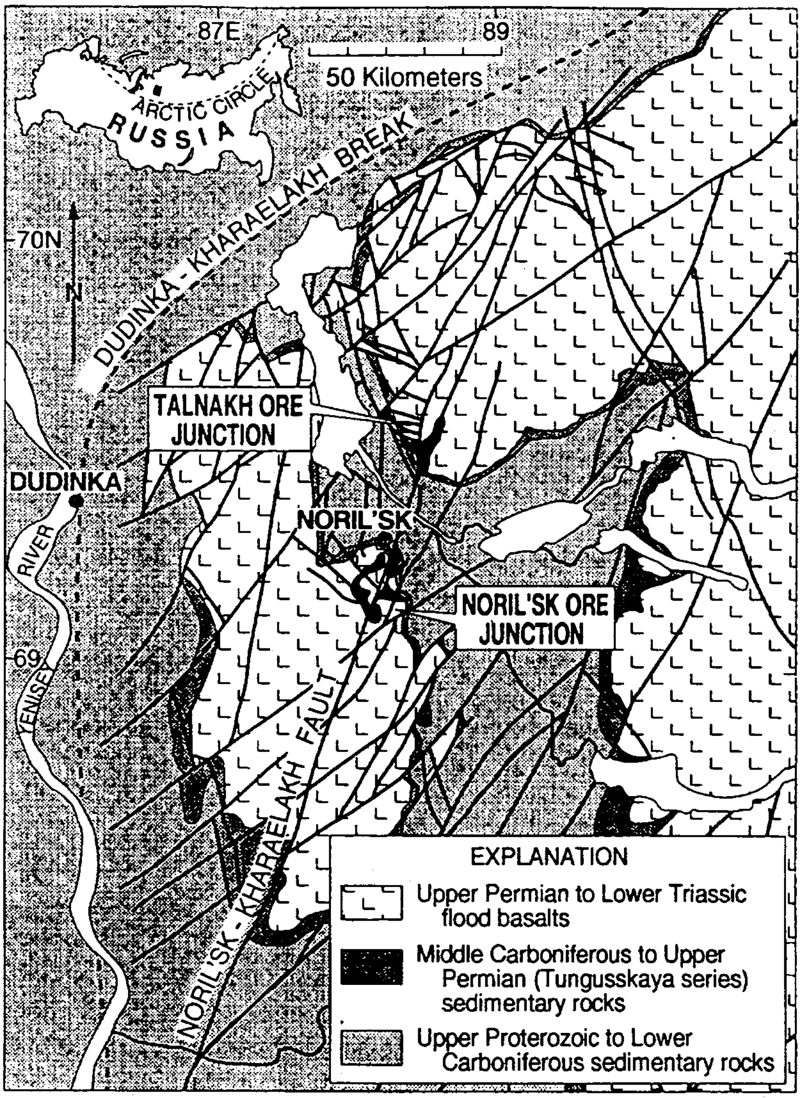


Fig. 1 Simplified geologic map of the Noril'sk-Talnakh district, showing major structural features and subsurface outlines of the Noril'sk-type, ore-bearing intrusions (black, true scale). The Kharaelakh and Noril'sk depressions are the ovoid areas, astride the Noril'sk-Kharaelakh fault and defined by the outcrop areas of basalt, which extend, respectively, north from the Talnakh ore junction and south from the Noril'sk ore junction.

Fig. II-1-3-2 Simplified geologic map of the Noril'sk-Talnakh district (Czamanske et al., 1995)

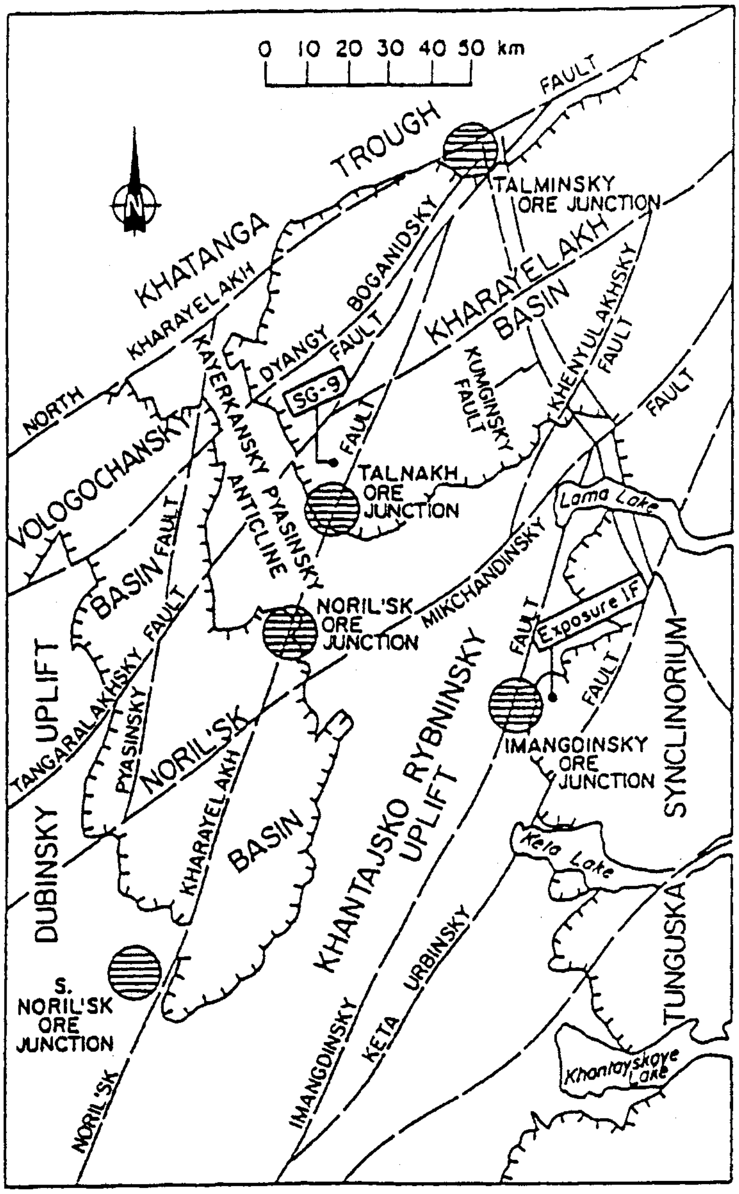


FIG. 3. Main structural elements of the northwest corner of the Siberian platform, together with the main ores zones and ore junctions. Locations of drill core SG-9 and exposure 1F are also shown. After Naldrett et al., 1992. Map was compiled by V. A. Fedorenko on the basis of data collected by NKGRE (Noril'sk-Complex Geological Exploration Expedition) and TsNIGRI (Central Geological Institute for Exploration and Research, USSR Ministry of Geology).

Fig. II-1-3-3 Main structural elements of the northwest corner of the Siberian platform (Naldrett, 1992)

fault which is one of the biggest structures in the region.

The recent distribution of the flood basalt is controlled by the three major basin structures. These structures from north to south are the Kharayelakh basin, the Vologochansky basin, the Noril'sk basin, and the Tunguska synclinorium. These basin structures were formed by subsidence, which occurred after the sedimentation of the flood basalts. Therefore, at the time of the flood basalts eruption, basaltic rocks were presumed to cover entire Noril'sk region. The keel (backbone) like structure in the NW-SE direction was formed by Kayerkan - Pyasino Uplift. By this movement, the deposits accompanied by mineralized intrusions, which was originally hosted within the sedimentary rocks covered by flood basalts, is considered to have been partly exposed on the surface (Fig. II-1-3-4).

1-3-3 Siberian Flood Basalts

(1) Stratigraphy of Basaltic Rocks

The flood basalts sequence of 3,500 m is considered to have been formed in 1 Ma between the Permian and the Triassic. The sequence is composed of several lavas, tuffs, and intrusions, and their percentage is 83.8, 9.6, and 6.5, respectively (Table II-1-3-3). The eruption of the flood basalts running through sedimentary rocks of the Tungusskaya series, particularly evaporate layer which includes carbonate and sulphate, might have played an important role for concentrating large volume of sulfides in the ores. The characteristic of the Siberian flood basalts is including much more amygdaloidal materials than flood basalts of other areas. The percentage of the amygdaloidal materials reaches 36 % in the Noril'sk region.

The stratigraphy of the flood basalts is shown in Fig. II-1-3-5. The basaltic rocks are classified into three assemblages.

Early Assemblage

Early assemblage is composed of the lavas of Ivakinsky (Iv), Syverminsky (Sv), and Gudchikhinsky (Gd) (from lower to upper), and its total thickness is approximately 500 m. This assemblage is high-Ti type and evolved from trachybasalt through basalt to picrite.

Middle Assemblage

The lowest layer is Khakanchansky tuff that is covered by lavas.

This assemblage consists of the lavas of Tuklonsky (Tk), Lower Nadezhdinsky (Nd_1), Middle Nadezhdinsky (Nd_2), Upper Nadezhdinsky (Nd_3), and Lower Morongovsky (Mr_1). The total thickness of this assemblage is approximate 500 to 600 meters. The Tk lava, the lowermost of these, is a low-Ti magma and is composed of basalt and picrite. The Nd_1 and Nd_2 lavas which cover the Tk lava were thought to have formed after crustal contamination and

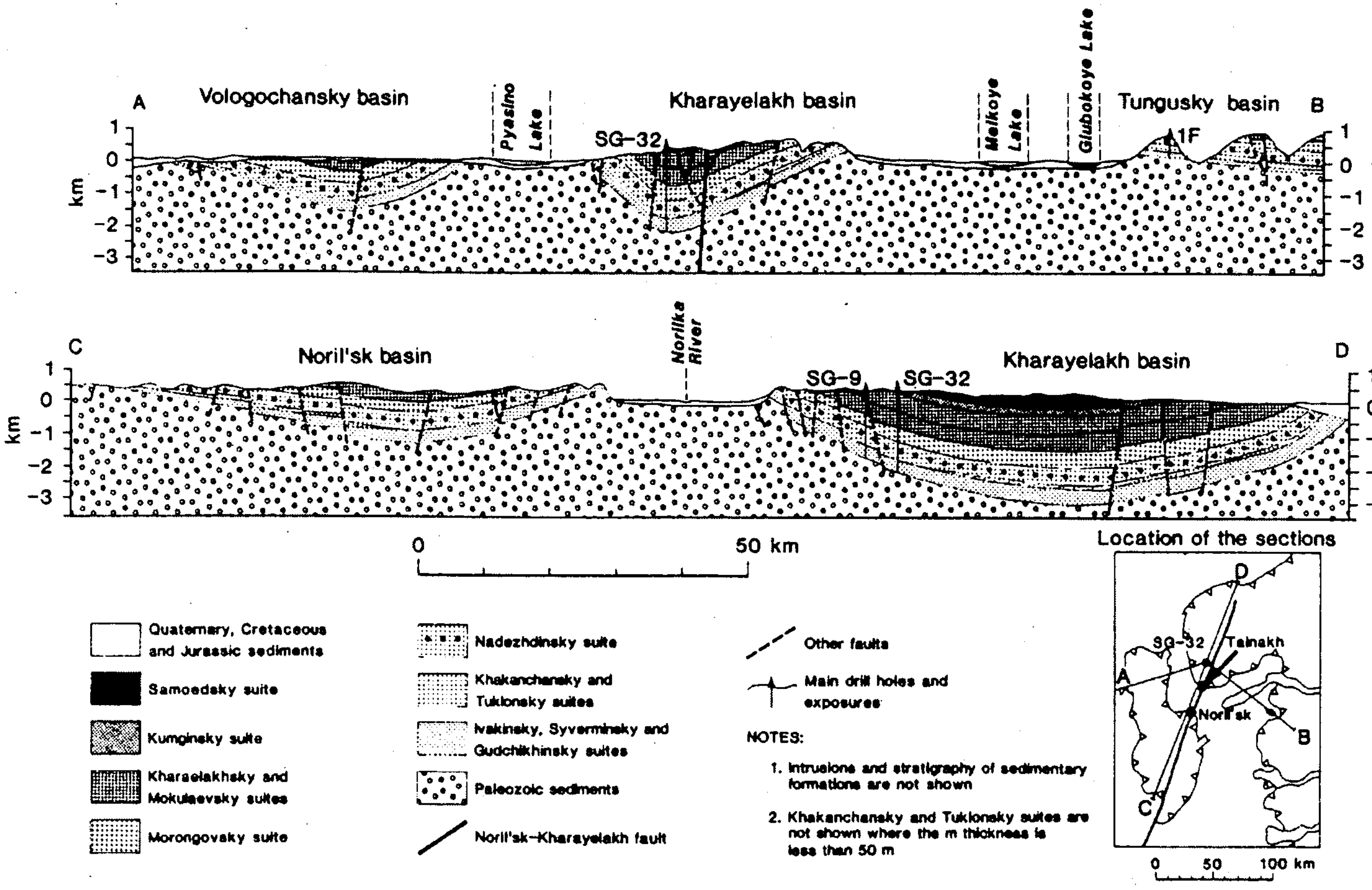


Figure 22.1c. North-south and east-west geological cross sections depicting the geology of the Noril'sk, Vologochansky, Kharayelakhsky and Tungusky synclinal sequences. Triangular boundary in inset map refers to margin of basaltic trap sediments under basalt sequence.

Fig. II-1-3-4 Geologic cross sections of the Noril'sk-Talnakh district platform (Naldrett, 1992)

Table I Table II-1-3-3 Volume percentages of the magmatic rock types in the Noril'sk region (fedorenko, 1994)

Table 15.1. Volume percentages of the magmatic rock types in the Noril'sk region.

	Lavas	Tuffs	Intrusions	Total
Granodiorite	—	—	>0.01%	>0.01%
Alkalic and subalkalic mafic rocks	2.0%	0.9%	1.5%	4.4%
Normal mafic rocks	81.0%	8.7%	4.9%	94.6%
Picrites and picrite-like rocks	0.8%	—	0.1%	0.9%
Picritic-mafic ore-bearing intrusions	—	—	>0.01%	>0.01%
Total	83.8%	9.6%	6.5%	99.9%

Total volume (including eroded masses) 150 000 km^3, within 45 300 km^2.

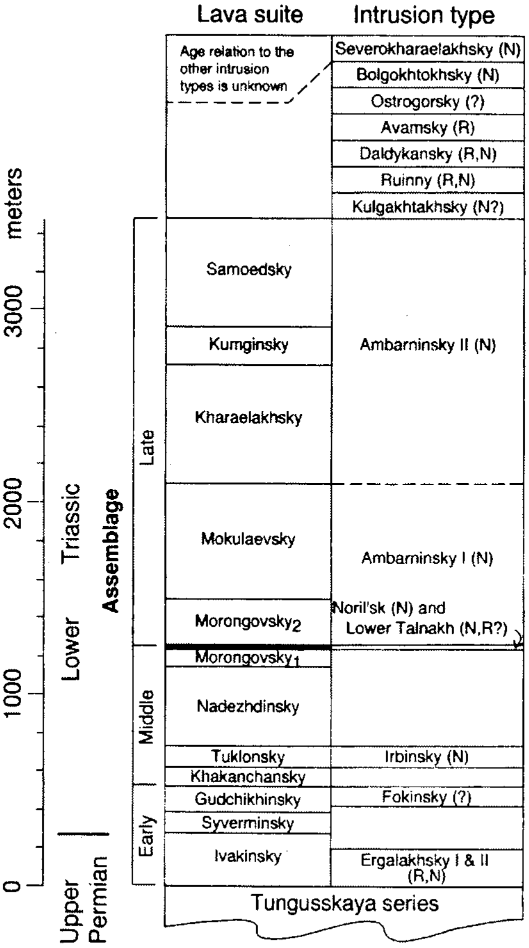


Fig. II-1-3-5 Correlation chart relating flood basalt stratigraphy of the Noril'sk region (Czamanske et al., 1995)

fractional crystallization of plagioclase, clinopyroxene and olivine of Tk basaltic magma. After eruption of these lavas, fresh mantle derived magma injected into the magma chamber, and parental magmas of the Nd_3 and Mr_1 lavas were formed.

The magmatic activity of this assemblage was important for the genesis of the Noril'sk deposits. As mentioned below, crustal contamination and sulfide segregation observed in Nd_1 and Nd_2 lavas are thought to have close relationship to the genesis of the deposits.

Late Assemblage

The assemblage consists of the lavas of Upper Morongovsky (Mr_2), Mokulaevsky (Mk), Kharaelakhsky, Kumginsky, and Samoedsky from lower to upper. The total thickness of the assemblage is 2,000 to 2,300 m. The lavas are mainly composed of low-Ti type magma.

(2) Crustal Contamination and Immiscible Sulfide Segregation

The crustal contamination, particularly the contamination of sulfur included in evaporates and other rocks, and following removal of immiscible sulfide melt from silicate magma are considered to be major requirements for the genesis of orthomagmatic sulfide deposits. Therefore, a silicate magma related to the genesis of ore may be depleted in sulfide and chalcophile elements. In the Noril'sk region these phenomena were clarified by the detailed geochemical studies of the related flood basalts. The crustal contamination and chalcophile elements depletion are markedly observed in the lavas of the middle assemblage.

Fig. II-1-3-6 shows La/Sm - Gd/Yb diagram for the lavas of the Noril'sk region. Tk lava shows low La/Sm and Gd/Yb. These rare earth elements ratios probably show the larger degree of partial melting of fertile magma. Comparing the Tk lava with the Nd_1 and Nd_2 lavas, which erupted after the Tk lava, the latter indicate increased La/Sm ratio, maintaining Gd/Yb constant. Since increasing of La/Sm with maintaining Gd/Yb constant means the crustal contamination, it is considered that contamination played a big role in the genesis of the magmas of the Nd_1 and Nd_2 lavas. Crustal contamination of these lavas is also indicated by initial ratio of $^{87}Sr/Sr^{86}$ by Lightfoot et al. (1991a). The $\delta\,^{34}S$ of the Noril'sk deposit indicates high values of +8 to +12‰. From this fact, sulfur is thought to have been supplied in the process of contamination from anhydrite that was included in the basement sedimentary rocks as one of the possibilities.

The reverse correlations between La/Sm and Ni, Cu, and Pt are obviously indicated in Fig. II-1-3-7. This fact suggests that Ni, Cu and Pt were depleted corresponding to the increasing of La/Sm in the Nd_1 and Nd_2 lavas, which contaminated crustal materials. This means that the crustal contamination and the depletion of chalcophile elements occurred at the same time in the same lava unit. Ni, Cu and Pt are the elements which are selectively distributed into sulfide melt when sulfide segregation occurs. They are selectively brought into the immiscible sulfide

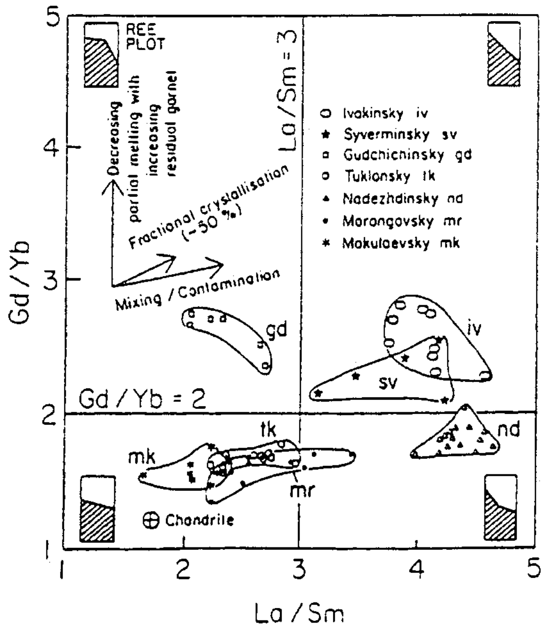


FIG. 6. Plot of Gd/Yb vs. La/Sm for basalts of the Noril'sk region. Adapted by Naldrett et al. (1992) after Lightfoot et al. (1990).

Fig. II-1-3-6 Relation between La/Sm versus Gd/Yb for basalts of the Noril'sk region (Naldrett, 1992)

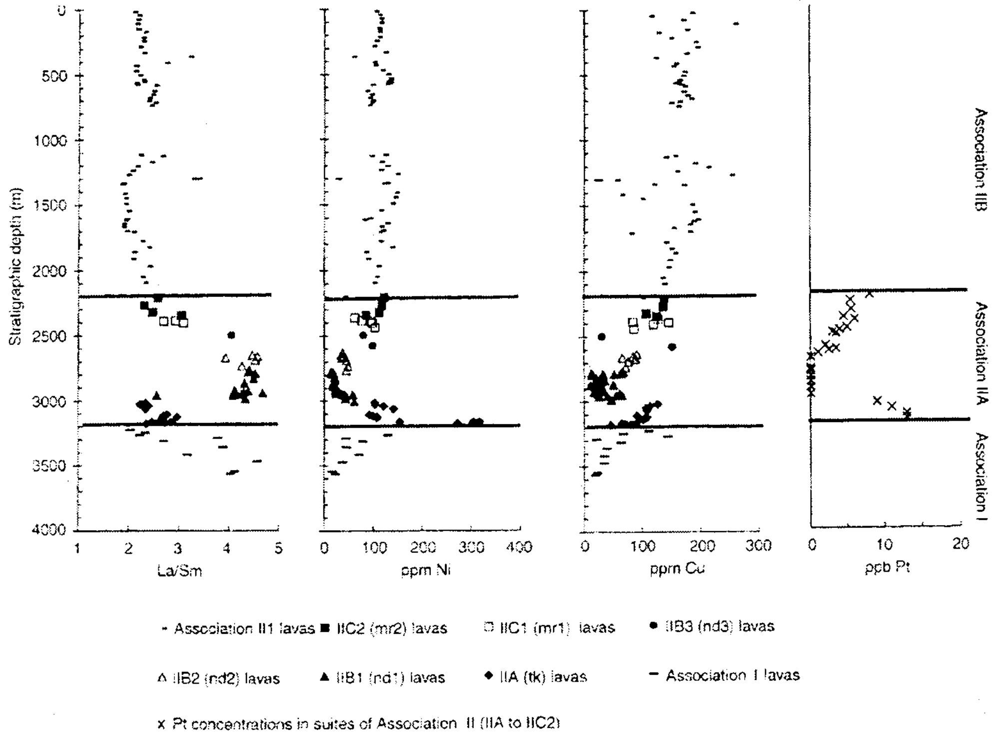


Fig. II-1-3-7 Vertical variation in La/Sm, Ni, Cu, Pt for basalts of the Noril'sk region (Naldrett, 1999)