STRATIGRAPHY OF THE QUATERNARY ASH AND PUMICEOUS PRODUCTS IN SOUTHWESTERN HOKKAIDO, N. JAPAN

(The Pliocene and Quaternary geology of Hokkaido, 1st report)

by

M. MINATO, S. HASHIMOTO,
Y. FUJIWARA, S. KUMANO
and S. OKADA

(With 2 tables and 48 figures)

(Contribution from the Department of Geology and Mineralogy, Faculty of Science, Hokkaido University No. 1245)

Introduction

Hokkaido, the northernmost main island of Japan, includes three Holocene volcanic belts (chains). (Fig. 1). The Nasu and Chokai belts extend in a northerly direction from northern Honshu, across the southwestern peninsula of Hokkaido, and along the coast of the Japan Sea as far north as Rishiri Island. The Kurile volcanic belt, with a NEE-SWW trend, may be traced through central Hokkaido to the eastern end of Shiretoko Peninsula (MINATO, M. et al, 1956). Beneath the Holocene volcanoes distributed along these three volcanic belts, Pleistocene volcanic products are widely developed. These, in turn rest on Neogene flows and pyroclastic deposits as well as Paleogene, Cretaceous and older formations (MINATO, M., YAGI, K., and HUNAHASHI, M. 1956).

The present paper deals with the Pleistocene volcanic products in the Noboribetsu and Shikotsu districts of south-western Hokkaido, especially with the ash and pumiceous deposits. The stratigraphic succession and petrography of ash falls, ash flows and associated sediments is presented along with correlation based on terrace chronology, paleoclimate and paleomagnetism. Further, our interpretation on the origin of these pumiceous products is briefly given.

1 Stratigraphy of the pumiceous volcanic products

The Pleistocene pumiceous deposits of southwestern Hokkaido may be classified into ash and pumice flows, either welded or non-welded, ash and pumice falls, and pumiceous gravel. Of these ash or pumice fall generally occupy the lower horizon of any given volcanic sequence such as the

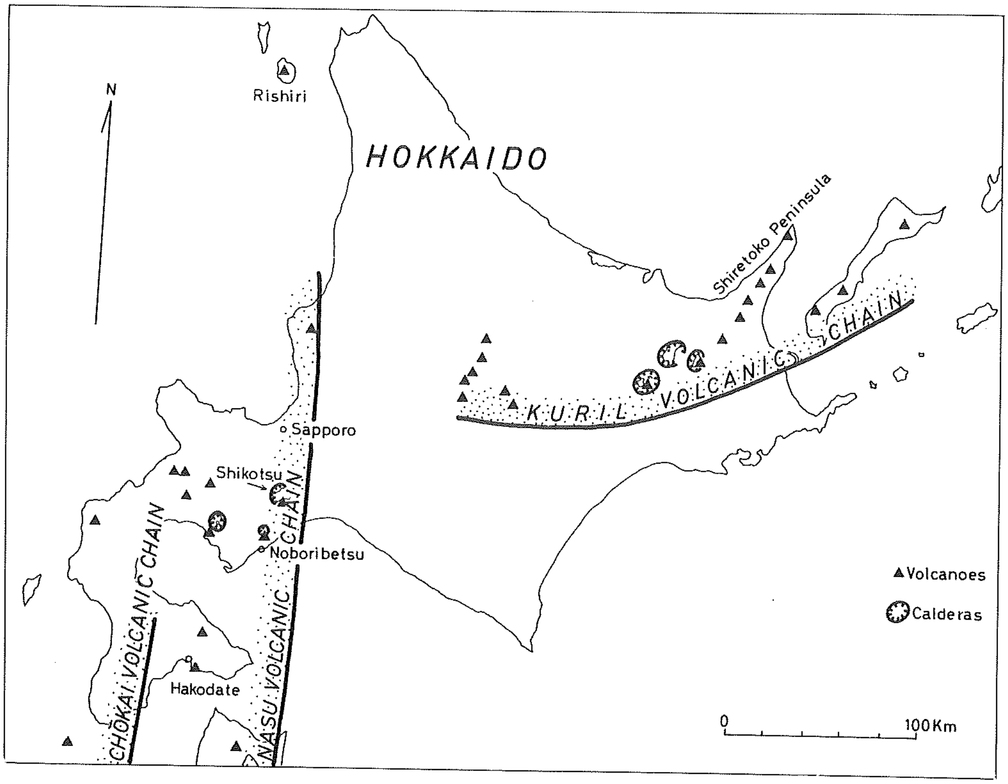


Fig. 1 Distribution of the Quaternary Volcanic Chains.

Noboribetsu, Ponayoro I and II, Shadai, Morino and Shikotsu Formations (Table 1). In fact, each ash or pumice fall member is composed of several separate falls with fairly distinct laminations. Each of these is undoubtedly the product of a volcanic explosion associated with an immense quantity of steam. Nevertheless, this kind of volcanic product, at least those parts most distant from the center of activity, may be regarded as a kind of aeolian deposit, transported by wind in the stratosphere and finally deposited on the land surface. Such pumice and ash fall are chiefly distributed eastward from the supposed center of explosion, probably reflecting a prevailing west or southwest stratosphere wind at the time of eruption. In addition, the volcanic ash or pumice falls are intercalated with numerous non-volcanic aeolian deposits such as rock flour or loess. These beds look like sandy loam and their boundary with volcanic ash falls is almost always very sharp, with little evidence of intermixing. The hiatus between the two may thus represent a considerable amount of time (Table 1).

Pumice flows or ash flows are always pure volcanic products which include both large and small pumices together with varying amounts of exotic rock

STRATIGRAPHICAL SEQUENCE OF PUMICEOUS VOLCANIC PRODUCTS IN THE NOBORIBETSU AND SHIKOTSU DISTRICTS

Terrace chronology	Formation / Member	Unit	Pumiceous volcanic product	Thickness in m.	Geomagnetic polarity	Palaeo-climate	Sea level lowering	International correlation
Lower terraces			Younger terrace gravel deposits					
Shikotsu volcanic Formation (Sh)	S.p.g.M.	Sh 3	Shikotsu pumiceous gravel	5				
	S.p. flow M.	Sh 2	Shikotsu pumice flow (hornblende dacite, partly welded)	200	N	Cold	- 106 m	Main Würm 1 Wh 1 31,900±1700, $30,400^{+3400}_{-2000}$ y.B.P.
	Shikotsu pumice fall Member	Sh 1 i	Shikotsu pumice fall (hornblende bearing rhyolite)	4				32,000±2000 y.B.P. $32,000^{+4700}_{-3100}$
		Sh 1 ℓh	Sandy loam	0.2				
		Sh 1 h	Shikotsu pumice fall (hornblende dacite)	1				
		Sh 1 ℓg	Sandy loam	0.2				
		Sh 1 g	Shikotsu pumice fall (hornblende bg. two pyroxene dacite)	0.1				
		Sh 1 ℓf	Sandy loam	0.01				
		Sh 1 f	Shikotsu pumice fall (two pyroxene dacite)	0.2				
		Sh 1 ℓe	Sandy loam	0.03				
		Sh 1 e	Shikotsu pumice fall (two pyroxene andesite)	0.2				W_1 / Wh 1
		Sh 1 ℓd	Sandy loam	0.05		Cool		
		Sh 1 d	Shikotsu pumice fall (two pyroxene andesite)	0.2				
		Sh 1 ℓc	Sandy loam	0.02				
		Sh 1 c	Shokotsu scoria fall (olivine bearing andesite)	3.4				
		Sh 1 ℓb	Sandy loam	0.01				
		Sh 1 b	Shikotsu scoria fall (two pyroxene andesite)	0.3				
		Sh 1 ℓa	Sandy loam	0.03				
		Sh 1 a	Shikotsu pumice fall (two pyroxene andesite)	1				
Middle terraces			Older lower terrace gravel deposits			Cold	- 80 m	Early Würm (Wooly
			Younger middle terrace gravel deposits				+ 12 m	Riss / Würm
Morino volcanic Formation (M)	Morino p.g.M.	M 3	Morino pumiceous gravel	10				
	Morino p.flow M.	M 2	Morino pumice flow (hornblende biotite dacite)	60+	N			
	Morino pumice fall Member	M 1 d	Morino ash fall (two pyroxene andesite)	0.4-0.7				
		M 1 c	Morino upper pumice fall (biotite olivine hornblende two pyroxene andesite)	1-1.3				
		M 1 b	Morino white ash (hornblende bg. two pyroxene dacite)	2-2.5		Cold		Riss
		M 1 a	Morino lower pumice fall (two pyroxene hornblende dacite)	3				
		M 0	Morino pyroclastic sediment / Older middle terrace gravel deposits					
Shadai volcanic Formation (S)	Shadai p.g.M.	S 3	Shadai pumiceous gravel	3-5		Cold		
	Shadai p.flow M.	S 2	Shadai pumice flow (olivine bg. andesite, partly welded)	20+	N			
	Shadai pumice fall Member	Shadai pumice fall (S 1)	alternation of coarse and fine grained tuff	1.3				
			clay	0.5				
			fine grained ash	1				Mindel / Riss
			ash with volcanic breccia / Oldest middle terr.gr.depo.	2-0.3				
Higher terraces			Younger higher terrace gravel deposits					
Ponayoro volcanic Form. II (PII)	P.II.p.flow M.	P II 2	Ponayoro pumice flow II2 (hornblende dacite) — Ns5 (Noboribetsu sandston F., Ns)	2-30				Mindel
	P.II.p.fall M.	P II 1	Ponayoro pumice fall II — Ns4	2-3.0				
Ponayoro volcanic Formation I (PI)	P.p.g.M.	P I 3	Ponayoro pumiceous gravel — Ns3	4		Warm (?)		Günz/ Mindel
	Ponayoro I, p.flow Member	P I 2	Ponayoro pumice flow I (dacite, non-welded) — Ns2	8-10	N			
	P.I p. fall M.	P I 1	Ponayoro pumice fall — Ns1	2-4		Warm		
Noboribetsu volcanic F. (N)	Noboribetsu p.flow M.	N 2	Noboribetsu pumice flow (two pyroxene andesite, well welded)	25-30				Güntz
	Nob. p.fall M.	N 1	Noboribetsu pumice fall	2		Cold	- 40 m(+)	
			Ranpoge gravel Formation	100		Cool	- 110 m	Donau
			Pliocene deposits					Pliocene

fragments. They are believed to have been erupted with a high content of steam. Near the center of eruption, this kind of flow is generally hard, well consolidated with relatively high virtual (apparent specific gravity) density throughout almost the entire cooling unit, whereas the marginal parts are softer, more loosely consolidated or almost unconsolidated. In between, there is an area where the upper and lower parts of such flows are not well consolidated, but the middle portion is harder, better welded and has relatively higher density than either the lower or upper portions.

Columnar or platy joints are generally developed in the consolidated parts of these flows especially near the center of volcanic activity. Irregular joints are locally developed in places more remote from the center, and then only in the middle part of a cooling unit.

The third type of product called pumiceous gravel is undoubtedly sedimentary in origin. Nevertheless, this kind of gravel is very rich in pebbles of pumice and pumiceous sand. It also contains lesser amounts of pebbles and sands derived from exotic rock fragements originally included in the pumiceous volcanic deposits. Thus the clasts, both pumiceous and exotic have been derived directly from the underlying pumice fall and/or flow. Such gravels should accordingly be treated as pyroclastic sediments formed by rapid wind and stream erosion of volcanic material immediately after its eruption. None of these gravels are believed to have been transported any great distance.

All of them rest unconformably on pumiceous falls or flows. Cross lamination, false bedding are common in all outcrops.

In summary, the pumiceous volcanic products described in this paper include three distinct types of deposits. These are in ascending order: fall, aeolian and volcanic in origin; flow of volcanic origin; and gravel of sedimentary origin.

a) The Noboribetsu volcanic Formation

The Noboribetsu volcanic Formation is typically developed on the small hill facing Volcano Bay (Funka-wan), just behind Nobcribetsu Station on the National railroad (Fig. 2) and is widely exposed in the hilly and mountainous region around the hot springs of Noboribetsu.

The lower member of the formation less than 2 m in thickness, is pumice fall (N 1) with beautiful rhythmic lamination composed of coarse to fine grained layers. Below this ash fall there is a very coarse grained pumiceous fall, about 2.5 m in maximum thickness. These ash fall deposits are unconformably covered by the next member the Noboribetsu pumice flow (N 2), 25-30 m in thickness, in the type locality.

The flow (N 2) is also pumiceous, well consolidated and nearly all outcrops exhibit irregular jointing. The mineral assemblage shows it to be andesitic; chief

Fig. 2 Distribution of the Noboribetsu volcanic Formation.
Black: outcrop ; Hatched lines: covered ; Crossed lines: presence is not proved at surface with certainty but is highly probable ; Numerals: elevation of outcrop in meters ; Double circles: drilling sites.
B: Kuttara Lake (or Kuttaraushi Lake)
C: Horobetsu River (or Porobetsu River)
D: Noboribetsu River
E: Shikifu River
K: Noboribetsu Station
R: Cape Rampoge
p-q: geological profile shown in Fig. 47
r-s: geological profile shown in Fig. 48

mineral constituents are plagioclase, augite, hypersthene and magnetite. Geomagnetic polarity is normal.

Both the pumice fall (N 1) and flow (N 2) are pinkish or purplish red in colour and easily distinguishable from the younger pumiceous volcanic products of the Ponayoro Formation. Their distribution is shown in Fig. 2.

It may be worth noting that lava bombs 0.2-0.3 m in diameter with many empty cavities, through which gases may have escaped, are locally and rarely found in the Noboribetsu fall (N 1), especially its basal part. The lithologic nature of these bombs closely resembles pumice flow (N 2) which overlies this fall.

No pumiceous gravel deposits covering the Noboribetsu pumice flow have been discovered, but they must have once existed.

The Noboribetsu volcanic Formation lies directly on the Rampoge gravel Formation at Cape Rampoge. The latter, about 100 m in total thickness is composed mainly of pumiceous sand, magnetite bearing sand, and gravel with various kinds of cobbles and pebbles including slate, chert, and Neogene Tertiary volcanic rocks.

No contacts between this Formation and the Shadai volcanic Formation have been observed but their stratigraphic relationship can be inferred from characteristic blocks of basaltic andesite included in the Noboribetsu pumice flow (N 2) and the Ponayoro volcanic Formations. According to S. Doi (1953) these xenoliths or exotic rock fragments may have been derived from the Shadai pumice flow (S 2). Thus the Shadai volcanic Formation was formerly regarded to be stratigraphically below the Noboribetsu volcanic Formation (Saito et al., 1953). The authors also once subscribed to this view (Minato et al., 1970), but now believe this is probably not the case. In fact the evidence given here suggests the Shadai volcanic Formation may be far younger than either the Noboribetsu or the Ponayoro volcanic Formations.

b) The Ponayoro volcanic Formations I and II and the Noboribetsu sandstone Formation

At its type locality near Noboribetsu Station (Fig. 3, locality K) the Ponayoro Formation may be divided into three members; Ponayoro I rests unconformably on Noboribetsu pumice flow and is overlain unconformably by Ponayoro volcanic Formation II (Figs. 4, 5, 6, 7, 8, 9, 10). The Noboribetsu sandstone Formation is a sandstone facies that transgresses most of Ponayoro time and comprises many separate sedimentary members separated by local unconformities. Locally the Noboribetsu sandstone member (Ns 1) is overlain unconformably by P I 2 whereas elsewhere this same pumice flow (P I 2) is overlain unconformably by beautifully cross laminated sandstone that is assigned to Noboribetsu sandstone member Ns 3, (Table 1). At still other localities, pumice flow (P II 2) belonging to the Ponayoro volcanic Formation II rests unconformably on Noboribetsu sandstone member Ns 4. Furthermore, Ponayoro (P I 2) is locally completely reworked and transported beyond the

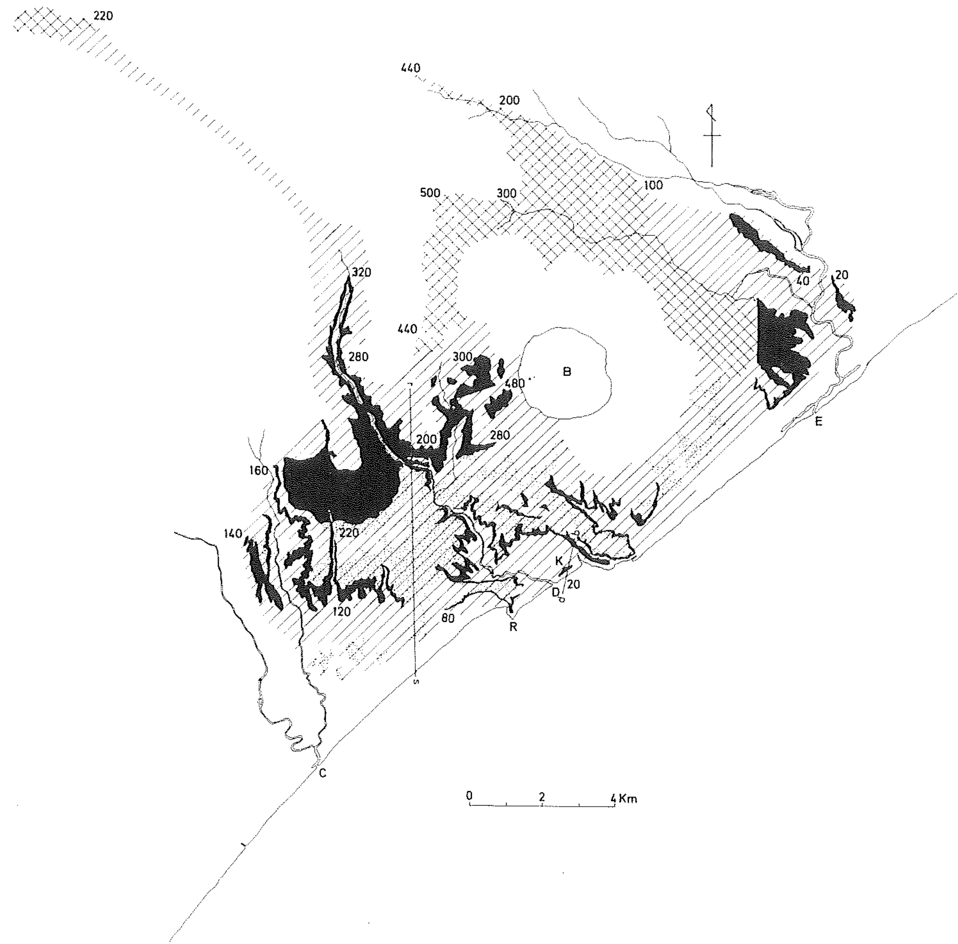


Fig. 3 Distribution of the Ponayoro volcanic Formation.
Black: outcrop ; Hatched lines: covered ; Crossed lines: Ponayoro volcanic Formation at the surface, but not completely distinguished from Noboribetsu volcanic Formation because of insufficient mapping ; Dots: Noboribetsu sandstone intercalated with Ponayoro volcanic Formation ; Numerals: elevation of outcrop in meters ; Other legends see Fig. 2.

original area of deposition. Outcrops along the road between Rampoge and Tomiura contain well rounded pebbles of pumice, probably derived from Ponayoro (P I 2). These are highly concentrated in deposits of reworked Ponayoro (P I 2), which is also unconformably covered by a sandstone member Ns 3 with beautiful laminations, belonging also to the Noboribetsu sandstone Formation.

It is thus concluded that the volcanic activity represented by both Ponayoro I and II persisted throughout the time that most of the Noboribetsu sandstone Formation was being deposited. The Ponayoro volcanic Formations

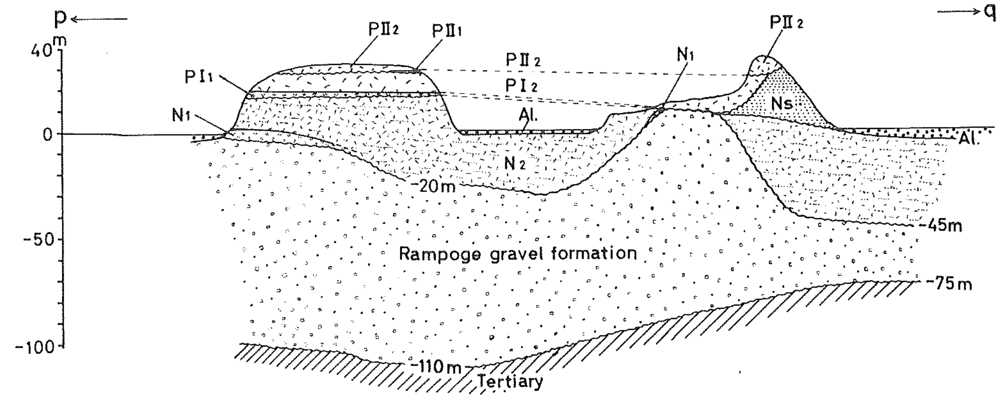


Fig. 4 Geological profile along the Noboribetsu coast. (p - q corresponds to section in Figs. 2 and 3)

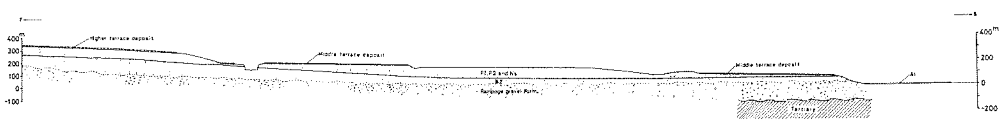


Fig. 5 Geological profile across the western part of Noboribetsu City. (r - s corresponds to location line in Figs. 2 and 3)

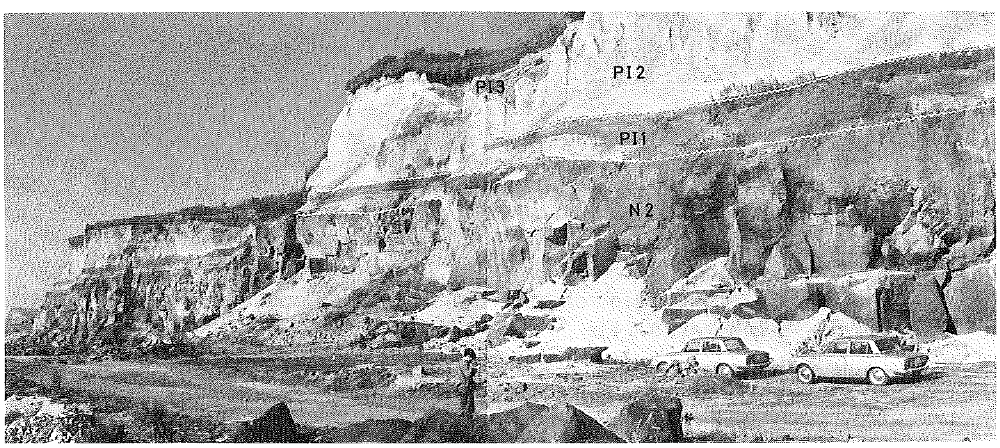


Fig. 6 Type locality of the Noboribetsu volcanic Formation, located on the hill facing Volcano Bay, about 0.5 km south of Noboribetsu Station. N 2: Noboribetsu pumice flow with irregular joints, well consolidated and welded. P I 1: Ponayoro pumice fall I, with beautiful laminations. P I 2: Ponayoro pumice flow I without lamination and loosely consolidated. P I 3: pumiceous gravel, which rests unconformably on P I 2. The top of the outcrop is occupied by ashes from Holocene volcanoes.

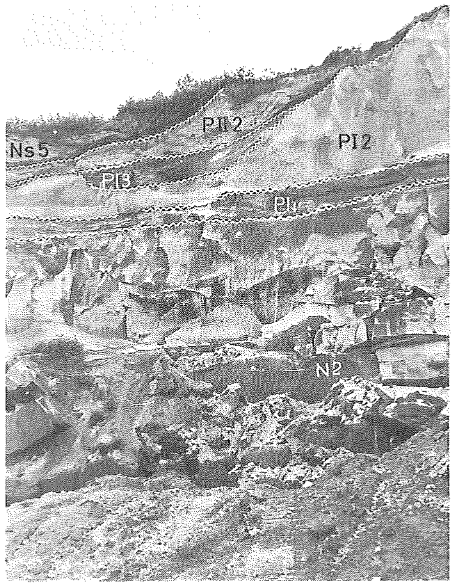


Fig. 7 Typical sequence of the Ponayoro volcanic Formation unconformably resting on the Noboribetsu pumice flow at the quarry behind Noboribetsu Station on the National railway. N 2: well welded Noboribetsu pumice flow ; P I 1: Ponayoro pumice fall I ; P I 2: Ponayoro pumice flow I ; P I 3: Ponayoro pumiceous gravel ; P II 2: Ponayoro pumice flow II ; Ns 5: Noboribetsu sandstone Formation with peat at its base.

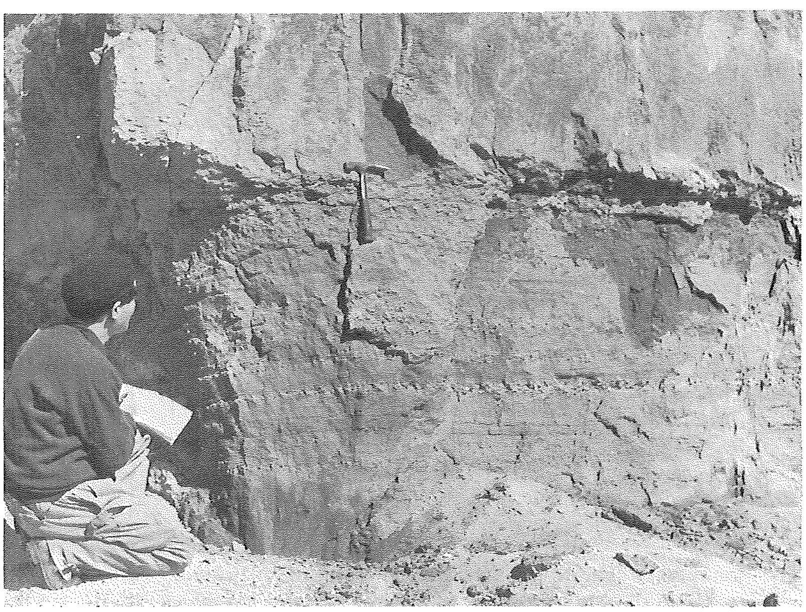


Fig. 8 The Noboribetsu pumice fall (N 1) with beautiful laminations at the type locality. This is unconformably covered by the Noboribetsu pumice flow (N 2).

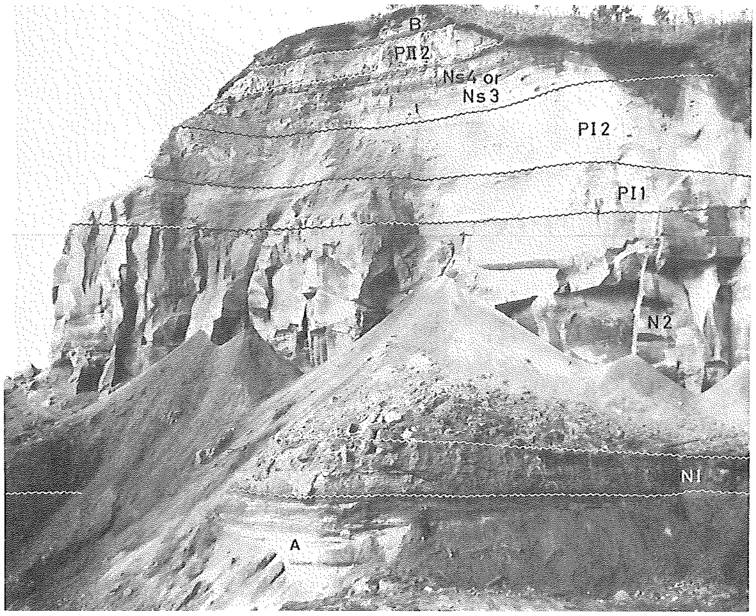


Fig. 9 Noboribetsu and Ponayoro volcanic Formations exposed at Rampoge Cape facing Volcano Bay. A: Rampoge gravel Formation ; B: Alternating volcanic ash and peat belonging to the Holocene.

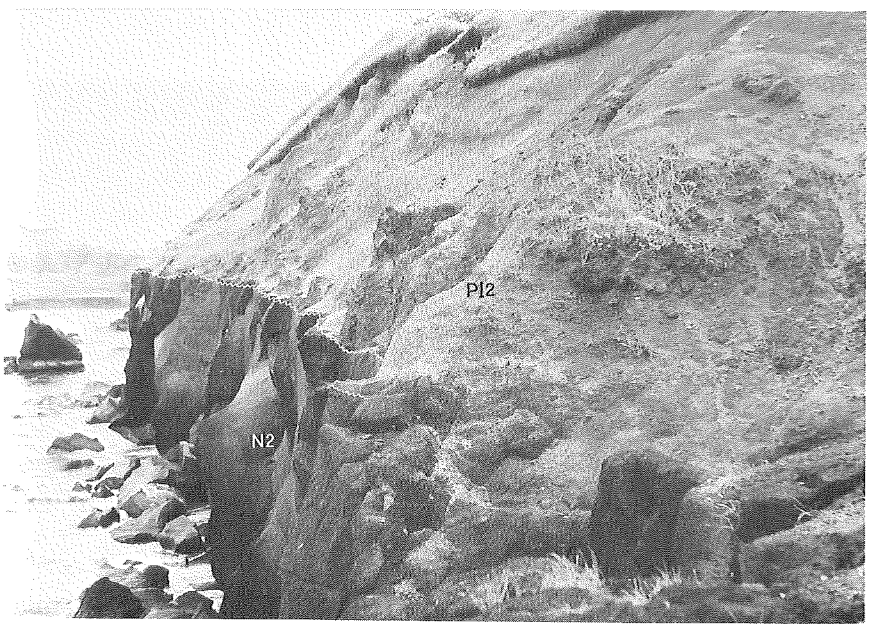


Fig. 10 The Ponayoro volcanic Formation I (P I 2), unconformably resting on Noboribetsu pumice flow (N 2). Exposure is located on the sea coast about 1.5 km east of Noboribetsu Station, on the National railway. The type locality of the Noboribetsu pumice flow may be seen in the left distance.

(P I and P II) were described by SAITO et al. (1953) as though they interfingered with the Noboribetsu sandstone. However, there is undoubtedly an unconformity or stratigraphic hiatus. Moreover the Noboribetsu sandstone Formation can be subdivided into five members by clearly defined unconformities. These are called Ns 1, Ns 2, Ns 3, Ns 4 and Ns 5 in ascending order.

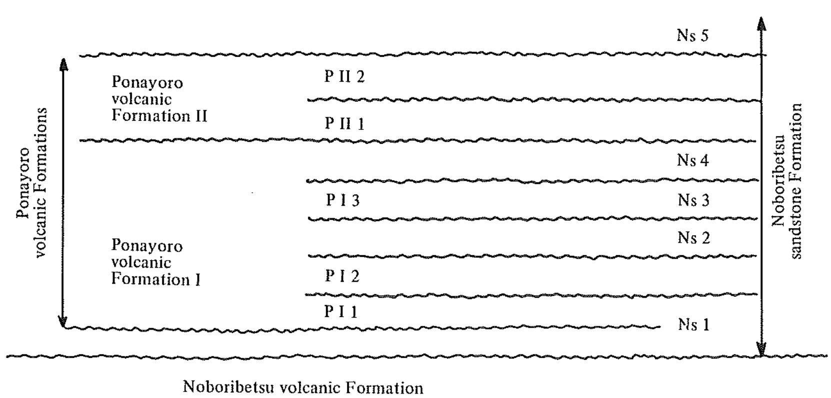
In fact, a new road cut between Rampoge and Tomiura, about 2 km southwest from Noboribetsu Station exposed strongly reworked pyroclastic sediments (Ns 2) overlying laminated sandstones (Ns 3). These members are cut by a fault which does not extend upwards into the overlying sandstones member (Ns 4). In other words, neither the sandstone member (Ns 4) nor the Ponayoro volcanic Formation II (P II 2) shows any disturbance there. This is positive evidence of a stratigraphic break between Noboribetsu sandstone members (Ns 3 and Ns 4). It must also be concluded that a major stratigraphic break separates Ponayoro Formations I and II.

The pumiceous gravel deposit (Ns 2) may be stratigraphically a little higher than the Ponayoro volcanic Formation P I 2. It is unconformably covered by a sandstone member (Ns 3) with remarkably thin laminations. This sandstone member (Ns 3) seems to be at least partly marine because rare trace fossils probably left by some Polychealita, as well as poorly preserved diatom-like remains were determined in the basal part of this member.

The uppermost member of the Noboribetsu sandstone Formation (Ns 5) rests unconformably on the Ponayoro volcanic Formation I, usually on P I 2 (Fig. 11). This member is very characteristic in its extremely well developed false bedding or cross lamination.

The Ponayoro I 3 and Noboribetsu sandstone member Ns 3 may be stratigraphically nearly equivalent and the lowest member of the Noboribetsu sandstone, called Ns 1 may be a little older than Ponayoro volcanic Formation

Table 2 **Stratigraphic relationship between the Ponayoro volcanic and Noboribetsu sandstone Formation**



I, since the former is unconformably covered by P I 2 in many places. However, the exact relationship between P I 1 and Noboribetsu sandstone member Ns 1 has not been observed in field.

Thus, the stratigraphic relationship between Ponayoro volcanic Formation I and II and the Noboribetsu sandstone Formation is fairly well established (Table 2).

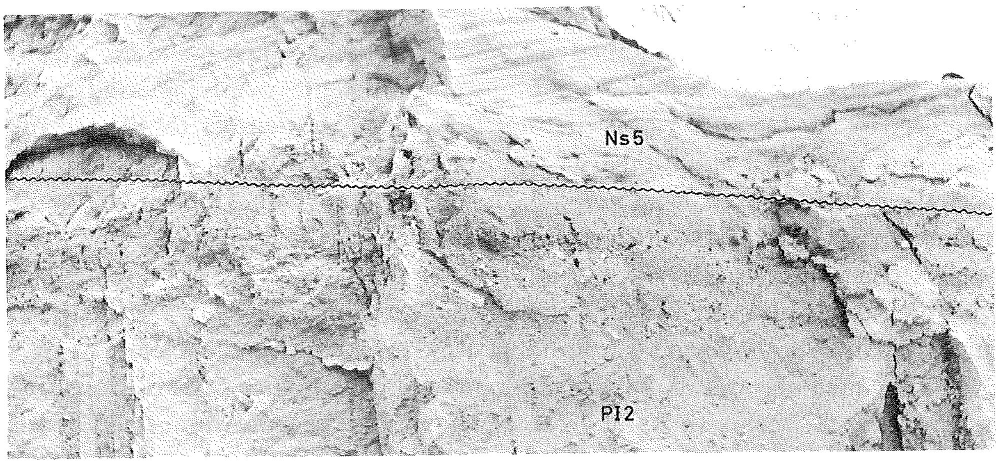


Fig. 11 Loosely consolidated Ponayoro pumice flow exposed in a road cut at Ponayoro, about 1 km east of Noboribetsu Station. The pumice flow is correlative with P I 2, and is unconformably covered by sandstone with false bedding belonging to the upper member of the Noboribetsu sandstone Formation (Ns 5).

c) The Ponayoro volcanic Formations I and II

The lowest stratigraphic unit of the Ponayoro volcanic Formation, pumice fall (P I 1) of Ponayoro volcanic Formation I, is 2 to 4 m in total thickness. It has thin rhythmic laminations (Fig. 12) and, at its type locality. It rests unconformably on the Noboribetsu pumice flow (N 2). This is covered by pumice flow (P I 2), about 8 to 10 m thick, which does not show any lamination and is loosely consolidated. The basal part of this flow contains many carbonized tree trunks. This flow is generally white to light gray and dacitic in lithologic composition. The main constituent minerals are plagioclase, augite, hypersthene and a small amount of quartz.

Locally the above flow is deeply dissected and this erosional surface is filled with a variable thickness of pumiceous gravel (P I 3). At the type locality this gravel, with a maximum thickness of about 4 m, is overlain unconformably by another pumice flow (P II 2), of Ponayoro volcanic Formation II.

In many places, however, the pumiceous gravel is missing and pumice flow P II 2 rests directly on Ponayoro I (Fig. 13).

Pumice flow (P I 2) of Ponayoro volcanic Formation I is white to gray in

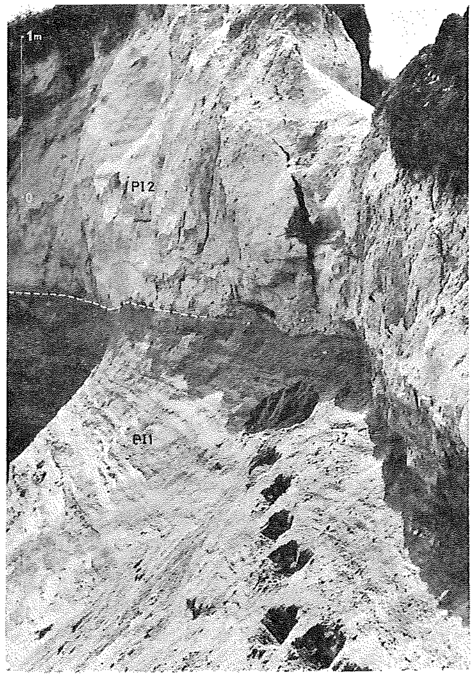


Fig. 12 The Ponayoro volcanic Formation exposed at the same locality shown in Fig. 6. The lower half (P I 1) belongs to the pumice fall with thin laminations, each indicating a volcanic explosion. The upper part (P I 2) is the pumice flow belonging to Ponayoro volcanic Formation I.

Fig. 13 Well stratified sandstone belonging to the lower member of the Noboribetsu sandstone Formation unconformably covered by Ponayoro pumice. This outcrop is located at the Kojohama tunnel between Noboribetsu and Kojohama.

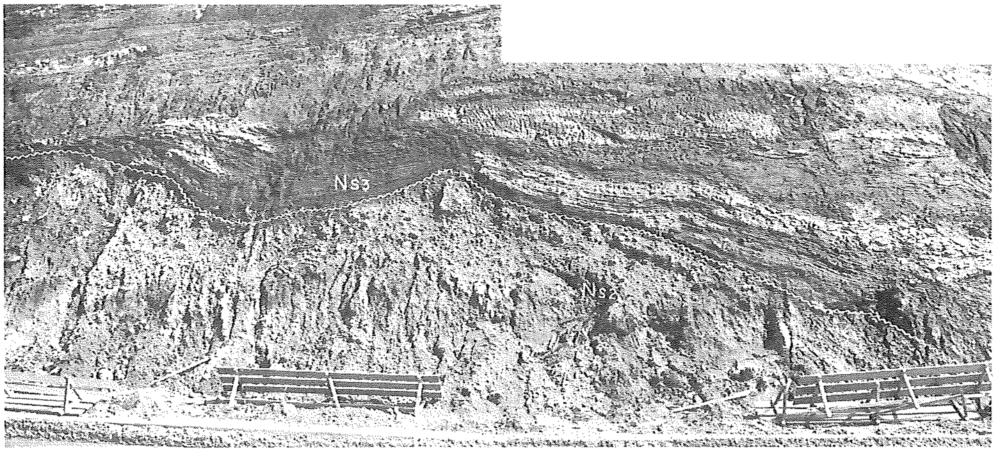


Fig. 14 Unconformity between the pumiceous deposits (Ns 2), derived from the Ponayoro pumice flow, and the sandstone member (Ns 3) of the Noboribetsu sandstone Formation. Pumices found below the unconformity are generally more or less rounded, and the pumiceous deposit shows poor stratification, while the overlying sandstones are beautifully laminated and coarse grained with small patches of pumiceous sand. Photo. taken at the road side between Rampoge and Tomiura.

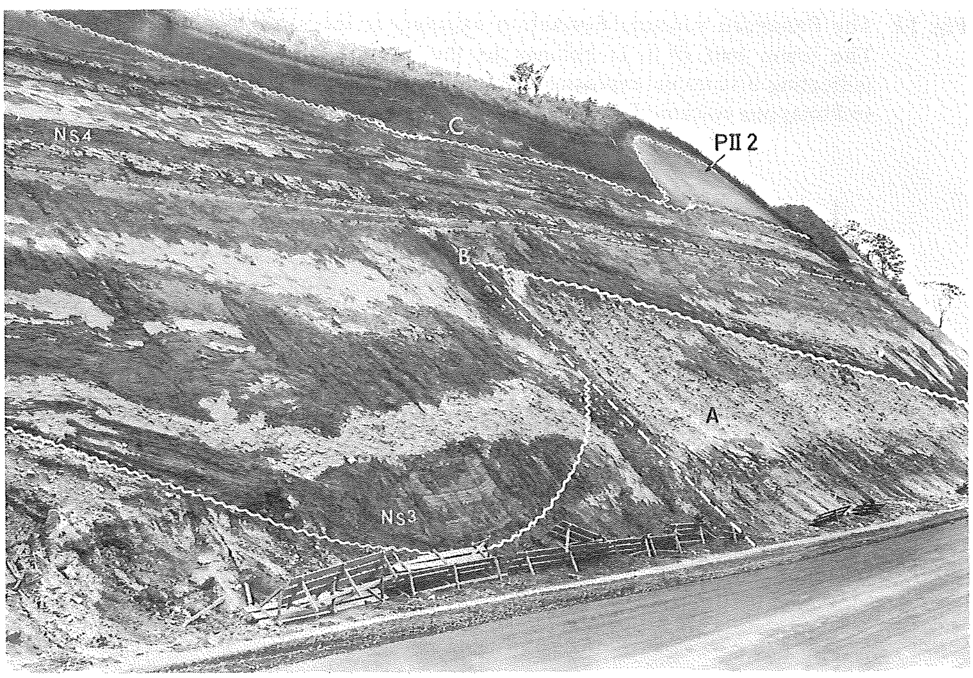


Fig. 15 Unconformity between the lower and upper members of the Noboribetsu sandstone Formation, observed at the roadside between Rampoge and Tomiura. (A): pumiceous deposit, probably reworked Ponayoro pumice flow I; (B): normal fault, strike, N10E; dip 50NW; (C): Holocene ash and humus deposits.

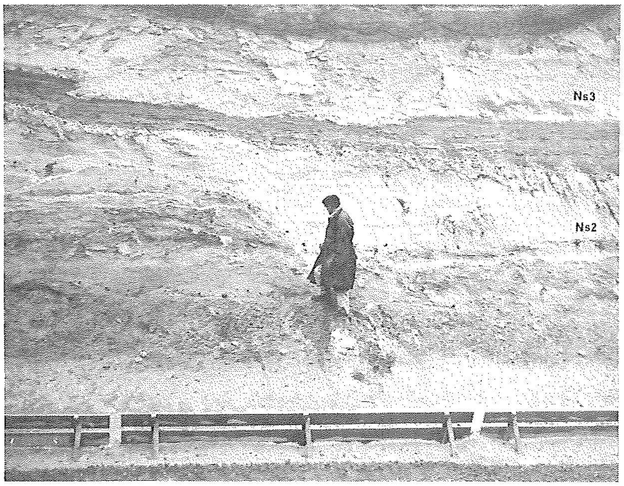


Fig. 16 Noboribetsu sandstone Formation, separated into two members by unconformity, exposed along the road side between Rampoge and Tomiura. The pumiceous deposits (Ns 2) with thin laminations may indicate a nearshore marine origin. The source material was probably largely Ponayoro pumice flow. The basal part of the sandstone member (Ns 3) of the Noboribetsu sandstone Formation is represented by laminated sandstone with pumiceous patches which grade upward into fine material with pumiceous sand. Noboribetsu pumice flow is present at the foot of this exposure, although it is strongly decomposed.

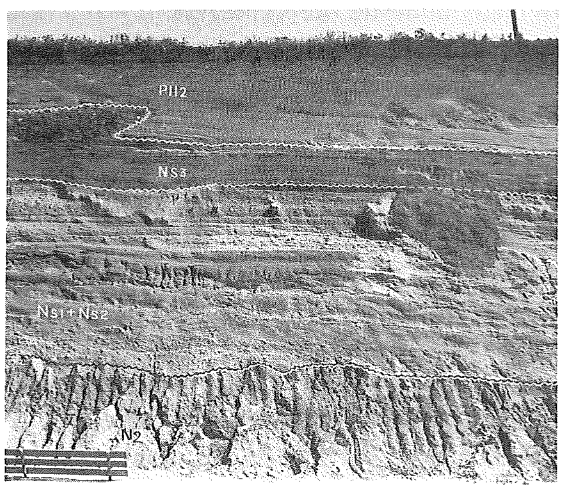


Fig. 17 Stratigraphical profile obserbed at the road side midway between Rampoge to Tomiura.
N 2: Noboribetsu pumice flow, the upper part of which is strongly decomposed, Ns 1 plus Ns 2: the lower half is chiefly composed of pumiceous clay, and the upper half consists of pumiceous sand with thin laminations; Ns 3: laminated sandstone, probably marine in origin; P II 2: Ponayoro pumice flow II resting unconformably on the Noboribetsu sandstone Formation Ns 3. This flow is covered by black, Holocene soil.

colour and lacks hornblende.

The ash fall deposit (P II 1) belonging to Ponayoro volcanic Formation II is only locally exposed. It is also pink, very thin and unconformably covered by pumice flow P II 2.

The Noboribetsu volcanic Formation and the Ponayoro volcanic Formations are unconformably covered in many places by the gravel beds belonging to the higher terrace in this region.

From this field evidence, the authors now consider that a series of older pumiceous volcanic products, such as the Noboribetsu and Ponayoro may be at least as old as Riss ice age. This is consistent with the normal geomagnetic polarity of pumice flow I (P I 2).

d) The Shadai volcanic Formation

This formation is well developed in the upper course of the Shadai and Moshiraoi Rivers (Fig. 18). At its type locality, it may be divided into three stratigraphic units: Shadai pumice fall and pyroclastic deposit (S 1), Shadai pumice flow (S 2) (Fig. 19) and Shadai pumiceous gravel (S 3) (Fig. 20).

The lowest member is exposed only in a limited area. Along the middle course of Moshiraoi River the lower member rests unconformably on Neogene (probably Pliocene) pyroclastic deposits composed of interbedded agglomerate, tuff and tuffaceous silt. There the lower member is about 3 m thick. Its base consists of ash with many andesite breccia layers, 2 – 0.3 m thick. These layers are overlain by fine grained ash, about 1.0 m thick which are in turn covered by thin alternations of very coarse and fine grained pumiceous ash, about 1.3 m in total thickness. Between this pumiceous fall and the preceding one, there is a lenticular, highly variable clay layer, less than one half meter in maximum thickness (Table 1).

Diastems are present at the base of each of these layers, thus deposition may have been interupted, although the time interval between periods of deposition was probably small.

At the type locality of the Shadai volcanic Formation, the alternating coarse and fine grained ash member, is unconformably overlain by a poorly consolidated pumice flow (S 2), more than 20 m thick.

This flow is extremely uniform, gray or black without layering, homogeneous in grain size of matrix, and includes large and small black pumice. The mineral assemblage is that of basic andesite. Irregular or columnar joints are developed locally in the better consolidated parts of this flow. Constituent minerals are chiefly plagioclase, augite hypersthene, and a small amount of olivine. Exotic lithic fragments, usually less than 5% of the total volume, are uniformly distributed throughout the flow. Its geomagnetic polarity is normal.

Erosional remnants of this flow are preserved in a relatively small area but

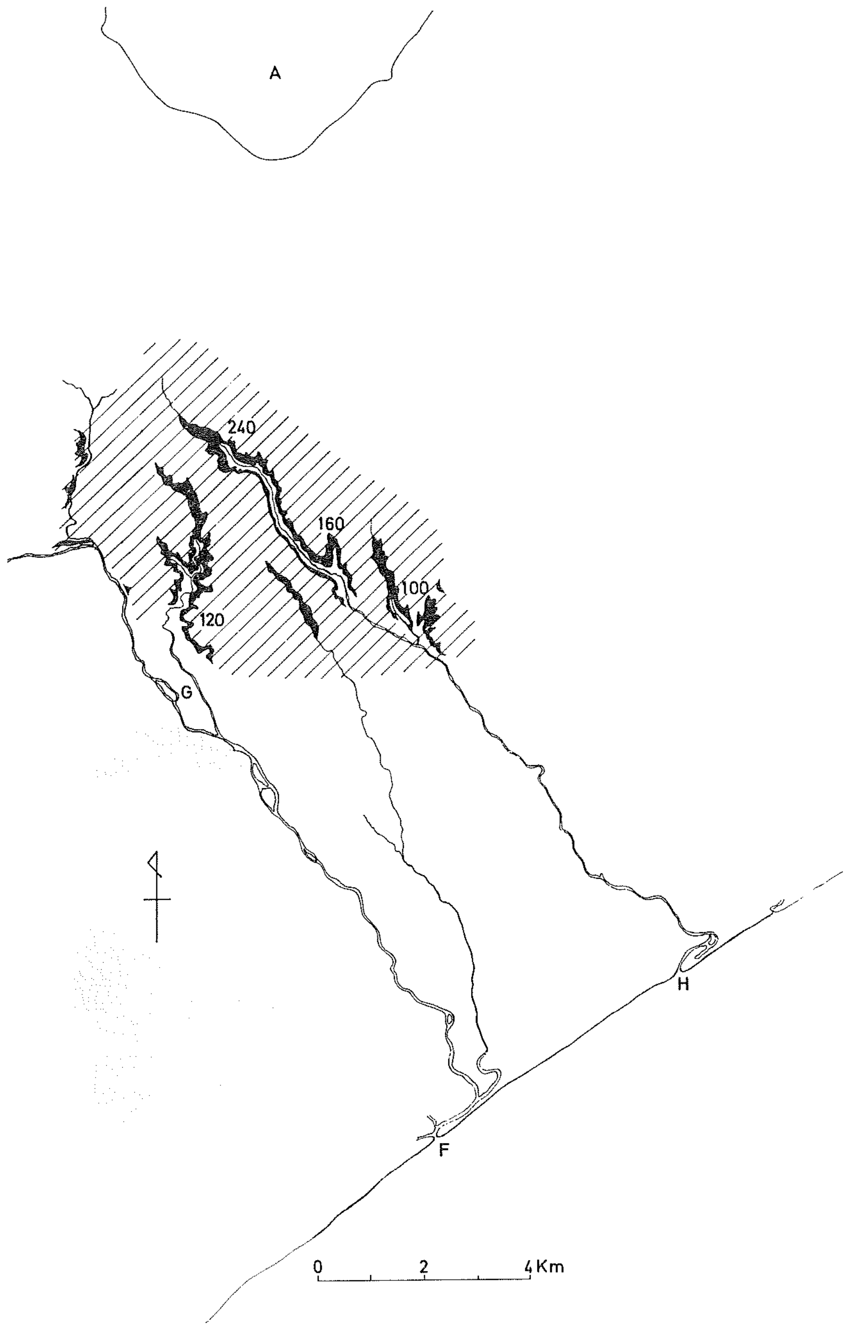


Fig. 18 Distribution of the Shadai volcanic Formation.
Black: outcrop ; Hatched lines: covered ; Numerals: elevation of outcrop in meters.
A: Shikotsu Lake
F: Shiraoi River
H: Shadai River

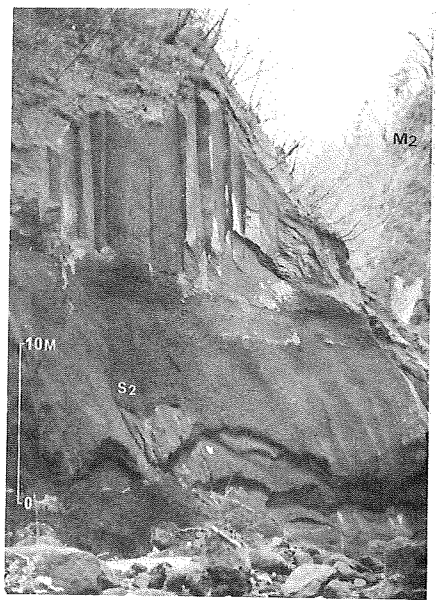


Fig. 19 Outcrop of jointed Shadai pumice flow (S 2) in the upper course of the Shadai River. M 2 is the Morino pumice flow. The Morino pumice flow fills a channel eroded into the Shadai volcanic Formation.

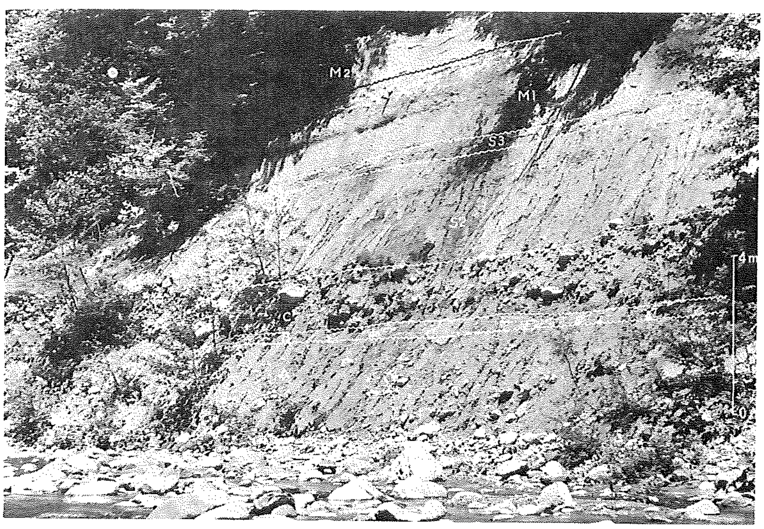


Fig. 20 The Shadai and the Morino volcanic Formations exposed in the middle course of the Shadai River, about 8.5 km northwest of Shadai Station on the National railway. A and C: gravel deposits ; B: clay layer between the gravel deposits, all belonging to the Rampoge gravel Formation ; S 2: the Shadai pumice flow ; S 3: the Shadai pumiceous gravel in which peat layer is intercalated. ; M 1: the Morino pumice fall (M 1 a,b,c) ; M 2: the Morino pumice flow. The bases of the Shadai and Morino volcanic Formations are apparently concordant at this outcrop, but these are difinitely disconformable.

it must formerly have had a much wider distribution. Most of the flow appears to have been eroded away before the Morino volcanic Formation was deposited. Its original thickness and distribution is so poorly known that it is impossible to determine the center from which it was erupted.

It is noteworthy that the ash flow (S 2) unconformably rests on gravel of the Rampoge Formation in certain places where the lower member (S 1) is missing. This gravel is composed of cobbles, and pebbles of Neogene volcanic and sedimentary rocks, as well as Mesozoic and/or Palaeozoic sedimentary rocks. Although the age of this gravel is uncertain it may correlate with the Hachashinai or Keihoku Formation widely distributed in central and northern Hokkaido.

The top member of the Shadai volcanic Formation is called the Shadai pumiceous gravel (S 3). It is grey to brown, and composed chiefly of pumice and pumiceous ash certainly derived from the underlying ash flow (S 2). In the gravel, cross lamination is characteristically developed in nearly every outcrop. It is about 3 to 5 m thick.

Locally thin peat layers are intercalated with the sediment. These contain a pollen assemblage indicative of an extremely cold climate.

The following species have been identified in a sample collected from a point along the Shadai River about 100 m in elevation: *Larix Gmelinii* GORDON 35.5%, *Picea jezoensis* CARRIÉRE plus *Picea Glehnii* MASTERS 21.0%, *Pinus pumila* REGEL 11.5%, *Abies sachalinensis* MASTERS 9.0% besides *Salix, Quercus, Alnus hirsuta* TURCZANINOW, *Betula ermani* CHAMISSO. Such an association of plants is quite different from the vegetation of the present forest in the mountainous region along the upper reaches of the Shadai and Shiraoi Rivers. To the authors it suggests a climate similar to that of central Sakhalin at present. The difference in latitude, estimated from a comparison of living vegetation with similar vegetation in the past, is concluded to be about five degrees. A more detailed description of paleoclimates is given by S. KUMANO, and Y. IGARASHI, (in press).

e) The Morino volcanic Formation

The Morino volcanic Formation generally rests unconformably on the Shadai volcanic Formation, since both the intervening Noboribetsu and Ponayoro volcanic Formation are commonly absent. The lowest unit of this formation, called the Morino pyroclastic sediment (M 0) is only locally developed (Figs. 21 and 22). It is about 3 m thick and composed mostly of tuffaceous sand or clay. Above this unit, there is a pumiceous ash layer (M 1a), about 2 m – 2.5 m thick, composed of very coarse grained pumice. This layer is in turn covered by 1 – 1.3 m of very fine grained ash (M 1b) with beautiful laminations. In contrast to the yellowish-brown ashes above and below, this ash

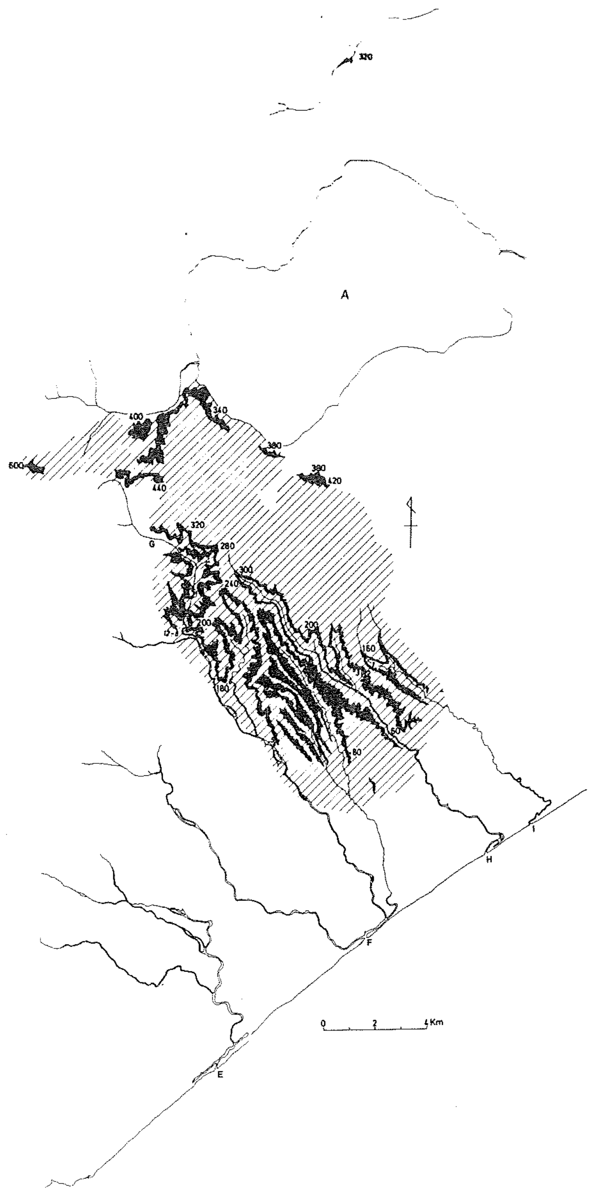


Fig. 21 Distribution of the Morino volcanic Formation.
Black: outcrop ; Hatched lines: covered ; Numerals: elevation of outcrop in meters ; Numerals (italic): 1–7 and 8–12 indicate localities of columnar sections shown in Fig. 46.
A: Shikotsu Lake
E: Shikifu River
F: Shiraoi River
G: Moshiraoi River
H: Shadai River
I: Betsubetsu River

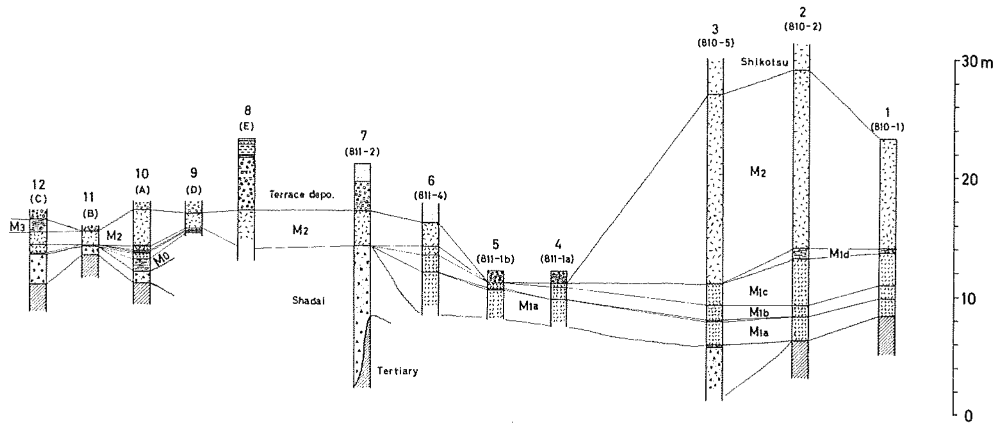


Fig. 22 Correlation of the columnar sections of the Morino volcanic Formation. (See Fig. 5 for locations)

layer (M 1b) is white when dry. The coarse grained ash (M 1a), below the white ash is dacitic. the chief constituent minerals being plagioclase, quartz, augite and hypersthene, whereas the white ash (M 1b) includes hornblende and biotite as well (Fig. 23). Remarkable pisolites, from 5 to 13 – 18 mm in diameter are found throughout this layer. These probably originated high in the atmosphere where falling ash may have formed spherical, accretionary lapilli around drops of rain (Figs. 24 and 25).

Beautiful laminations are also seen in this pisolite-bearing ash. The sequence within this member (M 1b) observed on the upper reaches of Betsubetsu River is given below in descending order:

Top	
2 cm	coarse ash with pumice
2-8 cm	fine ash with pumice
0-1 cm	fine ash with pumice
---------------	diastem ---------------
14 cm	fine-medium ash with pumice
1 cm	ash with pumice
36 cm	fine white ash with large pisolites
4 cm	fine ash with pumice
90 cm	fine white ash with large pisolites
	peat at the base

At the base of this white ash a thin peat bed is locally developed. Pollen from this layer is generally in a bad state in preservation but, as discussed later,

Fig. 23 The Morino pumice fall, exposed at the roadside between Shiraoi town and Morino Village, about 7 km northwest of Shiraoi Station along the National railway. M 1 a: lower, coarse grained ash of the Morino pumice fall (M 1) ; M 1 b: white ash with pisolites which unconformably rest on M 1 a, at the base of which, a thin peat layer (P) is present. Gravel bed of lower terrace, unconformably covering the Morino pumice fall deposit.

Fig. 24 Numerous large pisolites in the white ash member (M 1 b) of the Morino pumice fall ; upper Betsubetsu River.

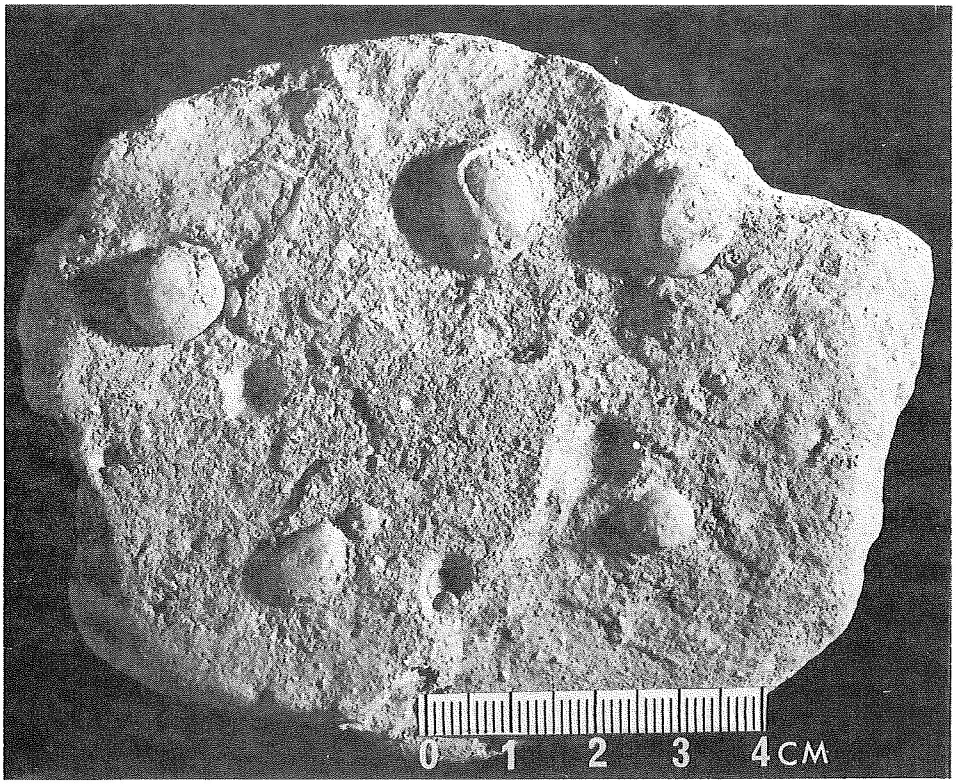


Fig. 25 Pisolites in the white ash (M 1 b) of the Morino pumice fall. Specimen collected at Morino, in the upper reaches of Betsubetsu River.

the association of pollen definitely indicates colder climatic conditions.

Above the white ash, there is another very coarse grained ash layer (M 1c), less than 5 m thick which has a complex, anomalous mineral assemblage including plagioclase, quartz, biotite, hornblende, augite, hypersthene and olivine (Fig. 26).

Above this is another ash fall deposit (M 1d), about 0.4 to 0.7 m thick, with beautiful laminations. It is only locally preserved and cannot be traced as widely as the underlying coarse ash (M 1c). Together the ash layers described above comprise the Morino ash fall (M 1) with a composite thickness of about eight meters.

The Morino pumice flow (M 2) is dacitic, composed chiefly of plagioclase, quartz, augite, hypersthene, and a small amount of hornblende and biotite. Usually this flow unconformably overlies the pumice fall (M 1) but in some places is rests directly on the Shadai volcanic Formation or a gravel bed correlative with the Rampoge Formation. It is at least 60 m thick. Most outcrops are loosely consolidated and easily eroded by heavy rains. Locally

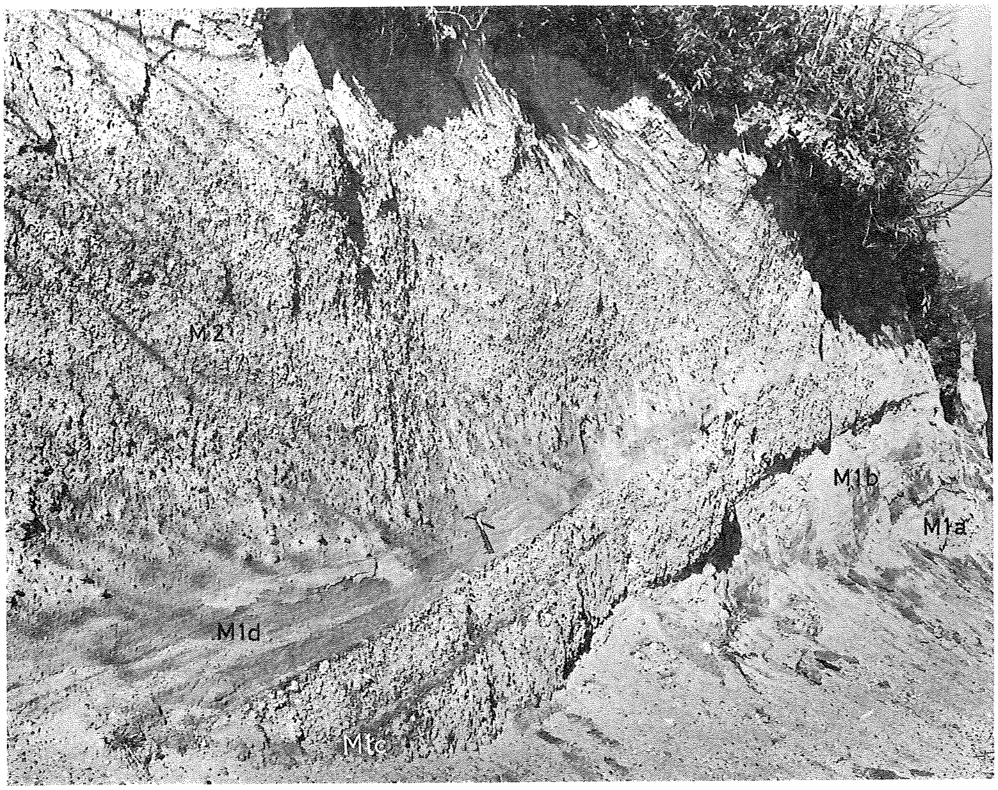


Fig. 26 The Morino volcanic Formation exposed in the upper reaches of Betsubetsu River, about 9 km NW of Shadai railway station. M 1 a, b, c and d belong to the pumice fall (M 1). M 2 is the Morino pumice flow, in which exotic rock fragments are especially rich in the basal part.

exotic rock fragments such as slate, chert, dioritic rocks, Neogene Tertiary volcanic and sedimentary rocks are abundant especially in its lower part. Also highly carbonized tree trunks are commonly buried in the basal part of the ash flow. Geomagnetic polarity of this pumice flow is normal.

The pumiceous gravel (M 3), related to this volcanic group is preserved locally and is about 20 m in maximum thickness.

As discussed later page 42, the Morino rests locally on flat-topped hills that are probably correlative with the higher terraces. It is overlain by gravel beds belonging either to the youngest middle, or lower terraces. On the basis of this evidence the authors have tentatively correlated the Morino volcanic Formation with the Riss ice age. This is in agreement with the pollen evidence for a climate much colder than the present.

The Morino volcanic Formation rests with apparent conformity on the Shadai, but they are probably separated by an erosional disconformity.

f) The Shikotsu volcanic Formation

The Shikotsu volcanic Formation (Sh) is the youngest volcanic assemblage treated in this paper (Fig. 27). It is divided into three stratigraphic members: the Shikotsu pumice fall (Sh 1) comprising seventeen units of interlayered pyroclastic and sandy loam deposits; the pumice flow (Sh 2); and the Shikotsu pumiceous gravel (Sh 3). The Shikotsu pumice fall (Sh 1) is widely distributed in the region southeast of Shikotsu caldera. The top sub-member (Sh 1i) is especially widespread, extending to Tokachi Province in Eastern Hokkaido and across the Hidaka Mountains (Figs. 28 and 29). The Shikotsu pumice flow is confined to an area relatively near Shikotsu caldera, although it is not uniformly distributed in all the directions as shown in Fig. 27. The Shikotsu pumiceous gravel is distributed locally within the area where the Shikotsu pumice flow is exposed.

The basal member of the Shikotsu volcanic Formation, Shikotsu pumice fall (Sh 1) may be separated into a number of sub-members comprising intercalated ash falls and non-volcanic aeolian deposits, resembling loess, rock flour or sandy loam (Table 1). The ash falls in this member (Sh 1) include both pumice fall layers, and scoria fall layers. The two types of falls are believed to be of similar origin and thus both are included in the Shikotsu volcanic Formation.

Every ash member in the Shikotsu 1 member (Sh 1) exhibits beautiful laminations of alternating coarse and fine grained pumice or scoria, which may suggest repeated explosions during its deposition. The uppermost member, hornblende bearing rhyolite ash, is thicker, (about 4 m maximum) than any other fall deposit in this member (Sh 1). At Cape Erimo, about 187 km east of Shikotsu caldera Lake, the supposed center of activity, it is about one half meter thick.

The middle member of the Shikotsu volcanic Formation is a pumice flow which has long been considered a single cooling unit. This may be true in most regions, however, the southwestern part of this member contains at least two recognizable cooling units (Figs. 30 and 31). This means that eruption of pumice flow (Sh 2) occured in at least two pulses, although the time interval between them was probably very small. Geomagnetic polarity of this flow is normal.

In general this pumice flow becomes harder, better consolidated, and has higher virtual density near the center of volcanic activity, conversely it becomes gradually softer and more poorly consolidated towards its margins. In between there is an area where only the middle part of the cooling unit is well consolidated. Columnar and/or platy joints are developed in the well consolidated part. In places more remote from Lake Shikotsu, joints are rarely found and usually irregular even though the middle part of the cooling unit is

Fig. 27 Distribution of the Shikotsu volcanic Formation.
Black: outcrop ; Hatched lines: covered ; Double circles: drilling sites (Shikotsu pumice flow and pumice fall presents in subsurface) ; Single circles: drilling sites (Shikotsu pumice fall present in subsurface) ; Numerals: elevation of the base of the Shikotsu pumice flow in meters, both at the surface (+) and subsurface (−) ; Long dash and line: outer limit of the Shikotsu pumice fall ; Fine line: coast line ; Dashed line: −50m isobathymetric line.
A: Shikotsu Lake
B: Kuttara (Kuttaraushi) Lake
J: Mouth of the Ishikari River
L: Sapporo City
M: Tomakomai City
a,b,c ..... f: location of drilling where the existence of Shikotsu volcanic Formation is proved along the coast line near Tomakomai City (see Fig. 27)

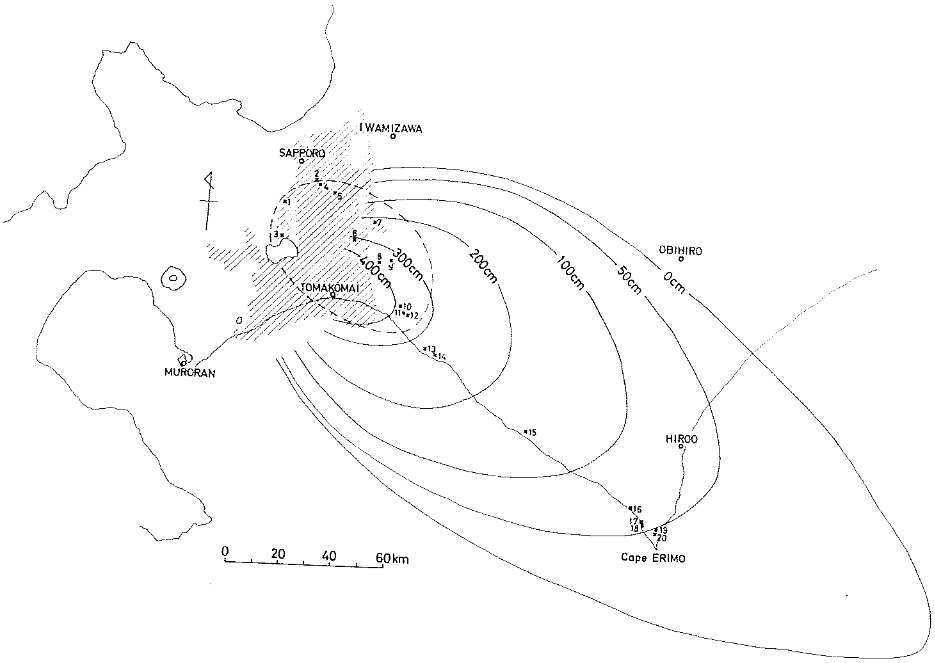


Fig. 28 Distribution of the Shikotsu pumice fall deposit (Sh 1 b, c and i). Numerals from 1 to 20 indicate the locations of columnar sections (Fig. 29). Hatched lines indicate the approximate distribution of the Shikotsu pumice flow both at the surface and subsurface. The isopach lines indicate the approximate thickness of the top unit (Sh 1 i). Dashed lines indicate the distribution of the scoria fall deposits (Sh 1 b and c).

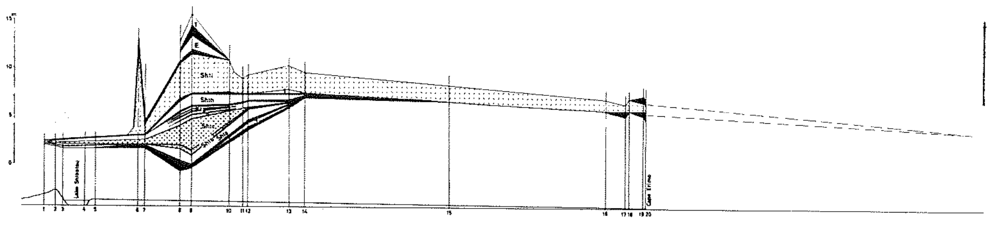


Fig. 29 Changing thickness of the Shikotsu pumice fall deposit observed at localities 1 to 20 (Fig. 28). Black colour indicates aeolian deposits intercalated with pumice and scoria fall deposits from Sh la – Sh li.
E: The Eniwa pumice fall
T: The Tarumae pumice fall, post Shikotsu in age

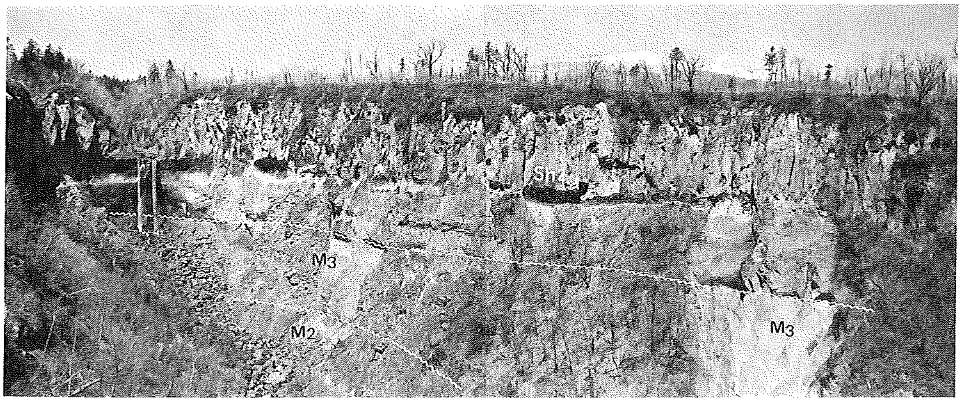


Fig. 30 The Morino volcanic Formation, M 2 and M 3, pumice and pumiceous gravel unconformably covered by the Shikotsu pumice flow (Sh 2). At this point the Shikotsu comprise a lower, weakly portion and a highly welded upper portion with well developed columner jointing. These are separated by a central unwelded part and are believed to represent two separate cooling units. The Shikotsu is overlain unconformably by ash from Eniwa Volcano and by slightly younger volcanic products from Tarumae, the steaming, snow covered volcano on the skyline.

Fig. 31 Shikotsu pumice flow along the lower course of the Shiraoi River, about 2.3 Km northwest of Shiraoi Station on the National railway. In this outcrop, well welded part of the Shikotsu pumice flow meges upwards into overlying unlaminated deposits which may also be part of the Shikotsu pumice flow.

fairly well consolidated and has relatively high virtual density.

The upper division, the Shikotsu pumiceous gravel (Sh 3), is composed mainly of pumice and ash derived from the middle and/or lower division of the Shikotsu volcanic Formation. It is about 5 m thick and has remarkable cross laminations. This gravel member unconformably covers the middle member over an extensive area and, because of its different appearance and genesis, it must definitely be distinct from the lower and middle members. The lower and middle members are products of volcanic activity, at least in their primary stage, while this gravel (Sh 3) is undoubtedly of sedimentary origin, although the material itself consists mainly of Shikotsu volcanic products. Locally, this gravel is divided into two units by an unconformity.

1) Buried topography concealed beneath the Shikotsu pumice flow

The topography before the eruption of pumice flow is restored as nearly as possible. This buried topography beneath the Shikotsu volcanic Formation may be divided into three elements: (1) hilly or mountainous topography deeply dissected by water, (2) terrace topography with sporadic monadnocks and (3) an old alluvial plain. Of these terrace topography is especially relevant to the history of volcanic activity.

Three groups of terraces buried under the Shikotsu volcanic Formation may be distinguished. These have elevations of approximately 200 m, 80 m and 40 m. All of them are extreamly flat and wide, and may be traced into the surrounding mountainous region to the east (Fig. 32). Large and small monadnocks which escaped erosion are found here and there on these terraces. The higher terrace, with an elevation of about 200 m, is also extensively developed in the eastern mountains where it has a surprisingly even surface. However, if we trace this terrace toward the caldera, especially in the southwestern part of the Shikotsu pumice flow, it becomes higher step by step. In fact, the same terrace (200 m above sea level) appears to have been separated into three fault bounded blocks with elevations of 200 m in the south, about 300 m in the middle, and almost 400 m near the caldera wall (Fig. 32).

A considerable upheaval must have occured before the eruption of pumice flow around the caldera of lake Shikotsu.

This was probably due to an increase in vapour pressure in the magma chamber beneath the surface. The presence of faulting and the abnormal elevation of the higher terrace near the caldera seems to be good evidence, for such upheaval. The authors believe upheaval of the surface before eruption may have reached at least 200 m near the present margin of Shikotsu caldera.

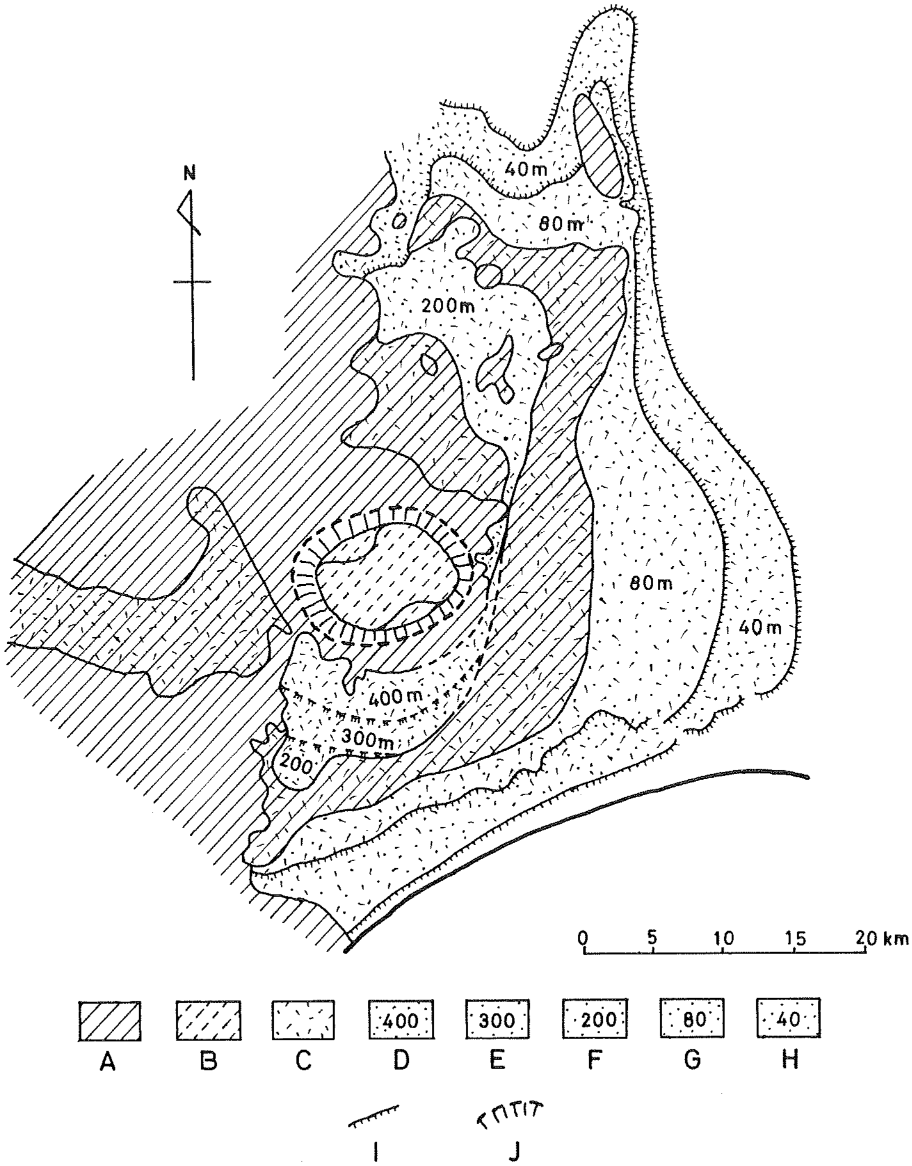


Fig. 32 Restored topography of the Shikotsu district, before eruption of the Shikotsu pumice flow.

A: Mountainous topography, now either mountains or monadnocks in the terrace region.

B: Probable mountainous topography before the sinking of Shikotsu Caldera.

C: Area presently covered by the Shikotsu pumice flow.

D,E,F,G,H: Older terrace topography now buried beneath the Shikotsu pumice flow. Figures show the mean altitude of each terrace.

I: Cliff or steep slope for each terrace.

J: The Shikotsu Caldera wall.

2) Thickness and temperature of the Shikotsu pumice flow

The pumice flow covers mountainous regions as well as terraces and alluvial plains (Fig. 33). In streaming downwards it buried old valleys in the deeply dissected mountainous region, where it locally reached great thicknesses. Fig. 34 is an isopach map of the Shikotsu pumice flow. It is more than 300 m thick in the region west of the caldera, while in the old alluvial plain of the northern and southwestern regions, where it spread out onto the terraces, the pumice flow reaches a maximum thickness of 160 m. In general the Shikotsu pumice flow is well consolidated, highly welded, and has columnar joints in those regions where its thickness exceeds 100 m.

Further, it is also well consolidated with high virtual density near the caldera. According to T. SUZUKI (1962) the temperature of the well consolidated part of the pumice flow was over 570°C when it came to rest. Further it is estimated that the temperature in the marginal, partly welded, portion of the pumice flow was 570-600°C, while areas more distant from the center of eruption are infered to have been about 430-510°C when the pumice flow settled into place. All these temperatures were estimated by T. Suzuki from measurements of natural remanent magnetization.

Evidence of former fumarole activity is present in the Shokotsu pumice flow at many places (Fig. 35).

3) Total volume of the Shikotsu pumice flow

In order to estimate the total volume of the Shikotsu pumice flow, it is of prime importance to know the true limits of its distribution prior to erosion. An apparent margin, determined by mapping is the coast line of Volcano Bay, and the foot of the hilly and mountainous region that grades into the alluvial plain in the northern and eastern regions. It is, however not a true margin.

Recently many water wells for industry and irrigation have been drilled in the alluvial plain north, east and south of lake Shikotsu. These have contributed greatly to our knowledge of pumiceous deposits below the surface. Subsurface pumiceous deposits have been found widely distributed beneath the alluvial plain in the course of recent subsurface exploration in this region (MINATO et at, 1967, 1968, 1969; MATSUSHITA et al, 1970; OBARA, T. et al, 1966, 1968; YAMAGUCHI et al, 1963, 1965, 1967). It is still not certain, however, whether these pumiceous deposits represent the pumice flow only. They may include pumice falls, or pumiceous gravel in addition to the pumice flow itself. Identification of these pumiceous materials is, however, impossible, based on badly broken core samples or drill cuttings. Nevertheless, in estimating the volume of the Shikotsu pumice flow, it does not matter, if we include some pumice fall or pumiceous gravel, since these deposits are

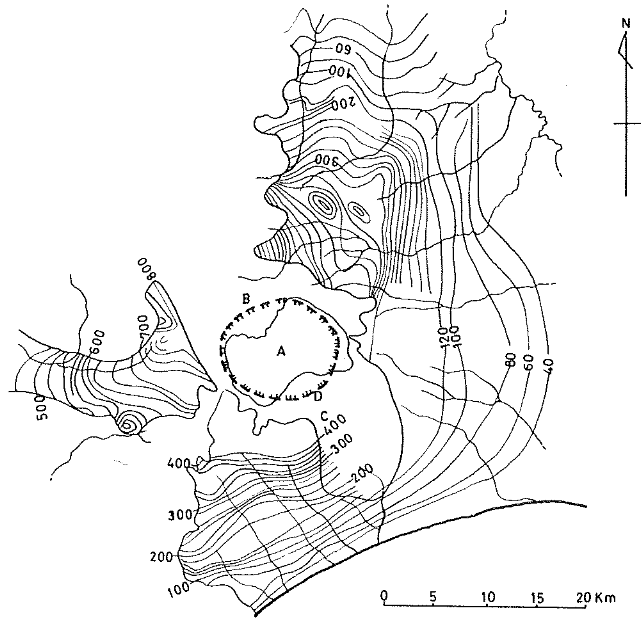


Fig. 33 Buried topography of the Shikotsu pumice flow. A: Lake Shikotsu Caldera ; B: Eniwa Volcano ; C: Tarumae Volcano ; D: Fuppushi Volcano

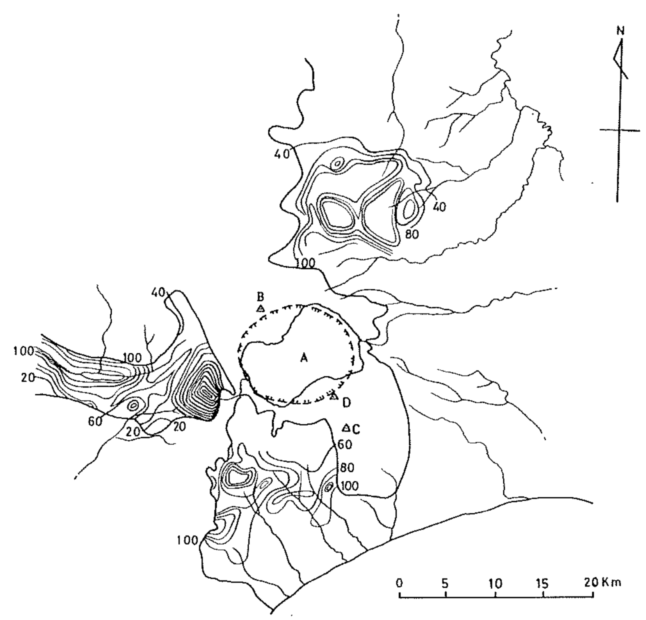


Fig. 34 Isopach map of the Sikotsu pumice flow.
A: Lake Shikotsu Caldera
B: Eniwa Volcano
C: Tarumae Volcano
D: Fuppushi Volcano

Fig. 35 Traces of fossil fumarole found in the Shikotsu pumice flow at Tokiwa, outskirt of Sapporo City. Vertical, hollow, pipe-like structures, both small and large, are observed in this cliff. The area surrounding these pipes is generally altered and stained a different colour by steam.

negligible small compared to the flow. Ash fall on the alluvial plain is less than 1 m thick. Secondarily, if pumiceous gravel were included, the main source of this gravel must have been the pumice flow. Thus, to estimate the volume of the pumice flow, subsurface pumiceous gravel must also be included.

The total volume of the Shikotsu pumice flow is estimated to be 110 km^3. This enormaous volume greatly exceeds the space within Shikotsu caldera (Figs. 36, 37).

If we assume that the original diameter of the bottom of the magma chamber was nearly the same as the longest diameter of the flat bottom of present Shikotsu lake, viz about 9.0 km, that the diameter of the roof of the magma chamber was about 13.0 km, and its depth equal to the mean hight from the present caldera rim to the bottom of the lake about 0.85 km, then the volume of the magma chamber would be about 81.6 km^3.

If the original bottom of the caldera was about 10.0 km in diameter, the width of the roof about 13.0 km, and the mean depth was 0.7 km, then the

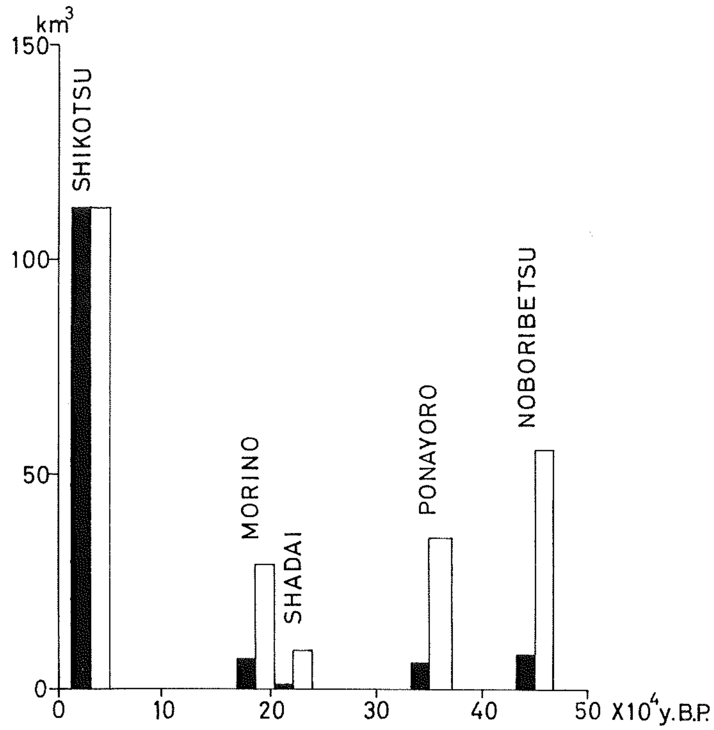


Fig. 36 Estimated volume of pumice flows belonging to the Shikotsu, Morino, Shadai, Ponayoro and Noboribetsu volcanic Formations. Black: present volume ; White: original volume prior to erosion.

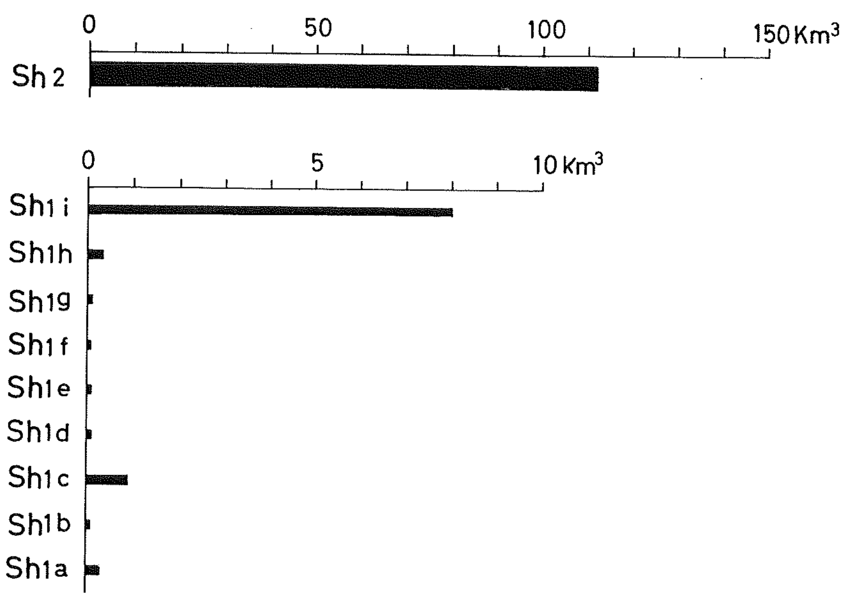


Fig. 37 Estimated volume of the Shikotsu pumice fall deposits (Sh 1) and the Shikotsu pumice flow (Sh 2).

total volume of the magma chamber would be 72.5 km³ .

The volcanoes Fuppushi, Eniwa, and Tarumae were born along the caldera wall, after the caldera sinking had occured (Fig. 38). Therefore the original state of this caldera must have been nearly circular in form, although it is now the elliptical shape of a silk cocoon due to partial filling with younger volcanic

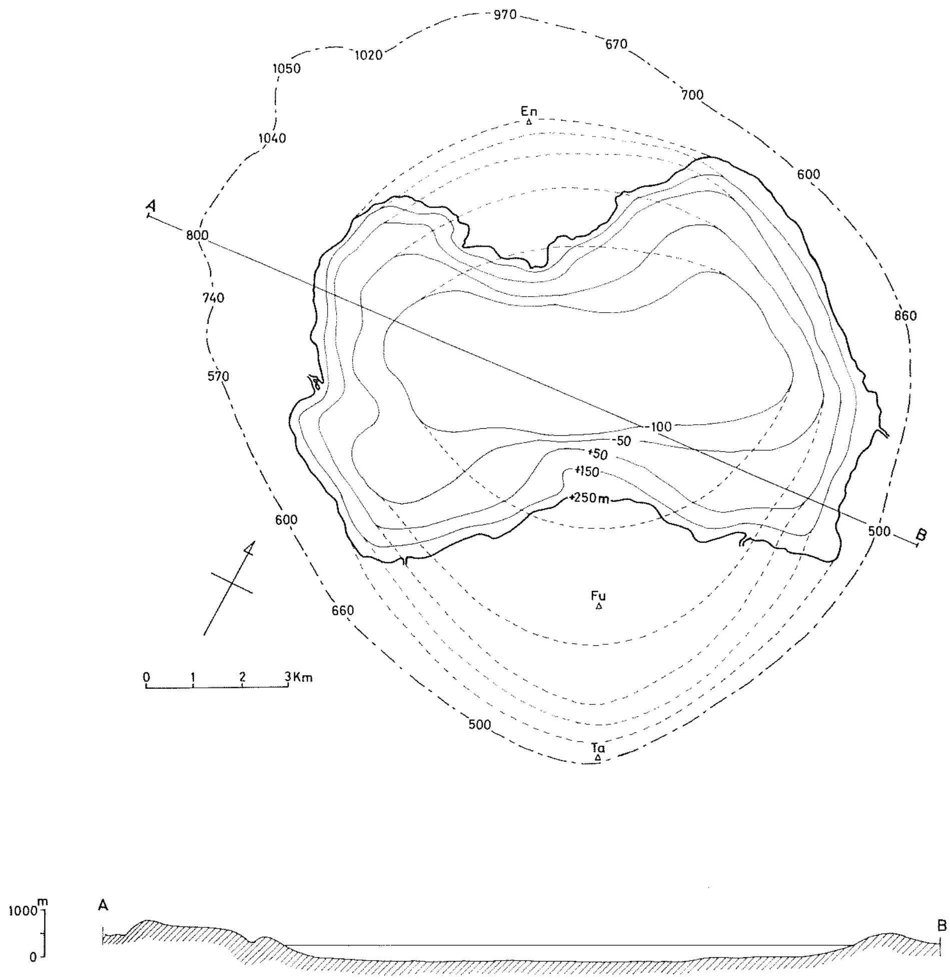


Fig. 38 Topography of Shikotsu Caldera.
En: Top of Eniwa Volcano
Fu: Top of Fuppushi Volcano
Ta: Top of Tarumae Volcano
All these volcanoes post date the caldera sinking. Numerals indicate altitude in meters. Thick line indicates the coastal line of Shikotsu Lake, about 250 m in altitude, thin lines are isobathymetric lines of the bottom of the Shikotsu Lake and dashed lines indicate probable depth of caldera in the original state before the birth of Eniwa, Fuppushi and Tarumae.

products. The diameter of the caldera in its original state may have been nearly equal to the distance, about 13.5 km, between the volcanoes Eniwa and Tarumae (Fig. 38).

If that were the case, the total amount of space within the interior of Shikotsu caldera would still be far smaller than the total volume of the Shikotsu pumice flow. Before it erupted, the pumice flow may have been naturally compressed in its magmatic condition deep below the surface. Nevertheless, a difference of 30 to 40 km^3 in volume between the Shikotsu pumice flow and the volume of Shikotsu caldera may be beyond the error of calculation, even though the escape of a certain amount of water contained in magma is taken into consideration.

In view of this it hardly seems possible that the magma chamber of the Shikotsu pumice flow could occupy the present space within Shikotsu caldera, even if one assumed a thin bridge- like roof. Before going further into this problem, it is necessary to consider the problem of exotic rock fragments in order to resolve the space problem.

4) Exotic rock fragments in the Shikotsu pumice flow

Exotic lithic fragments in the Shikotsu pumice flow are generally small, mostly less than 30 cm in diameter, and angular. Three types are recognized; the first, comprising Pre-Neogene Tertiary rocks includes hornfels, sandstone, slate, chert etc.; the second, comprising rocks from Neogene and Pleistocene formations includes green tuff, propylite, rhyolite, silicified shale, sandstone, black shale, siltstone, two pyroxene andesite, and hornblende andesite; thirdly plutonic rocks such as granite, dioritic granite etc., whose age may be Miocene and/or Mesozoic (Figs. 39, 40).

It has been established that volcanic and pyroclastic rocks of the Miocene and Pliocene are extensively developed in and around Lake Shikotsu. These are unconformably covered by lower Pleistocene deposits rich in gravels. This gravel is in turn overlain unconformably by terrace gravel deposits of various heights. Locally thick lava flows, probably early Pleistocene in age, rest unconformably on the Neogene Tertiary deposits. Slate chert, and basic tuff are found beneath the Neogene rocks, however their age is unknown. These rocks beneath the Neogene may be older than Cretaceous. Their extensive development in the subsurface is proved by seismic investigation around Shikotsu Lake. In fact slate, faulted against Neogene rocks, is locally exposed along the wall of Shikotsu caldera.

Further, grano-dioritic rocks or quartz porphyry probably of late Miocene age have been noted by one of the authors (Y. F.), along the cliffs of the Shikotsu caldera wall.

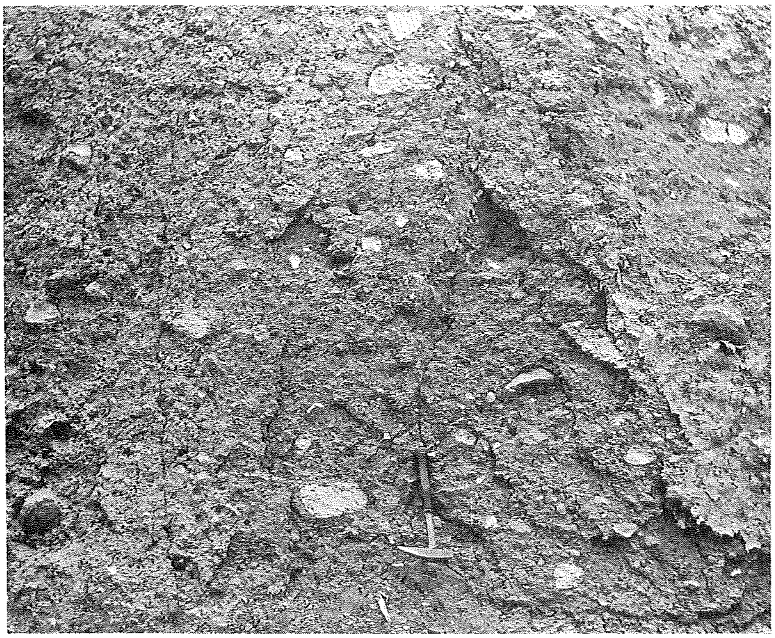


Fig. 39 Highly welded Shikotsu pumice flow outcropping in the upper reaches of Betsubetsu River. Large pumices (white) and exotic rock fragments are especially abundant in this part.

Fig. 40 Outcrop of the Shikotsu pumice flow, highly welded part, in which various kinds of exotic rock fragments, irregular in size and from are especially rich. Upper Betsubetsu River.

The lithology of exotic rock fragments included in the Shikotsu pumice flow suggests that the magma ascended through fault controlled fissures cutting Neogene and lower Quaternary sedimentary and volcanic rocks, pre-Neogene sedimentary rocks, and older and younger plutonic rocks. The latter, except for the Miocene granitic rocks, intrude Pre-Neogene rocks and are unconformably covered by the Neogene rocks. In general exotic rock fragments are larger and more abundant in the part of the pumice flow nearest the caldera. The most common exotic fragments in the Shikotsu pumice flow are Neogene and Quaternary rocks, and sedimentary rock fragments probably belonging to the pre-Neogene formations, are more abundant than plutonic fragments.

Uniform distribution of andesite or basic andesite rocks as exotic fragments in the Shikotsu pumice flow is especially noteworthy.

It is probable, that dacitic magma formed far below the level of the Neogene and Quaternary rocks, for such rocks are included as exotic fragments in the Shikotsu pumice flow. Perhaps, the top of the magmatic chamber may have been at the level of pre-Neogene, either Miocene or pre-Miocene, sedimentary and plutonic rocks.

All the exotic rock fragments observed in the Shikotsu pumice flow may be from the walls of openings or fissures through which the magma finally erupted. They were abraded and partly rounded by the violent movement of the ascending magma that brought them to the surface.

2 Petrography

a) The Noboribetsu volcanic Formation

The pumiceous fall deposit (N 1) lying at the base of this formation is andesitic in composition. Crystal constituents are plagioclase, augite and hypersthene with minor amounts of magnetite. Many of the plagioclases are corroded and show zoning, especially at their margins. Tuffaceous, interstitial material consists of cemented flakes of vesicular glass. Lithic fragments are abundant and include various types andesite such as augite andesite and felic andesite in which the texture of the groundmass varies from holocrystalline granular to glassy with tiny plagioclase microlites.

This fall (N 1) is overlain by the highly welded Noboribetsu pumice flow (N 2), in which the crystalline materials are plagioclase and pyroxene. Plagioclase is of two types. The first comprises zoned idiomorphic to subidiomorphic crystals, corroded at the core and/or edge. These are inferred to be basic in composition. The others, which are smaller in size, comprise fragmental, acidic crystals which are not corroded.

Pyroxene phenocrysts include augite and hypersthene 2 to 0.5 mm in length. Holocrystalline gabbroid patches made up of plagioclase and pyroxene, are sporadically distributed.

The groundmass is composed of very fine shards of vesicular glass and fragments of plagioclase. Foreign lithic fragments include siltstone, slate and andesite with pilotaxitic to felted groundmass.

b) The Ponayoro volcanic Formations I and II

The Ponayoro dacitic pyroclastic flow (P I 2) is composed of phenocrysts of plagioclase, augite, hypersthene and small amounts of quartz and glass shards. The plagioclase, up to 3 mm across, is euhedral or fragmental. It has irregularly corroded cores and oscillatory zoned rims. The phenocrysts of quartz, usually rounded by corrosion and rimmed with brown glass, are sporadically distributed. Hypersthene is much more abundant than augite. Both are idiomorphic, and up to 2 mm in length. Hornblende and biotite are sometimes present.

The groundmass consists of clear vesicular glass or bubbly glass. Exotic lithic fragments are common and include metaslate and fine-grained amphibole biotite hornfels.

The Ponayoro pyroclastic flow (P II 2), is highly pumiceous. The mineral fragments and phenocrysts are almost the same as those of the underlying flow (P I 2) except for the presence of brownish green hornblende. Lithic fragments, such as hornfels and metasediments are common.

c) The Shadai volcanic Formation

The Shadai pumice flow (S 2) is a basic andesitic phyroclastic deposit, containing considerable amounts of lithic fragments including several types of andesite and metasediments.

Phenocrysts are plagioclase, augite, hypersthene and olivine. The plagioclase is euhedral, complexly twinned, and weakly zoned. Corrosion is detected in the cores. Augite is more abundant than hypersthene. Both pyroxenes are idiomorphic and up to 2 mm in length.

The goundmass is vesicular, brown glass shards enclosing tiny microlites of plagioclase.

Of the lithic fragments, andesite is most prominent. The most abundant variety is olivine augite andesite with pilotaxitic to hyalopilitic groundmass. Andesite of almost the same composition but with a glassy groundmass is also common. The phenocrysts of these andesites sometimes grow together to form gabbroic crystal aggregates of plagioclase and augite. Chloritized propylite inclusions are not uncommon. These include slightly metamorphosed sandstone and siltstone.

d) Morino volcanic Formation

The pumice fall deposits (M 1a) occupying the basal part of the Morino

Formation are dacitic. Phenocrysts include quartz and plagioclase as main constituents, accompanied by minor augite, hypersthene and greenish hornblende. The quartz crystals are corroded, and show shadow extinction. Plagioclase is of two kinds, one being zoned, large crystals corroded at the core, the other, broken and acidic in composition, is neither zoned nor corroded. The cementing material consists of vesicular, clear glass fragments.

Lithic inclusions are classified as quartz porphyry, characterized by plagioclase and quartz phenocrysts in a granular aggregate of quartz, plagioclase, hornblende and biotite.

The ash fall deposit (M 1b), characterized by the occurence of pisolites and well laminated structures, is dacitic to felsic andesitic in composion in spite of its light-colored appearance. Under the microscope, it is seen to consist mostly of tiny shards of vesicular glass surrounding angular fragments of plagioclase, euhedral to fragmented augite and hypersthene crystals. Minor hornblende is also present.

The upper ash fall called the (M 1c) is highly pumiceous and lithic fragments are common. The overlying Morino ash fall (M 1b) is andesitic. Phenocrystic minerals are plagioclase, mostly euhedral and unzoned, hypersthene and olivine. Remnant cores of pyroxene are present in some of the hornblende crystals. Biotite is rare. Lithic inclusions are andesite, dacite, chert and siltstone. The groundmass is composed of vesicular to globular glass.

The uppermost member of the Morino Formation (M 1d) is layered andesitic pumice. The crystal fragments are composed of plagioclase, augite and hypersthene, angular in shape, and up to 1 mm in length. The groundmass is pumice mixed with vesicular glass shards having pearlitic cracks. No directional orientation is observed in the shards. Lithic fragments include augite-hypersthene andesite with pilotaxitic groundmass, felsic andesite with bostonitic groundmass, and metaslate. Usually all inclusions are rounded and fine-grained.

The Morino pumice flow (M 2) lying unconformably above the Morino pumice fall deposits is andesitic. The phenocrysts comprise basic to intermediate plagioclase, euhedral augite, and hypersthene and rarely fragmental hornblende. The groundmass consists of tightly packed shards of vesicular glass.

e) The Shikotsu volcanic Formation

The Shikotsu pumice flow (Sh 2) occupies a very wide area around Lake Shikotsu. Some variation in the mineralogy and type of pyroclastic constituents is to be expected, due to differences in the wall rock of fissures from which the eruption occurred as well as to evolution of the magma itself.

At Betsubetsu-gawa the pumice flow is perfectly welded. Phenocrysts include plagioclase, hornblende, augite and hypersthene. The plagioclase, commonly corroded, is euhdral to fragmental and up to 2 mm in length.

Zoning is weak except at the margins. Subophitic aggregates of augite and plagioclase form sporadic patches. Hornblende is subhedral, up to 2 mm in length, and usually lacks any evidence of corrosion. Pyroxenes are euhedral, up to 2 mm in length and the amount of augite exceeds that of hypersthene. Intergrowths of two pyroxenes or of hornblende and pyroxene are found.

The groundmass is composed of pumiceous glass shards having "flow structure" or a very fine-grained, structurless aggregate of glass. Seams consisting of granular aggregates of plagioclase, augite and quartz micro-phenocrysts are occasionally seen.

Lithic inclusions are hornfels, metasiltstone and granodioritic rock.

At Tokiwa, north of Lake Shikotsu, glassy welded tuff is exposed. This rock contains few phenocrysts of plagioclase or augite and no quartz. It is composed mainly of clear, vesicular glass which is fragmented but tightly welded.

The Shikotsu pumice fall (Sh 1), lying beneath the Shikotsu pumice flow (Sh 2), has nine interlayered fall units. The characteristics of units are briefly described below;

Base

Sh 1a Composition: Augite hypersthene andesite. Hypersthene exceeds augite. The compsotion of the hypersthene corresponds to En 66, Fs 34.

Sh 1b Composition: Augite hypersthene andesite. Hypersthene exceeds augite. Fragments of sedimentary origin are very abundant. Scoria of olivine augite hypersthene andesite is commonly included.

Sh 1c Scoria fall unit. Scoria is composed of olivine augite hypersthene andesite. Crystal fragments are basic plagioclase, hypersthene and augite. Hypersthene and augite are present in nearly equal amounts. The composition of the hypersthene corresponds to En 67, Fs 33.

Sh 1d Composition: Augite hypersthene andesite. Hypersthene exceeds augite.

Sh 1e Same as Sh 1d

Sh 1f Composition: Augite hypersthene dacite. Well zoned plagioclase forms the great majority of crystals. Quartz is a minor constituent.

Sh 1g Same as Sh 1f, except for a very minor amount of hornblende.

Sh 1h Composition: Hypersthene augite dacite. Plagioclase shows faint zoning. Quartz is much more abundant than in Sh 1g. Hornblende is a minor constituent.

Sh 1i Composition: Hornblende bearing augite hypersthene rhyolite. The composition of the hypersthene corresponds to En 65, Fs 35.

3 Correlation of the pumiceous volcanic products

a) The Noboribetsu and Ponayoro volcanic Formations

The Noboribetsu and Ponayoro volcanic Formations cover nearly the same region. From their relationship to terrace stratigraphy both are considered to be much older than either the Shadai or the Morino. The latter are covered unconformably by the higher terrace deposits in many localities. Near Noboribetsu spa, the higher terrace has an elevation of about 200 m and is more highly dissected than the middle terrace. Both are overlain by the Shadai, Morino and Shikotsu volcanic Formations.

The base of the Noboribetsu pumice fall has an elevation of about 10 m below present sea-level, as shown by numerous drill holes along the coast of Volcano Bay near Noboribetsu Station (Fig. 34). Further, the base of the Noboribetsu pumice flow is about 45 m below sea-level. The lithology of both the pumice fall and flow indicates that they are terrestrial products rather than marine. Thus sea-level must have been much lower than at present, when the Noboribetsu fall and flow were deposited. This was probably during an ice age or sub-ice age, possibly correlative with the Günz ice age. Furthermore, the Shadai is considered to be older than the Morino and both are definitely of Riss age. The Noboribetsu volcanic Formation may, therefore be correlative with the Günz.

The Ponayoro volcanic Formation, including the Noboribetsu sandstone Formation, overlain by gravel beds of the higher terraces, may be of Günz/Mindel to Mindel age. At many places the upper part of the Noboribetsu pumice flow (N 2) was strongly weathered prior to deposition of the Ponayoro volcanic Formation I. Furthermore, the member Ns 3 of the Noboribetsu sandstone Formation contains marine facies indicative of warmer climate. Thus the interval from the base of the Ponayoro volcanic Formation I to the top of Ns 3 is considered to be correlative with the interglacial between Günz and Mindel ice ages. The upper half of the Noboribetsu sandstone Formation including Ns 4 and Ns 5, up to the higher terrace gravel beds, is tentatively correlated with the Mindel ice age.

b) The Shadai volcanic Formation

The Shadai is almost certainly older than the Morino volcanic Formation. Colder climate during deposition of Shadai pumiceous gravel is well established from pollen analysis. It is reasonable that the Shadai is approximately correlative with the Riss ice age.

c) The Morino volcanic Formation

In many places the Morino volcanic Formation unconformably overlies the Shadai volcanic Formation, which is in turn unconformably overlain by gravel beds belonging to the youngest middle, and lower terraces.

The lower and middle terraces, are of wide extent within the volcanic area, including Cape Erimo on the Pacific coast. Moreover, terraces of the same age are well preserved along rivers running through the Hidaka Mountain Range, especially in their middle and lower courses.

Multiple Pleistocene glaciations are recognized in the higher mountains of the Hidaka Range (M. MINATO and S. HASHIMOTO, 1954), although glaciers are no longer present. Detailed study of the topography of cirques and the stratigraphy of morainic deposits indicates two distinct ice ages. The older one has been called the Poroshiri ice age, and the younger one the Tottabetsu ice age. The interstadial between them is called the Poroshiri/Tottabetsu interice age (M. MINATO and S. HASHIMOTO, 1955). The Poroshiri ice age is further subdivided into two sub-ice ages and the Tottabetsu into at least four sub-ice ages. The record is well preserved in the stratigraphic sequence of morainic deposits, which are separated into many groups by unconformities (S. HASHIMOTO and M. MINATO, 1955).

The moraines and cirque walls, corresponding to the Poroshiri ice age are more dissected than those of the Tottabetsu ice age. Further, it is evident that the morainic deposits of the Poroshiri ice age are unconformably covered by those of the Tottabetsu ice age. The Poroshiri ice age is therefore older than the Tottabetsu. The difference in the altitude of the snow line during these two ice ages is estimated to have been about 300 m. The floor of Poroshiri cirques is usually about 1,300 m in elevation while those of the Tottabetsu ice age are about 1,600 m in elevation.

Although the series of repeated advances and recessions of cirque glaciers within each ice age cannot be correlated in detail, S. HASHIMOTO and S. KUMANO (1955) have succeeded in establishing correlations between the morainic deposits and terrace gravel in the upper reaches of Tottabetsu River. The morainic deposits of the Poroshiri ice age are correlated with the middle terrace gravel and the Tottabetsu to the lower terrace.

The lower terrace in the Hidaka Mountains was traced into the lower terrace developed in the coastal region. The latter seems to be correlative with the Würm ice age which contains molars of wooly mammoth similar to those in the lower terrace gravel at Cape Erimo.

Thus the middle terraces may correspond to the third ice age, the Riss of Europe. It is possible, however, that there are certain terraces amongst the middle terraces which are partly equivalent to the interglacial between Riss and Würm.

Locally, along the upper reaches of the Moshiraoi River, the Morino rests unconformably on the Shadai and is unconformably overlain by gravel of the younger, middle terrace. In addition, pollen assemblage shows a very cold climate when the Morino pumice fall was deposited. Conifers are very abundant, slightly exceeding 50% of the entire forest with *Picea* greatly exceeding the number of *Abies*. *Alnus* comprises about 31% of the total, and such temperate forms as *Quercus*, *Juglans* and *Corylus* are also present. This is based on pollen analysis of the peat collected from the base of white ash (M 1b). The Morino volcanic Formation may, therefore, be roughly correlated with the younger Riss ice age.

d) The Shikotsu volcanic Formation

At Cape Erimo, Y. KATSUI (1958) first observed the Shikotsu pumice fall resting unconformably on a gravel bed (the Ogoshi gravel bed) belonging to the lower terrace. Prior to this, molars of wooly elephant, *Elephas primigenius* BLUMENBACH were found in the same gravel bed and described by M. MINATO (1955). He correlated this with the lower terrace which is undoubtedly equivalent to early Würm (W 1).

Remains of mammoth are widely known in Siberia, and so far as the arctic is concerned, they were most aboundant during the warm interval between the Riss and Würm, the interstadial between the early Würm (=Fruhwürm=W 1) and main würm (=Hauptwürm=Wh), and during the warm interval of the final stage of the Würm, perhaps equivalent to the Alleröd stage (A. HEINTZ, 1965; M. MINATO, 1967).

In contrast, mammoth remains found along the southern margin of its distribution, including Cape Erimo, should denote a cold age (M. MINATO, 1967). This is a reasonable assumption since the mammoth was well adapted to a cold, servere climate. Thus the authors believe, the gravel horizon containing mammoth molars is indicative of either an ice age or sub-ice age.

In fact the top member of the Shikotsu pumice fall (Sh 1i) was dated as $32{,}000\ ^{+4{,}700}_{-3{,}100}$ ys. B.P. (GaK-519), 32,000±2,000 ys. B.P. (GaK-714) by Carbon^{14} dating based on buried trunks of Yezo Spruce (*Picea jezoensis* CARRIÉRE) (Figs. 41, 42).

The Shikotsu pumice flow, unconformably covering the fall deposits, was dated as $30{,}400\ ^{+3{,}400}_{-2{,}400}$ ys. B.P. (GaK-1932), 31,900±1,700 ys. B.P. As a result, the Shikotsu pumice flow may be correlative with the earlier phase of the main-Würm, and the top member of the pumice fall with the later stage of the interstadial W 1/Wh. This top member (Sh 1i) unconformably covers the gravel bed containing mammoth molars at Cape Erimo. Thus, the gravel bed of the lower terrace at Cape Erimo may certainly be correlated with the early Würm. It follows that the lower to middle part of the Shikotsu pumice fall belongs to the latest stage of the early Würm or to the early or middle stage of the interstadial W 1/Wh.

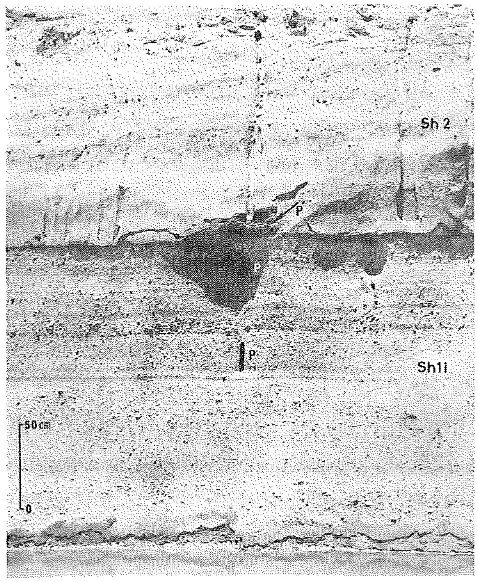


Fig. 41 Shikotsu volcanic Formation exposed at the roadside between Bibi and Hayakita, about 1.2 km south of Bibi Station along the National railway. Sh 1 i: top member of the Shikotsu pumice fall (Sh 1) ; Sh 2: Shikotsu pumice flow ; P: remains of the trunk of an erect tree perfectly carbonized as natural charcoal ; P′: remains of carbonized trunk (same as "P") horizontally on the unconformable plain between Sh 1 i and Sh 2.

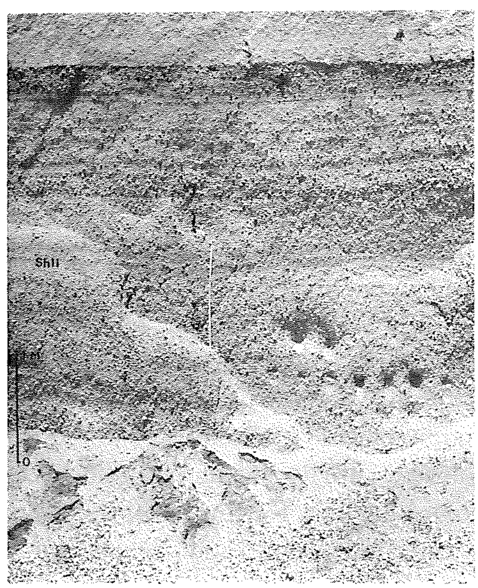


Fig. 42 Thin rhythmic laminations in Shikotsu pumice fall (Sh 1 i), at Bibi. The carbonized trunk of a Yezo spruce is observable in the middle of this member. Sh 1 i is overlain by the Shikotsu pumice flow.

In most of the region studied, the base of these subsurface pumiceous deposits is below present sea-level: about −30 m in the northern part of Sapporo city; −20 ~ −30 m east of Chitose airport; and −30 to −40 m below sea level in the coastal region of Tomakomai city. This is a sure indication that it was a cold phase or ice age, as sea-level was much lower, when the Shikotsu pumice flow was erupted (Fig. 43). The Shikotsu pumice flow has been dated as about 30,000 ys. B.P., thus its early main Würm age is well established.

According to MINATO (1967), MINATO et al. (1967), sea level during the time the mammoth-bearing gravels of Cape Erimo were being deposited was 60 to 80 m lower than at present. This is supported by data on the subsurface geology of the Niigata lowland facing the Japan Sea in central Honshu and by studies of submarine topography in Tsugaru straits (MINATO, 1966).

The Shikotsu ash fall or pumice fall (Sh 1) is divisible into 17 units, which are actually alternation of ash fall and non-volcanic deposits of aeolian origin (Table 1).

All these non-volcanic deposits contain a certain amount of pumice, either as pumiceous sand or clay minerals derived from alteration of volcanic glass. Nevertheless, the main constituents of these fine deposits must have been derived from a tree-less landscape. It was probably fairly cool and dry, and the hilly or mountainous region of Hokkaido may have been mostly bare rock. Under such conditions, dust of clay or fine sand may have been easily transported great distances by wind. Volcanic materials from pumice falls, or flows on the pyroclastic plateau may also have been disturbed at the surface and transported, partly by wind, and intermixed with aeolian material (Figs. 44, 45).

It is also probable that some of this material may have been carried by upper atmosphere winds from the continental mainland where loess, or loess-like paleosoils such as those of Northern China are widely distributed. Similar phenomena have been observed periodically during recent time. It is probable that all of these factors contributed to the aeolian deposits intercalated with the Shikotsu pumice fall (Sh 1).

The clay mineralogy is treated in detail by one of the authors (S.O.) in another paper of this journal.

In summary periodic volcanic explosions persisted through the age W1/Wh. Dormant stages of volcanic activity are represented by diastems at the base of each non-volcanic aeolian deposit. Further, eruption may have included many separate explosions repeated again and again and now represented by laminations in each ash fall unit.

At many places the Shikotsu pumiceous flow (Sh 2) is observed beneath river gravel of the younger lower terrace, probably latest Pleistocene in age.

Pumiceous gravel is also observed unconformably below pumice ash of earliest Holocene age. Therefore the age of the Shikotsu gravel may be regarded as latest Pleistocene.

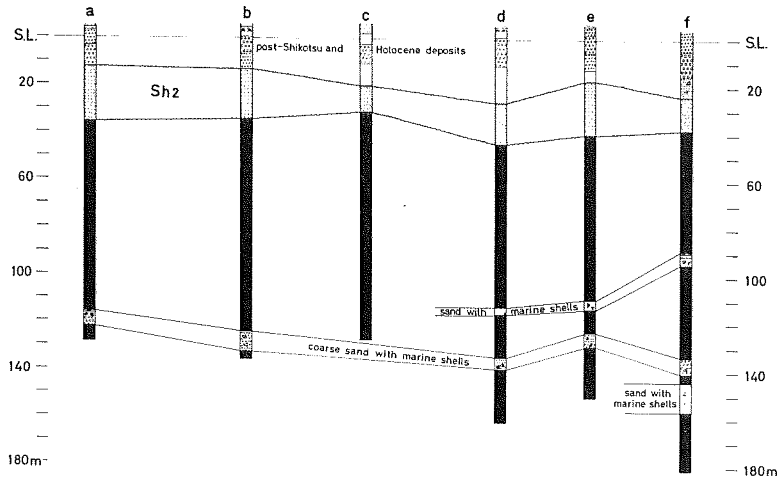


Fig. 43 Subsurface Shikotsu volcanic Formation proved by drillings along the coast line near Tomakomai City. Locations of drillings are shown in Fig. 26.

Fig. 44 The Shikotsu pumice fall (Sh 1) typically developed at Hayakita. The top of this outcrop is composed of the Holocene ash from Eniwa and Tarumae alternating with fossil soils. The Shikotsu pumice fall rests unconformably on marine deposits of silt, gravel, and loam like clay with shells of *Ostrea*, (probably lower Pleistocene). Diastems are clearly recognizable between each pumice layer and its overling "rock flour-like" palaeosoil at this outcrop. Sh 1 i is characterized by beautiful thin rhythmic laminations. It is easily distinguished from other members of the Shikotsu pumice fall by its white colour, while, Sh 1 c and b, composed of olivine bearing scoria, are characterized by their black colour.

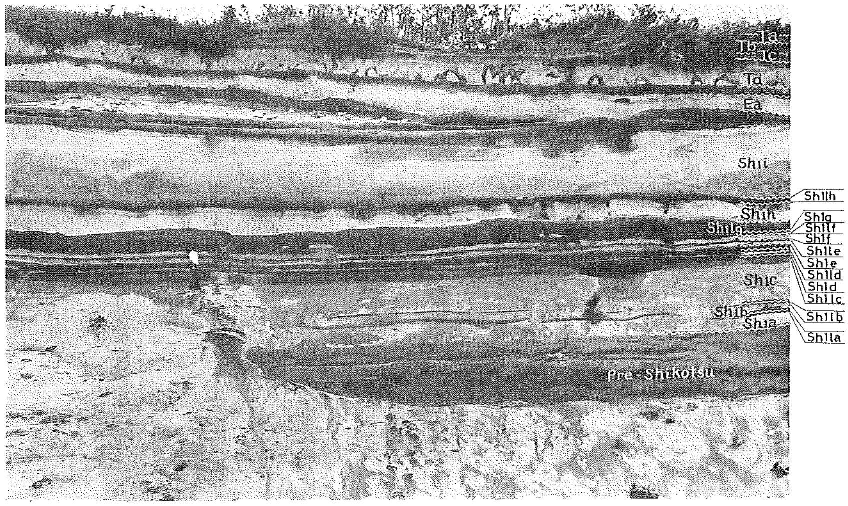


Fig. 45 Close up view of the same outcrop shown in Fig. 44, showing stratigraphy in more detail.

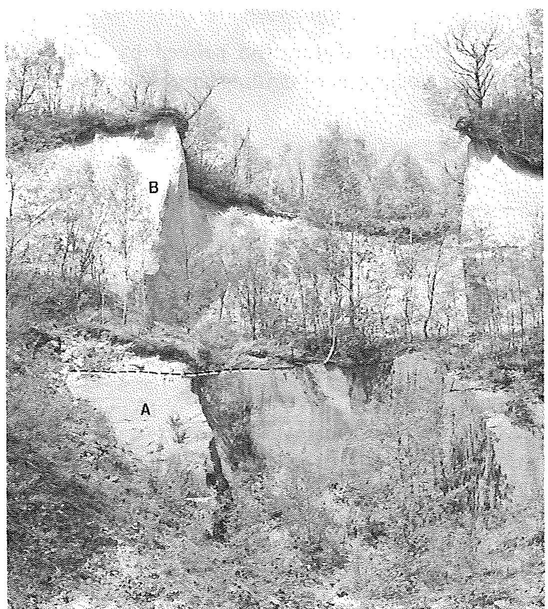


Fig. 46 The Shikotsu pumice flow exposed at Tokiwa, outskirts of Sapporo City, along the Makomanai River, a tributary of the Toyohira River, about 3 km south of Ishiyama. Although the entire volcanic pile shown in this photograph undoubtedly belongs to a single cooling unit, the upper half (B) is unconsolidated and soft, gradually grading into (A) which is rather well consolidated, hard part and with relatively high virtual density.

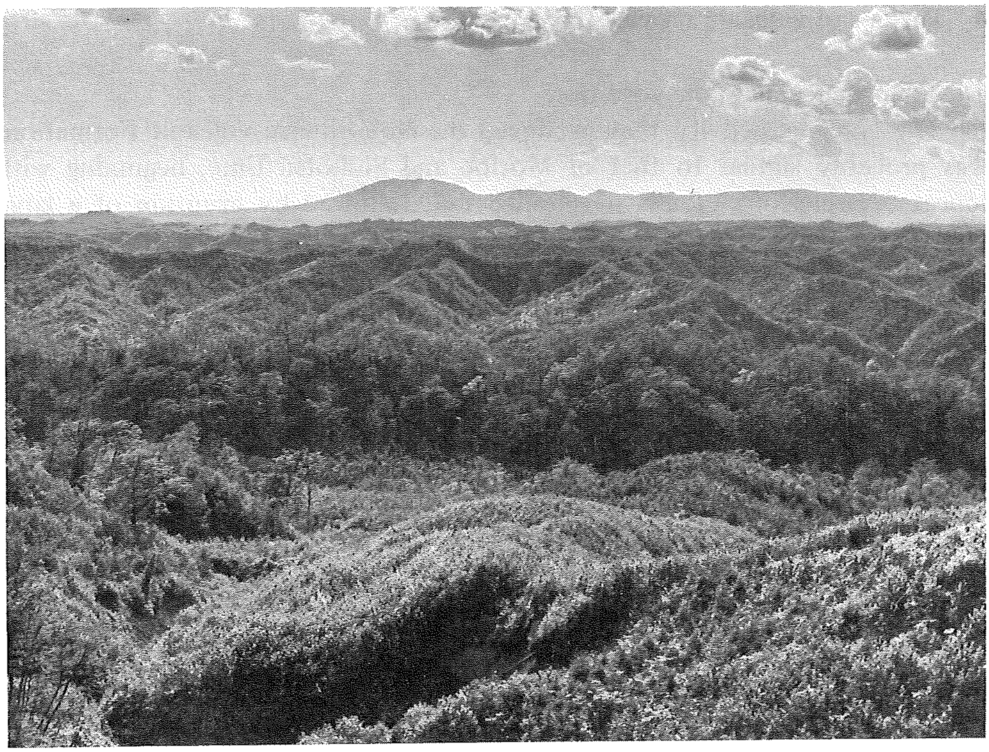


Fig. 47 Typical pyroclastic plateau composed of the Shikotsu volcanic Formation, in the upper reaches of the Shadai and Shiraoi Rivers. Immediately after eruption of the Shikotsu pumice flow the top of this plateau may have been flat although it has since been considerably dissected. Kuttara Volcano is visible on the horizon.

Fig. 48 Shikotsu Caldera Lake, viewed midway from the lake shore to the top of Mount Monbetsu-dake (865.8 m). The conical mountain on the right side is the volcano Eniwa, while Tarumae with its lava dome on top and Fuppushi, deeply dissected and covered with thick vegetation, are seen in the left side of the photograph. Distance between the top of Eniwa Volcano and Tarumae is about 13.0 km.

4 History of volcanic activity

a) Noboribetsu and Ponayoro time

The volcanic activity that produced the Noboribetsu volcanic Formation, was probably similar to that of Morino and Shikotsu time, beginning with repeated explosions of ash or pumice fall, followed by eruption of a large pumice flow. This flow is well consolidated with relatively high density nearly everywhere, indicating a fairly high temperature, when it was deposited.

Although the original extent of the Noboribetsu pumice flow is unknown it must certainly have been much greater than at present. The highest known occurrence of Noboribetsu pumice flow (N 2) is located about 3 km west of Kuttara (-ushi) Caldera (Fig. 2). SAITO et al, 1953 once proposed, that Kuttara caldera was formed after deposition of the Noboribetsu pumice flow, and that the Noboribetsu pumice flow might have been erupted from the area now occupied by Kuttara Caldera Lake.

Nevertheless, it is not certain, where the center of Noboribetsu activity is located. Our investigations suggest that it was probably not the present caldera of Kuttara Lake. If the caldera was formed after the deposition of Noboribetsu pumice flow (N 2) it must have formed somewhere west of present Kuttara Lake even though the lake is situated near the centre of the flow.

A very long hiatus separates the eruption of the Noboribetsu pumice flow and the eruption of the Ponayoro volcanic Formation, as is evident from the erosional unconformity between them.

The Ponayoro volcanic Formation reflects a sequence of volcanic eruptions similar to that of the Noboribetsu, Morino and Shikotsu volcanic Formations, initial explosions producing fall deposits followed by pumice flows. The source of the Ponayoro volcanic products is unknown, although they are widely distributed in the area surrounding the caldera lake, Kuttaraushi, and their highest exposure is near the assumed source of the Noboribetsu volcanic Formation.

In view of this the authors believe there may have been at least two episodes of caldera subsidence. First, an older caldera may have been formed northwest of Lake Kuttaraushi, immediately after the eruption of the Noboribetsu pumice flow.

This caldera was rapidly dissected and destroyed. Volcanic activity resumed in the region of the older caldera. After the eruption of either the Ponayoro pumice flow I or II (P I 2 or P II 2) a second calderal sinking may have occurred. However, the present caldera of Lake Kuttaraushi may not be the result of this volcanic activity.

b) Morino time

Volcanic activity during Morino time was probably similar to the eruptions that produced the Noboribetsu, Ponayoro I and II, and Shadai volcanic Formations, beginning with repeated explosions alternating with dormant stages. Many separate ash and pumice fall deposits, separated by stratigraphic breaks are observed in the field.

The Morino volcanic Formation has a relatively narrow distribution compared with the Shikotsu volcanic Formation. This may be partly due to its smaller original volume, but partly it may also be the result of severe erosion and denudation for a long period after its deposition.

It is impossible to correctly restore the original distribution and volume of the Morino volcanic Formation. Only the present volume, calculated from existing exposures is shown in Fig. 34.

The exact center from which the Morino pumice flow originated is unknown. The highest exposures, about 600 m above sea-level, are located about 6 km west from the caldera wall of Shikotsu Lake (Fig. 5), suggesting that Shikotsu Caldera may have been their source.

The Morino flow is loosely consolidated and nowhere are columner or platy joints observed, indicating that it was deposited at relatively low temperature.

Such low temperature pumice flows commonly show thin lamina or stratification even in single cooling units. Although they are not widespread, such laminations appear from place to place then merge suddenly into homogeneous, unconsolidated ash flow without any obvious stratification.

The authors believe the presence of laminations is a good indication that eruption of the pumice flow was accompanied by immense quantities of hot water that streamed down the slope carrying pumice fragments which were finally deposited like a sedimentary rock. Possibly hot water only was involved in the early stages.

From such observations, the Morino pumice flow is considered to have been deposited, at low temperature although this has not been confirmed by magnetic study.

Exotic rock fragments in the lower part of the Morino are similar to those in the Shikotsu pumice flow, comprising Neogene and Quaternary volcanic and pyroclastic rocks, as well as slate, chert and diorite. The magma chamber of the Morino pumice flow like that of the Shikotsu must have been below the Neogene Tertiary deposits.

Sinking of the caldera is believed to have occurred after eruption of the Morino pumice flow, but this is difficult to confirm on the basis of field evidence. The pumice fall and flow of the Morino volcanic Formation may have been largely eroded away and the caldera itself greatly dissected or completely destroyed.

c) Shikotsu time

The thickness of laminations varies from one fall deposit to another and also differs within a single fall unit. At Bibi the Shikotsu pumice fall (Sh 1 i) is 5 to 6 m thick and individual laminations range from 5 to 10 cm in thickness. Thus the Shikotsu pumice fall (Sh 1 i) may be regarded as the product of at least several tens of explosions. The entire Shikotsu pumice fall must therefore be the result of several hundred explosions.

The chemical composition of magma in the sub-surface chamber must have been changing from basic to acidic and finally pumice ash flows were erupted. Subsequent collapse produced the present caldera of Lake Shikotsu.

Probably, explosions occurred in the area now occupied by the caldera of Lake Shikotsu and pumice falls spread towards the east or southeast from this center since each ash fall deposit in the Shikotsu pumice fall (Sh 1) decreases in thickness away from this lake towards the east or southeast.

Distribution of each Shikotsu pumice fall unit has not been mapped in detail but its general outline is shown in Fig. 28.

Total volume of the Shikotsu pumice fall (Sh 1) is approximately 10.0 km^3 (Fig. 38).

The Shikotsu pumice flow crops out over a wide area, although it is partly concealed below the younger volcanoes, Fuppshi, Eniwa and Tarumae, which surround the caldera wall of Shikotsu Lake. The Shikotsu pumice flow is moderately dissected by streams and rivers, but the original topography of its surface can be determined to some extent (Fig. 37).

The highest point west of Shikotsu Lake where the Shikotsu pumice flow is distributed, is about 840 m in elevation, the original surface of deposition of this flow seems to have been streaming eastwards at first, then westwards. In all probability, eruption occurred from somewhere at the western margin of the present caldera wall. The flow material seems to have been erupted from that point at a low angle, instead of upward into the atmosphere.

Material of the pumice flow may have been propelled explosively by an immense quantity of steam and hot water. Such an eruption might be directed horizontally, being quite different from normal volcanic explosions in which material is transported vertically.

This may explain why that pumice flow is not uniformly distributed around Lake Shikotsu caldera, but is found only in a narrow zone west of the lake, although it is rather widely developed to the east. If it were erupted at a high angle, it should certainly be preserved in all directions from the center of activity.

The erupted material appears to have been blasted into the western mountainous region as high as 840 m above present sea level. Later it may have streamed down the slope of the older topography; viz it may have streamed first eastward, then changed its course towards the west. The erupted material was probably ejected with considerable initial velocity, since the stream of pumice flow seems to have crossed over a low hill in its path. This is concluded from the restoration of the original topography of the pumice flow, and the top of the pre-pumice flow topography.

Simultaneously, in the northern area, the pumice flow appears to have been streaming northwards from an area about 640 m in elevation, located somewhere near the margin of the present caldera wall. As in the case of the western region, the stream of pumice flow in this area is inferred to have crossed over small hills in its course down the slope. Thus the initial surface of the pumice flow slopes gradually northward from an altitude of 640 m to an altitude 360 m, then rises as high as 420 m against a monadnock-like hill 539 m high. Moreover the stream of pumice flow seems to have risen as high as 40 m against the small hill, Shimamatsu-yama. Similarly, the stream may have risen upwards against the small hill, Shirahata-yama, although the main body of the stream must have branched before reaching these hills and turned directly down the slope.

South of Lake Shikotsu, the original surface of the pumiceous flow slopes gradually southward from a height of about 400 m towards the present shoreline. Perhaps another pumice flow was erupted in this region from a second fissure that appeared not far from the caldera wall.

Although the Shikotsu volcanic Formation is composed mainly of rhyolitic and dacitic rocks, some relatively basic rocks are also present, especially among the older products of the early phase of eruption, viz. olivine bearing scoria falls (Sh 1 b and c, Table 1). Initially basaltic magma may have been formed at depth, probably in the upper mantle; this may have ascended along with enormous amounts of superheated steam and/or superheated water into the crust, and thence along deep faults. A certain amount of crustal material, perhaps basement complex plus Palaeozoic sediments, exposed in the fissure walls was partly assimilated by the magma. Various plutonic rocks may also have contaminated the magma. Such contamination may have produced the magma acidic that erupted explosively from Shikotsu Caldera.

After the initial explosion, of basaltic andesite, the magma may have changed composition from andesite through dacite to rhyolite. This evolution is reflected in the changing composition of material produced in successive explosions.

The early change from andesite to basaltic andesite probably resulted from partial melting of crustal rocks in the presence of a tremendous supply of superheated hot water or steam. This contamination probably occurred during ascent of the magma from the mantle to the magma chamber.

Appendix: the Rampoge gravel Formation

The Rampoge gravel Formation, about 100 m thick is widely developed in the subsurface of the region treated in this paper.

It is composed of boulders, cobbles and pebbles of Neogene and lower Pleistocene volcanic and sedimentary rocks, in addition to chert, slate and granitic rocks. Some parts of the formation also contain pumiceous gravel or alternating pumiceous clay and sand. Intercalated magnetite sand is also locally developed.

The presence of such a deposit below the surface has been established by drilling in the alluvial plain along the coast facing Volcano Bay, where the Rampoge Formation is unconformably covered by the Noboribetsu and rests unconformably on Neogene Tertiary rocks, of probable Miocene age.

Although precise correlation is impossible. similar gravel deposits, about 100 m thick, are widely developed in the northern and central part of Hokkaido, where they fill several deeply dissected older basins. Further, such gravel formations are locally covered by pumice flows, probably equivalent to the boundary zone between the Matuyama and Brunhes palaeomagnetic epochs. Such gravels are now considered to be older than the Günz ice age. Similar gravel formations are also widely developed in the region around Ikeda and Obihiro cities in Tokachi province, where the gravel formation unconformably overlies pyroclastic formations of Jaramillo age. Hence, the age of the gravel formation is presumably correlative with the Donau cold stage (Minato et al, 1970).

It is obvious, from the presence of interbedded pumiceous sediments, that repeated volcanic eruptions occurred during the deposition of these gravels.

Acknowledgements

Many persons have kindly assisted in various ways during the course of this study.

Our sincere gratitude is expressed to our respected teacher, Professor Toshio ISHIKAWA for his guidance and encouragement.

We are indebted to Professors M. HUNAHASHI, K. YAGI, S. UOZUMI, Y. KATSUI, I. YOKOYAMA, M. KATO, and Doctors K. KANAYAMA, J. WATANABE, Y. HARIYA and M. AKIYAMA, who greatly helped us with laboratory work.

Drs. M. SAITO, H. OSANAI and K. MITANI, Geol. Surv. Hokkaido, Sapporo helped us kindly with field work in many ways.

Professor S. HJELMQVIST (Lund), Professor J. G. SOUTHER (Vancouver), Dr. A. WAUSCHKUHN (Heidelberg) and Dr. G. NAPPI (Roma) accompanied us in the field many times during the time of their stay at Hokkaido University, and have kindly discussed many problems concerning the pumiceous falls and flows with us. We have learned very much through these discussions.

Professor J. G. SOUTHER, especially, helped us greatly in preparation of this paper, in critically reading our manuscript, and correcting it both scientifically and linguistically. Without his kind help this work could not have been finished. We wish to express our hearty thanks to him.

Last but not least, we wish to say that we appreciated very much the assistance given to us by Mrs. Souther also in reading the manuscript. Sincere thanks are due to her for her kindness.

Bibliography

DOI, S. (1953): Explanation Text of the Geological Map of Japan (Scale 1: 50,000) "Shiraoi", Geol. Surv. of Hokkaido (in Japanese with English abstract)

DOI, S. (1957): Explanation Text of the Geological Map of Japan (Scale 1: 50,000) "Tarumae", Geol. Surv. of Hokkaido (in Japanese with English abstract)

FUJIWARA, Y. (1971): Palaeomagnetic Studies of the Pyroclastic flows in the Shikotsu and Noboribetsu area. (in press)

HASHIMOTO, S. and KUMANO, S. (1955): Zur Gletschertopographie im Hidaka Gebirge, Hokkaido, Japan. Jour. Geol. Soc. Japan, Vol. 61, No. 716, pp. 208-217

HASHIMOTO, S. and MINATO, M. (1955): On the Ice Age and Post-glacial age of the Hidaka mountain range. Jour. Fac. Sci. Hokkaido Univ., Ser. IV, Vol. IX No. 1, pp. 7-20

HEINTZ, A. (1965): Determination of the absolute age of the fossil remains of Mammoth and wooly Rhinoceros from the permafrost in Siberia by the help of Radio Carbon. Norsk Geol. Tidsskrift, Vo. 45, Pt. 1, pp. 73-79

ISHIKAWA, T. (1937): Recent state of Tarumae-San. Bull. Volc. Soc. Japan, Vol. 3, No. 3, pp. 292-296 (in Japanese)

ISHIKAWA, T. (1940): On xenoliths in the lavas of Volcano Tarumai. Bull. Volc. Soc. Japan, Vol. 4, No. 2, pp. 109-140 (in Japanese)

ISHIKAWA, T. (1949): Occurrence of aegirine augite from Volcano Tarumai, Hokkaido. Bull. Geol. Comm. Hokkaido, No. 12, pp. 9-15 (in Japanese)

ISHIKAWA, T. (1950): New eruption of Usu Volcano, Hokkaido during

1943-1945. Jour. Fac. Sci. Hokkaido Univ., Ser. IV, Vol. VII No. 3, pp. 237-260

ISHIKAWA, T. (1952): The chemical characteristics of the lavas from Volcano Tarumai, Hokkaido, Japan. Jour. Fac. Sci. Hokkaido Univ., Ser. IV, Vol. VIII, No. , pp. 107-135

ISHIKAWA, T. (1953a): Eruption of Usu Volcano, Hokkaido, Japan. Proc. 7th Pacific Science Congress, Vol. 2, pp. 368-375

ISHIKAWA, T. (1953b): Xenoliths included in the lavas from Volcano Tarumai, Hokkaido, Japan. Jour. Fac. Sci. Hokkaido Univ., Ser. IV, Vol. VIII, No. , pp. 225-244

ISHIKAWA, T. (1966): Geological study on hot springs in Noboribetsu. Jour. Balneological Soc. Japan, Vol. 16, No. 2, pp. 29-50 (in Japanese)

ISHIKAWA, T., MINATO, M., KUNO, H., MATSUMOTO, T. and YAGI, K. (1957): Welded tuffs and deposits of pumice flow and nuée árdente in Japan. XX Congreso Geologico International, Section I, pp. 137-150

KATSUI, Y. (1958): On the Fossil Forest embedded in the Shikotsu Pumice fall deposit, Hokkaido. Jour. Geol. Soc. Japan, Vol. 64, No. 755, pp. 379-385 (in Japanese with English abstract)

KATSUI, Y. (1959): On the Shikotsu pumice fall deposit. Bull. Volc. Soc. Japan, 2nd ser. Vol. 4, No. 1, pp. 33-48 (in Japanese with English abstract)

KUMANO, S. (1970): Age of Shikotsu welded tuff, Hokkaido. $-C^{14}$ age of the Quaternary deposits in Japan, 57 – (in Japanese)

KUMANO, S. and IGARASHI, Y. (1971): Pollen assemblage of peat intercalated in the Shadai and the Morino volcanic group, Pleistocene in Age. (in press)

MATSUSHITA, K., FUJIWARA, Y. KUMANO, S. and MINATO, M. (1970): Subsurface geology of Hakodate city and explanation text for Quaternary geological map. Hokkaido Prefectural Government (in Japanese)

MINATO, M. (1955): Zur den Mammotheusfaunen Hokkaidos. Japanese Jour. Geol. Geogr. Vol. 26, No. 1-2, pp. 105-113

MINATO, M. (1966a): The Final Stage of Land Bridges in the Japanese Islands. Chikyu Kagaku, No. 85-86 pp. 2-11 (in Japanese with English abstract)

MINATO, M. (1966b): ^{14}C age of the Toya ash flow II – ^{14}C age of the Quaternary deposits in Japan, 27 – Chikyu Kagaku, No. 82, pp. 42-43 (in Japanese)

MINATO, M. (1967a): Sea level Changing of the Quaternary time and Palaeogeographical change of the Japanese Islands. Japanese Society of Systematic Zoology, Circular No. 36, pp. 1-3 (in Japanese)

MINATO, M. (1967b): On the age of Mammoths in Japan and Siberia. Chikyu Kagaku, Vol. 21, No. 2, pp. 13-17

MINATO, M., FUJIWARA, Y. and KUMANO, S. (1968): Subsurface geology of the Sapporo city with explanation text for Quaternary geological map. Hokkaido Prefectural Government (in Japanese)

MINATO, M., FUJIWARA, Y. and S. KUMANO (1969): Subsurface geology of the Tomakomai city with explanation text for Quaternary geological map. Hokkaido Prefectural Government (in Japanese)

MINATO, M., GORAI, M. and HUNAHASHI, M. (ed.) (1965): The Geologic Development of the Japanese Islands. Tsukiji Shokan, Tokyo

MINATO, M. and HASEGAWA, Y. (1959): Studies of the Welded tuffs in Japan – On the Neppu Welded tuff, 1st Report – Jour. Geol. Soc. Japan, Vol. 65, No. 760, pp. 66 – 70 (in Japanese with English abstract)

MINATO, M. and HASHIMOTO, S. (1954): Zur Karbildung im Hidakagebirge, Hokkaido, Japan. Proc. Japan Acad., Vol. 30, No. 2, pp. 106-108

MINATO, M., HASHIMOTO, S., FUJIWARA, Y. and KUMANO, S. (1970): Volcanic Activities of the Pliocene and Pleistocene in Hokkaido. Quaternary Research, Vol. 9, No. 3-4, pp. 128-129

MINATO, M., ISHII, J. and KUMANO, S. (1959): A Study of the Welded tuffs in Japan, 2nd Report – On the Shikotsu Welded tuff – Jour. Geol. Soc. Japan, Vol. 65, No. 763, pp. 209-221 (in Japanese with English abstract)

MINATO, M. and ISHIKAWA, T. (1955): Age of the Welded tuffs in Northern Japan. INQUA IV Congress, Rome, 1953, pp. 1-8

MINATO, M., SUYAMA, K., HASEGAWA, K., OYA, A., TAKAHASHI, Y., NAKAGAWA, K. WADA, N. and SHIBAZAKI, T. (1967): Absolute Age of Subsurface Late Quaternary Deposits in the Niigata Lowland. Jour. Fac. Sci. Hokkaido Univ. Ser. IV, Vol. XIII, No. 4, pp. 401-406

OBARA, T. et al. (1966): Explanatory Text of the Hydrogeological maps of Hokkaido No. 15 "Hakodate". Geol. Surv. of Hokkaido (in Japanese with English abstract)

OBARA, T. et al. (1968): Explanatory Text of the Hydrogeological maps of Hokkaido No. 3, "Takikawa, Rumoi" Geol. Surv. of Hokkaido (in Japanese with English abstract)

SAITO, M., OSANAI, H. and SAKO, S. (1953): Explanation Text of the Geological map of Japan (Scale 1: 50,000) "Noboribetsuonsen" Geol. Surv. of Hokkaido (in Japanese with English abstract)

SUZUKI, J. and ISHIKAWA, (SHIMOTOMAI), T. (1933): Tarumai Volcano. Bull. Volc. Soc. Japan, Vol. i, No. 3, pp. 17-43 (in Japanese)

SUZUKI, J. and ISHIKAWA, T. (1943): Tarumai-san and Lake Shikotsu. Geol. Guide Book of Hokkaido, No. 1, pp. 1-24 (in Japanese)

SUZUKI, J. ISHIKAWA, T. and ISHIBASHI, M. (1943): Noboribetsu hot spring and Kuttara lake. Geol. Guide Book of Hokkaido, No. 2, pp. 1-16 (in Japanese)

SUZUKI, T. (1962): Natural. Remanent Magnetism of Shikotsu welded tuff deposit. Geophys. Bull. Hokkaido Univ. No. 9, pp. 1-10 (in Japanese with English abstract)

YAMAGUCHI, K. et al. (1963): Explanatory Text of the Hydogeological maps of Hokkaido No. 13 "Tomakomai, Muroran". Geol. Surv. of Hokkaido (in

Japanese with English abstract)
YAMAGUCHI, K. et al. (1965): Explanatory Text of the Hydrogeological maps of Hokkaido No. 8, "Sapporo", Geol. Surv. of Hokkaido (in Japanese with English abstract)
YAMAGUCHI, K. et al. (1967): Explanatory Text of the Hydrogeological maps of Hokkaido No. 4, "Asahikawa", Geol. Surv. of Hokkaido (in Japanese with English abstract)

(Manuscript received August 31, 1971)