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Citation	Geological Magazine, 143(6), 753-770 https://doi.org/10.1017/S001675680600255X
Issue Date	2006-11
Doc URL	https://hdl.handle.net/2115/17119
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Type	journal article
File Information	GM143-6.pdf



Late Jurassic–Early Cretaceous intra-arc sedimentation and volcanism linked to plate motion change in northern Japan

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(Received 5 October 2005; accepted 10 January 2006)

Abstract – The Sorachi Group, composed of Upper Jurassic ophiolite and Lower Cretaceous island-arc volcano-sedimentary cover, provides a record of Late Jurassic–Early Cretaceous sedimentation and volcanism in an island-arc setting off the eastern margin of the Asian continent. Stratigraphic changes in the nature and volume of the Sorachi Group volcanic and volcanoclastic rocks reveal four tectonic stages. These stages resulted from changes in the subduction direction of the Pacific oceanic plate. Stage I in the Late Jurassic was characterized by extensive submarine eruptions of tholeiitic basalt from the back-arc basin. Slab roll-back caused rifting and sea-floor spreading in the supra-subduction zone along the active Asian continental margin. Stage II corresponded to the Berriasian and featured localized trachyandesitic volcanism that formed volcanic islands with typical island-arc chemical compositions. At the beginning of this stage, movement of the Pacific oceanic plate shifted from northeastward to northwestward. During Stage III, in the Valanginian, submarine basaltic volcanism was followed by subsidence. The Pacific oceanic plate motion turned clockwise, and the plate boundary between the Asian continent and the Pacific oceanic plate changed from convergent to transform. During Stage IV in the Hauterivian–Barremian, *in situ* volcanism ceased in the Sorachi–Yezo basin, and the volcanic front migrated west of the Sorachi–Yezo basin.

Keywords: Cretaceous, Jurassic, island-arc, volcanism, tectonics, Asia.

1. Introduction

The Late Jurassic–Early Cretaceous period was characterized by a significant reconfiguration of the continents and oceanic plate movement in the NW Pacific (Kirillova, 2003*a,b*; Nakanishi, Tamaki & Kobayashi, 1992; Ren *et al.* 2002). During this interval, continental Siberia collided with both the combined Mongolia–China and the Omolon–Kolyma continents along its southern and eastern margins, respectively (Oxman, 2003; Van der Voo, Spakman & Bijwaard, 1999; Zonenshain, Kuzmin & Natapov, 1990). These collisions resulted in the formation of the amalgamated Asian continent. Subsequently, the conjugation between the Asian continent and the oceanic plate below the Pacific Ocean (the Farallon–Izanagi plate) changed from a convergent to a transform boundary (Engelbreton, Cox & Gordon, 1985). Many studies have confirmed that this change in Pacific oceanic plate movement halted the growth of accretionary complexes and induced the northeastward migration of the NE Japan Block during the Early Cretaceous period (e.g. Takahashi & Matsukawa, 2000; Tazawa, 2002). Although this change in plate movement is thought to be reflected in subduction-related volcanism, little is known about the temporal–spatial changes in

Early Cretaceous supra-subduction volcanism along the active continental margin of Asia.

The Horokanai Ophiolite and Sorachi Group, represented by the Upper Jurassic ophiolites and their Lower Cretaceous island-arc volcano-sedimentary covers, are exposed in central Hokkaido, northern Japan (Ishizuka, 1980; Takashima, Yoshida & Nishi, 2002). As these strata are biostratigraphically well studied based on well-preserved microfossils and exhibit continuous succession without significant unconformity, they are suitable for clarifying the Late Jurassic–Early Cretaceous geodynamic evolution of the island-arc system of Asia. Using the history recorded in these strata, this paper reconstructs the temporal–spatial evolution of the volcanic and sedimentary basins of central Hokkaido during the Late Jurassic–Early Cretaceous period and clarifies the linkage between the volcano-tectonic evolution of the island-arc system and the change in Pacific oceanic plate movement.

2. Regional geological setting

The Japanese Islands are now separated from the Asian continent, but were an eastern constituent of the continent before the Miocene opening of the Japan Sea. They are mainly composed of upper Palaeozoic to Cenozoic accretionary complexes constructed along

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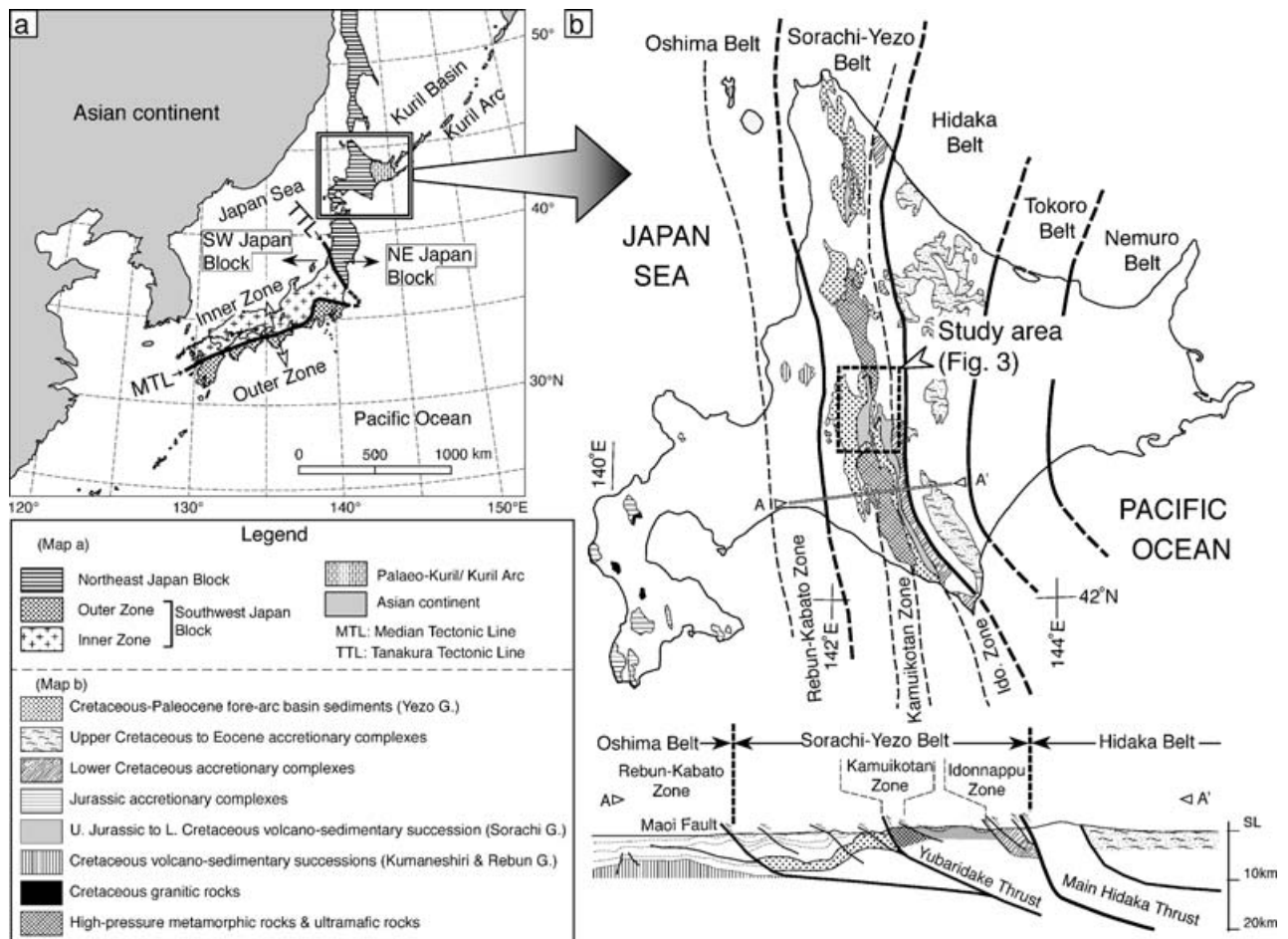


Figure 1. (a) Simplified geological map and (b) structural profile showing the distribution of the Mesozoic formations of Hokkaido. Dashed rectangle in (b) marks the study area. Structural profile is modified from Ito (2002).

the East Asian continental margin, which have been intruded and covered by volcano-plutonic rocks. Structurally, the Japanese Islands are mainly divided into two blocks (the NE Japan and SW Japan blocks) by the Tanakura Tectonic Line (TTL) (Fig. 1a). The SW Japan Block is subdivided into the Inner and Outer zones by the Median Tectonic Line (MTL) (Fig. 1a). Both tectonic lines were originally a series of large-scale left-lateral strike-slip fault systems which have been active since Early Cretaceous times. The NE Japan Block and the Outer Zone of the SW Japan Block were originally located southwest of the Inner Zone of the SW Japan Block, and migrated northeastward along the MTL–TTL after the Early Cretaceous (e.g. Osozawa, 1994; Tazawa, 2002).

The island of Hokkaido is tectonically subdivided into the western and eastern sub-blocks which collided during Palaeogene times along the Hidaka Belt of a lower Palaeogene accretionary complex (Fig. 1b). Western Hokkaido is the northernmost constituent of the NE Japan Block, while eastern Hokkaido, represented by the Tokoro and Nemuro belts, is the Palaeo-Kuril island-arc (Fig. 1b). The Mesozoic rocks exposed in western Hokkaido can be divided into two N–S-trending tectonostratigraphic divisions. From

west to east, these belts are the Oshima (a late Early–Late Cretaceous volcanic arc on a Jurassic accretionary complex), Sorachi–Yezo (a Late Jurassic–early Early Cretaceous island-arc and late Early Cretaceous–Paleocene fore-arc basin and accretionary complex), as shown in Figure 1b (Kiminami *et al.* 1986). Cretaceous submarine volcano-sedimentary successions (the Rebun and Kumaneshiri groups), distributed along the eastern margin of the Oshima Belt, are distinguished as the Rebun–Kabato Zone (Fig. 1b) from the Cretaceous granitic rocks of the western Oshima Belt. These divisions formed along the W-dipping subduction zone of the Pacific oceanic plate (Farallon, Izanagi and Kula plates) under the eastern margin of the Asian continent (Okada, 1974).

The Sorachi–Yezo Belt and the Rebun–Kabato Zone were deformed by dextral slip and block-like rotation during the Oligo-Miocene due to the opening of Kuril Basin (Jolivet, Shibuya & Fournier, 1995; Takeuchi, Kodama & Ozawa, 1999). Furthermore, they were shortened by collision caused by the southwestward migration of the Kuril fore-arc sliver beginning in the Miocene (Kimura, 1985), resulting in the development of N–S-trending thrust and fold systems within the belts (Fig. 1b). The lateral shortening distance in

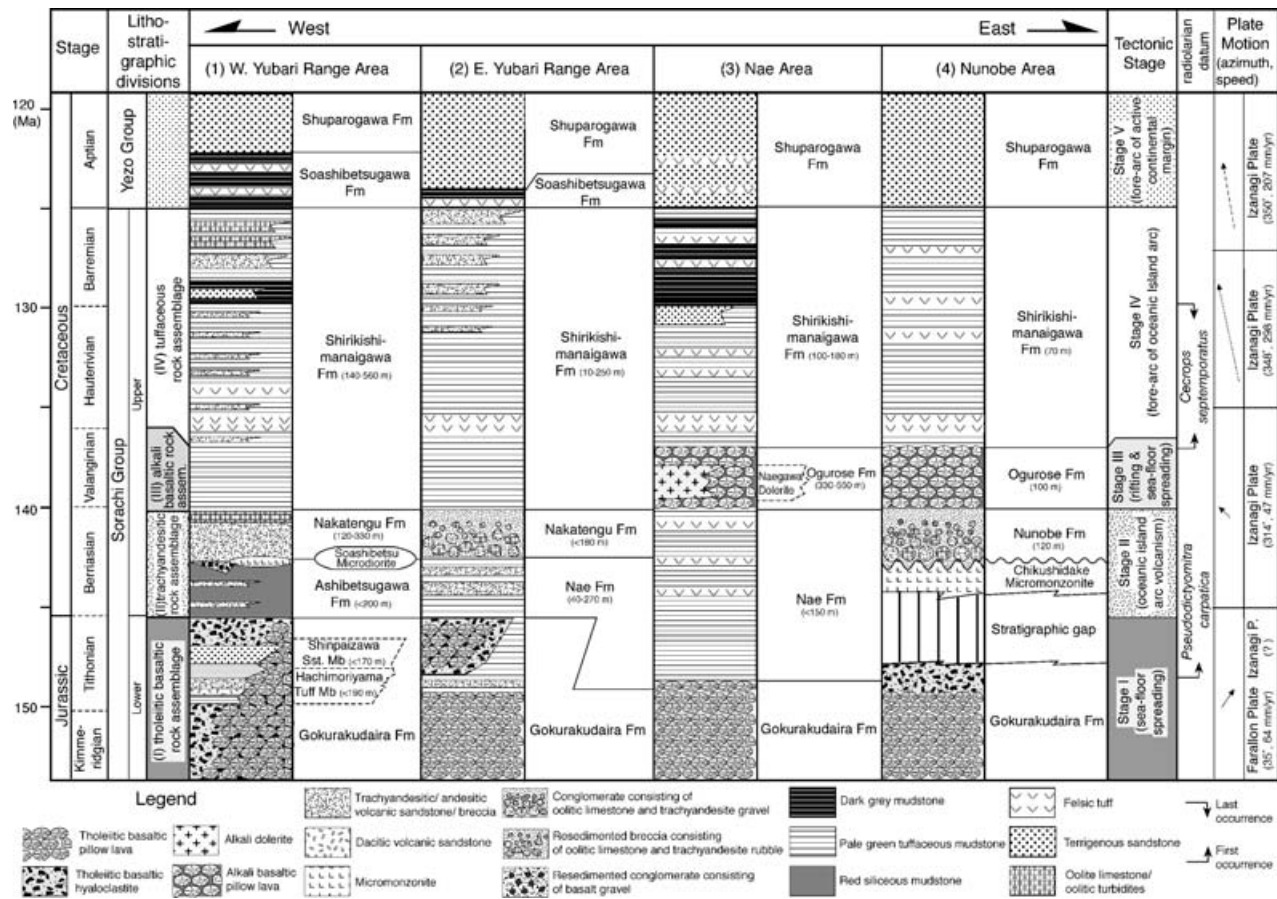


Figure 2. Generalized isochronous stratigraphic nomenclature of the Sorachi Group for the four sections studied in this region. Pacific oceanic plate motion is from Engebretson, Cox & Gordon (1985). Time scale is from Ogg, Agterberg & Gradstein (2004).

central Hokkaido is considered to be 60 km (Ito, 2002).

The Sorachi–Yezo Belt consists of a continuous succession from the Horokanai Ophiolite through the Sorachi Group to the Yezo Group (Fig. 2), including the accretionary complexes of the unmetamorphosed Idonappu and high-pressure metamorphosed Kamuikotan zones (Fig. 1b). The Horokanai Ophiolite and the lower part of the Sorachi Group are composed of Late Jurassic tholeiitic oceanic crust (Ishizuka, 1981; Takashima, Yoshida & Nishi, 2002); the overlying upper Sorachi Group is represented by subaqueous calc-alkaline and alkaline volcano-sedimentary sequences, suggesting an oceanic island-arc setting (Girard *et al.* 1991; Niida, 1992; Takashima *et al.* 2002). The Yezo Group conformably overlies the Sorachi Group in very thick sandstone and mudstone sequences (Takashima *et al.* 2004). The sandy clastics of the Yezo Group were derived from Cretaceous igneous rocks and Jurassic accretionary complexes of the Oshima Belt, a contemporaneous continental arc setting (Kito *et al.* 1986).

3. Lithostratigraphy of the Late Jurassic–Early Cretaceous island-arc sequence

The Sorachi Group represents Late Jurassic–Early Cretaceous island-arc belt sequences (Fig. 1b). The

widest exposure of this group occurs in the central Sorachi–Yezo Belt, where intermittent outcrops are found in four areas from the rear of the arc (west) to the trench side (east) within a N–S-trending fold-and-thrust system. As shown in Figure 3, these areas are (1) the western Yubari Range, (2) the eastern Yubari Range, (3) Nae and (4) Nunobe. The Sorachi Group consists mainly of subaqueous volcanic and volcanoclastic rocks with minor intercalations of terrigenous clastic sediments; the group can be subdivided into four rock assemblages (Fig. 2). The basal assemblage, represented by the uppermost Jurassic Gokurakudaira Formation (Table 1), is dominated by tholeiitic basalt in all areas, as is the uppermost constituent (basalt member) of the Horokanai Ophiolite (Takashima, Yoshida & Nishi, 2002). The overlying second and third assemblages are characterized by a predominance of trachyandesitic volcanoclastic and intrusive rocks and alkali basaltic rocks, respectively. The former assemblage dates to Berriasian times, and the latter dates to the Valanginian. The fourth assemblage, excluding *in situ* igneous rocks, consists mainly of tuffaceous mudstone with subordinate intercalations of trachyandesitic volcanic sandstones and terrigenous clastics. This assemblage ranges in age from Hauterivian to Barremian. The Sorachi Group is conformably covered by terrigenous turbidites and

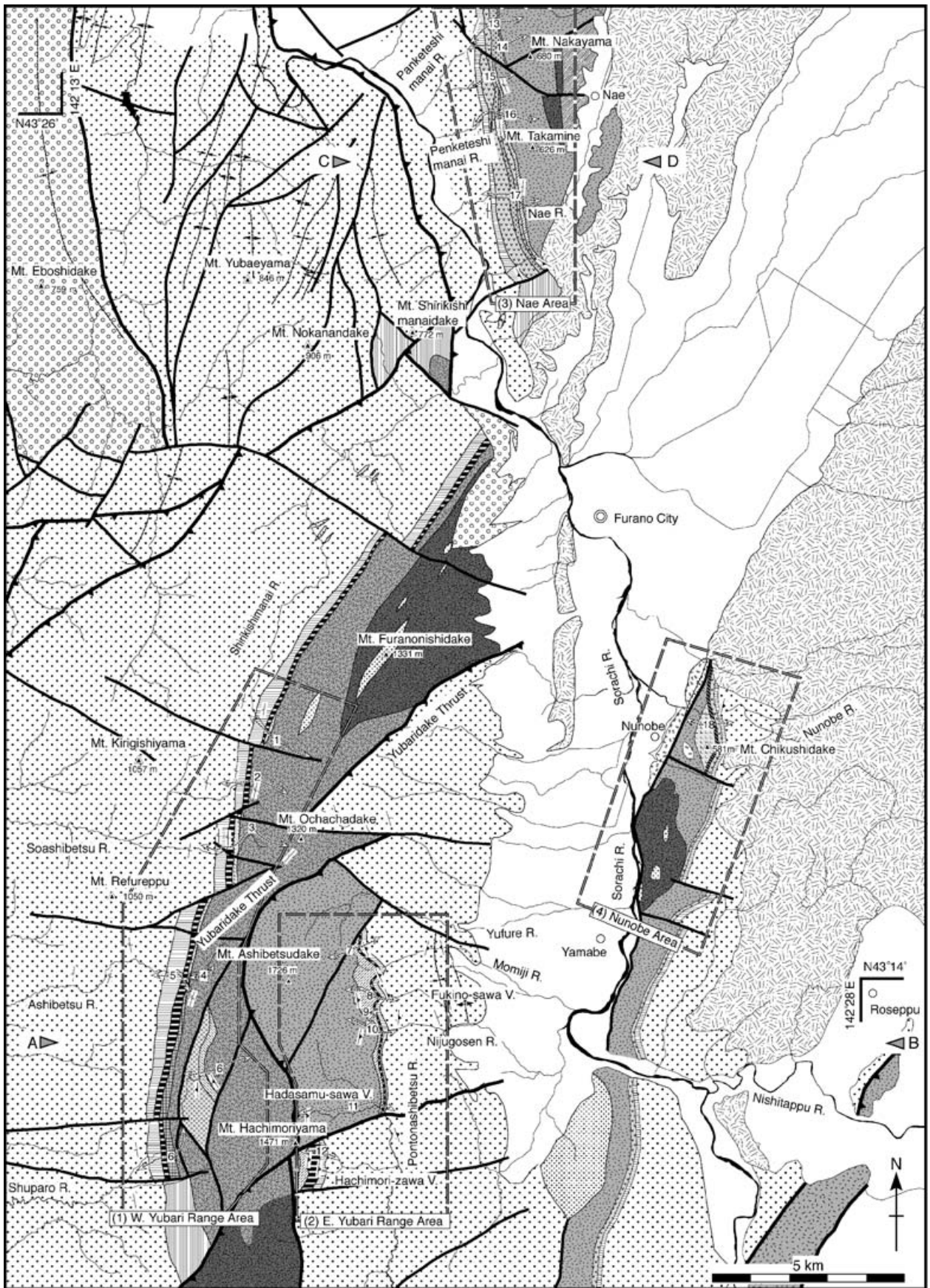


Figure 3. For legend see facing page.

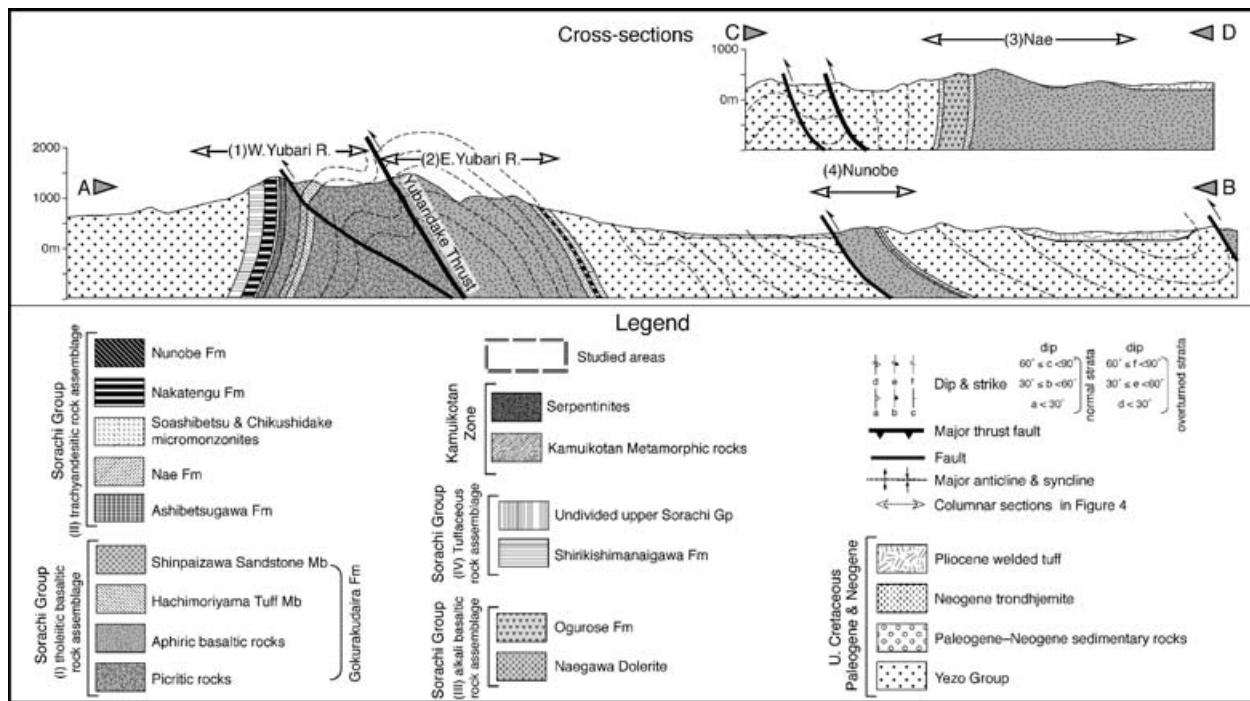


Figure 3. Geological map and structural profile sections of the central Hokkaido Island region.

Table 1. Summary of the lithostratigraphic units of the Sorachi Group

Lithostratigraphic unit	Distribution	Type section	Definition	Thickness	Major lithology
Gokurakudaira Fm.	All areas	Mt Gokurakudaira (W. Yubari Range)	Takashima, Nishi & Yoshida (2001)	> 700 m	Basaltic pillow lava and hyaloclastite
Hachimoriyama Tuff Mb.	W Yubari Range	Shuparo River	Takashima, Nishi & Yoshida (2001)	< 190 m	Tuffaceous mudstone and trachyandesitic–dacitic volcanic breccia
Shinpaizawa Sandstone Mb.	W Yubari Range	Shuparo River	Takashima, Nishi & Yoshida (2001)	< 170 m	Terrigenous sandstone and mudstone
Ashibetsugawa Fm.	W Yubari Range	Ashibetsu River	Takashima, Nishi & Yoshida (2001)	< 200 m	Red siliceous mudstone
Nae Fm.	Nae and E Yubari Range	Penketeshimanai River	New	< 1300 m	Pale green tuffaceous mudstone
Soashibetsu Micromonzonite	W Yubari Range	Soashibetsu River	New	–	Micromonzonite sill
Chikushidake Micromonzonite	Nunobe	Nunobe quarry	Takashima <i>et al.</i> (2002)	–	Micromonzonite sill
Nakatengu Fm.	W Yubari Range and E Yubari Range	Ashibetsu River	Takashima, Nishi & Yoshida (2001)	< 330 m	Trachyandesitic volcanic breccia and sandstone with oolitic limestones
Nunobe Fm.	Nunobe	Nunobe quarry	Takashima <i>et al.</i> (2002)	120 m	Volcanogenic conglomerate, sandstone and mudstone
Ogurose Fm.	Nunobe and Nae	Nunobe quarry	Takashima <i>et al.</i> (2002)	100–500 m	Basaltic pillow lava
Naegawa Dolerite	Nae	Nae River	Kito (1987)	–	Dolerite sill
Shirikishimanaigawa Fm.	All areas	Shirikishimanai River	Takashima, Nishi & Yoshida (2001)	140–560 m	Pale green tuffaceous mudstone

Mb. – Member; Fm. – Formation

hemipelagic mudstone of the Yezo Group in all areas (Fig. 2).

3.a. Tholeiitic basaltic rock assemblage (the lower Sorachi Group: Gokurakudaira Formation)

The tholeiitic basaltic rock assemblage, represented by the Gokurakudaira Formation, is equivalent to the uppermost basaltic lava unit of the Horokanai Ophiolite

(Takashima, Nishi & Yoshida, 2001; Takashima, Yoshida & Nishi, 2002). Although tholeiitic basalts prevail in this assemblage, dacitic–trachyandesitic volcanoclastic rocks and terrigenous sediments are intercalated in the western Yubari Range area (Fig. 4, column 6); these members are referred to as the Hachimoriyama Tuff and Shinpaizawa Sandstone, respectively (Takashima, Nishi & Yoshida, 2001).

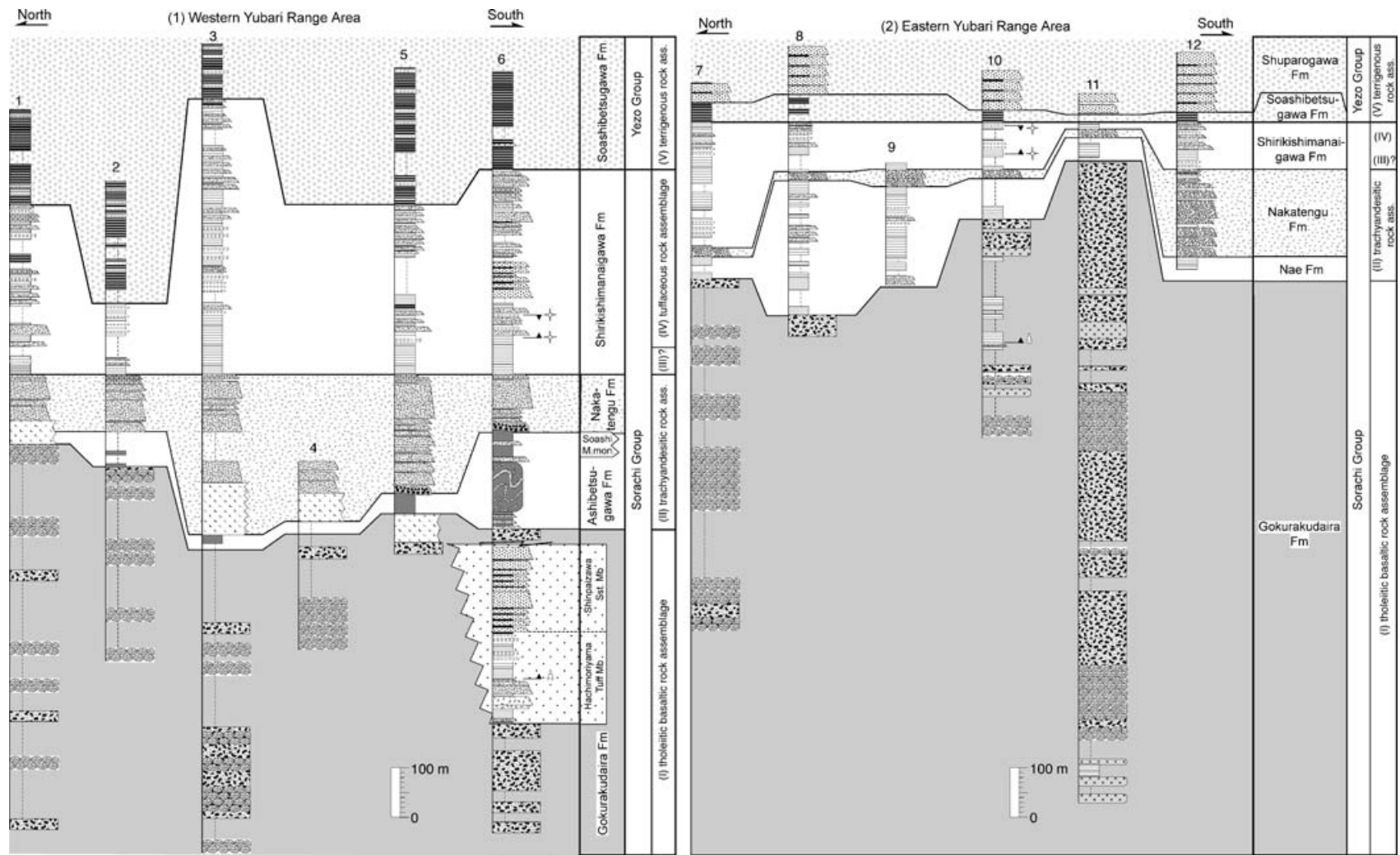


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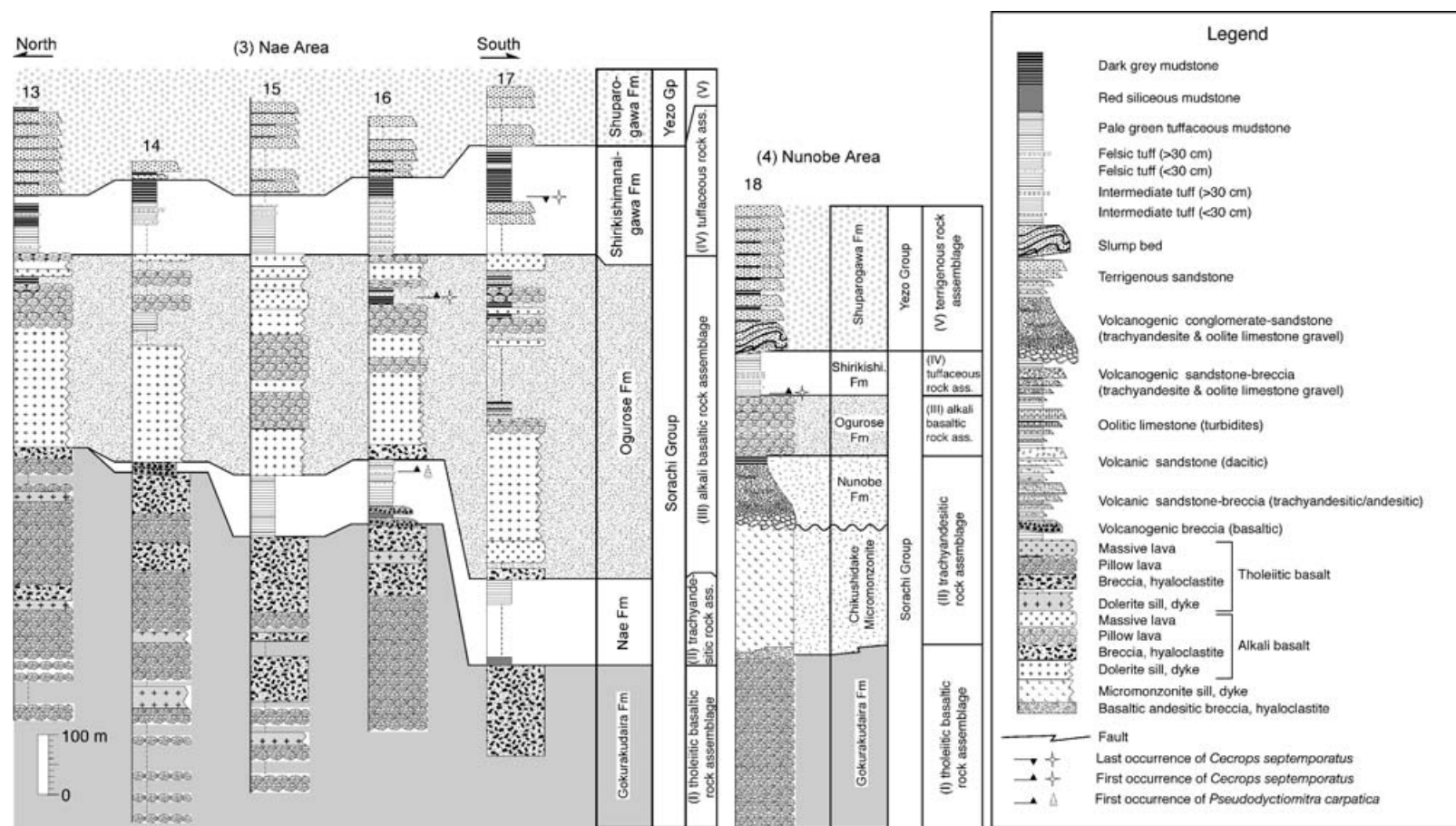


Figure 4. Correlation of selected columnar sections from the study areas. 1–6 – western Yubari Range area. 1 – Shirikishimanai River; 2 – northern Soashibetsu River; 3 – Soashibetsu River; 4 – northern Ashibetsu River; 5 – Ashibetsu River; 6 – Shuparo River. 7–12 – eastern Yubari Range area. 7 – Ashibetsudake new trail; 8 – Fukino-sawa Valley; 9 – northern Nijugosen River; 10 – Nijugosen River; 11 – Hadasamu-zawa Valley; 12 – Hachimori-zawa Valley. 13–17 – Nae area. 13 – northern Panketeshimanai River; 14 – Panketeshimanai River; 15 – southern Panketeshimanai River; 16 – Penketeshimanai River; 17 – Nae River. 18 – Nunobe area, Nunobe Quarry.

Table 2. Petrographic summary of the igneous rocks of the Sorachi Group

Lithostratigraphic unit	Rock type	Phenocryst	Groundmass (texture)
Gokurakudaira Fm.	Aphyric basalt Picrite	Ol (30–70 %) > sp (<1 %)	Pl ≥ cpx > opq, (intergranular) Cpx > pl > sp, (dendrite)
Hachimoriyama Tuff Mb.	Olivine basaltic andesite Trachyandesite fragments of vol. bre. Dacite fragments of vol. sst.	Ol (3–20 %) > sp (<1 %) Pl ≫ cpx* Pl > qz > cpx*	Glass Glass > pl > opq, (intersertal / hyalopilitic) Glass ≫ pl > qz > opq, (hyalopilitic)
Ashibetsugawa Fm.	Andesite fragments of vol. sst.	Pl > cpx > qz*	Pl > glass > opq, (intersertal)
Nae Fm.	Trachyandesite fragments of vol. sst.	Pl > cpx*	Glass > pl > opq
Nakatengu Fm.	Aphyric basalt gravel Picrite gravel Trachyandesite fragments of vol. bre.	Ol (20–50 %) Pl ≫ cpx ≫ opq*	Pl > cpx > opq, (intergranular) Cpx > glass Pl > glass > opq, (intersertal)
Nunobe Fm.	Trachyandesite gravel	Pl (20–50 %) > cpx (1–10 %) > opq (0–5 %)	Glass ≫ pl > opq
Soashibetsu Micromonzonite	Micromonzonite		Pl ≫ opq > qz > hbl > cpx
Chikushidake Micromonzonite	Micromonzonite		Pl ≫ cpx > opq > hbl > kf
Ogurose Fm.	Aphyric basalt	Pl (0–5 %) > cpx (0–2 %)	Pl > cpx > opq, (intergranular)
Naegawa Dolerite	Dolerite		Pl > cpx > opq, (ophitic)
Shirikishimanaigawa Fm.	Trachyandesite fragments of vol. sst.	Pl > cpx > opq*	Glass ≫ pl ≫ opq

vol. – volcanic; sst. – sandstone; bre. – breccia; ol – olivine; sp – spinel; cpx – clinopyroxene; pl – plagioclase; qz – quartz; opq – opaque mineral; hbl – hornblende; kf – alkali feldspar. * Proportions were not measured because of small area of rock fragments.

3.a.1. Gokurakudaira Formation

The volcanic rocks of the Gokurakudaira Formation consist of basaltic pillow lava and hyaloclastite with minor intercalations of thin siliceous mudstone. The pillows are closely packed and fitted together and range in width from 30 to 80 cm (Fig. 5a). The hyaloclastites consist of rubble smaller than 60 cm across and a fine-grained matrix composed of glass shards. The basalts are divided into two rock types: the aphyric type, distributed in the eastern Yubari Range, Nae and Nunobe areas (Fig. 6a), and the picritic type, distributed in the western Yubari Range area (Fig. 6b). The aphyric basalt consists of idiomorphic plagioclase, granular clinopyroxene and opaque minerals (Table 2), while the picritic basalt consists mainly of olivine and clinopyroxene with lesser amounts of plagioclase and spinel (Table 2). Olivine-phyric basaltic andesites occur at the top of the formation in the Nunobe area (Fig. 4). The andesites consist of idiomorphic phenocrysts of olivine and glassy groundmass (Table 2).

Takashima *et al.* (2002) noted that the basalts of this formation resemble the tholeiitic basalts of the back-arc basin based on whole-rock major and trace element geochemistry and the chemical compositions of olivine-spinel minerals.

3.a.2. Hachimoriyama Tuff Member

The Hachimoriyama Tuff Member is a volcano-sedimentary succession dominated by pale green tuffaceous mudstone with intercalations of dacitic-trachyandesitic volcanoclastic rocks (Fig. 4, column 6). The pale green tuffaceous mudstone conformably cov-

ers the basaltic breccia of the Gokurakudaira Formation. The mudstone exhibits medium bedding and contains abundant radiolarian fossils. This member intercalates a 50 m thick unit consisting of dacitic and trachyandesitic volcanoclastic breccia-sandstone beds. Each volcanoclastic bed has a sharp, erosional base and a flat top showing the S_3-T_{b-d} sequence described by Lowe (1982). The dacitic volcanic sandstone beds are 0.3–2 m thick and consist of corroded quartz and dacite fragments (Table 2), admixed with subordinate amounts of idiomorphic plagioclase, clinopyroxene, opaque minerals and pumice, in order of decreasing abundance. The trachyandesitic breccia and sandstone beds are usually 0.3 to 4 m thick and made of plagioclase-phyric trachyandesite fragments (Table 2), idiomorphic plagioclase and clinopyroxene, in order of decreasing abundance.

3.a.3. Shinpaizawa Sandstone Member

Sandstone dominates the Shinpaizawa Sandstone Member and alternates with beds of blue-grey sandstone and dark grey mudstone (Fig. 5b), both of which contain abundant plant fragments. The sandstone beds also exhibit the S_1-T_{b-e} sequence described by Lowe (1982) and are composed of well-sorted and medium- to coarse-grained lithic or feldspathic arenite, consisting mainly of detrital quartz and feldspar (smaller than 2 mm), with subordinate amounts of rock fragments, plants, biotite, microcline, muscovite and zircon. The rock fragments are mainly rhyolite, granite, and spherulite of rhyolite, with very small amounts of muscovite-quartz schist and hornfels exhibiting a granoblastic texture.

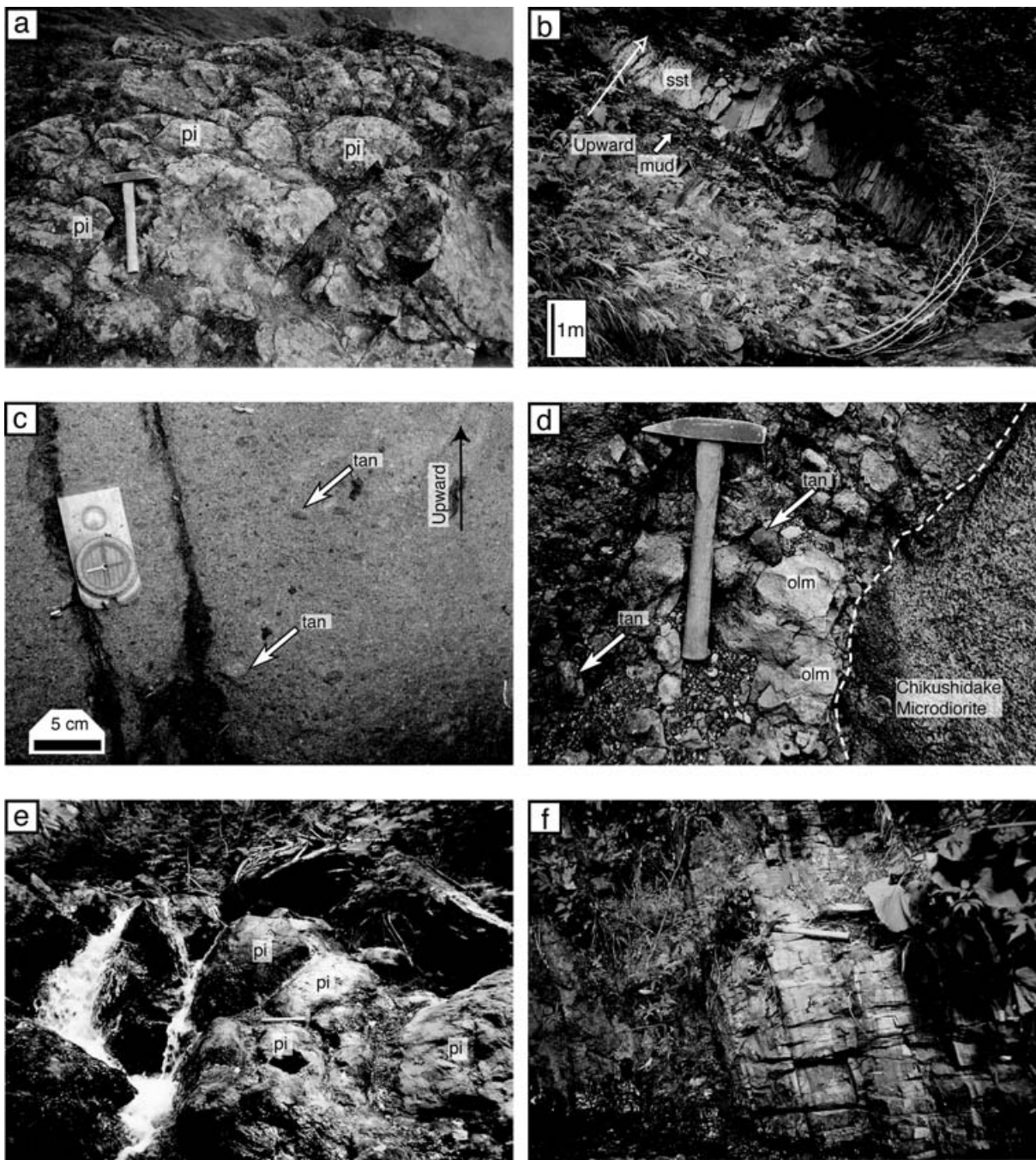


Figure 5. Photographs of the representative lithofacies of the Sorachi Group. Hammer length = 0.3 m. a – basaltic pillow lava; Gokurakudaira Formation, Mt Ashibetsudake, eastern Yubari Range area. b – terrigenous sandstone beds; Shinpaizawa Sandstone Member, Shuparo River, western Yubari Range area. c – trachyandesitic breccia; Nakatengu Formation, Ashibetsu River, western Yubari Range area. d – unconformable contact between the Chikushidake Micromonzonite and basal conglomerate of the Nunobe Formation, Nunobe quarry, Nunobe area. e – basaltic pillow lava; Ogurose Formation, Panketeshimanai River, Nae area. f – pale green tuffaceous mudstone; Shirikishimanaigawa Formation, Shuparo River, western Yubari Range area. Pi – pillow lobe; tan – trachyandesite.

3.b. Trachyandesitic rock assemblage (lower part of the Upper Sorachi Group: the Ashibetsugawa, Nae, Nakatengu and Nunobe formations and the Soashibetsu and Chikushidake micromonzonites)

The trachyandesitic rock assemblage is characterized by a major occurrence of trachyandesitic volcanoclastic

and intrusive rocks with minor oolitic limestones. The lower part of this assemblage is dominated by mudstone represented by the Ashibetsugawa and Nae formations, while very thick trachyandesitic volcanoclastic rocks and micromonzonite prevail in the upper part represented by the Nakatengu and Nunobe formations and the Soashibetsu and Chikushidake micromonzonites.

3.b.1. Ashibetsugawa Formation

The Ashibetsugawa Formation, distributed only in the western Yubari Range (Fig. 4, columns 1–6), is comprised of red siliceous mudstone and occasionally intercalates with medium- to thick-bedded trachyandesitic or andesitic volcanic sandstones. The red siliceous mudstone of this formation conformably overlies the basaltic rocks of the Gokurakudaira Formation. The mudstone exhibits medium bedding, occasionally accompanied by thin beds of pale green mudstone. These mudstones have few trace fossils but many radiolarian fossils. The intercalated trachyandesitic/andesitic volcanic sandstones are dark grey to bottle green in colour and are turbidites showing the S_3 – T_{b-c} divisions of Lowe (1982). These sandstones contain poorly sorted lithic arenite, consisting mainly of trachyandesite or andesitic fragments (Table 2) with subordinate amounts of pumice, clinopyroxene, plagioclase, corroded quartz, opaque minerals and hornblende.

3.b.2. Nae Formation

The Nae Formation, distributed in the eastern Yubari Range and Nae areas (Fig. 4, columns 7–17), is represented by pale green to blue-green tuffaceous mudstone that intercalates with felsic–intermediate tuff and trachyandesitic or andesitic volcanic sandstone beds. The tuffaceous mudstone of this formation conformably covers the basalts of the Gokurakudaira Formation in both areas. The pale green tuffaceous mudstone beds are medium bedded and contain abundant radiolarian fossils. The porous, soft and pale green felsic–intermediate tuff beds, which are intercalated frequently in the middle part of this formation, are 5 to 20 cm thick.

3.b.3. Nakatengu Formation

The Nakatengu Formation, distributed in the western and eastern Yubari Range areas, is defined by a predominance of thick beds of trachyandesitic volcanoclastic breccias. The formation conformably overlies the Ashibetsugawa or Nae formations. Although this formation is distributed in both the western and eastern Yubari Range areas, the lithology differs slightly between these two areas. The trachyandesitic breccias in the western Yubari Range area do not include exotic fragments and have an E-to-W palaeocurrent direction, while those in the eastern Yubari Range area contain ample oolite limestone rubble and exhibit a W-to-E palaeocurrent direction.

3.b.3.a. Western Yubari Range area. The Nakatengu Formation in the western Yubari Range area conformably overlies the red mudstone of the Ashibetsugawa Formation and consists mainly of trachyandesitic

breccias–sandstones with one to seven intercalations of oolite limestone beds at the top (Fig. 4, columns 1–6). Basaltic breccias occur locally at the base of this formation (Fig. 4, columns 5–6).

The resedimented basaltic breccia intercalated at the base of this formation is thick- to very thick-bedded (0.3–4 m), consisting of massive, ungraded lower portions and thinner, normally graded tops. Subangular to subrounded fragments of basalt and dolerite of boulder to granule sizes are contained in a red granule matrix. The basalt fragments are similar to those of the Gokurakudaira Formation, consisting mainly of aphyric basalt with minor picrite.

Trachyandesitic volcanoclastic breccia and sandstone are the major components of this formation (Fig. 5c). The breccias have well-developed stratification. Bed thickness ranges from 2 to 10 m, with the thickest reaching 50 m. These beds of poorly sorted lithic rudaceous arenite are bluish-green in colour, and are composed mainly of trachyandesite rubble (smaller than 2 cm; Table 2), idiomorphic plagioclase grains and pumice, with subordinate amounts of idiomorphic clinopyroxene grains and rip-up clasts of red or pale green mudstone (Fig. 6c). The fabric of the rip-up clast indicates that the palaeocurrent of the breccias was roughly E to W.

Stratified grey oolite limestones are intercalated at the top of this formation. These limestones consist mainly of ooids (70–95 % in volume), with subordinate amounts of trachyandesite fragments, mineral grains and fossils (benthic foraminifera, fragments of coral, algae, echinoids and bivalves), in order of decreasing abundance (Fig. 6d). The trachyandesite fragments are similar to those of the underlying breccia beds. The limestone beds range in thickness from 0.05 to 2.7 m and are turbidites exhibiting the T_{b-d} divisions of Lowe (1982).

3.b.3.b. Eastern Yubari Range area. The Nakatengu Formation in the Eastern Yubari Range area conformably covers the pale green tuffaceous mudstone of the Nae Formation. This formation is represented by several beds of resedimented breccia (Fig. 4, columns 7–12) ranging in thickness from 1 to 4 m, and exhibiting the R_3 – S_1 divisions of a high-density turbidite (Lowe, 1982). Angular to subangular fragments of blue-grey trachyandesite and subordinate amounts of grey oolitic limestone of boulder to granule size are contained in a grey matrix made of mineral grains, ooids and small fragments of trachyandesite. Microscopic observations have revealed that these trachyandesite gravels are plagioclase–clinopyroxene phyric trachyandesite (Table 2). The fabric of rudites roughly indicates palaeocurrent directions from W to E; this directional trend is opposite that of the Nakatengu Formation in the western Yubari Range area.

3.b.4. Soashibetsu Micromonzonites

Micromonzonite sheets intrude into strata lower than the Nakatengu Formation and attain a maximum thickness of 100 m in the Soashibetsu River section (Figs 3, 4, columns 1–5). These holocrystalline sheets exhibit intergranular texture and are composed of idiomorphic plagioclase, with minor amounts of granular opaque minerals, allotriomorphic quartz, hornblende and granular zircon, in order of decreasing abundance (Table 2). The major and trace compositions of the microdiorites are closely related to those of the trachyandesite fragments of the Nakatengu Formation.

3.b.5. Chikushidake Micromonzonite

The Chikushidake Micromonzonite is distributed only in the northern part of the Nunobe area and intrudes into the Gokurakudaira Formation in a N–S direction (Figs 3, 4, columns 4–18). The micromonzonite, unconformably overlain by the basal conglomerate of the Nunobe Formation, is grey to greenish-grey in colour and 220 m thick. The lateral extent can be traced meridionally for 1700 m. The micromonzonite is comprised of idiomorphic plagioclase and subordinate amounts of granular clinopyroxene, granular opaque minerals and allotriomorphic hornblende, in order of decreasing abundance (Table 2; Fig. 6e).

3.b.6. Nunobe Formation

This formation, distributed only in the Nunobe area, unconformably overlies the Chikushidake Micromonzonite and exhibits an upward-fining lithology from clast-supported basal conglomerate through sandstone to mudstone (Fig. 4, column 18).

The basal conglomerate overlies the Chikushidake Micromonzonite with irregular contacts (Fig. 5d), and is comprised of subrounded to rounded gravels. This conglomerate is clast supported, poorly sorted and structureless. The gravels consist mainly of plagioclase–clinopyroxene–phyric trachyandesite, with minor amounts of micromonzonite, oolite limestone, red–pale green mudstone and trachyandesitic volcanoclastic sandstone, in order of decreasing abundance. Gravels are generally 5–20 cm in the basal part and decreasing in size upwards. In the basal portion, this conglomerate occasionally contains large (1 to 3 m in size) blocks of oolite limestone. The oolitic limestone in the gravels is composed mainly of ooids with diameters of 1 to 4 mm and containing benthic foraminifera, gastropods, coral and bivalves, as well as fragments of the above-mentioned trachyandesite and some crystal grains derived from trachyandesite.

The conglomerate grades into laminated greenish/dark grey mudstone at a horizon approximately 87 m above the base through sandstone. The mudstone contains few radiolarian fossils.

3.c. Alkali basaltic rocks assemblage (middle part of the Upper Sorachi Group: the Ogurose Formation)

This rock assemblage is represented by the alkali basaltic rocks of the Ogurose Formation and the Naegawa dolerite and is distributed in the Nae and Nunobe areas (Fig. 4, columns 13–18).

3.c.1. Ogurose Formation

This formation consists mainly of pillow basalt with small amounts of basaltic breccia and mudstone. The pillow lobes are 0.5–1.50 m and contain vesicles (Fig. 5e). The pillow lobes of this formation are distinguishable from those of the Gokurakudaira Formation by their larger size and vesicles. The breccias consist mainly of bottle-green basalt and dolerite rubble mixed with subordinate amounts of reddish, fine-grained matrix. The basalts are aphyric and consist of plagioclase, clinopyroxene and opaque minerals (Table 2); chemical analysis has revealed that these basalts are low-K₂O-type alkali basalt (Niida, 1992).

The intercalated mudstones can be classified into the following two types: a pale green to grey tuffaceous mudstone and a dark-grey coloured mudstone containing plant fragments.

3.c.2. Naegawa dolerite sheet

The Naegawa dolerite sheet is intruded within various horizons of the Ogurose Formation in the Nae area. The sheet extends a distance of 7 km in a N–S direction and is approximately 200 m thick (Fig. 3). These dolerites have an ophitic texture and consist mainly of hypidiomorphic clinopyroxene and idiomorphic plagioclase with lesser amounts of hypidiomorphic to granular opaque minerals and allotriomorphic hornblende, in order of decreasing abundance (Table 2; Fig. 6f). Chemical analysis of the major bulk rocks shows a correspondence to low-K₂O-type alkali basalts (Niida, 1992), similar to the pillow lava of the Ogurose Formation.

3.d. Tuffaceous mudstone rocks assemblage (upper part of the Upper Sorachi Group: the Shirikishimanaigawa Formation)

Represented by the Shirikishimanaigawa Formation, this rock assemblage is marked by the predominance of tuffaceous mudstone and the lack of *in situ* igneous rocks in the Sorachi–Yezo Belt.

3.d.1. Shirikishimanaigawa Formation

The Shirikishimanaigawa Formation covers the trachyandesitic rock assemblage in the western and eastern Yubari Range areas directly (Fig. 4, columns 1–12) and overlies the alkali basaltic rock assemblage in the Nae and Nunobe areas (Fig. 4, columns 13–18).

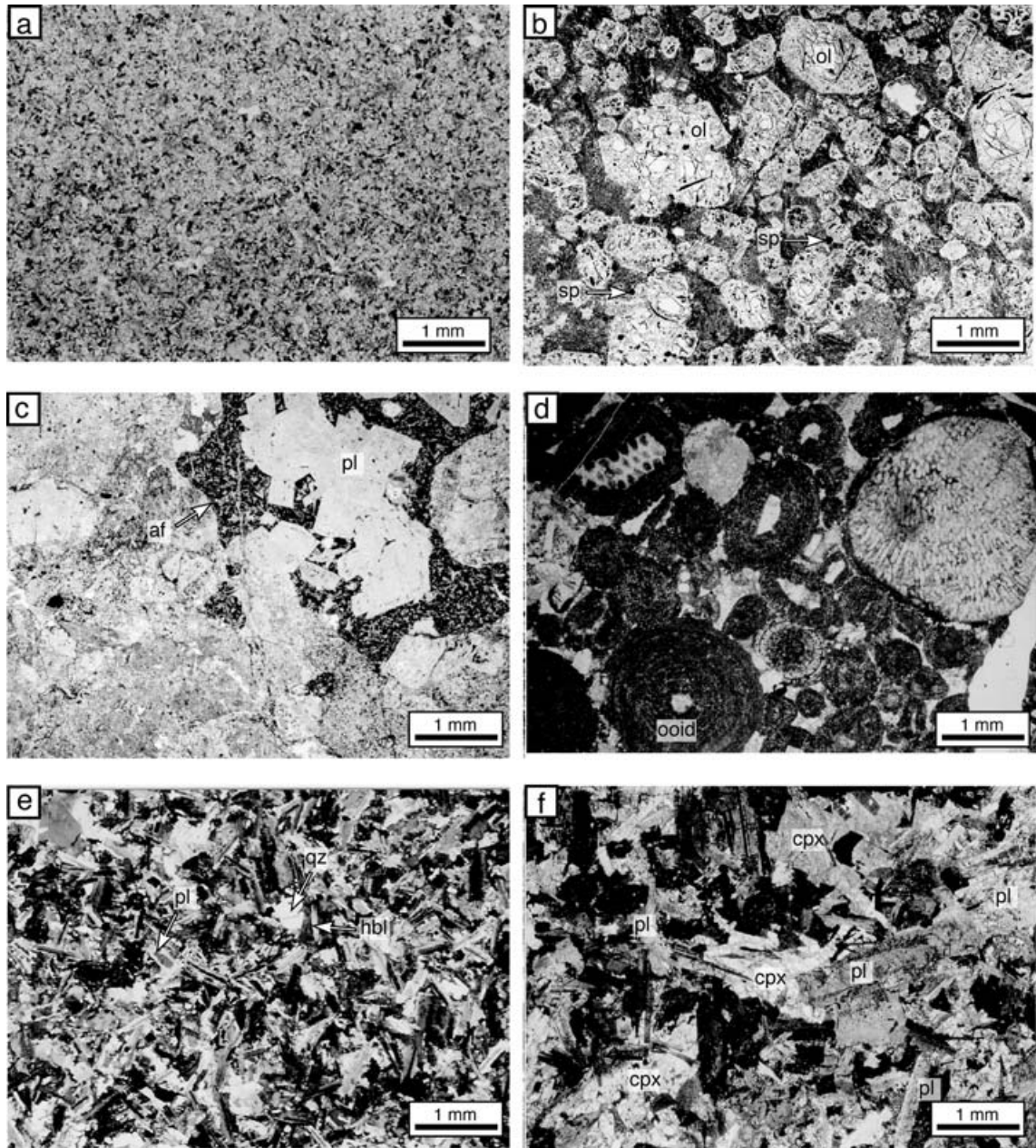


Figure 6. Microscopic photograph of representative rocks of the Sorachi Group. a – aphyric basalt (plane polarized light); Gokurakudaira Formation, Panketeshimanai River, Nae area. b – picrite (plane polarized light); Gokurakudaira Formation, Soashibetsu River, western Yubari Range area. c – trachyandesitic volcanic breccia (plane polarized light); Nakatengu Formation, Shuparo River, western Yubari Range area. d – oolite limestone (plane polarized light); Nakatengu Formation, Ashibetsu River, western Yubari Range area. e – micromonzonite (crossed polars); Chikushidake Micromonzonite, Nunobe River, Nunobe area. f – dolerite (crossed nicols); Naegawa Dolerite, Panketeshimanai River, Nae area. Ol – olivine; sp – spinel; af – trachyandesite fragment; bt – biotite; pl – plagioclase; qz – quartz; cpx – clinopyroxene; hbl – hornblende.

Although this formation is mainly made up of pale green tuffaceous mudstone and felsic tuffs, andesitic volcanic, calcareous and terrigenous turbidite sandstone beds occur in the upper part. Their palaeo-current direction is from NE to SW.

The pale green tuffaceous mudstones are usually medium-bedded and contain abundant radiolarian fossils (Fig. 5f). The mudstone is frequently intercalated with felsic tuff beds ranging from 10 cm to 1 m in thickness.

The andesitic volcanic sandstones are frequently intercalated in the upper part of this formation in the western and eastern Yubari Range areas (Fig. 4, columns 1–12). The sandstones are poorly sorted lithic arenite, consisting mainly of idiomorphic plagioclase and corroded quartz with subordinate amounts of andesite fragments (Table 2), clinopyroxene, hornblende and pumice. The volcanic sandstones are generally 10 to 30 cm thick and exhibit well-developed stratifications and graded bedding.

Terrigenous sandstone beds and dark grey mudstones occur in the southern part of the western Yubari Range and Nae areas (Fig. 4, columns 5–6, 13–17). These sandstone beds are blue-grey in colour and range in thickness from 0.3 to 2 m. They are medium-grained and well-sorted quartz arenite, consisting of rounded quartz, feldspar, wood fragments, opaque minerals, microcline and zircon, in order of decreasing abundance.

4. Radiolarian biostratigraphy of the Sorachi Group

The Sorachi Group contains numerous well-preserved radiolarian fossils, as detailed by a number of radiolarian biostratigraphic studies (Kito, 1987, 1995; Kito *et al.* 1986; Minoura *et al.* 1982; Okada *et al.* 1991; Takashima, Nishi & Yoshida, 2001). From examining various areas in Hokkaido, these studies have identified three datum planes within the Sorachi Group. In ascending order, these planes are represented by the first occurrence of *Pseudodictyomitra carpatica*, the first occurrence of *Cecrops septemporatus* and the last occurrence of *C. septemporatus* (e.g. Kito, 1987, 1995; Takashima, Nishi & Yoshida, 2001). These planes correlate to Kimmeridgian–Tithonian, Late Valanginian and Early Barremian times, respectively (Baumgartner *et al.* 1995).

Figures 2 and 4 illustrate the three datum planes. The first occurrence of *P. carpatica* coincides with the middle of the Hachimoriyama Tuff Member in the western Yubari Range, the lower Nae Formation in the eastern Yubari Range area and the upper Nae Formation in the Nae area. The first occurrence of *C. septemporatus* is associated with the lower part of the Shirikishimanaigawa Formation in the western and eastern Yubari Range and Nunobe areas, as well as with the upper Ogurose Formation in the Nae area. The last occurrence of *C. septemporatus* was identified in the middle to upper Shirikishimanaigawa Formation in all areas. The basal part of the Yezo Group was correlated with the lower Aptian, based on the integrated stratigraphy of planktonic foraminifera, radiolaria and carbon isotope ratios (Ando *et al.* 2002, 2003; Takashima *et al.* 2004).

According to the above data, the four rock assemblages of the Sorachi Group (tholeiitic basaltic rock, trachyandesitic rock, alkali basaltic rock and tuffaceous rock assemblages, in ascending order) were correlated with Kimmeridgian–Tithonian, Berriasian, Valanginian and Hauterivian–Barremian, respectively.

5. Discussion: Late Jurassic–Early Cretaceous geodynamic evolution of the eastern Asian continental margin

The Early Cretaceous reconstruction map shown in Figure 7 was based on the palaeomap by Tazawa (2004) and Sakashima *et al.* (2003), considering the

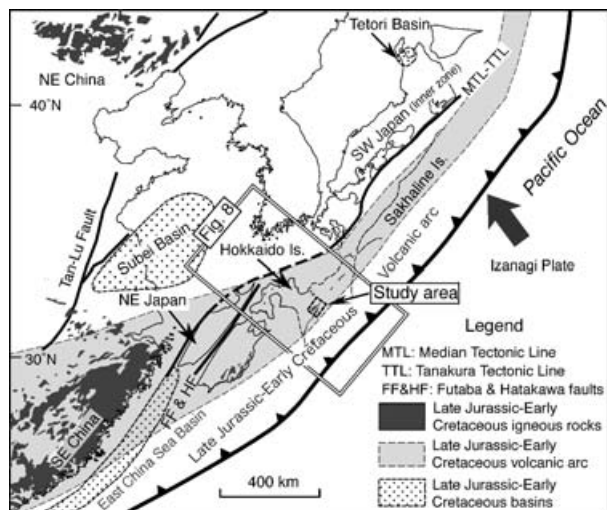


Figure 7. Early Cretaceous reconstruction map of the eastern Asia.

palaeomagnetic reconstructions of the N–S China Block (Enkin *et al.* 1991; Kirillova, 2003b; Meng, 2003; Ren *et al.* 2002; Zorin, 1999). The Valanginian palaeolatitude of $31.5^{\circ} \text{N} \pm 5^{\circ}$ in the Nae area, derived from the palaeomagnetic data of the Naegawa dolerite (Hoshi & Takashima, 1999), coincided with the relative position on this palaeomap. The Sorachi Group is thought to have formed along a series of volcanic zones that extended from southeastern China. Based on combined lithostratigraphic and biostratigraphic correlations, the volcanic and sedimentary phases represented by the Sorachi Group can be divided into four stages, as outlined below (Fig. 8).

5.a. Stage I (Kimmeridgian–Tithonian: sea-floor spreading)

This stage was characterized by a predominance of BABB (back-arc basin basalt)-like tholeiitic basalts, represented by the Gokurakudaira Formation (e.g. Takashima, Yoshida & Nishi, 2002). The terrigenous and dacitic–trachyandesitic volcaniclastic turbidites supplied from the Asian continental margin were deposited only in the western Yubari Range area (Fig. 8, a.1). Takashima, Yoshida & Nishi (2002) subdivided this period into three stages: (1) rifting along the fore-arc, (2) sea-floor spreading and (3) post-spreading based on the petrological data of the Gokurakudaira Formation.

According to Okada (1999), extensive rift basins, such as the East China Sea and Subei and Tetori basins, formed along the eastern margin of the Asian continent during this period (Fig. 7). Furthermore, contemporaneous continental extension accompanied by a large amount of volcanism occurred in SE China (e.g. Li *et al.* 2004; Jiang *et al.* 2005), NE China (Ren *et al.* 2002; Meng, 2003) and SE Russia (Kirillova, 2003a, b). Based on the geochemical and

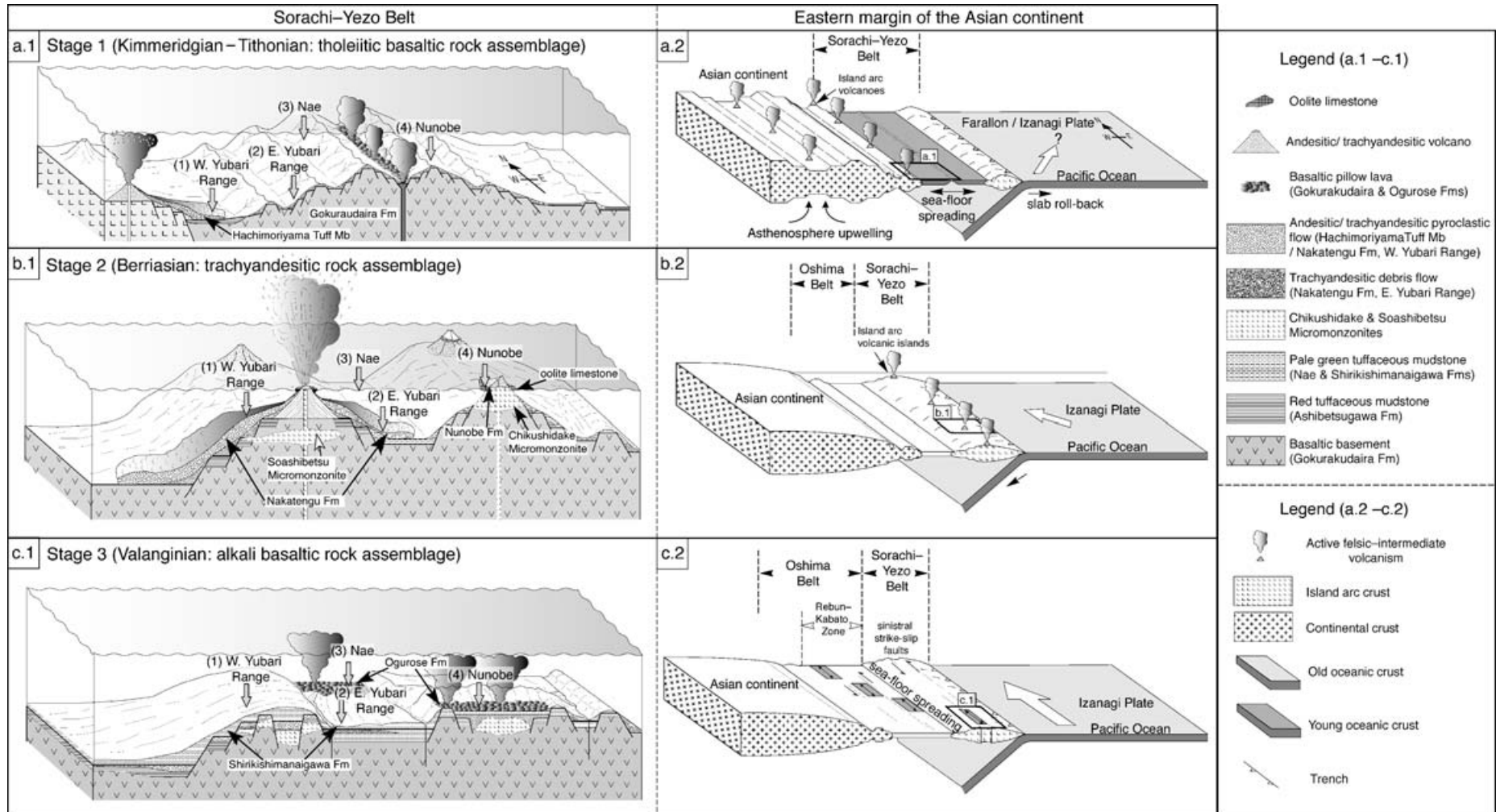


Figure 8. Schematic geodynamic evolution models during the Late Jurassic to Early Cretaceous interval. (1) Sorachi–Yezo Belt; (2) eastern margin of the Asian continent.

isotopic signatures of the upper Jurassic igneous rocks, these regions are thought to have experienced rapid lithospheric extension and thinning, associated with the geothermal elevation due to upwelling of the asthenosphere (Sewell & Campbell, 1997; Meng, 2003; Li *et al.* 2004).

The oceanic plate stratigraphy reconstructed from the Mesozoic accretionary complex in Hokkaido (Oshima Belt and Kamuikotan Zone) indicates that the subducting Pacific oceanic plate (probably the Farallon and/or Izanagi plates) was *c.* 100–140 million years old during the Jurassic–Early Cretaceous period (e.g. Ueda & Miyashita, 2005). This age is considered to be old enough to cause trench roll-back (Molnar & Atwater, 1978). Contemporaneous relative motion of the Farallon Plate against the Asian continent is considered to have occurred in an ocean-ward (northeastward) direction, although the velocity was only 1 cm per year in the ocean-ward component (Engebretson, Cox & Gordon, 1985). Both the trench roll-back and ocean-ward direction of the subducting oceanic plate may have caused rapid extension of continental crust and upwelling of the asthenosphere along the eastern margin of the Asia during Late Jurassic times (Fig. 8, a.2).

5.b. Stage II (Berriasian: formation of island-arc volcanic islands)

Stage II is defined by the predominance of trachyandesitic volcano-sedimentary rocks (Fig. 8, b.1). Trachyandesitic volcanism climaxed in the latter part of this stage, as represented by the Nakatengu and Nunobe formations and the Chikushidake and Soashibetsu micromonzonite sheets. Palaeocurrent data suggest that the trachyandesitic volcaniclasts of the Nakatengu Formation flowed from the east into the western Yubari Range area and from the west in the eastern Yubari Range area. These flow directions indicate that the main volcanic body was located between the western and eastern Yubari Range areas. The Chikushidake Micromonzonite and Nunobe Formation suggest that another trachyandesite volcano formed in the Nunobe area. Both volcanoes may have emerged above the sea surface, as suggested by the accompanying oolitic limestone.

The relative plate motion of the Pacific oceanic plate against the Asian continent (that is, the Izanagi Plate) changed from ocean-ward (northeastward) to continent-ward (northwestward) during the period (Engebretson, Cox & Gordon, 1985; Fig. 8, b.2). Trachyandesitic igneous rocks with typical island-arc affinities (high LILE/HFSE ratio and negative anomaly in Nb, described by Takashima *et al.* 2002) might have influenced the subducting slab of the Izanagi Plate.

5.c. Stage III (Valanginian: rifting and sea-floor spreading)

Rifting and submarine basaltic volcanism characterize this stage (Fig. 8, c.1). The emerged trachyandesitic

volcano subsided into the deep marine region, and basaltic andesitic pillow lava, represented by the Ogurose Formation, erupted in the Nunobe area. Although the Nae area remained in the deep marine environment following Stage I, voluminous basaltic pillow lava erupted contemporaneously. However, no volcanism occurred in the western and eastern Yubari Range areas, where tuffaceous mudstones of the basal Shirikishimanaigawa Formation continued to accumulate.

The Izanagi plate turned northward and subducted obliquely under the Asian continent (Fig. 8, c.2). Niida (1992) noted that the igneous rocks of the Ogurose Formation are alkali basalt with a high Na₂O/K₂O ratio that occurs in restricted areas of the transform boundary. These characteristics suggest that the initiation of sinistral strike-slip movement behind the trench caused the basaltic volcanism subsequent to rifting. Contemporaneous submarine basaltic volcanism occurred in the Rebus–Kabato Zone. The formation of pull-apart basins accompanied by sea-floor spreading resembles that of the modern Andaman arc setting.

5.d. Stage IV (Hauterivian–Barremian: cessation of *in situ* volcanism)

In situ volcanism in the Sorachi–Yezo Belt was extinct after this stage, which is represented in all study areas by a predominance of tuffaceous mudstone of the Shirikishimanaigawa Formation. The andesitic tuffs and volcanogenic sandstones are thought to have been supplied from the Rebus–Kabato Zone of the western Oshima Belt after the later part of this stage (Kiminami *et al.* 1992). A westward shift of the volcanic front from the Sorachi–Yezo Belt to the Oshima Belt might have occurred in this stage.

Sinistral strike-slip faults, such as the Tan–Lu Fault, developed extensively in the eastern margin of Asian continent after Hauterivian times (e.g. Okada, 1999). This sinistral strike-slip movement may have disrupted the accretionary complex growth, formed numerous half graben, and uplifted metamorphic belts along the supra-subduction zone (Takahashi & Matsukawa, 2000). The drastic change in the facies from the submarine volcano-sedimentary successions of the Sorachi Group to the terrigenous successions of the Yezo Group suggests the influence of the above-mentioned geodynamics.

6. Summary

The Late Jurassic–Early Cretaceous period was characterized by the significant reconfiguration of oceanic plate movement in the NW Pacific. The Upper Jurassic ophiolite and Lower Cretaceous island-arc volcano-sedimentary covers of the Sorachi Group were formed within the island-arc setting off the eastern margin of the Asian continent. Therefore, the group records the volcanism and sedimentation associated with the

changing movement of the subducting oceanic plate during that interval. Stratigraphic changes in the nature and volume of volcanic and volcanoclastic rocks of the Sorachi Group indicate four tectonic stages.

Stage I was characterized by extensive submarine eruptions of BABB-type-tholeiitic basalt. Slab roll-back caused rifting and sea-floor spreading of the supra-subduction zone along the active Asian continental margin during this stage.

Stage II has been dated to the Berriasian and included localized trachyandesitic volcanism that formed volcanic islands with chemical compositions typical of island-arc settings. The direction of the Pacific oceanic plate movement shifted from northeastward to northwestward at the beginning of this stage.

Stage III, in the Valanginian, was characterized by submarine basaltic volcanism followed by subsidence. The Pacific oceanic plate motion turned clockwise, and plate conjugation between the Asian continent and the Pacific oceanic plate changed from a convergent to a transform boundary. The formation of pull-apart basins accompanied by sea-floor spreading was similar to that of formations occurring in the modern Andaman arc setting.

Stage IV coincided with the Hauterivian–Barremian. In this stage, *in situ* volcanism ceased in the Sorachi–Yezo basin, and the volcanic front migrated from the Sorachi–Yezo Belt to the Oshima Belt. This sinistral strike-slip movement is thought to have disrupted growth of the accretionary complex, and formed numerous half graben and uplifted metamorphic belts along the supra-subduction zone in the eastern margin of the Asian continent.

Acknowledgements. We express sincere gratitude to Professors Tunemasa Saito, Keiichi Shiraki, Jun-ichi Kimura and Taniel Danelian for helpful suggestions, and Laurent Jolivet and A. J. Barber for helpful reviews, which improved the paper considerably. We also thank Ikuo Takahashi, Yasunori Miyamoto, Shigeaki Kamota (Tokyo University), Kazuo Kobayashi, Kou Takashima and Koichi Matsuda for support during our fieldwork. This study was supported financially by the JSPS Research Fellows Scheme (No. 07622), 21st Century Center of Excellence (COE) Program on ‘Natural History’ at Hokkaido University.

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