*Precambrian Ophiolites and Related Rocks*
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*Chapter 1*

# THE JORMUA OPHIOLITE: A MAFIC-ULTRAMAFIC COMPLEX FROM AN ANCIENT OCEAN-CONTINENT TRANSITION ZONE

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The Jormua Ophiolite is an allochtonous mafic-ultramafic rock complex, thrusted onto the Karelian Craton margin, that formed within a passive margin environment $\sim 100$ km southwest from its present position. This complex consists of two distinct units: (1) fragments of Archean subcontinental lithospheric mantle that became exposed from beneath the Karelian craton by detachment faulting following the final break-up of the craton, and (2) alkaline and tholeiitic igneous suites that were emplaced within and through the lithospheric mantle at $\sim 2.1$ Ga and 1.95 Ga, respectively.

At the prerift stage of continental breakup (c. 2.1 Ga), residual lithospheric peridotites became intruded by alkaline melts that formed “dry” clinopyroxene cumulate dikes. Slightly later, this same piece of mantle became extensively intruded by hydrous alkaline magmas that resulted in formation of high-pressure hornblendite-garnetite cumulates deep in the ophiolite stratigraphy and fine grained OIB-type dikes at more shallow levels. Simultaneously, the residual peridotites became metasomatized due to porous flow of the melt in the peridotite matrix. Alkaline magmatism was soon followed by lithospheric detachment faulting that exposed the subcrustal peridotites at the seafloor, where they at 1.95 Ga became covered by tholeiitic (EMORB) pillow and massive lavas and intruded by coeval dikes and gabbros.

Since transitional contacts between all main ophiolite units can be demonstrated, the Jormua Ophiolite Complex is interpreted to represent a practically unbroken sample of seafloor from an ancient ocean-continent transition (OCT) zone, strikingly similar to that reported from younger similar tectonic settings, such as the Cretaceous West Iberia nonvolcanic continental margin.

## 1. INTRODUCTION

Though included only as a connotation in the current *de facto* ophiolite definition (Anonymous, 1972), it is generally accepted that ophiolite complexes represent fragments of oceanic lithosphere that formed in a number plate tectonic settings (oceanic spreading ridges, island arcs, back arc basins, leaky transforms, nascent ocean basins, etc.). The

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special importance of Precambrian ophiolites is that their presence or absence in the rock record is usually considered one of the critical evidences for or against operation of modern type plate tectonism in Precambrian. In addition, the chemical composition of associated basalts provide an uncontaminated window into the Precambrian convective mantle, and in rare cases—such as Jormua—the petrology of the mantle rocks can be studied *in situ* from excellent outcrops. The 1.95 Ga Jormua complex was the first early Proterozoic ophiolite ever reported (Kontinen, 1987). Since then a few early Proterozoic and even Archean ophiolites have been discovered and described but still their number is notably low (Scott et al., 1992; Dann, 1991; Kusky et al., 2001).

Being in many respects similar to the Northern Apennines ophiolites (e.g., Rampone and Piccardo, 2001) and sharing several of the salient features of the modern ocean-continent transition zones (Louden and Lau, 2001) the Jormua Ophiolite Complex has been interpreted as a break-up-related “passive margin ophiolite” (Kontinen, 1987; Peltonen et al., 1996, 1998). It is made up of two components of distinct origin: (a) subcontinental ($> 2.8$ Ga) lithospheric mantle (SCLM) component, and (b) asthenospheric component that consists of remnants of the 1.95 Ga mantle diapir and various types of igneous rocks emplaced within and through the mantle tectonites $\sim 1.95$–2.1 Ga. Thus, the main importance of Jormua for understanding the evolution of Precambrian plate tectonic processes is the evidence it provides of continental rifting and break-up related tectonic and magmatic processes. The other ophiolitic rocks in Finland—the Outokumpu and Nuttio complexes (Fig. 1)—which appear to share the same large-scale tectonic setting along the Karelian Craton margin, provide us samples from more mature oceanic basin and island-arc setting, respectively (Koistinen, 1981; Vuollo and Piirainen, 1989; Hanski, 1997). Together, in a synthesis that remains to be compiled, these occurrences provide a tantalizing opportunity to interpret the break-up of the Karelian Continent, and the igneous processes that took place in the Svecofennian ocean from its birth until its closure.

This contribution is intended to be a compact overview of the geology of the Jormua Ophiolite Complex and a state-of-art summary of what is known and inferred about its genesis. Emphasis is placed on the field description of the main ophiolite units. Chemical and isotopic compositions of both the crustal and mantle rocks have extensively been recently described elsewhere (Peltonen et al., 1996, 1998) and only some salient points shall be touched in this context. For the same reason no analytical data is included. There are still many lines of research that have not yet been applied to this rare piece of ancient oceanic and continental lithosphere. We encourage more research on Jormua so that more of its messages from the geological past will be revealed. In the meantime, we believe that the tectonic framework upon which the future work will bounce is already well established.

## 2. THE REGIONAL SETTING OF THE JORMUA OPHIOLITE COMPLEX

The Jormua Ophiolite Complex is the northernmost and the most completely preserved example of the ophiolite fragments within the Paleoproterozoic North Karelia Schist Belt

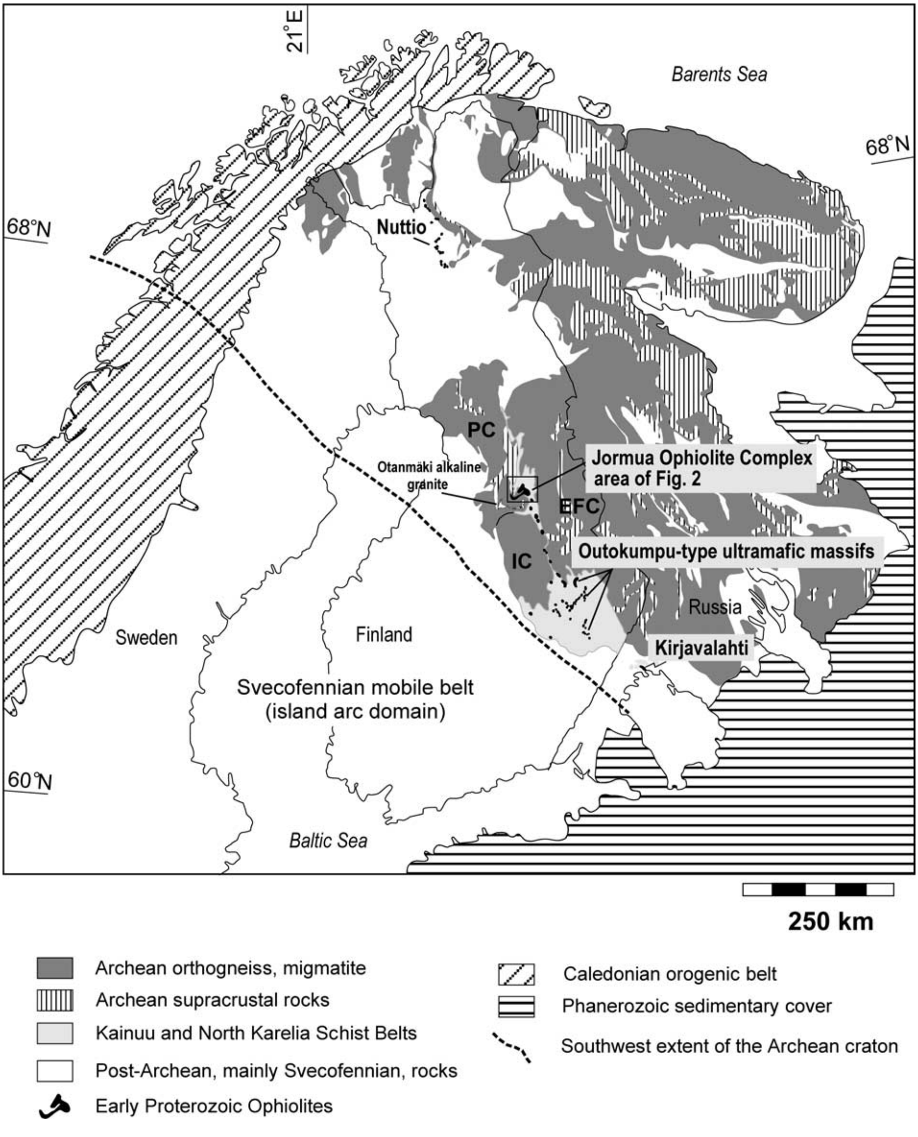


Fig. 1. Geological map of the eastern part of the Fennoscandian Shield emphasizing the location of the Jormua Ophiolite Complex and other early Proterozoic ophiolite fragments. Archaean blocks: PC = Pudasjärvi Complex; IC = Iisalmi Complex; EFC = Eastern Finland Complex. Modified from Koistinen et al. (2001) and Hanski (1997).

and the Kainuu Schist Belt in the central part of the Fennoscandian Shield (Fig. 1). These two Paleoproterozoic schist belts, which consist mainly of 2.3–1.90 Ga metasediments (grouped under the term Karelian in the Finnish literature), are located 0–100 km to the east of the suture between their Archaean basement structure (Karelian Craton) and the 1.93–1.80 Ga Svecofennian island arc domain (Fig. 1). Approximately 1.9 Ga ago the southwest margin of the Karelian Craton was covered by thrusted allochthonous complexes and deformed by the related compressional and subsequent wrench/thrust tectonics. The thrusting took place before the D1 deformation as a response to the collision between the Karelian Craton and the cratonized Svecofennian arc collage (Gaál and Gorbatschev, 1987; Kärki and Laajoki, 1995; Kohonen, 1995; Korsman et al., 1999). The thrust belt contains a 200 km long chain of ophiolite fragments whose distribution is related to the early thrusting, further modified by the later multistage regional deformation (Koistinen, 1981; Kontinen, 1987; Kärki and Laajoki, 1995).

The Kainuu Schist Belt that encloses the Jormua Ophiolite occupies a structural depression between two rigid blocks of the basement structure: the Eastern Finland Complex and Pudasjärvi-Iisalmi Complexes (Fig. 1). The belt is up to 30 km wide but nowhere more than 2–3 km thick on the basis of structural and gravimetric data. It thus represents a relatively thin veneer of faulted and folded autochthonous and allochthonous supracrustal rocks and ophiolite fragments on the thick Archaean basement structure. The belt is dissected by a folded N-S trending strike-slip fault zone along which the Archean basement blocks have moved both vertically and horizontally (Kärki and Laajoki, 1995).

The central part of the Kainuu Schist Belt around the Jormua Ophiolite comprises three major unconformity or thrust-bound lithofacies: (1) the autochthonous, cratonic to epicratonic Jatuli (2.3–2.1 Ga) sequence, consisting predominantly of quartzites derived from fluvial to shallow marine, mature quartz-rich sands; (2) the 2.1–1.95 Ga rift-phase related "lower Kaleva" assemblage, characterized by metaturbiditic conglomerates, quartz wackes, graywackes and shales, as well as turbidite-hosted P-Mn-C-rich silicate-carbonate iron formations and abundant, metal-rich (Cu, Ni, Zn) graphitic black schists; and (3) the allochthonous "upper Kaleva" sequences, dominated by deep marine metaturbiditic graywacke-shale deposits whose depositional age is bracketed by the age of the Jormua ($\sim$ 1.95 Ga; Peltonen et al., 1998) and the youngest detrital zircon SHRIMP ages of $1.92 \pm 0.12$ Ga (Claesson et al., 1993). Many of the detrital zircons in these "upper Kalevian" metagraywackes are thus younger than the mafic sequence of the Jormua Ophiolite. The Jatulian mature arenites, and the "lower Kalevian" sequence, which are presumably rift-related deposits contain mainly recycled Archean detritus, whereas the younger, flysch-like "upper Kalevian" metagraywackes and shales contain also abundant Proterozoic material.

An additional important geological unit, probably closely related to the origin of the Jormua Ophiolite Complex, is the $\sim$ 1.96 Ga Otanmäki gneissic, peralkaline-alkaline A-type granite to the SSW of Jormua (Fig. 1). These granites have intruded Archaean gneisses and Jatuli-type cover sediments and are present as a narrow strongly foliated tectonic slice. At their southern margin the Otanmäki gneissic granites are in a faulted contact with the rocks of the Kainuu Schist Belt and the Archaean rocks of the Iisalmi Complex. We are tempted to believe that the Otanmäki gneissic alkaline granite is an allochthonous unit not belonging to the basement structure of the Kainuu Schist Belt.

## 3. PRINCIPAL FEATURES OF THE MAIN BLOCKS

The earliest stages of the Svecofennian deformation, related to the early tectonic processes that contributed to the detachment of the Jormua Ophiolite Complex from oceanic environment and its subsequent thrusting across the foreland, involved tectonic disruption of the original ophiolite assemblage. Consequently, the Jormua Ophiolite now consists of four major fault-bounded blocks (Fig. 2), which represent diverse parts through the ancient ocean-continent transition zone (Peltonen et al., 1996, 1998). Extensive shearing along the Kainuu Schist Belt in the latest stages of the Svecofennian tectonism (Kärki and Laajoki, 1995) and associated parasitic faulting and folding further disrupted and deformed the ophiolitic blocks, some of which now have forms of shear-controlled "mega-augens". The salient characteristics of these blocks are summarized in Table 1.

The *eastern block* consists of several fault-bounded slices of serpentinized mantle tectonites (mainly harzburgites) and minor dunitic pods, some of which enclose small nodular- and orbicular-textured podiform chromitite lenses. Mantle peridotites have been intruded by gabbro stocks and basaltic sheeted dike complexes. The eastern block is practically the only block that is associated with the extrusive seafloor sequence. Reconstructed stratigraphy of the ophiolite suggests that the dike complex and locally also mantle peridotites are directly overlain by metabasaltic pillow lavas intercalated with some massive lavas and pillow breccias. According to diamond drilling data the pillow lavas at the western margin of the eastern block are overlain by basic tuffs intercalated with sedimentary carbonates. These metatuffs are—at least in a tectonostratigraphic sense—overlain by the typical upper Kaleva metaturbiditic black shales and graywackes. Thus, in terms of igneous stratigraphy, the eastern blocks expose the most complete ophiolite within the Jormua igneous complex.

The *northern block* is scantily exposed and hence the least studied of the Jormua blocks (Fig. 2). Nevertheless, the presently available data suggests that this block is fairly similar with the eastern block. The main exposed components are mantle tectonites, gabbroic feeder dikes, and more extensive gabbro-diorite intrusions and some massive metabasaltic amphibolites, probably of sheeted dike origin. Highly altered, epidote and iron sulfide-rich gabbros are known from one locality.

The *central block* resembles the eastern block in some respects but several fundamental differences are evident (Table 1). Both extrusive rocks and gabbroic pods and dikes are uncommon within the central block. Instead, the mantle tectonites have been intruded by abundant fine grained EMORB dikes. The abundance of these dikes progressively increases from NW to SE (Fig. 2). In the northwest single anastomosing dikes intrude peridotites. In the following, these dikes are referred to as "deep dikes" because of their apparent location deep in the ophiolite stratigraphy. Towards southeast "deep dikes" gradually coalescence into thicker units finally forming a spectacular sheeted dike complex with only rare inter-dike screens of mantle peridotites or gabbro. The mantle peridotites (serpentinites) of the

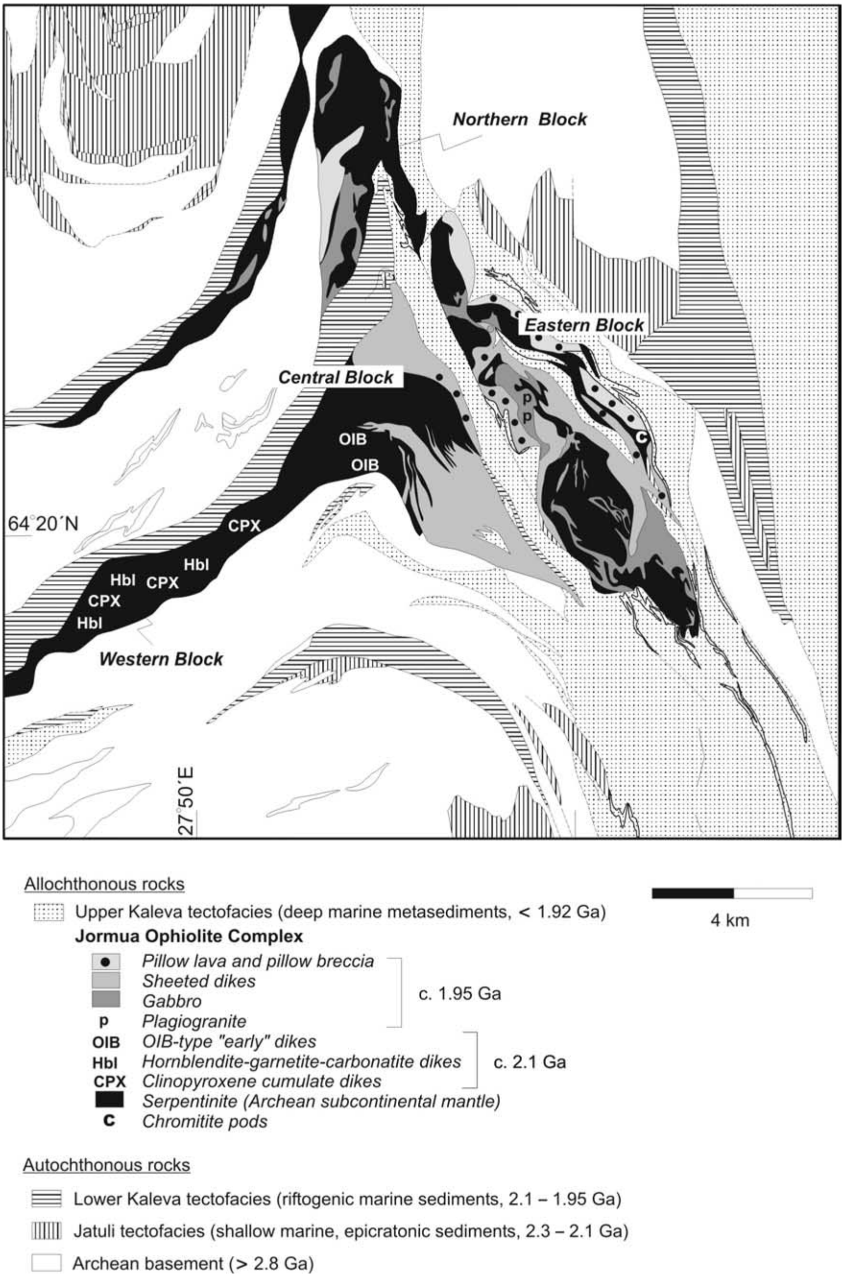


Fig. 2. Geological map of the Jormua Ophiolite Complex. Modified after Kontinen (1998).

Table 1. Characteristics of the Jormua Ophiolite complex

| Rock type | Western block | Central block | Eastern block | Northern block |
|---|---|---|---|---|
| *Crustal units* | | | | |
| Extrusive unit | − | − | ++ | + |
| Sheeted dike complex | − | ++ | ++ | + |
| Gabbros/plagiogranites | − | − | ++ | + |
| Ultramafic cumulates | − | − | ? | − |
| *Intrusive to mantle tectonites* | | | | |
| EMORB-dikes | ? | ++ | ++ | + |
| Gabbroic feeder dikes | − | + | ++ | + |
| Chromitite pods | − | − | + | − |
| OIB-type dikes | ? | + | − | − |
| Clinopyroxenite mantle dikes | ++ | + | − | − |
| Hornblendite mantle dikes | ++ | − | − | − |
| Garnetite veins | + | − | − | − |
| Carbonatitic veins | + | − | − | − |
| *Mantle tectonites* | | | | |
| Lherzolites ($> 3$ wt% $Al_2O_3$) | + | − | + | ? |
| Depleted lherzolites ($1 \leqslant Al_2O_3 \leqslant 3$ wt%) | ++ | ++ | ++ | + |
| Harzburgites and dunites ($< 1$ wt% $Al_2O_3$) | − | + | + | + |

+, present; ++, abundant; −, absent.

central block are intruded by an additional generation of ultramafic-mafic dikes which are absent in the eastern block. These dikes, which have OIB-type geochemical characteristics and resemble ultramafic lamprophyres, are intruded by the more voluminous EMORB dikes and are therefore labelled as “early dikes”. While the EMORB dikes intersect the mantle tectonite foliation at high angles the general trends of the OIB-type dikes are subparallel. This clearly implies that EMORB and OIB magmas were emplaced during distinct episodes, and that between the emplacement of OIB and EMORB dikes, the tectonite foliation was rotated from subvertical to almost horizontal.

The contact between the *western block* and central blocks is unexposed. Thus, the possibility remains that they form a single long continuous sheet, but their significant internal differences suggest that this is probably not the case (Fig. 2). First, the western block is not associated with “upper Kaleva” graywackes, but instead is bounded by slices of the Archaean basement and rift-related “lower Kaleva” sediments. Second, the mantle peridotites are less depleted in their basaltic constituents and harzburgitic and dunitic residues are uncommon. Furthermore, gabbros, basaltic dikes and pillow lavas are absent from the western block. Instead, mantle peridotites are extensively intruded by clinopyroxenite and hornblendite dikes and pods representing igneous cumulates that crystallized in melt channels and pathways within the upper mantle. Isotopic data suggest that these cumulates are broadly coeval and closely related to the OIB-type dikes found in the central block

(Peltonen et al., 1998). Overall, the western block shares more common features with orogenic lherzolite massifs (i.e., subcontinental lithospheric mantle) than with true ophiolites.

## 4. RECONSTRUCTED STRUCTURE OF THE COMPLEX

Although the Jormua Ophiolite Complex has been tectonically disrupted into several distinct blocks, the reconstruction of the original igneous stratigraphy can be made with reasonable confidence. This is because transitional contacts between the main ophiolitic units, i.e., extrusive rocks, sheeted dikes complex, gabbros and mantle peridotites can be demonstrated in the field. A revised stratigraphic reconstruction for the Jormua Ophiolite Complex is presented in Fig. 3.

The upper part of the stratigraphic column is based on the geology of the eastern and central blocks of the Jormua Ophiolite Complex. The extrusive unit consists of pillow and massive lavas capped by some basic tuffite and sedimentary carbonates. The extrusive unit is relatively thin (0–400 m) and one may argue that locally lavas were deposited directly onto mantle tectonites exposed at the seafloor. In modern seafloor, mid-ocean ridges with mantle peridotite outcrops are characterized by slow spreading rates and deep axial valleys that are expected to form at magma-poor ridge regions where a substantial fraction of the oceanic lithosphere is made of tectonically uplifted mantle material (Cannat, 1993). Downwards in the stratigraphic section, pillow lavas occur as interdike screens within the uppermost sheeted dikes complex, and some dikes are present within the lava unit implying coeval formation of lavas and dikes. Thick mafic-ultramafic cumulate layers are absent from the Jormua Ophiolite Complex. This is, however, not because of incomplete preservation of the original sequence, but is a characteristic feature of slow spreading-ridge ophiolites where thick axial lithosphere prevents magma pooling at crustal depths. In Jormua, the sheeted dike complex is not rooted in the cumulates but instead is rooted in the mantle tectonites (Figs. 2 and 3). Going downwards the coherent sheeted dike complex gradually gives way to dike swarms with abundant mantle tectonite interdike screens and finally into sparse anastomosing basaltic dikes (“deep dikes”) intruding mantle tectonites. Furthermore, indirect evidence for the absence of large magma chambers in Jormua is provided by the geochemistry of the basalts; the analysed lava and sheeted dike samples cannot be related to each other by fractional crystallization processes but represent rather unmodified melt fractions which did not undergo fractionation at an intermediate magma storage (Peltonen et al., 1996). Isotropic gabbro (+ plagiogranite) pods characterize the middle section of the stratigraphic column (Fig. 3). Importantly, these gabbros are frequently cross-cut by sheeted dikes, but are *never* observed to intrude the dike complex. This suggests that gabbros and seafloor magmatism represent distinct magmatic episodes and that the U-Pb zircon ages provided by the gabbros give a maximum age for the seafloor volcanism. However, the absolute time difference is believed to be small, with the gabbro stocks being related to the initial stages of the continental rifting, while lavas and dikes record a slightly more advanced stage of the oceanization. Distinct types of gabbros are found beneath the large high-level gabbro-plagiogranite pods. These occur in the form subvertical dikes that

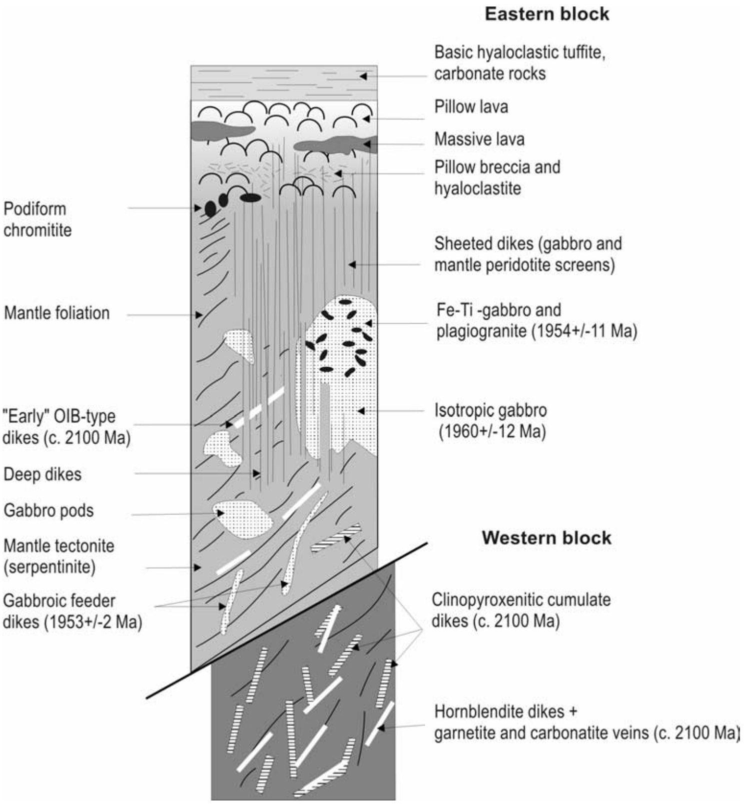


Fig. 3. Igneous stratigraphy of the Jormua Ophiolite Complex. Age data from Huhma (1986), Kontinen (1987), Peltonen et al. (1998), and Peltonen et al. (2003, unpublished).

intrude the mantle tectonites (hereafter: gabbroic feeder dikes). Their internal fractionation is indicative of them being feeder dikes for upper-level magmas. They have yielded equal crystallization age (1953 ± 2 Ma; Peltonen et al., 1998) with the gabbro stocks (1960 ± 12 Ma) and plagiogranites (1954 ± 11 Ma; Kontinen, 1987) and it is not evident whether they are comagmatic with high-level gabbro stocks or with sheeted dikes or lavas.

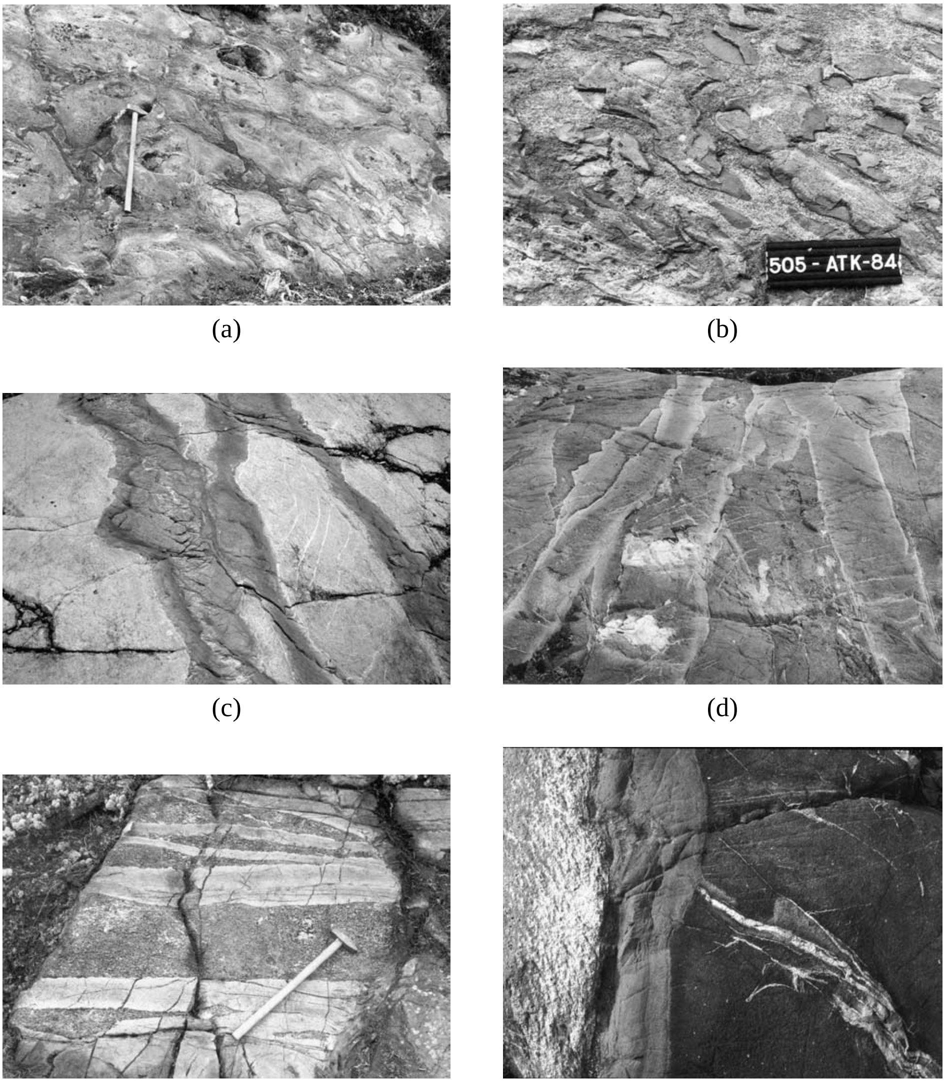
The lower part of the stratigraphic column refers to the western block of the complex. Since the western block is lithologically distinct from other blocks and the contact between the western and central block is unexposed a continuous stratigraphic column was not drawn. This part of the Jormua Ophiolite Complex does not resemble a true ophiolite but bears striking similarities with fragments of subcontinental lithospheric mantle (SCLM), such as orogenic lherzolite bodies of the French Pyrenees. Thus, the Jormua Ophiolite consists of two distinct parts; one similar to slow-spreading type ophiolites (oceanic lithosphere) and another that is similar to orogenic lherzolites (subcontinental lithospheric mantle). Importantly, juxtaposition of these parts is not coincidental since similar c. 1.95 Ga old dikes facies are present in both fragments. This suggests that these two distinct parts share a common history and led Peltonen et al. (1998) to suggest that as a whole the Jormua Ophiolite Complex records an almost continuous sequence across an ocean-continent transition (OCT) zone.

## 5. ALTERATION AND METAMORPHISM

Seafloor metamorphism, alteration during obduction and tectonic transport, and finally the Svecofennian regional metamorphism, have together resulted in extensive destruction of the primary mineralogy of the mafic and ultramafic lithologies of the Jormua Ophiolite. Fortunately, however, chemical changes with respect to most elements are far less pronounced. The metamorphic history of the ophiolite commenced already at the seafloor stage—evidence of which has mostly been lost by later imprints. Hydrothermal circulation on the seafloor resulted in alteration of basalts and veining of the basaltic dikes by albite-filled fractures (Fig. 4f). Lavas, in turn, are anomalously depleted in Fe, a feature that has been related to the seafloor weathering (Peltonen et al., 1996). It is not clear anymore to what extent the mantle peridotites were serpentinized at this stage. However, since the basaltic lid is thin in Jormua and field evidence suggests that some mantle tectonites were exposed at the seafloor, it is likely that mantle peridotites became at least partially serpentinized before obduction.

The alteration that took place during the obduction and tectonic transport is only poorly characterized. The serpentinization of the mantle tectonites continued due to their interaction with meteoric waters. This alteration proceeded at relatively low temperature conditions resulting in extensive replacement of olivine and pyroxenes by pseudomorphic lizardite and local carbonatization and silicification of the margins of the tectonite massifs. Basaltic and gabbroic dikes in contact with peridotites became rodingitized due to their interaction with serpentinizing fluids. This resulted in considerable loss of silica and alkalies from the dikes (Fig. 8) and replacement of the primary igneous mineral parageneses of the gabbro dikes by hydro-grossular garnet, diopside, epidote, and chlorite.

Much of the present mineral parageneses of the Jormua mafic and ultramafic rocks, however, represent the metamorphic equilibria attained during the Svecofennian regional metamorphism. Within the Kainuu Schist Belt metamorphism culminated under low-P high-T-type conditions in the amphibolite facies between 1.87 and 1.85 Ga. The cooling was a prolonged event and it was not until $\sim 1.80$ Ga that temperatures fell below 500 °C. Thus, the metamorphism significantly outlasted the deformation that was essentially over by 1.86 Ga (Tuisku, 1997). The metamorphic mineral paragenesis in the metabasalts typically is sodic plagioclase + actinolitic hornblende ± epidote ± chlorite. Due to the activity of $CO_2$-rich metamorphic fluids some lava samples became slightly depleted in LREE. This is evident in the Sm-Nd isochron diagram where basalt samples form an isochron with a slope corresponding to an age of $1.72 \pm 0.12$ Ga (Peltonen et al., 1996). The slope of this isochron is strongly controlled by the three pillow-lava samples having the most LREE-depleted patterns. Since this "errorchron" age is significantly less than the U-Pb zircon age ($\sim 1.95$ Ga)



(a) (b)

(c) (d)

(e) (f)

Fig. 4. Outcrops of (a) pillow lava, (b) pillow breccia, (c) “deep dikes”, i.e., EMORB dikes intruding mantle tectonites at the root zone of the sheeted dikes complex. Note the anastomosing shape of the dikes and the dark alteration selvages at their margins due to interaction with adjacent serpentinites (former residual mantle peridotites), width of the photo ∼ 2 m, (d) sheeted dikes complex with 100% dike-in-dike sets, width of the photo ∼ 3 m, (e) sheeted dikes with gabbro interdike screens, (f) “deep dike” with seafloor alteration-related albite veins overprinted by late alteration selvage between dike and enclosing mantle tectonite at left, width of the photo ∼ 30 cm. (f) Reprinted with the permission from Journal of Petrology, vol. 37, Oxford Univ. Press.

of the Jormua Ophiolite, or the age of the obduction ($\sim$ 1.90–1.87 Ga), it is clear that the LREE depletion of these three samples cannot be of igneous origin. In mantle tectonites, the regional metamorphism resulted in dehydration and replacement of the earlier low-T pseudomorphic lizardite serpentine by non-pseudomorphic antigorite serpentine. Present stable metamorphic parageneses of serpentinites are dependent on the bulk rock composition and include *antigorite* + *magnetite* and *antigorite* + *tremolite* + *magnetite* in the eastern and central block serpentinites. Olivine is added to the parageneses in the western block. On the basis of published mineral stability curves (e.g., Will et al., 1990) we estimate that these parageneses imply peak-metamorphic temperatures of approximately 480 and 530 °C for pressures of 2 and 5 kb, respectively, in the west and slightly lower temperatures in the east. As a result of nearly complete serpentinization, the analysed $H_2O_{(tot)}$-contents of peridotite samples now range between 9.4 and 12.0 wt%. However, since $SiO_2/MgO$ ratios of Jormua serpentinites are still very similar to fresh or only slightly serpentinized mantle peridotites elsewhere, it is highly probable that serpentinization largely conserved both $SiO_2$ and MgO, in which case the volume of the peridotites must have increased (O'Hanley, 1996).

Within the Jormua Ophiolite Complex talc-carbonate rocks occur as altered marginal variants of serpentinite massifs. Their mineralogy is dominated by carbonate and talc in approximately equal proportions, together with some magnetite and sulfides. Extensive talc-carbonate alteration is restricted to narrow marginal zones of serpentinites. Talc-carbonate alteration may be a post-metamorphic process (Eckstrand, 1975) or, alternatively, *antigorite-carbonate-talc* and *carbonate-talc* assemblages could have been stabilized under prograde conditions but at significantly higher $XCO_2$ than the carbonate-free mineral assemblages. Similar metamorphic zonation in serpentinite bodies has been described from metakomatiites (Gole et al., 1987). By analogy, the concentric metamorphic mineralogy of serpentinite massifs could have been created when the breakdown of pre-metamorphic serpentines ($XH_2O = 1$) and the infiltration of serpentinite margins by $CO_2$-rich fluid (originating from adjacent calcareous metasediments and pre-metamorphic alteration zones undergoing decarbonatization) generated gradients in the composition of metamorphic fluid. Carbonate-free assemblages represent equilibration beyond the limit of $CO_2$-infiltration. Peltonen et al. (1998) discussed in length the mobility of REE during serpentinization or deserpentinization reactions. They came to the conclusion that in the absence of suitable ligands (such as sulfate or carbonate) in the fluids, the alteration—although severe—did not seriously affect the REE characteristics of the peridotites.

## 6. THE CRUSTAL UNIT

### 6.1. Lavas and Hyaloclastites

The extrusive crustal part of the Jormua Ophiolite is rather thin, approximately averaging only 100–400 m (Fig. 3). The thickness of the whole basaltic lid of the ophiolite that includes lavas, sheeted dikes and high-level gabbro stocks was variable ($< 500$ to $> 1.5$ km).

Locally, it is apparent that the basaltic flows were deposited directly onto mantle peridotites. Most of the extrusive metavolcanic rocks of the Jormua Ophiolite Complex occur within the eastern block (Fig. 2; Table 1) as tectonic slices up to 400 m thick and kilometers in length, and typically in faulted contact with adjacent lithologies. Typically, lavas are bordered by serpentinites and talc-carbonate rocks or gabbros-plagiogranites in the structural footwall (to the west), and by upper Kalevian black schists and metagraywackes in the structural hanging wall (to the east). Most of the extrusive part of the Jormua consists of pillow lavas ($\sim 50\%$; Fig. 4a) together with substantial amounts of pillow breccias (Fig. 4b) and hyaloclastites that make up to 25% of the extrusive unit. The remaining 25% consists of massive lava flows or flow parts. Some dikes and gabbro intrusions, one $> 15$ m thick differentiated gabbro-pyroxenite sill, for example, are present within the extrusive sequence. Importantly, interstitial or intercalated terrigenous sedimentary material is completely absent. Based on the presence of hyaloclastite interpillow matrix, minor pillow breccias, and the vesicle-rich nature of some of the pillowed flows Kontinen (1987) argued that the lavas erupted in a relatively shallow-water environment. Relict porphyritic and glomeroporphyritic textures are commonly recognizable in lavas which at present consist essentially of recrystallized plagioclase and nematoblastic calcic amphibole.

The chemical composition of the lavas, such as their high Mg# [$\mathrm{Mg}/(\mathrm{Mg}+\mathrm{Fe}^{2+}_{\mathrm{tot}}) = 0.59$ to 0.73] and high Cr and Ni abundances suggest that lavas are not strongly fractionated. On the Cr vs. Y diagram (Fig. 5), for example, lava samples plot along or only slightly below the partial melting trend suggesting that the primary magma has undergone only minor fractionation (Fig. 5). Since chromite saturates early in MORB (Fisk and Bence, 1980) fractionation should rapidly deplete the residual melt in chromium. Most lava samples cannot be related to each other (or to the sheeted dikes) by fractional crystallization. Instead, the chemical composition of the lavas is consistent with them representing individual melt fractions produced through variable degrees of partial melting from which only minor amounts of chromite, olivine, and plagioclase have been segregated. Such chemical characteristics are in perfect agreement with the igneous stratigraphy inferred from field observations that demonstrated the absence of large magma chambers where pre-eruptive fractionation could have taken place.

The trace element composition of Jormua basalts has been extensively discussed by Kontinen (1987) and Peltonen et al. (1996). Lavas (and most of the dikes) form a rather homogeneous group that has a composition closely similar to that of enriched mid-ocean ridge basalts (EMORB) of the modern seafloor. They are characterized by flat REE (Fig. 6) and, e.g., Nb, Ta, and Th abundances in excess of that typical for NMORB. On the basis of trace element and Nd isotope data Peltonen et al. (1996) concluded that the chemical composition of Jormua lavas and sheeted dikes result from mixing of NMORB and OIB mantle sources. Furthermore, on the Th/Yb vs. Ta/Yb diagram (Pearce, 1983) lava (and dike) samples form a coherent group of analyses that plot along the diagonal mixing array between depleted and enriched mantle sources. This implies that they all contain broadly uniform amounts of enriched endmember, and are free of any geochemical crustal (arc-type) signature.

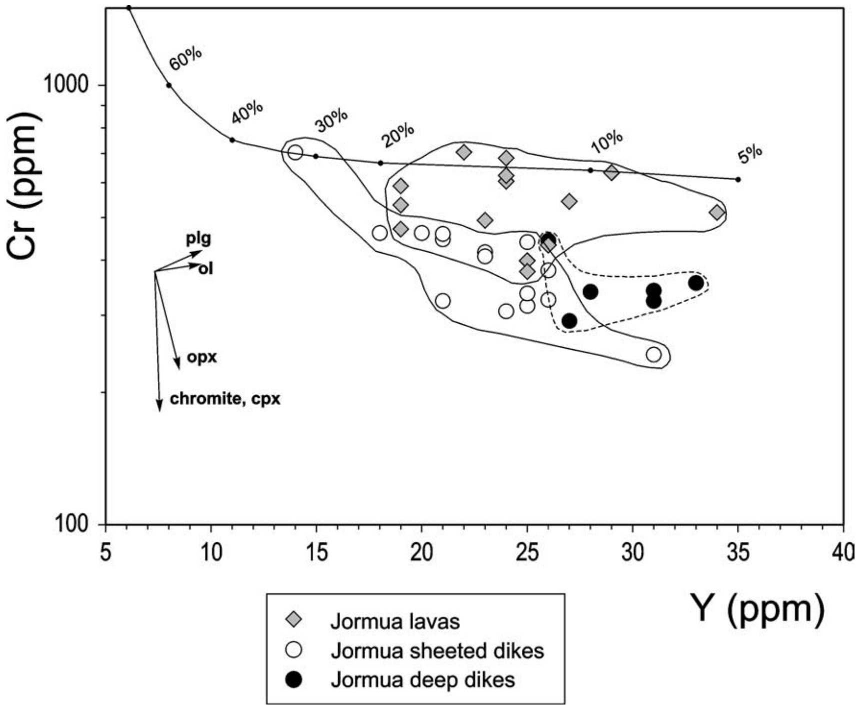


Fig. 5. Cr vs.Y plot for lavas and basaltic dikes of the Jormua Ophiolite. Mineral vector calculations after Peltonen et al. (1996). The subhorizontal line is the partial melting trend of Pearce (1982).

### *6.2. Sheeted Dike Complex*

The sheeted dike complex, with its $> 1$ km thickness and $\sim 10$ km$^2$ areal coverage, is the major crustal unit of the Jormua Ophiolite. The central block (Fig. 2) emphasizes one of the most spectacular phenomena of Jormua: the "rooting" of the sheeted dike complex in the uppermost mantle. Stratigraphically the lowest part of the complex consists of individual anastomosing basaltic dikes ("deep dikes") that intrude the mantle tectonite (Fig. 4c). Margins of thick "deep dikes" are characterized by 10–30 cm wide, dark green, chlorite rich alteration selvages while thin "deep dikes" may be thoroughly altered. Compared to dike interiors the alteration margins are strongly depleted in, e.g., Si, Ca, and alkalies, and enriched in Mg, Cr, Ni, and loss of ignition reflecting their pervasive hydration and double diffusive interaction with mantle peridotite (Peltonen et al., 1996). This interaction took place either during serpentinization of the peridotite host (rodingitization), or later during regional metamorphism, or both. Moving upwards in the stratigraphy "deep dikes" coalescence into groups of multiple dikes with progressively smaller mantle tectonite and gabbro interdike screens demonstrating the consanguinity of "deep dikes" to the coherent sheeted dikes complex. Presence of lava, gabbro and mantle tectonite as interdike screens

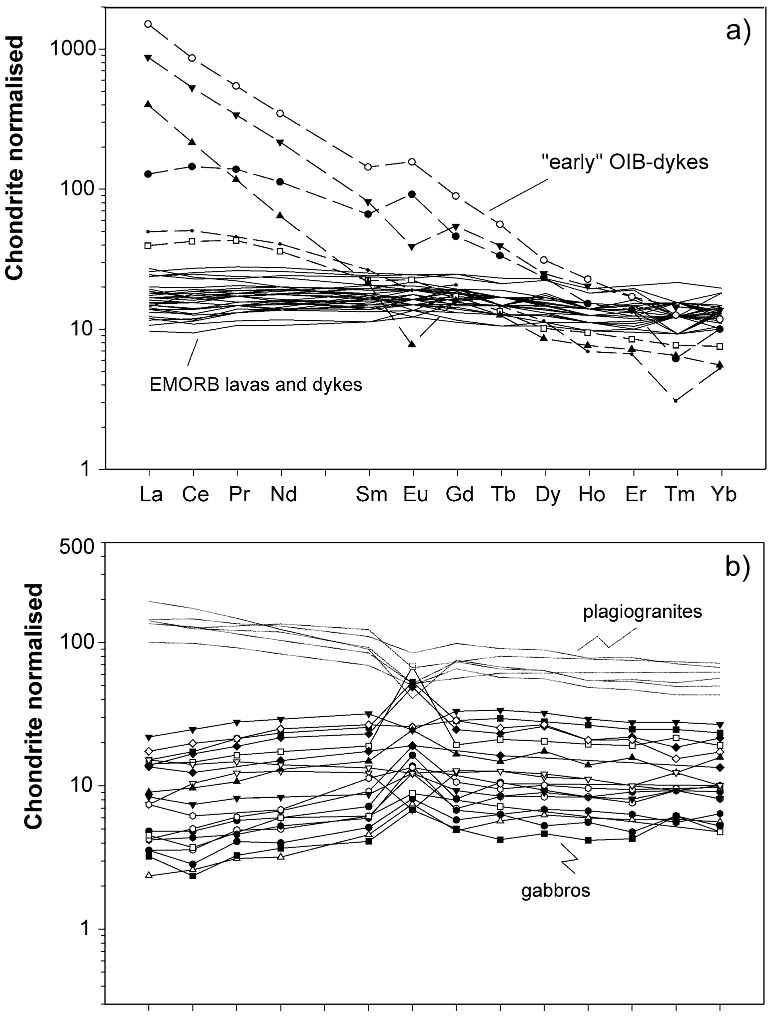


Fig. 6. Chondrite-normalized (Boynton, 1984) rare earth element plots. (a) Lavas and basaltic dikes. Two distinct basalt suites are present: EMORB-type basalts with flat REE patterns and "early suite" OIB-type lavas with fractionated HREE and high LaN/YbN. (b) Gabbros and plagiogranites of the Jormua Ophiolite. The gabbros include samples from both from high-level gabbro stocks and gabbroic feeder dikes which have similar patterns and equal range of absolute concentrations.

(septa) in the Jormua sheeted dikes complex demonstrate that the contacts between the main ophiolite units are transitional, as required for ophiolite recognition by, e.g., Bickle et al. (1994).

At higher crustal levels the sheeted dike complex consist of 100% of subparallel metadolerite and metabasalt dikes (Fig. 4d). Dikes in the sheeted complex are generally 20–120 cm thick, aphyric or plagioclase-phyric with sharp chilled mutual contacts. The older dikes, which tend to be thick and coarse grained, were intruded by thinner and finer grained younger dikes, and became transformed to interdike screens of "half", "one-way chilled", and "marginless" dikes. Branching and apophyses along dike margins are common. Some of the dikes contain abundant plagioclase concentrated by magmatic flow in the dike interiors. No other microtextures have survived the recrystallization during regional metamorphism. The occasional presence of widely separated serpentinite and gabbro septa attest in a striking way the magnitude of extension during the formation of the mafic lid of the Jormua Ophiolite Complex (Fig. 4e).

Although the "deep dikes", sheeted dikes and overlying basalts are clearly coeval magmatic rocks with broadly similar chemical and isotopic compositions (Kontinen, 1987; Peltonen et al., 1996), minor differences emphasize the intricacy of this magmatism. The Cr (ppm) vs. Y (ppm) diagram (Fig. 5) emphasizes that while the lavas represent almost unmodified melt fractions, most of the "deep dikes" and sheeted dikes are significantly more fractionated and cannot represent feeders for the lavas. Probably this is related to the rate of the magma flow in the dike. Those dikes that acted as feeders for the lavas were characterized by high flow rates which prevented extensive fractional crystallization of the melt and resulted in eruption of lavas with primitive composition. Most of the dikes are, however, "blind" and never fed any basalts but instead underwent fractionation during ascent.

### *6.3. Gabbros*

A thick layered gabbro unit, characteristic of many classic young ophiolites is distinctly absent in the Jormua Ophiolite Complex. Instead, all gabbro occurrences in Jormua, even the largest ones (0.5 × 1.5 km in areal extent), represent stocks and dikes intrusive into the uppermost mantle. Most gabbro outcrops are made of isotropic or "varied-textured", coarse to pegmatoid gabbro (Fig. 7a) and any clear modal layering or banding is absent even in the largest occurrences. Gabbro bodies in the central part of the eastern block are frequently intruded by fine grained to aphanitic, usually aphyric, typically 0.2 to 1.2 m wide basaltic dikes. These are separated by cm to meter wide gabbro screens (septa) that comprise 30–60% of many of the gabbro outcrops (Fig. 4e). Locally subparallel dikes form several meter wide zones of dike-in-dike sets. Many of the dikes show clear chilled margins against the gabbro screens and older dikes.

Two types of gabbros have been distinguished in the field: grayish green Mg-gabbros, and dark green Fe-gabbros characterized by relatively low MgO, low $SiO_2$ and distinctly high Fe and Ti reflected in abundance of ilmenite. Mineral assemblages in gabbros are usually thoroughly metamorphic: of the primary phases only An-rich plagioclase is sporadically preserved in the Mg-gabbros and coarse ilmenite in the Fe-gabbros. The most voluminous Fe-gabbros are present in the central part of the eastern block. Transitions from adjacent Mg-gabbros take place within a few meters by abrupt increase in ilmenite

(a)

(b)

Fig. 7. Outcrops of (a) varied-textured ilmenite-bearing high-level gabbro stock, and (b) leucotonalite (plagiogranite) dikes and veins in fine grained high-level gabbro.

content. Grain-size is characteristically variable ranging from fine to coarse and even pegmatoid over short distances. Irregular fine grained dike-like parts in some ferrogabbro outcrops suggest that coeval Fe-basalt dikes are rooting in the Fe-gabbro stocks. However, no Fe-rich lavas or dikes in the sheeted dike complex have been recognized so far.

On the AFM ternary diagram gabbro samples follow a tholeiitic fractionation trend showing pronounced Fe (+ Ti) enrichment in the most evolved samples of the igneous suite (Fig. 8). Incompatible element abundances (such as Ti and Zr) are significantly lower in all gabbros compared to lavas or sheeted dikes of the complex (Kontinen, 1987). This implies that the gabbros are cumulates with only small amounts of intercumulus liquid remaining. Either substantial post-cumulus growth has taken place or, maybe more likely, the gabbroic cumulates have been depleted in residual liquid by filter pressing due to their crystallization in a dynamic environment. Furthermore, the compatible elements Cr and

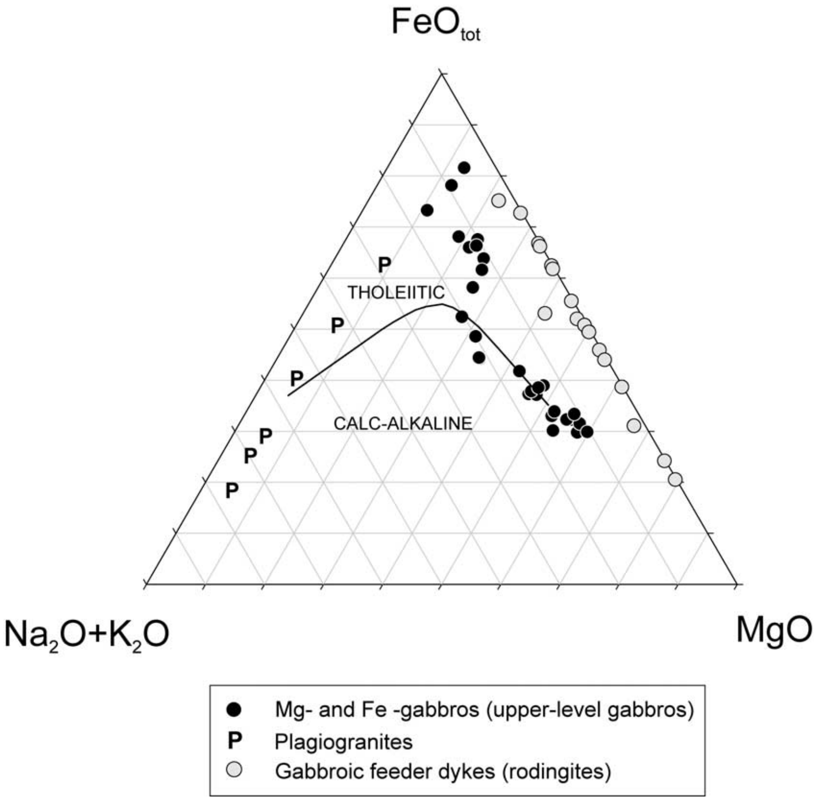


Fig. 8. AFM triangular plot for gabbros and plagiogranites of the Jormua Ophiolite Complex emphasizing the alkali depletion of gabbroic feeder dikes due to their rodingitization and, on the other hand, the extreme alkali (sodium) enrichment of the plagiogranites. Discrimination line after Irvine and Baragar (1971).

Ni are also present in significantly lower concentrations than is common for the lavas and dikes with the same Mg level. This suggests that the parental magma for the gabbros was already relatively evolved and implies that they probably are not coeval with lavas or dikes.

### *6.4. Plagiogranites*

Plagiogranites (i.e., leucotonalites) are well exposed only at one locality in the eastern block where they are closely associated with gabbros, microgabbros and diorites. Two main types of occurrences are present. First, some plagiogranite is present as a few meters wide and at least several tens of meters long zones of multiple, successive, and apparently syn-magmatically deformed dike injections within high-temperature ductile shear zones in Mg-gabbros. Plagiogranite in these zones is present as networks of irregular, cm to dm thick, branching and cross-cutting dikes. Outcrop features suggest coeval emplacement of microgabbroic-basaltic dikes with the plagiogranite dikes and mingling of these magmas. Second, plagiogranite is also found as dike networks within microgabbro-diorite that occurs as marginal facies of large ferrogabbro bodies (Fig. 7b). Outcrop features suggest emplacement of the microgabbros-diorites and plagiogranites as a multistage progressive process involving mingling of the various pulses of magma.

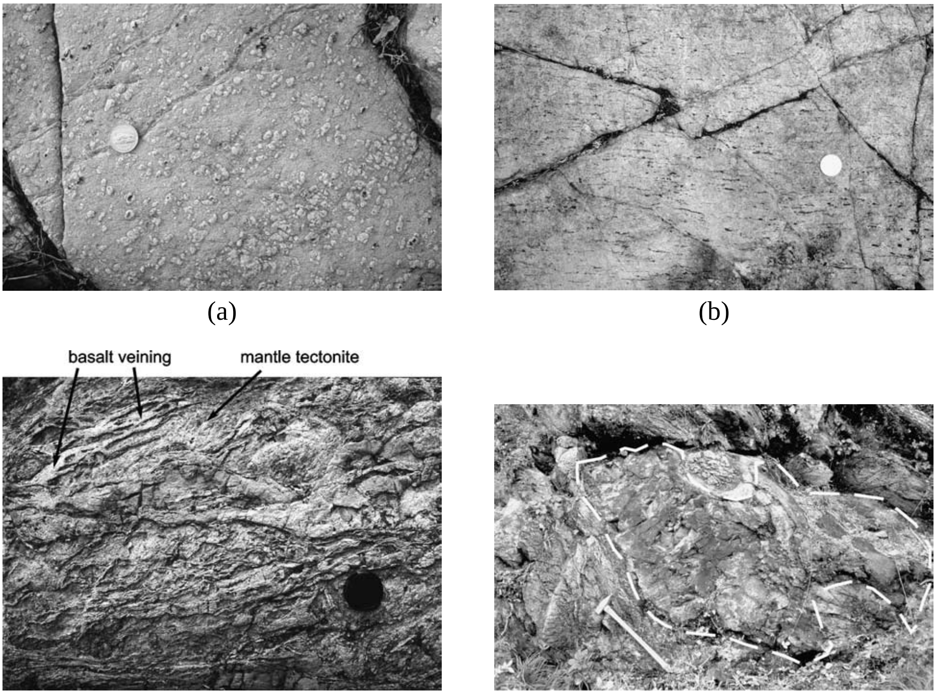
The leucotonalitic to trondhjemitic segregations (plagiogranites) of Jormua Ophiolite Complex have the chemical characters of ocean ridge granites being, e.g., very high in $Na_2O$ and low in $K_2O$ (Fig. 8). Chondrite normalized REE patterns of the leucotonalite segregations are somewhat fractionated at a relatively high level of REE abundances and have negative Eu minimas (Fig. 6b). The high Y and Nb concentrations of the diorites-leucotonalites places them in the within-plate granite field in the Nb vs. Y discrimination diagram of Pearce et al. (1984), which is in line with the overall EMORB character of the Jormua mafic rocks. Zircons from one leucotonalite segregation yielded a somewhat unprecise U-Pb age of $1954 \pm 12$ Ma. In addition, $\varepsilon_{\mathrm{Nd}}$ (1.95 Ga) for this sample is $+1.9$, which is close to the $+2$ average for the lavas and dikes implying that plagiogranite origin is intimately related to the oceanic crust-forming magmatism.

## 7. THE MANTLE SECTION

### *7.1. Mantle Peridotites (Metaserpentinites)*

Mantle peridotites comprise approximately 55% of the area of the Jormua Ophiolite Complex. At present, the peridotites are mainly antigorite metaserpentinites whose mineralogical composition is controlled by bulk rock compositions and metamorphic grade. The eastern and central block peridotites are still characterized by outcrop textures typical for residual mantle tectonites, and by the absence of any well-defined textural or compositional layering. Serpentine pseudomorphs (bastite recrystallized to antigorite) after residual orthopyroxene occur as high relief lumps in the weathered outcrops (Fig. 9a). They are embedded within a “groundmass” consisting of somewhat darker serpentine + magnetite dust that is replacing mantle olivine. Locally, pyroxene pseudomorphs form mm to cm thick bands and strained chromite grains form schlierens thus defining the tectonite foliation (Fig. 9b). This foliation is cross-cut by 1950 Ma old gabbroic feeder dikes implying that the foliation is of mantle origin and not due to $\sim 1880$ Ma regional deformation.

Chromite is the only primary mineral that is preserved in the mantle peridotites (Liipo et al., 1995). Most of the disseminated chromite grains in the serpentinites have thoroughly been altered to ferri-chromite and chromian magnetite. Only occasionally do the serpentinites contain disseminated grains with unaltered chromite cores. In these grains the mutual boundary between the chromite core and ferri-chromite outer shell is sharp both optically and chemically. Ferri-chromite in turn gradually grades to chromian magnetite towards the grain margin. Electron microprobe analyses imply that at the scale of hand samples, there is only minor intra and inter grain variation in Cr# [Cr/(Cr + Al)] of



(a) (b)

(c) (d)

Fig. 9. (a) "Knobby"-textured serpentinite (former residual harzburgite) where bastite pseudomorphs after orthopyroxene remain as high-relief knots in the antigorite serpentine matrix after mantle olivine, (b) chromite (now largely chromian magnetite) striations define mantle foliation, (c) residual mantle tectonite infiltrated by basaltic melt. Such samples are responsible for the relatively high REE abundances in some peridotite samples and their flat chondrite-normalized patterns (Fig. 11a), (d) small podiform chromitite body enclosed by talc-carbonate altered eastern block mantle tectonite. (a) Reprinted with the permission from Journal of Petrology, vol. 39, Oxford Univ. Press.

the chromite cores. Mg# [$Mg/(Mg + Fe^{2+})$], in turn, varies greatly being higher in the interiors of the large chromite cores and lower in interiors of the small ones and gradually decreases from the chromite cores towards their margins (Kontinen and Peltonen, 1998). This implies that Mg# have been strongly modified from the original mantle values by alteration and metamorphism. However, the apparent immobility of Cr and Al in the chromite cores suggests that the variation in the Cr# (45–70) may still closely reflect the primary mantle melting-controlled values. Relatively high and variable Cr# suggests that the eastern and central block peridotites represent residues after variable but generally high degrees of partial melting.

Chemical composition of the metaserpentinites imply similar origin as was deduced from the compositions of chromite. On the Pd/Ir vs. Ni/Cu metal ratio diagram of Barnes et al. (1988) talc- and carbonate-free serpentinite samples form a tight cluster close to the mantle field (Fig. 10a). Two talc-carbonate altered samples are displaced from the mantle field: a serpentinite-talc schist contact zone sample (0.73 wt% $CO_2$) contains 170 ppm Cu ($>$ 5 times that of primitive mantle) and one of the massive serpentinites (1.72 wt% $CO_2$) is strongly depleted in Pd. Uniform and low Pd/Ir is inconsistent with a cumulate origin for any of these samples. Due to similar partition coefficients between melt and residual sulfides during partial melting the Pd/Ir is not sensitive to variations in the degree of mantle melting. This is, instead, illustrated by Cr/Al vs. Ni/Al plot (Fig. 10b). In this diagram—where both ratios increase as a function of mantle melting—Jormua serpentinites record a wide range of ratios indicating variable degrees of melt extraction from peridotites.

Incompatible element abundances bear evidence for a complex post-melting history of the Jormua mantle peridotites. Chondrite-normalized REE patterns bring out major differences between peridotites from different blocks of the Jormua Ophiolite Complex (Fig. 11). Serpentinites from the eastern block yielded two distinct types of patterns. First, several samples are characterized by U-shaped chondrite-normalized patterns—a form that is typical for dunites and harzburgites from the basal sections of ophiolites elsewhere (e.g., McDonough and Frey, 1989). Such patterns indicate that peridotites have first been depleted in LREE and MREE during mantle melting and later enriched in LREE. Second, some eastern block samples contain much more REE and yield flat patterns, similar to those of Jormua EMORB, but at a lower level. Some of these samples may represent small dunitic cumulate pods but some are characterized by typical residual mantle outcrop textures and more likely represent residual peridotites with substantial amounts of infiltrated and trapped basaltic melt (Fig. 9c). Western block peridotites yield truly distinct forms of chondrite-normalized patterns. They are characterized by relatively steep patterns between HREE and MREE but somewhat depleted LREE resulting in upward-concave patterns. These enriched peridotites yield similar initial $^{143}Nd/^{144}Nd$ as the OIB-type “early dikes” and hornblenditic mantle dikes that intrude the western block peridotites. This was explained by Peltonen et al. (1998) by coeval flow of alkaline melt in dikes (conduit flow) and in the residual peridotite matrix (porous flow) that was at least partly driven by filter pressing of the melt from the dikes.

### 7.2. Chromitites

Massive chromitite bodies and peridotites rich in disseminated chromite are known only from the eastern block where they occur within a 700 m long talc-carbonate altered peridotite slice between two pillow lava slices (Fig. 2). Most of the chromitite-bearing lithology in this relatively poorly exposed zone comprises brecciated serpentinized dunites with scattered small (cm to dm size) broken fragments of massive, nodular, or orbicular chromitite. Only two larger than one meter-size chromitite bodies are currently known (Fig. 9d). The largest of the presently known pods, which is about 0.8 m wide and at least 5 m long is located in heavily carbonated serpentinite fringed by talc-carbonate rocks. Margins of this folded and boudinaged chromitite lens comprise strongly fractured and altered chromite, the fractures being filled with carbonate and chlorite, whereas the core part of the body contains surprisingly fresh coarse grained chromite (Fig. 12). This chromite has a moder-

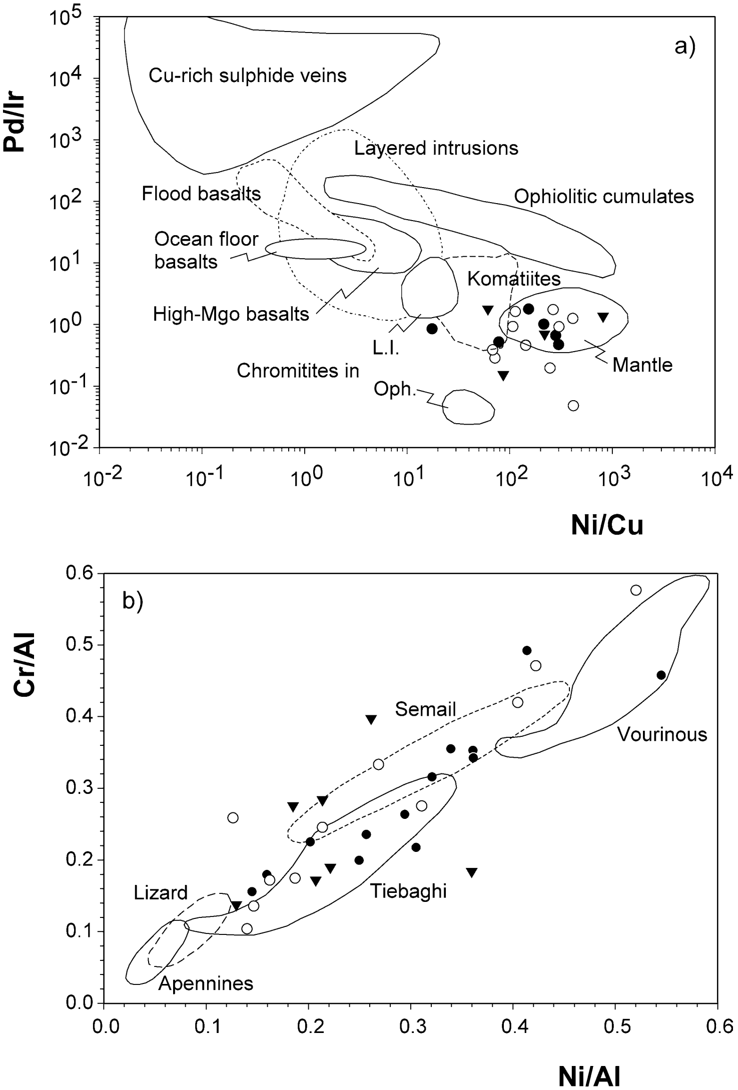
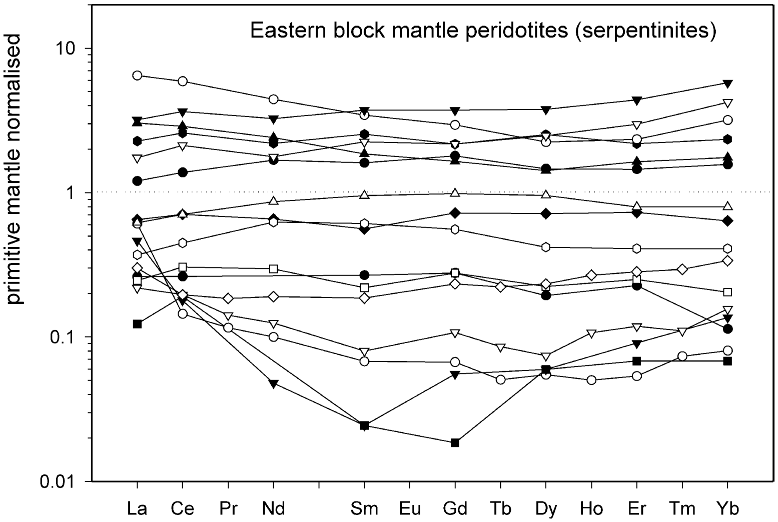
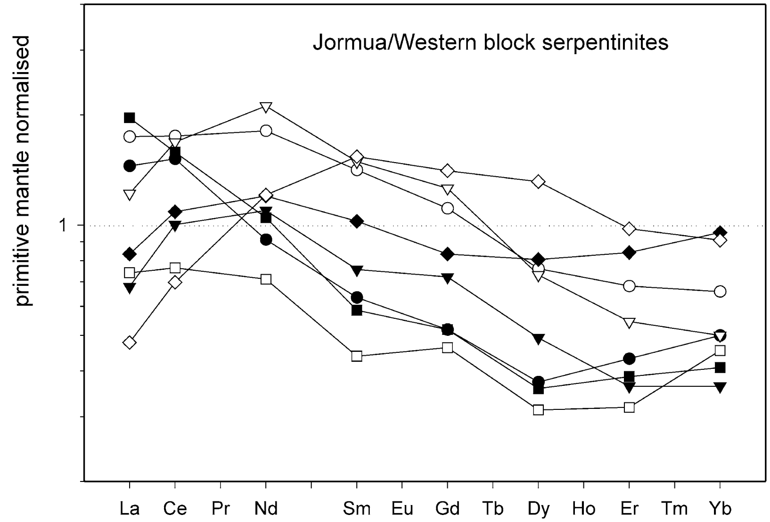


Fig. 10. (a) Pd/Ir vs. Ni/Cu plot of Barnes et al. (1988) for serpentinite samples from the Jormua Ophiolite. With the exception of some talc-carbonate altered samples they all plot within the mantle field consistent with their residual origin. Low Pd/Ir is inconsistent with cumulate origin for any of the samples. (b) Cr/Al vs. Ni/Al diagram illustrating the compositional variability of the Jormua mantle tectonites due to extraction of variable melt fractions. The trend from the Lizard (least depleted) to Vourinous peridotites (most depleted) illustrates that produced by increasing degree of partial melting of mantle peridotite. Reference fields after Roberts and Neary (1993). Symbols in (a) and (b): open circle (eastern block peridotites), filled circle (central block peridotites), and black triangle (western block peridotites).



(a)



(b)

Fig. 11. Primitive mantle (McDonough and Sun, 1995) normalized REE patterns for (a) eastern block serpentinites and (b) western block serpentinites. Note the large range in REE abundances for the eastern block samples indicating that some peridotites contain substantial amounts of infiltrated basaltic liquid (see also Fig. 9c) while some have U-shaped patterns more typical for oceanic peridotites. The pattern shapes for the western block peridotites are distinct and mimic those of alkaline (hornblenditic) dikes of the western block (Fig. 15b) suggestive of them being metasomatized by corresponding melt or fluid.

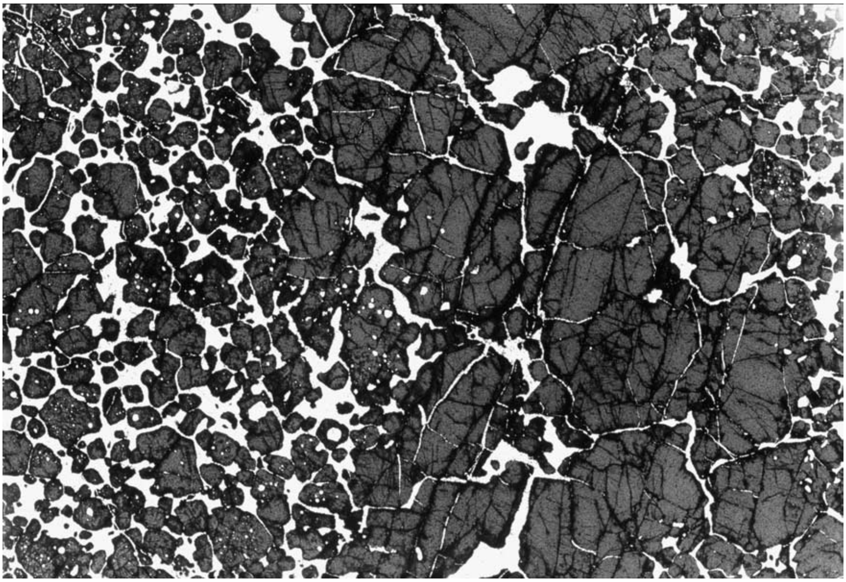


Fig. 12. Photomicrograph of podiform chromitite from the eastern block of the Jormua Ophiolite Complex. Transparent light, width of the field $\sim$ 3 cm, photo by J. Väätäinen.

ately aluminous composition with average Mg# and Cr# of 76 and 55, respectively, and low $TiO_2$ content of $\sim 0.24$ wt%. Small silicate inclusions were present in many of the chromite grains but are now commonly replaced by secondary minerals. The preserved ones comprise relatively sodic tsermakitic hornblende having compositions strikingly similar with the amphibole inclusions in chromitites of some oceanic and ophiolitic peridotites (e.g., McElduff and Stumpfl, 1991). Interestingly, the chromitites yielded initial $\gamma_{\mathrm{Os}}$ values of $+0.8 \pm 0.5$ and $3.0 \pm 0.1$ consistent with their derivation from a convective MORB-like oceanic mantle at the time of the ophiolite formation $\sim$ 1.95 Ga (Tsuru et al., 2000).

### *7.3. Gabbroic Feeder Dikes*

The eastern block mantle peridotites are intruded by a suite of gabbroic dikes. Typically these dikes are couple of meters wide and show symmetric texture indicative of them representing subvertical channels. They range from subparallel to discordant relative to the mantle foliation and branches from the main dikes cross-cut the foliation at high angle (Fig. 13). Locally, the veining of the host peridotite has resulted in detachment of peridotite xenoliths from the dike wall, leaving them ”floating” in the gabbro. Typically, the dike margins are composed of coarse grained (up to 5 cm long) often plastically deformed clinopyroxene crystals enclosed by fine grained dark green intercumulus material, whose primary composition remains obscure because of its pervasive alteration to chlorite. Locally, the clinopyroxene crystals are aligned parallel to the dike margins indicative of the

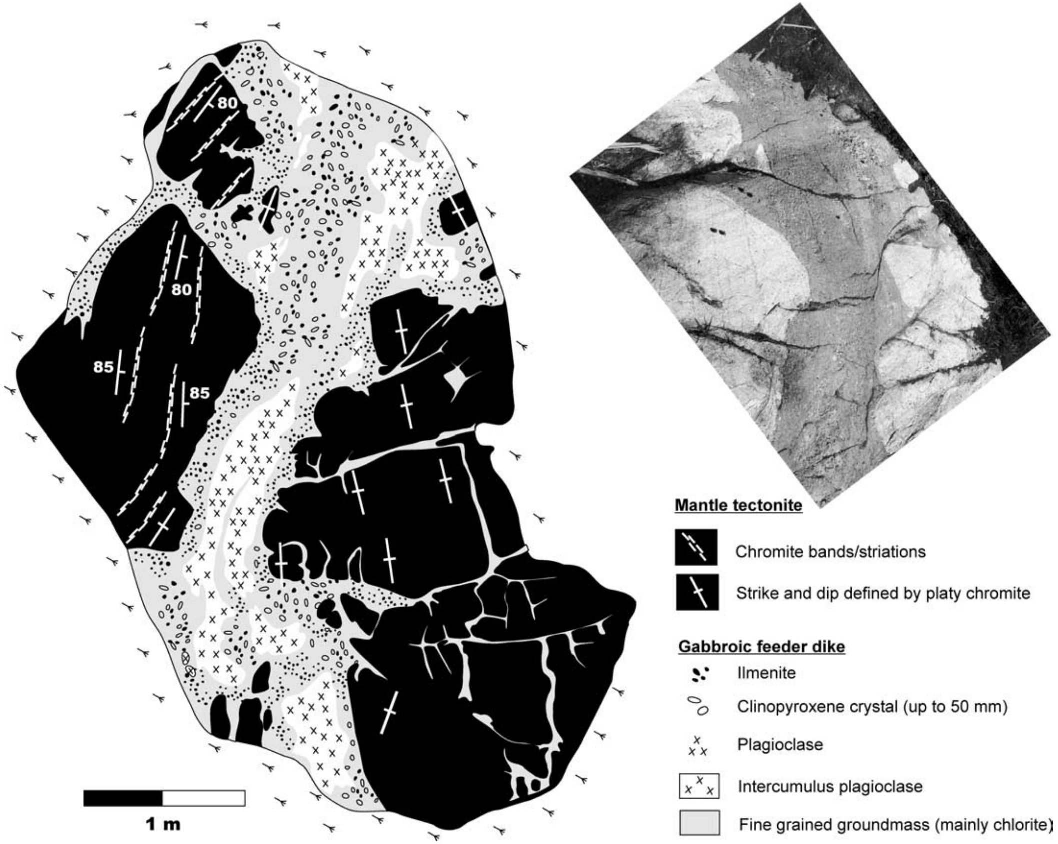


Fig. 13. A sketch of an outcrop of gabbroic feeder dike. Note that the dike is broadly parallel to the mantle foliation, but in the meantime brecciates the peridotite—features that are indicative of semibrittle environment for gabbro emplacement.

magma flow in the dike. Towards their core parts the dikes comprise increasingly coarse grained or pegmatoidal clinopyroxene + plagioclase + ilmenite cumulates. In many places the plagioclase has been thoroughly replaced by grossular garnet and epidote, and ilmenite by sphene and rutile as a result of rodingitization and subsequent regional metamorphism.

The irregular contacts of the gabbros suggest that the mantle tectonite was undergoing deformation at the time of the emplacement, and the coarse grain size of these rather thin dikes imply their slow cooling at the high ambient temperatures of the host peridotite. Importantly, too, the alteration history of the gabbroic feeder dikes and basaltic "deep dikes" are distinct. The former are often pervasively rodingitized with abundant grossular garnet while the latter are altered (epidotized) but not rodingitized *sensu stricto* (never garnet). This is believed to be indicative that gabbros intruded fresh (i.e., nonserpentinized) peridotites that later became serpentinized resulting in coeval rodingitization of the enclosed gabbro dikes. In contrast, the absence of rodingitization reactions in the "deep dikes" suggests that they intruded already extensively serpentinized peridotites.

Rare earth element patterns of the gabbroic feeders are identical to those of the high-level gabbros (Fig. 6b). Large ranges in the elemental abundances testify to the strong across-dike fractionation that took place in the dikes and that is broadly similar with the fractionation of the high level gabbros. Importantly, samples from both the gabbro dikes and high level stocks yield similar initial $^{143}$Nd/$^{144}$Nd values and fit along a well-defined Sm-Nd isochron. The slope of the isochron corresponds to an age (1936 ± 43 Ma) that is equal to the U-Pb zircon ages of both the gabbro dikes and high-level stocks (Peltonen et al., 1998). As a summary, we believe that the internal structure, alteration, and chemical and isotopic composition of these gabbroic feeder dikes imply that they represent feeders for the high-level gabbro bodies. However, because gabbros are frequently cross-cut by EMORB dikes, but are never observed to intrude the basaltic dikes, the gabbros are not directly related to the extrusive rocks in Jormua. More likely, their emplacement preceded (probably by a few million years) that of the sea floor volcanism. This is consistent with the evidence of the rheological properties of mantle at the time of the emplacement of the gabbro dikes (above) which suggests that they intruded the peridotites at relatively high ambient temperatures, perhaps before the mantle was exposed beneath the continental crust by lithospheric detachment faulting.

### *7.4. "Early" OIB-Type Dikes*

A distinct suite of fine grained dikes with chemical characteristics similar to oceanic island basalts (OIB) have been observed in the central block only (Figs. 3 and 6a). They occur as subvertical, NNE-trending, $<$ 10–200 cm wide dikes that run subparallel with chromite foliations of the enclosing mantle tectonite. Their mineralogy and LILE element abundances have been strongly modified due to rodingitization. At present they mainly consist of chlorite, ilmenite, magnetite, sphene, apatite, carbonate and trace sulfides. Immobile elements, such as REE, Zr, Nb, Y, and Al can still be applied to determine their origin and led Peltonen et al. (1996) to argue that they represent primitive alkaline melts

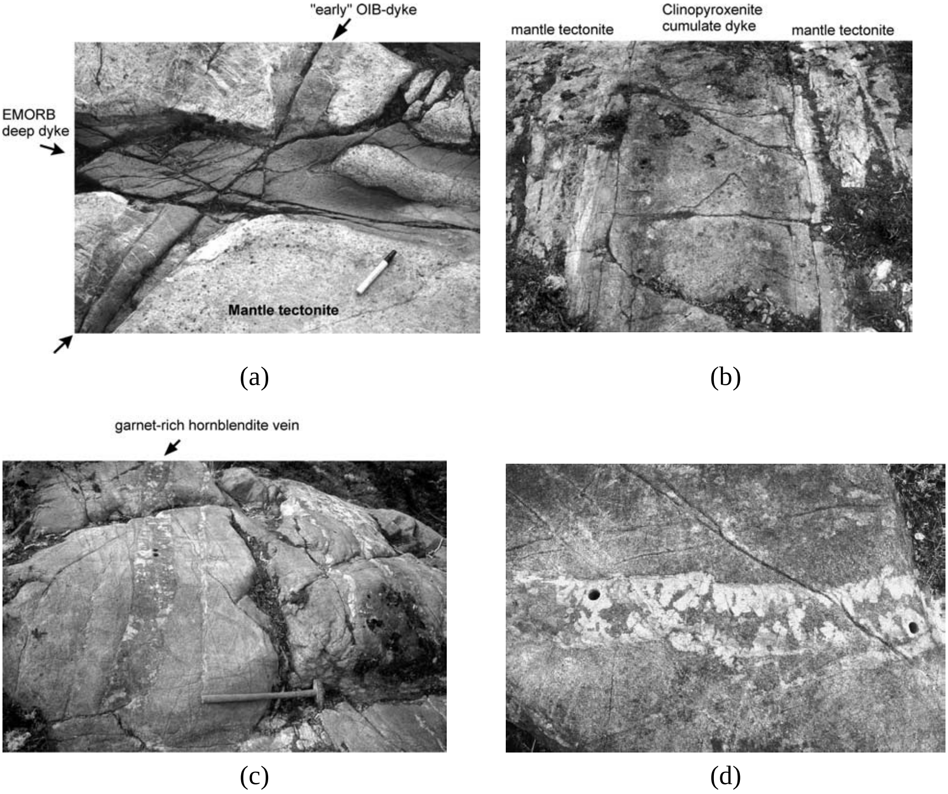


Fig. 14. (a) An outcrop illustrating the cross-cutting relationship of “early” OIB-type dikes and deep dikes (EMORB) within the central block mantle tectonites, (b) clinopyroxenitic cumulate dike intruding mantle tectonite, (c) thick hornblenditic mantle dike (gray) with garnetite and garnet rich veins (mottled), (d) a close-up of garnetite vein with $> 50$ vol% garnet crystals (white; now pseudomorphosed) growing inside from the conduit wall defining comb-layering. (c) Reprinted with the permission from Journal of Petrology, vol. 39, Oxford Univ. Press.

(ultramafic lamprophyres) from a $\sim 2.3$ Ga [Nd($T_{DM}$)] plume source. Also “early dikes” are completely devoid of any subduction-related geochemical component.

Since abundant EMORB dikes cross-cut the OIB-dikes at high angles, it is evident that they represent distinct episodes of magmatism (Fig. 14a). Preliminary U-Pb zircon ages determined by SIMS from one OIB-dike are consistent with field evidence that emplacement of OIB-dikes indeed preceded that of tholeiitic gabbro magmatism and ocean floor volcanism by some tens of millions of years (Peltonen et al., in preparation). Most likely their emplacement was related to the initial stages of continental rifting. These dikes are among the oldest Precambrian alkaline rocks described in the literature (Blichert-Toft et al., 1996).

### *7.5. Clinopyroxenite Feeder Dikes*

Cumulus-textured clinopyroxenite dikes are common within the western block of the Jormua Ophiolite (Figs. 3 and 14b). Such dikes are present but rare in the central block and are completely absent from the eastern block. These dikes are typically from a few dm up to one meter wide having relatively straight and linear sharp contacts against the enclosing mantle tectonites. Locally they occur in thick dike-in-dike swarms or may form small cumulate pods within the mantle tectonite. They are subparallel with the mantle foliation but in detail are discordant. These dikes consist of clinopyroxene ortho- or mesocumulates with only minor intercumulus material and are collectively called “dry” clinopyroxenites to distinguish them from hydrous hornblendite-garnetite veins (next section). Most of the primary clinopyroxene crystals, however, have been retrogressively replaced by fibrous actinolite. The high abundances of, e.g., Mg, Cr and Ni, convex-upward primitive mantle normalized REE patterns (Fig. 15a) and low abundances of incompatible elements all reflect the accumulation of calcic pyroxene and low modal amount of intercumulus melt in these dikes. Particularly close analogies for such mantle dikes can be found from the orogenic lherzolite massifs of the French Pyrenees (e.g., Conquéré, 1971; Bodinier et al., 1987a).

Two clinopyroxene cumulate dikes from central and western blocks yielded magmatic, growth-zoned zircons with relatively large spread of $^{207}$Pb/$^{208}$Pb ages between 3106 and 2718 Ma. Sm-Nd isotope data, however, clearly suggests that the crystallization age of the dikes is Proterozoic. This implies that Archean zircon grains in these dikes are xenocrysts inherited from deeper sources of the continental mantle (Peltonen et al., 2003). Therefore, central and western block mantle tectonites (which are intruded by such dikes) must represent ancient subcontinental lithospheric mantle (SCLM) that became exposed from underneath the Karelian craton during the 1.95 Ga rifting event. Since the clinopyroxenitic mantle dikes bear no evidence of having gone through melting after their formation, the mantle peridotites exposed in the central and western blocks cannot be the source for the Jormua gabbros, dikes or lavas.

### *7.6. Hornblendite Mantle Dikes and Garnetite Veins*

In addition to “dry” clinopyroxenites the western block tectonites are characterized by abundant hydrous intrusives. Frequently, the hydrous veins are subparallel with the “dry” dikes, but in detail cross-cut them. They form a somewhat heterogeneous suite of dikes and veins with significant modal and grain size variations within individual dikes. Hydrous mantle dikes include at least the following rock types (in approximate order of abundance): pure medium-grained hornblendites (Fig. 14c), garnetite veins (Fig. 14d), pegmatitic hornblendites, magnetite-ilmenite-zirconolite-rich cumulates and carbonatitic segregations. By their chemical composition the hydrous dikes are more evolved than the clinopyroxenites. Igneous mineralogy is not well-preserved but primitive mantle normalized REE patterns are particularly informative for the origin of hydrous dikes (Figs. 15b, c). These patterns

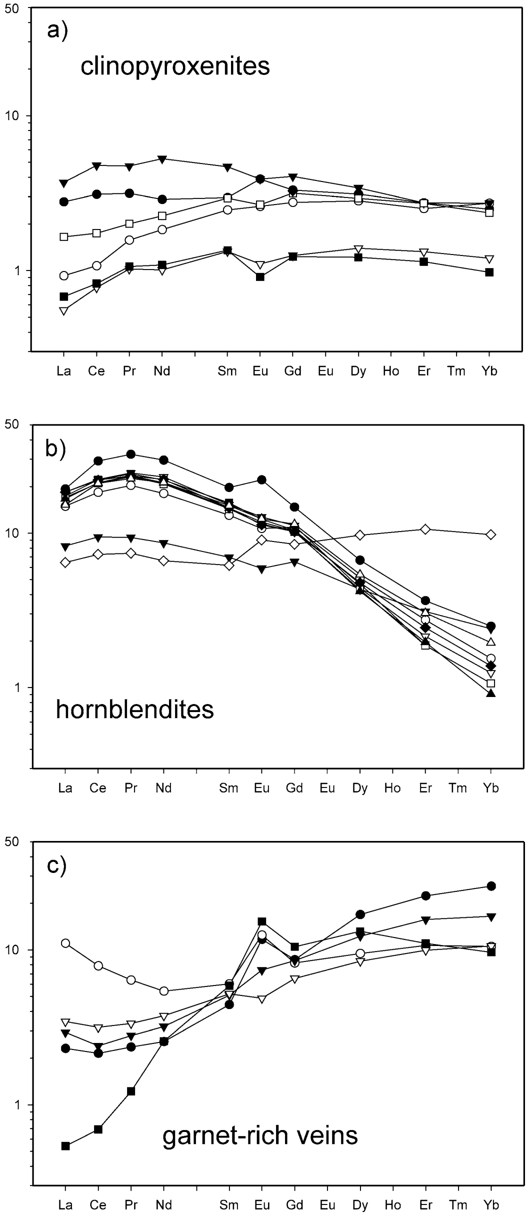


Fig. 15. Primitive mantle (McDonough and Sun, 1995) normalized REE patterns for cumulus-textured alkaline mantle dikes from the Jormua Ophiolite: (a) clinopyroxene cumulate dikes, (b) hornblendites, and (c) garnet-rich veins.

largely reflect the mineralogical composition of the dikes. Hornblendites are characterized by steep fractionated patterns with convex-upward LREE part of the spectrum, while garnetite vein patterns clearly reflect the accumulation of garnet that strongly partitions HREE. These types of dikes, especially the garnet-bearing ones that imply high crystallization pressures, do not occur in the mantle sections of true ophiolites. They are, however, common in orogenic lherzolite massifs (SCLM), such as Lherz and Freychinéde, French Pyrenees (Conquéré, 1971; Bodinier et al., 1987b; Fabriés et al., 1991; Woodland et al., 1996) where they represent high-pressure cumulates of the continental magmatism that passed through the uppermost subcontinental lithospheric mantle.

In Jormua, the hydrous dikes are intimately associated also with sporadic occurrences of carbonatite-like vein material. In fact, petrographic observations suggest that there exists a complete sequence from hornblendite veins with intercumulus carbonatite to veins consisting of more than 50% carbonates. This may be indicative that the carbonatitic material represents an extreme differentiation product of the hornblendite-producing alkaline magma. Carbon isotope values for these carbonatites are typical for upper mantle (unpublished) and clearly distinct from secondary (metamorphic) carbonates of the talc-carbonate rocks. At present, carbonatitic segregations consist of carbonates ($>$ 50 vol%), amphiboles, phlogopite, chlorite, magnetite, apatite, ilmenite, zircon, zirconolite and baddeleyite. Microscopic vugs consisting of carbonatitic material have been described from mantle xenoliths and mantle xenocrysts (e.g., Ionov et al., 1996; Zhang and Liou, 1994) but, to our knowledge, the carbonatitic veins within the Jormua mantle tectonites are the first mesoscopic carbonatite occurrence described from mantle samples.

Zircons from one carbonatite vein have been dated by SIMS (Peltonen et al., in preparation). This sample yielded a bimodal distribution of ages. Most of grains record ages close to 1950 Ma that equals the age of the EMORB magmatism in Jormua. Some grains, however, are significantly older being $\sim$ 2.1 Ga. The results indicate that the igneous age of the carbonatites (and by corollary hydrous dikes in general) is close to 2.1 Ga but that most of the grains were recrystallized, as indicated by their morphology and lack of color, in the 1950 Ma thermal event. Such a time sequence is supported by field observations that imply that the only EMORB dike which is known from the western block cross-cuts not only the “dry” clinopyroxenites but also hydrous dikes. Importantly, the age of this carbonatite vein equals that of the central block OIB-dikes upper in the ophiolite stratigraphy, which indicates that hydrous cumulate dikes of the western block represent deep-seated equivalents of the OIB-type alkaline dikes (Fig. 3).

## 8. GEODYNAMIC SETTING OF THE JORMUA OPHIOLITE COMPLEX AND EVOLUTION OF THE KARELIAN CONTINENTAL MARGIN

The internal stratigraphy of the Jormua Ophiolite Complex (e.g., absence of thick cumulate layers; thin basaltic lid), together with the presence of subcontinental lithospheric mantle imply that Jormua formed at the final stages of continental rifting representing the first sea floor to be generated. On the basis of the structure of the Jormua alone, it cannot be judged whether this break-up led to development of a major ocean. Therefore, two alternative paleogeographic settings of origin are possible: (a) either the Jormua Ophiolite Complex formed between the Eastern Finland and Pudasjärvi-Iisalmi Archean complexes (Fig. 1) within a continental rift zone that never developed into major ocean, or (b) Jormua formed within the westernmost passive margin of the craton and has been tectonically transported over the Pudasjärvi-Iisalmi complexes (Fig. 1). The rift zone model (a) seriously contradicts the lithofacies of the associated ("upper Kaleva") metasediments. Instead, we prefer the passive margin model (b) because there is no evidence of rift sedimentation around 1.95 Ga within the Kainuu Schist Belt, and because the Jormua Ophiolite (as Karelidic ophiolite fragments in general) has been obducted together with deep water slope-rise graywackes (Koistinen, 1981; Kontinen and Sorjonen-Ward, 1991) that were deposited less than 1920 ± 10 Ma ago (Huhma, 1986; Claesson et al., 1993). The monotonous deep water turbiditic lithofacies, complete absence of any type of volcanic interbeds or synsedimentary intrusions, and the presence of 1.92–1.97 old sedimentary source component from a remote unknown terrain (Claesson et al., 1993) clearly exclude the origin of "upper Kaleva" as a continental rift fill.

In the passive margin model the Jormua Ophiolite can be envisaged as screens of oceanic lithosphere within a recently developed ($\sim$ 1950 Ma) continental margin which, following the thermal subsidence, became covered by the "upper Kaleva" slope-rise turbidites (Fig. 16). This model implies that both the Jormua Ophiolite and the somewhat older (early rifting) Otanmäki alkaline gneisses are allochthonous and that their present appearance as mega-boudinaged slices within basement and cover sediment slices is due to imbrication and shearing. The deposition of the upper Kaleva metasediments as well as ophiolite obduction took place somewhere between 1920 ± 20 Ma and 1871 ± 5 Ma. The lower limit is provided by the youngest detrital zircons in these metasediments (Claesson et al., 1993), and the upper limit by the age of the oldest granite intruding the "upper Kaleva" schists (Huhma, 1986). Evidence of the flat-lying nappes that were responsible for the thrusting of the Jormua klippe onto the craton some 1.9 Ga ago has mostly been destroyed by the subsequent regional deformation.

Though there is evidence of a 2 Ga mantle plume in the south-east are Fennoscandian Shield (e.g., Puchtel et al., 1998), the limited amount of 1950 Ma volcanism at the westernmost margin of the Karelian Craton suggests that it developed as a non-volcanic continental margin. The presence of both exposed continental lithospheric mantle and asthenosphere-derived igneous rocks in the Jormua Ophiolite Complex suggest a heterogeneous and asymmetric stretching and rifting process, which resulted in delamination and exposure of the subcontinental lithospheric mantle in an early stage of the ocean opening (Fig. 16; Whitmarsh et al., 2001). Phanerozoic ophiolites similar to the Jormua include the Ligurian/western Alps ophiolites that also have been related to continental break-up by asymmetric passive rifting (e.g., Lemoine et al., 1987; Rampone and Piccardo, 2001, and references therein). Modern environments that may be analogous to the provenance of the Jormua include the West Iberian non-volcanic margin where the continent-ocean transition zone consists of partially serpentinized continental mantle tectonites veined by

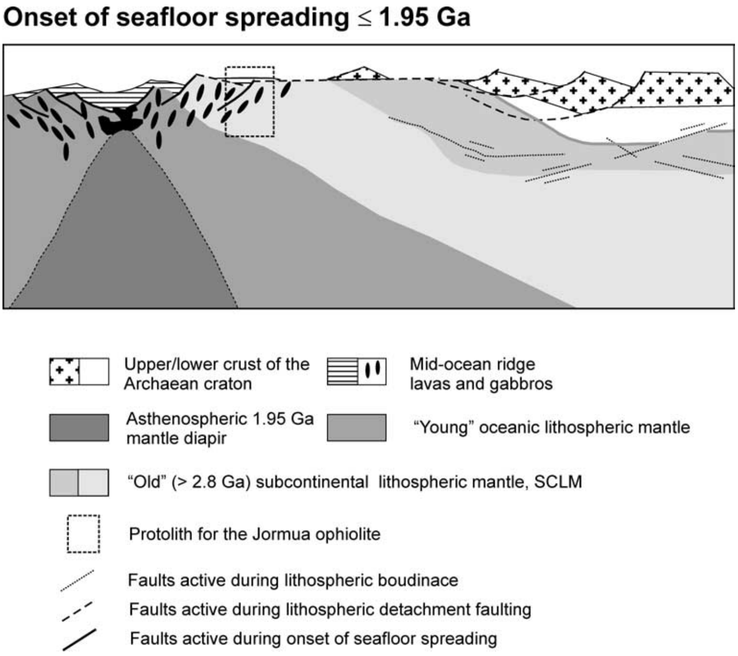


Fig. 16. Proposed tectonic setting for the protolith of the Jormua Ophiolite Complex within an ocean-continent transition zone. Modified after Whitmarsh et al. (2001) emphasizing the situation at the present West Iberia passive margin.

EMORB dikes, gabbros and pyroxenites akin to those in Jormua (Chian et al., 1999; Cornen et al., 1999).

Sedimentary deposits along this ~ 1.95 Ga non-volcanic continental margin that could be related to the break-up/ocean opening are rare. One of the reasons for the obvious sediment starved nature is the peneplain nature of the Karelian continent at that time and thus lack of higher mountainous terrains along the break-up zone to supply large quantities of detritus. Furthermore, there is evidence that suggests that the whole Karelian Craton may have been submerged 1980 Ma ago shortly before the opening (Puchtel et al., 1998). The absence or very thin Jatuli-type sedimentary cover along the continental margin indicates that the break up zone probably rose above sea level and was subjected to some erosion before its rifting.

Despite the obvious sediment starved nature of the opening, there still is puzzlingly little evidence of the break-up along the craton margin, and most of this evidence comes from thrusted units. One explanation could be that the break-up zone and inferred thinned margin is buried below the Svecofennian terrane in the west of the suture (Fig. 1). This scenario is however not supported by isotope data from syn- and postcollisional granites to the west of the exposed suture (Huhma, 1986; Lahtinen and Huhma, 1997; Rämö et al., 2001). Therefore, perhaps the Svecofennia-Archaean suture represents a major strike-slip fault along which much of the thinned continental margin and underlying mantle was removed already before the amalgamation of the Svecofennian terrane. In this case the thrusting of the eastern Finland ophiolites and related units may have been a tectonic episode that significantly preceded and was unrelated to the actual Svecofennian collision.

The present tectonic setting of the Jormua Ophiolite Complex (within klippes transported far from their inferred tectonic root west of the suture) provides few clues for unraveling the possible causes of detachment of the Jormua from the seafloor and its subsequent obduction on to the continent. One and purely speculative suggestion would be that maybe there was a shortlived event of attempted subduction beneath the continental margin preceding the obduction. This may have resulted in uplifting of the thin transitional crust that in turn facilitated the bulldozing of ultramafic seafloor and "upper Kaleva" turbidites from somewhat more distant oceanic realm onto the continent. Continental mantle in rift zones lies open to serpentinization (e.g., Perez-Gussinye and Reston, 2001) that could have made the provenance of Jormua boyonant and facilitated the obduction.

## 9. EPILOGUE

The Jormua Ophiolite is a truly unique mafic-ultramafic rock complex that consists of two distinct components: (1) Archean subcontinental lithospheric mantle that became exposed on the seafloor due to detachment faulting, and (2) a suite of convective mantle-derived alkaline and tholeiitic igneous rocks that intruded the SCLM before and during the continental rifting between 2.1 and 1.95 Ga. The mantle exposed in Jormua thus mainly represents the uppermost sub-crustal lithosphere of the Archean Karelian Craton. Intriguingly, mantle xenoliths representing this same continental mantle have been recently recovered from $\sim 500$ Ma kimberlite pipes that intrude the craton margin 100 km SSE of Jormua. The mantle xenolith suite consists garnet peridotites and mantle eclogites derived from a depth range of $\sim 110$–240 km (Peltonen et al., 1999; Kukkonen and Peltonen, 1999). Combined, an astonishing window to understand the evolution of the Karelian mantle for over $\sim 3$ Ga period and over its entire vertical depth seems to be at hand. Unfortunately, the high degree of alteration and metamorphism of the Jormua mantle samples decreases their value; primary minerals are generally no longer available and the multistage alteration hampers study of the most subtle geochemical aspects. Nevertheless, relatively good exposure of glacially polished outcrops over an area of 50 $km^2$ will provide many new insights to the structure and composition of Precambrian mantle.

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