

# A 2.44 Ga syn-tectonic mafic dyke swarm in the Kolvitsa Belt, Kola Peninsula, Russia: implications for early Palaeoproterozoic tectonics in the north-eastern Fennoscandian Shield

V.V. Balagansky<sup>a,\*</sup>, M.J. Timmerman<sup>b</sup>, N. Ye. Kozlova<sup>a</sup>, R.V. Kislitsyn<sup>a</sup>

<sup>a</sup> *Geological Institute of Kola Science Centre, Russian Academy of Sciences, 14 Fersman St., Apatity 184209, Russia*

<sup>b</sup> *School of Earth Sciences, Leeds University, Leeds LS2 9JT, UK*

Received 5 April 1999; accepted 1 November 1999

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## Abstract

The Kolvitsa Belt in the south-western Kola Peninsula formed coeval with the earliest Palaeoproterozoic rift-belts in the Fennoscandian Shield. The Palaeoproterozoic history of this belt comprises the deposition of the 2.47 Ga Kandalaksha amphibolite (metabasalt) sequence onto 2.7 Ga granitoid gneisses, the intrusion of the 2.45–2.46 Ga Kolvitsa Massif of gabbro-anorthosite and the subsequent multiple injection of mafic dykes and magmatic brecciation, followed by the intrusion of 2.44 Ga dioritic dykes, and extensive shearing at 2.43–2.42 Ga. The gabbro-anorthosite and dykes contain high-pressure garnet-bearing assemblages that have previously been considered as evidence for metamorphism in a compressional setting of the Kolvitsa Belt at 2.45–2.42 Ga, i.e. coeval with the formation of the Imandra–Varzuga rift-belt and layered mafic intrusions in an extensional setting. The Kochinny Cape study area on the White Sea coast presents a unique remnant of a 2.44 Ga mafic dyke swarm that endured ca. 1.9 Ga collision but preserved its primary structural pattern well. All these dykes were intruded along numerous NW-trending shear zones within the Kolvitsa Massif and contain angular xenoliths of sheared gabbro-anorthosite. Every new batch of mafic melt underwent shearing during or immediately after solidification, and later dykes intruded into already sheared dykes. Thus, rocks of the Kolvitsa Massif and its dyke complex were successively injected into a large-scale shear zone which was active from ca. 2.46 to 2.42 Ga. Multiple injection of mafic melts, the presence of mutually intruding, composite, sheared mafic dykes, of magmatic breccias with gabbroic groundmass, and of host rocks fragments (showing no evidence of tectonic stacking at the time of brecciation), all indicate an extensional setting. Shearing was also extensional as it occurred simultaneously with the multistage magmatism. The asymmetric morphology of deformed dykes, and asymmetric flexures within weakly deformed lenses show that all these extensional shear zones, apart from a few exceptions, are dextral, were formed in a transtensional setting and are attributed to general W–E to WSW–ENE extension. Structural data available for 2.4–2.5 Ga magmatic rocks elsewhere in the Kola region suggest that the same kinematics operated on a regional scale. The presence of the

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\* Corresponding author.

*E-mail address:* balagan@geoksc.apatity.ru (V.V. Balagansky).

garnet-bearing assemblages in gabbro-anorthosite and dykes may be explained by crystallisation and shearing of the magmatic rocks at deep crustal levels. Alternatively, corona development might have occurred much later as a result of tectonic loading due to the juxtaposition and overthrusting of the Umba Granulite Terrane onto the Kolvitsa Belt at ca. 1.9 Ga. In view of the field evidence and published ages, an overall extensional setting rather than a combination of compressional and extensional zones is preferable for Palaeoproterozoic tectonics in the north-eastern Fennoscandian Shield at 2.5–2.4 Ga. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Magmatism; Shear zone; Transtension; Palaeoproterozoic; Kola peninsula

## 1. Introduction

In the North Atlantic Province, like many ancient shields, the start of the Palaeoproterozoic was characterised by rifting and break-up of Neoarchaean cratons and the emplacement of 2.4–2.5 Ga mafic dyke swarms and layered mafic intrusions (Zagorodny and Radchenko, 1988; Balashov et al., 1993; Shcheglov et al., 1993; Heaman, 1994; Park, 1994; Bridgwater et al., 1995; Amelin et al., 1996). David Bridgwater (Bridgwater et al., 1994, 1995) was one of the researchers who demonstrated that studies of these dyke swarms can provide crucial data on their emplacement mechanism, the thermo-tectonic evolution of the Palaeoproterozoic, and their use for correlations between fragments of Nena, the Palaeoproterozoic continent (acronym Northern Europe–North America). Earliest Palaeoproterozoic rifting appears to have been limited in Labrador, Greenland and Scotland, and dykes are the only markers of the Palaeoproterozoic tectonic regime in these regions. Many of the dyke swarms show evidence of being syn-tectonic in the sense that their emplacement was coeval with regional shearing of the Archaean host rocks. In some areas the earliest dykes were intruded in an extensional (Bridgwater et al., 1995) and in others in a compressional environment (Park, 1994). In many cases, dyke emplacement occurred along shear zones.

In the Kola region of the north-eastern Fennoscandian Shield, both Palaeoproterozoic rift-belts and coeval mafic dykes swarms are widespread. The early Palaeoproterozoic tectonic setting for the entire region is disputed, and tectonic models for the 2.4–2.5 Ga period usually propose

(i) an overall extensional setting; or (ii) a combination of extensional and compressional zones. The basic point of all models is the fact that the Pechenga and Imandra–Varzuga palaeorifts (Fig. 1A) originated in an extensional setting 2.3–2.5 Ga ago, and this environment is thought to have been characteristic for the entire Kola region (Zagorodny and Radchenko, 1988; Shcheglov et al., 1993). One of the rift-related units is the Kolvitsa Belt and the 2.45–2.46 Ga Kolvitsa Massif of metagabbro-anorthosite (Fig. 1B), believed to have formed in a compressional setting (Mitrofanov et al., 1995a; Mitrofanov and Bayanova, 1997). Anti-clockwise P–T–t paths at ca. 2.45–2.40 Ga, as deduced from garnet-bearing metamorphic assemblages in the Kolvitsa Massif, have been interpreted to indicate a subduction setting (Alexejev, 1997). As a result, a synchronous ‘extension-compression’ geodynamic model has been suggested for the Kola region, named the ‘Kola rift-obduction system’ (Mitrofanov et al., 1995c; Mitrofanov and Bayanova, 1997). This paper presents data on a unique remnant of a 2.44 Ga dyke swarm within the 2.45–2.46 Ga Kolvitsa Massif, which has endured a ca. 1.9 Ga collision event, but still preserved its primary structural pattern. The data indicate an extensional setting for the Kolvitsa Belt and provide new insights into the geological evolution of the Kola region in earliest Palaeoproterozoic times.

## 2. Geological setting of the Kolvitsa Belt

The mafic metavolcano–plutonic Kolvitsa Belt, KB (below the prefix ‘meta-’ is omitted) is well

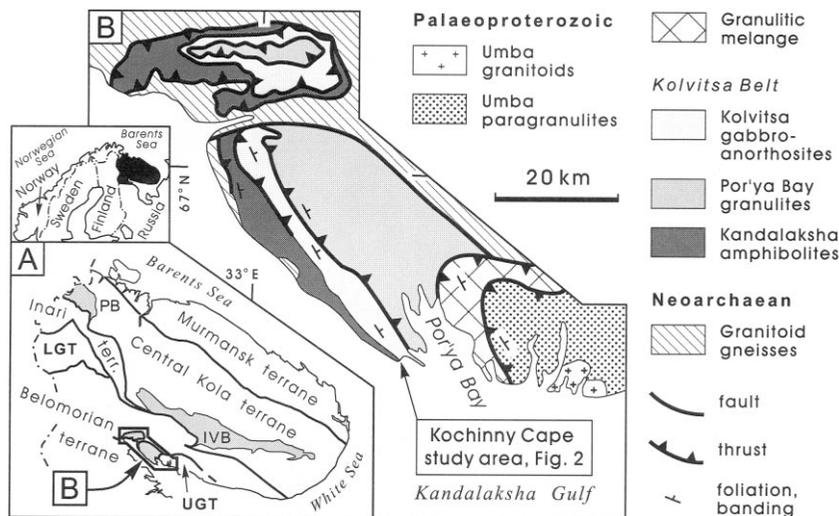


Fig. 1. (A) Palaeoproterozoic tectonostratigraphic terranes in the Kola region (modified after Balagansky et al., 1998a). Dispersed terranes largely made up of Neoproterozoic rocks (fragments of a rifted Neoproterozoic craton): Belomorian, Central Kola, Inari and Murmansk composite terranes. Accreted terranes made up of Palaeoproterozoic rocks (tectonic packages of island-arc formations): Lapland Granulite (LGT) and Umba Granulite (UGT) terranes; Palaeoproterozoic rift-belts: Imandra-Varzuga (IVB), Kolvitsa and Pechenga (PB) belts. (B) Simplified geological map of the Palaeoproterozoic Kolvitsa Belt (after Mitrofanov, 1996).

exposed on the north-eastern coast of the Kandalaksha Gulf of the White Sea and is interpreted to be an extension or close analogue of the Tanaelv Belt in northern Finland and Norway. Several gently NE-dipping lithotectonic units can be distinguished (Fig. 1B). The oldest and structurally lowermost rocks are 'Belomorian' granitoid gneisses, dated at 2.7 Ga (U–Pb method, Tugarinov and Bibikova, 1980; Balagansky et al., 1998b). These are largely tectonically overlain by strongly lineated amphibolites (metabasalts) and subordinate intercalated biotite-amphibole gneisses (meta-andesites) of the Kandalaksha sequence (Priyatkina and Sharkov, 1979; Vinogradov et al., 1980). The mafic to intermediate metavolcanics of the Kandalaksha sequence yielded a  $2.50 \pm 0.05$  Ga Rb–Sr isochron age, magmatic zircon from a meta-andesite yielded a U–Pb crystallisation age of 2.47 Ga, and magmatic zircon from a granitoid boulder from a basal conglomerate at Pentelsky Cape yielded a minimum Pb–Pb age of 2.58 Ga (Balagansky et al., 1998b).

The Kolvitsa Massif of gabbro-anorthosite has a 2.45–2.46 Ga crystallisation age (Mitrofanov et

al., 1995b; Frisch et al., 1995) and separates the Kandalaksha sequence from the Por'ya Bay Complex (PBC) to the north-east. At Kochinny Cape this Massif is cut by mafic to intermediate dykes (Fig. 1B and Fig. 2A, Balagansky and Kozlova, 1987; Bridgwater et al., 1995) which have yielded 2.43–2.44 Ga U–Pb zircon ages (Kaulina, 1996; Balagansky et al., 1998b). Metamorphic zircons from the Massif have been dated at 2.42–2.44 Ga (U–Pb method, Mitrofanov et al., 1995b; Balagansky et al., 1998b). Much younger U–Pb zircon ages indicate that both gabbro-anorthosite host rock and dykes underwent a thermal event at 1.90–1.92 Ga (Frisch et al., 1995; Kaulina, 1996).

The PBC is made up of intercalated mafic to intermediate granulites that contain high-pressure garnet-clinopyroxene assemblages (Priyatkina and Sharkov, 1979; Vinogradov et al., 1980; Krylova, 1983; Timmerman et al., 1997). Rb–Sr and Sm–Nd isotope systematics of these rocks are similar to those of the Kandalaksha sequence and the Kolvitsa Massif (Balagansky et al., 1998b). This, combined with ca. 2.3 Ga U–Pb ages for metamorphic zircons (Kaulina, 1996) suggest that the age of their protoliths is likely to be 2.4–2.5 Ga.

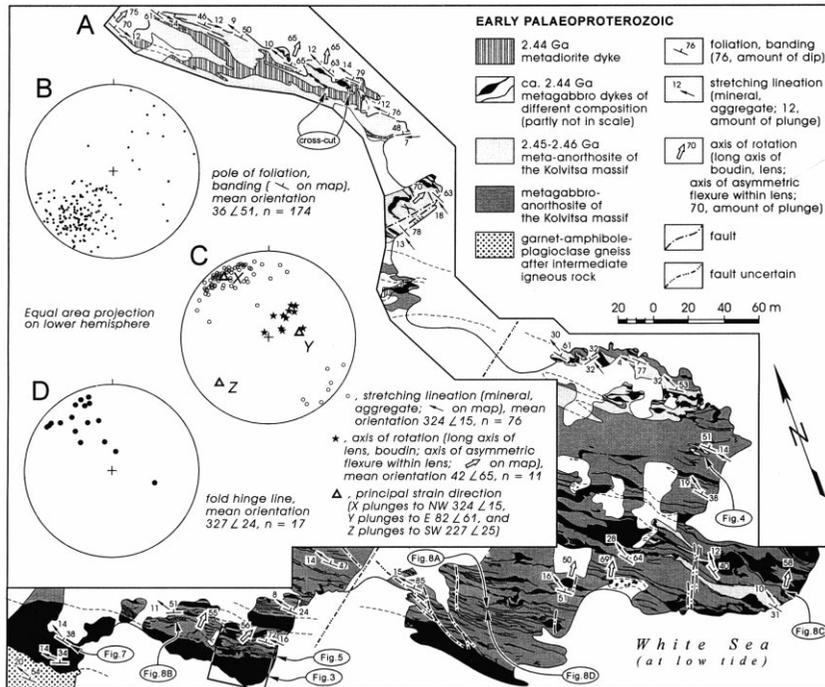


Fig. 2. (A) Geological map of the Kolvitsa gabbro-anorthosite Massif at the Kochiny Cape area (compiled using data of V.A. Alekseyev, V.V. Balagansky, M.N. Bogdanova and N.Ye. Kozlova). (B–D) Orientation of planar (B) and linear (C, D) fabrics. The plots were drawn using FABRIC-3, a computer program package for the evaluation of orientation data by E. Wallbrecher and W. Unzog. Arrows labelled ‘cross-cut’ indicate places where diorite dykes cross-cut older mafic dykes.

The transition of amphibolite- to granulite-facies mineral assemblages occurs within the central parts of the Kolvitsa metagabbro-anorthosite and is parallel to its NW–SE strike (Priyatkina and Sharkov, 1979). The available age data imply that the Kolvitsa Belt is coeval with the earliest Palaeoproterozoic (‘Sumian’) rift-belts and layered mafic intrusions in the Fennoscandian Shield.

On the north-eastern coast of Por’ya Bay, a high-grade shear zone is exposed that formed during the juxtaposition and thrusting of the overlying metasedimentary Umba Granulite Terrane (UGT, Fig. 1B) onto the Kolvitsa Belt under high-pressure granulite-facies conditions (Priyatkina and Sharkov, 1979; Vinogradov et al., 1980; Krylova, 1983). This zone represents a granulite-facies tectonic mélangé within which Por’ya Bay mafic to intermediate orthogneisses and UGT paragneisses form tectonic lenses that range from a few metres to a few kilometres long. The lenses

are separated by high-pressure, strongly lineated granulite-facies ultramylonites (orthopyroxene-sillimanite assemblages; Balagansky et al., 1986a; Kozlova et al., 1991). The UGT is generally regarded to be the south-easternmost extension or close analogue of the Lapland Granulite Belt in northern Finland and Norway. Zircons from paragneisses metamorphosed and sheared under granulite-facies conditions during mélangé formation have yielded U–Pb ages of ca. 1.9 Ga (Tugarinov and Bibikova, 1980; Kislitsyn et al., 1999). Sm–Nd model ages of the Umba metasedimentary granulites vary from 2.1 to 2.5 Ga, i.e. the time of fractionation of the Sm–Nd ratio during the formation of new continental crust from the mantle (DePaolo, 1981). This in combination with the ca. 1.9 Ga age of metamorphism strongly suggests that deposition of their sedimentary protoliths occurred at ca. 2.0 Ga (Timmerman, 1996; Daly et al., 2000 this volume).

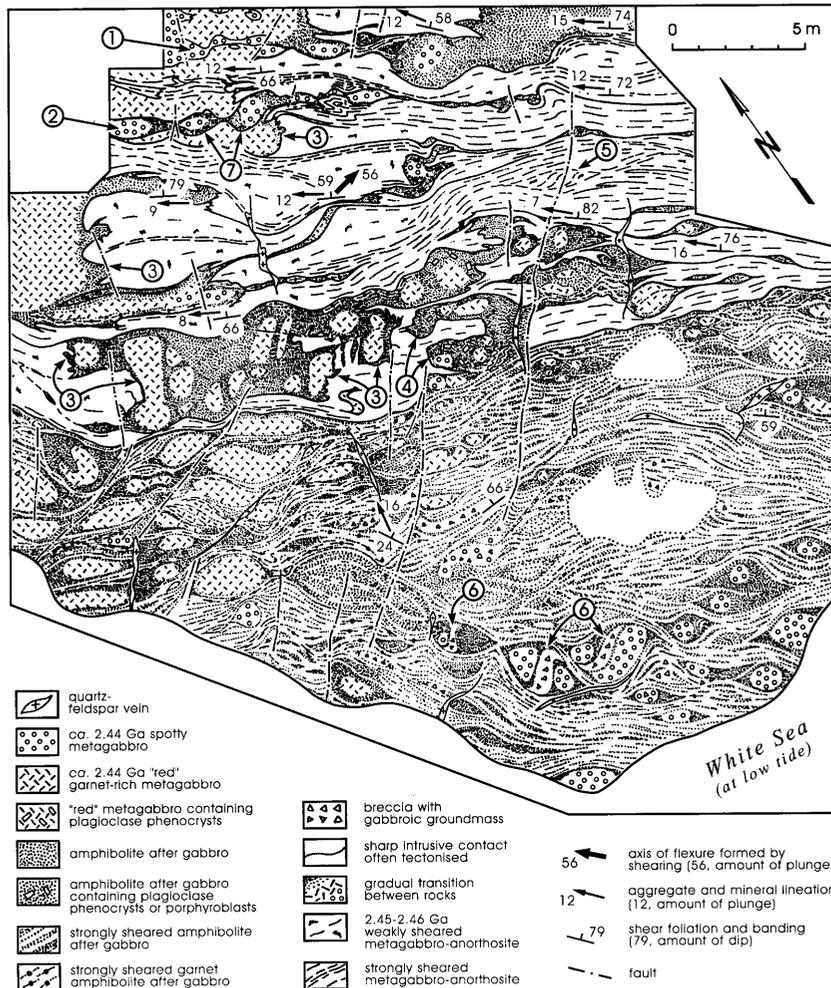


Fig. 3. Detailed map of the southern contact of the Kolvitsa gabbro-anorthosite Massif in Kochinny Cape. Numbered arrows indicate younger gabbro cross-cutting older gabbro and its gabbro-anorthosite host, resulting in a composite dyke with sheeted structure (1, 2), dykes with stubby morphology (3), apophyses with stubby morphology (4), asymmetric flexure within a lens of weakly deformed gabbro-anorthosite (5), brecciation zones of specific mafic dykes with abundant host fragments (6), and asymmetric boudins of a younger dyke within an undeformed older dyke (7).

### 3. Kochinny Cape study area

The study area is well exposed and is situated at the south-western margin of the Kolvitsa Massif of gabbro-anorthosite on the northern White Sea coast where it was mapped on a scale of 1:200 (Fig. 2A). Sheet-like mafic bodies are ubiquitous (Fig. 2A and Fig. 3) and have previously been interpreted as xenoliths of the Kandalaksha sequence amphibolites within the Kolvitsa Massif

(Priyatkina and Sharkov, 1979; Vinogradov et al., 1980). In contrast, Balagansky and Kozlova (1987) reported strong field evidence that these bodies are anastomosing mafic dykes of at least two generations, which cross-cut the metamorphosed, sheared and folded gabbro-anorthosite host (Fig. 4). Later, Balagansky et al. (1998b) established that the intrusion of these dykes occurred ca. 2.44 Ga ago, i.e. shortly after the crystallisation and shearing of the Kolvitsa Mas-

sif. All dykes underwent the same reworking history (Balagansky and Kozlova, 1987; Bridgwater et al., 1995) during which both gabbro-anorthosite host and dykes were metamorphosed under high-pressure amphibolite-facies conditions (Alexejev, 1997; Glebovitsky et al., 1997). In gabbro, gabbro-anorthosite and troctolite, ubiquitous garnet - orthopyroxene-amphibole/clinopyroxene  $\pm$  spinel coronas developed between igneous olivine or orthopyroxene, and plagioclase. In addition, ilmenite and plagioclase in anorthosite reacted to titanite-garnet-epidote/clinozoisite  $\pm$  chlorite coronas.

### 3.1. Kolvitsa Massif

The study area is made up by gabbro-anorthosites and anorthosites. The gabbro-anorthosite is strongly sheared, with locally preserved remnants of massive, medium-grained varieties with ophitic textures. In these remnants, igneous clinopyroxene and hornblende frequently developed garnet  $\pm$  clinopyroxene rims against plagioclase that form a corona texture. The anorthosite is also sheared, but very often has well-preserved massive, igneous textures formed by large and often euhedral, magmatic labradorite crystals (An<sub>65</sub>) up to 10 cm long. These rocks constitute a 600 m thick and ca. 60 km long

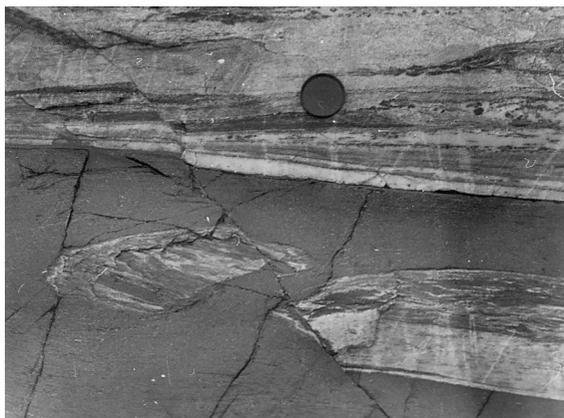


Fig. 4. Anastomosing mafic dykes cross-cutting foliated and metamorphosed anorthosite and gabbro-anorthosite. For location see Fig. 2A. (Hereafter: exposure surfaces are (sub)horizontal; the camera cap is 4 cm in diameter).

sheet-like unit that is interpreted to be a member of the large-scale layering of the Kolvitsa Massif (Priyatkina and Sharkov, 1979; Vinogradov et al., 1980). The bottom part of this anorthosite unit is exposed in the study area. In addition, a few thin anorthosite units occur within the gabbro-anorthosites (Fig. 2A). All these units have sharp contacts with the sheared gabbro-anorthosite host and one of them cuts a gabbro-anorthosite that had previously been strongly sheared, folded and completely metamorphosed into leucocratic garnet amphibolite (Balagansky et al., 1986b).

Amphibolites that structurally underlie the gabbro-anorthosites represent a metamorphosed composite mafic dyke (Fig. 2A and Fig. 3 Balagansky and Kozlova, 1987; and this study), rather than metabasalts of the Kandalaksha sequence (Priyatkina and Sharkov, 1979; Vinogradov et al., 1980; Krylova, 1983). Garnet–amphibole–plagioclase orthogneisses of intermediate composition that structurally underlie this dyke (Fig. 2A) possibly represent the host rocks of the Kolvitsa Massif, but later deformation has obscured all older relations.

### 3.2. Kochinny Cape dyke swarm

#### 3.2.1. Composition and injection succession

The mafic dykes differ very much from each other in structure, texture and mineralogy. They belong to several generations, as is clear from their mutual cross-cutting relations. The earliest dykes are fine-grained (<0.5 mm) garnet-rich rocks with homogeneous textures. Relics of magmatic minerals are represented by only clinopyroxene, usually replaced by hornblende and garnet. The garnet content is very high (locally up to 45%), giving these rocks a dark-red colour. Corona textures similar to those in the massive gabbro-anorthosite are typical. The plagioclase content is low (10–12%) and in very rare cases plagioclase forms small phenocrysts.

Porphyritic gabbro dykes of the second generation contain phenocrysts of a relatively Ca-rich plagioclase (ca. An<sub>65</sub>) locally up to 7 cm long. Phenocrysts are distributed irregularly in a characteristically spotty, fine-grained groundmass

(spotty texture). Moreover, large parts of such porphyritic gabbro dykes may be phenocryst-free. The spotty texture is formed by isometric, dark-green, fine-grained (<0.5 mm) garnet–hornblende–diopside–plagioclase segregations set in a black, fine-grained plagioclase–hornblende groundmass. Corona textures are also common in this generation of dykes. The density of these segregation varies from isolated spots to spots that are in close contact with each other, thus giving the appearance of a groundmass that contains angular plagioclase–hornblende segregations. The third generation consist of spotty gabbro dykes that are identical in appearance to those of the second generation, but are free of phenocrysts (as in Fig. 4). Dykes of this generation cut sheared porphyritic gabbro dykes or contain angular xenoliths of them. Both spotty gabbro dyke generations constitute the majority of the dykes at Kochinny Cape. In agreement with David Bridgwater (pers. comm. to V.B., 1995), we suspect that dykes with these compositions actually form many more generations, but much further field work would be required to establish necessary cross-cutting relations.

Thin hornblendite dykes usually a few centimetres wide consist mainly of hornblende and actually are monomineralic. These are perhaps the youngest generation because they cross-cut strongly sheared older mafic dykes and the gabbro-anorthosite host and contain angular xenoliths of both (Fig. 5). The morphology of the thinnest anastomosing dykes very much resembles a network of undeformed cracks and joints; nevertheless, some parts of these dykes underwent ductile deformation.

Despite the obvious cross-cutting relations between the ‘red’, porphyritic and spotty gabbros, they locally show gradual mutual transitions. This implies firstly that injections of different magmas sometimes took place simultaneously and secondly, that melt that gave rise to gabbro of a certain type was injected repeatedly.

Apart from the hornblendites and a few places considered below (Section 3.2.6), all dyke margins are usually strongly foliated or sheared and transformed into various amphibolite types (Fig. 3). Thin granitoid veins occur in some foliated mar-



Fig. 5. Hornblendite dyke with angular, square xenolith of gabbro-anorthosite. Two black bands within the xenolith are mafic dykes that were strongly sheared jointly with their gabbro-anorthosite host. Note that another xenolith of the same dykes and gabbro-anorthosite is marked by a borehole, located near the right side of the photo. For location see Fig. 2A (Hereafter: the compass size is 11 by 8cm and oriented to the north).

gins. Younger dykes cross-cut both non-foliated and foliated older dykes.

Dioritic dykes also form an anastomosing complex. Their thickness varies from a few centimetres to 10–15 m. These dykes cross-cut at least the spotty gabbro dykes, which can be seen in outcrops and on a map scale (Fig. 2A). In contrast to the mafic dykes, the dioritic ones are completely foliated and contain no magmatic minerals, apart from zircon.

### 3.2.2. Isotopic ages

No magmatic zircon has been found in any of the mafic dykes so far. Their anorthosite host yielded U–Pb zircon ages of  $2450 \pm 7$  Ma (Mitrofanov et al., 1995b) and  $2462 + 7 / - 6$  Ma (Frisch et al., 1995) that overlap within error. These zircons have been shown to be igneous in origin (Mitrofanov et al., 1995b). Spotty mafic dykes (second and third generations) are cross-cut by dioritic dykes. Zircons from one diorite show fine-scale euhedral zoning of the igneous type, contain no inherited cores and yielded a U–Pb age of  $2436 \pm 6$  Ma, which is interpreted as the age of magmatic crystallisation (Kaulina, 1996). Thus, the overwhelming majority of the dykes in question were injected during a short time span,

from  $2450 \pm 7$  Ma and  $2436 \pm 6$  Ma. Since younger dykes were injected into older, already sheared dykes, shearing and metamorphism took place in the same time interval. Furthermore, structural and metamorphic reworking must have continued after the emplacement of the  $2436 \pm 6$  Ma dioritic dykes because these also underwent strong shearing. This is in keeping with that both sheared mafic dykes and their gabbro-anorthosite host contain metamorphic zircon with ages ranging from  $2423 \pm 3$  Ma (Mitrofanov et al., 1995b) to  $2437 \pm 10$  Ma (Balagansky et al., 1998b).

Zircon from a hornblendite dyke of the youngest generation yielded a U–Pb age of  $2431 \pm 3$  Ma (Bogdanova et al., 1993). Dykes of this kind are only locally and weakly deformed, which suggests that shearing had largely terminated by 2.43 Ga. To check this suggestion, one of the authors (V.V.B.) together with David Bridgwater collected a sample from a pegmatite that cross-cuts strongly sheared dioritic and mafic dykes, but is not deformed itself. The zircons in this sample are well-formed crystals that exhibit fine-scale euhedral magmatic zoning, and have neither inherited cores nor metamorphic overgrowths. These zircons yielded a U–Pb age of  $2387 \pm 4$  Ma (unpublished results of R. Kislitsyn). This age is interpreted as the time of magmatic crystallisation and provides clear evidence that all younger thermal events in Kochinny Cape mainly took place under static conditions.

The main stages of the history of the Kochinny Cape area are summarised in Table 1.

### 3.2.3. Major element and isotope geochemistry

The major element fractionation trend of and the difference in Fe/Mg ratios between the mafic dykes are shown in Fig. 6. Apart from porphyritic gabbros, the total contents of major elements are comparable to normal tholeiites (Table 2) and all the dykes belong to the tholeiitic series. The porphyritic gabbros fall into the calc-alkaline field. However, these gabbros are often characterised by the presence of plagioclase phenocrysts that are irregularly distributed within a single dyke, with some parts of dykes displaying an abundance of phenocrysts and their glomerocryst-like aggregations, whereas other parts are phenocryst-free.

This suggests that the calc-alkaline trend of the porphyritic gabbros was due to the enrichment of plagioclase phenocrysts and that the gabbros should also be considered to belong to the tholeiitic series.

Sr initial ratios at 2.45 Ga and  $\epsilon_{\text{Nd}}$  (2.45 Ga) values of the Kolvitsa Belt igneous rocks vary from 0.7011 to 0.7027 and from +0.3 to –0.6 respectively (Balagansky et al., 1998b) and overlap with those of other 2.45–2.50 Ga layered mafic intrusions in the Fennoscandian Shield (Balashov et al., 1993; Amelin and Semenov, 1996). For these intrusions Amelin and Semenov (1996) suggested either a mantle plume source with insignificant crustal contamination, or an enriched mantle source origin. Similar mantle sources for the parent melt(s) of the Kolvitsa Belt were suggested by Balagansky et al. (1998b).

### 3.2.4. Sheeted structures

Later dykes very frequently intruded into earlier ones, thus forming composite dykes with sheeted structures (Balagansky and Kozlova, 1987; Bridgwater et al., 1995). In some cases cross-cutting relations between later and earlier gabbros are prominent (Fig. 3). Injections of new magma batches frequently took place parallel to dyke walls; cross-cutting relations between the numerous gabbroic varieties, together constituting a single dyke, were established in a few places. Composite dykes of this kind very much resemble 100% sheeted dykes. As a rule, all large dykes are composite.

### 3.2.5. Magmatic breccias

No breccias with anorthositic or gabbro-anorthositic groundmass as mentioned in Priyatkin and Sharkov (1979) have been found during this study, but intrusion breccias with gabbroic groundmass are often present within many mafic dykes. These breccias contain numerous fragments of the host dykes and formed as a result of emplacement of later mafic melts into releasing bends during syn-magmatic deformation. Thus, these actually represent younger dykes of a specific type, characterised by their limited length and an abundance of xenoliths. This is supported by the initial sheet-like morphology of

Table 1  
Succession of geological events in the Kochinny Cape area and the Kolvitsa Belt (*in italics*)

| Geological event   | Isotopic age, Ma  |
|--|---|
| Cooling below ca. 600°C in the Kochinny Cape area (closure temperature of the Sm–Nd system in garnet, Mezger et al., 1992)                               | 1889 ± 30 <sup>a</sup> , 1884 ± 28 <sup>a</sup> (Alexejev et al., 1999)                       |
| <i>Cooling below ca. 600°C in the high-pressure granulite-facies tectonic melange (closure temperature of the Sm–Nd system in garnet)</i>                | 1891 ± 8 <sup>a</sup> (Alexejev et al., 1999)   |
| Thermal event in the Kochinny study area   | 1905 ± 26 <sup>b</sup> (Frisch et al., 1995),   |
| Migmatisation post-dating shearing in the melange  | 1919 ± 18 <sup>b</sup> (Kaulina, 1996)  |
| Juxtaposition of the Umba Granulite Terrane and the Kolvitsa Belt; formation of the high-pressure granulite-facies tectonic melange                      | 1912 ± 2 <sup>b</sup> (Kislitsyn et al., 1999)  |
| Granulite-facies metamorphism of the Umba Granulite Terrane  | 1910 ± 60 <sup>b</sup> (Tugarinov and Bibikova, 1980)   |
| Deposition of sedimentary protoliths of the Umba Granulite Terrane   | ca. 2000 <sup>c</sup> (Daly et al., this volume)  |
| Pegmatite cross-cutting mafic granulites in the Por'ya Bay area  | 2056 ± 3 <sup>b</sup> (Kaulina, 1996)   |
| Sub-alkaline granites cross-cutting mafic granulites in the Por'ya Bay area  | 2289 ± 20 <sup>b</sup> (Kaulina, 1996)  |
| Undeformed pegmatite cross-cutting dykes in the Kochinny Cape area   | 2387 ± 4 <sup>b</sup> (Kislitsyn et al., unpubl. data)  |
| Thermal event dykes in the Kochinny Cape area  | 2394 ± 14 <sup>b</sup> (Balagansky et al., 1998b)   |
| Amphibolite-facies metamorphism and shearing in the Kochinny Cape area   | 2428 ± 9 <sup>b</sup> (Balagansky et al., 1998b)  |
| Emplacement (?) of hornblende dykes in the Kochinny Cape area  | 2431 ± 3 <sup>b</sup> (Bogdanova et al., 1993)  |
| Emplacement of diorite dykes in the Kochinny Cape area   | 2436 ± 6 <sup>b</sup> (Kaulina, 1996)   |
| Amphibolite-facies metamorphism and shearing in the Kochinny Cape area   | 2437 ± 10 <sup>b</sup> (Balagansky et al., 1998b)   |
| Multiple injection of mafic dykes, mainly spotty and porphyritic varieties; injection of composite dykes with sheeted structures; coeval shearing        |   |
| Amphibolite-facies metamorphism and shearing in the Kochinny Cape area   |   |
| Crystallisation of anorthosites of the Kolvitsa Massif in the Kochinny Cape area   | 2450 ± 7 <sup>b</sup> (Mitrofanov et al., 1995b)  |
| Amphibolite-facies metamorphism and shearing in the Kochinny Cape area   | 2462 ± 7/–6 <sup>b</sup> (Frisch et al., 1995)  |
| Crystallisation of gabbro-anorthosites of the Kolvitsa Massif at Kochinny Cape   |   |
| Formation of volcanic and sedimentary protoliths of the Kandalaksha sequence amphibolites and the Por'ya Bay Complex of mafic to intermediate granulites | 2497 ± 50 <sup>d</sup> , 2467 ± 3 <sup>b</sup> (Balagansky et al., 1998b)                     |
| Deformation, metamorphism, exhumation, erosion, pebbles and boulders of granitoid gneisses   | 2583 ± 6 <sup>b</sup> , minimal age of granitoid making up boulder (Balagansky et al., 1998b) |
| Formation of magmatic protoliths of the 'Belomorian' granitoid gneisses  | 2700 ± 50 <sup>b</sup> (Tugarinov and Bibikova, 1980)   |
|  | 2708 ± 10 <sup>b</sup> (Balagansky et al., 1998b)   |

<sup>a</sup> Sm–Nd dating on garnet.

<sup>b</sup> U–Pb dating on zircon.

<sup>c</sup> Based on Sm–Nd model ages from metasedimentary granulites and U–Pb ages of metamorphic zircons.

<sup>d</sup> Rb–Sr dating on whole rock samples.

Table 2  
Representative major element analyses of the Kochinny Cape mafic dykes<sup>a</sup>

| Sample  | SiO <sub>2</sub> | TiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | FeO   | MnO  | MgO  | CaO   | Na <sub>2</sub> O | K <sub>2</sub> O | H <sub>2</sub> O <sup>-</sup> | P <sub>2</sub> O <sub>5</sub> | CO <sub>2</sub> | S <sub>tot</sub> | LOI  | Total  |
|---|------------------|------------------|--------------------------------|--------------------------------|-------|------|------|-------|-------------------|------------------|-------------------------------|-------------------------------|-----------------|------------------|------|--------|
| <i>'Red' gabbro (first generation dykes)</i>      |                  |                  |                                |                                |       |      |      |       |                   |                  |                               |                               |                 |                  |      |        |
| 1019-1  | 45.61            | 1.26             | 15.33                          | 2.11                           | 13.10 | 0.25 | 8.30 | 11.25 | 1.93              | 0.19             | 0.00                          | 0.07                          | 0.07            | 0.09             | 0.57 | 100.13 |
| 1019-3  | 47.63            | 1.06             | 16.40                          | 1.93                           | 9.79  | 0.19 | 8.59 | 10.77 | 2.20              | 0.50             | 0.10                          | 0.06                          | 0.06            | 0.00             | 0.43 | 99.71  |
| 1023-1  | 45.33            | 0.68             | 14.18                          | 4.66                           | 13.22 | 0.24 | 7.17 | 10.92 | 1.83              | 0.15             | 0.00                          | 0.14                          | 0.08            | n.d.             | 0.80 | 99.40  |
| 1034-3  | 46.71            | 1.09             | 15.90                          | 1.66                           | 9.69  | 0.20 | 8.99 | 9.85  | 2.30              | 0.72             | 0.53                          | 0.06                          | 0.15            | 0.06             | 1.61 | 99.52  |
| Porphyritic gabbro (second generation dykes)      |                  |                  |                                |                                |       |      |      |       |                   |                  |                               |                               |                 |                  |      |        |
| K-3   | 48.98            | 0.66             | 21.39                          | 1.42                           | 6.30  | 0.13 | 4.98 | 10.98 | 2.72              | 0.55             | 0.20                          | n.d.                          | 0.14            | 0.23             | 0.94 | 99.62  |
| 1001-1  | 48.05            | 0.85             | 19.26                          | 1.54                           | 7.84  | 0.15 | 5.84 | 10.44 | 3.13              | 0.64             | 0.11                          | 0.08                          | 0.07            | 0.15             | 1.66 | 99.81  |
| 1002-1  | 47.90            | 0.76             | 20.13                          | 2.07                           | 6.64  | 0.13 | 5.17 | 11.05 | 2.97              | 0.52             | 0.06                          | 0.08                          | 0.05            | 0.15             | 1.78 | 99.46  |
| 1004-1  | 48.03            | 0.71             | 18.35                          | 1.72                           | 8.49  | 0.16 | 7.04 | 11.07 | 2.02              | 0.54             | 0.06                          | 0.05                          | 0.04            | n.d.             | 1.27 | 99.55  |
| 1511-1  | 50.17            | 0.93             | 16.60                          | 2.39                           | 8.34  | 0.16 | 6.30 | 9.15  | 3.57              | 0.66             | 0.04                          | 0.09                          | 0.00            | 0.10             | 1.33 | 99.83  |
| 1524  | 47.94            | 0.54             | 18.30                          | 2.88                           | 7.02  | 0.16 | 7.14 | 10.77 | 2.96              | 1.04             | 0.08                          | 0.04                          | 0.00            | 0.04             | 1.48 | 100.39 |
| Spotty gabbro (second and third generation dykes) |                  |                  |                                |                                |       |      |      |       |                   |                  |                               |                               |                 |                  |      |        |
| 1005-1  | 49.24            | 1.26             | 14.84                          | 2.66                           | 10.23 | 0.21 | 6.32 | 10.18 | 2.62              | 0.41             | 0.14                          | 0.13                          | 0.05            | 0.02             | 1.14 | 99.45  |
| 1006-1  | 51.43            | 1.41             | 13.64                          | 3.00                           | 12.08 | 0.20 | 5.23 | 9.54  | 2.14              | 0.32             | 0.00                          | 0.15                          | 0.00            | n.d.             | 0.72 | 99.86  |
| 1007-1  | 49.28            | 1.21             | 16.34                          | 2.08                           | 10.39 | 0.20 | 6.68 | 10.70 | 2.31              | 0.26             | 0.00                          | 0.09                          | 0.06            | 0.08             | 0.38 | 100.06 |
| 1023-3  | 47.57            | 1.09             | 16.44                          | 1.78                           | 9.97  | 0.17 | 8.56 | 10.85 | 1.87              | 0.21             | 0.00                          | 0.09                          | 0.14            | n.d.             | 0.97 | 99.71  |
| 1034-1  | 48.77            | 1.00             | 16.33                          | 2.17                           | 9.34  | 0.19 | 7.16 | 10.26 | 2.30              | 0.56             | 0.19                          | 0.14                          | 0.07            | 0.00             | 1.03 | 99.51  |
| 1034-2  | 48.60            | 1.46             | 14.97                          | 2.92                           | 10.55 | 0.21 | 6.52 | 10.28 | 2.24              | 0.52             | 0.24                          | 0.14                          | 0.09            | 0.00             | 0.79 | 99.53  |
| 1509  | 47.92            | 1.76             | 13.95                          | 0.43                           | 14.94 | 0.30 | 5.45 | 9.76  | 3.03              | 0.24             | 0.21                          | 0.22                          | 0.05            | 0.02             | 1.43 | 99.71  |
| 1518  | 52.42            | 1.16             | 14.30                          | 2.24                           | 10.05 | 0.20 | 6.04 | 9.30  | 3.13              | 0.55             | 0.06                          | 0.13                          | 0.07            | 0.07             | 0.38 | 100.10 |
| 1520  | 48.61            | 1.31             | 13.61                          | 0.93                           | 12.93 | 0.22 | 6.20 | 10.57 | 2.80              | 0.49             | 0.24                          | 0.14                          | 0.08            | 0.03             | 1.31 | 99.47  |

<sup>a</sup> All samples were analysed at the Geological Institute in Apatity; n.d. = not determined.

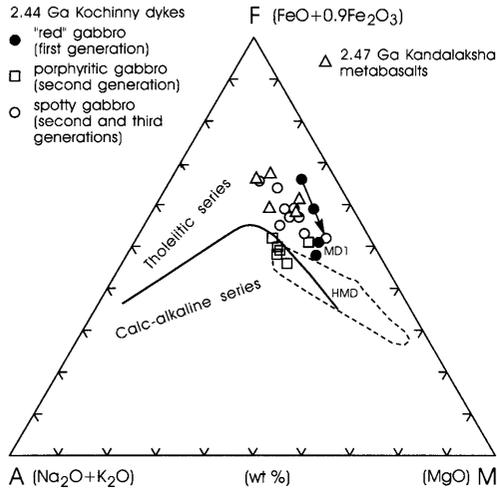


Fig. 6. AFM diagram for the 2.44 Ga Kochinny Cape mafic dykes. The arrow links older and younger gabbros within a composite dyke. Shown for comparison are 2.47 Ga Kandalaksha metabasalts (Vinogradov et al., 1980, and Balagansky et al., unpublished), dyke swarm MD1 and the field of other high-Mg dykes in Greenland (HMD), dated at ca. 2.2 Ga (Bridgwater et al., 1995).

some breccias (Fig. 3). Fragments differing in composition from the host rocks occur in some breccias. The fragments are irregularly distributed in the groundmass and are not in contact with each other (Fig. 7). Breccias are characteristic of the large composite dyke that limits the Kolvitsa Massif to the south-west (Fig. 3). The ground-

mass of some breccias gradually changes into gabbro of the host dykes, which suggests that tectonism and the emplacement of younger dykes (accompanied by extensive brecciation) occurred during and immediately after consolidation of the older dykes.

### 3.2.6. Dyke morphology

Mafic dykes are usually strongly deformed and boudinaged, and pinch-and-swell structures are typical. Nevertheless, many dykes that display pinch-and-swell structures can be traced without any break across the entire study area. A stubby morphology is characteristic of dykes in weakly foliated gabbro-anorthosite host rocks, the dykes displaying practically no signs of deformation and foliation (Fig. 3). Some stubby dykes represent apophyses of larger dykes, which strongly suggests that no post-dyke tectonic movements have occurred (Fig. 3). Thus, the stubby morphology is a primary magmatic feature. Cusped-lobate structures are characteristic of the stubby terminations, with cusps of dyke material penetrating into the gabbro-anorthosite host. This suggests that both dykes and gabbro-anorthosite host underwent ductile deformation, but that the gabbro-anorthosite was more competent.

Fig. 3 shows a spotty dyke, which cross-cuts both gabbro-anorthosite and an older and much thicker, undeformed garnet-rich gabbro. This im-

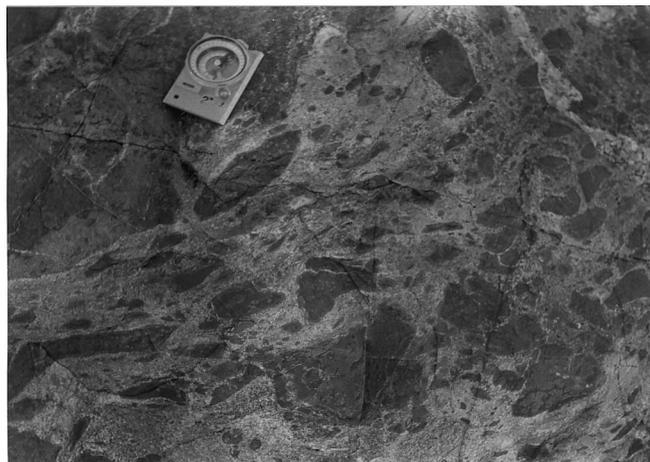


Fig. 7. Breccia with gabbroic groundmass within a composite mafic dyke. For location see Fig. 2A.

plies that the spotty dyke must have preserved its primary morphology within the undeformed gabbro. This conclusion is consistent with the fact that this portion of the dyke is not foliated, underwent amphibolitisation only along its margins, and has a well-preserved primary spotty texture. This is in contrast to the part that is situated within gabbro-anorthosite (a few metres from the non-foliated part south-eastwards, Fig. 3) and is strongly sheared and transformed into an amphibolite layer a few centimetres thick. Therefore, the pinch-and-swell structure of this spotty dyke within the undeformed gabbro is a primary feature, comparable with the primary stubby morphology. Some pinch-and-swell structures of other dykes also seem to have formed at the magmatic stage. The fact that despite the strong deformation the primary morphology of the dykes has been preserved can be explained satisfactorily by syn-tectonic dyke emplacement, which is supported by isotope data (see Section 3.2.2).

Despite being everywhere strongly foliated and deformed, the dioritic dykes show no signs of boudinage or pinch-and-swell structure. One of the NW-trending dykes in the south-west of the study area has been traced for ca. 3.5 km along strike.

## 4. Structural data

### 4.1. Orientation data

Compositional banding, contacts of dykes and planar fabrics generally dip to the NNE at moderate angles (Fig. 2B). Sheared and foliated gabbro-anorthosites, as well as many dykes display mineral and mineral aggregate lineations that plunge very gently to the NW (Fig. 2C). The same orientation is characteristic of stretched plagioclase phenocrysts and garnet–hornblende–diopside–plagioclase segregations, the latter being isometric in undeformed dykes. Long axes of boudins, swells and lenses of less sheared rocks within strongly sheared rocks plunge to the NE and are (sub)perpendicular to the lineation (Fig. 2C). Folds are not characteristic in the study area

and occur only locally. These are open to isoclinal and fold some dykes as well as the planar shear fabrics in both dykes and gabbro-anorthosite host. Where rocks are folded by tight to isoclinal folds and are lineated, lineation and hinge lines are mutually parallel. Hinge lines of folds show a less well-defined preferred orientation and scatter along a great circle; nevertheless their mean orientation is similar to that of the lineation (Fig. 2C and D).

In a few places it was possible to observe the three-dimensional form of deformed garnet–hornblende–diopside–plagioclase segregations: they have strongly flattened and stretched forms similar to prolate ellipsoids. Deformed plagioclase phenocrysts much resemble strongly flattened pencils. This provides the basis for reconstructing the orientation of the strain ellipsoid for the study area. The longest axes of these ellipsoids and ‘pencils’ are parallel to mineral and aggregate lineations, and the mean orientation of the lineation is interpreted as the principal finite strain direction  $X$ . The principal plane  $XY$  of finite strain is defined by the principal strain direction  $X$  and the mean orientation of rotation axes, which allows us to reconstruct the orientation of all three orthogonal principal strain directions (Fig. 2C).

### 4.2. Sense of shear

An asymmetric morphology is very characteristic of many structures, which is best seen in sections parallel to the lineation and perpendicular to the foliation. Sections of this type are characteristic of the overwhelming majority of exposures. This asymmetry implies that deformation was dominated by a simple shear component.

Almost all deformed mafic dykes occur as chains of asymmetric boudins, all of which, apart from a few exceptions, indicate dextral shear (Fig. 3 and Fig. 8A). This sense of shear is also indicated where shear zones cross dykes (Fig. 8B). If a dyke is located within a shear zone, the same shear-sense is indicated by the asymmetrical structure of its sheared margins (Fig. 8C) and/or by asymmetric flexures of foliation and composi-

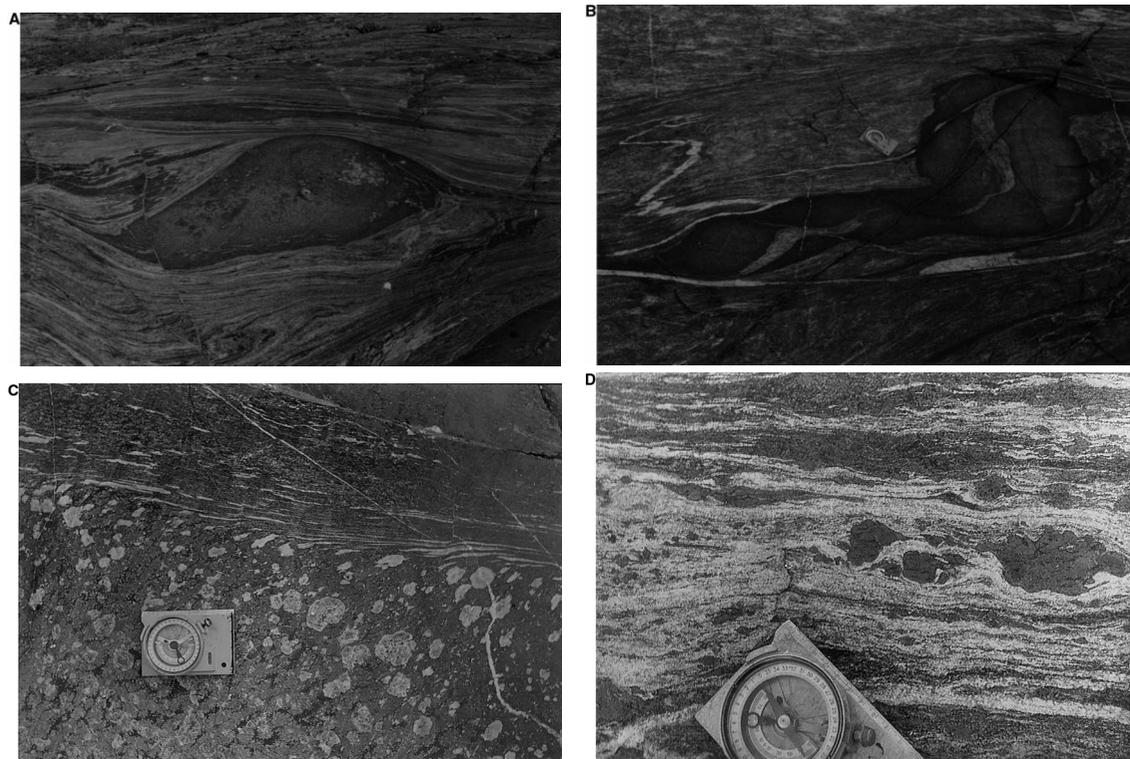


Fig. 8. Dextral shear in the Kochinny Cape study area as shown by: (A) strongly sheared and boudinized mafic dyke in intensely sheared gabbro-anorthosite, (B) shear zones crossing mafic dykes in gabbro-anorthosite, (C) sheared north-eastern margin of a NW-trending porphyritic gabbro dyke, and (D) asymmetric segregation in gabbro-anorthosites. For location see Fig. 2A.

tional banding within swells or boudins of the dyke. Apart from a few exceptions, the shear sense is also dextral for asymmetric flexures within lenses of weakly deformed gabbro-anorthosite surrounded by strongly sheared material (Fig. 3). Right-handed shear is displayed by rigid hornblende-clinopyroxene segregations and their wedge-shaped straight 'tails' which form  $\sigma$ -type structures of monoclinic internal symmetry in gabbro-anorthosites (Fig. 8D). Finally, the asymmetric morphology of the primary magmatic pinch-and-swell structures of the dykes also implies dextral shear (Fig. 3).

Right-handed shear is characteristic of deformed linear brecciation zones within ordinary and composite dykes (Fig. 3). Undeformed parts of these zones represent NE-trending dykes that cross-cut

the NW-trending host dykes and in rare cases display evidence of sinistral shear. According to Ramsay and Huber (1987) NE strike and sinistral shear may be characteristic of secondary Riedel shears  $R_2$  within a NW-trending zone of right-handed shear (see Fig. 9B). This directly shows that the brecciation resulted from dextral shearing along consolidated dykes, and that shearing continued after brecciation.

Thus, all rocks underwent dextral shearing, indicating that the study area is located within a large shear zone. Hinge lines of folds that developed during shearing were undergoing progressive re-orientation into parallelism with the extension direction during incremental shear, but this re-orientation was not fully completed.

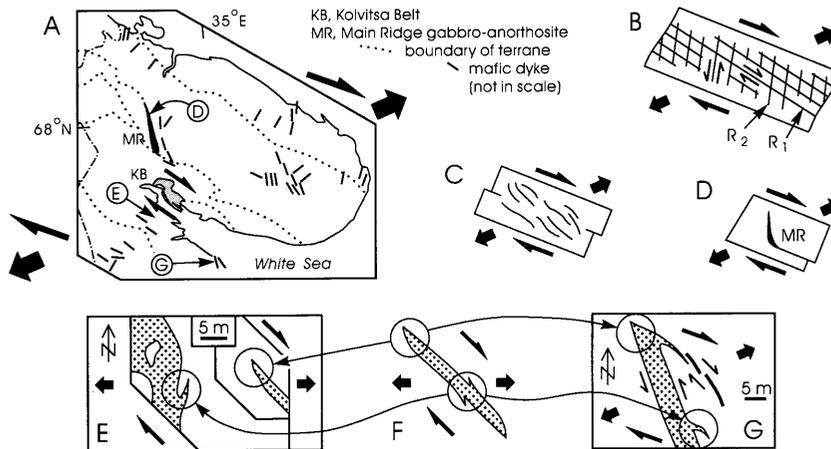


Fig. 9. Orientation of regional crustal extension as shown by orientation and morphology of dykes (modified after Balagansky et al., 1998a). Orientation of: (A) 2.4–2.5 Ga mafic dykes in the north-eastern Fennoscandian Shield (Stepanov, 1990; Shcheglov et al., 1993; Mitrofanov and Smolkin, 1995; Mertanen et al., 1999), (B) conjugate Riedel shears  $R_1$  and  $R_2$  resulting from secondary fault development in a N–W-trending zone of dextral shear (after Ramsay and Huber, 1987), (C) joints developing in a N–W-trending zone of dextral shear due to oblique extension, as shown by experimental modelling (Tron and Brun, 1991). (D) Model of emplacement of the 2.45 Ga Main Ridge gabbro-anorthosite into a releasing bend during dextral transtension. Morphology of: (E) Karelite potassium-rich granite dykes dated at 2.45 Ga (Bibikova et al., 1993), (F) dykes resulting from dextral shear movements (after Morris and Hutton, 1993), (G) mafic dykes of a Iherzolite-gabbroanorthite complex in Karelia (Stepanov, 1990) dated at ca. 2.45 Ga (Slabunov et al., 1999).

## 5. Discussion

### 5.1. Structural control of dyke injection

The overwhelming majority of dykes were intruded along numerous minor shear zones in the Kolvitsa gabbro-anorthosites. All shear zones were formed in the same kinematic setting of dextral movements complicated by a few minor sinistral shear zones. Some pinch-and-swell structures, as well as magmatic brecciation were formed during magma emplacement under conditions of dextral shear. All mafic rocks, including the Kolvitsa gabbro-anorthosite, were sheared prior to injection of later mafic melt batches. The timing of formation of the Kolvitsa Massif and its dyke complex, comprising multiple and alternating phases of melt emplacement and shearing, is constrained by the 2467 Ma age of the Kandalaksha sequence and the  $2387 \pm 4$  Ma age of an undeformed pegmatite that cross-cuts sheared dioritic and mafic dykes. Data in Table 1 suggest that the large-scale transtensional shear zone developed from ca. 2.46 to 2.42 Ga and acted as a

deep conduit for multiply injected mafic (including gabbro-anorthosite) to intermediate melts. David Bridgwater and his colleagues (1994, 1995) and Alexejev (1997) came to similar conclusions.

### 5.2. Extensional vs. compressional setting

An extensional setting during the development of the dykes is strongly implied by the following data:

1. Both mafic dykes of all generations and the dioritic dykes form anastomosing complexes, the most important component of which being mafic composite dykes with sheeted structures. The formation of complexes of this kind (especially sheeted dykes) is possible only in an extensional setting.
2. Numerous magmatic breccias display no tectonic distortion or stacking of the fragments at the time of brecciation. The overwhelming majority of fragments are composed of the host rocks and were usually moved only a few tens of centimetres.

3. Some dykes and their host xenoliths display angular outlines. In Fig. 5 angular xenoliths look like boudins that have moved away from each other, but the dyke morphology shows no signs of compression during dyke injection.
4. Undeformed parts of dykes usually have a NE strike and are not folded, whereas their deformed parts are sheared and stretched along NW-trending shear zones, with dykes and the country rocks displaying very high degrees of plasticity during deformation (for example Fig. 3). If shearing has resulted from N–S or NE–SW oriented compression<sup>1</sup>, less deformed areas would have been characterised by folds that should have developed in the NE-trending, very ductile rocks. This is not the case. Like the NE-trending linear brecciation zones, undeformed NE-trending dykes seem to mark secondary Riedel  $R_2$  shears within a NW-trending zone of dextral shear.

Therefore, the dextral shear zones into which the dykes were intruded are extensional. Also extensional should be both the larger shear zones into which the anorthosites intruded and the large-scale shear zone that acted as a channel for the Kolvitsa Massif gabbro-anorthosite.

The garnet-bearing coronas and assemblages that are widespread in these rocks are indicators of high pressure, which can exist at great depths in both extensional and compressional settings. Such corona textures are mainly the result of diffusion reactions between igneous olivine, orthopyroxene and plagioclase (e.g. Ashworth and Birdi, 1990) and occur in mafic rock of different tectonic setting. The structural and field data presented above in combination with isotope ages, unambiguously show that the Kolvitsa Massif of gabbro-anorthosite and its dyke swarm were formed and sheared in an extensional setting from ca. 2.46 to 2.42 Ga. There are at least two explanations for the formation of the garnet-bearing assemblages. Firstly, the dykes may have intruded into previously thickened crust and crystallised at deep crustal levels (Bridgwater et al., 1994, 1995). A depth of dyke emplacement of ca. 35 km has

been suggested based on thermo-barometry on corona assemblages (10–11 kbar, Alexejev, 1997; Glebovitsky et al., 1997). In this case corona formation would signify an isobaric cooling history following magmatic crystallisation.

Another possibility is that the dykes were emplaced at relatively shallow levels, and a much later high-pressure, high-temperature amphibolite-facies metamorphic overprint took place under relatively static conditions (Timmerman, 1996). For instance, Davidson and van Breemen (1988) showed by dating igneous baddeleyite and metamorphic zircon overgrowths from corona gabbros in the Grenville Province, that the garnet-bearing coronas were a result of a later metamorphic overprint on an igneous mineral assemblage. Thus, the garnet-bearing coronas may have been the response to increasing pressures connected with crustal thickening (e.g. Indares, 1993). This overprint was most likely due to accretion and overthrusting of the Umba Granulite Terrane onto the Kolvitsa Belt. In this scenario, like the first one, corona development occurred at a deep crustal level, but resulted from tectonic loading and burial at ca. 1.9 Ga rather than at ca. 2.4 Ga. Further to the east this accretion event resulted in high-pressure granulite-facies mineral assemblages (e.g. orthopyroxene-sillimanite) in the tectonic melange that separates these units. The presence of ca. 1.9 Ga metamorphic zircons in ca. 2.45 Ga rocks at Kochinny Cape (Frisch et al., 1995; Kaulina, 1996) favours this tectonic burial scenario.

We suggest that the evidence from Kochinny Cape indicate that extension and magmatism in the Kolvitsa Belt occurred simultaneously with the formation of the earliest Palaeoproterozoic belts (such as the Pechenga and Imandra-Varzuga belts) during rifting of a Neoarchean craton. The depth of intrusion of the Kolvitsa Massif and its dykes and the timing of the garnet-bearing coronas and assemblages remain unclear so far.

### 5.3. Kinematics

The Kochinny Cape dyke swarm intruded in a setting in which dyke walls moved away from, and simultaneously parallel to each other due to

<sup>1</sup> Note that all Palaeoproterozoic orientations are referred to present north in the Kola region.

dextral movements, i.e. oblique extension or transtension (Timmerman and Balagansky, 1994; Timmerman, 1996). From the presented structural orientations and shear-sense indicators (see paragraph 4), the direction of general extension at ca. 2.45 Ga is inferred to have been horizontal with a general E–W orientation. Structural data available for 2.4–2.5 Ga magmatic rocks in the Kolvitsa Belt and elsewhere in the Kola region also imply that at that time the Neoarchaean continental crust underwent dextral oblique or transtensional rifting due to a general WSW–ENE extension (Fig. 9). Therefore, the Kochinny Cape area presents an unique example of a 2.44 Ga mafic dyke swarm that has well preserved its primary structural pattern resulted from the emplacement of mafic melts into an active extensional shear zone, despite its location near the 1.9 Ga collisional suture (Priyatkina and Sharkov, 1979; Mitrofanov et al., 1995a,c; Daly et al., 2000 this volume).

The validity of the kinematic reconstruction is supported by palaeomagnetic data that suggest that since ca. 2.45 Ga the Kola and Karelian regions have not been significantly displaced and rotated relative to each other, despite the 1.9 Ga collision (Arestova et al., 1999). The structural pattern resulting from this 1.9 Ga collision (Balagansky et al., 1986a; Balagansky 1992) is the same in the 2.47 Ga Kolvitsa Belt, in the 2.44 Ga Tolstik mafic intrusion (Tolstik Peninsula, NE Belomorian Terrane), and in the Palaeoproterozoic Kukas Lake rift-belt (boundary Belomorian–Karelian terranes). A major and prominent component of the collisional structural pattern is a W–E or WNW–ESE-trending (sub)horizontal lineation that has developed almost throughout the Belomorian Terrane, including the Tolstik Peninsula and the Kolvitsa Belt (Balagansky et al., 1986a; Balagansky 1992). Palaeomagnetic data on the 2.44 Ga Tolstik mafic intrusion suggest that the 1.9 Ga collision resulted in only a rotation of this intrusion around a WNW–ESE-trending horizontal axis (tilting; Krasnova and Gus'kova, 1997) that coincides with the WNW–ESE-trending regional subhorizontal lineation. Therefore, this tilt could not have significantly distorted the primary orientation of the direction

*X* of the principal strain ellipsoid in the ca. 2.42–2.46 Ga Kochinny Cape shear zones as rotation axis and the direction *X* were mutually subparallel. Since the tectonic setting was extensional at 2.42–2.46 Ga (see Section 5.2), the NW-trending subhorizontal direction *X* (Fig. 2C) and dextral movements are crucial for a valid reconstructing of the regional W–E extension.

Early Palaeoproterozoic shear zones were formed in the North Atlantic Province during two stages, 2.6–2.4 and 2.4–2.0 Ga (Park, 1994). In comparison with later stages, the tectonic evolution of the period 2.6–2.4 Ga is the least well-known and shear zones of this age are attributed to a general N–S compression. The period 2.4–2.0 Ga is characterised by widespread extension or transtension, as well as by dextral transtension at about 2.0 Ga. The data presented in this paper suggest that this part of the Shield was subjected to dextral transtensional rifting due to a general WSW–ENE extension from 2.5 Ga to ca. 2.0 Ga.

## 6. Conclusions

The Early Palaeoproterozoic history of the Kolvitsa Belt comprises the deposition of the 2.47 Ga Kandalaksha amphibolite (metabasalt) sequence onto 2.7 Ga granitoid gneisses, the intrusion of the 2.45–2.46 Ga Kolvitsa Massif gabbro-anorthosite and the subsequent multiple injection of mafic dykes and magmatic brecciation, followed by the intrusion of 2.44 Ga dioritic dykes, and shearing of all these dykes and gabbro-anorthosite host at 2.43–2.42 Ga. Field and structural data presented above allow us to conclude the following:

1. All dykes, well exposed in Kochinny Cape on the White Sea coast, form an anastomosing swarm, intruded along numerous NW-trending shear zones within the Kolvitsa Massif, and contain angular xenoliths of sheared gabbro-anorthosite. Every new batch of mafic melt underwent shearing during or immediately after solidification, and later dykes intruded into already sheared older dykes. Thus, rocks of the Massif and its dyke complex were successively injected into a large-scale shear zone which was active from 2.46 to 2.42 Ga.

2. Multiple injection of mafic to intermediate melts, the presence of composite mafic dykes with sheeted structures, and magmatic breccias with a gabbroic groundmass, and the fragments of host rocks (which show no evidence of tectonic stacking at the time of brecciation) strongly indicate an extensional setting. Therefore, the shearing that was simultaneous with the multistage magmatism was also due to extension.
3. The asymmetric morphology of boudins and lenses of dykes, asymmetric flexures and  $\sigma$ -structures indicate that all shear zones are dextral, apart from a few minor sinistral ones. All these zones were formed under transtensional conditions. The mean orientations of the stretching lineation (NW  $324^\circ \angle 15$ ) and shear planes (NE  $36^\circ \angle 51$ ) enable this transtensional shearing to be attributed to a general W–E or WSW–ENE extension. Structural data available for 2.4–2.5 Ga magmatic rocks elsewhere in the Kola region suggest similar kinematics.
4. These data are not comparable with a model of metamorphism in a compressional setting of the Kolvitsa Belt and its gabbro-anorthosite Massif at 2.45–2.42 Ga, i.e. simultaneously with the regional extensional setting in which the Imandra–Varzuga rift-belt and mafic layered intrusions were formed. The presence of high-pressure garnet-bearing coronas and assemblages may be explained by intrusion of mafic melts into previously thickened crust and crystallisation and shearing at great depth in an extensional setting (Bridgwater et al., 1994, 1995). Alternatively, corona development might have occurred much later, at ca. 1.9 Ga, as a result of tectonic loading and burial related to the juxtaposition and overthrusting of the Umba Granulite Terrane onto the Kolvitsa Belt (Timmerman, 1996). In view of the field evidence and published ages, an overall extensional setting, rather than a combination of extensional and compressional zones, is preferable for tectonic development in the north-eastern Fennoscandian Shield at 2.5–2.4 Ga.

## Acknowledgements

We gratefully acknowledge David Bridgwater's interest and encouragement in our study of the Kochinny Cape dyke swarm, which he considered as the best example in the North Atlantic realm. We very much thank V.B. Alekseyev, N.L. Alexejev, M.N. Bogdanova, J.S. Daly, V.A. Glebovitsky, M.M. Yefimov, M. Marker and F.P. Mitrofanov for fruitful discussions of many aspects of the geology of the Kolvitsa Belt and the study area in particular. Some field work would not have been possible without the help of the Kandalaksha State Sanctuary Area and of M.M. Yefimov, for which we are grateful. Two journal referees, R.H. Hall and anonymous one, are appreciated for their constructive criticism of the manuscript and the English correction. M.J.T. acknowledges a travel grant of the ESF (European Science Foundation). This study was financially supported by the Soros' Foundations (grants NM 1000, NM 1300 and s96-1577) and is a contribution to the INTAS-RFBR 95-1330, RFBR 00-05-65468 and SVEKALAPKO-EURO-PROBE projects.

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