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Collision Structures in the Early Precambrian Crust of the Eastern Baltic Shield: A Geological Interpretation of Seismic Data along Profile 4B

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In terms of the DSS-based concept, which was popular in the 1970–1980s, the crustal structure in the eastern Baltic Shield (EBS) was described by a layered–block model [1]. It was suggested that the major EBS structures are large blocks (megablocks) bounded by nearly vertical deep-rooted faults. The gently dipping internal layering within such blocks was regarded as a regular succession of crustal layers including the granulite–basic rock layer in the lower crust, the dioritic layer in the middle crust, and the granitic layer exposed at the present-day surface or overlapped by the Paleoproterozoic volcanosedimentary filling of rift depressions.

The regional seismic research by means of reflection methods on the basis of vibratory sources with a multifold coverage in the observation system, which began operating in 1985, opened up fresh opportunities for study of the crust and upper mantle beneath the ESB [2, 3]. The most complete seismic reflection pattern was obtained in 1999 along profile 4B (GNPP Spetsgeofizika). The profile transected the major geological structures of the ESB including the Late Archean Karelian granite–greenstone terrane (KGGT), the Late Archean–Paleoproterozoic Belomorian gneiss belt with a thrust-faulted internal structure, and the Paleoproterozoic Shombozero (Gaikol) boundary structure related to the East Karelian volcanosedimentary belt (Fig. 1).

The time and migrated CMP sections in combination with sections of the upper crust obtained from DSM were used for the geological interpretation. The methods of geological interpretation applied to the intricate Early Precambrian structures remain poorly developed. Despite the variety of complex and cumbersome procedures of wave field processing, the resulting patterns often cannot be reliably interpreted in geological terms. More trustworthy structural models are issued from the geometry (morphology) of seismic reflection patterns. The correlation of geometric features of seismic reflections with actually observed (mapped) geological objects in the EBS led to the working hypothesis that the reflection patterns mimic the principal directions of rock anisotropy, i.e., the general trends of gneissosity and schistosity in metamorphic rocks and migmatite complexes. In slightly and moderately deformed rocks, they nearly coincide with the orientation of compositional layering including bedding. In highly deformed sequences, these directions commonly fit the orientation of metamorphic schistosity and banding on limbs of tight isoclinal folds and the respective attitude of their axial planes. Experience in the study of metamorphic sequences shows that the major faults follow the same directions. On the regional seismic section with a resolution corresponding to a scale of 1 : 500 000, the selected structural domains (structurally quasi-homogeneus regions) are interpreted as relatively large tectonic sheets 3–5 km and more in thickness. These sheets are composed of gneiss–amphibolite–migmatite complexes that underwent an intense, often isoclinal folding, which is not displayed in reflection patterns.

For the first time in studying the Baltic Shield, we have obtained a detailed seismic reflection pattern along profile 4B (Fig. 2) characterizing the crust and upper mantle from the day surface down to a depth of 80 km (25 s). The density of reflections varies in a wide range without a regular change in reflectance or, on the contrary, in transparency downsection through the crust. Relatively rare and short reflectors are typical of the mantle level. They are mainly grouped into a nearly horizontal zone at a depth corresponding to 20 s. The base of the crust is marked by an abrupt decrease in the number and extent of reflectors. The clearly expressed Moho discontinuity gently plunges toward the eastern end of the profile. Within the crust, reflectors make up

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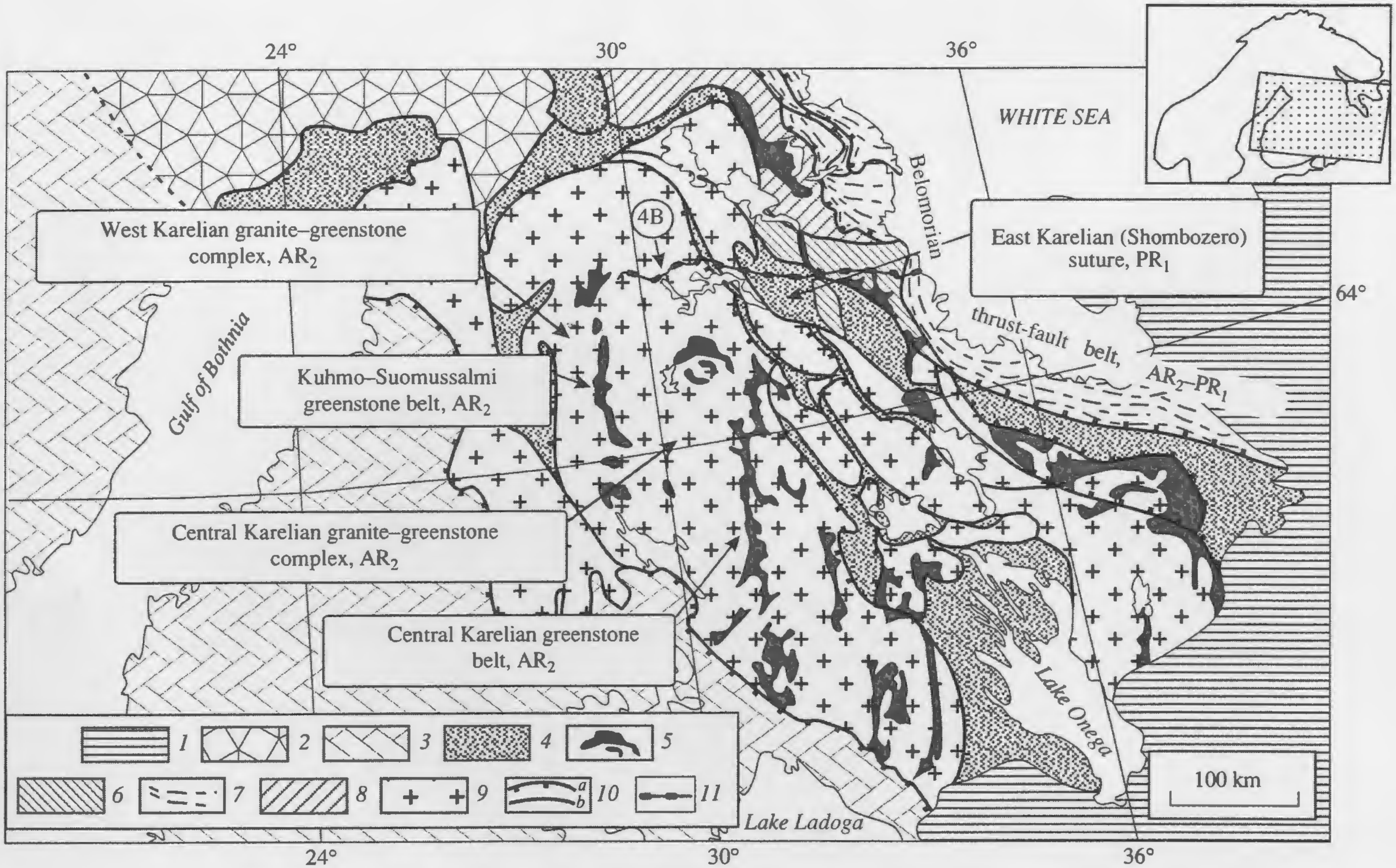

Fig. 1. Geology of the southeastern Baltic Shield and the location of profile 4B. (*1*) Riphean and Phanerozoic sedimentary cover of the Russian Platform; Paleoproterozoic: (*2*) intrusive and volcanic complexes of the Svecofennian active margin, (*3*) volcanosedimentary and intrusive complexes of the Svecofennian accretionary orogen, (*4*) volcanosedimentary belts (sutures and deformed riftogenic basins); (*5*) Late Archean greenstone belts in the Karelian granite–greenstone terrane and Belomorian belt basement; Belomorian belt (Archean–Paleoproterozoic): Belomorian Group including (*6*) upper tectonic nappe composed of granite–greenstone association and (*7*) gneiss–amphibolite complexes of the Khetalamba, Chupa, and Keret nappes; (*8*) granite–greenstone complex of the basement of Belomorian belt; (*9*) Late Archean of the Karelian granite–greenstone terrane (mainly granites and migmatites); (*10*) major upthrow and thrust faults (*a*) with proved orientation of the fault surface and (*b*) other faults; (*11*) profile 4B.

distinct groups and record (with some breaks) the boundaries of gently dipping structural domains.

The combined analysis of seismic data along profile 4B and geological maps of the transect allowed us to interpret the structure of the Early Precambrian crust as a set of eastward plunging nappe–overthrust, overthrust–underthrust assemblages deformed (Figs. 2, 3). The interpretation of reflection pattern and data on spatial distribution of some rated parameters (pseudoacoustic impedance and others) that depend on the petrophysical properties of medium provides the tracing of rock complex boundaries mapped at the surface down to the depth of the Moho. Virtually all major structural units crossed by profile 4B from the west to the east consist of packets of tectonic sheets that extend throughout the entire crust. In most cases, the packet boundaries are flattened out in the lower crust and merge with the Moho.

The tectonic zone separating the Belomorian belt and the Shombozero structure is most prominent (Figs. 2–4). This zone encompasses a series of structurally homogeneous tectonic sheets (domains) with internal elements striking parallel to the main zone. At the present-day erosional level, the Shombozero structure is a low-angle antiform, which was formed at the bend of the tectonic sheet packet composed of Paleoproterozoic volcanosedimentary rocks. At the western limit of the Shombozero structure, this packet plunges westward. The seismic reflection pattern indicates that two bands of Paleoproterozoic rocks (Kalevala and Shombozero) crossed by the profile may be regarded as exposures of the same packet of tectonic sheets. The overlying gneiss–migmatite complex likely takes part in the structure of the Paleoproterozoic gneissic dome produced by rheomorphic reactivation of Archean crust during the Paleoproterozoic collision. It should be noted that the inferred common character of Paleoproterozoic structures requires additional justification. The structure of the Belomorian belt is also illustrated in Fig. 4. The morphology of structural lines portrayed by the astonishingly fine and definite pattern of seismic reflections testifies to the southwestward overthrusting of the Belomorian belt with a sequential runover of moving tectonic sheets and their deformation giving rise to the formation of anticlines displaced in the general direction of tectonic transportation. Geometric relationships depict a boundary tectonic zone as a upthrown or thrust-fault structure relative to the hanging wall and as a underthrusted structure with respect to the footwall.

Several packets of tectonic sheets plunging toward the eastern end of the profile make up the KGGT structure. These packets differ from each other in the abundance of reflectors, and hence, in the level of acoustic impedance (Figs. 2, 3). In some segments of the profile, the sheet boundaries are traced rather distinctly in the reflection pattern as one structural trend crosscuts another. The correlation of geological structures exhibited in the section and at the surface provides the recognition of tectonic sheet packets related to at least three granite–greenstone complexes of the KGGT: Central Karelian, Kuhmo–Sumoussalmi, and West Karelian (Fig. 3). Tectonic sheets of the Central Karelian granite–greenstone complex cut the Moho discontinuity in the eastern part of profile. In contrast, the tectonic sheets of the West Karelian complex gradually attenuate with depth and pinch out near the Moho.

In some places, the Moho discontinuity is probably ruptured by mushroom-shaped intrusions (Figs. 2–4). The ruptures in the Moho are accompanied by clearly detectable bends of reflectors parallel to the Moho, which record fine layering of the lower crust at contacts with intrusive bodies. Because such bends are most evident on the migrated section, it cannot be ruled out that they might have resulted from the modification of reflection pattern in the course of migration (the so-called migration smile). Precautions have been taken to minimize this side effect during processing. Only the strongest reflectors were used in the geological model. The largest bodies deduced from the seismic reflection pattern are spatially correlated with negative gravity anomalies. In general, the structural relationships and geophysical data allow us to suggest that such bodies most likely are composed of enderbite–charnockite rocks that were actively intruded as mantle-derived magmas into the crustal structure that was formed due to the late Paleoproterozoic collision.

The structure of the lower crust and Moho discontinuity along profile 4B indicates the tectonic and mechanical nature of this fundamental boundary displayed as a zone of intense tectonic flow separating the crustal and mantle rocks that were individualized with respect to their structure and composition. This zone, in turn, underwent further mechanical deformations.

Slightly expressed subhorizontal seismic reflections in the mantle are largely concentrated within a nearly horizontal zone. Only tentative suggestions can be made on their nature because of an information paucity. In particular, one can speculate that the zone of mantle reflectors is a track of the Paleoproterozoic subduction zone.

In general, the structure of EBS crust demonstrates that it was formed as a result of large-scale lateral motions of sheetlike crustal fragments typical of collision-related plate tectonic processes. The geological situation and available geochronological data lead to the inference that the assemblage of inclined tectonic sheets was formed in the Late Archean as a result of sequential accretion of island-arc, oceanic, and continental fragments to the ancient core of the Karelian Craton. The Paleoproterozoic collision likely further complicated the crustal structure; however, its principal features were retained [4]. The proposed model substantially modifies the previously elaborated concept of the EBS crust as a combination of blocks with nearly vertical lateral boundaries and specific internal layer-

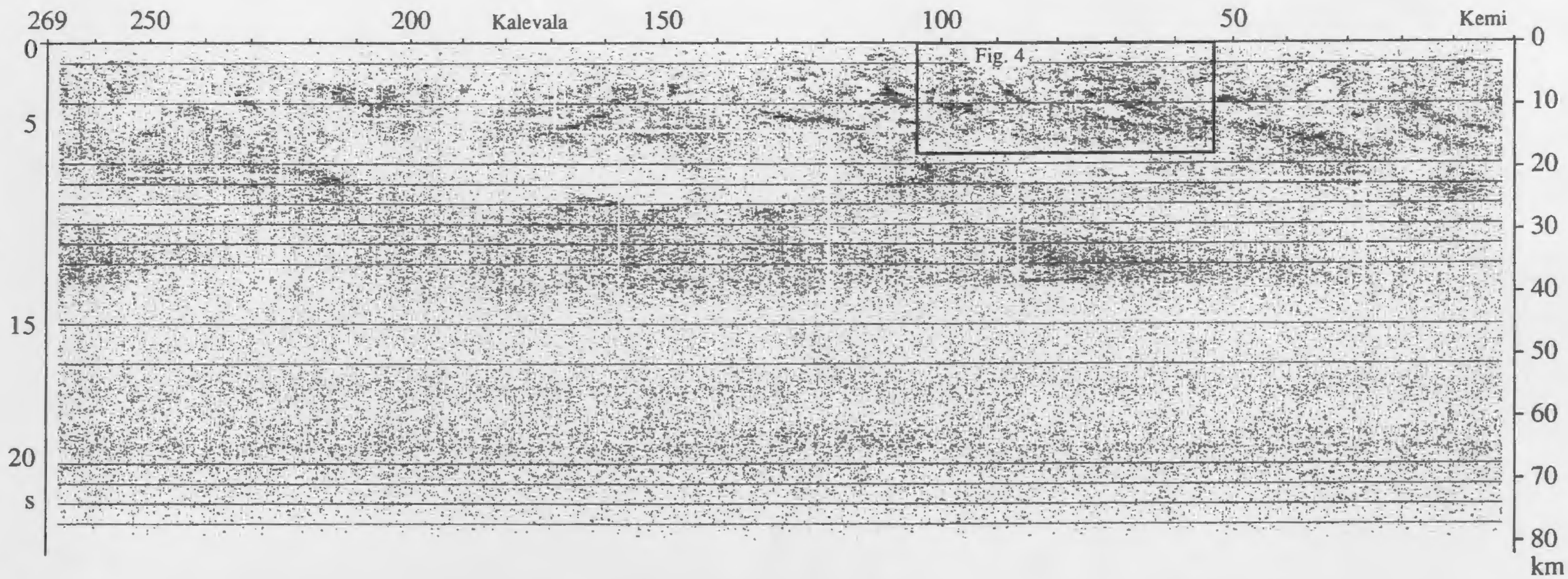

Fig. 2. The transection through lithosphere along profile 4B (CMP seismic reflection pattern), The box shows the fragment presented in Fig. 4 in an enlarged view.

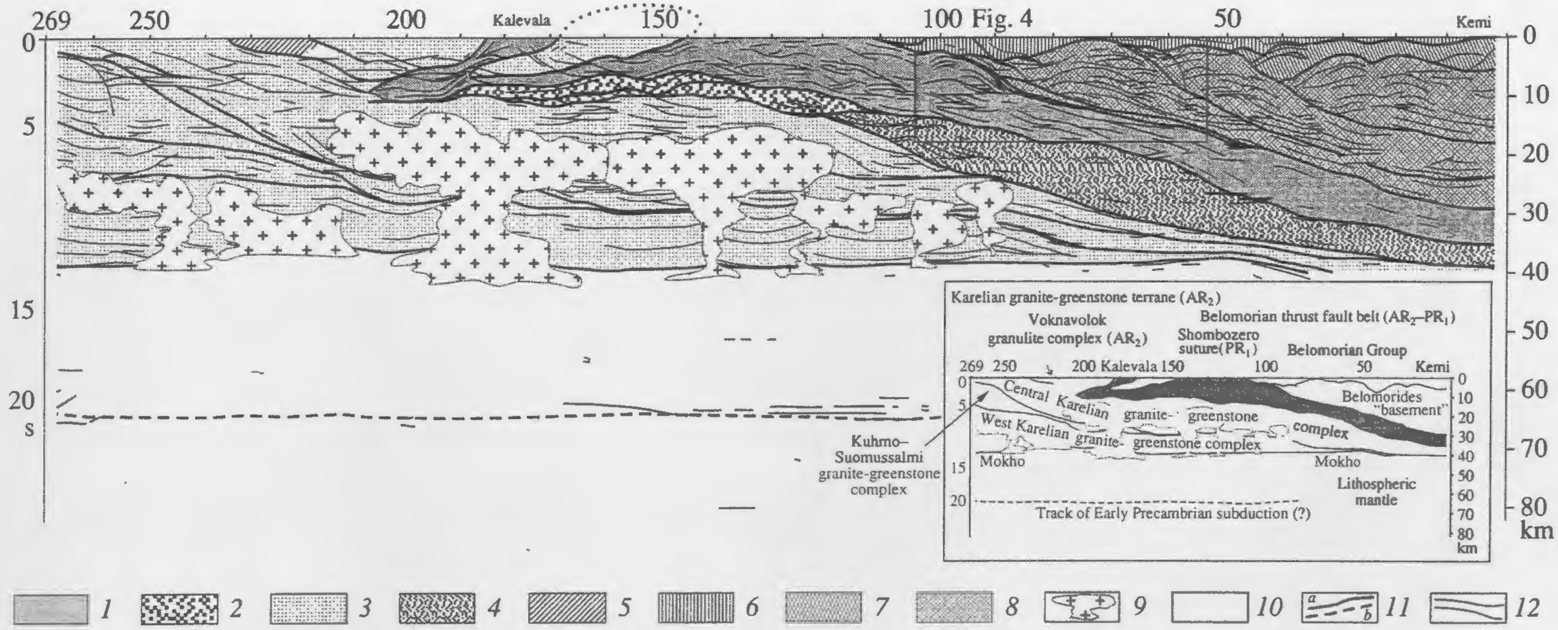

Fig. 3. Geological section through the lithosphere along profile 4B. Major tectonic units are shown in the inset. The box is the fragment presented in Fig. 4 in an enlarged view. (*1*) Paleoproterozoic volcanosedimentary belt; (*2*) rocks belonging either to the Paleoproterozoic belt or to Late Archean granite–greenstone complex (the former version is preferential from geometric relationships); (*3*) Late Archean granite–greenstone complexes; (*4*) rocks belonging either to Paleoproterozoic belt or to Late Archean granite–greenstone complex (the latter version is preferential from geometric relationships); (*5*) Voknavolok granulite complex (not shown in Fig. 1); Late Archean and Paleoproterozoic rocks of the Belomorian belt: (*6*) granite–greenstone association of the upper tectonic nappe, (*7*) inferred rocks of lower tectonic nappes, (*8*) inferred granite–greenstone complexes of the Belomorian belt basement; (*9*) post-Paleoproterozoic plutons; (*10*) lithospheric mantle; (*11*) upthrow and thrust faults: (*a*) reliable, (*b*) inferred; (*12*) boundaries of structural domains.

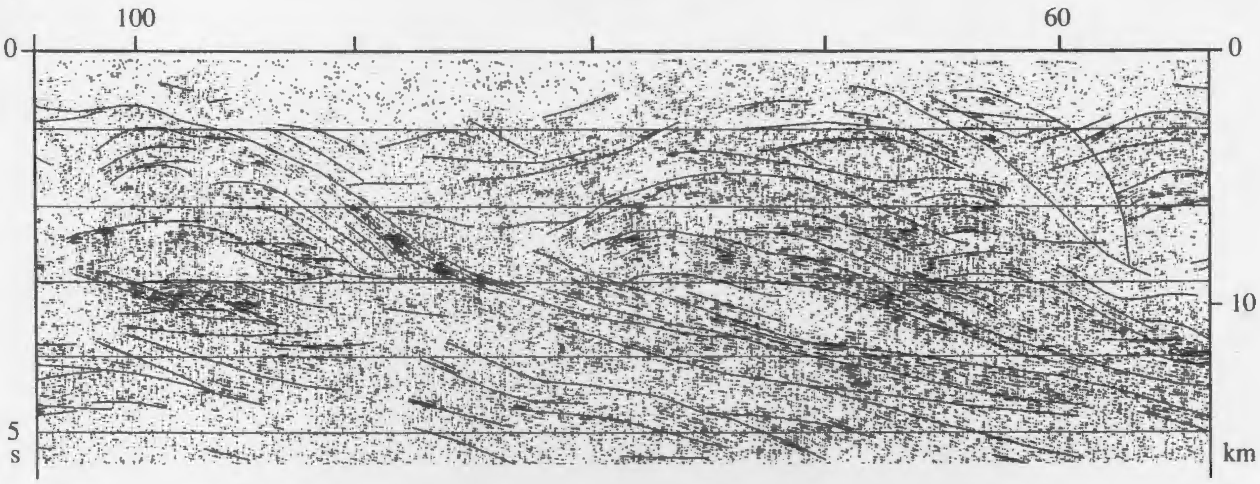

Fig. 4. The enlarged fragment of the CMP seismic reflection pattern showing tectonic zone separating the Shombozero structure and Belomorian Belt. Nappe–fold structures of the Belomorian Belt are shown in right part of the section. Limits of structural domains are drawn.

ing. At the same time, this model is consistent with the crustal structure in other Early Precambrian regions, in particular, in the North American Craton, which was thoroughly studied recently in the context of the LITHOPROBE integral program [5–7].

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