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The Reconstruction of the Early Paleozoic Structure of the Barents Sea Sedimentary Basin Inferred from Geophysical Surveys along Profile I-AR

By Mark L.Verba[1] and Tamara S. Sakoulina[1]

THEME 5: The Barents Shelf and the East Greenland Margin: A Comparison

Summary: The tectonic zoning of the basement and the geological structure of the deeply buried base of the Barents Basin sedimentary cover have long been subject of much controversy due to the deficiency of adequate geophysical information and lack of perception of the magnitude of lateral displacements that occurred in the course of post-mid-Paleozoic rift-related crustal extension. Application of palinspastic reconstructions for geological interpretation of new geophysical evidence obtained under federal-supported program of deep crustal investigations enabled better understanding of latest Precambrian to early Paleozoic basin history which apparently was also strongly affected by rifting of ancient crystalline basement. A major early Paleozoic West Kola Paleo-Trough was recognized for the first time and interpreted as epicontinental connection between Iapetus and Ripheus paleo-oceans. No features suggesting Caledonian collisional tectonism were detected in either early Paleozoic fill of this trough or in underlying essentially undisturbed Riphean sequences resting on crystalline infrastructure; however, as the result of deep burial beneath younger cover strata in central Barents depression and impact of strike-slip tension, the units within this stratigraphic interval experienced significant compaction and acquired geophysical properties transitional between those typical of high-velocity crust and middle-upper cover deposits.

INTRODUCTION

The Riphean and lower Paleozoic sequences forming the base of the sedimentary cover of the Barents Sea shelf represent the least studied portion of the basin fill section; as the result, their contribution to oil and gas generation potential of this region remains largely unknown. This paper concentrates on early Paleozoic history of the Barents Sea area, whereas available evidence on composition and hydrocarbon prospects of the North European Riphean successions has been summarized elsewhere (SIEDLECKA et al. 1995, ROBERTS 1995, SIMONOV et al. 1998. OLOVJANISHNIKOV et al. 1997).

Lower Paleozoic sequences on the North European margin are known on Svalbard, in Scandinavia, in Pechora lowlands and on the northern island of Novaya Zemlya (Fig. 1). All these occurrences are not only widely separated around the vast Barents Sea shelf containing record of post-early Paleozoic rifting and lateral crustal displacements (VERBA 1977, 1985, 1992, GRAMBERG 1988), but also represented by different lithologies with variable degree of Caledonian deformation.

In Scandinavia classic Caledonian thrust assemblages are composed of predominantly out-of-shelf deposits (GAYER 1989). On western Spitsbergen the lower Paleozoic facies suggests active shelf environment. Their Caledonian penetrative deformation postulated by HARLAND & GAYER (1972) is strongly obscured by Cenozoic tectonic imprint and has been challenged in later publications (DALLMANN et al. 1988, MANBY 1988, MORRIS 1988, BERGH et al. 1997). An apparent conformity of structural lineations in late Riphean to early Paleozoic and younger (up to early Tertiary) sequences suggests the Cenozoic age of major deformational event, whereas Caledonian tectonism was probably marked mainly by local intense blue-schist metamorphism associated with fault zones (OHTA 1979) and caused by transpressional stress (HARLAND 1998). On Novaya Zemlya the entire exposed section, including lower Paleozoic upper slope facies, is affected by Mesozoic folding (KORAGO et al. 1992). In the Pechora Basin the lower Paleozoic sequence consists of variable, mildly deformed lithologies incorporated in a syneclise platform cover. Clearly, correlation and paleotectonic interpretation of early Paleozoic assemblages in all these locations along the periphery of Barents shelf could be greatly facilitated by better knowledge of their stratigraphic equivalents in the central Barents Sea which are likely to provide the critical links.

Apparent presence of certain features common in all early Paleozoic assemblages around the Barents Sea was noted by many researchers (KRASILSHCHIKOV 1973, HARLAND & DOWDESWELL 1988, SIEDLECKA 1975, RØNNEVIC et al. 1982 and others) and led them to believe that Scandinavian structures might extend beneath the Barents shelf and form there a continuous ensemble linking together the above mentioned widely separated bedrock exposures with more or less intense Caledonian signature. All these concepts ignored significant lateral crustal displacements caused by late Paleozoic to Triassic rifting, and neither of them was unanimously accepted. A new insight in the problem appeared possible due to recent geophysical investigations performed in 1995-1998 by Russian specialists along a regional geotransect connecting the super-deep Kola well with a deep stratigraphic well drilled in central Franz Josef Land. In the southern 700 km of the geotransect strip marine deep seismic refraction soundings were combined with reflection studies, ship-borne gravity and magnetic observations, and aeromagnetic survey (MATVEEV et al. 1996, VERBA et al. 1997). As result, it appeared possible for the first time to characterize a continuous crustal section transversing major structural units of the Barents shelf from the northern slope of the Baltic Shield and across the southern slope and the core of the Central Barents High (MITROFANOV & SHAROV 1998; Fig. 2 and Tab. 1) and to use this new knowledge as a basis for improved interpretation of modern

[1] GNPP SEVMORGEO, Rozenshtein ul. 36, 198095 St.Petersburg, Russia; <verba@sevmorgeo.com>

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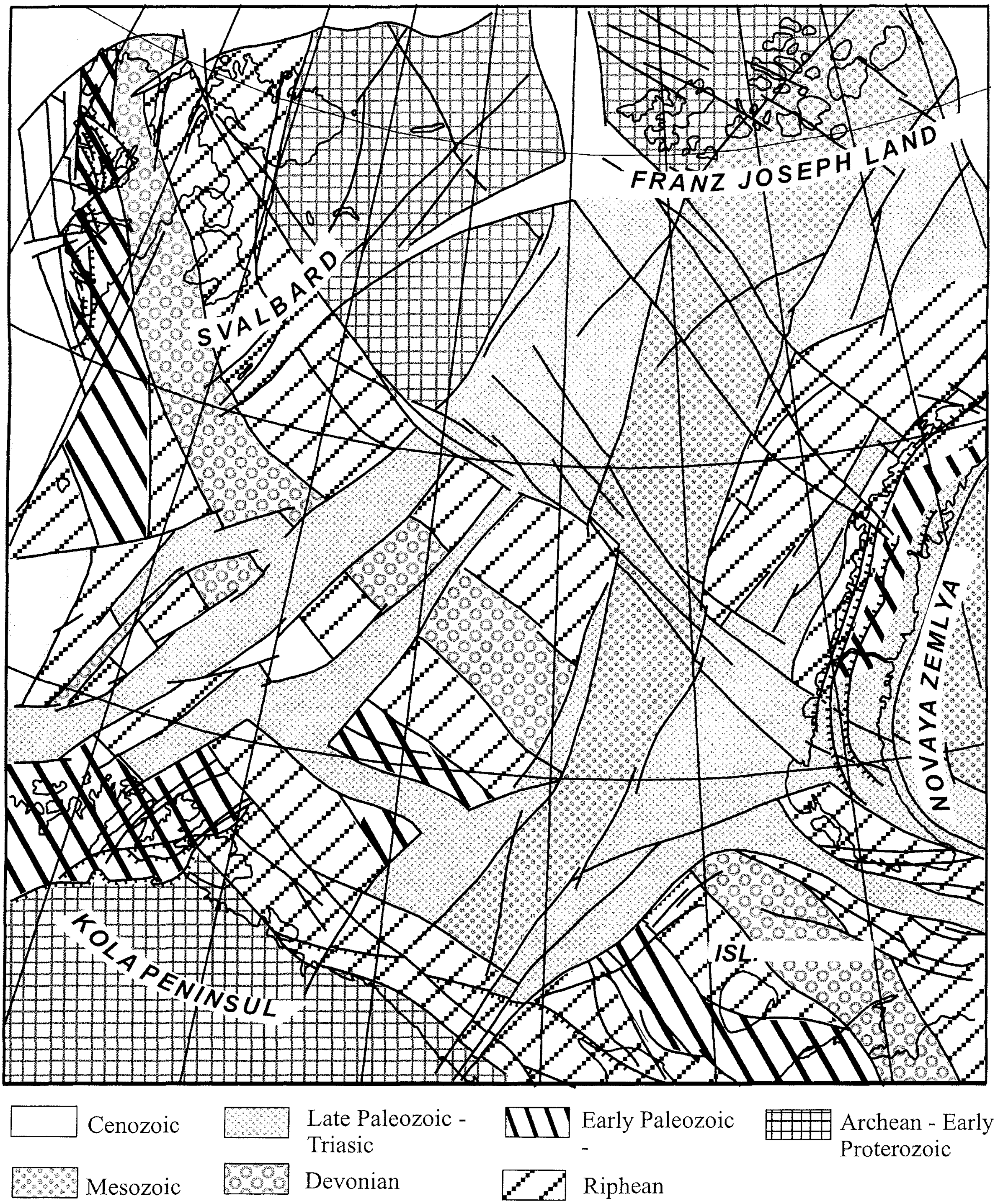

Fig.1: Distribution of riftogenic sedimentary sequences in relation to basement highs.

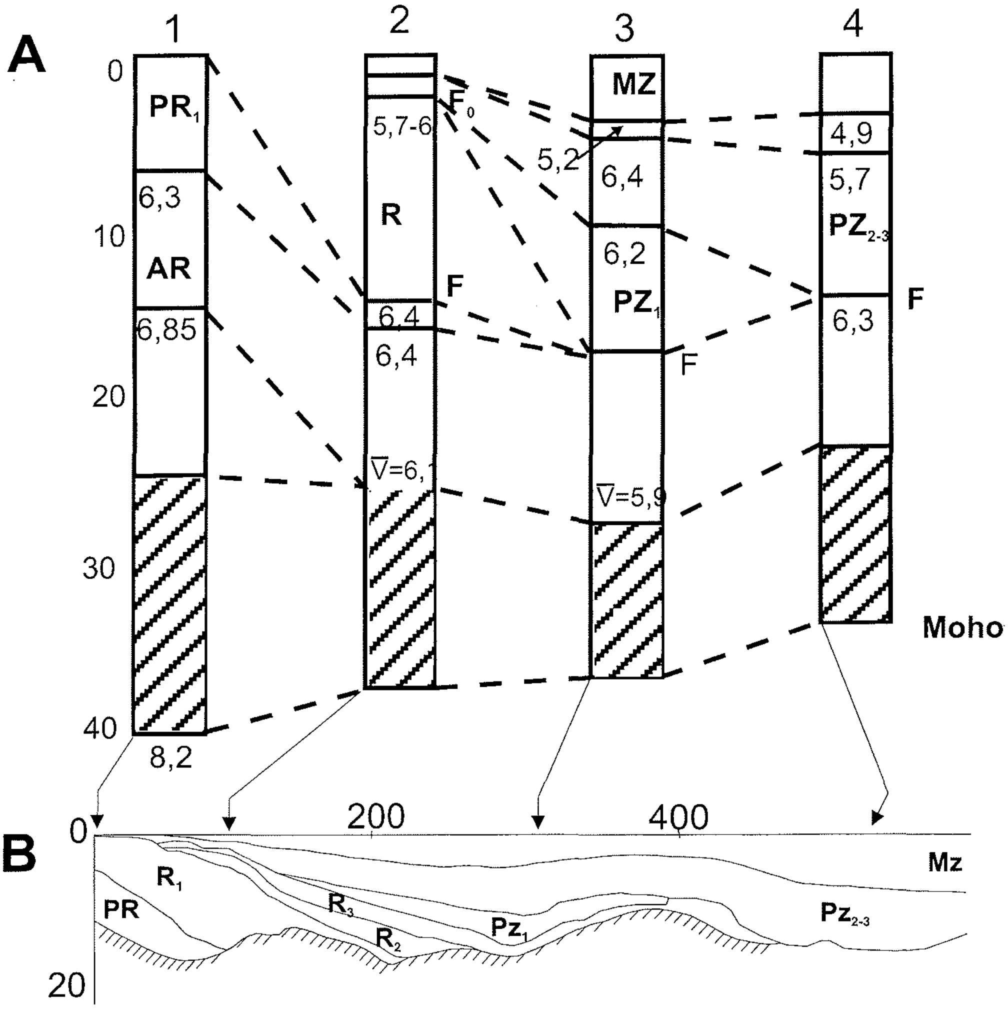

Fig. 2: Seismic refraction section (A) and composite crustal profile (B) along southern segment of geotraverse 1-AR. Refraction sites 1-4 are designated in Figure 2a as 2-1, 2-2, 2-3, 2-4. Note high seismic velocities, lack of structural disturbance throughout the entire Riphean to Mesozoic section and its clinoform appearance.

multichannel seismic data obtained under other projects (SIMONOV et al. 1998; Fig 3), as well as of earlier seismic evidence (LITVINENKO 1968, TULINA et al. 1988).

GEOLOGICAL INTERPRETATON OF GEOPHYSICAL DATA

The sedimentary cover in the southern part of the Barents Basin is represented by an almost continuous stratigraphic section incorporating sequences of Riphean to late Mesozoic age. The section demonstrates the absence of major unconformities and only minor degree of fold deformations suggesting that throughout the entire Phanerozoic history the region was not affected by collision-related tectonism. Distribution of supracrustal cover units is predominantly controlled by fault-bounded troughs (Fig. 1, 3) whose rift nature during predominantly late Paleozoic and Triassic stages of basin evolution was demonstrated in earlier publications (VERBA 1985, GRAMBERG 1988, VERBA 1996). In this contribution the emphasis is made on preceding structural environments and related tectono-stratigraphic assemblages.

The basement of the South Barents Basin is formed by a

Distance	V_1/H_1	V_2/H_2	V_3/H_3	V_4/H_4	V_5/H_5	V_6/H_6	V_7/H_7	V_8/H_8	V_9/H_9
30	5.7/0.3	7.3/8.4							
50	5.0/0.2	6.1/1.2	5.9/11.2	6.3/20.5	(6.1)/26	8.1/40			
90	2.7/0.25	4.3/0.8	5.8/2.8	6.3/15.6	(6.1)/26.5	(6.3)/39			
150	2.4/0.3	6.0/1.0	5.1/2.8	6.8/6.2	5.5/13.1	6.8/22.6			
190	2.8/0.5	3.4/0.9	4.4/2.4	6.2/3.2	5.3/3.8	6.3/8.8	7.2/13.8	7.0/22.6	8.3/38
210	2.6/0.3	3.4/0.8	4.4/2.0	6.5/3.8	5.4/4.9	7.0/10.6	7.2/17.5	(6.2)/38	
270	2.7/0.4	3.7/1.2	4.7/2.7	605/4.0	6.4/10.0	6.7/10.0	5.1/14.4	6.6/17.2	
330	2.9/0.2	3.4/0.6	4.6/1.6	5.4/3.3	7.6/25.5	(6.1)/38			
390	3.1/0.2	3.5/0.6	4.7/1.7	6.2/3.2	5.6/8.6	6.4/16.3			
420	3.4/0.2	3.8/0.8	4.8/2.0	5.2/2.9	6.0/7.8	6.7/20.4	8.0/34		
450	3.0/0.2	3.8/0.9	4.2/1.8	5.8/3.4	6.3/6.1	5.5/14.6	6.7/19.6	(6.0)/40	
510	2.7/0.3	3.7/1.1	4.3/1.9	4.8/4.5	5.3/6.4	(6.0)/36.5			
550	2.4/0.2	3.3/0.5	4.4/1.8	4.8/4.4	5.2/5.9				

Tab. 1: Selected values of boundary velocities at major crustal boundaries and depth of their occurrence (V/H) from refraction data. Values in brackets refer to average velocities obtained from reflection data.

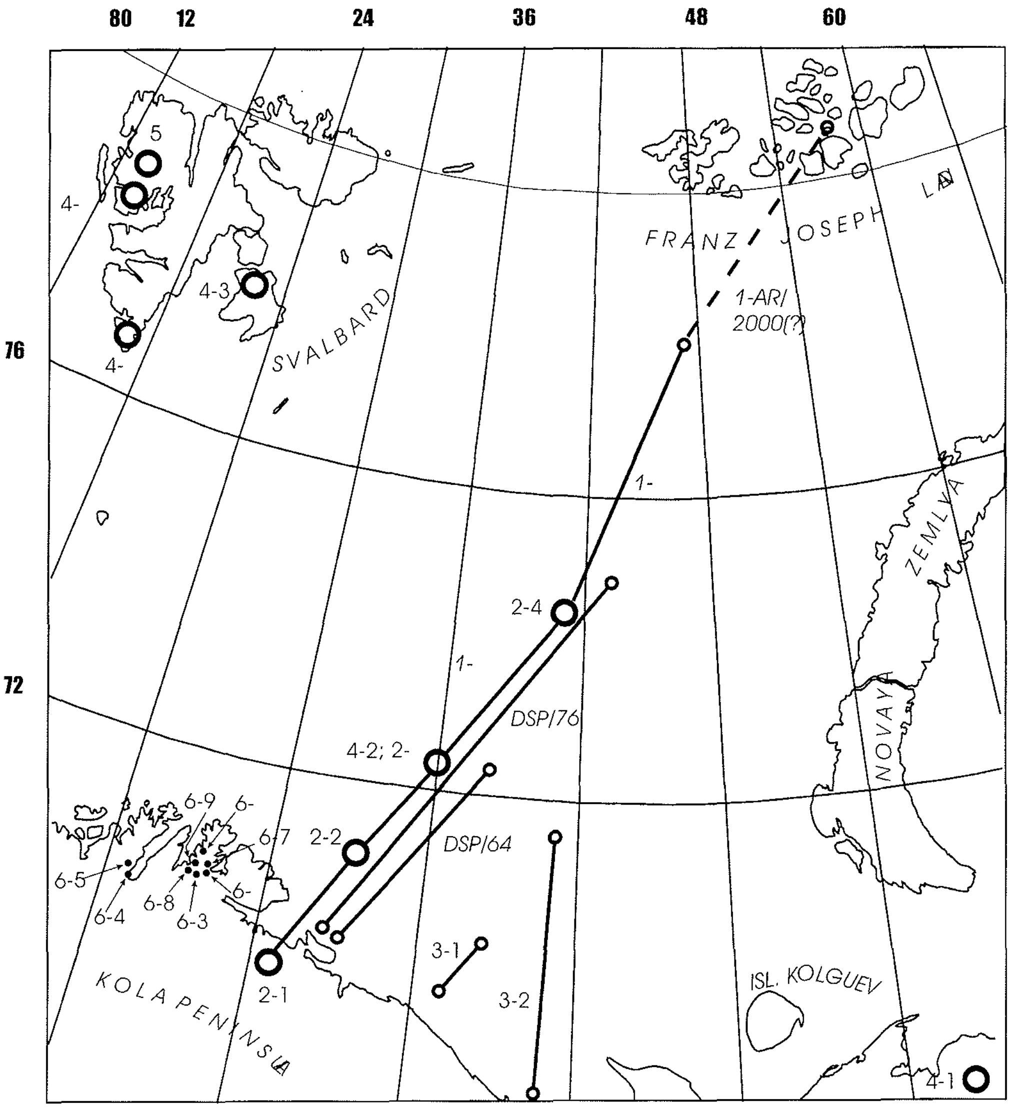

Fig. 2a: Location of profiles and observations given in figures. Numbers refer to figures and subfigures.

granite-metamorphic layer whose surface is represented by refractor F_1 usually observed at about 12-15 km depth; beneath the Central Barents Rise it is found at 10 km, whereas towards the Kola Peninsula coast it ascends to sea bottom level. The basement includes Archean rocks and an overlying Paleoproterozoic unit whose velocity parameters suggest a somewhat lower metamorphic grade. The interval between the top of the basement (F_1) and a regional seismic horizon F_0 long recognized as a base of undeformed Paleozoic sediments (LITVINENKO 1968) is interpreted as a Riphean sequence whose upper part correlates with the terrigenous section described in the Rybachii Peninsula coastal outcrops (SIEDLECKA et al. 1995, ROBERTS 1995). The main portion of this seismic interval has thickness up to 9 km and is characterized by uniform layer velocities on the order of 5.2-5.3 km/s believed to correspond to the terrigenous Barents Sea Complex known from the Varanguer Peninsula (GAYER 1989). The presence within this sequence of dense low magnetic rocks is suggested by gravity and magnetic data. Limited, variably inclined diffraction zones are locally observed in seismic records and believed to mark narrow zones of fault-related disturbances depicted by Russian and Norwegian magnetic surveys. This agrees with the earlier notion that this area was not affected by large-scale collisional folding (ÅM 1975).

Velocity parameters of the Riphean sequence are consistent with the interpretation of its composition as dominated by low grade terrigenous lithologies. Indeed, at shallow depths (0.5-1.0 km below sea bottom) the boundary velocities at F0 do not exceed 5.7-5.8 km/s but seaward these values gradually increase to 6.1-6.3 km/s and 6.4-6.5 km/s at 5 km and 10 km depths, respectively. Such good correlation between velocity and depth probably indicates a lateral continuity of Riphean lithologies, as well as preservation of their ability for compaction which is in marked contrast with much stronger metamorphosed basement complexes. Similar conclusions can be made on the basis of analysis of organic matter which in rocks of the Rybachii Peninsula shows only relatively low degree of maturation corresponding to intermediate catagenic stage (SIMONOV et al. 1998). On the other hand, even the lowest velocity values (5.7-5.8 km/s) imply the presence of sufficiently dense rocks. On the whole, the data suggest that Riphean sequences away from northern Scandinavia and the Kola Peninsula become progressively less deformed and must

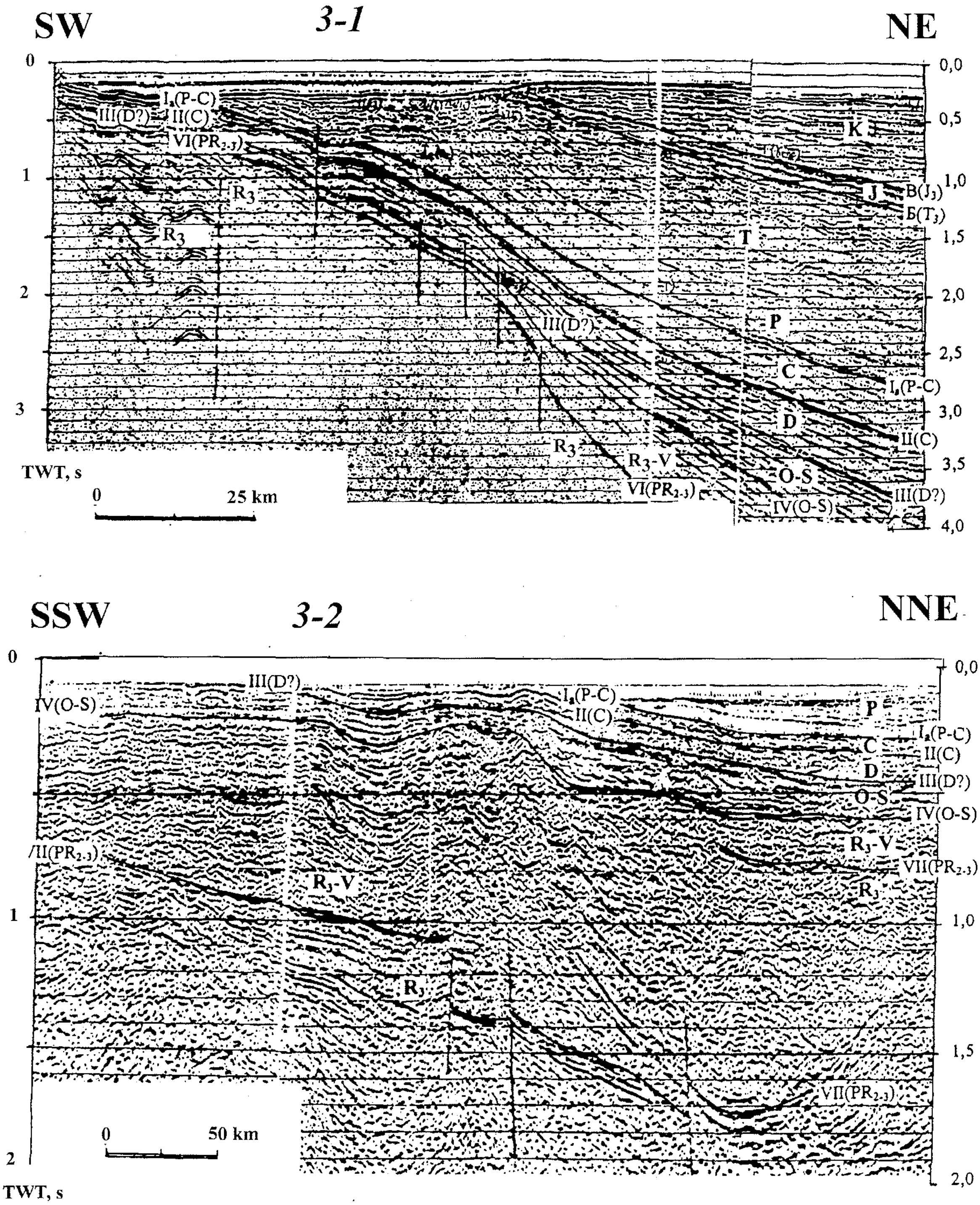

Fig. 3: Time sections across the northern slope of the Baltic Shield along lines 3-1 and 3-2 (see Fig. 2a). Note conformable relationship of Lower Paleozoic sequences with older and younger units and local nature of structural deformation in Riphean strata.

therefore be considered as the base of the sedimentary cover of the Barents Basin.

The overlying Phanerozoic section includes three major tectono-stratigraphic assemblages. Of these only the two upper ones were characterized by earlier MCS surveys and reliably stratified with reference to well data as "upper terrigenous Barents Sea complex" (late Permian to early Cretaceous) and "middle complex" (Devonian to early Permian, possiblyincludeing late Silurian) (Gramberg 1988). Processing of new geophysical data allowed to recognize for the first time that an older undeformed cover sequence was present between the top of the Riphean succession and the base of the "middle complex". Its maximum thickness reaches 2.5-3.0 km and delineates the position of a fault-bounded West Kola Trough which apparently controlled the sedimentation. The conformable relationship of this sequence with underlying Riphean and overlying middle Paleozoic units implies its essentially early

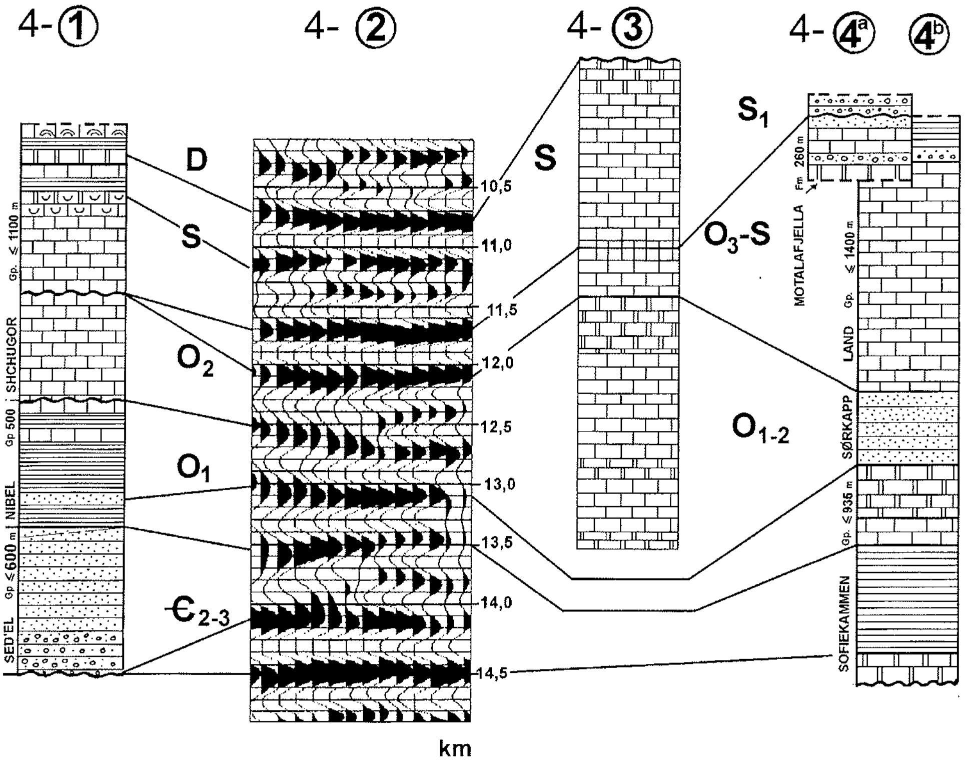

Fig. 4: Correlation of geological sections documented in Pechora Basin: 4-1, after DEDEEV at al. (1988) and Svalbard: 4-3 borehole Raddedalen, after SHVARTS (1985), 4-4 West Spitsbergen and 4-4a Sorkap Land, after HARLAND (1997) and 4-2 with fragments of DSP section in West Kola Trough, after MATWEEV (1996). For site locations see Figure 2a.

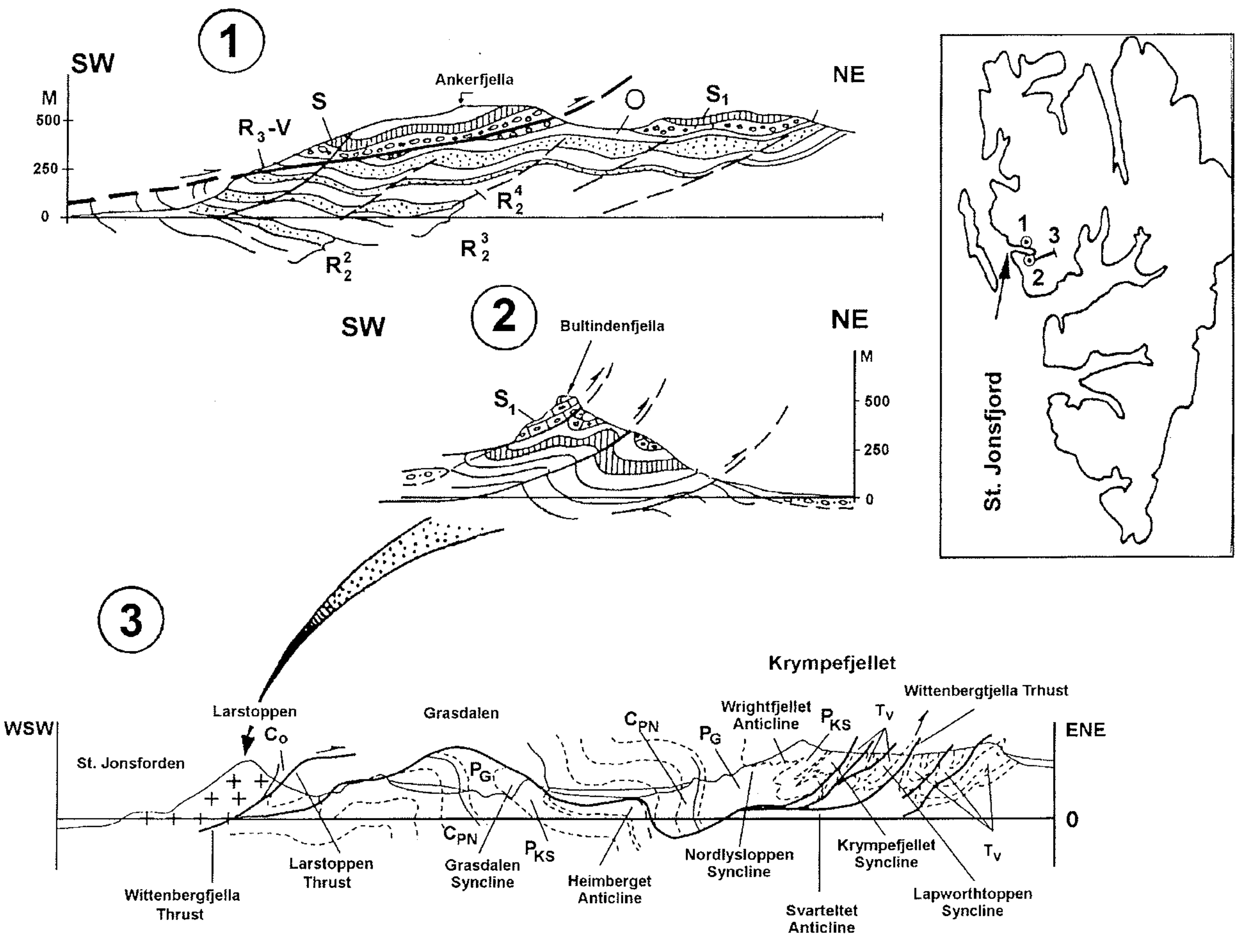

Fig. 5: Cenozoic nappes in the West Spitsbergen fold belt (1 and 2 from field observations of the first author, 3 after HARLAND (1997, p. 408; sketch in (2) is a detail of Heckla Hoek series structure). Note the absence of apparent structural unconformity at the base of Silurian and uniformity of tectonic deformation in the entire exposed section.

Paleozoic age spanning most of Cambrian, Ordovician and, perhaps, lower Silurian stratigraphic intervals, whereas gravity modeling in combination with seismic interpretations suggests distinctly layered, mainly moderately dense terrigenous lithologies probably containing higher density carbonate facies with boundary velocities up to 6.2-6.4 km/s in the upper part of the section. Lack of evidence of Caledonian folding in combination with graben-like configuration of the West Kola depression may indicate that early the Paleozoic evolution of the Barents Basin was to a large extent influenced by initial stages of epi-platform rifting.

DISCUSSION

Despite geographic proximity of the West Kola paleo-trough to the Scandinavian Caledonian fold belt, Riphean and early Paleozoic sequences accumulated in this depression are very distinct from their Caledonian equivalents in both composition of the main stratigraphic units and degree of their structural deformation. At the same time, they seem to display much stronger affinities with more distant coeval successions on Spitsbergen and in the Pechora Basin. For example, the thickness and seismic facies of the lowermost cover sequences on the Central Barents Rise are comparable to the Cambrian-Ordovician terrigenous Oslobreen Series and Ordovician carbonate Kirtonryggen Series of Spitsbergen, whereas in the Pechora Basin they can be matched with the Izhma-Omrinsky Complex (Fig. 4). Although such correlation is based on very broad lithological characteristics accessible from seismic data, it positively shows the absence of either facial features typical of deep-water offshore sedimentation, or strong Caledonian collision-related tectonism. All these sections are affected by only moderate near-fault deformations presumably associated with strike-slip movements. The existence of such lateral tectonic displacements were noted by many researches both in the Pechora Basin and on Spitsbergen, and some of them specifically stressed a close connection of Caledonian folds on Spitsbergen with major transcurrent faults (HARLAND & GAYER 1972, HARLAND 1998).

Field geological and geophysical data from the West Spitsbergen zone of Alpine dislocations (MANBY 1988, BERGH et al. 1977) and observations conducted by the authors in the St. Johns Fjord area show that the angular unconformity between the Ordovician and late Precambrian sequences is, as a rule, not really a well pronounced one. The Bultinden Series, despite its stratigraphic position in place of an epi-Caledonian molasse, has limited distribution, small thickness and mostly carbonate composition suggesting low elevation of the source area. Latest investigations have also cast doubt on a traditional assignment to a Caledonian orogenic sequence of the Devonian Old Red Sandstone which occupies one of major Spitsbergen rift-related troughs. The conventional notion of an

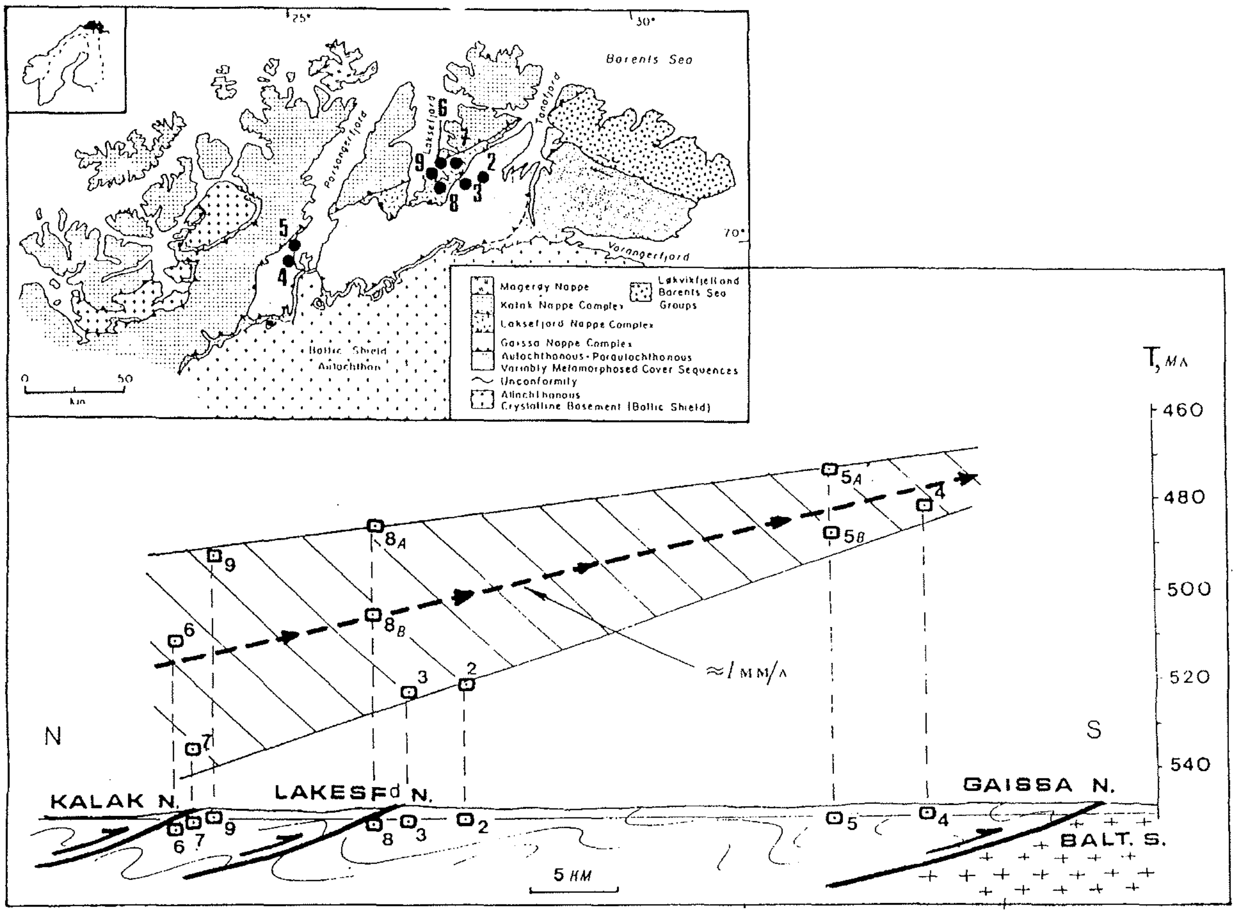

Fig. 6: Migration of thrusting across the Caledonian suture. Sample sites (inset) are shown on the geological map of Finmarken after GAYER (1989). Diagram presents isotopic ages obtained from analyzed samples (DALLMEYER 1989) against generalized profile illustrating position of main nappes. Note successive rejuvenation of thrust-related deformation ages toward the Baltic Shield.

independent Caledonian structural event is further challenged by uniform involvement in Cenozoic thrusting of the entire stratigraphic section from the Riphean to Paleogene; there is no appreciable difference in intensity of deformation in oldest and youngest units or evidence of more than one structural disturbance in the Riphean beds. It may also be noted that thrusts on Spitsbergen become successively younger to the west, whereas in Scandinavia their age changes in the opposite direction (Fig. 5).

The typical Caledonian geology (GAYER 1989) suggests that closure of the Iapetus Ocean and the formation of Scandinavian collisional suture did not occur quite simultaneously. On Finmark the collision was manifested by orogeny that terminated in Wenlockian (by 420 Ma), whereas farther to the south it started later and lasted till about 395 Ma. Judging by change in the age of trusting to southeast from 510 to 475 Ma within the distance of 40 km, the propagation of the collisional front averaged approx. 1 mm per year (Fig. 6). In West Spitsbergen the rate of folding was similar though the direction of thrust youngening was reverse.

It therefore appears that the lithological composition, structural style and post-depositional history of early Paleozoic rocks on Spitsbergen preclude their interpretation as a continuation, or a distal analog of the Caledonian collisional suture of Scandinavia. We consider them as a fragment of an independent major structural zone (West Kola Trough) that extended from Spitsbergen towards the Pechora Basin and controlled to a large extend the early stages of the evolution of the sedimentary cover in the Barents Basin.

The common features recognized in widely separated early Paleozoic assemblages on Spitsbergen, Central Barents Rise and in the Pechora Basin suggest their former closer geographical proximity subsequently disrupted by post-early Paleozoic tectonic displacements. The latter were most likely related to late Paleozoic to early Mesozoic rifting whose extensional effect must be "subtracted" from the present day structural array in order to restore the pre-existing relationships.

Following such approach, pre-Devonian palinspastic recon-

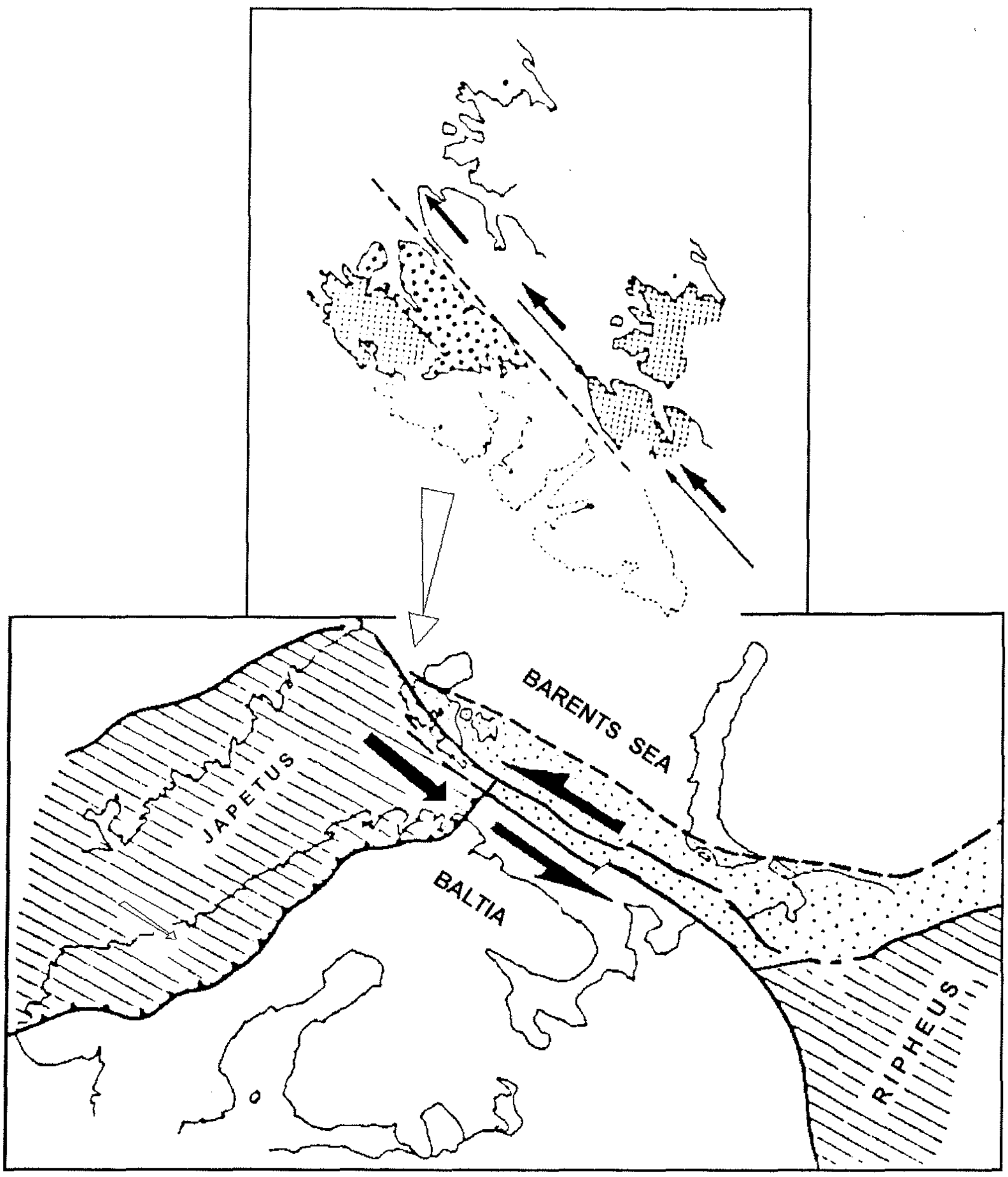

Fig. 7: Palinspastic reconstruction of epi-cratonic riftogenic Early Paleozoic West Kola Trough (dotted) connecting the Iapetus and Ripheus oceans (harched). Top diagram iluustrates strike-slip movement in the Billefjorden Rault Zone (after HARLAND et al. 1974).

struction was made for the entire Barents Sea region (Fig. 7) and showed that in early Paleozoic time Spitsbergen, Central Barents Rise and Pechora Basin were all closely associated within, or immediately adjacent to an extended system of sublatitudinal epi-platform depressions which probably formed an intracratonic link between the Iapetus and Uralian Oceans. Because this system was parallel to Caledonian stress producing the Scandinavian collision suture, it was affected by regional strike-slip displacements which evolved in the same direction and caused local near-fault disturbances (sometimes accompanied by blue-schist metamorphism, for example on the Motafiella Mountain) in the sedimentary fill of the West Kola Trough. The existence of this strike-slip displacements along Billefjord fault was supposed already by HARLAND (1964).

CONCLUSION

Understanding the pre-rift crustal structure of major extensional basins and assessing the scope of lithospheric extension that occurred during their evolution can only be achieved by means of palinspastic reconstructions. Paleotectonic sketches for the Arctic region based on such approach have already been published (ZONNENSHAIN & NATAPOV 1987) but only for the Mesozoic part of its geological history. The same methodology applied by the authors to earlier stages of evolution of the Barents Basin allowed to recognize an intracratonic rift-related West Kola paleotrough believed to exist in early Paleozoic time between Iapetus and Uralian Oceans.

Unlike the Caledonian s.str. (collision-related) and less severely folded coeval complexes around the Barents Sea periphery, the lower Paleozoic sequence accumulated in the West Kola Trough was not appreciably affected by the Caledonian event and became an integral part of the Barents Basin sedimentary cover in which it formed a transition from underlying undeformed, strongly lithified Riphean beds composing the base of the West Kola Trough section to more typical cover strata characterized by much larger lateral extent. On Figure 2 the lower Paleozoic and other cover sequences appear to form a single mega-clinoform suggesting a monotonous progradational evolution during almost 1.5 Ga away from the northern margin of the Baltic Shield.

Finally, in the absence of collisional folding in the Barents Basin throughout such a prolonged period of geological history it appears very difficult to determine a stratigraphic position of deeply buried basement to cover boundary and, consequently, to define the age of the basement cratonization in this part of the East European Platform (as well as in much better studied Spitsbergen and the Pechora Basin where this issue is still subject to much debate).

The great thickness of the sedimentary fill accumulated alongside ancient continental margins within an extremely large stratigraphic interval and resulting ambiguous basement/cover relationships require implementation of seismic modeling that would be based on imaging geological section as a gradational rather than discrete environment. Consequently, basin modeling and hydrocarbon evaluations should include in consideration not only those sequences which occur within the "oil window" but also older cover sequences found at deeper structural levels. In particular, the Riphean and early Paleozoic cover units known to contain significant amounts of organic matter in their early stage of catagenic transformation must conceivably be regarded as possible hydrocarbon prospects whose generation potential has yet not been totally exhausted. Numerous oil shows found in these old sediments on Spitsbergen, Rybachi Peninsula and in the Pechora Basin suggest that coeval sequences on the Central Barents High may also appear promising for future discoveries.

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