

Formation Mechanisms of Ultradeep Sedimentary Basins: The North Barents and Some Other Basins*

Eugene V. Artyushkov¹, I. V. Belyaev², Peter A. Chekhovich³, G. S. Kazanin⁴, S. P. Pavlov⁴, and S. I. Shkarubo⁴

Search and Discovery Article #10558 (2013)**

Posted December 23, 2013

*Adapted from an oral presentation given at AAPG 3P Arctic Polar Petroleum Potential Conference & Exhibition, Stavanger, Norway, October 15-18, 2013

**AAPG © 2013 Serial rights given by author. For all other rights contact author directly.

¹The Schmidt Institute of Physics of the Earth (IPE), Moscow, Russian Federation

²State SEVMORGEО Company, St. Petersburg, Russian Federation

³The Earth Science Museum, Lomonosov Moscow State University, Moscow, Russian Federation (p.chekhovich@gmail.com)

⁴Marine Arctic Geological Expedition (MAGE JSC), Murmansk, Russian Federation

Abstract

In the North Barents Basin, 16-18 km deep, the consolidated crust is attenuated by two times. However, the system of normal faults in the basement ensures crustal stretching of only ~10% which gave rise to deposition of 1-2 km of sediments at the base of the sedimentary cover. Since the Late Devonian, 14 km of new deposits were formed in the basin in the absence of significant stretching. In this part of the sequence, all the reflectors are continuous (undisrupted) except at the narrow vertical magmatic channels which were formed near the Jurassic/Cretaceous time boundary. Under such circumstances, the subsidence required a large density increase in the lithosphere. This was predominantly caused by the transformation of gabbroids into dense eclogites in the mafic lower crust which occurred at the episodes of fluid infiltration from the mantle. The transformation was enhanced by the pressure and temperature increase in course of the formation of a thick sedimentary cover. The analysis of the seismic reflection profiling and gravity data shows that the Moho in the basin is underlain not by mantle peridotites but by a layer of eclogites, ~15 km thick. Their formation from a less dense gabbroids in the lower crust was sufficient to produce the sediment loaded subsidence of 14 km in the absence of stretching. Mafic eclogites are considerably denser than mantle peridotites; however, having high P-wave velocities they are commonly placed under the Moho boundary. The same situation is typical of the North Caspian, South Caspian, and North Chukchi basins ~20 km deep. As the North Barents Basin, they are several kilometers deeper than it could be expected under the observed thickness of their consolidated crust. If the Moho was underlain by mantle peridotites, negative isostatic anomalies ~150-200 mGal would arise at the surface. Yet only weak positive Faye anomalies are observed above the basins. This indicates that thick lenses of dense eclogites underlie the Moho in the basins. A similar result was recently obtained for the Gulf of Mexico (Mooney and Kaban, J.G.R., 2010). The transformation of large masses of gabbroids and basalts into eclogites in the crustal layer is possible only in highly ferruginous rocks. This is why ultradeep basins arise only in some regions. Under increased pressure and temperature and in a presence of fluid low grade metamorphism occurs in the upper crust overlain by ~20 km of sediments. This increases P-wave velocities and density of silicic rocks to the values typical of mafic oceanic crust.

References Cited

- Bird, D.E., K. Burke, S.A. Hall, and J.F. Casey, 2005, Gulf of Mexico tectonic history; hotspot tracks, crustal boundaries, and early salt distribution: AAPG Bulletin, v. 89/3, p. 311-328.
- Gac, S., R.S. Huismans, N.S.C. Simon, and Y.Y. Podladchikov, 2010, Origin of the large subsidence at eastern Barents Sea basins; insights from density-isostatic modelling and dynamic modelling: Geophysical Research Abstracts, v. 12, p. EGU2010-9430.
- Ivanova, N.M., T.S. Sakulina, I.V. Belyaev, Y.I. Matveev, and Y.V. Roslov, 2011, Depth model of the Barents and Kara Seas according to geophysical survey results, *in* A.M. Spencer, A.F. Embry, D.L. Gautier, A.V. Stoupakova, and K. Sorensen, eds., Arctic petroleum geology: Memoirs of the Geological Society of London, v. 35, p. 209-221.
- Lebedeva-Ivanova, N., 2010, Geophysical Studies Bearing on the Origin of the Arctic Basin: Ph.D. Thesis, Uppsala University, Uppsala, Sweden, 79 p.
- Mooney, S.D. and M.K. Kaban, 2010, The North American upper mantle; density, composition, and evolution: Seismological Research Letters, v. 81/2, p. 379-380.
- Spear, F.S. and F.P. Florence, 1992, Thermobarometry in granulites; pitfalls and new approaches, *in* D.D. van Reenen, C. Roering, L.D. Ashwal, and M.J. de Wit, eds., Special issue; The Archaean Limpopo granulite belt; tectonics and deep crustal processes: Precambrian Research, v. 55/1-4, p. 209-241.

Artyushkov E.V.¹,
Belyaev I.V.²,
Chekhovich P.A.^{1,3},
Kazanin G.S.⁴,
Pavlov S.P.⁴,
Shkarubo S.I.⁴



FORMATION MECHANISMS OF ULTRADEEP SEDIMENTARY BASINS:

THE NORTH BARENTS AND SOME OTHER BASINS

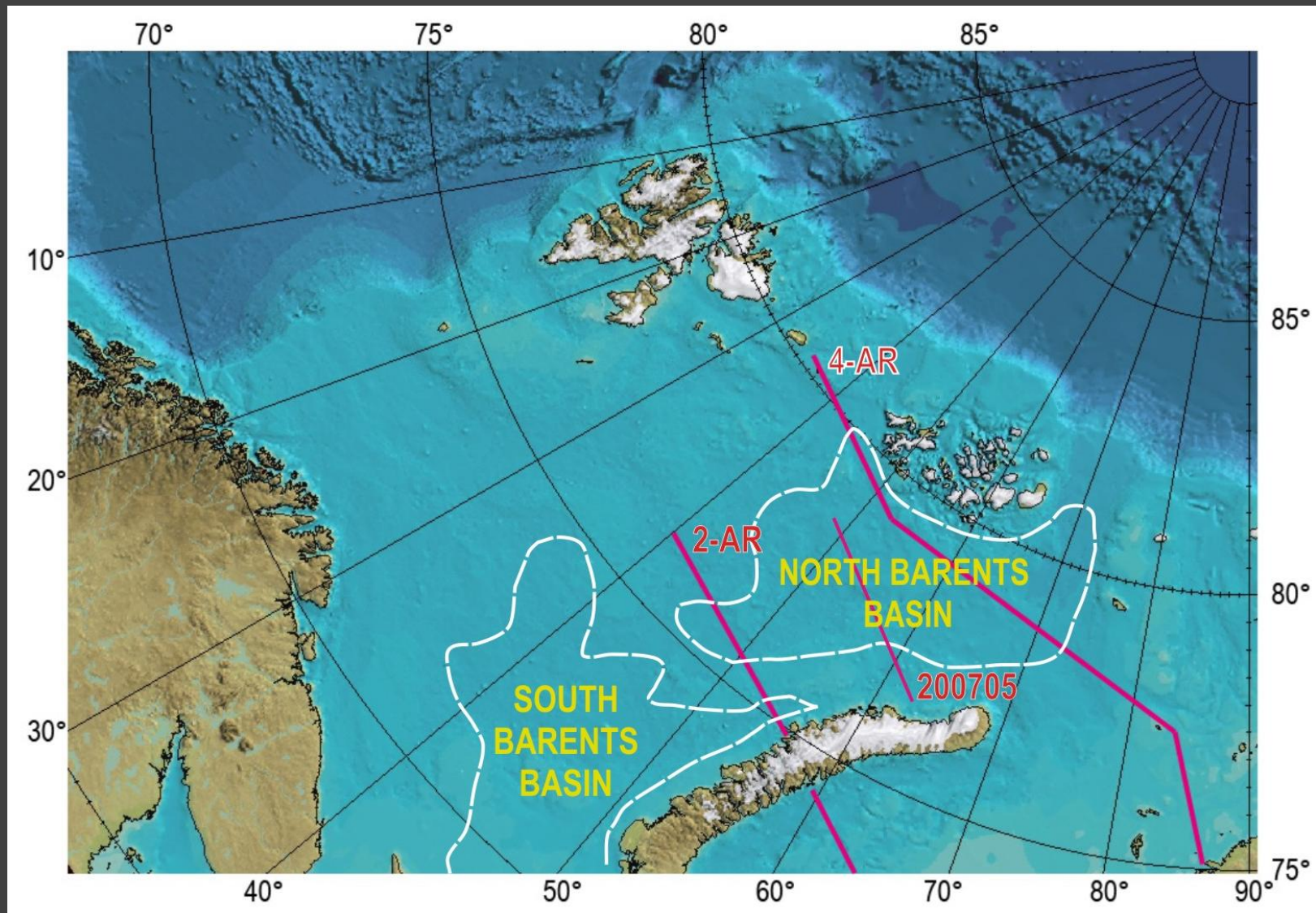
¹ Institut of Physics of the Earth, Moscow, Russian Federation

² State SEVMORGEO Company, St-Petersburg, Russian Federation

³ The Earth Science Museum at Moscow State University, Russian Federation

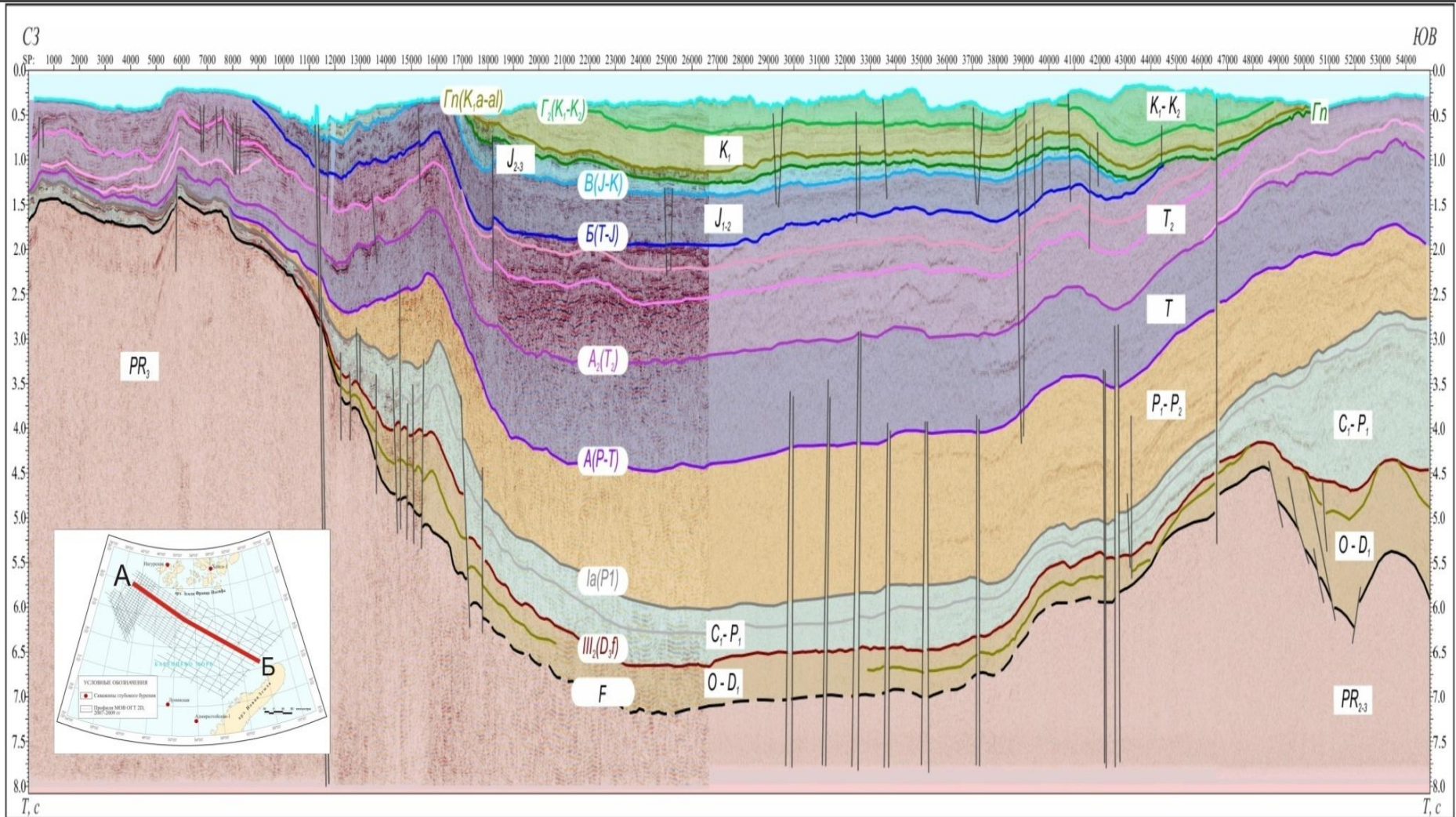
⁴ MAGE, Murmansk, Russian Federation

BARENTS – NORTH KARA REGION



Seismic reflection profile across the North Barents Basin,

15 km deep. Only minor extension can be seen at the basement and at the regional Upper Devonian reflector III2.

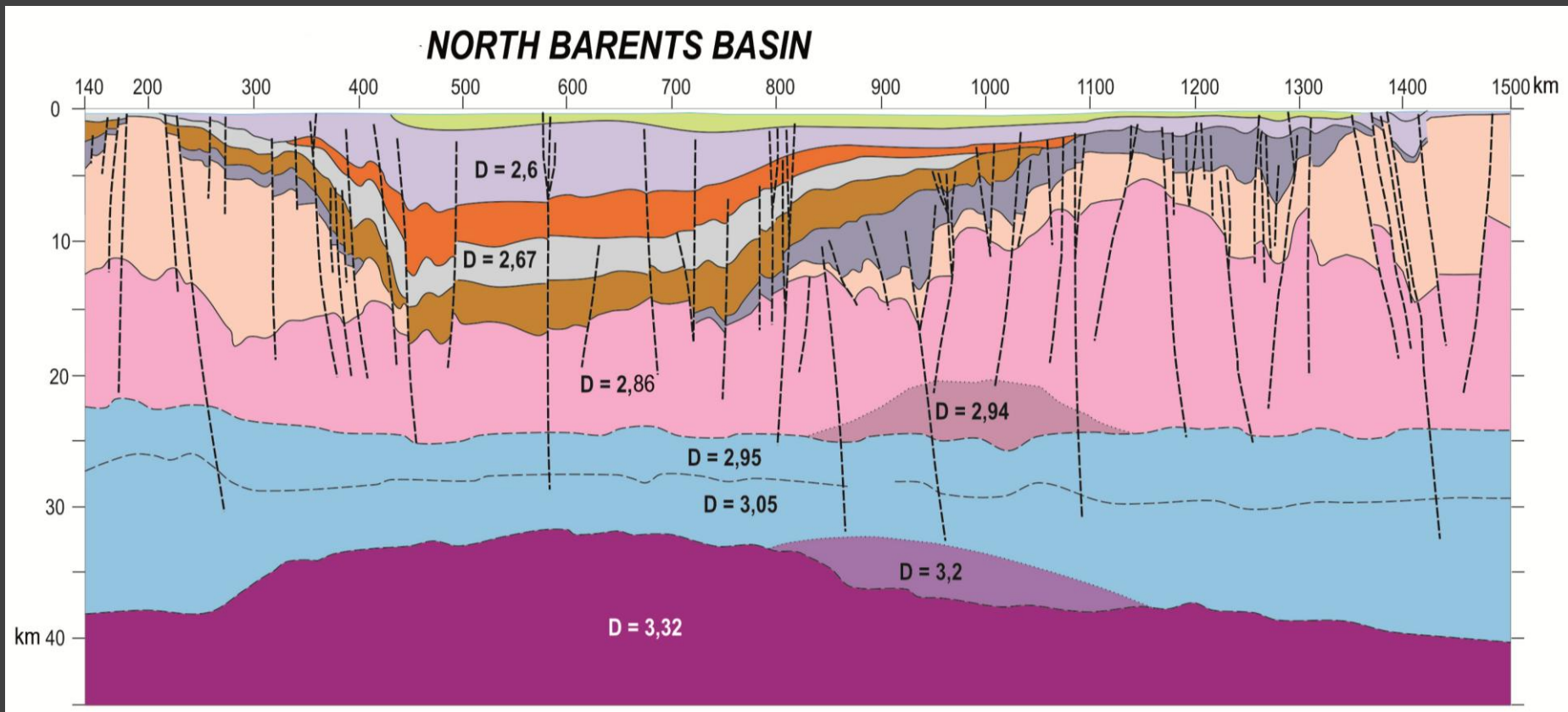


The subsidence of oceanic crust ceases 80 Ma after its formation at the axis of spreading. In the ultradeep basins one half of the sediments or more was formed long after the start of the crustal subsidence when the subsidence of oceanic crust would be already over. This precludes the occurrence of oceanic crust under the basins.

Basin	onset of crustal subsidence, Ma	The start of rapid subsidence, Ma	Time lag between the onset of the subsidence and the start of rapid subsidence Ma	thickness of sediments that were formed after the start of rapid subsidence km
North Barents	>380	260	>120	10-11
North Caspian	>540	380	>160	13-15
North Chukchi	380	130	250	13-14
South Caspian	≥65	5	≥60	10

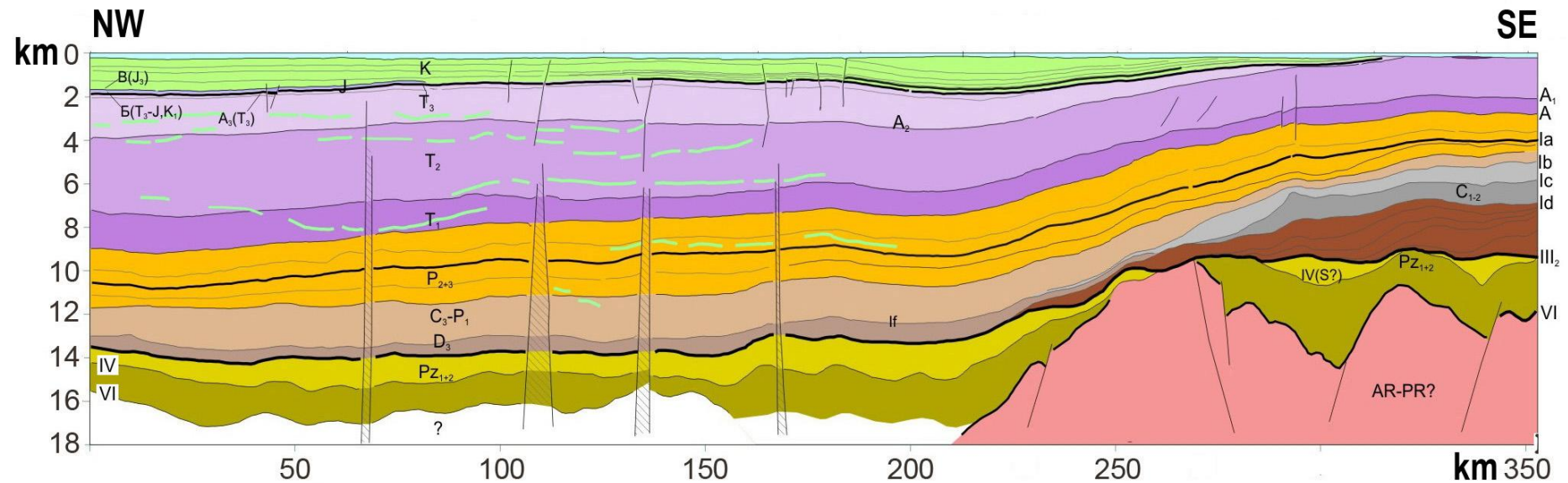
CRUSTAL STRUCTURE ALONG REGIONAL PROFILE 4-AR, NORTH BARENTS-KARA (modified after Ivanova et al., 2011)

In this profile consolidated crust is attenuated by two times at least. The basement B of the basin is broken by the system of normal faults. However, the sum of lateral displacements of the basement at the faults ensures crustal extension of only about 10%. Such a minor stretching can result in deposition of 2 km of sediments. The formation of 14 km of the overlying deposits required a large density increase in rocks below the Moho. Many authors suggested that was due to the transition of gabbro to eclogite.

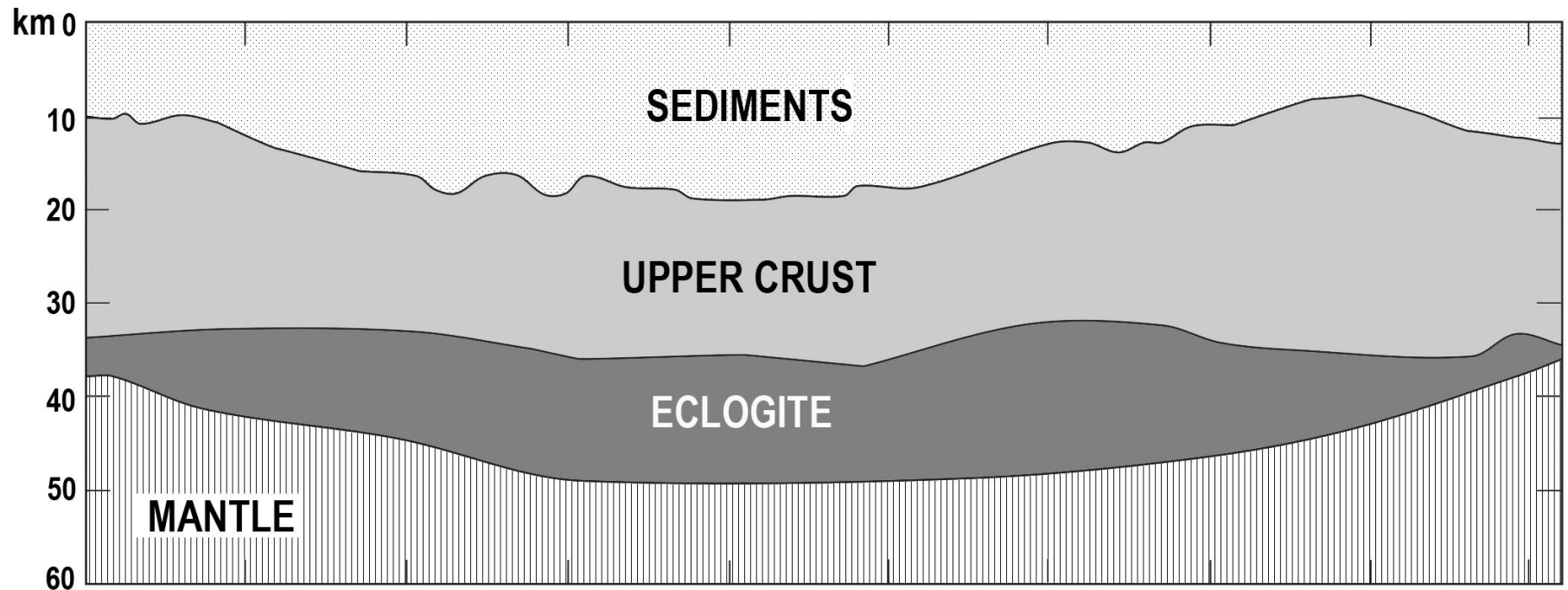


Seismic reflection profile across the North Barents Basin

9-10 km of sediments were formed since the Upper Permian and until the Cretaceous. This episode of subsidence began >120 Ma after the start of the subsidence in the basin in the Ordovician. This precludes the existence of oceanic crust under the basin. No large rotated blocks occur at the Upper Devonian regional reflector III₂. This means that since that time 14 km of sediments were formed without significant stretching.



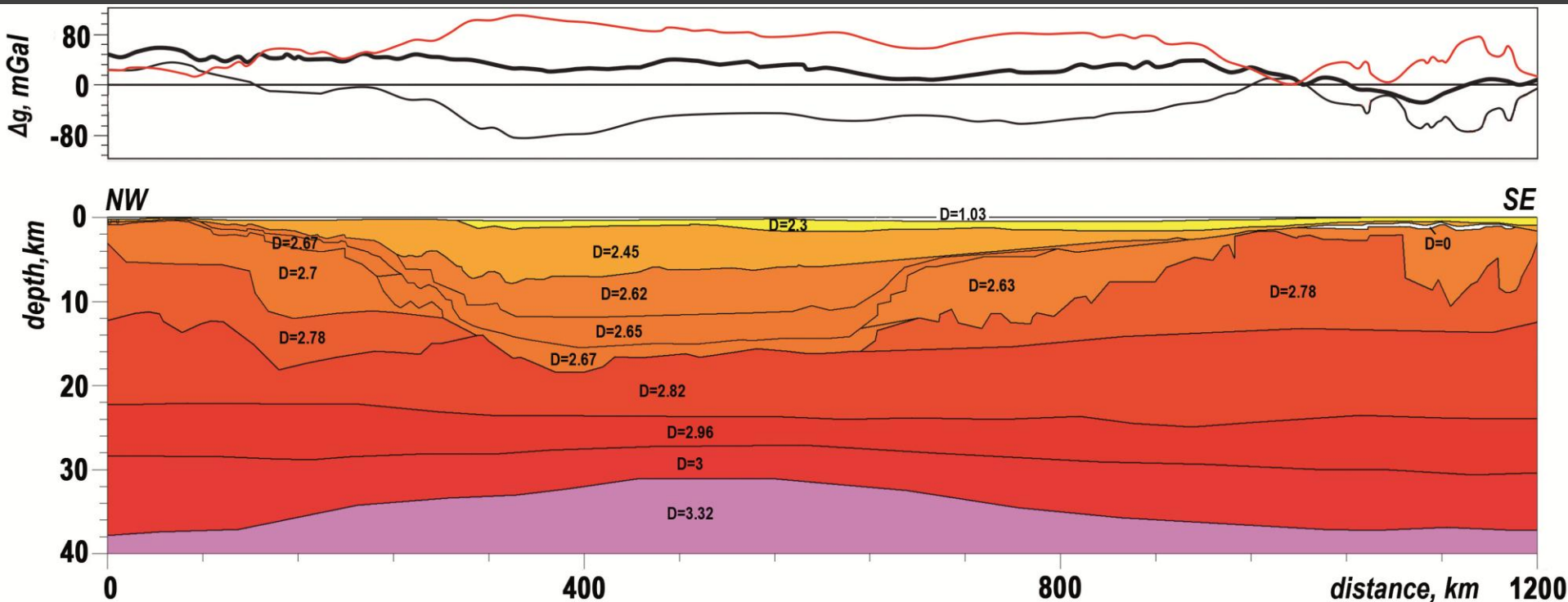
Lens of eclogite under the Moho discontinuity in the East Barents basin (modified after [Gac et al., 2010]). The occurrence under the Moho of these rocks which are denser than mantle peridotites ensure a large crustal subsidence with the formation of an ultradeep sedimentary basin



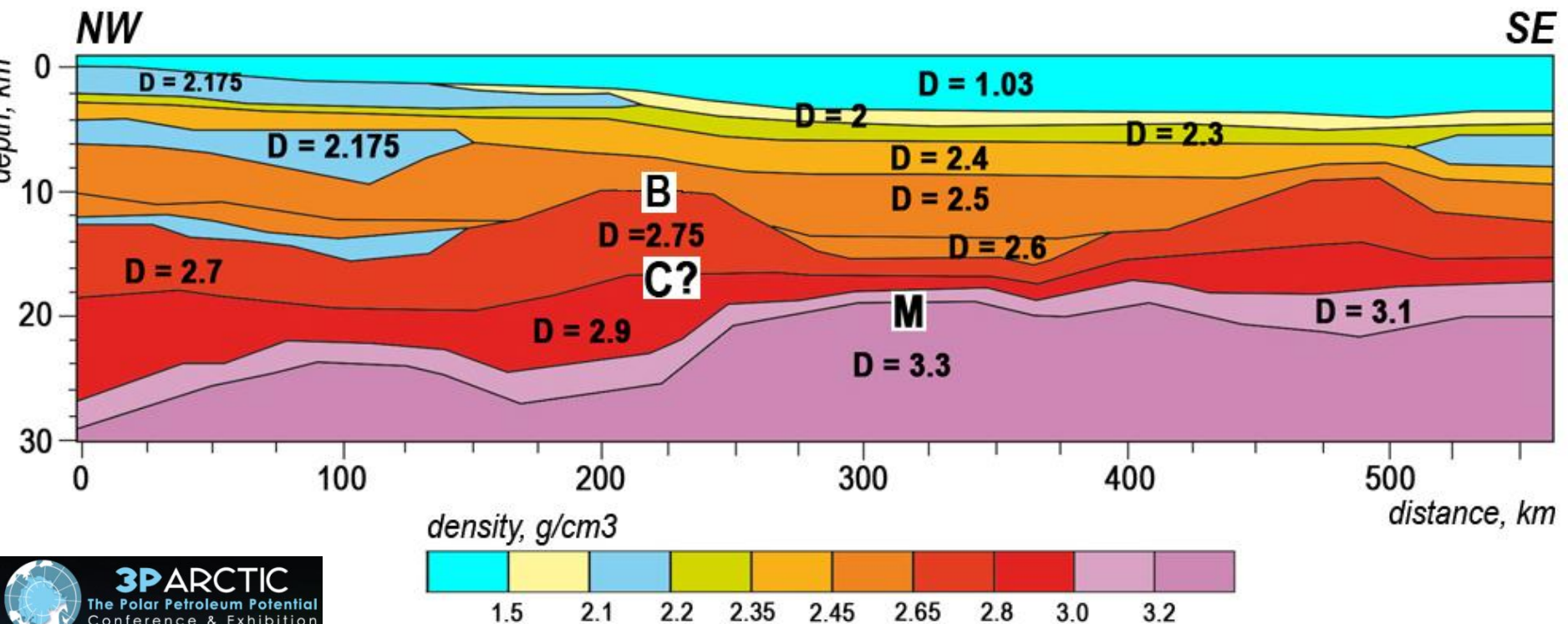
Ultradeep basins are considerably deeper than it can be expected according to the thickness of their crystalline crust.

Basin	Sediments thickness, km	Crustal thickness, km	Maximum sediment thickness on oceanic crust, km	Additional sediment thickness, km
North Barents	16	16	12	4
North Caspian	18	15	12	6
North Chukchi	18	11	13	5
South Caspian	20	12-18	11-13	7-9

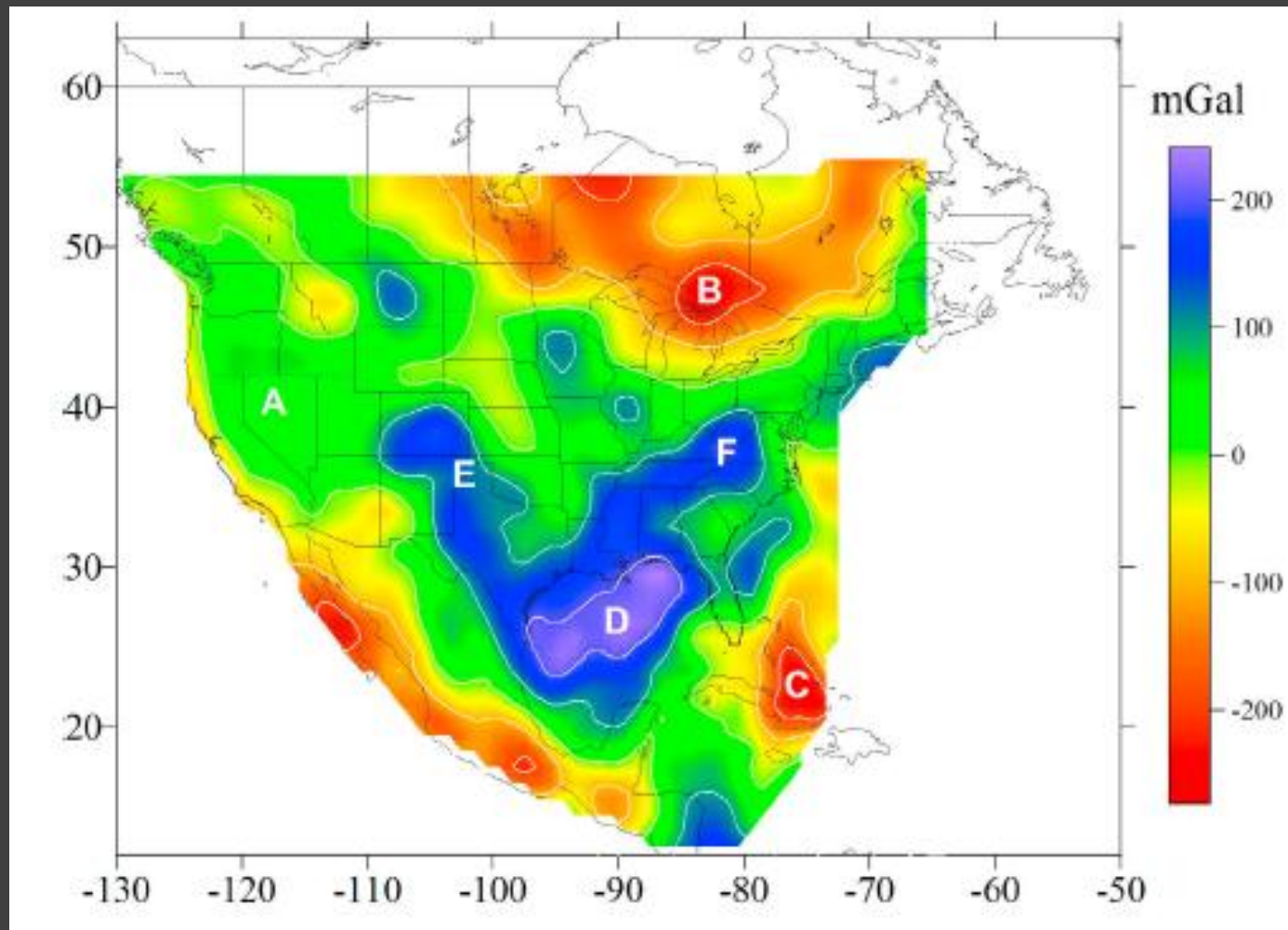
In profile 4-AR the mean density of consolidated crust is 2.9 g/cm^3 which is typical of oceanic crust. Oceanic basin underlain by the crust, 14 km thick, would be completely filled with 12 km of sediments. The North Barents Basin is 4 km deeper. In a presence in this profile of mantle peridotites with density 3.32 g/cm^3 under the Moho, large negative isostatic anomalies would be observed at the surface (thin line). In fact, slight positive free air anomalies occur above the basin (bold line). To produce them, a layer of dense eclogites 16-20 km thick should underlie the Moho. These mafic rocks pertain to the crust by their composition. However, having P-wave velocities close to those in peridotites they are commonly considered as a part of the subcrustal lithosphere.



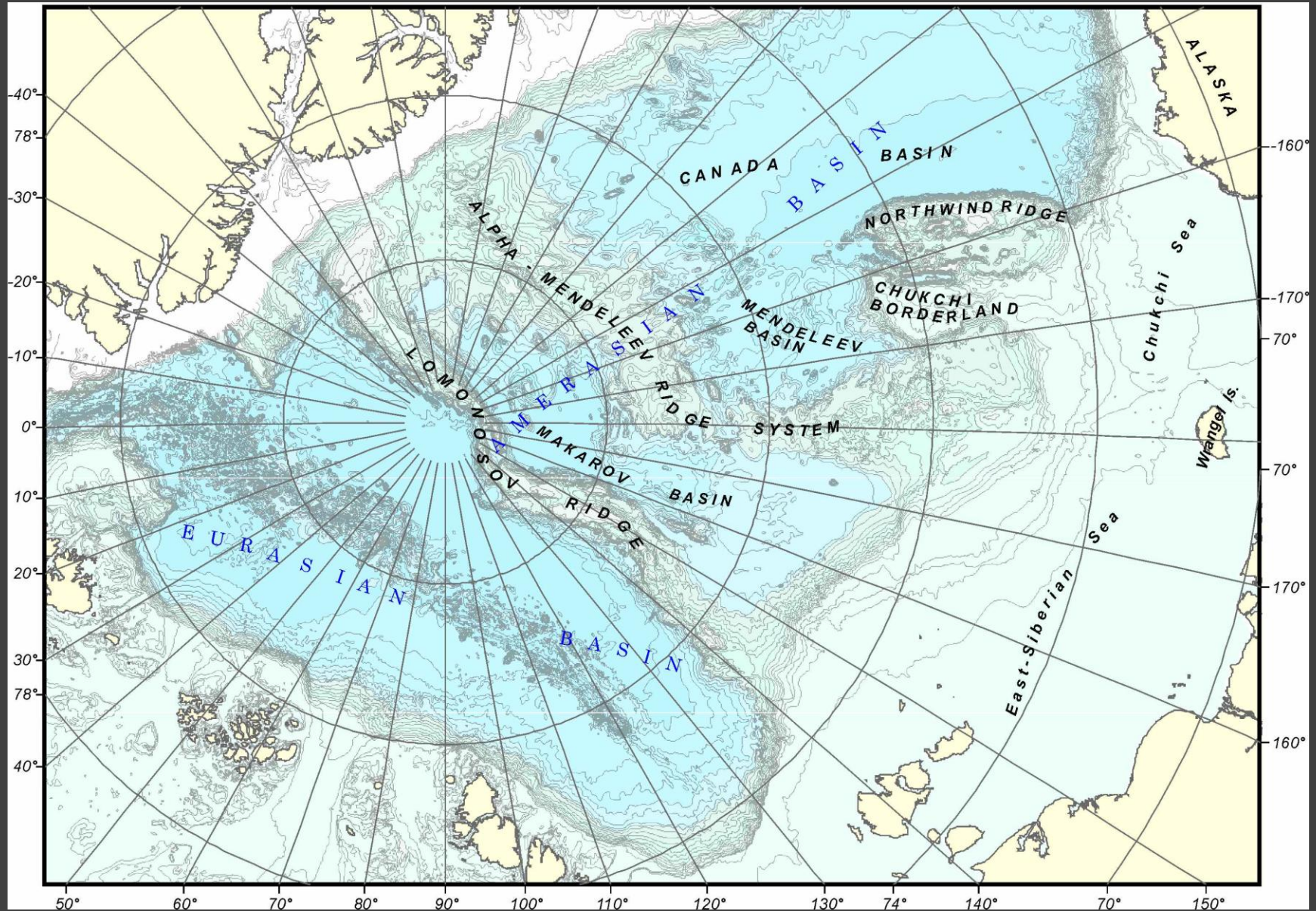
Density model along the seismic profile across the Gulf of Mexico (modified after Bird et al., 2005). The crystalline crust is attenuated to 4-15 km and it is commonly considered as the oceanic crust. However, in its upper part the crystalline crust includes a layer of rocks with the density typical for the granitic layer. Furthermore, as follows from the occurrence of very large gravity anomalies (next slide), large masses of mafic eclogite are located below the Moho which is atypical for oceanic areas.



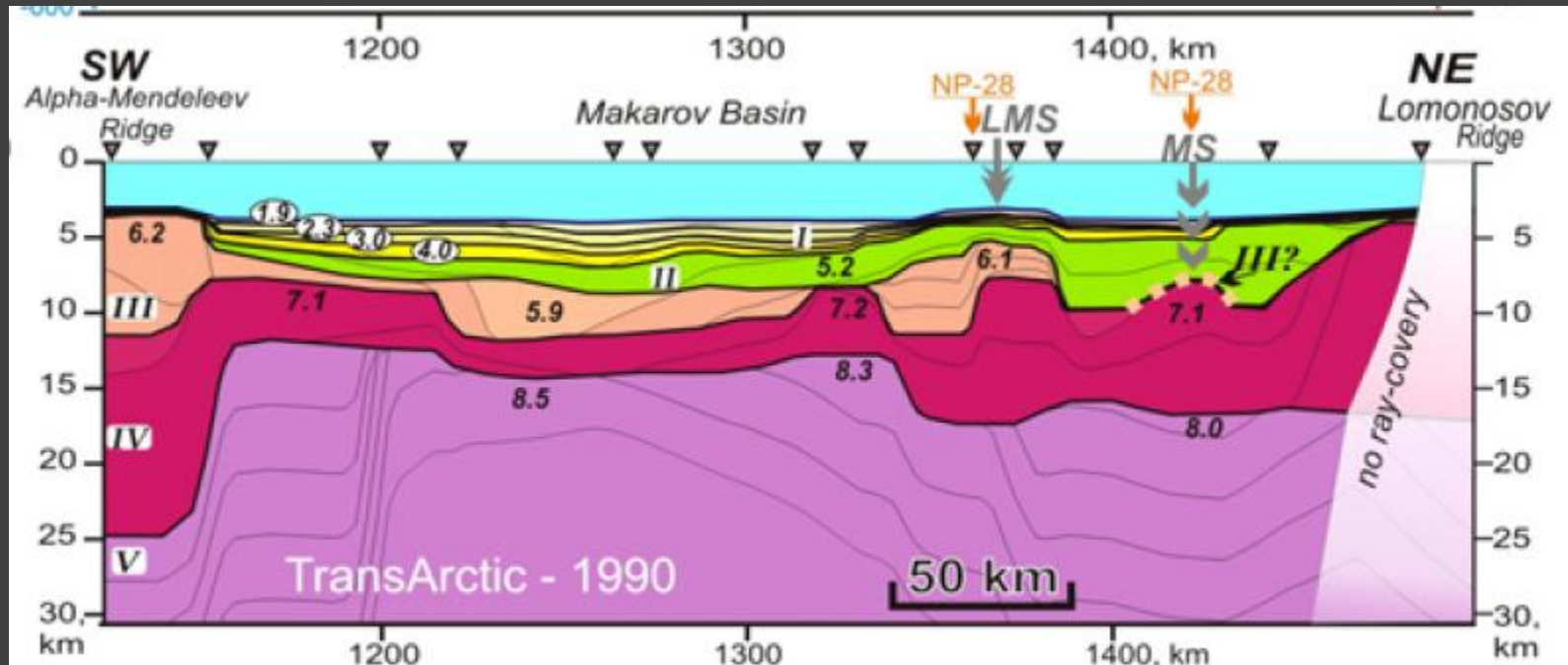
Compositional mantle gravity anomaly in the Gulf of Mexico (Mooney, Kaban, 2010). The anomaly of such a scale, ~ 200 mGal, indicates the existence of large masses of eclogites below the Moho boundary which are considerably denser than mantle peridotites. According to their mafic composition, eclogites pertain to the crust. Together with the crystalline crust located above the Moho they form a layer, 30-40 km thick. Such a thickness is typical for continental crust. Its subsidence with the formation of a deep-water basin can be explained by the transformation of gabbro in the lower crust to dense eclogites.



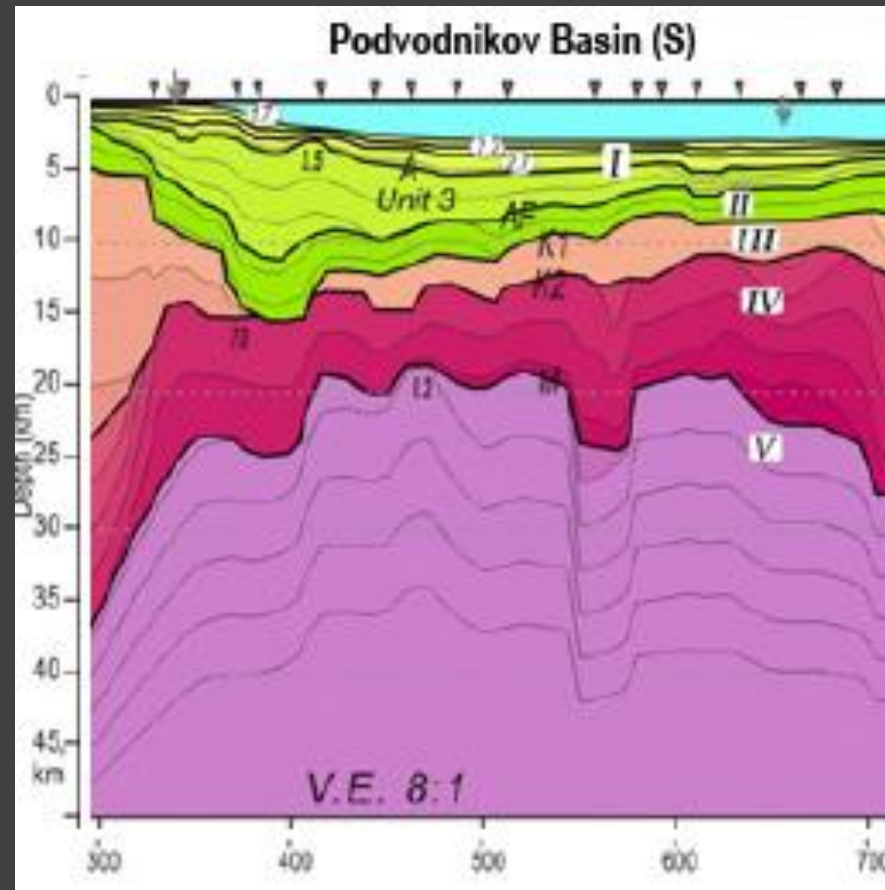
Main tectonic units in the deep-water part of the Arctic Ocean



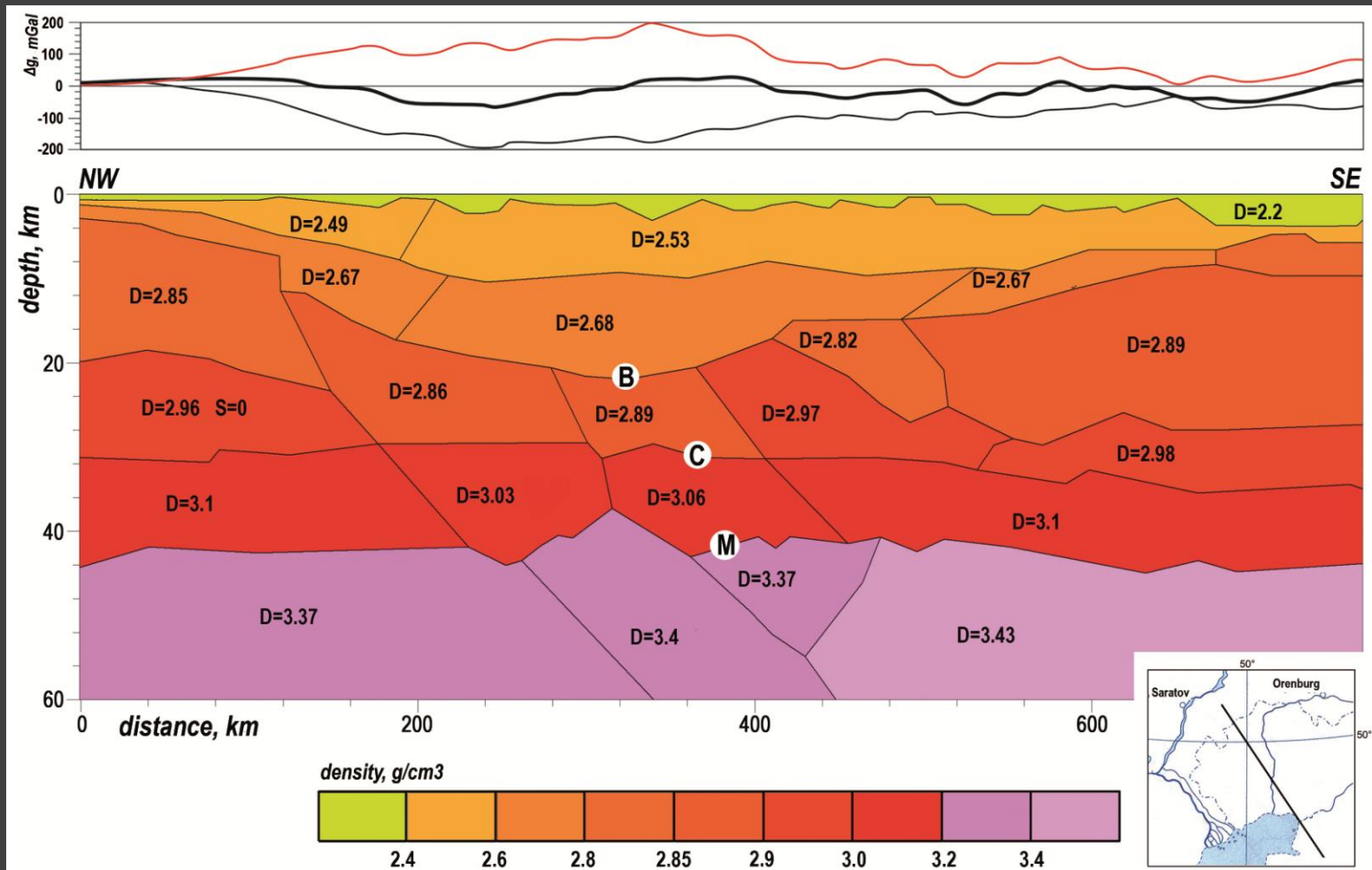
Seismic profile across the Makarov Basin in East Arctic (Lebedeva-Ivanova, 2010). The crustal structure resembles that in the Gulf of Mexico. Hence it is possible that in the Makarov Basin the Moho boundary is also underlain by a thick layer of eclogites.



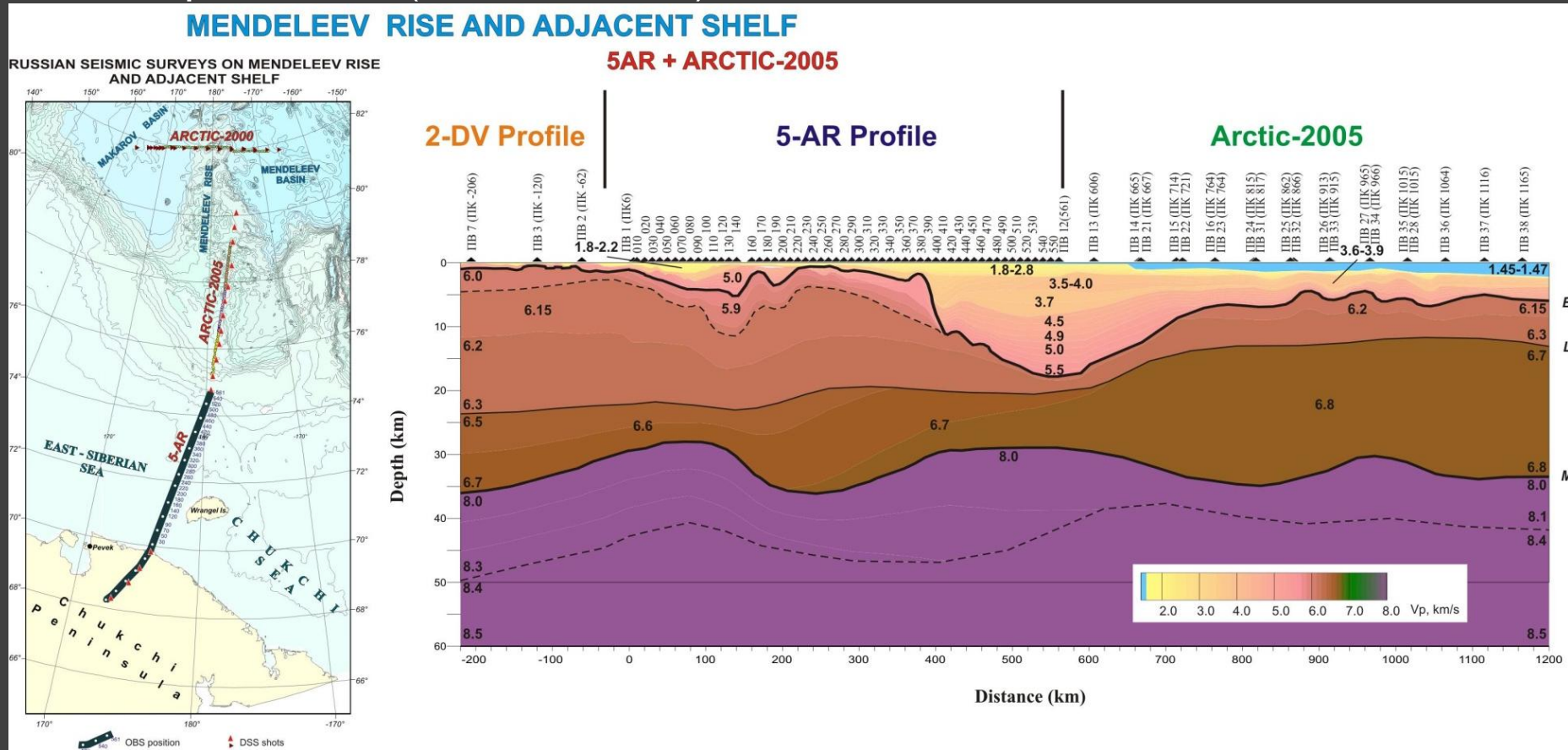
Crustal structure in the fragment of the TransArctic-1989 profile, in the southern part of the Podvodnikov Basin in East Arctic (Lebedeva-Ivanova, 2010).



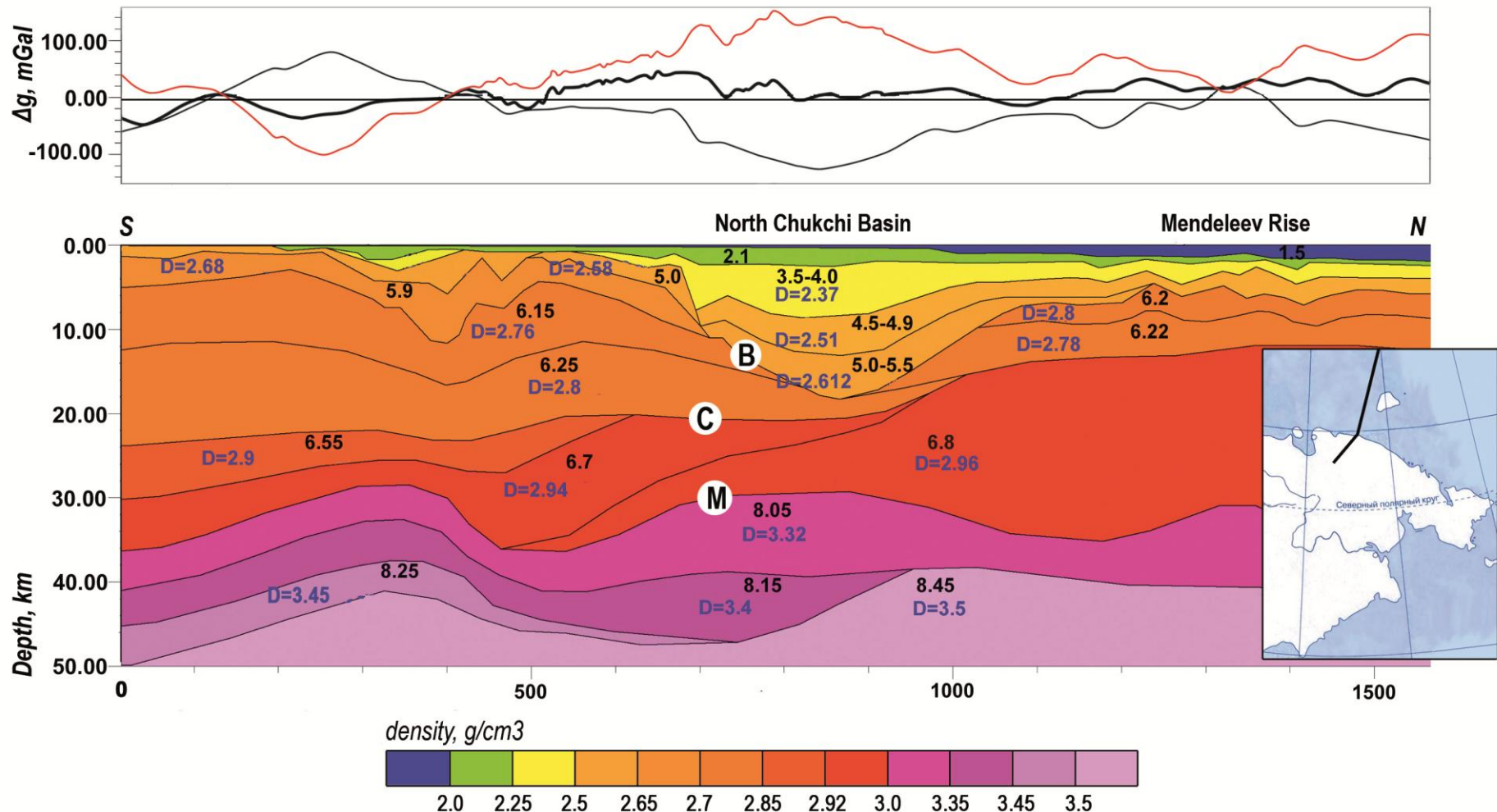
Density of the crust in profile across the North Caspian Basin 20 km deep. In this profile, it is supposed that the Moho discontinuity is underlain by ultramafic rocks. Then, negative isostatic anomalies up to 200 mGal would be observed at the surface (thin line). Low free air anomalies exist there in actually (bold line). This means that a thick layer of eclogites exists under the Moho which produces extremely high positive gravity anomalies up to 200 mGal (red line).



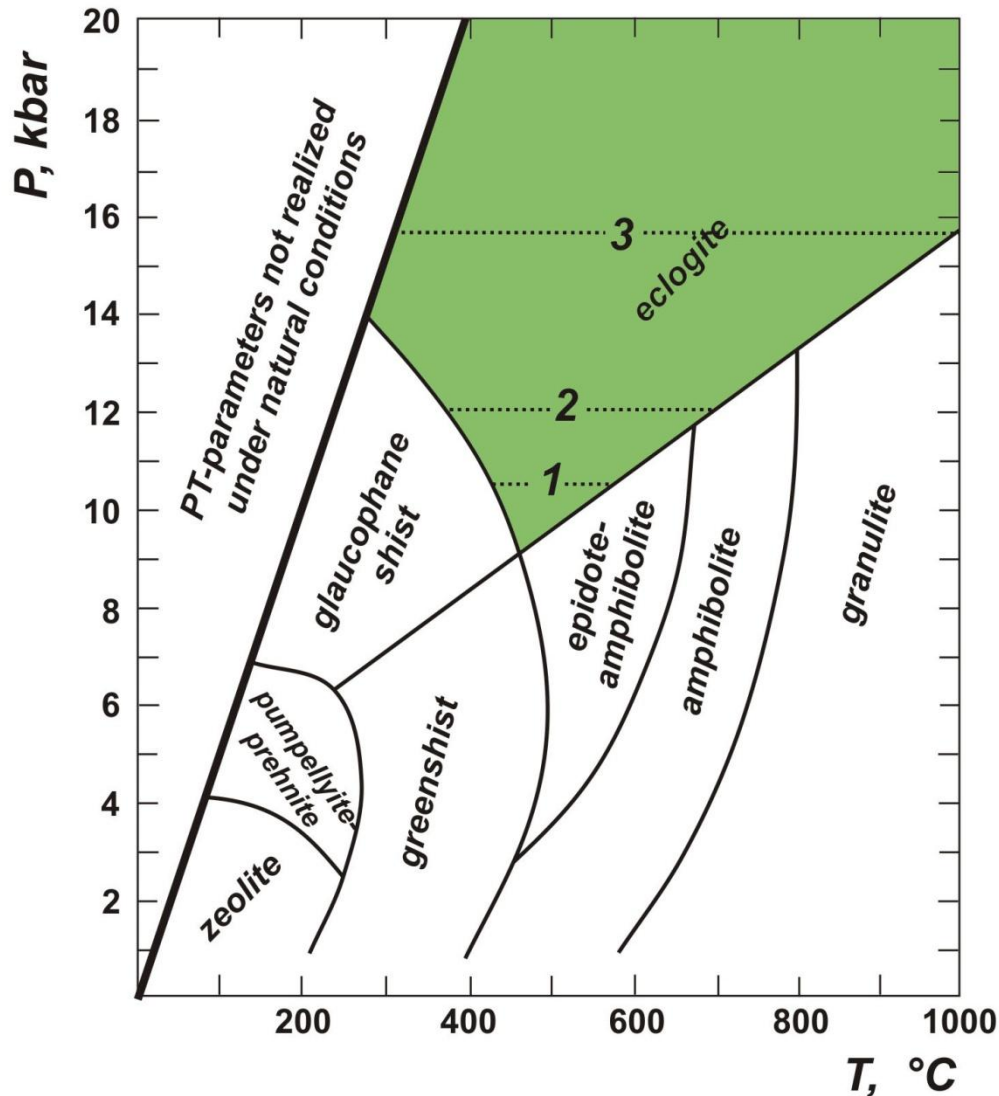
The crustal structure in the North Chukchi Basin and on the Mendeleev High. In the North Chukchi basin the crystalline crust is attenuated down to 12 km and it includes a thin granitic layer in its upper part. Up to 12-13 km of sediments have been formed in the basin since the Barremian, while the formation of the basin began >100 myr earlier. This indicates that the basin is underlain by continental crust. In its lower part a thick layer of mafic eclogites is located with high P-wave velocities similar to those in mantle peridotites (see next slide)



North Chukchi Basin and the southern part of the Mendeleev Rise along the profile 5-AR and ARCTIC-2005. Thin black line above the profile shows the isostatic anomalies which would be observed, if the Moho was underlain by mantle peridotites. In fact, the free-air anomalies shown by bold line exist above the basin. To produce them a thick layer of dense eclogites should exist under the Moho which produce positive anomalies shown by red line



PT-diagram showing metamorphic facies in iron-rich mafic rocks. Modified after Spear, 1992

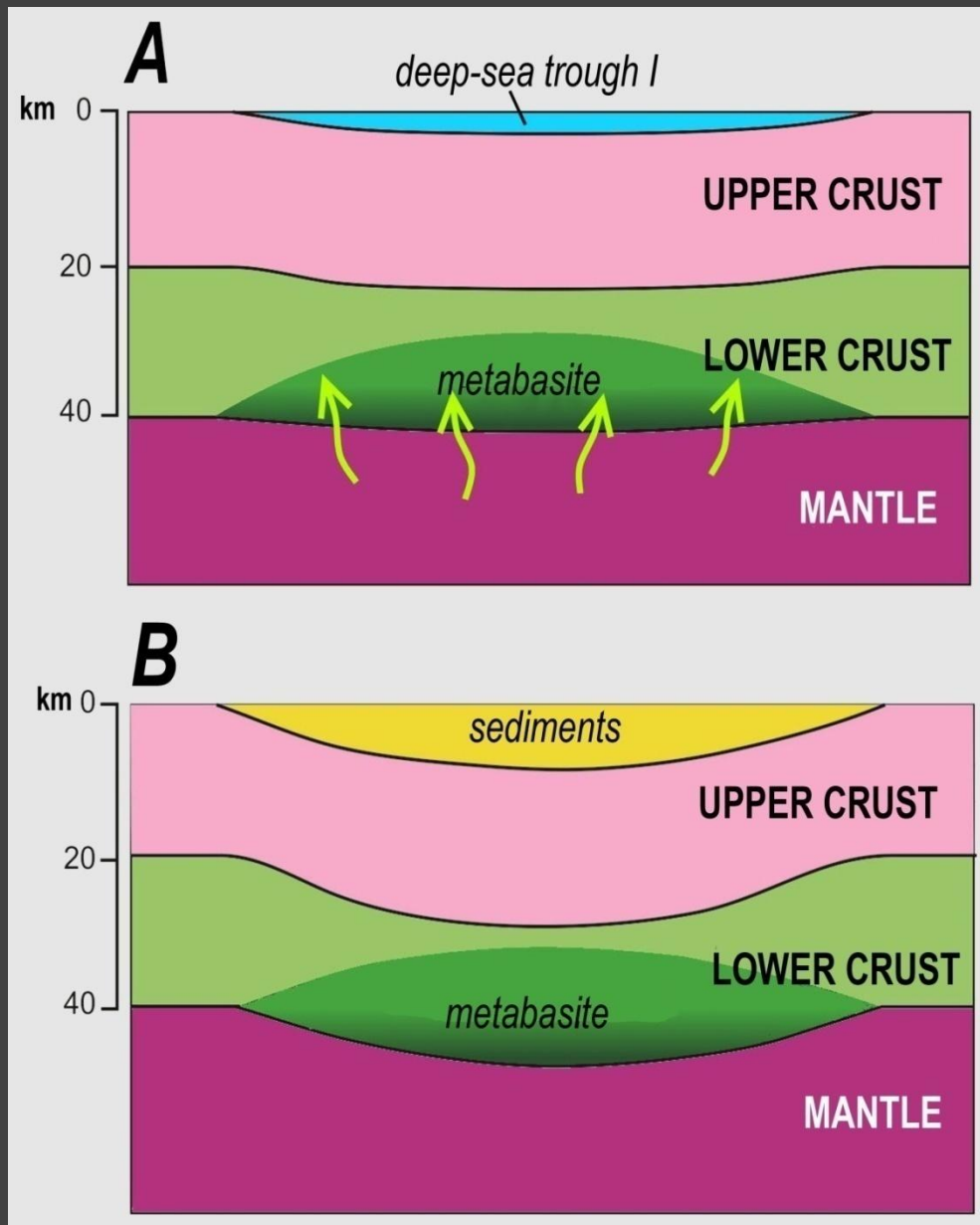


3 – pressure at the Moho after deposition of ~ 20 km sediments

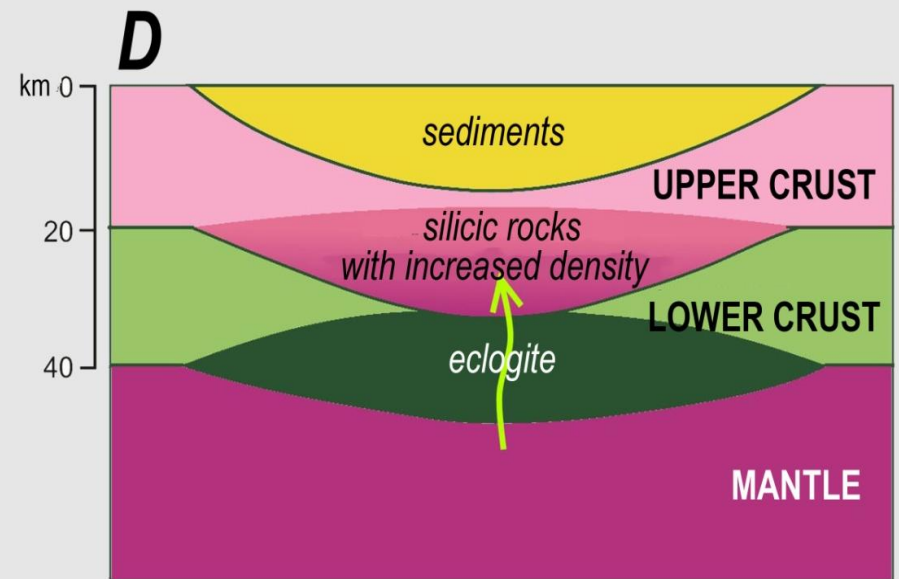
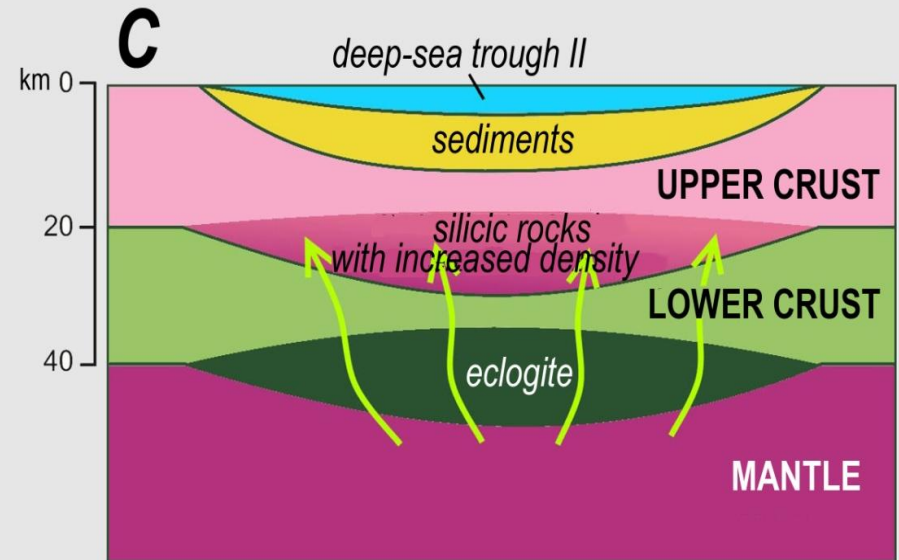
2 – pressure at the Moho after original deepwater depression had been filled with sediments

1 – average pressure at the base of the 40-km thick crust

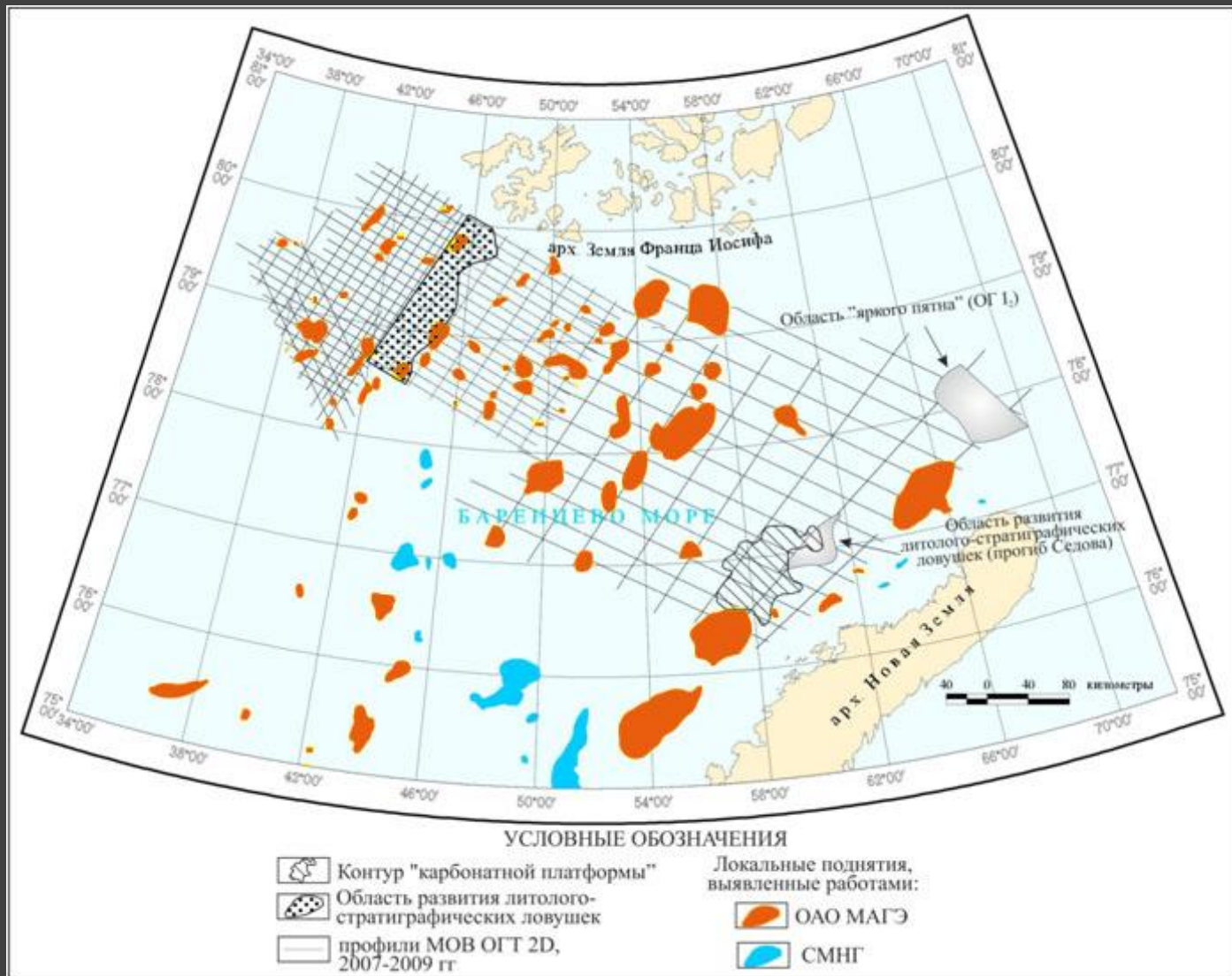
Iron-rich basic rocks (gabbroids) in the lowermost crust can be transformed into eclogites at a depth of 34-35 km and deeper. However, in dry rocks the reaction is extremely slow. A strong increase in its rate occurs when mantle fluids infiltrate the crust. This results in contraction of rocks and rapid crustal subsidence with the formation of a deep-water basin. In the North Barents Basin for the first time such a deep-water basin was formed in the Late Devonian. After basin filling with sediments and the isostatic subsidence under their load the pressure in the lower crust increases considerably which ensures a possibility for a new density increase from metamorphic reactions in a presence of fluids



The formation of dense metabasites mainly results from the formation of dense garnet in gabbro. This becomes possible at a depth of 15-18 km, and the content of gabbro increase with the depth. At the next episode of fluid infiltration into the crust additional contraction of mafic rocks with the formation of a new deep-water basin takes place. In the North Barents Basin this happened at the start of Late Permian. Additional large-scale subsidence occurred in the Triassic. After deposition of 20 km of sediments, in all the lower crust basic rocks were transformed into eclogites. Due to a large increase in pressure and temperature in the upper crust, significant metamorphism occurred in this layer. As a result iron-rich silicic rocks acquired P-wave velocities and densities typical of oceanic crust or the basaltic layer of continental crust



Perspective positive structures in the North Barents Basin



Conclusions

1. The main cause of the formation of ultradeep sedimentary basins is rock contraction in the crust due to a deep metamorphism
2. The rate of metamorphism strongly increases at the epochs of fluid infiltration from the mantle
3. In most cases this results in the formation of deep-water basins
4. Large hydrocarbon basins usually coincide with regions of rapid crustal subsidence
5. Large similarity between the North Caspian and South Caspian basins and the North Barents and North Chukchi basins in Arctic indicates that the two latter basins can have a very large petroleum potential
6. Deep-water basins underlain by the crust with high P-wave velocities typical of oceanic crust can in actually be underlain by deeply metamorphosed continental crust.
7. This can well be the case for the deep-water basins in the Amerasian Basin.

**Thank you for your
attention...**

