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GEOLOGY

The Formation of Ultradeep Sedimentary Basins Through Metamorphism with Rock Contraction in Continental Crust

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Abstract—Sedimentary covers are up to 15–20 km thick in ultradeep sedimentary basins. Joint interpretation of seismic reflection sounding and gravimetric data indicates that eclogites are located in the basins under the Moho. In these rocks the velocities of P-waves are close to those in mantle peridotites. The basins show only moderate crustal stretching and their formation was caused primarily by the transformation of gabbroids into dense eclogites in the lower part of the continental crust. The transformation took place episodically as mantle fluids infiltrated the lower crust and it was ensured by pressure rise in the lower crust occurring with the accumulation of sediments. Moderate metamorphism developed in silicic upper crust as temperature and pressure increased under thick sedimentary covers. In iron-rich metasedimentary rocks, deep metamorphism resulted in the density increase, and P-wave velocities there increased to those characteristic of the oceanic crust.

Keywords: ultradeep basins, North-Barents Basin, lithospheric stretching, eclogitization, rapid crustal subsidence, mantle fluids.

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Sedimentary covers are up to 18–20 km thick in the East-Barents, North-Chukchi, North-Caspian and South-Caspian ultradeep basins [1–4]. Consolidated crust there is as thin as 12–20 km, while average P-wave velocities there are higher and close to those characteristic of the oceanic crust. Formed at the axis of spreading, oceanic crust had subsided for ~80 myr. Since the Late Permian, 10–12 km of sediments have accumulated in the East-Barents Basin, but the subsidence started ~200 myr earlier. Similar subsidence history is characteristic of the other above mentioned basins, which is only possible if they are underlain by the continental-type crust. Consolidated crust thickness over the Moho (M) within these basins is ~12–20 km, i.e. significantly larger than the average thickness of oceanic crust, h_{oc}^{0} = 7 km. With the crustal thickness of 12–20 km, thickness of the sedimentary cover in the basins should be 4–6 km smaller than is observed, which was noted by the other researchers [4].

An increase of sediment thickness by 4–6 km accompanied by the removal of the same amount of denser mantle peridotites from under the Moho would have led to the appearance of strong negative isostatic gravity anomalies (~100–200 mGal) at the surface. But only minor free-air gravity anomalies are actually observed over the basins. This led to the conclusion [1–4] that not peridotites, but denser eclogites, occur there under the Moho holding consolidated crust over the Moho deeply submerged (Fig. 1). The formation of eclogites from gabbroids in the lower crust has been used to explain the large magnitudes of crustal subsidence in the ultradeep basins. P-wave velocities, V_p, in eclogites are close to those in mantle peridotites [5]. Therefore, eclogites, which pertain to the crust by their average composition, are shown under the Moho on the seismic profiles [1–4]. As a result, consolidated crust looks very thin in the ultradeep basins (Fig. 1).

Figure 2 presents a rock density section along a fragment of the 4-AP profile running through the northern part of the East-Barents Basin. The densities of rocks are calculated based on the velocity profile given in [6]. Above the Moho, rock density can usually be determined with sufficient accuracy from P-wave velocities, V_p [5]. Velocities, V_p, equal to 7.9–8.0 km/s under the Moho could point to a presence of mantle peridotites with density $\rho_m \sim 3.32$ g/cm^3 as well as of denser eclogites with $\rho_e \sim 3.4$–3.5 g/cm^3 [7]. If the

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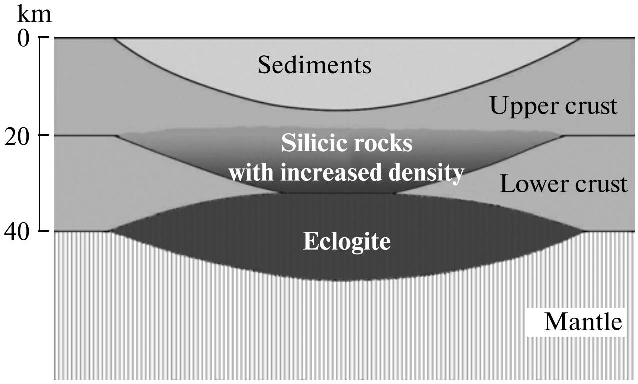

Fig. 1. Scheme of crustal structure in a deep sedimentary basin formed as a result of metamorphism with rock contraction caused by infiltration of mantle fluid. Basaltic layer is deeply metamorphosed, and P-wave velocities in it are close to those typical for the mantle. In the granitic layer, which underwent moderate metamorphism, P-wave velocities are close to those in the oceanic crust.

case had been mantle peridoties, calculations indicate that there would have been negative isostatic gravity anomalies, Δg_{is}, with the magnitude of up to 40–80 mGal over the basin (thin line in the upper part of Fig. 2). However, what is actually observed are positive free-air anomalies, Δg_{fa}, with the magnitude of several tens of milligals (bold line). The actually observed free-air anomalies suggest the presence of eclogites under the Moho which are denser than peridotites and which create at the surface the anomalies with the magnitude of $\Delta g_{an} = \Delta g_{fa} - \Delta g_{is}$ (dashed line). In the deep part of the depression these gravity anomalies are as high as 80–110 mGal. To generate the anomalies of such magnitude, eclogitic layer thickness has to be equal to:

$$(h_e)_{km} = [(\Delta g_{an})_{mGal}/42(\rho_e - \rho_m)]. \quad (1)$$

Assuming $\rho_e = 3.45$ g/cm^3, $\rho_m = 3.32$ g/cm^3, $\Delta g_{an} =$ 80–110 mGal, we find:

$$h_e = 16\text{–}20 \text{ km}. \quad (2)$$

Due to the formation of that thick eclogitic layer through the transformation of gabbroids with the density of $\rho_{gb} = 2.94$ g/cm^3 in the basaltic layer, a sedimentary basin forms on the surface of the crust; the depth of such sedimentary basin is:

$$h_{sed} = (\rho_m/\rho_{gb})[(\rho_e - \rho_{gb})/(\rho_m - \rho_{sed})]h_e. \quad (3)$$

Assuming the sediment density $\rho_{sed} = 2.56$ g/cm^3, $h_{sed} =$ 12–15 km which is close to what is actually observed (~16 km) in the North-Barents Basin. In this case, eclogitization of the basaltic layer could possibly have been the main cause of crustal subsidence in the basin.

Strong crustal stretching—riftogenesis—could also have been an important factor contributing to crustal subsidence. Riftogenesis was usually accompanied by the formation of listric normal faults with kilometer-scale basement displacements [8]. However, only minor stretching is observed in the basins mentioned above. Summation of the basement's horizontal displacements along the faults via the 2-AP and 4-AP profiles across the North-Barents Basin (Fig. 12.6 and 12.8 in [6]) gives a relative crustal stretching of $\varepsilon \leq 10\%$. According to standard equations [1, 3], such crustal stretching could have accounted for the deposition of only ~2 km of the Early and Mid Paleozoic sediments above the basement. These sediments are overlain with erosional unconformity by another 14–15 km of sediments deposited since the Late Devonian. In order to account for the latter, crustal stretching would have to be as large as 120%. However, in this part of the profile, all the reflectors are continuous, except in some limited in size areas of vertical magmatic intrusions (see, for example, Fig. 6 in [3]). This

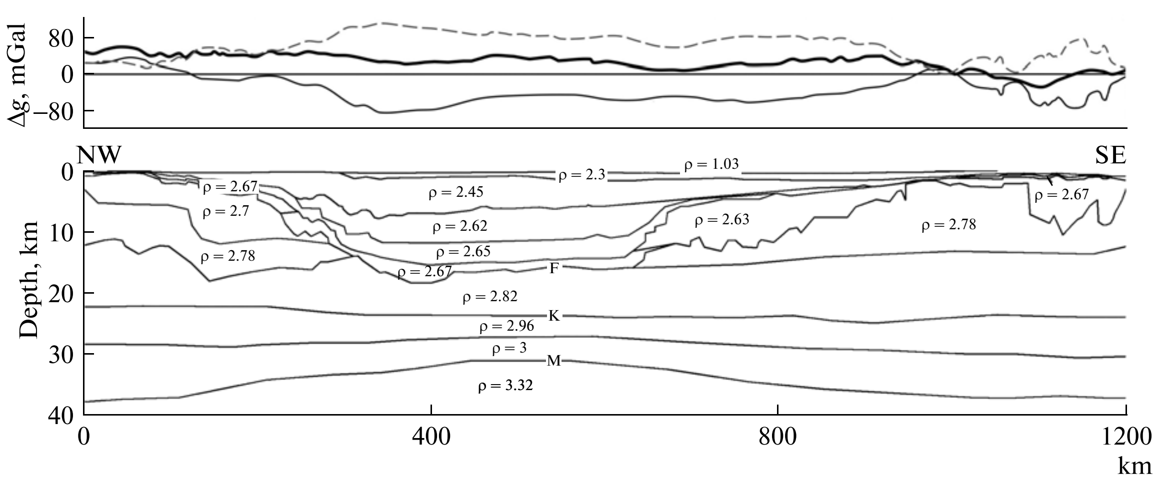

Fig. 2. Rock density (ρ) above the Moho along the 4-AR profile across the North-Barents Basin. In the upper part of the figure are shown free-air gravity anomalies and the isostatic anomalies calculated based on the assumption that peridotites with the density of 3.32 g/cm^3 are located under the Moho. K is the Conrad discontinuity and F is the basement surface.

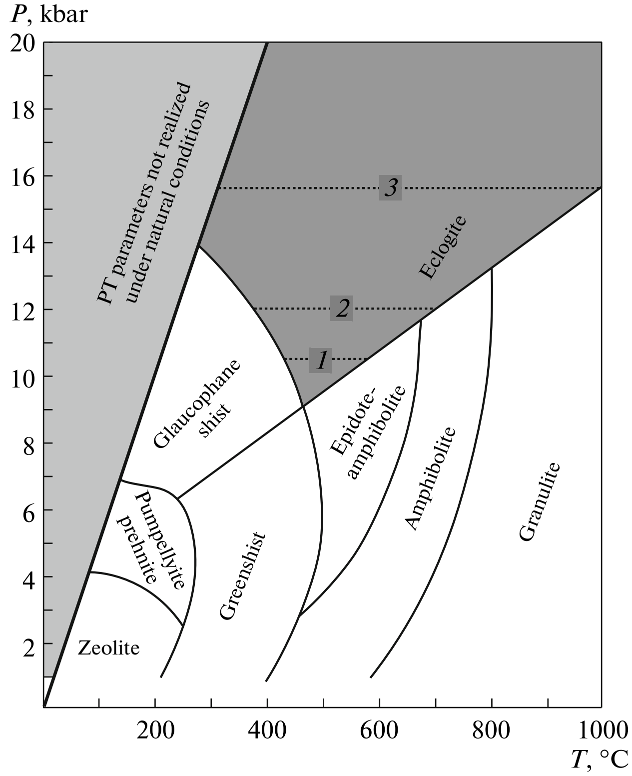

Fig. 3. A $P-T$ diagram showing metamorphic facies in iron-rich mafic rocks (modified after [9]). Dotted lines indicates: *1*—average pressure at the base of the 40 km thick crust; *2*—pressure at the Moho after the original deepwater depression had been completely filled with sediments; *3*—pressure at the Moho after deposition of ~20 km of sediments in the basin.

leads us to conclude that there has not been any noticeable crustal stretching over the last 380 myr and, therefore, crustal stretching cannot be regarded as the main cause of the crustal subsidence. In this case, the subsidence would require rock contraction in the lower crust. As it follows from Eq. (3), the subsidence with the accumulation of a 14-km thick sedimentary layer would require the formation of a 18-km thick eclogitic layer in the lower crust. This is close to the estimate (2) obtained from a joint analysis of the gravimetric and crustal structure data for the basin's northern part.

The gabbro-eclogite transition results in a 15–20% increase in rock density due to the formation of dense garnet. Eclogite formation in continental crust requires very specific conditions [3]. In most mafic rocks the transition does not take place down to a depth of ~40 km [9, 10]. Eclogite formation begins from the depth of 34–35 km where pressure rises up to 9 kb (Fig. 3) only in mafites with a high content of iron at temperatures T ~ 500°C. Gabbro-eclogite transition develops gradually with the increase in the garnet content. Garnet formation begins already at a depth of 15–18 km which allows for mafites transformation into denser metamafites. With the increase of pressure, the content of garnet in the lower crust increases [9, 11], and rock density there may reach 3.0–3.1 g/cm^3 or more. Almost not developing in dry conditions, such metamorphism becomes strongly accelerated during the episodes of infiltration of mantle fluid.

Rock contraction is accompanied by the crustal subsidence. Filling of the void thus formed with sediments and the isostatic crustal subsidence under their load causes the temperature and pressure to increase in consolidated crust. Therefore, at the time of a next fluid infiltration, metamorphism takes place at a higher pressure (Fig. 3) which causes further rock contraction. After ~20 km of sediments are accumulated (Fig. 3) a new equilibrium temperature distribution is established, the temperature and pressure conditions in the lower crust become such that iron-rich basites can be deeply metamorphosed in a presence of mantle fluid. On the profile of Fig. 2, such eclogitized lower crust with high V_p values is located under the Moho.

Metasedimentary rocks—metapelites, mesocratic paragneisses, acidic metagreywackes and tuffs—occur in large volumes at many areas in the upper continental crust. They are often characterized by a high content of iron. After their submergence under the load of a thick sedimentary layer down to a depth of ~20 km, garnet formation also occurs in them [9, 11, 12]. As a result, silicic rocks within the granitic layer become denser, and P-wave velocities become close there to those characteristic of the oceanic crust. On the profile shown in Fig. 2, these rocks with the average density of 2.90 g/cm^3 are located above the Moho.

Prior to the start of the subsidence, granitic layer surface in the North-Barents Basin was located close to the sea level. In that epoch, rock density in that layer had likely been close to that of the rocks in the upper crust's 14-km thick layer in the areas adjacent to the depression as shown in Fig. 2: ρ_{cl} = 2.7–2.78 g/cm^3. Together with the ~18 km thick layer of eclogitized lower crust located under the Moho, the total thickness of the consolidated crust in the deep part of the basin is ~32 km which is typical of many continental areas.

In addition to an increase in the P-wave velocities in consolidated crust above the Moho under ultradeep basins, metamorphism causes significant changes in the seismic refraction velocity profiles. If we assume the Conrad discontinuity on Fig. 2 to coincide with the base of the layer with the density of 2.82 g/cm^3 which is close to that of the granodioritic layer on the continents, this layer will appear to be thinned by 3.1–3.2 times in the deeper part of the basin compared to the adjacent areas. The "basaltic layer", which is located between the Moho and Conrad and which comprises sublayers with densities of 2.96 g/cm^3 and 3.0 g/cm^3, is thinned considerably less—by 1.8–2.1 times. Increased thinning (compared to that of the "basaltic layer") is also characteristic of several other ultradeep basins, for example, the North-Chukchi Basin [13]. Flows in the less viscous sediments were too weak to stretch the "granitic layer." The material of that layer could not flow from the deeper part of the depression to the adjacent areas with small sediment thickness which is why the pressure in consolidated crust is higher there. This demonstrates it once again that not crustal stretching but deep metamorphism was the cause of the strong (by several times) thinning of consolidated crust observed on the seismic profiles above the Moho.

It has to be noted that in deep basins, such as the North-Barents (Fig. 2) and North-Chukchi [13], a 2–6 km thick granitic layer often remains in the upper part of consolidated crust, which is not characteristic of the oceanic crust. Similar crustal structure is observed in the eastern part of the Russian Arctic sector—at the Mendeleyev High and Podvodnikov (Submariners) Basin [14]. Within the Mendeleyev Ridge, consolidated crust is 25–30 km thick and it includes a 3–6 km thick seismic layer of granite with the density of 2.65–2.75 g/cm^3. This allows us to attribute the crust of these structures to the continental type.

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