DOI: https://doi.org/10.24028/gj.v44i3.261977

Geological Theory versus Plate Tectonics. A Comment to the paper by V.V. Gordienko «About Geological Theory»

Y. Khazan, 2022

Frankfurt am Main, Germany

Received 25 January 2022

To doubt everything, to believe everything,
are two solutions that are equally convenient:
both of them save us from the need to think.
A. Poincaré [Poincaré, 2020]

The article by V.V. Gordienko «About Geological Theory» published in Geophysical Journal [Gordienko, 2022] discusses various aspects of the Advective-Polymorphic Hypothesis (APH) developed by the author. In its main content, the paper does not differ or differs but little from other publications of the author on this topic (for example, [Gordienko, 2013, 2017]). In this article, the emphasis is on the possibility of interpreting the APH as a geological theory. The second word here (theory) means a suggestion to consider the APH from the same point of view as theories in mathematics and physics, i. e. as a logical construction based on a certain set of axioms. The word «geological» means that a certain set of geological facts is chosen as a system of axioms, going back to the concept of endogenous regimes by V.V. Belousov [Belousov, 1978].

As in other publications of the author (e. g., Gordienko [2013, 2017, 2018]), in this paper much attention is paid to criticism of the Plate (Global) Tectonics. The author of this comment, in contrast to V. V. Gordienko, is a supporter of global tectonics, since some observations are naturally, and sometimes uniquely explained in this paradigm. At the same time, there is a range of problems in which plate tectonics cannot be effective simply because it is not able to provide a necessarily detailed description of geological processes. Actually, the absence of a clear divide between classical geotectonics and plate tectonics is the reason for the mutual misunderstanding between geologists and supporters of plate tectonics.

To some extent, the relationship between the fundamental and applied physics can serve as an illustration of what the relationship between geology and plate tectonics could be. With the exception of radioactive decay and some laboratory experiments, all observed natural phenomena on the planet and within it are due to electromagnetic and gravitational interactions. However, despite the fact that there are exact equations describing these processes, many problems cannot be solved from the first principles because of technical complexity. In these cases, phenomenological approaches (say, elasticity theory, fracture mechanics, heat conduction theory, GLAG theory of superconductivity), physical modeling (e. g., wind tunnels), or methods of the field of chemistry are used. There are no contradictions between the fundamental and applied physics, because their areas of applicability are separated.

In tectonics, unlike physics, there are no «exact equations» that describe tectonic processes, so it is impossible to separate the areas of applicability of the «fundamental» and «applied» tectonics in the same way. With some degree of conventionality, we can say that plate tectonics tends to describe tectonic processes with an emphasis on physics, while classical tectonics considers them to a greater extent in a historical context. As a result, the construction of plate tectonics, especially in the early stages of its development, when the plates were allocated rather arbitrarily, are faced with accusations of being anti-historical (V.V. Belousov), while attempts to explain everything and everyone by purely geological methods lead to statements that contradict the physical and even common sense.

In particular, such a contradiction to common sense is the refusal to recognize the reality of the subduction process. I already wrote about this earlier [Khazan, 2014], but the commented article shows that there is a need to return to this again.

It should be said that the question of the nature of the seafloor spreading and subduction, or, more precisely, of the spreading/subduction system, is the key point of controversy between the classical tectonics and the plate tectonics. No compromises are possible here: if the spreading/subduction system is functioning, then there can be no doubt about the correctness of the fundamental provisions of plate tectonics, in particular, about the possibility and even inevitability of large-scale flows in the mantle and horizontal movements on a global scale. On the contrary, if spreading/subduction does not exist, then horizontal displacements on a global scale are impossible and, therefore, the classical tectonics notions of the primacy of vertical movements in the tectonosphere are valid.

The easiest way to demonstrate the validity of the basic principles of the plate tectonics is to study coseismic movements in subduction zones [Stern, 2002; Hyndman, 2007; Wang, 2007; Bilek, Lay, 2018], since in these zones everything happens right before our very eyes and can be studied instrumentally in real time.

Megaearthquakes with a magnitude of 8 and above occur at a frequency of about 0.7 per year [Engdahl, Villaseñor, 2002]. During the 20th century, 45 such earthquakes were recorded, and in the 21st century there have already been 17 of them, including the Sumatra 2004 and Tohoku 2011 magnitude M9+ earthquakes. Naturally, weaker events with a magnitude of 7 to 8 occur much more frequently. The high frequency of great earthquakes makes it possible to effectively use stationary observation networks on land and on the ocean floor. For example, in the section of the Japan Trench, where the Tohoku earthquake of magnitude 9.1 occurred on March 11, 2011, a network was deployed that included GPS sensors on land and ocean floor as well as bottom pressure sensors, which were used to determine the vertical coseismic displacement of the ocean floor [Iinuma et al., 2012].

Plafker [1965] drew attention to the fact that during the Alaska earthquake on March 27, 1964, the vertical coseismic displacements of the surface, which were observed in a band about 800 km long and about 200 km wide located on the continental side of the ocean trench, were clearly zoned: the trenchward edge of the band was ascending, while closer to the continent, the vertical coseismic displacements changed sign and became descending. Afterwards, it was found that during the subduction earthquakes, such zoning of vertical surface movements is ALWAYS observed (e. g., [Plafker, Savage, 1970; Plafker, 1972; Chlieh et al., 2007; Iinuma et al., 2012]). Meanwhile, horizontal coseismic movements of both the oceanic plate and the continent in the epicentral zone are ALWAYS directed towards the trench.

ALL these observations at once, as well as the ORIGIN of the TRENCH, are explained by the subduction of the oceanic plate under the continental one. The oceanic plate pulls the edge of the continental one down, forming a trench. At some section of the quasi-horizontal fault between the plates (in the future seismogenic zone), relative displacements are blocked, so that the continental plate bends upwards somewhat. When the seismogenic zone breaks, the bend is removed, the freed (oceanic) edge of the continental plate jumps up, generating a tsunami, and the rest of the bowed section of the plate moves down. The oceanic plate moves under the continent for tens of meters, and the resulting fault propagates in the direction perpendicular to the movement of the plate (transverse shear crack) and runs a distance of hundreds to thousands of kilometers. At present, coseismic motions are observed instrumentally. However, it was also previously known that all tide sensors in the Pacific Basin recorded a positive tsunami wave arising from the upward movement of the ocean floor in the tsunami source [Plafker, Savage, 1970; Ho et al., 2019].

No other explanation for these observations is possible. And it is quite characteristic that V.V. Gordienko, who is a fundamental opponent of plate tectonics and subjects it to merciless, although by no means always fair criticism, never mentions these observations, which irrefutably testify to the reality of subduction. Instead, V.V. Gordienko emphasizes particular issues, e. g., the absence of pronounced seismicity at the outer (oceanward) edge of the trench.

The point is that at the oceanic edge of the trench, where the cold and, accordingly, rigid oceanic plate bends and must inevitably crack, only weak seismicity is observed, despite the fact that detailed seismic data indicate a large number of normal faults on the oceanic slope of the trench (e. g., [Ranero et al., 2003]). This phenomenon has a special name «the dichotomy of a rigid plate and a soft slab» (Petersen et al., 2018) (here, a slab means a subducting part of an oceanic plate). To explain it, water percolation into the crust and upper mantle weakening the plate is usually considered (e. g., [Tilmann et al., 2008]). The problem of the dichotomy between a rigid plate and a soft slab seems to have been resolved by Gerya et al. [2021], who showed that the weakening of the slab can be a consequence of its brittle-plastic damage down to the level of individual grains of the crystal structure. This phenomenon explains the development of faults with a large displacement near the trench, the appearance of pronounced boundaries and localized areas of reduced effective viscosity inside the subducting slab [Gerya et al., 2021].

Another remark, made by V.V. Gordienko in Section 5, says that the movement of the plate is accompanied by heating by 4—5 thousand degrees per 1 million years due to friction. To give such an estimate, it is necessary, at a minimum, to explain how it was obtained. Since this is not presented in the paper, I regard this estimate as simply a misunderstanding.

In the article under discussion, spreading is not considered, but in other publications V.V. Gordienko even goes so far as to accuse everyone who investigates band magnetic anomalies that testify to spreading in the MOR, of data manipulation. It is pointless to discuss these accusations, but it makes sense to consider a couple of meaningful remarks [Gordienko, 2017].

The first of them refers to the dating of rocks near the axis of the rift valley of the Mid-Atlantic Ridge (MAR) on opposite sides of it. According to Silantiev et al. [2000], the K-Ar ages of two rock samples taken at a distance of 5 and 6 km from the spreading axis are 3.5 Ma and 9 Ma, respectively, and at a spreading rate of 2.8 cm/yr., these samples should have been about 100 km and 250 km from the spreading axis, respectively. Silantiev et al. [2000] suggested that the spreading in this section of the MAR has an impulsive character, while V.V. Gordienko believes that this apparent contradiction indicates that the canonical plate tectonics is erroneous. I think that the reason for the discrepancy between the age determined from magnetic anomalies and the radioisotope one is due to the well-known difficulties in the K-Ar isotope dating [Kelley, 2002; Dickin, 2005]. (A good example of such errors are the dates of the lunar samples delivered by Apollo 11. In this case, there is certainly no contamination of the samples with atmospheric argon, but, nevertheless, the dates of the K-Ar method have a significant scatter, while the Ar-Ar dates of the same rocks are quite consistent [Kelley, 2002]). At present, K-Ar dating is mainly used to calibrate standards [Kelley, 2002], while the ^{40}Ar-^{39}Ar method is used for real dating [McDougall, Harrison, 1999; Kelly, 2002; Dickin, 2005; Schaen et al., 2021]. This technology also has its difficulties, but there are protocols that allow one to get correct results [Kim, Cho, 2020]. Finally, Kostitsyn et al. [2018] performed U-Pb dating of rocks along the Vema transform fault, located near the ridge section sampled by Silantiev et al. [2000]. These data, as well as the Ar-Ar dating of the amphibole in ultramafic mylonites [Cipriani et al., 2009] and the U-Pb age of zircon from gabbro [Skolotnev et al., 2010], demonstrate a linear increase in the age of rocks with distance from the spreading axis, corresponding to the rate spreading of 16.2 ± 0.8 mm/year, and the ages of the samples correspond to those based on magnetic anomalies, which means that the samples were formed on the spreading axis.

The second remark refers to a more complicated situation. Among the zircons sampled in the MAR rift [Bortnikov et al., 2008, 2019; Lissenberg et al., 2009; Kostitsyn et al., 2015; Bea et al., 2020] and dated by the U-Pb method, there are young zircons 0.6—2.0 Ma old [Bortnikov et al., 2008; Lissenberg, 2009; Kostitsyn, 2015; Bortnikov et al., 2019; Bea et al., 2020], which are clearly of spreading-related igneous origin. However, in addition to these zircons, there are zircons of other age groups (6.7—11.2 Ma, 12.9—17.6 Ma) [Lissenberg, 2009; Bortnikov et al., 2019] and even zircons of the Proterozoic-Archean age (2—3.2 Ga [Kostitsyn et al., 2015; Bortnikov, 2019]. Bortnikov et al. [2022] showed that these are relics of the oceanic lithospheres, which during the magmatic evolution of the MAR rift valley were involved in the partial melting of the mantle. According to V.V. Gordienko, the existence of these zircons questions the entire concept of plate tectonics. It seems to me, that the findings of young zircons are more important, since they definitely indicate that, in accordance with the conception of spreading, magmatism existed in the vicinity of the mid-Atlantic rift axis and its age corresponds to the modern distance of the rocks from the rift axis. If the data allow one to determine the MAR spreading rate, it turns out to be very low, about 1.5 centimeters per year [Lissenberg et al., 2009; Kostitsyn et al., 2018].

I reiterate once again: the observations of coseismic movements in subduction zones leave no doubt about the reality of the latter. Considering that the oceanic crust and lithosphere are renewed every approximately 200 million years, the reality of subduction unquestionably means both the reality of spreading and its consistency with subduction. Indeed, otherwise, either fracture/subsidence of the oceanic crust (if spreading lags behind subduction) or uplifts (if subduction lags behind spreading) would be observed.

The most important and, at the same time, the most complicated and controversial is the question of the energy sources of global tectonic movements. It is quite clear that the energy is drawn from the heat and/or potential energy of the gravitational field (the contributions of tidal friction and rotation deceleration are apparently negligible). The whole question is by what mechanism the energy supplied is transformed into mantle flow. There are several fundamentally possible mechanisms in global tectonics (global geodynamics), the relative role of which is the subject of discussion. These are the pushing of plates apart in the spreading zone, the negative buoyancy of the descending slab, as well as instabilities at the mantle-core boundary. In the latter case, thermal instability seems to be the most realistic source of energy supporting the global mantle flow, since there is a heat flow from the core to the mantle, ensuring the functioning of convection in the outer core and the magnetic dynamo. This option is an all the more interesting one because the Earth is the only silicate planet in the solar system that has a strong magnetic field and simultaneously demonstrates a plate tectonic behavior. This coincidence is most likely not accidental, since the plate tectonics, with hot plates brought to the surface, is the most efficient mechanism for cooling the planet providing the largest heat flux passing through the mantle. The greater is this heat flux, the more heat is removed from the core resulting in more intense outer core convection and stronger magnetic field [Aryasova, Khazan, 2018].

The purely geological approach, or in any case, the geological approach in the interpretation of V. V. Belousov and V. V. Gordienko, suggests the choice of options that is limited by the assumption of the primacy of vertical movements over horizontal ones. V.V. Belousov simply speaks of the ascent of hot portions of matter from the lower mantle, without specifying exactly how they acquired extra heat that ensures buoyancy [Belousov, 1978, p. 212]. V.V. Gordienko assumes that in the mantle there regularly occur «activizations», during which 1—3 hot portions of matter of the order of 50 km diameter (according to V.V. Gordienko's assumptions) ascend; he calls these portions «quanta of tectonic action» (QTA).

According to V. V. Gordienko, QTAs in the upper mantle or crust are heated by radioactive heat sources. This scheme raises many questions. For example, V.V. Gordienko suggests that the formation of extended structures — rifts and mid-ocean ridges — is the result of the combined action of a large number of individual independent QTAs. In other words, the structures with a length of tens of QTAs and a transverse size of 1—2 QTAs are composed of several tens of independent elements. What mechanism ensures their «self-organization» is not even discussed.

But the main problem, however, lies in the fact that it is not clear how, in general, the instability that generates QTA could arise. The point is that in this case the positive feedback, which is necessary for the development of any instability, does not function. (With positive feedback, the rate of a growth of an infinitesimal perturbation is proportional to its magnitude, so that a random deviation from an equilibrium grows exponentially. Known examples: instability of a homogeneous gravitating gas; instability of a liquid cooled from above; the development of an epidemic at the stage of exponential growth).

In the examples given, the perturbation is self-reinforcing, since, as it develops, the conditions for further growth are improving. In contrast, if in a homogeneous medium with radioactive heat sources the temperature in a certain region increased due to random reasons, this does not affect the heat release in any way, since the radiogenic heat release does not depend on temperature at all, and the thermal perturbation dissipates. The only possibility is if there are so much more heat sources in a volume than around, that excess heating exceeds heat transfer, and the volume may begin to ascent. However, in this case, the ascending region takes the excess sources with it, i. e. this is an isolated episode. A permanent instability of this type is impossible. In principle, it is quite possible that in the early stages of the planet evolution, irregularities in the distribution of radioactive isotopes could lead to a onetime development of an instability/instabilities of this type. But there are no reasons that could cause regular «activizations» to occur. And even more so, no reason exists for lineaments with the length much greater than their width to form.

The monograph [Gordienko, 2017] is prefaced with an epigraph from A. Poincaré [Poincaré, 1999]: «To say that a rule is accepted by everyone does not mean to substantiate it ...». V.V. Gordienko, of course, has in mind the plate tectonics, which is taken for granted by the vast majority of researchers, although some, including V.V. Gordienko, criticize it. But if one starts waving quotes from the greats, then I much more like the idea from another book by Poincaré [Poincaré, 2020], which very accurately characterizes the situation in the geological and geophysical science: «To doubt everything, to believe everything — two solutions that are equally convenient: both save us from having to think». We can conclude that the proof of the reality of subduction is, as they say, far «beyond reasonable doubt», inevitably implying as explained above, the reality of spreading, as well as the existence of large-scale flows in the Earth's mantle.

Some time ago Aryasova and Khazan [Aryasova, Khazan, 2016, 2018] showed that even such a seemingly particular manifestation of the spreading-subduction system as the stabilization of the ocean depth and oceanic heat flow in areas of old oceanic crust requires the penetration of convective mixing to a great depth into the mantle, possibly down to the core boundary. In other words, it follows from the existence of the spreading-subduction system that the thermal structure of the planet is a single whole. The development of a quantitative model of the functioning of a heat engine called «the planet Earth» is the main task of global tectonics, which would be more correctly called global geodynamics, meaning that we are talking about solving purely dynamic problems. This direction of research seems to me very promising, although it is difficult to expect that the approaches of global geodynamics will be effective for geological problems of a regional scale, the study of the Earth's crust, the theory of ore formation, and solving the problems of the mineral deposit formation. I think that this is where the boundary lies between the areas of applicability of classical geology/geotectonics, on the one hand, and global geodynamics, on the other.

References

Aryasova, O.V. & Khazan, Y.M. (2016). A new approach to computing steady-state geotherms: The marginal stability condition. *Tectonophysics, 693*, 32—46. https://doi.org/10.1016/j.tecto.2016.10.014.

Aryasova, O., & Khazan, Y. (2018). From global tectonics to global geodynamics. *Geofizicheskiy Zhurnal, 40*(5), 71—97. https://doi.org/10.24028/gzh.0203-3100.v40i5.2018.147475 (in Russian).

Bea, F., Bortnikov, N., Montero, P., Zinger, T., Sharkov, E., Silantyev, S., Skolotnev, S., Trukhalev, A., & Molina-Palma, J.F. (2020). Zircon xenocryst evidence for crustal recycling at the Mid-Atlantic Ridge. *Lithos, 354-355*, 105361. https://doi.org/10.1016/j.lithos.2019.105361.

Belousov, V.V. (1978). *Endogenous regimes of the continents*. Moscow: Nedra, 232 p. (in Russian).

Bilek, S.L., & Lay, T. (2018). Subduction zone megathrust earthquakes. *Geosphere, 14*(4), 1468—1500. https://doi.org/10.1130/ges01608.1.

Bortnikov, N.S., Sharkov, E.V., Bogatikov, O.A., Zinger, T.F., Lepekhina, E.N., Antonov, A.V., & Sergeev, S.A. (2008). Finds of young and ancient zircons in gabbroids of the Markov Deep, Mid-Atlantic Ridge, 5°54′—5°02.2′ N (results of SHRIMP-II U-Pb dating): implication for deep geodynamics of modern oceans. *Doklady Earth Sciences, 421*(5), 859—866. https://doi.org/10.1134/S1028334X08050334.

Bortnikov, N.S., Silantyev, S.A., Bea, F., Montero, P., Zinger, T.F., Skolotnev, S.G., & Sharkov, E.V. (2019). U-Pb Dating, Oxygen and Hafnium Isotope Ratios of Zircon from Rocks of Oceanic Core Complexes at the Mid-Atlantic Ridge: Evidence for the Interaction of Contemporary and Ancient Crusts in the Spreading Center of the Ocean Floor. *Doklady Earth Sciences, 489*(2), 1396—1401. https://doi.org/10.1134/s1028334x19120109.

Bortnikov, N.S., Silantyev, S.A., Bea, F., Montero, P., Zinger, T.F., Skolotnev, S.G., & Sharkov, E.V. (2022). Multiple Melting of a Heterogeneous Mantle and Episodic Accretion of Oceanic Crust in a Spreading Zone: Zircon U-Pb Age and Hf-O Isotope from an Oceanic Core Complex of the Mid-Atlantic Ridge. *Petrology, 30*, 1—24. https://doi.org/10.1134/S0869591122010040.

Chlieh, M., Avouac, J.-P., Hjorleifsdottir, V., Song, T.-R. A., Ji, C., Sieh, K., Sladen, A., Hebert, H., Prawirodirdjo, L., Yehuda Bock, Y., & Galetzka, J. (2007). Coseismic Slip and Afterslip of the Great Mw 9.15 Sumatra-Andaman Earthquake of 2004. *Bulletin of the Seismological Society of America, 97*(1A), S152—S173. https://doi.org/10.1785/0120050631.

Cipriani, A., Bonatti, E., Seyler, M., Brueckner, H.K., Brunelli, D., Dallai, L., Hemming, S.R., Ligi, M., Ottolini, L., & Turrin, B.D. (2009). A 19 to 17 Ma amagmatic extension event at the Mid-Atlantic Ridge: Ultramafic mylonites from the Vema Lithospheric Section. *Geochemistry, Geophysics, Geosystems, 10*(10). https://doi.org/10.1029/2009gc002534.

Dickin, A.P. (2005). Radiogenic Isotope Geology (Ch. 10, pp. 254—290). Cambridge: Cambridge Univ. Press. https://doi.org/10.1017/CBO9781139165150.011.

Engdahl, E.R., & Villaseñor, A. (2002). Global seismicity: 1900—1999. In W.H.K. Lee, H. Kanamori, P.C. Jennings, C. Kisslinger (Eds.), *International Handbook of Earthquake and Engineering Seismology* (Part A., 81 (A), pp. 665—690). https://doi.org/10.1016/s0074-6142(02)80244-3.

Gerya, T.V., Bercovici, D., & Becker, T.W. (2021). Dynamic slab segmentation due to brittle—ductile damage in the outer rise. *Nature, 599*, 245—250. https://doi.org/10.1038/s41586-021-03937-x.

Gordienko, V.V. (2022). About geological theory. *Geofizicheskiy Zhurnal, 44*(2), 68—92. https://doi.org/10.24028/gj.v44i2.256266.

Gordienko, V.V. (2018). On the motion of lithospheric plates in the oceans and transition zones. *Geofizicheskiy Zhurnal, 40*(3), 129—144. https://doi.org/10.24028/gzh.0203-3100.v40i3.2018. 137181 (in Russian).

Gordienko, V.V. (2013). On the plate tectonics hypothesis. *Geofizicheskiy Zhurnal, 35*(6), 71—

100. https://doi.org/10.24028/gzh.0203-3100.v35i 6.2013.116451 (in Russian).

Gordienko, V.V. (2017). Thermal processes, geodynamics, deposits, 305 p. Retrieved from http://www.geokniga.org/bookfiles/geoknigateplovyeprocessy.pdf (in Russian).

Ho, T.-C., Satake, K., Watada, S., & Fujii, Y. (2019). Source estimate for the 1960 Chile earthquake from joint inversion of geodetic and transoceanic tsunami data. *Journal of Geophysical Research: Solid Earth, 124*(3), 2812—2828. https://doi.org/10.1029/2018JB016996.

Hyndman, R.D. (2007). The seismogenic zone of subduction thrust faults: What we know and don't know. In T. Dixon, J.C. Moore. (Eds.), *The Seismogenic Zone of Subduction Thrust Faults* (pp. 15—41). New York: Columbia Univ. Press.

Iinuma, T., Hino, R., Kido, M., Inazu, D., Osada, Y., Ito, Y.,Ohzono, M., Tsushima, H., Suzuki, S., Fujimoto, H., & Miura, S. (2012). Coseismic slip distribution of the 2011 off the Pacific Coast of Tohoku Earthquake (M 9.0) refined by means of seafloor geodetic data. *Journal of Geophysical Research: Solid Earth, 117*(B7), B07409. https://doi.org/10.1029/2012jb009186.

Kelley, S. (2002). K-Ar and Ar-Ar dating. *Rev. Min. Geochem., 47*(1), 785—818. https://doi.org/10.21 38/ rmg.2002.47.17.

Khazan, Ya.M. (2014). Plate tectonics: «for» and ... «for». *Geofizicheskiy Zhyrnal, 36*(5), 170—174 (in Russian).

Kim, J., & Cho, I.H. (2020). Improvement of ^{40}Ar/^{39}Ar age determinations for Quaternary basaltic rocks by eliminating the peak suppression effect. *Journal of Analytical Science and Technology, 11*(9). https://doi.org/10.1186/s40543-020-00207-9.

Kostitsyn, Y.A., Belousova, E.A., Silant'ev, S.A., Bortnikov, N.S., & Anosova, M.O. (2015). Modern problems of geochemical and U-Pb geochronological studies of zircon in oceanic rocks. *Geochemistry International, 53*(9), 759—785. https://doi.org/10.1134/s0016702915090025.

Kostitsyn, Y.A., Silantyev, S.A., Anosova, M.O., Shabykova, V.V., & Skolotnev, S.G. (2018). Age of plutonic rocks from the Vema fracture zone (Central Atlantic) and nature of their mantle sources. *Geochemistry International, 56*(2), 89—110. https://doi.org/10.1134/s0016702918020039.

Lissenberg, C.J., Rioux, M., Shimizu, N., Bowring, S.A., & Mevel, C. (2009). Zircon Dating of Oceanic Crustal Accretion. *Science, 323*(5917), 1048—1050. https://doi.org/10.1126/science.1167330.

McDougall, I., & Harrison, T.M. (1999). *Geochronology and Thermochronology by the ^{40}Ar/^{39}Ar*. Oxford: Oxford Univ. Press, 288 p.

Petersen, R.I., Stegman, D.R., & Tackley, P.J. (2016). The subduction dichotomy of strong plates and weak slabs. *Solid Earth, 8*(2), 339—350. https://doi.org/10.5194/se-8-339-2017.

Poincaré, A. (1999). *Probability Theory*. Izhevsk: Editorial staff of the journal «Regular and Chaotic Dynamics», 280 p. (in Russian).

Poincaré, A. (2020). *Theorem of the century. The world from the point of view of mathematics*. Moscow: Rodina Publishing House LLC, 461 p. (in Russian).

Plafker, G. (1965) Tectonic deformation associated with the 1964 Alaska earthquake. *Science, 148*, 1675—1687. https://doi.org/10.1126/science.148.3678.1675.

Plafker, G. (1972). Alaskan earthquake of 1964 and Chilean earthquake of 1960: Implications for arc tectonics. *Journal of Geophysical Research, 77*, 901—925. https://doi.org/10.1029/JB077i005p00901.

Plafker, G., & Savage, J.C. (1970). Mechanism of the Chilean earthquakes of May 21 and 22, 1960, Geol. *Bulletin of the Seismological Society of America, 81*, 1001—1030. https://doi.org/10.1130/0016-7606(1970)81[1001:MOTCEO]2.0.CO;2.

Ranero, C.R., Phipps Morgan, J., McIntosh, K., & Reichert, C. (2003). Bending-related faulting and mantle serpentinization at the Middle America trench. *Nature, 425*, 367—373. https://doi.org/10.1038/nature01961.

Schaen, A.J., Jicha, B.R., Hodges, K.V., Vermeesch, P., Stelten, M.E., Mercer, C.M., Phillips, D., Rivera, T.A., Fred Jourdan, F., Matchan, E., Hemming, S.R, Morgan, L.E., Kelley, S.P., Cassata, W.S., Heizler, M.T., Vasconcelos, P.M., Benowitz, J.A., Koppers, A.A.P., Mark, D.F., Niespolo, E.M., Sprain, C.J, Hames, W.E., Kuiper, K.F., Turrin, B.D., Renne, P.R., Ross, J., Nomade, S., Guillou, H., Webb, L.W., Cohen, B.A., Calvert, A.T., Joyce, N., Ganerød, M., Wijbrans, J., Ishizuka, O., He, H., Ramirez, A., Pfänder, J.A., Lopez-Martínez, M., Qiu, H., & Singer, B.S. (2021) Interpreting and reporting $^{40}Ar/^{39}Ar$ geochronologic data. *Geological Society of America Bulletin, 133*, 461—487. https://doi.org/10.1130/b35560.1.

Silantiev, S.A., Levskiy, L.K., Arakelyants, M.M., Lebedev, V.A., Bugo, A., & Kannat, M. (2000). The age of magmatic and metamorphic events in the Mid-Atlantic Ridge: interpretation of K-Ar isotope dating data. *Russian Journal of Earth Sciences, 2*(3), 269—278. https://doi.org/10.2205/2000ES000044.

Skolotnev, S.G., Bel'tenev, V.E., Lepekhina, E.N., & Ipat'eva, I.S. (2010). Younger and older zircons from rocks of the oceanic lithosphere in the Central Atlantic and their geotectonic implications. *Geotectonics, 44*(6), 462—492. https://doi.org/10.1134/s0016852110060038.

Stern, R.J. (2002). Subduction zones. *Reviews of Geophysics, 40*(4), 3-1—3-38. https://doi.org/10.1029/2001RG000108.

Tilmann, F.J., Grevemeyer, I., Flueh, E.R., Dahm, T., & Gossler, J. (2008). Seismicity in the outer rise offshore southern Chile: Indication of fluid effects in crust and mantle. *Earth and Planetary Science Letters, 269*, 41—55. http://dx.doi.org/10.1016/j.epsl.2008.01.044.

Wang, K. (2007). Elastic and Viscoelastic Models of Crustal Deformation in Subduction Earthquake Cycles. In T.H. Dixon, C. Moore (Eds.), *The Seismogenic Zone of Subduction Thrust Faults* (pp. 540—575). New York Chichester, West Sussex: Columbia University Press. https://doi.org/10.7312/dixo13866-017.