Comments on «On the magnetic field of the oceans» by V.V. Gordienko

Y.M. Khazan, 2024

Frankfurt am Main, Germany

In recent paper published in the Geophysical Journal, Gordienko [2024], a consistent opponent of plate tectonics (PT), tried to explain why the concept of linear magnetic anomalies, which together with the idea of ocean floor spreading is one of the main pillars of PT, is erroneous or, at the very least, questionable. From my point of view, it is one of the most important successes of geophysics in the 20th century. It deserves to have its history told at least briefly to understand whether this concept is confirmed by observations. I rely on literary sources, though the list of references is far from being exhaustive. As an accessible and comprehensive introduction to paleomagnetism, I recommend the online edition Tauxe et al. [2018], as well as the Encyclopedia of geomagnetism and paleomagnetism [Gubbins, Herrero-Bervera, 2007]. The most complete chronology of magnetic field reversals to date can be found in the paper by Gee and Kent [2007]. How it all began is described in Cox et al. [1964] and Gallet [2021].

In the most general terms, it is currently assumed that mid-ocean ridge (MOR) volcanism is accompanied by plate spreading. The melt intruding into the crust in the central MOR rift cools down, solidifies. When its temperature drops to the Curie point, ferromagnetic inclusions become magnetized, remembering the direction of the external magnetic field, so that a central magnetic anomaly arises. With further spreading, the central anomaly breaks and a symmetrical pair of equally magnetized anomalies appears. If the Earth's magnetic field changes, e.g., a polarity reversal occurs, the direction of magnetization of the next central anomaly and the next pair of symmetrical anomalies will be opposite to the previous one. Thus, the Earth's oceanic crust turns into a recorder, preserving a record of variations in the Earth's magnetic field and the history of the ocean floor spreading.

This is, of course, an idealized picture. Reality, as always, turns out to be more complex than simplified constructions. However, the most important thing is that before it became possible to use the ocean crust as a recorder, it was necessary to understand that the record existed and to learn how to read it, i.e., one required an instrument that would allow to study tectonics by studying the magnetization of the ocean crust.

The solution to this problem took the first half of the 20th century.

The existence of residual magnetization in rocks has been known since the invention of the compass since it was noticed that in some places the magnetic needle deviates from its standard position. In the late 19th — early 20th centuries, it was discovered that some artifacts exposed to high temperatures (the remains of burnt buildings, bricks, ceramics, and kilns for firing them) retain a weak but stable residual magnetization. Such magnetization is studied by archaeomagnetism. It was based on the observations of G. Folgheraiter (e.g. Principe, Malfatti [2020]). Now, more than 100 years later, these methods are still widely used (Gallet [2021]). For example, Vaknin et al. [2022] used archaeomagnetic dating to reconstruct biblical (!) military campaigns in the Southern Levant from 3000 to

Citation: Khazan, Y.M. (2024). Comments on «On the magnetic field of the oceans» by V.V. Gordienko. *Geofizychnyi Zhurnal*, *46*(5), 118—127.

2500 years ago. The dating in this case was based upon a very characteristic dependence of the magnetic field intensity on time with significant short-period variations and spikes, in some cases twice the intensity of the modern field. The unusual polarity of magnetization of rocks (serpentinites) was first mentioned by Alexander von Humboldt in a letter published in 1797 [Humboldt, 1797]. In 1855, Brown, while studying the magnetic field in India, also discovered rocks with magnetization opposite to the local field [Fuller, 1970; Smith, 1971], but did not attach any importance to these observations, so they were published only five years later and forgotten for a hundred years.

The next step was taken by researchers who studied the residual magnetization of lava flows and the sedimentary rocks heated by them. In particular, Brunhes [1906] described a lava flow overlying a clay layer baked by this lava flow. Brunhes selected oriented cubes of basalts and baked earth and determined the direction of the natural thermoremanent magnetization (NTM) vector. For all samples, the magnetization direction was the same, being the opposite to the modern field direction. Since the length of the outcrop exceeded 100 m, the magnetization could not be caused by some accidental event, such as a lightning strike. In 1906, Brunhes presented a report at a meeting of the French Physical Society, on the discovery of Miocene formations in the French Central Massif with both the lava flows and the underlying baked earth exhibiting magnetization opposite to the modern magnetic field. These results were later rechecked and fully confirmed. At present, Brunhes' results are so highly valued that the first orthozone of the general magnetostratigraphic scale (0—780 thousand years) was named after him. However, at the beginning of the century, the possibility of an oppositely directed terrestrial magnetic field seemed so incredible that these discoveries were not even mentioned in his obituary (1910).

Despite the general skepticism regarding the change in polarity of the geomagnetic field, research in this direction continued. Mercanton [1926, 1932] found both directly and reversely magnetized igneous rocks throughout the northern (Spitsbergen, Greenland, Jan Mayen, Iceland, Faroe Islands, Mull) as well as southern hemisphere (Australia). Matuyama [1929] determined the magnetization direction of 139 Quaternary samples collected from 36 lava manifestations in Japan, southern Korea, and northeastern China. He found that the samples from two groups, with the magnetization direction of the «normal» one being close to the direction of the modern field, and the magnetization of the second group being opposite to it. Matuyama was the first to correlate the magnetization direction of the samples and the age of the eruption and concluded that «normal» lavas are younger (Pleistocene) than lavas with reverse magnetization. As a result, the idea was formulated that the magnetization of igneous rocks and minerals is thermoremanent, i.e., it is acquired during the cooling of rocks with an initial temperature exceeding the Curie point.

These observations did not completely eliminate doubts about the reality of polarity reversals. In the late 1940s, the question arose about how stable thermoremanent magnetization is, and whether the reverse polarity of magnetized rock samples is a consequence of a spontaneous change in polarity, which has purely internal causes, not related to an external field [Graham, 1949, 1953]. In particular, Néel [1951] theoretically showed that spontaneous polarity reversal can occur during heating and subsequent cooling of fine-grained material consisting of two components with different Curie temperatures. Such processes were subsequently discovered in laboratory experiments with rocks [Nagata et al., 1951]. It turned out, however, that in nature these phenomena are very rare, if they occur at all. The final point in this problem was put by Wilson [1966], who collected a set of 90 pairs of samples taken from the contacts of dykes. Each pair included a sample of the dyke material itself and a sample of the host rock that had been annealed. All samples acquired normal, reverse, or intermediate magnetization during cooling. It turned out that in 84 pairs both samples had the same — normal or reverse — magnetization. In three pairs, the magnetization of the two samples was intermediate between normal and reverse, but the same. And only in three pairs was the magnetization of the dyke material and the host rock opposite, i.e., spontaneous polarity reversal can affect only about 3 % of the samples. In other words, thermoremanent magnetization is a reliable indicator of the direction of the global magnetic field at the moment of cooling of the material.

To be accurate, the observed natural magnetization of rocks may be at least partially due to chemical magnetization that occurs because of oxidation of the parent rock at temperatures below the Curie point. A discussion of this issue can be found in the paper by Banerjee and Cox [1971].The last thing necessary to turn paleomagnetism into a tool for studying geodynamics is to relate paleomagnetic measurements to a time scale. Stratigraphic methods allow fixing the basic time reference points but do not have sufficient resolution. The radioisotope dating is, of course, much more accurate. In particular, Cox et al. [1964] were the first to use K-Ar dating for this purpose. The first sufficiently detailed scale recording the reversals of the geomagnetic field was compiled by Heirtzler et al. [1968]. This scale covered a time of up to about 80 million years. The most complete modern geomagnetic time scale, covering 160 million years, can be found in the review by Gee and Kent [2007]. Such a scale makes it possible to use paleomagnetic methods as a tool for geodynamic analyses.

By the early 1960s, several pieces of the «puzzle» became known that fit together perfectly, forming the theory of ocean floor spreading — one of the fundamental components of plate tectonics.

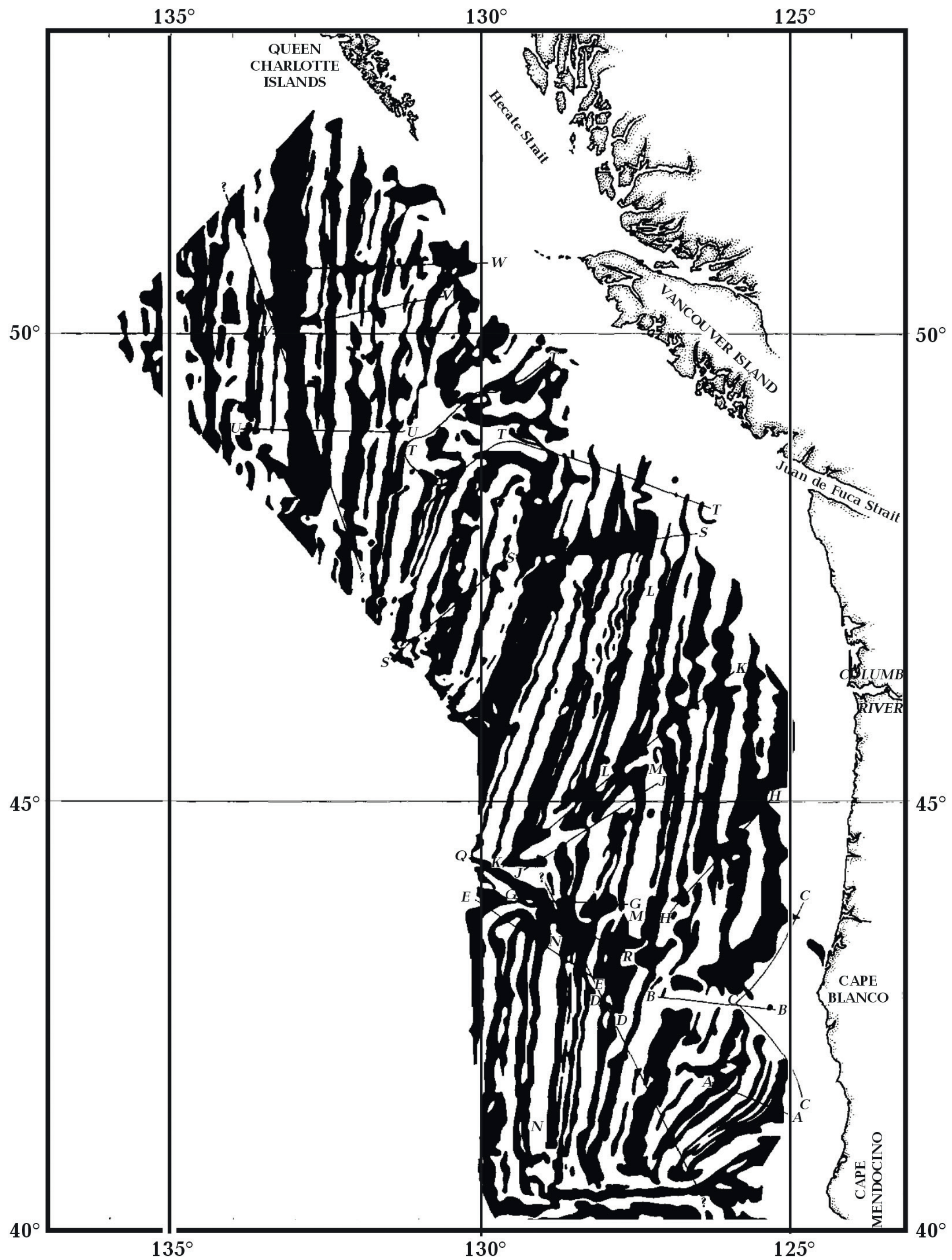
The first piece of this «puzzle» was the proof that the Earth's magnetic field has flipped many times in its history, as discussed above, and these reversals are «recorded» as thermoremanent magnetization of rocks.

The second piece of the «puzzle» was detailed surveys of the magnetic field in the oceanic region using towed magnetometers along parallel routes about 5 nautical miles apart (or even less if the field changed quickly). These surveys revealed a surprising field structure (e.g., [Raff, Mason, 1961, Fig. 1]). It turned out that the magnetic anomalies form a very regular structure, consisting of parallel stripes, hundreds of kilometers long and tens of kilometers wide.

The third element of the «puzzle» is the intuitive concept of ocean floor spreading proposed by Dietz [1961]. Dietz had only qualitative considerations that suggested the possibility of ocean floor expansion, but the term he coined turned out to be very successful, and the meaning we now put into this concept belongs to Vine and Matthews [1963], and Vine and Wilson [1965].

Vine and Matthews [1963] studied magnetic field profiles in the North Atlantic and northwest Indian Ocean. They noticed what they called «granularity»: the variations in the field looked as if the oceanic crust beneath them were made up of blocks, with large gradients of the field at the boundaries of the blocks. Vine and Matthews pointed out that if we assume that all the blocks have the same polarity of magnetization, then, to explain the «granularity», we have to suppose that the properties of the blocks are quite different. For a long chain of blocks, this seems completely unnatural. If the blocks have alternating magnetization, the variations in the field along the profile are easily explained, but then about half of the oceanic crust has a magnetization opposite to the present one.

The result of all these considerations was the unification of all three pieces of the «puzzle» into what is now called the spreading theory. It assumes that new crust is created at mid-ocean ridges. After the solidification of the erupted magma and cooling below the Curie point, a central magnetic anomaly appears, which always has a polarity that coincides with the modern magnetic field. It is clear that, having agreed with the spreading theory, it is necessary to check whether its predictions are confirmed by observations. Control tests for the spreading model are the symmetry of the sequence of linear anomalies relative to the ridge, the similarity of the



Overview of the magnetic field in the Pacific Ocean west of the US and Canadian coasts. The black areas show normal field polarity. See Fig. 1 by Raff, Mason [1961].

profiles on traverses crossing the same ridge but located several tens of kilometers apart, and, finally, the sameness of these sequences of anomalies in different oceans.

The first such check was performed by Vine and Wilson [1965], who studied the variations of the magnetic field along the profiles crossing the East Pacific Rise and the Juan de Fuca Ridge. They showed that the variations of the field along three parallel profiles crossing the Juan de Fuca Ridge and spaced 45 km apart are virtually indistinguishable. A comparison of one of the profiles with its inverted version made the symmetry of the profile obvious. At the same time, the sequence of anomalies on the profiles crossing the Juan de Fuca Ridge is practically the same as on the profile through the East Pacific Rise.

It is now generally accepted that the spreading model successfully passes all these tests (more examples one can find in the review by Gee and Kent [2007]).

The modern timescale of magnetic field reversals is usually presented as a time axis, on which black and white rectangles show periods of direct and reversed magnetic field directions [Gee, Kent, 2007]. Such a scale looks like a bar code, and it is the same for all oceans and all mid-ocean ridges. Nevertheless, the time axis digitization for various ridges may differ, since it depends on the spreading rate, which does not necessarily have to be the same for all the MORs. The time reference of the scale is carried out according to key chrons and boundaries of geological periods. The timescales of magnetic reversals for the Atlantic, Pacific and Indian Oceans are presented by [Malinverno et al., 2020, Fig. 4]. If there is a sufficiently dense grid of magnetic profiles and all anomalies on the profiles are identified, then by connecting identical anomalies it is possible to obtain a system of isochrones [Müller et al., 1997]. It allows one to calculate the spreading rates on different ridges and the rate of new crust creation. For example, according to Cognéand Humler [2006], the globally averaged spreading rate is approximately 5 cm/year, and the production of the new crust is approximately 2.7 km^2/year. It should be noted that observations of the ocean crust magnetic anomalies cannot resolve short-term field excursions that are detected during a detailed study of sediments (e.g. [Melnyk et al., 2022]). Therefore, the timescale uses only those chrons that can be determined from marine magnetic anomalies.

Thus, all the pieces of the «puzzle» fell into place, and, in general, the spreading picture is logical and consistent. Additionally, within the framework, the dependence of the oceanic heat flow and ocean depth on the crustal age is naturally explained. As is known, up to the crustal age of about 60 to 70 million years, the oceanic heat flow decreases proportionally to $t^{-1/2}$, and the ocean depth increases proportionally to $t^{1/2}$ (e.g., [Parsons, Sclater, 1977]). Even though the observations are quite «noisy», both dependencies are clearly manifested (e.g. [Hasterok, 2013]). Their physical cause is that in the vicinity of the ridge, the convection in the plate moving away from the ridge is disrupted, and the plate cools purely conductively from the surface. Due to this, the heat flow decreases with age, and the cooled part of the plate experiences thermal contraction. As Aryasova and Khazan [2016] showed, just at the plate age of 60 to 70 million years the upper part of the cooling plate becomes unstable. As a result, convective mixing is triggered, which keeps the heat flow and temperature of the upper part of the plate (and, consequently, the ocean depth) constant.

Although the picture is quite convincing, attempts are being made to prove that the spreading concept is erroneous or at least questionable. The publication by V.V. Gordienko [2024] also pursues this goal. It should be said that the criticism and doubts of V.V. Gordienko are based on real and well-known difficulties of theoretical geophysics: the inverse problem of magnetometry as well as gravimetry has no unique solution. Therefore, it is difficult to determine the detailed structure of the sources of magnetic anomalies. This problem is, of course, well known. For example, as noted in Gee and Kent [2007], «despite more than 40 years of study, many aspects of the magnetization source responsible for lineated marine magnetic anomalies remain uncertain».

However, it should be emphasized (and this is the most important) that the geodynamic interpretation of the system of magnetic anomalies is based only on their existence and reference to the timescale, and does not depend on their internal structure. Therefore, a lack of complete certainty about the internal structure of the sources of anomalies does not affect the geodynamic interpretation of observations. So, I do not see the point in discussing the specific comments of V.V. Gordienko, who criticizes the models of the structure of magnetization regions. The exclusions are two Gordienko's comments that deal with observations that are inconsistent with the ideas about spreading.

V. Gordienko refers to the article by Johnson, Merrill [1978], which reports that during deep-sea drilling it was discovered that in the 600-m-thick layer of the crust the sign of magnetization changes with depth, as if the anomalies were located horizontally. Such an arrangement of magnetic boundaries does not correspond well to the concept of linear anomalies, the boundaries of which in the simplest model should be vertical. However, it was later discovered that this result was not repeated in any other borehole — this is an isolated case. Moreover, in the article by Tivey et al. [1998], published 20 years later, by a group of authors that includes H. Johnson, an author of the article Johnson, Merrill [1978], it is directly written that with a complex spatial structure of the magnetization region, a single borehole cannot allow determining the geometry of the boundaries of magnetized blocks.

The second difficulty mentioned by V.V. Gordienko is the discovery, in the Mid-Atlantic Ridge, of zircons with ages up to Archean, significantly exceeding the age of the ocean floor on which they were located.

According to the spreading theory, rocks near the mid-ocean ridges, i.e. where plates originate, should be relatively young, a few million years old at most. However, Pilot et al. [1998] found zircons as old as 330 and 1300 million years in drill cores from the western slope of the Mid-Atlantic Rift Valley, about 2000 km from the continents and far from the islands. If these zircons had formed with the gabbro in which they were found, their age would have to be about 1 million years. It was suspected that these zircons resulted from contamination of the samples. However, since then, zircons much older than the host rocks have been discovered by various research groups, both in drill cores and by dredging (e.g. [Bortnikov et al., 2008]) (many examples can be found in Bea et al. [2020]). In addition to the uncertainty concerning the origin of these zircons, it is difficult to explain how they could have passed through the mantle since zircons are unstable in low-silica mafic and ultramafic melts. This problem is now actively discussed and studied experimentally (e.g. [Bjerga et al., 2022]). The general opinion is that old zircons are a consequence of crustal recycling (e.g. [Bea et al., 2001, 2020; Bortnikov et al., 2008]), but the specific mechanism of zircon entry into the mantle and subsequent movement to the surface is still unknown. The only thing that can be considered established is that zircons can remain in a metastable state up to a pressure of >8 GPa and a temperature of up to about 900° C, i.e. they «survive» in the mantle at fairly high pressures and temperatures.

Thus, all the fundamentally important predictions of the spreading theory are in good agreement with observations. The only uncertainty with the ages of zircons requires additional study, but, in my opinion, does not compromise the theory.

If we agree with the validity of the spreading concept, then the question of confirming the PT can be considered resolved. However, there is also direct observational evidence of the functioning of the subduction, which is the second main element of PT [Stern, 2002; Dixon, Moore, 2007; Zheng, Zhao, 2017; van Keken, Wilson, 2023]. These confirmations include, first of all, the existence of a deep-sea trench at the plate boundary, as well as the completely defined and always the same nature of coseismic movements during subduction earthquakes.

A deep-sea trench at the plate boundaries occurs because a moving oceanic plate «pulls» the edge of the continental plate downwards. At the same time, due to the pushing of the oceanic plate on the edge of a continental one, the latter bends upwards. The relative movement of the plates occurs with slippage along a quasi-horizontal fault between them. If slippage is blocked at some section of the fault (in the future earthquake source region), elastic stresses accumulate and, upon reaching the yield strength of the blocked section, a strong earthquake occurs and both plates are released. In this case, the oceanic plate moves forward underneath the continent, and the continental plate straightens out, causing its edge to jump up, and generating a tsunami. Thus, near the trench, the vertical coseismic movements of the continental plate are ascending. With distance from the trench, their amplitude decreases, and then they change sign and become descending with a decreasing amplitude (e.g. [Plafker, 1972; Plafker, Savage, 1970]). It is important not only that such coseismic movements are observed during all subduction earthquakes, but also that there are no other explanations for these observations.

If the slip along the fault between the continental and oceanic plates were not blocked, then, at a relative velocity of 5—10 cm/year, the oceanic plate would move 15—50 m in 300—500 years (a typical interval between strong earthquakes). When an earthquake occurs, this «delayed» movement is realized as horizontal coseismic displacements.

This is, in general, a unique case. Real plate movements, which, as someone noted, occur at the speed of fingernail growth and are only observable instrumentally, accumulate over hundreds of years to become visible to the naked eye.

Here are some examples. During the 2011 Japanese earthquake, the coseismic horizontal displacement was 42 m [Kodaira et al., 2012]; during the 1960 Chilean earthquakes it was at least 20 m and possibly 40 m [Plafker, Savage, 1970]. During the 1964 Alaska earthquake, the coseismic horizontal displacement was up to 30 m [Holdahl, Sauber, 1994]. All of the above facts are purely observational and indicate the reality of subduction. However, they are far from exhausting all that is known about it. For example, there are tomographic images of plates subducting into the mantle, and seismic images of the trench taken before and after the 2011 Great Japan Earthquake clearly show the subduction of an oceanic plate beneath a continent [Kodaira et al., 2012].

Spreading and subduction do not operate independently. The creation of new crust by the ocean floor spreading must be consistent with the crust destruction at subduction zones. If the rates of spreading at mid-ocean ridges are roughly the same as the rates of plates approaching a subduction zone, then the consistency of spreading and subduction requires that the mid-ocean ridge and subduction zone systems be roughly the same length. The total length of subduction zones, calculated using a digital plate boundary model [Bird, 2003] (https://www.earthbyte.org/subduction-zone-lengths-a-modelled-reality/), is about 62,000 km. Estimates of the MOR length vary from >60,000 km [Wilson, 2007] to about 75,000 km [Harris, 2012], which is, to a first approximation, really consistent with the estimate of the length of subduction zones.

And finally: it is no coincidence that the Earth is the only planet in the solar system that has plate tectonics and a strong magnetic field at the same time. The magnetic field is maintained by convection in the outer core, which requires intense heat removal. Plate tectonics, in which hot material is brought to the planet's surface, provides heat removal unattainable via all other conceivable options.

In general, everything we know about spreading and subduction comes together to form a logical, coherent picture, and its main components are confirmed by observations, implying the validity of plate tectonics as well.

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/.

Banerjee, S., & Cox, A. (1971). Rock magnetism. Eos, *Transactions American Geophysical Union, 52(5)*, IUGG 216—IUGG 220. https://doi.org/10.1029/eo052i005piu216.

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.

Bea, F., Fershtater, G.B., Montero, P., Whitehouse, M., Levin, V.Y., Scarrow, J.H., Austrheim, H., & Pushkariev, E.V. (2001). Recycling of continental crust into the mantle as revealed by KytlymDunite zircons, Urals Mts. Russia. *Terranova, 13*, 407—412. https://doi.org/10.1046/j.1365-3121.2001.00364.x.

Bird, P. (2003). An updated digital model of plate boundaries. *Geochemistry, Geophysics, Geosystems, 4(3)*, 1027. https://doi.org/10.1029/2001GC000252.

Bjerga, A., Stubseid, H.H., Pedersen, L.-E.R., & Pedersen, R.B. (2022).Radiation damage allows identification of truly inherited zircon. *Communications Earth Environment, 3*, 37. https://doi.org/10.1038/s43247-022-00372-2.

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 gabroids 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*, 859—866. https://doi.org/10.1134/S1028334X08050334.

Brunhes, B. (1906). Recherches sur la direction d'aimantation des roches volcaniques. *Journal of Physics: Theories and Applications, 5*(1), 705—724. https://doi.org/10.1051/jphystap:019060050070500.

Cogné, J.-P., & Humler, E. (2006). Trends and rhythms in global seafloor generation rate. *Geochemistry, Geophysics, Geosystems, 7*, Q03011. https://doi.org/10.1029/2005GC001148.

Cox, A., Doell, R.R., & Dalrymple, G.B. (1964).Reversals of the Earth's Magnetic Field. *Science, 144*(3626), 1537—1543. https://doi.org/10.1126/science.144.3626.153.

Dietz, R. (1961) Continent and Ocean Basin Evolution by Spreading of the Sea Floor. *Nature, 190*, 854—857. https://doi.org/10.1038/190854a0.

Dixon, T.H., & Moore, J.C. (2007). *The Seismogenic Zone of Subduction Thrust Faults*. Series: MARGINS Theoretical and Experimental Earth Science Series. NY: Columbia University Press, 692 p. https://doi.org/10.7312/dixo13866.

Fuller, M.D. (1970). Geophysical aspects of paleomagnetism. *Critical Reviews in Solid State and Material Sciences*, (2), 137—219. https://doi.org/10.1080/10408437008243420.

Gallet, Y. (2021). The dawn of archeomagnetic dating. *Comptes Rendus Géoscience, 353*(1), 285—296. https://doi.org/10.5802/crgeos.73.

Gee, J.S., & Kent, D.V. (2007). Source of Oceanic Magnetic Anomalies and the Geomagnetic Polarity Timescale. *Geomagnetism.Treatise on Geophysics, 5.* https://doi.org/10.1016/B978-044452748-6.00097-3.

Gordienko, V.V. (2024). On the magnetic field of the oceans. *Geofizychnyi Zhurnal, 46*(5), 106—117. https://doi.org/10.24028/gj.v46i5.300743.

Graham, J.W. (1949). The stability and significance of magnetism in sedimentary rocks. *Journal of Geophysical Research, 54*(2), 131—167. https://doi.org/10.1029/JZ054i002p00131.

Graham, J.W. (1953). Changes of ferromagnetic minerals and their bearing on magnetic properties of rocks. *Journal of Geophysical Research, 58*(2), 243—260. https://doi.org/10.1029/JZ058i002p00243.

Gubbins, D., & Herrero-Bervera, E. (Eds.). (2007). *Encyclopedia of geomagnetism and paleomagnetism*. Springer: Dordrecht, The Netherlands. 1054 p. https://link.springer.com/book/10.1007/978-1-4020-4423-6.

Harris, P.T. (2012). Seafloor Geomorphology — Coast, Shelf, and Abyss. In P.T. Harris, E.K. Baker (Eds.), *Seafloor Geomorphology as Benthic Habitat* (pp. 109—155). Elsevier. https://doi.org/10.1016/B978-0-12-385140-6.00006-2.

Hasterok, D. (2013). A heat flow based cooling model for tectonic plates. *Earth and Planetary Science Letters, 361*, 34—43. https://doi.org/10.1016/j.epsl.2012.10.036.

Heirtzler, J.R., Dickson, G.O., Herron, E.M., Pitman, W.C., & Le Pichon, X. (1968). Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents. *Journal of Geophysical Research, 73*(6), 2119—2136. https://doi.org/10.1029/jb073i006p02119.

Holdahl, S.R., & Sauber, J. (1994). Coseismic slip in the 1964 Prince William Sound earthquake: A new geodetic inversion. *Pure and Applied Geo-*

physics, 142(1), 55—82. https://doi.org/10.1007/BF00875968.

Humboldt, A. (1797). Über die merkwürdige magnetische Polarität einer Gebirgsgruppe von Serpentinstein. *Neues Journal der Physik*, Bd. 4, 136—140. Retrieved from https://www.deutschestextarchiv.de/humboldt_polaritaet_1797.

Johnson, H., & Merrill, R. (1978). A direct test of the Vine+Matthews hypothesis. *Earth and Planetary Science Letters, 40*, 263—269. https://doi.org/10.1016/0012-821X(78)90096-1.

Kodaira, S., No, T., Nakamura, Y., Fujiwara, T., Kaiho, Y., Miura, S., Takahashi, N., Kaneda, Y., & Taira, A. (2012). Coseismic fault rupture at the trench axis during the 2011 Tohoku-oki earthquake. *Nature Geoscience, 5*(9), 646—650. https://doi.org/10.1038/ngeo1547.

Malinverno, A., Quigley, K.W., Staro, A., & Dyment, J. (2020). A Late Cretaceous-Eocene Geomagnetic Polarity Time Scale (MQSD20) that steadies spreading rates on multiple mid-ocean ridge flanks. *Journal of Geophysical Research: Solid Earth, 125*(8), e2020JB02003. https://doi.org/10.1029/2020jb020034.

Matuyama, M. (1929). On the Direction of Magnetisation of Basalt in Japan, Tyôsen and Manchuria. *Proceedings of the Imperial Academy, 5*(5), 203—205. https://doi.org/10.2183/pjab1912.5.203.

Melnyk, G., Hlavatskyi, D., Poliachenko, I., Bakhmutov, V., Shenderovska, O., & Yakukhno, V. (2022). Current State of Knowledge of the Brunhes Chron Geomagnetic Excursions. *16th Int. Conf. Monit. Geol. Processes and Ecol. Condition of the Environment, Nov 2022* (pp. 1—5). https://doi.org/https://doi.org/10.3997/2214-4609.2022580137.

Mercanton, P.L. (1926). Inversion de l'inclinaison magnètique terrestre aux âges geologiques. *Journal of Geophysical Research, 31*(4), 187—190. https://doi.org/10.1029/te031i004p00187.

Mercanton, P.L. (1932). Inversion de l'inclinaison magnètique aux ages geologiques. Nouvelles constatations. *C. R. Hebd. Seances Acad. Sci., 188*, 1371—1372.

Müller, R.D., Roest, W.R., Royer, J.Y., Gahagan, L.M., & Sclater, J.G. (1997). Digital isochrons of the world's ocean floor. *Journal of Geophysical Research: Solid earth, 102*, 3211—3214. https://doi.org/10.1029/96JB01781.

Nagata, T., Uyeda, S., & Akimoto, S. (1952). Self-Reversal of Thermo-Remanent Magnetism of Igneous Rocks. *Journal of Geomagnetism and Geoelectricity, 4*(1), 22—38. https://doi.org/10.5636/jgg.4.22.

Néel, L. (1951). L'inversion de l'aimantation permanente des roches. *Annales de Géophysique, 7*, 90—102.

Parsons, B., & Sclater, J.G. (1977). An analysis of the variation of ocean floor bathymetry and heat flow with age. *Journal of Geophysical Research, 82*(5), 803—827. https://doi.org/10.1029/JB082i005p00803.

Pilot, J., Werner, C.-D., Haubrich, F., & Baumann, N. (1998). Paleozoic and Proterozoic zircons from the Mid-Atlantic Ridge. *Nature, 393*, 679—679. https://doi.org/10.1038/31452.

Plafker, G. (1972). Alaskan earthquake of 1964 and Chilean earthquake of 1960: Implications for arc tectonics. *Journal of Geophysical Research, 77*(5), 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. *Geological Society of America Bulletin, 81*, 1001—1030. https://doi.org/10.1130/0016-7606(1970)81[1001:MOT-CEO]2.0.CO;2].

Principe, C., & Malfatti, J. (2020). Giuseppe Folgheraiter: the Italian pioneer of archaeomagnetism. *Earth Sciences History, 39*(2), 305—335. https://doi.org/10.17704/1944-6187-39.2.305.

Raff, A.D., & Mason, R.G. (1961). Magnetic survey off the west coast of North America, 40° N latitude to 52° N latitude. *Geological Society of America Bulletin, 72*, 1267—1270. https://doi.org/10.1130/0016-7606(1961)72[1267:MSOTWC]2.0.CO;2.

Smith, P.J. (1971). Field reversal or self-reversal? *Nature, 229*(5284), 378—380. https://doi.org/10.1038/229378a0.

Stern, R.J. (2002). Subduction zones. *Reviews of Geophysics, 40*(4), 1012. https://doi.org/10.1029/2001RG000108.

Tauxe, L, Banerjee, S.K., Butler, R.F., & van der Voo, R. (2018). *Essentials of Paleomagnetism:*

Fifth Web Edition. Retrieved from https://earthref.org/MagIC/books/Tauxe/Essentials/.

Tivey, M.A., Johnson, H.P., Fleutelot, C., Hussenoeder, S., Lawrence, R., Waters, C., & Wooding, B. (1998). Direct measurement of magnetic reversal polarity boundaries in a cross-section of oceanic crust. *Geophysical Research Letters*, *25*(19), 3631—3634. https://doi.org/10.1029/98gl02752.

Vaknin, Y., Shaar, R., Lipschits, O. et al. (2022). Reconstructing biblical military campaigns using geomagnetic field data. *Proceedings of the National Academy of Sciences*, *119*. https://doi.org/10.1073/pnas.2209117119.

VanKeken, P.E., & Wilson, C.R. (2023). An introductory review of the thermal structure of subduction zones: I — motivation and selected examples. *Progress in Earth and Planetary Science*, *10*, 42. https://doi.org/10.1186/s40645-023-00573-z.

Vine, F., & Matthews, D. (1963). Magnetic Anomalies Over Oceanic Ridges. *Nature*, *199*(4897), 947—949. https://doi.org/10.1038/199947a0.

Vine, F.J., & Wilson, J.T. (1965). Magnetic Anomalies over a Young Oceanic Ridge off Vancouver Island. *Science*, *150*(3695), 485—489. https://doi.org/10.1126/science.150.3695.485.

Wilson, M. (2007). Mid-ocean ridges. In *Igneous Petrogenesis* (pp.101—150). Dordrecht: Springer. https://doi.org/10.1007/978-94-010-9388-0_5.

Wilson, R.L. (1966). Palaeomagnetism and rock magnetism. *Earth-Science Reviews*, *1*(2-3), 175—212. https://doi.org/10.1016/0012-8252(66)90005-5.

Zheng, Y-F., & Zhao, Z.-F. (2017). Introduction to the structures and processes of subduction zones. *Journal of Asian Earth Sciences*, *145*(Part A), 1—15. https://doi.org/10.1016/j.jseaes.2017.06.034.