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TESTING THE GAD HYPOTHESIS: A PERSONAL VIEW

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Abstract

The Earth's magnetic field looks like that produced by a dipole at the geocentre. Furthermore, when averaged over a sufficient length of time, the magnetic poles coincide with the geographic poles. One speaks, therefore, of a geocentric axial dipole, or GAD. The problem for Earth scientists is whether or not this has been the case throughout geological time. This is a very important point. Without the GAD model, paleomagnetic poles would be incorrectly located, leading to errors in plate-tectonic reconstructions and the configuration of climatic belts. This article offers a brief summary of the various ways these difficulties have been approached. Two observational tests have been proposed: the single-plate test and the paleoinclination test. They are complementary. The former offers a "snapshot" based on temporally restricted paleomagnetic observations from a single plate. The latter is based on the statistics of paleomagnetic inclination values spanning long intervals of geological time from as many plates as possible. A more recent development is computational, using geodynamo simulations to assess likely magnetic field morphologies and the effects of polarity reversals. Overall, it appears that the GAD model is valid back to the late Paleozoic. But for much of geological time there is still no direct proof one way or the other. The ramifications for early Earth scenarios, when there may have been no inner core, are particularly serious.

Keywords: paleomagnetism, Permian, geocentric axial dipole, GAD, geodynamo.

Introduction

When the eminent British geologist Sir Roderick Impey Murchison visited Kazan in 1841, he wrote at length of the generous hospitality he received. One hundred and seventy years later, I whole-heartedly concur: friendly company, excellent food, singing by remarkably talented students – and let us not forget a first-rate scientific conference! Murchison's visit was part of his extended investigations into the geology of Russia, one major outcome of which was the formal setting up of the Permian System. This happens to be particularly relevant to the topic of the present paper, namely, the morphology of the Earth's magnetic field in the geological past. This issue is by no means as arcane as it might seem. The assumption that the field has always been that of a central aligned dipole (the geocentric axial dipole, or GAD, model) is crucial to working out the movements of the tectonic plates and the configuration of past climatic belts. One of the few ways of testing the GAD model is the so-called single-plate method, wherein contemporaneous paleomagnetic results from a large, coherent, continental block are checked against the predictions of the GAD. And the best candidate is the Permian of Eurasia, as explained in the next section. Following that, an alternative test based on the statistical properties of paleomagnetic directions is described.

Then a brief summary is given of ongoing computational work on various geodynamo scenarios and the resulting geomagnetic morphologies.

The single plate test

The underlying idea of this test is simple. Do paleopoles of the same age, from widely distributed locations on a large, coherent continental block, coincide? If they do, then the GAD is confirmed. But what if they do not? It is still possible to find the true pole, if one assumes that the field is the sum of a number of zonal components: dipole, quadrupole, octupole, etc. This is done by determining the intersection points of the paleomeridians from each sampling site (Fig. 1). For example, a field consisting of a dipole and quadrupole of the same sign leads to a virtual geomagnetic pole (VGP) that is further away from the observation site than that of a pure GAD; the VGP is said to be "far-sided". But the true pole can be obtained from the intersection of the paleomeridians drawn from each observation site to its own VGP. The angular discrepancy between the GAD paleopoles and the intersection points gives a measure of the higher-order components. In this way, Bazhenov & Shatsillo [1] showed that Permian data from Eurasia (including Tatarstan–Murchison would approve) restrict the quadrupole and octupole to modest contributions (4% and 12%, respectively). It is interesting to note that the great 16th-century cartographer Gerard Mercator used the same method to locate the Earth's magnetic pole. Of course, he did not talk of dipoles and quadrupoles, but his use of early measurements of declination (then called variation) gets to the crux of the matter. Given N observation sites (rather than just two), there are $N(N-1)/2$ intersections whose dispersion must be treated statistically. For example, Bazhenov & Shatsillo [1] analyzed 9 paleomeridians leading to 36 intersection points that have a geographic distribution that is markedly elongated because the great circles involved all cross at small angles. The situation is very similar to the classic plate tectonic problem of determining Euler poles from transform faults.

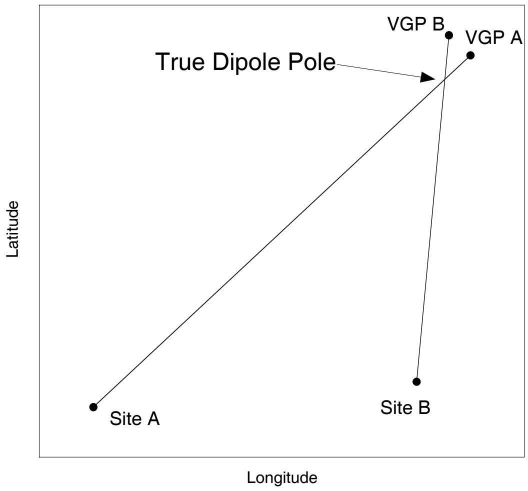

Fig. 1. Schematic representation of the Intersecting Great Circle Method. Both VGPs are "far-sided", but if the field contains only zonal components then the intersection of the paleomeridians gives the true dipole pole (TDP)

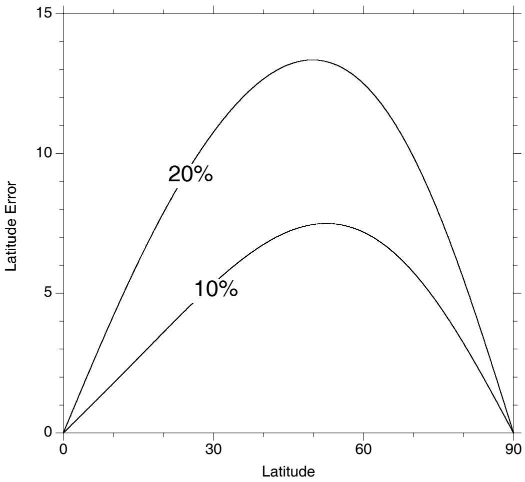

Fig. 2. Absolute value of latitudinal error in locating paleopoles for fields consisting of a dipole plus an octupole. Labels indicate the magnitude of the octupole compared to the dipole

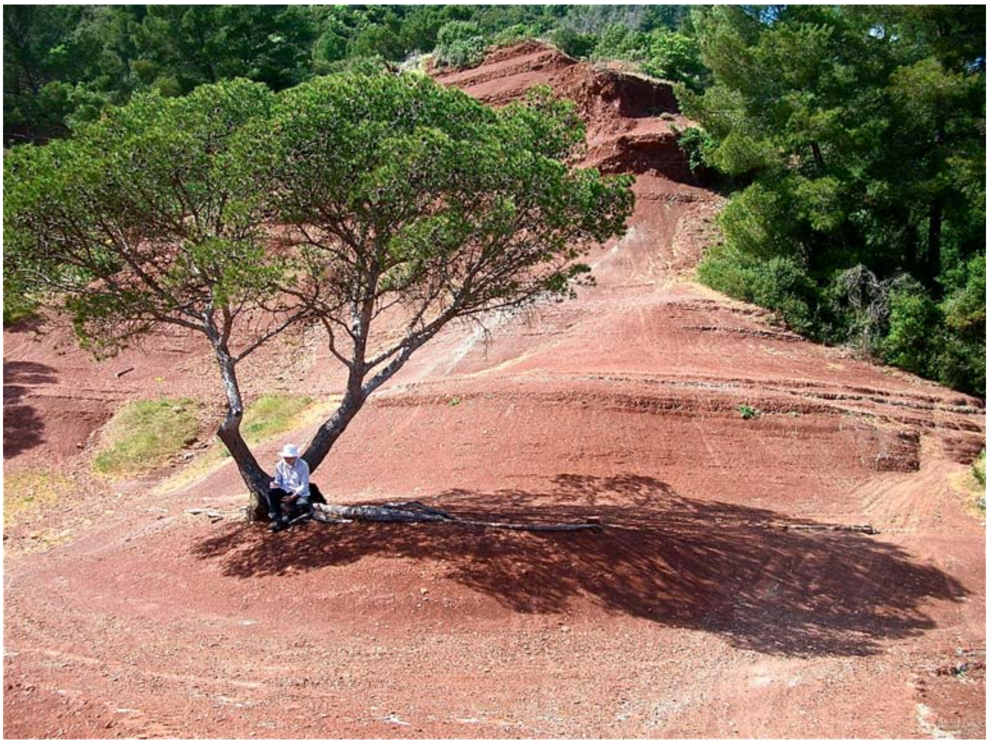

Fig. 3.The author on a Permian section in southern France, April 2011

Figure 2 shows the magnitude of the latitudinal discrepancy arising from working out a VGP based (erroneously) on the assumption of a GAD, when, in fact, the field has a significant octupole component. Pole location errors exceeding 1000 km are certainly possible, a difficulty that has for decades plagued attempts to reconstruct Wegnerian Pangea. In a careful analysis of all relevant data, Domeier et al. [2]

describe what they refer to as “the road to reconciliation” of the long-standing incompatibility between classic continental reconstructions and available paleomagnetic data. Reconciling already published information is a laudable goal, but it is also desirable to generate new data against which predictions can be tested. Thus, Vladimir Pavlov and myself have initiated a new Russia-Canada collaboration to sample as many geological targets as possible along a paleomeridional traverse across Permian Eurasia – from Iberia to Siberia. We have started by sampling at four localities in southern France (see Fig. 3). We chose this region deliberately, because it was rejected in its entirety by Bazhenov & Shatsillo [1], who expressed concerns about errors resulting from local tectonic rotations.

For the new collection, we have carried out detailed thermal demagnetization experiments on several hundred stratigraphically-ordered samples and obtained well-defined VGPs. When combined with published data, these indicate that the fear of local tectonic rotations is largely unfounded. Furthermore, the overall paleomagnetic signature from the Permian of southern France strongly supports the GAD [3].

The Paleo inclination test

An early suggestion for testing the GAD introduced a statistical procedure based on the angle of inclination (I). This is possible because all zonal fields (dipole, quadrupole, octupole, etc.) have their own distinct cumulative distribution functions (CDF). For a dipole (Fig. 4):

$$P_{\mathrm{GAD}} = \sin(\tan^{-1}(\tan(|I|/2))). \quad (1)$$

The probability density function (PDF) is given by the first derivative of Eq. (1), and is illustrated for 1-degree bands in Fig. 5. Clearly, there is very little chance of observing inclination values exceeding 80°. The most probable value is ~67°, which occurs at a latitude of ~50°.

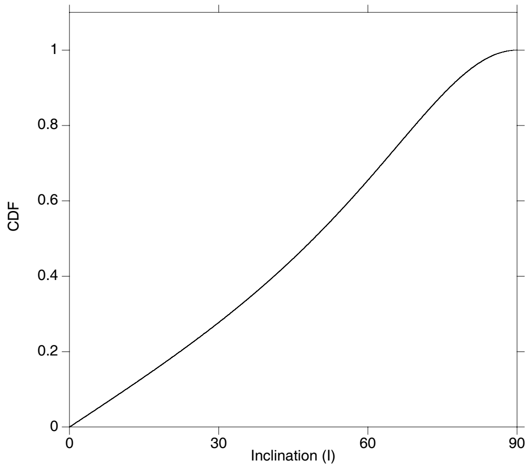

Fig. 4. Cumulative Distribution Function of Inclination values for a GAD

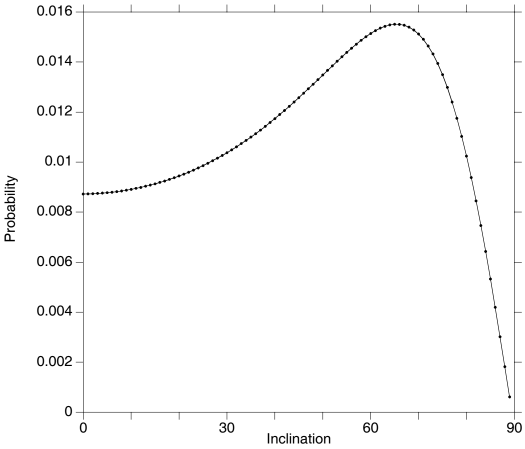

Fig. 5. Probability of finding abs(I) in 1° bands for a GAD

In the original paper describing the method, Evans [4] compiled 1271 Phanerozoic results and showed that they were compatible with a GAD model. Higher-order morphologies (quadrupole, octupole, etc.) all failed the Chi-squared test. This was a useful first step, but complications soon arose. Kent & Smethurst [5] and Meert et al. [6] considered sub-divisions of the Phanerozoic, prompting the question of how much geological time is required for the paleo-inclination test to succeed. Evans & Hoye [7] approached this problem in terms of a random-walk model over a sphere. They considered a single continental plate (dubbed Capland) in the form of a spherical cap covering 25% of the globe, similar to the present-day ratio of continental to oceanic crust. Each computer run started by placing Capland on the globe in a location determined by a random number generator. A community of hypothetical palaeomagnetists were then allowed to sample Capland at S randomly chosen sites. The centre of Capland (C) was then moved α degrees in a random direction, and the process repeated. In this way, a drift history can be built up from a sequence of arc segments. Each segment was assigned a duration of 100 million years, which can be regarded as typical of major plate re-arrangements. The angle α was fixed at 50°, giving C a speed of ~6 cm/yr (a typical value for most plates). The number of "sampling" sites, S, was varied from 100 to 1000, and 10000 runs were carried out for each case. The conclusion was that the entire Phanerozoic (~600 million years) would generally be enough to adequately sample the globe, but that ~300 million years would often suffice. This is essentially what Bloxham [8] found using a greatly expanded compilation of 3355 inclination values spanning the last 250 Myr.

Initially, the paleo-inclination test was applied to the problem of distinguishing a pure dipole field from a pure quadrupole, etc. But most experts would probably be unhappy to consider a field with absolutely no dipole content–except during a reversal, perhaps. Consequently, it is instructive to ask if the paleo-inclination method is effective for mixed fields containing dipole, quadrupole and octupole components (bearing in mind that the test was never intended for such refinements). Several examples of mixed fields were considered by Kent & Smethurst [5]. It turns out that the test is very insensitive to quadrupole content, but the opposite is true for octupole content (Fig. 6). A marked excess of shallow inclinations arise when the dipole and

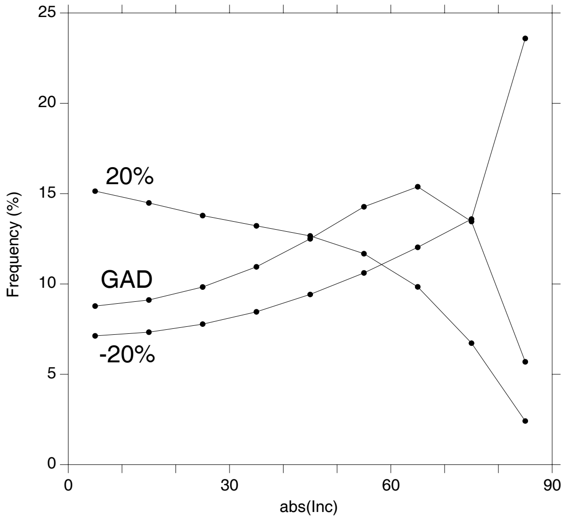

Fig. 6. Inclination statistics for a pure GAD, and for fields containing ±20% octupole. (10° bins)

octupole have the same sign, but more steep inclinations occur when the they have opposite signs. But what is the effect of reversals? If the octupole was to reverse significantly more often than the dipole, the inclination bias would be diminished, or even eliminated. On the other hand, if the octupole and dipole reverse synchronously, then the paleo-inclination test should prove useful. This problem is currently being investigated by means of numerical geodynamo simulations (see below).

In addition to difficulties that might arise from non-dipole field components, we must consider the long-standing issue of "sedimentary flattening". King [9] demonstrated experimentally that depositional remanent magnetization (DRM) is often characterized by a shallower inclination than that of the ambient field in which the sediments were deposited. It was found that,

$$\tan I \; = f \tan I' \tag{2}$$

(where I – observed inclination, I' – ambient field inclination, and f is the factor between 0 and 1, usually called the flattening factor). One of the main ingredients in the "road to reconciliation" announced by Domeier et al. [2] (see above) is the assumption of widespread flattening in the paleomagnetic record, which they characterize by $f = 0.6$. If f is known, it is a straightforward exercise to use equation (2) to "unflatten" any set of observations. An example of allowing for the flattening effect in the paleo-inclination test is illustrated in Fig. 7. A hypothetical distribution of "observed" inclinations (defined at 1° intervals and binned into 10° bins) is given. The distribution is arbitrary, but is similar to some of the distributions obtained by Kent & Smethurst [5] from real data (see their Fig. 2b). As would be expected, unflattening shifts the peak to the right, and makes the whole curve look much more like that of a GAD (see Fig. 5).

In closing this section, it is worth pointing out that the twin problems of flattening and octupole components are both minimized for sites near the paleoequator, which is the case for southern France in the Permian (see above).

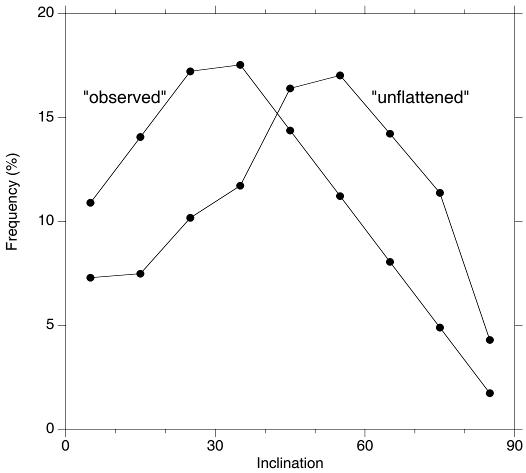

Fig. 7. Paleo-inclination distributions for an arbitrary hypothetical set of "observations", and its "unflattened" counterpart (*f* = 0.6) (10° bins)

Geodynamo simulations

Recently, my colleague Moritz Heimpel has been looking at how numerical geodynamo models might throw light on the GAD problem [10]. Several convective regimes within the Earth have been investigated to explore the conditions under which GAD models are likely to arise. It is found that the quadrupole has very little effect, but that the octupole has the potential to create significant departures from the GAD. However, for the majority of runs even this is small. It is only in the absence of a solid inner core, in the early Earth, that problems arise (Fig. 8). Octupole components up to 12% are found, leading to a maximum (median) error of 9° (5°) in locating paleopoles. By contrast, a present-era Earth model (with the dynamo driven thermochemically at the inner core boundary) yields extremely small octupole components and negligible paleopole location errors. Another important finding is that the octupole reverses synchronously with the dipole. Whether or not this is always the case – and what it may mean for the reversal process – is the focus of current studies. But, in the present context, it implies that the paleo-inclination test will continue to be useful.

Concluding remarks

Currently it appears that the GAD is a valid working model back to the late Paleozoic. Before that (i.e. the vast majority of geological time), the situation is less clear, particularly for the deep Precambrian. To give just one example, recent ideas about Earth's earliest super-continents – Vaalbara and Zimgarn [11] – will require paleogeographic adjustments (maybe small, maybe large) if the GAD did not exist at that time.

What's next? Of course, more data is always desirable: for the single-plate test, for the paleo-inclination test, and for the Precambrian in general. It is also likely that geodynamo simulations will continue to offer guidance. But here's a list of a few lines of enquiry that I feel would pay dividends:

(1) In the paleo-inclination test, how should we deal with unevenly distributed sampling sites in the compiled paleomagnetic data? Some areas, such as Iceland, have

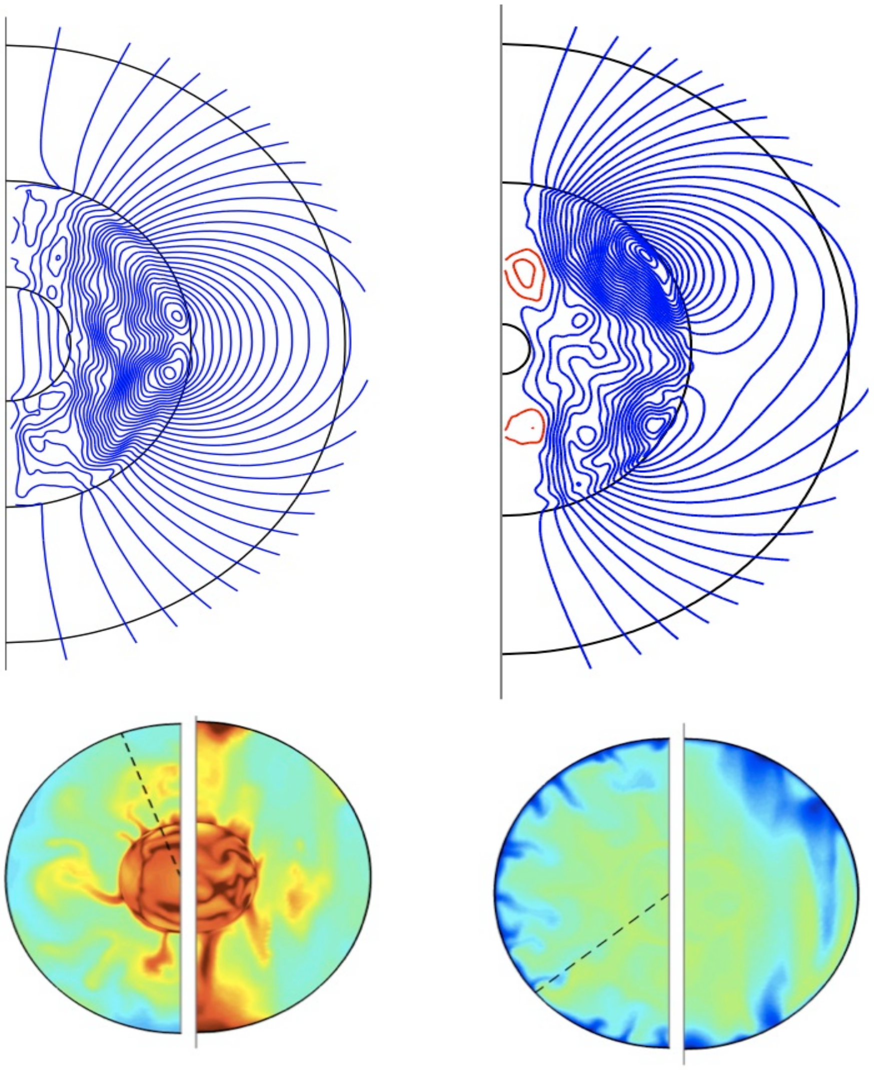

Fig. 8: Snapshots of numerical geodynamo simulations contrasting (left) a present-era Earth model with (right) an early-Earth model. (Top) Magnetic field lines. (Bottom) Equatorial and meridional sections showing positive (red) and negative (blue) buoyancy. The dashed line in each equatorial section indicates the position of the corresponding meridional section

been intensively studied, whereas others, such as Antarctica, have few results. The optimum binning/weighting procedure remains to be determined.

(2) More attention must be paid to "unflattening". The so-called E/I method of Tauxe & Kent [12] must be more widely used.

(3) The random-walk model of Evans & Hoye [7] could be improved by using more than one spherical cap. Half a dozen smaller plates, drifting independently, would constitute a more realistic model. My guess is that the overall time required to cover the globe will be reduced.

I want to close by thanking everyone who made my (all too brief) stay in Kazan so enjoyable, particularly Danis, Dilyara, and Boris. I look forward to the next time, with the fervent wish to see the seminal geology described by Murchison so long ago.

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ТЕСТИРОВАНИЕ ГИПОТЕЗЫ О ГЕОЦЕНТРИЧЕСКОМ ОСЕВОМ ДИПОЛЕ: ЛИЧНЫЙ ВЗГЛЯД

М.Э. Эванс

Аннотация

Магнитное поле Земли в первом приближении выглядит как поле, порожденное диполем, расположенным в её центре. Более того, при усреднении положения магнитных полюсов по достаточно длинному временному интервалу положение среднего геомагнитного полюса совпадает с географическим. Следовательно, мы можем говорить о геоцентрическом осевом диполе (ГОД). Для исследователей Земли очень важным является вопрос о том, насколько характерным было такое положение вещей для всей геологической истории. Без модели ГОД возможно неправильное определение местоположения палеомагнитных полюсов, что приводит к ошибкам в реконструкциях тектоники плит и конфигурации климатических поясов. В статье представлено краткое описание различных способов преодоления данных трудностей. Предложены два взаимодополняющих наблюдательных теста: тест по одной плите и тест палеонаклонений. Первый предполагает получение «моментального снимка» отдельной плиты на основе анализа совокупности ограниченных по времени палеомагнитных наблюдений. Второй тест основан на анализе статистики палеонаклонений, охватывающей длительные интервалы геологического времени и полученной для максимально возможного количества плит. В развитие этого метода, для учёта особенностей конфигурации геомагнитного поля и влияния его возможных инверсий, нами предлагается использовать численные методы, основанные на расчёте различных моделей геодинамо. В целом модель ГОД оказывается справедливой вплоть до позднего палеозоя. Однако для большей части геологического времени прямых доказательств ее справедливости до сих пор пока нет. Различия в структуре геомагнитного поля могут быть особенно важными на ранних этапах геологической истории Земли, когда её внутреннее ядро, возможно, еще отсутствовало.

Ключевые слова: палеомагнетизм, пермь, геоцентрический осевой диполь, ГОД, геодинамо.

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