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Long-term variations of the gravitational potential and of the geodynamical properties of a deformable Earth due to axial despinning

Abstract

The aim of the present study is to investigate the variation of global geodynamical and tectonic processes during the Phanerozoic (Pz) and to some extent during the Archean (Arch, 3.8-2.5 Ga BP) and Proterozoic (Ptz, 2.5-0.54 Ga BP). For this purpose first the strength of the virtual dipole moment (VDM) obtained with the use of results of paleomagnetic observations and the length of day (LOD) determined on the basis of paleontological and paleosedimentological data for the last 2.5 Ga will be investigated. We shall demonstrate that in the case of early Earth the strength of the virtual dipole moment was significantly smaller than during Pz. Although this increase for the last 3.5 Ga is statistically significant it is connected with considerable uncertainty. The long term despinning of the axial rotation due to tidal friction underwent also significant changes and it has been found that the LOD increased on average 4.4 times faster during the Pz than before, during Ptz and Arch.

Keywords: Phanerozoic, Proterozoic, Archean, virtual dipole moment, length of day,

Introduction

The problem of development of some main processes of global geodynamics during the Archean (Arc, 3.8-2.5 Ga BP), the Proterozoic (Ptz, 2.5-0.54 Ga BP) and the Phanerozoic (Pz, 0.54 Ga BP to present) – like the geomagnetic field, the length of the day (LOD) – will be analyzed in this study. We are going to investigate possible time variations of these phenomena in two steps: first independently for the Pz and than for the earlier eons (Arc+Ptz). By comparing data obtained for the epochs prior and after ~0.5 Ga we will demonstrate the remarkable changes in global geodynamics during the late Proterozoic and early Phanerozoic.

The strength of the virtual dipole moment (VDM) of the geomagnetic field during Arch and Ptz was – according to many experts of paleomagnetic observations – about one half or even one quarter of its present value (e.g. Miki et al., 2009; Tarduno et al., 2006 and 2007; Biggin et al., 2009; Macouin et al., 2003 and 2004; Klaydson et al., 2007; Shcherbakova et al., 2012; Schreider et al., 2012; Yoshihara and Hamano, 2004; Varga et al., 2012). In contrast, other researchers are of the opinion that the field has not changed during the last 3.5 Ga (e.g. Smirnov et al., 2003; Yoshihara and Hamano, 2000; Selkin et al., 2008; Yu and Dunlop, 2001; Strik et al., 2005). The uncertainty is due to the sparsity of paleomagnetic data from the Early and Middle Archean. Moreover, it is possible that during this early period of the Earth the dipole character of the geomagnetic field was not as pronounced as it became later.

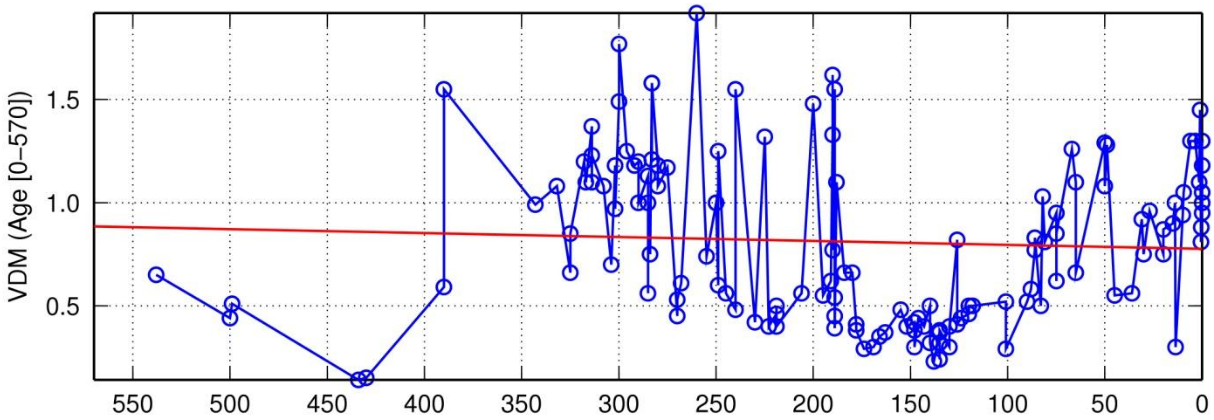
From the mid-twentieth century scientists have analyzed tidal rhythmites remaining in paleontological and paleosedimentological formations in attempt to extrapolate our knowledge on length of day (LOD) to remote geological past. Quantitative analyses of paleo-tidal data may facilitate more precise elucidation of tidal periodicities. The existing data indicates that the Earth experienced in Pz – in comparison with Arch and Ptz – a high rate of tidal dissipation which resulted in an increase of the speed of axial despinning (Abe and Ooe, 2001; Denis et al. 2002; Varga and Mentes, 2006; Zhang et al., 2012; Williams, 2000).

Geomagnetic data on geodynamical history

The differentiation of the Earth into a metallic core and silicate mantle took place gradually over a time span of approximately 50 million years. In the liquid core the geomagnetic field was generated which was dipole-dominated throughout Earth's history. It is generally accepted that the magnetic fields of planets and stars are influenced by axial rotation, but the exact role of the axial spin in field generation is still unclear. The oldest data about the field strength, expressed as virtual dipole moment (VDM) is 3.5 Ga old (Yoshihara and Hamano, 2004). For oldest field intensities still very short database is currently available. An undisputed fact is that the field has always been of the same order of magnitude and that it displayed the same kind of fluctuations since at least 3.2 Gy ago (Hulot et al., 2010).

The values of VDM data for Archean and Proterozoic – as it was mentioned in the introduction – are very different in various papers. The data evaluation should take into account the significant short-period variability of the magnetic field. It is not certain that the ancient geomagnetic field changes were such as in our time. It can be mentioned – as an example – the fast attenuation of VDM in the course of XXth century. The 5%-per-century abatement of the geomagnetic dipole moment is of course an anomaly. Fast reduction of field strength holds also in less extent for more extended time-intervals. VDM values derived from archeomagnetic data from the present epoch till 12 000 BP show that the dipole moment decrease is significantly smaller (0.4%-per-century), but in the light of history of geomagnetic field it is still a high value (Varga et al., 2007). Therefore, a paleomagnetic analysis of individual geological formations characterize only a very short period. Consequently – keeping in mind – high variabilitycan of geomagnetic field it can not be established undoubtedly that the VDM was lower in the Archean than at present. For this purpose very cautiously interpreted global data base is needed. Therefore to some extent, more reliable results can be obtained with a joint processing of more VDM data. Result of Macouin et al. (2004) suggests the existence of a long-term evolution of the dipole field intensity during the past 3 billion years (from 3×10^{22} $A\cdot m^2$ at 1000-2000 Ma to 8×10^{22} $A\cdot m^2$ at present times). Our regression calculation based on data by Tarduno et al. (2006) show that the VDM had a gradient of $(1.6\pm0.3)\cdot10^{22} A\cdot m^2/Ga$ for the Arch+Ptz. A similar value was obtained from the data base published by Schreider et al. (2011) for the time from 3.5 Ga to present ($(1.3\pm0.4)\cdot10^{22} A\cdot m^2/Ga$).

For the purposes of the present study a catalogue of VDM data determined with the use of the Thellier-Thellier method was employed, which was published in authentic, internationally recognized contributions (Biggin et al., 2009; Sumita et al., 2001; Klaydson et al., 2007; Macouin et al., 2003; Miki et al., 2009; Schreider et al., 2012; Smirnov et al., 2003; Strik et al., 2005; Yu and Dunlop, 2001; Yoshihara and Hamano, 2000 and 2004). The catalogue consists of 212 data (74 for Archean-Proterozoic and 138 for the Phanerozoic). The statistical investigation of these data was carried out separately for the case of Arch+Ptz and for Pz (Fig. 1). For the time interval 3.500 Ga - 0.570 Ga the time dependent slope is statistically different from zero (VDM=a·time+b; $a=(0.00019\pm7.89\cdot10^{-5})\ A\cdot m^2/Ma$), while for the Phanerozoic the temporal variation cannot be proven to be significant. This can be directly seen from the figure because the variation of the data around the regression line is quite big. The slope estimate is $a=(-0.00019\pm2.84\cdot10^{-4})\ A\cdot m^2/Ma$.



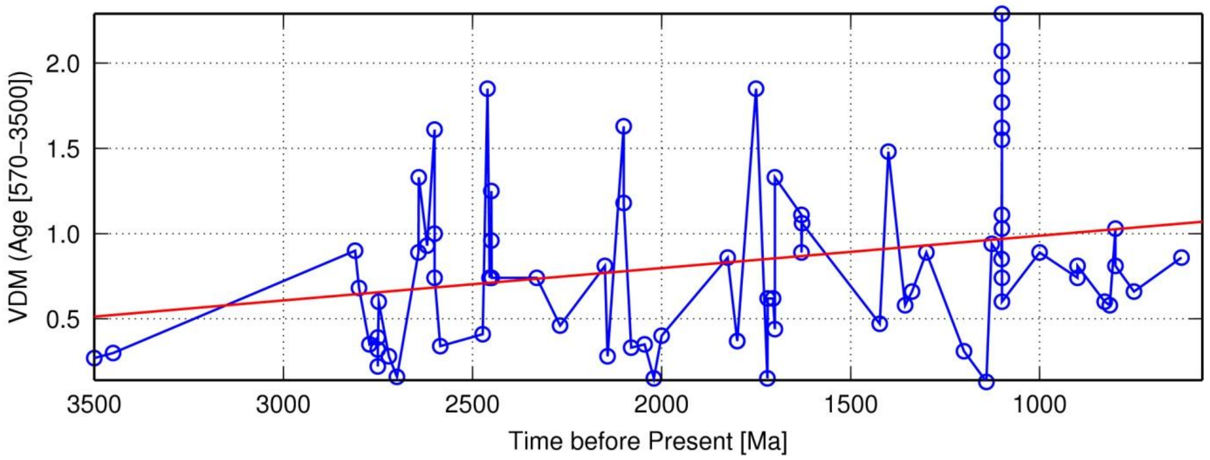


Figure 1: Dipolic geomagnetic moment values during the time intervals from 0.570 Ga to present (above) and from 3.500 Ga to 0,570 Ga (below). The straight lines shows the regression VDM=a·t+b with numerical values for the slope a=(0.00019±0.000284)A·m²/Ma and a=(0.00019±7.89·10⁻⁵)A·m²/Ma for the Pz and Arch+Ptz respectively.

The question whether the slope estimate a reflects a significant trend in the change of VDM in the time-interval from 3.500 Ga to 0,570 Ga (Arcean+Proterozoic) has been verified using a F statistical hypothesis test. Assuming identically normally distributed data the test statistics $T_a = a^2 / \sigma_a^2 = 6.26$ follows an F-distribution with n=55 degrees of freedom (number of data – estimated parameters = 55). Using a confidence level of α=5% the null hypothesis H_0 *a*=0 is rejected on the basis of the critical value $F_{0.05}(1,55)=4.0$. Consequently, the test supports that the slope is statistically significant. In case of time-interval from 0.570 to present $T_a = a^2 / \sigma_a^2 = 0.40$ and n=136 the value $F_{0.05}(1,136)=3.9>T_a$ and consequently the slope estimate *a* statistically is not significant.

Consequently the magnitude of the VDM monotonously increased during the Archean and Proterozoic under the influence of some processes which took place in the liquid core of the Earth and which stopped at the beginning of Pz. The total energy of hydrodynamic currents generating the geomagnetic field and occurring inside the liquid core could not increase in time. The growth of VDM was caused presumably by a process which strengthened the dipolic character of the geomagnetic field. For example, this could happen by strengthening the dipolic nature of the geomagnetic field.

Length of day (LOD) variations

Among the phenomena influencing the long-term evolution and dynamics of the Earth only one has an external origin: the long-term despinning of axial rotation due to tidal friction. For the purpose of investigating this phenomenon a LOD data set has been compiled from the data mentioned in Varga et al. 1997, Yuangao et al. 2004, Zhenyu et al. 2007, and Zhang et al. 2012. Based on a statistical analysis of paleontological and paleosedimentological data obtained from the sequences of different colorations in fossil corals, bivalves and brachiopods for the Pz, and stromatolites and tidal deposits (tidalites) for the Ptz, it has been found that during the Pz the LOD increased on average at a rate of 5.4 h/Ga (1.94ms/century), while during the Ptz, the average rate was only 1.24h/Ga (0.45ms/century), i.e. 4.4 times smaller (Fig. 2).

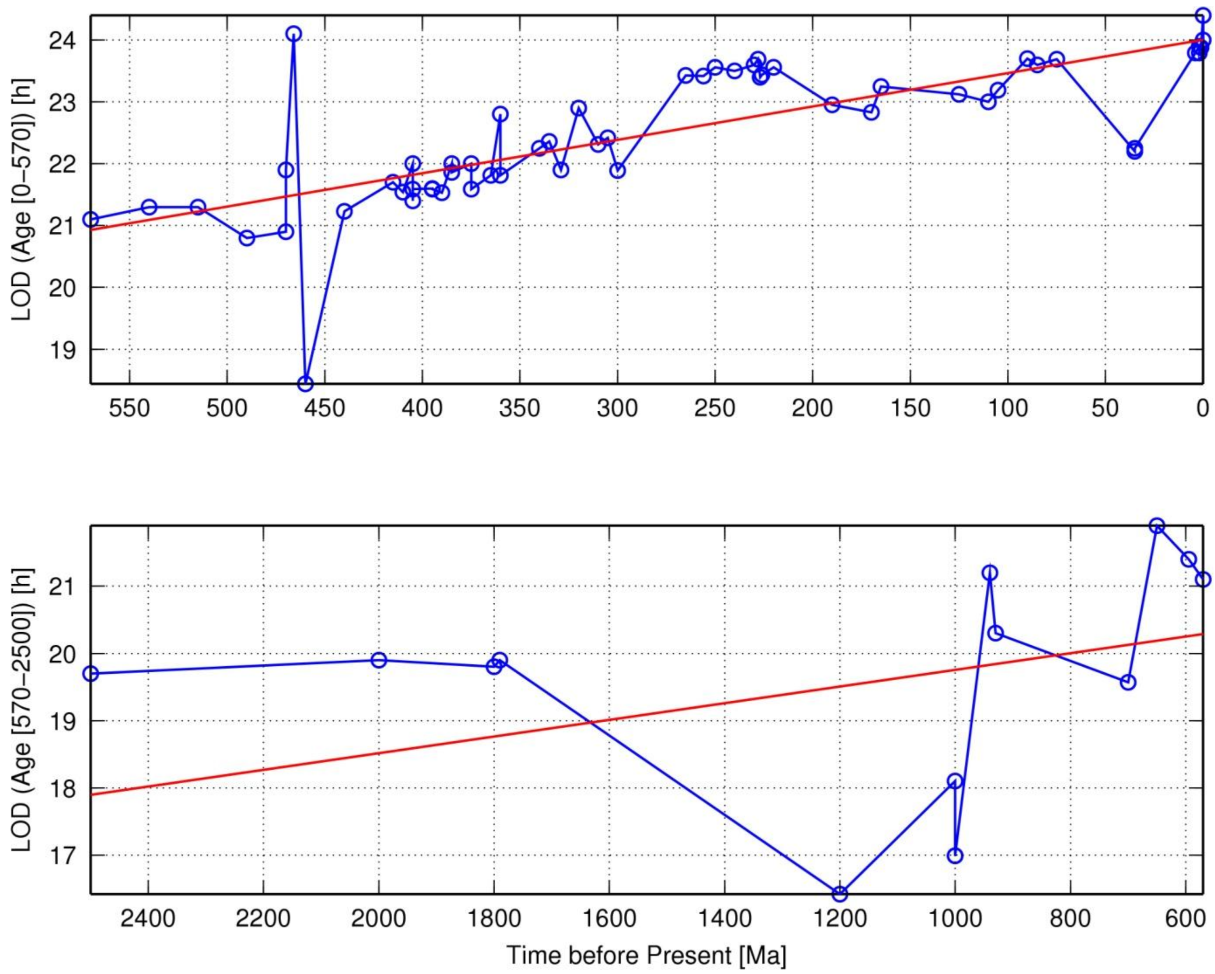


Figure 2: Length of day data for the time intervals from 0.570 Ga to present (above) and from 2.500 Ga to 0,570 Ga (below). The straight lines shows the regression line LOD= a·t+b with numerical values a=(0.0054±0.0006) h/Ma and a=(0.00124±0.00072) h/Ma for the Pz and Arch+Ptz respectively.

The statistical study of LOD data base gives for the slope *a* (*LOD=a·t+b*)
- (0.00124±0.00072) h/Ma for Arch+Ptz)
- (0.0054±0.0006) h/Ma for Pz.

The significance of the trend estimate of LOD in the time-interval from 2.500 Ga to 0,570 Ga (Arcean+Proterozoic) has been verified using again F statistical hypothesis test. Assuming identically normally distributed data the test statistics $T_a = a^2 / \sigma_a^2 = 6.80$ follows an F-distribution with n=11 degrees of freedom (number of data – estimated parameters = 55). Using a confidence level of α=5% the null hypothesis H_0 *a*=0 is rejected on the basis of the critical value $F_{0.05}(1,55)=3.36$. Consequently, the test supports that the slope is statistically significant. In case of time-interval from 0.570 to present $T_a = a^2 / \sigma_a^2 = 46.25$ and n=55 the value $F_{0.05}(1,136)=2.80$ is smaller than T_a and consequently the slope estimate *a* statistically significant.

Consequently, at 3Ga BP, an LOD was presumably of about 18.5-18.0 h. In contrast to the change rate ΔLOD during Pz, however, the rate during the Ptz cannot be proven to be statistically significant. Reliability of the data for the epoch 3 Ga BP is partly confirmed by Eriksson and Simpson (2000), who detected tidal formations in the sedimentary rocks from South Africa, dating 3.2 billion years ago. Their analysis ascertains that tides were not unusually strong at that time and that the Archean (3.8-2.5 Ga BP) lunar orbit was similar to that seen today.

The effectiveness of tidal friction in regulation of LOD can be investigated with the use of total tidal energy E_T, which can be determined as a sum of three energies (energy of axial rotation of the Earth, Moon's orbital energy around the common centre of mass and the mutual potential energy):

$$E_T = \frac{1}{2}C\omega^2 + \frac{1}{2}a_m^2 n_m^2 \cdot \left(\frac{M \cdot M_m}{M + M_m}\right) - G\frac{M \cdot M_m}{a_m}$$

Here *C, ω* and *M* are the polar moment of inertia, the angular speed and the mass of the Earth, a_m, n_m and M_m are the Earth-Moon distance, the Moon's orbital speed and the mass of the Moon respectively. *G* is the gravitational constant. Using Kepler's third law

$$n_m^2 a_m^3 = G(M + M_m)$$

We get for the total rotational energy

$$E_T = \frac{1}{2}\left(C\omega^2 - \frac{MM_m}{a_m}\right).$$

Dropping the subscript *T* the basic equation for tidal dissipation can be obtained as a time derivative of the former equation:

$$\dot{E} = C\omega\dot{\omega} + \frac{1}{2}G\frac{MM_m}{a_m^2}\dot{a}_m\varpi \ .$$

In the r.h.s. the time derivatives should be replaced by the time derivative of Kepler's law

$$\dot{a}_m = -\frac{2}{3}\frac{a_m}{n_m}\dot{n}_m \ .$$

The principle of conservation of momentum of the Earth-Moon system is

$$C\omega + \frac{MM_m}{M + M_m}a_m^2 = \text{constant} \ .$$

With a simple combination of the two last equations one gets

$$\dot{\omega} = \frac{1}{3}\frac{M_m}{M + M_m}\frac{Ma_m^2}{C}\dot{n}_m \cdot .$$

Using $\dot{a}_m$ and $\dot{\omega}$ together with Kepler's law this leads to

$$\dot{E} = C(\omega - n_m)\dot{\omega} \ .$$

Because $\omega = 7.2685 \cdot 10^{-5}\,s^{-1} > n_m = 2.425 \cdot 10^{-6}\,s^{-1}$ it can be assumed that

$$\dot{E} \approx C\omega\dot{\omega} \approx C\omega^2\frac{\Delta LOD}{LOD} .$$

Using this equation it can be concluded that the energy dissipation $\dot{E}$ during the Pz was $3.2 \cdot 10^{12}$ W, while prior to Pz it amounted to $0.7 \cdot 10^{12}$ W.

The kinetic energy of rotation is $E_K = \frac{C\omega^2}{2}$. Since $C\omega = const$ and $\omega = \frac{2\pi}{LOD}$ we get $E_K = const \cdot LOD^{-1}$. With the use of this equation it can be concluded that during the last 3 Ga the Earth lost 33% of its rotational energy. The LOD 0.5Ga BP was ~21 h . This means that the rotational energy loss rate was 4.1 times higher during the Pz than earlier in the Arch and Ptz.

The above findings imply that near the boundary of Ptz and Pz there took place a significant change in the despinning of the Earth's axial rotation

Discussion

In previous sections features of geodynamic processes VDM and LOD during the Arch+Ptz and Pz were compared. The common feature of these processes is that they were different before and during the Phanerozoic (VDM stopped growing, the axial despinning rate became 4.4 times bigger).

It is assumed that in the time between Neoproterozoic and early Phanerozoic the Earth has undergone significant geological change. From the statistical point of view the clear increase of the VDM (possibly connected with magnetohydrodynamical processes in the Earth's core) from Mesoarchean, was probably terminated around ~600 Ma BP. The growth of VDM at this time is associated by many authors with the growth of the inner core. In this case the development of the core was continuous from 3.5 Ga BP (or even from an earlier date) till ~600 Ma BP, when this process was probably, for some reason, completed.

Two mechanisms may be invoked to explain the significant change in despinning of axial rotation. The first mechanism is connected with changes in the density redistribution in the core due to emergence of solid inner core, which, in principle, can compensate the despinning effect of the tidal friction. This idea seems unlikely because the inner core formation is connected only with a slight inertia momentum change, which can not explain the significant change in despinning rate between Ptz and Pz (4.4 times). The second mechanism involves the idea that the effect of tidal friction is transmitted to the solid Earth through the oceanic tides in the shelf zones. The amount of exposed land (what is obviously related to the length of the shelf zones) during Pz is known to some extent (Fig. 3), but our knowledge for earlier eons about the area of continents is incomplete. According to Rogers and Santosh (2003) the amount of exposed land was much smaller before the Pz and therefore the length of shelf zones was also shorter.

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References

Biggin A.J., Strik G. H. M. A., Langereis C.G., 2009: The intensity of the geomagnetic field in the late-Archaean: new measurements and ananalysis of the updated IAGA palaeointensity database, Earth Planets Space, 61,9–22.

Denis C., Schreider A.A., Varga P., Závoti J., 2002: Despinning of the Earth rotation in the geological past and geomagnetic paleointensities, Journal of Geodynamics, 34, 97-115.

Eriksson, K.E., Simpson E.L., 2000: Quantifying the oldest tidal record. 3.2 Ga Moodies Group, Barberton Greenstone Belt, South Africa, Geology, 28, 9, 831-834

Hulot G., Finlay C.C., Constable C.G., Olsen N., Mandea M., 2010: The magnetic field of planet Earth, Space Science Review, 152, 159-222.

Klaydson R. Celino, Ricardo I. F. Trindade, Tohver E., 2007: LTD-Thellier paleointensity of 1.2 Ga Nova Floresta mafic rocks (Amazon craton), Geophysical Research Letters 34, L12306, 6 pp., doi:10.1029/2007GL029550.

Macouin M., Valet J.P., Besse J., Buchan K., Ernst, R., LeGoff M., Scharer U., 2003: Low paleointensities recorded in 1 to 2.4 Ga Proterozoic dykes, Superior Province, Canada, Earth and Planetary Science Letters, 213, 1-2, 79–95.

Macouin M., Valet J.P., Besse J., 2004: Long-term evolution of the geomagnetic dipole moment, Physics of the Earth and Planetary Interiors, 147, 2-3, 239–246.

Miki M., Taniguchi A., Yokoyama M., Gouzu C., Hyodo H., Uno K., Zaman H., Otofuji Y., 2009: Palaeomagnetism and geochronology of the Proterozoic dolerite dyke from southwest Greenland: indication of low palaeointensity, Geophysical Journal International, 179, 18-34.

Rogers J.J.W., Santosh M., 2003: Supercontinents in Earth history, Gondwana Research 6, 357-368~~.~~

Shcherbakova V. V., Lubnina N. V., Shcherbakov V. P., Zhidkov G. V., 2012: Palaeointensity and palaeodirection determinations of Paleoproterozoic dykes in the Kaapvaal Craton (South Africa), Geophysical Research Abstracts, 14, EGU 2012-7571, 2012, EGU General Assembly 2012

Schreider A. A., Schreider Al. A. , Varga P., Denis C., 2011: Variations of the Earth's magnetic field in the Phanerozoic, Oceanology, 51, 3, 505–509

Schreider A. A., Schreider Al. A., Varga P., Denis C., 2012: Virtual dipole moment variations through the Proterozoic-Phanerozoic eons, Oceanologia, 52, 4, 545-549.

Selkin P. A., Gee J. S., Meurer W. P., Hemming S. R., 2008: Paleointensity record from the 2.7 Ga Stillwater Complex, Montana, Geochemistry Geophysics Geosystems 9, Q12023, 25 pp., doi:10.1029/2008GC001950

Smirnov, A. V., Tarduno J. A., Pisakin B. N., 2003: Paleointensity of the early eodynamo (2.45 Ga) as recorded in Karelia: A single-crystal approach, Geology, 31, 5, 415–418.

Sumita I., Hatakeyama T., Yoshihara A., Hamano Y., 2001: Paleomagnetism of late Archean rocks of Hamersley basin, Western Australia and the paleointensity at early Proterozoic, Physics of the Earth and Planetary Interiors, 128, 223–241.

Strik G., Tauxe L., Langereis C.G., 2005: Similarity between the late Archaean and current geodynamo: secular variation and palaeointensity analysis of 2.8-2.7 Ga flood basalts from the Pilbara Craton, Australia, Geophysical Research Abstracts, 7, 03364, SRef-ID: 1607-7962/gra/EGU05-A-03364

Tarduno J. A., Cottrell R. D., Smirnov A. V., 2006: The paleomagnetism of single silicate crystals: recording geomagnetic field strength during mixed polarity intervals, superchrons, and inner core growth, Reviews of Geophysics, 41, RG 1002, 1-32.

Tarduno, J. A., R. D. Cottrell, M. K.Watkeys, and D. Bauch, Geomagnetic field strength 3.2 billion years ago recorded by single silicate crystals, Nature, 446, 657–660, 2007.

Varga, P., Denis, C., Varga, T., 1997: Tidal friction and its consequences in paleogeodesy, in the gravity field variations and in tectonics. Journal of Geodynamics, 25, 1, 61-84.

Varga P., 2006: Temporal variation of geodynamical properties due to tidal friction. Journal of Geodynamics, 41, 140-146.

Varga P., Mentes Gy., 2006: Strain data and seismicity, Marees Terrestres Bulletin. d'Information, 141, 11287-11292.

Varga P., Bus Z., Süle B., Schreider A., Bizouard C., Gambis D., Denis C., 2007: Variation in the rotation rate of the Earth and the geomagnetic field, Acta Geodaetica et Geophysica Hungarica, 42, 4, 433-448.

Varga P., Krumm F.W., Doglioni C., Grafarend E.W., Panza G., Riguzzi F., Schreider A.A., Sneeuw N., 2012: Did a change in tectonic regime occur between the Phanerozoic and earlier Epochs?, Rendiconti Lincei, 23, 2, 139-148.

Williams, G.E.J., 2000: Geological constraints on the Precambrian history of Earth's rotation and the Moon's orbit. Reviews in Geophysics, 38, 37–59.

Yuangao Q., Guwei X., Yiming G., 2004: Relationship between Earth-Sun-Moon 1000 Ma ago: Evidence from the stromatolites, Chinese Science Bulletin, 49, 21, 2288-2295

Yoshihara, A., Hamano Y., 2000: Intensity of the Earth's magnetic field in late Archean obtained from diabase dikes of the Slave Province, Canada, Physics of the. Earth and Planetary Interiors, 117, 1–4, 295–307.

Yoshihara, A., Hamano Y., 2004: Paleomagnetic constraints on the Archean geomagnetic field intensity obtained from komatiites of the Barberton and Belingwe greenstone belts, South Africa and Zimbabwe, Precambrian Research, 131, 1-2, 111-142.

Yu Y., Dunlop D.J., 2001: Paleointensity of the late Precambrian Tudor Gabbro, Journal of Geophysical Research, 106, B11, 26.331-26.343.

Zhang W., Sun Y., Kelley N., Lei Y., Yu H., 2012: Long-term electromagnetic core–mantle coupling, and the Earth's rotation acceleration in the Mesozoic Era, Russian Geology, 53, 491-499.

Zhenyu Z., Yaoqi, Z., Guosheng J., 2007: The periodic growth increments of biological shells and the orbital parameters of Earth-Moon system, Environmental Geology, 51, 7, 1271-1277.

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