Earthquake Waves and the Geomagnetic Dynamo

Abstract. *It is proposed that earthquake waves energize the geomagnetic dynamo. Fluid motions generated by earthquakes may have enough energy to be in equipartition with fields as large as 100 gauss. Seismic waves from meteoritic impacts with energies sufficient to reverse the field occur every 170,000 years.*

One of the models which has been proposed to account for the geomagnetic field involves convective motions in the liquid core (*1*). However, Kennedy and Higgins (*2*) have found that convection may not be permitted in the liquid core. This result depends on the belief that Gruneisen's gamma factor is probably too large to permit convection. Their conclusions are not universally accepted [for example, see (*3*)], but as their results have not been conclusively disproved, it is necessary to consider alternative sources to drive the geomagnetic dynamo. The effects of earthquakes are considered here.

The total energy released in earthquakes is 10^{26} to 10^{27} erg/year (*4*). If this energy were communicated to the entire liquid core in the form of kinetic energy, the energy density of the resultant motions would be 1 to 10 erg/cm^3, assuming that all of the energy were dissipated in 1 year. Actually, lifetimes of motions against viscous damping are $D^2/\nu \approx 100$ years, if the length scales (D) of velocity variations are of the order of 500 km or larger. [We have assumed that the kinematic viscosity $\nu \leqslant 10^6$ cm^2/sec (*5*).] So the energy released over the previous 100 years may be available for kinetic energy at any time. With energy densities in the range 10^2 to 10^3 erg/cm^3, equipartition with fields of 50 to 150 gauss is possible.

Even if only a fraction of the earthquake energy is communicated to kinetic energy in the core, there will still be sufficient energy density to achieve equipartition with a 5-gauss field (the field is at least of this order at the core-mantle boundary) as long as the communicated energy is concentrated in the outer regions of the liquid core. This is a natural feature to expect when energy is being fed into the core from the mantle, and it is in fact in just these regions that the nondipole field is thought to originate. Won and Kuo (*6*) have estimated that the fraction of energy reaching the inner core after a large earthquake is approximately 10^{-4}. The energy transmitted to the liquid core is therefore expected to exceed this value. But even if only 10^{-4} of earthquake energy is converted into kinetic energy in the liquid core, the energy requirements can still be met provided the energy is concentrated in a layer 100 km deep beneath the core-mantle boundary. [Note that the skin depth estimated by Elsasser (*7*) for the shortest period variations in the field is 50 km.] That earthquakes are in fact sufficiently energetic to have detectable effects on a global scale is indicated by the fact that energy from earthquakes is apparently large enough to energize the Chandler wobble (*8*).

The earthquake hypothesis of geomagnetism has some interesting implications.

1) The length of the day has been correlated with geomagnetic variations (*9, 10*) and also with earthquake activity (*11*). This is an indirect indication of a correlation between geomagnetism and earthquakes.

2) The Pacific Ocean is well known as a region where both the nondipole field and the secular variation are anomalously small (*12*). It is interesting that the most obvious pattern of earthquake activity encircles the Pacific. Earthquakes with deep focuses in particular are confined to the Pacific ring (*4*). The energization of motions in the core beneath the Pacific may be sufficiently large to ensure a semipermanent center of magnetic action in this location, with little drift permitted.

3) Finally, a relatively small seismic perturbation could probably reverse the earth's field, since only minor changes in velocity of the liquid in the core are sufficient to change the sign of the dipole field (*10, 13*). Strong seismic waves created by the impact of a large meteorite could provide such a perturbation. In this regard, the two most recent reversals of the field seem to coincide with the ages of two groups of microtektites (*14*) presumably produced in large meteoritic or cometary impacts with earth's surface. If this hypothesis is true, the pattern of geomagnetic reversals would then reflect the statistics of terrestrial capture of the stray bodies of the solar system. In order to release 10^{27} ergs, a meteorite arriving at 10 km/sec must have a mass of the order of 10^{15} grams. With a mean density of the order of 10 g/cm^3, the radius is 3×10^4 cm. To estimate the rate of infall of meteorites of this size, we note that the rate of infall of meteorites with radius greater than about 5 cm is 500 per year (*15*). The integral size distribution of meteoritic bodies is close to a power law with index 2.1 (*16*). The average time interval between large impacts is therefore

$$T = \frac{1}{500}\left(\frac{3 \times 10^4}{5}\right)^{2.1} = 1.7 \times 10^5 \text{ years}$$

Cox (*17*) has noted that the reversals of the field follow a Poisson distribution with a characteristic time between reversals of 2×10^5 years—close to the above estimate of the time between large impacts.

Confirmation of the choice of 2.1 for the integral index of meteoritic sizes is provided indirectly by results of Urey (*18*). He claims that geologic eras lasting about 10^7 years are terminated by the impacts of bodies of mass 10^{18} g or more. The radius of such masses is at least ten times the radius of the bodies considered here to be responsible for geomagnetic reversals. Their flux is therefore expected to be $10^{2.1}$ times less, indicating a mean time interval between impacts of about 2×10^7 years. This is close to the mean time interval required by Urey.

The hypothesis that the geomagnetic dynamo can be excited by an earthquake has been proposed by Won and Kuo (*6*). However, the very large earthquakes they considered are very rare [$\leqslant 1$ per year (*4*)] and tend to have shallow focuses, so that communication of energy to the liquid core is inefficient. Furthermore, the oscillations of the inner core in their model have energy densities four to five orders of magnitude smaller than the energy density of a 5-gauss field. As Elsasser (*7*) has stressed, it is physically reasonable to expect that the energy densities of motions and fields should be more nearly equal.

DERMOTT J. MULLAN
Bartol Research Foundation of the Franklin Institute, Swarthmore, Pennsylvania 19081

References and Notes

1. E. N. Parker, *Astrophys. J.* **158**, 815 (1969).
2. G. C. Kennedy and G. H. Higgins, *J. Geophys. Res.* **78**, 900 (1973).
3. M. C. Frazer, preprint.
4. J. Bartels and P. ten Bruggencate, Eds., *Landolt-Börnstein* (Springer-Verlag, Berlin, 1952), vol. 3, pp. 371–376.
5. R. Hide, *Nature Phys. Sci.* **233**, 100 (1971).
6. I. J. Won and J. T. Kuo, *J. Geophys. Res.* **78**, 905 (1973).
7. W. M. Elsasser, *Rev. Mod. Phys.* **22**, 1 (1950).
8. K. Shimazaki and H. Takeuchi, in *Rotation*

of the Earth, P. Melchior and S. Yumi, Eds. (Reidel, Dordrecht, 1972), p. 224.
E. C. Bullard, C. Freedman, H. Gellman, J. Nixon, *Phil. Trans. Roy. Soc. London Ser. A* **243**, 67 (1950).
E. C. Bullard and H. Gellman, *ibid.* **247**, 213 (1954).
11. R. A. Challinor, *Science* **172**, 1022 (1971).
12. R. R. Doell and A. Cox, *J. Geophys. Res.* **70**, 3377 (19(*Science* **171**, 248 (1971).
13. W. M. Elsasser, *Rev. Mod. Phys.* **28**, 135 (1966); S. K. Runcorn, *Ann. Geophys.* **11**, 73 (1955).
14. S. A. Durrani and H. A. Khan, *Nature* **232**, 320 (1971).
15. J. A. Wood, *Meteorites and the Origin of Planets* (McGraw-Hill, New York, 1968). p. 12.
16. E. J. Öpik, *Advan. Astron. Astrophys.* **2**, 254 (1963).
17. A. Cox, *J. Geophys. Res.* **75**, 7501 (1970).
18. H. C. Urey, *Nature* **242**, 32 (1973).
19. Partially supported by NASA contract NGR-39-005-066. The author holds a Presidential Internship under NSF grant GZ-2294.

15 March 1973; revised 24 May 1973

Testicular Morphology in Rats Vasectomized as Adults

Abstract. *Vasectomy was performed on 63 rats at age 81 to 105 days. Examination 28 to 58 days later disclosed no significant reductions in testis size with respect to preoperative testis length and to testis length and weight in unoperated controls. The fact that the minimal atrophy observed was primarily left-sided sugested that these effects were artifacts of the procedure or systemic left-right differences in the animals.*

Sackler *et al.* (*1*) reported that vasectomy of immature rats results in significant reductions of urinary 17-ketosteroid output and testis weight. As they and others point out, further research is needed on the procedures and consequences of vasectomy (*1, 2*), especially in view of the social importance of this issue. At the same time, however, any conclusions should be based on data derived from an appropriate experimental model. Since my colleagues and I needed vasectomized adult rats in some of our studies (*3*), we developed a surgical procedure and have performed more than 130 operations since late 1970. While testicular atrophy has been found in some of our animals, it appears that these instances can be attributed to artifacts of the surgery, rather than to vasectomy per se.

Surgery was performed on 53 BLU:(LE) hooded rats under pentobarbital sodium anesthesia with clean surgical procedures, care being taken to avoid resection of the deferential blood vessels (*4*). In comparisons of pre- and postoperative measurements of testis length (*5*), no decreases were found (Table 1). Since, in many studies of vasectomy in animals, either the deferential vessels are resected or the status of these vessels is not reported, ten additional rats were vasectomized, this time with ligation and resection of the deferential vessels along with the ductus deferens. While the postsurgical interval in these animals was less than that of Sackler *et al.* (*1*), there is evidence that many complications of vasectomy are at their peak 1 month after surgery (*6*).

This latter group did not differ from ten age-matched, unoperated controls in body weight or testis weight (Table 1). However, the analysis of variance (*7*) for testis length yielded a significant interaction of group by side-of-body ($F = 11.5$; d.f. = 1, 18; $P < .01$). Length of right testes of vasectomized rats (2.27 ± 0.06 cm) and controls (2.24 ± 0.04 cm) did not differ, whereas left testes of vasectomized rats (2.17 ± 0.06 cm) were smaller than the left testes of controls (2.31 ± 0.03 cm) ($t = 3.3$; $P < .01$). Furthermore, the within-group comparisons of testis length for the 63 vasectomized rats yielded a significant interaction of surgery by side-of-body ($F = 5.6$; d.f. = 1, 186; $P < .05$), reflecting the fact that testes on the right increased in length between surgery (2.16 ± 0.01 cm) and postmortem examination (2.23 ± 0.02 cm) ($t = 2.8$; $P < .01$), whereas presurgical (2.17 ± 0.01 cm) and postsurgical (2.15 ± 0.03 cm) measurements of left testes did not differ. This left-right discrepancy was corroborated by the fact that a greater proportion of left testes (23.8 percent) than right testes (3.2 percent) decreased in length after surgery ($\chi^2 = 15.4$; d.f. = 1; $P < .01$). In addition, all adhesions observed in these 63 rats occurred on the left side. The reason for this left-right difference cannot yet be explained. There is the possibility of some subtle difference in technique between the two sides. There is also evidence that disturbances of the circulation of the left testis and scrotum may be more damaging than disturbances on the right. The fact that 98 percent of cases of varicocele (a congested condition of the scrotal blood vessels) in humans occur on the left side has been explained by the relatively inefficient system of venous return from this side (*8*).

It would thus appear that these effects on testis size were related to a compromise of the testicular circulation or to other complications of surgery. The fact that Sackler *et al.* (*1*) found decreases in urinary 17-ketosteroid output in vasectomized rats but not in vasoligated rats suggests that these changes may be explained in a similar way.

Many aspects of vasectomy require further investigation (*1, 2*). It is important, however, that the effects of surgery be clearly distinguished from the effects of vasectomy per se. While the data presented here do not demonstrate that vasectomy is necessarily an innocuous procedure, they do indicate that certain apparently deleterious effects of vasectomy may result from pro-

Table 1. Body weight, testis length, and testis weight (grams per kilogram of body weight) in vasectomized and control rats. Data are mean ± standard error of mean.

Animals (No.)	Age at surgery (days)	Post-surgical interval (days)	Body weight		Testis length		Testis weight (g/kg)
			Final (g)	Gain (%)	Initial (cm)	Final (cm)	
			Vasectomy, deferential vessels intact				
53	90.1 ± 0.6	41.5 ± 1.2			2.16 ± 0.01	2.18 ± 0.02	
			Vasectomy, deferential vessels occluded				
10	102.0 ± 0.8	29.8 ± 0.4	469.9 ± 13.4	16.0 ± 1.2	2.22 ± 0.03	2.22 ± 0.04	3.81 ± 0.12
			Control				
10	100.0 ± 0.0	27.0 ± 2.4	474.4 ± 9.2	14.8 ± 2.1		2.28 ± 0.03	3.82 ± 0.08