station, the great thickness of the third layer, or "oceanic layer," would be startling if one assumed that it represented the structure under the entire basin. We have found stations like this before, however; the one that it resembles most is station MK9-10, lying in a similar topographic position on the continental rise on the east side of the Bering Sea (*5*), a similar small ocean basin separated from the main basin of the Pacific. The average of reversed profile MK9-10 is plotted to the right of that of station MN5 in Fig. 2 for comparison. In the case of the Bering Sea, the thickened "oceanic layer" is found only at the margins of the basin; the central portion has a normal oceanic crust overlain by greatly thickened sedimentary and "basement" layers, with the mantle depressed accordingly.

The zone of thickened "oceanic layer" may be of considerable significance if it is normally found at the margins of enclosed basins. Unfortunately, stations are rarely made in this topographic position, and, when they are, the large vertical exaggeration used in making crustal sections makes them less noticeable. They may demonstrate part of the process by which a piece of ocean can be converted into continent: the sedimentary section thickens by deposition at the top at the center of the basin, and the crustal section thickens by conversion or addition from below at the edges. Such a possibility (among others) has been suggested in Menard (*6*).

GEORGE G. SHOR, JR.
Marine Physical Laboratory,
Scripps Institution of Oceanography,
La Jolla, California 92037

References and Notes

1. G. G. Shor, Jr., "Refraction and reflection techniques and procedure," in *The Sea* (Interscience, New York, 1963), vol. 3, pp. 20–38.
2. J. Ewing and M. Ewing, *Trans. Amer. Geophys. Union* **47**, 276 (1966).
3. All topographic names are those used by D. C. Krause, *New Zealand Oceanog. Inst. Mem.* **41**, in press.
4. G. H. Sutton and G. R. Bentley, *Lamont Geol. Observ. Tech. Rept.* **3** (1953), 5 pp.
5. G. G. Shor, Jr., *Marine Geol.* **1**, 213 (1964).
6. H. W. Menard, *J. Geophys. Res.* **72**, 3061 (1967).
7. Supported by NSF as part of the International Indian Ocean Expedition, and by ONR. For help I thank G. Hohnhaus, R. Ackermann, F. Stone, D. Newhouse, J. C. Harrison, and Captain L. Davis and the crew of R.V. *Argo*. Helen Kirk assisted with data reduction, D. Krause provided prepublication data on the Coral Sea, and H. W. Menard discussed the data and the structural interpretation. Contribution from the Scripps Institution of Oceanography.

5 October 1967

Paleomagnetic Field Reversals and Cosmic Radiation

Abstract. *Faunal changes observed in association with reversals of the geomagnetic field have been attributed to increased radiation dosages produced by cosmic rays when the field intensity is greatly reduced. However, at currently observed cosmic ray and solar particle intensities, the additional dosages produced at sea level during a period of complete removal of the geomagnetic field are negligible. Furthermore, even complete dumping of the energetic particle in the radiation belts would not give rise to the necessary increased dosages.*

Paleomagnetic studies of rock samples taken from many parts of the world have provided strong evidence that the geomagnetic field undergoes occasional reversals of polarity. Measurements based on simultaneous paleomagnetic and radiometric studies of lava flows have traced at least four major geomagnetic field reversals in the past 4 million years, together with indications of several short periods of reversed magnetic polarity (*1*). Similar results have been obtained [Opdyke *et al.* (*2*)] from paleomagnetic studies of sediments in Antarctic deep-sea cores. These authors also examined the marine protozoan radiolarian species in these sedimentary cores and found striking faunal boundaries that were related to field reversals observed in the same cores. A correlation of paleomagnetic and paleontological evidence from the Cambrian to the Recent present (*3*) also suggests that field reversals strongly influence population trends. From these coincidences or near coincidences of the faunal changes with the field reversals it has been suggested (*2*) that there must be a causal relation between the two effects. The nature of this causal relation has been the subject of speculation. In particular, it has been pointed out that during a magnetic field reversal the intensity of the geomagnetic field most probably decreases temporarily to essentially zero. As a consequence, the earth's surface would have been exposed to a greater cosmic ray intensity than normal. The resulting increase in the radiation dosage is assumed to be responsible for the observed faunal changes, most probably due to an enhanced mutation rate that strongly affects the evolutionary development of individual species (*4*).

I now point out that the increased radiation dosages that would be experienced at sea level as a consequence of a complete removal of the shielding effect of the geomagnetic field would be so small that a significant effect on population levels would be extremely unlikely.

The effect of reducing the intensity of the geomagnetic field to zero on the radiation dosages experienced at sea level may be regarded as threefold. First, there will be an increase in dosage due to the additional cosmic ray particles allowed to make an impact on the top of the earth's atmosphere in regions previously shielded. Second, those particles intermittently emitted by the sun will be able to reach all parts of the upper atmosphere with full intensity and thus produce increased radiation. Third, it is possible, although rather unlikely, that some or all of the particles stored in the radiation belts might be "dumped" into the earth's atmosphere. Each of these effects are considered after a discussion of the role of energetic particles falling on the top of the earth's atmosphere in determining the total radiation dose experienced by organisms at sea level.

The earth's atmosphere is so thick that essentially none of the corpuscular radiation falling on it can reach the surface without having suffered several nuclear interactions. For energetic protons, which make up a major fraction of the incident particles and are the most penetrating, this thickness corresponds to approximately ten interaction mean free paths. Thus, the probability of a proton reaching the earth's surface without having interacted is less than 5×10^{-5}. Similarly, the heavier nuclei, with their shorter mean free paths, have a still smaller probability of not interacting. The radiation dose at sea level is thus almost entirely due to the secondary particles created in the atmosphere, and sensible contributions to this dosage are only made by incident particles having sufficient energy to produce secondary particles capable of penetrating to sea level. Incident protons with energies below a few Bev are thus incapable of affecting the direct radiation dose at sea level. How-

ever, low-energy particles may produce nuclear interactions in the upper atmosphere, and these may result in the formation of radioactive isotopes which, if they are sufficiently long lived, may be carried down to the earth's surface by atmospheric mixing. Of the possible radioisotopes, C^{14} appears—at least under equilibrium conditions—to be by far the most important in that it has under normal conditions a global production rate one order of magnitude greater than that of the next most abundantly produced isotope, H^3 (*5*). The mixing time required for isotopes produced in the stratosphere before they reach the surface layers of the oceans is from 1 to 10 years, which is insignificant compared to the half life of C^{14} (5730 years), but not compared to that of H^3 (12.5 years). The only other radioisotope that could conceivably be produced with sufficient abundance to affect dosages would be Be^{10}, which under normal conditions has a production rate one-fifth that of H^3, but a very long lifetime (2.5×10^6 years) and thus a low disintegration rate.

In addition to the radiation dosages produced by extraterrestrial particles sea-level organisms also receive radiation from the naturally occurring radioactivity in the earth's crust. These dosages have been considered in extensive detail in the various reports issued on the effects of nuclear weapon tests, and for our purposes here it is sufficient to quote some typical figures taken from the report of the United Nations Scientific Committee (*6*). In ordinary regions of the earth's surface the radiation dose over land surfaces due to naturally occurring gamma radiation is of the order of 70 mrad/year. Similarly, the dose due to particle emission in human bone tissue, which is presumably roughly similar to that expected in the shells of marine organisms, is about 40 mrad/year due to Ra^{226}, 9 mrad/year due to K^{40} (a naturally occurring radioisotope), and 1.6 mrad/year due to C^{14} produced by cosmic rays. On the ocean surface, away from local rocks, the natural radioactivity will principally be due to the K^{40} in seawater, the concentration being about 4×10^{-13} curie/cm^3, an amount which corresponds to a dose of about 10 mrad/year. This may be compared with the normal value for C^{14} in the ocean, 3×10^{-4} mrad/year. The much larger dose from C^{14} found in bone material is of course due to the ability of growing tissue to concentrate the carbon.

These figures provide us with the necessary background for considering the effects of a geomagnetic-field removal. The most immediate effect is due to the additional cosmic ray particles that will be able to reach portions of the upper atmosphere hitherto shielded by the field. The cosmic ray dose at sea level would thus be expected to increase everywhere to the values normally only recorded near the magnetic polar regions. However, the thickness of the atmosphere is so great that these additional low-energy particles are relatively inefficient in producing sea-level radiation. The total increase in cosmic ray dosage at sea level between the equator and the polar regions is only 14 percent and removal of the field would only increase the equatorial dose rate from 35 to 41 mrad/year. The difference over Antarctica, where the previously mentioned changes in populations of radiolaria were detected, would be essentially zero.

The production of radio isotopes by these additional cosmic ray particles is the next effect to consider. Under normal conditions the production rate is latitude-sensitive, but on field removal the rate will clearly rise everywhere to the normal polar rates. It has been shown in detail (*7*) that the polar production rate of C^{14} is about double the global average. Thus, after sufficient time has elapsed for adequate mixing to occur, one would expect the dosages due to C^{14} to also double on field removal. A similar doubling of the dosages due to the other particle-produced radioactive isotopes would also be expected but would make a negligible contribution, although the initial rise in the dosages would be due to the shorter-lived isotopes with their higher activities.

In addition to the normal cosmic ray particles the earth is intermittently bombarded by energetic solar particles. These may be very copious but rarely have sufficient energy to produce direct secondary effects at sea level. At most, these particles produce an increase of a factor of 2 over the sea-level dosage due to cosmic rays for a period of not more than a few hours. However, it might be anticipated that they would make an appreciable contribution to the production of radioactive isotopes. The contribution of solar particles to the global production of C^{14} during the last solar cycle of activity, which was considerably more active than previous recorded solar cycles, was shown (*8*) to be less than 3 percent of the global production due to the cosmic rays. Since these solar particles can reach approximately 10 percent of the total area of the atmosphere in the presence of the geomagnetic field, a removal of the field would result in, at the most, a production of 30 percent more C^{14} nuclei. Similarly the increased production of H^3 would be at most 3 percent. The smallness of these increases is principally due to the very steep energy spectrum of the solar particles which results in the majority of the particles losing their energy by ionization losses before they can make nuclear interactions.

Finally, we are left with the problem of radiation produced by dumping of particles trapped in the radiation belts. Here it should be noted first that only under rather special circumstances will there be any appreciable additional dumping during the onset of a field removal. A steady weakening of the field would simply allow the trapped particles to escape and would reduce the number of particles that are normally brought down into the atmosphere. Only if the field undergoes rather peculiar perturbations, such as the dipole component taking up an extremely eccentric position, will the dumping increase during a field reversal. It should also be noted that the majority of the energetic particles in the radiation belts are electronic, rather than nucleonic, and that these will not produce appreciable radiation dosages at sea level even if dumped into the atmosphere. Protons of energy above 10 Mev, the minimum energy necessary to produce C^{14}, the radioisotope with the lowest threshold energy, are mainly confined to the inner radiation belt, between 1.3 and 2.0 earth radii. The total energy of the magnetic field in this region is 2×10^{24} ergs, and from considerations of the effects of external currents due to trapped particles on the geomagnetic field less than 1 percent of this energy can be used to confine particles. In fact, the "loading" of the field is probably several orders of magnitude less than this upper limit (*9*). If we neglect this factor and consider that in this region all the particles are protons

having an average energy of 20 Mev then there will be at most 6×10^{27} protons stored. Now, isotopes produced in one locality will rather rapidly achieve a global distribution; thus we can treat these protons as if they are dumped uniformly over the surface of the earth. Thus some 10^9 protons will fall on each square centimeter of the top of the atmosphere. Even this number, which is certainly a gross overestimate, is one order of magnitude less than the number of solar particles brought in during a solar cycle, which are relatively ineffective in producing radioisotopes. Thus dumping of particles from the radiation belts are of negligible importance.

These results can be summarized as follows. The effect of removing the field is to increase the radiation dosage due to the cosmic radiation by 0 to 6 mrad/year between the polar regions and the equator and to increase that due to radioactive isotopes selectively taken up by organisms by not more than 2 mrad/year. These values are so small, particularly in comparison with the general background radiation levels always present, that it seems inconceivable that they could appreciably affect the evolution of any organisms. The hypothesis that the additional energetic particle radiation allowed to fall on the earth when the geomagnetic field is reversed is the causative agency for population changes thus appears untenable unless it is assumed that these periods are associated with greatly increased particle radiation from some external source.

C. J. WADDINGTON
School of Physics and Astronomy, University of Minnesota, Minneapolis

References and Notes

1. A. Cox, R. R. Doell, G. B. Dalrymple. *Science* **144**, 1537 (1964); R. R. Doell, G. B. Dalrymple, A. Cox, *J. Geophys. Res.* **17**, 531 (1966); I. McDougall and D. H. Tarling, *Nature* **200**, 54 (1963).
2. N. D. Opdyke, B. Glass, J. D. Hays, J. Foster, *Science* **154**, 349 (1966).
3. J. F. Simpson, *Geol. Soc. Amer. Bull.* **77**, 197 (1966).
4. R. J. Uffen, *Nature* **198**, 143 (1963).
5. D. Lal and B. Peters, *Handbuch der Physik*, **46/2**, 551 (1967).
6. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, General Assembly Official Records, 13th Session, Suppl. No. 17 (A/3838).
7. R. E. Lingenfelter, *Rev. Geophys.* **1**, 35 (1963).
8. R. E. Lingenfelter and E. J. Flamn, *J. Atmos. Sci.* **21**, 134 (1964).
9. J. D. Van Allen (Reidel, Dordrecht, Netherlands, 1966).
10. Supported by the Office of Naval Research under contract Nonr-710(60).

2 August 1967

Electron Microprobe and Optical Absorption Study of Colored Kyanites

Abstract. *The characteristic blue color of the mineral kyanite is shown to be caused by traces of Ti^{+++} in the range of a few parts per million. Evidence from the intensity and position of optical absorption bands indicates that the unusually intense color probably arises from electron delocalization into narrow d-bands.*

The mineral kyanite (Al_2SiO_5) quite often exhibits a characteristic blue color which has so far remained unexplained. The bright blue color plus its relatively great hardness have resulted in its use as a gemstone. In some of the mineralogical literature it is presumed that the color is due to ferric iron, although published analyses (*1*) indicate that a variety of transition elements are present in small amounts, any one of which is a possible chromophore. The problem is intriguing, because the trace element content varies rather widely among specimens from different localities and yet the blue color is almost a hallmark of naturally occurring kyanite.

We have used a combination of electron microprobe, absorption spectroscopy, and emission spectroscopy to demonstrate that the color arises from very small amounts of trivalent titanium substituting for aluminum in the kyanite structure. The titanium is usually in concentrations in the range of 20 to 50 parts per million and at that concentration has an absorption that dominates the absorption of other impurity elements which may be present at the fractional percent level. The intensity and band positions in the absorption spectrum further indicate that the single d-electron of the Ti^{+++} is delocalized and that the absorption process can best be explained by a narrow d-band model.

Kyanites from six localities were selected. Five of these were the characteristic blue kyanites and the sixth (Brazilian) was a transparent pale green crystal with a few blue patches. All specimens were analyzed for bulk trace element content by emission spectroscopic techniques. Polished sections were prepared for microprobe examination and oriented polished slices of the India and the Brazilian kyanites were prepared for the optical absorption measurements.

The electron microprobe was operated at 30 kev and 0.20 μa, with a 10-μ spot size and a 52° take-off angle. Calibrations were made by using pure metal standards and a specimen current of 0.005 μa. The x-ray count data were corrected for background but were not corrected for effects of absorption and so forth, so that reported concentrations may be in error by up to $\pm$ 20 percent of the measured amount. Optical absorption spectra were recorded in transmission on a Beckmann DK-2A spectrophotometer. A matched pair of Glan prisms were used to measure the polarized spectra. The emission spectrographic analyses were made by use of external standards. The analyses are semiquantitative, being good to about $\pm$ 50 percent of the amount present (*2*).

Table 1 summarizes the emission spectrographic and electron microprobe

Table 1. Semiquantitative emission spectrographic (Spec.) and electron microprobe (E.P.) analyses of kyanite. Results are in parts per million. ND, not detected. Sought but not detected: B, Cu, Ag, Zn, Co, Ni, Mo, Sn, Pb, Ge, In, Sb, Cd, Bi, Y, Yb, Sr, Ba.

Element	Chesterfield, Mass.		Litchfield, Conn.		Whitehorse, Pa.		Zillerthal, Tyrol		India (Placer)		Brazil (Green)	Brazil (Blue)
	Spec.	E.P.	Spec.	E.P.	Spec.	E.P.	Spec.	E.P.	Spec.	E.P.	E.P.	E.P.
Fe	1000	900	1000	1000	1500	1000	5000	5600	1500	800	9000	7000
Cr	50	150	150	20	50	70	ND	ND	150	100	ND	ND
V	200	100	200	90	200	100	200	100	100	200	60	60
Ti	60	20	80	270	100	1200	100	70	40	90	10	60
Mn	ND		ND		ND		ND		ND		100	100