

Quest for a nuclear georeactor

R.J. de Meijer*, E.R. van der Graaf, K.P. Jungmann

Kernfysisch Versneller Instituut, Rijksuniversiteit Groningen, Zernikelaan 25, 9747AA Groningen, The Netherlands

Abstract

Knowledge about the interior of our planet is mainly based on the interpretation of seismic data from earthquakes and nuclear explosions and of composition of meteorites. Additional observations have led to a wide range of hypotheses on the heat flow from the interior to the crust, the abundance of certain noble gases in gasses vented from volcanoes and the possibility of a nuclear georeactor at the centre of the Earth. This paper focuses on a proposal for an underground detector set-up to develop further antineutrinos as a tool to map the distribution of radiogenic heat sources, such as the natural radionuclides and the hypothetical nuclear georeactor.

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1. Introduction

We seldom realise that we have penetrated the Earth by only 12 km, a distance equivalent to the cruising altitude of airplanes. Consequently we know little about the interior of our planet, except from seismic information and study of the composition of meteorites. Current understanding starts from seismological investigations by, e.g. Oldham (1906) and Gutenberg (1914) that lead to the hypothesis that up to half the radius of the Earth is occupied by a fluid core. From the interpretations of earthquakes Lehmann (1936) recognised a small, solid inner core. The fact, that meteorites consist of nickel-rich ferrous iron, lead to the assumption that the fluid core of the Earth consists of molten nickel-iron. Density information stems from the work of Birch (Birch, 1952) who hypothesised from seismological models and knowledge on high-pressure equations of state that the outer core was composed of a liquid iron alloy and an inner solid core of crystalline iron. The melting temperature of the alloy at the respective pressure defines the boundary. Estimates for this temperature, at the pressure of 330 Gpa, range between 5000 and 6000 K. Fig. 1 presents the principal divisions and physical states of the Earth's interior. The absence of

shear velocity V_s of earthquake waves is the basis for a fluid core. The density curve shows, in addition to the major changes at the principal sections, steps in the upper mantle at about 420 and 660 km depth.

Heat loss from the core depends on the radial temperature gradient at the boundary of the core and the overlying mantle and is strongly related to mantle dynamics. There exists a large uncertainty in the temperature drop ΔT , due to the temperature at the inner-core boundary: $\Delta T = 1000\text{--}1800\text{ K}$ (Anderson, 2002) over a layer of a few hundred kilometres (Lay et al., 1998). Including the thermal conductivity of the mantle silicates yields a heat flow of $0.04\text{--}0.08\text{ W/m}^2$, leading to a total heat flow from the core of $6\text{--}12\text{ TW}$ (Buffett, 2003); a considerable part of the estimated total heat flow from the Earth of $40\text{--}50\text{ TW}$. The total heat flow at the core-mantle boundary raises vital questions about the thermal evolution of the core and its heat sources in relation to power required to maintain the magnetic field. Radiogenic elements like ^{40}K are thought to play an essential role (Rama Murthy et al., 2003). In his paper Buffett concludes that “the thermal state of the core remains unclear and that better knowledge of the partitioning of all radiogenic elements between various reservoirs in the planet will help to reduce some ambiguity”.

Another ambiguity concerns on the chemical composition of the various compartments or reservoirs and

*Corresponding author. fax: +31-50-3634003.

E-mail address: demeijer@kvi.nl (R.J. de Meijer).

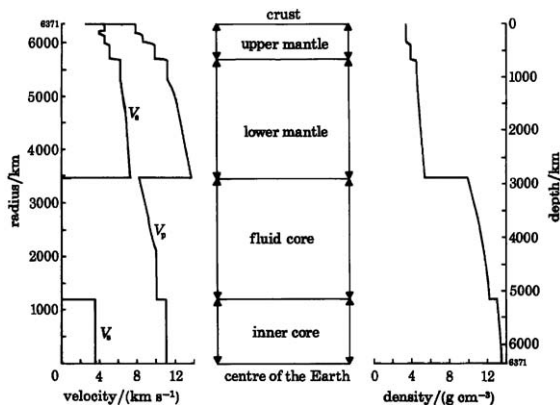


Fig. 1. Schematic representation of the principal partitions and physical states of the Earth's interior. The compressional and shear velocities of earthquake waves, presented in the right panel, are indicated by V_p and V_s , respectively. In the right panel the density as function of depth is presented. (Figure taken from Herndon, 1980.)

especially the core. In general one assumes that there is a liquid Fe–Ni alloy core, surrounded by a lower and upper mantle and covered by a crust. The bulk composition of the Earth is usually assumed to be the same as that of chondritic meteorites. Within this assumption subsequent hypotheses are made to account for observations at the Earth's surface. An intriguing issue is the presence of helium in our atmosphere and in particular its isotope ^3He . Whereas ^4He is continuously produced by alpha decay, the only way to obtain ^3He is either as a primordial relict (e.g. Seta et al., 2001) or by decay of tritium. For the primordial relict theory the assumption has to be made that the mantle contains a degassed and a deeper-lying, less degassed reservoir. The former shows up at the mid-ocean ridge basalts, the latter in mantle-plume basalts. Mantle plumes with extreme high $^3\text{He}/^4\text{He}$ ratios are found at some oceanic islands such as Iceland, Hawaii, Samoa and the Galapagos (Kurtz and Geist, 1999). One assumption commonly made in interpreting noble gas data from mantle plumes is that the source of mantle plumes is relatively non-degassed lower mantle material. Under this assumption, high $^3\text{He}/^4\text{He}$ ratios indicate plume-like upwelling, since the deep Earth is believed to be a source of primordial ^3He with a relatively low time-integrated (U+Th)/He ratio (Georgen et al., 2003). In oceanic islands not only are high $^3\text{He}/^4\text{He}$ ratios found but also normal mid-oceanic island values. This is explained by assuming mixed reservoirs (Stuart et al., 2003).

Recently Bercovici and Karato (2003) proposed a filtering of the mantle at the 410 km density discontinuity (see Fig. 1). They propose that the ascending mantle rises out of a transition zone, between the 410 and 660 km discontinuities, into the upper mantle above

410 km. The material undergoes dehydration-induced partial melting which filters out incompatible elements, including He and other noble gases. They propose that this filter model can explain geochemical observations without the need for isolated mantle reservoirs. This model could bridge the gap between geochemists supporting a two-layer model at a boundary of 660 km and seismologists, supporting a whole-mantle model of circulation (Hofmann, 2003).

2. The nuclear georeactor

A possible explanation for some of the above questions lies in the hypothesis of an 8 km diameter, nuclear georeactor at the centre of the Earth. This hypothesis originates from the work of Herndon (1992) in applying Fermi's nuclear reactor theory to demonstrate the feasibility of planetary scale nuclear fission reactors. Such reactors could be the energy source of the giant outer planets, three of which radiate about twice the energy they receive from the Sun. Subsequently Herndon developed the feasibility of such a reactor at the centre of the Earth as a contributive source to geodynamic processes like plate movements (Herndon, 1993, 1994, 1996). Such a reactor could have started in the same way as the natural reactors at Gabon, but is so large that it breeds its own ^{235}U and should have a power production of 3–10 TW. In it tritium is produced via ternary fission. Calculations at Oak Ridge National Laboratory (Hollenbach and Herndon, 2001) show that a planetary-scale nuclear reactor can operate over the lifetime of the Earth as a breeder reactor and can produce substantial tritium (decaying to ^3He) to explain the high $^3\text{He}/^4\text{He}$ ratios observed in oceanic basalts and fumes of volcanoes at Iceland and Hawaii. Seifritz (2003) shows that the operation of such a breeder reactor is consistent with our knowledge on breeder reactors and corresponds to a stable state.

The possibility of a nuclear georeactor is linked to the state of oxidation in the deep interior of the Earth. Herndon made convincing arguments for a state of oxidation like an enstatite chondrite, different from the more oxidised, ordinary chondrites considered by Birch. As a consequence of the highly reduced state some so-called lithophile elements including some Si, Mg, Ca, U and possibly Th occur in part of the core. These elements, tending to be incompatible in an iron alloy, are expected to precipitate at relative high temperatures. Due to their density MgS and CaS will float to the core-mantle boundary, whereas uranium sulphide (US) and nickel silicide will sink to the Earth's centre.

At pressures that prevail in the core, U and Th, being high-temperature precipitates and the densest substances would tend to concentrate in the Earth core by the action of gravity. In that process it will ultimately form a

fissionable, critical mass. Fission produces much less dense fission products (about half as dense) that tend to separate from the more dense actinides. In this way a critical reactor condition can maintain.

According to Herndon (2003) and Hollenbach and Herndon (2001) the frequent, but irregular variability in intensity and direction of the Earth's magnetic field may be understandable from such a fission reactor. The production of fission fragments counteracts the operation of the reactor and if the rate of production exceeds the rate of removal by gravitational diffusion, the output of the reactor will decrease and may even shut down, leading to a diminution and ultimately the disappearance of the Earth's magnetic field. As fission products diffuse out of the reactor region and actinides diffuse inwards, the reactor restarts and the geomagnetic field re-establishes itself, either in the same or in the reverse direction. The coupling between the georeactor and the geomagnetic field cannot be direct (Hoyng, 2003) and has to proceed through changing heat-flow patterns in the core and ultimately in the mantle.

Although the georeactor hypothesis seems to be able, in principle, to explain phenomena such as elevated $^3\text{He}/^4\text{He}$ ratios and reversal of the geomagnetic field questions remain about the specific mechanisms involved. It is assumed that fission products are separated from the fuel by diffusion or by buoyancy effects. For both processes it still has to be shown if they are effective enough. First estimates for diffusion, based on an extrapolation (using Arrhenius law) to core temperatures of diffusion coefficients and activation energies for helium in apatite (Dunai, 2000) indicate that transport over a distance of 1 km in a solid metal inner core will take 1 million years. This is probably at least an order of magnitude too slow to explain geomagnetic reversals on average every 200 000 years by fission products drifting outwards and so cleaning up the core for a reactor restart. Detailed calculations are needed in order to estimate transport velocities due to buoyancy but these velocities are expected to be insignificant because of the micro-gravity conditions in the inner part of the core (Seifritz, 2003). Also it is difficult to imagine the large outward flux of ^3He , needed to explain elevated $^3\text{He}/^4\text{He}$ ratios, produced inside the georeactor because an intact solid inner core will form an almost impenetrable barrier for transport. Moreover the heat produced by the georeactor has to be removed through the solid inner core and normal heat conductivities for solids are not large enough to prevent the reactor from heating up to very high temperatures.

All these estimates are based on extrapolating transport coefficients at ambient conditions to the high temperatures and pressures inside the core. Moreover these estimates assume a uniform metallic core being one solid piece. A more granular structure of the inner core with a structure of "pores" or fissures will allow a larger

and faster transport of gaseous substances and heat. In such a case it is hard to imagine that the core will be uniform and likely preferential pathways may exist, which act as chimneys and may cause a non-uniform heating of the inner–outer core boundary.

3. Antineutrinos as a tool to probe the Earth's interior

One of the few methods to investigate the distribution of natural radionuclides in various reservoirs of the Earth and/or the existence of a nuclear georeactor are antineutrinos produced in β -decay and/or fission, respectively. Fortunately decay and fission processes can be distinguished by the energy of the antineutrinos; 2–3 MeV for decay and up to 10 MeV for fission. To map the U–Th distribution and to localise a nuclear georeactor directional information is required in antineutrino detection.

The science and technology of detecting antineutrinos, $\bar{\nu}_e$, is well established. In common with many experiments we propose to use the detection reaction based on inverse β -decay: $\bar{\nu}_e + p \rightarrow e^+ + n$. The visible energy of the positron signal directly provides the $\bar{\nu}_e$ energy $E(\text{MeV}) = E(\bar{\nu}_e) - 1.8 + 1.022 = E(\bar{\nu}_e) - 0.78$. The signal can be tagged by the signal produced after several tens of microseconds by thermalised neutrons captured by hydrogen in the organic liquid scintillator. The delayed coincidences suppress background enormously and the chance coincidence rate in a kiloton scintillator mass detector such as installed at Kamioka, Japan, can be limited to several events/year (Raghavan, 2002). This corresponds to a sensitivity limit of an antineutrino flux $\Phi(\bar{\nu}_e)_{\text{min}} \sim 10^4 \text{ cm}^{-2} \text{ s}^{-1}$.

Antineutrinos, $\bar{\nu}_e$, are produced in β -decay of members of the decay series of U and Th. The antineutrinos from the geo-reactor will have an identical energy spectrum to those produced in power reactors and they can reach the surface of the Earth essentially without any interaction. One practical method to detect antineutrinos is by the inverse β -decay: $\bar{\nu}_e + p \rightarrow e^+ + n$ with a threshold of 1.8 MeV. In the U series there are contributions from the β -decay of $^{234\text{m}}\text{Pa}$, ^{214}Bi with Q -values of 2.29 and 3.26 MeV, respectively and ^{228}Ac , ^{212}Bi and ^{208}Tl with $Q = 2.11, 2.25$ and 1.8 MeV, respectively. The detection of antineutrinos is favoured by the Coulomb fields of these high- Z nuclei, which enhances the energy distribution towards the high-energy side of their spectrum (Raghavan et al., 1998). The specific emission probabilities above threshold becoming 0.40 and 1.6 per decay for U and 1.6 for Th. The intensity of the U/Th antineutrinos depends on the distribution of these natural radionuclides relative to the position of observation. In the crust the concentrations of these radionuclides are more than an order of magnitude higher than in the upper mantle. The

thickness of the crust varies from about 5 km at the ocean floors to about 50 km under the Himalayas. The mantle is much thicker but the distribution of the radionuclides is unknown. Some ideas about the distribution depend on the assumed model. The strength of the signal at various sites on Earth will therefore be an indication of the distribution of these radionuclides in the compartments of the Earth, even if no directional information can be derived from the antineutrino detection. According to calculations by Raghavan et al. (1998), 40% of the signal will come from sources in the crust within about 450 km, 70% from within 1200 km and 90% from about 6000 km.

For reactors, either power reactors or a geo-reactor, the antineutrino spectrum follows from their mean fuel composition, the numbers of antineutrinos per fission event and their spectrum (see Achkar et al., 1996 and references therein). Also for these neutrinos the flux depends on the distance between power reactor and detector. The existing underground laboratories at Gran Sasso, Italy, and Kamioka, Japan, are both situated on the crust and, especially Kamioka, near power stations.

At any point near the surface a 3–10 TW georeactor would yield a flux $\Phi(\bar{\nu}_e)_{\text{geo}} \sim 1-3 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$, which is an order of magnitude larger than the estimated detector background of $\sim 10^4 \text{ cm}^{-2} \text{ s}^{-1}$. Thus the detection of antineutrinos from the core is a valid proposition provided the background is sufficiently low. The background arises primarily from operating commercial power reactors within several 1000 km and U, Th and K in the crust of the Earth, mainly located at the continents. Nominally a georeactor is spectrally nearly indistinguishable from power reactors, but the georeactor would provide a strongly directional signal. Geo U/Th signals cut off at a positron energy of about 2.5 MeV. Model calculations indicate that such measurements are feasible with an underground detector set-up, provided the background due to the geological formation and antineutrinos produced in nuclear power reactors is sufficiently low. This condition excludes observation in the existing underground laboratories such as Borexino at Gran Sasso, Italy, and Kamland at Kamioka, Japan and favours locations such as Hawaii, the Aleutian islands and the Antilles. Fig. 2 shows the positron energy spectrum for Hawaii and Kamioka (taken from Raghavan, 2002). It shows that the background at Kamioka is too large for proper detection. This was recently confirmed by measurements with the Kamland detector yielding 9 ± 6 geo-antineutrinos from an exposure of 1.4×10^{31} protons year (Fiorentini et al., 2003). In a low-background environment one would expect, from a 10 times larger fiducial volume, a signal of some 100 events per year in a detector following the basic design of the Kamland or Borexino experiments (see Fig. 3). Directional information could be extracted from the recoiling neutron in the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$,

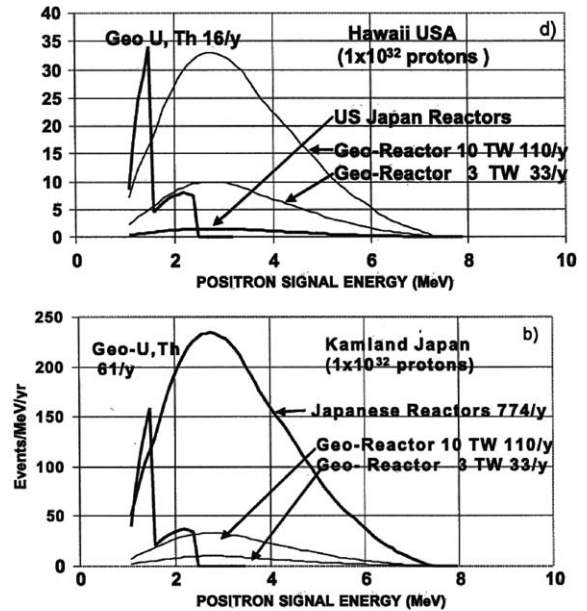


Fig. 2. Calculated positron energy spectrum for two locations: Hawaii and Kamioka. The two locations differ quite strongly in the flux from U/Th antineutrinos and from the antineutrinos produced in nuclear power stations. The situation of Hawaii will be quite similar to the one expected at Curaçao. (Figure taken from Raghavan, 2002).

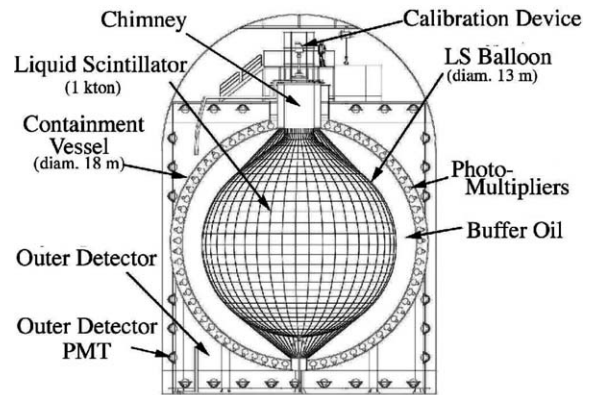


Fig. 3. Schematic presentation of the Kamland detector at Kamioka, Japan. The central part consists of a liquid scintillator sphere of several metres diameter, surrounded by a sphere of photo-multipliers. The outer detector contains the Cherenkov counters as active shielding against muons. (Figure taken from http://kamland.lbl.gov/FiguresPlots/kamland-figs_paper2002/xdetector5.jpg).

for which the recoil angle on average is $\langle \Phi_{\text{recoil}} \rangle = \arccos(2/(3A))$ with A the mass number of the scattering material. For the antineutrinos of geophysical interest

the neutron travels a distance of the order of a few cm between the locations of positron creation and neutron absorption, respectively. An antineutrino detector with such position resolution could follow the principle of the ANTARES experiment (see Fig. 4). This should add significant information about the location of the main antineutrino source.

4. Proposed underground antenna in Curaçao

We propose an underground antenna to investigate the internal state of the Earth to be built in Curaçao. The geology of Curaçao, as studied by Klaver (1987)

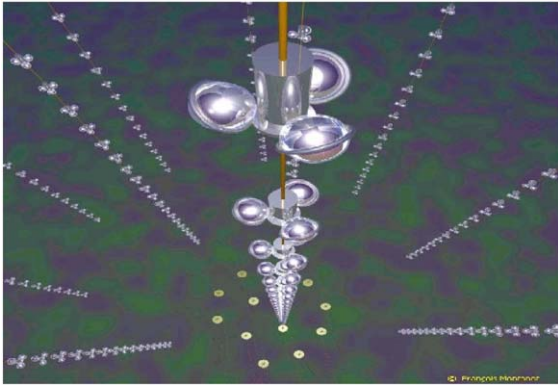


Fig. 4. Artistic view of the detectors of the ANTARES experiment. Strings of phototubes are immersed in the active detector volume. This concept allows also sufficient position resolution for antineutrinos in a large scintillator, underground detector by determining the recoil direction of neutrons in the inverse β -decay process. (Figure taken from <http://antares.in2p3.fr/Gallery/index.html>).

indicates that it is a mantle plume originating from the boundary of the core and the mantle, some 80 million years ago. Sample analysis (Klaver, 1987) indicates that indeed the Curaçao basalt is more than an order of magnitude lower in K, Th and U compared to sands in, e.g. The Netherlands. Parts of the island of Curaçao, represent the magma after 5 km of material has been eroded.

The proposal foresees in a step by step approach, starting from re-examination of surface rock formations, drilling for deeper material and finally building an underground detector array. Curaçao is more than 1000 km away from the Florida power reactors and from the mountain ranges of the Andes (see Fig. 5). It provides therefore not only a very low background of natural radionuclides but, since it is surrounded by a considerable mass of ocean water, the antineutrino flux from sources in the earth's crust and power reactors will be strongly reduced. That means that the laboratory will be especially sensitive to antineutrino sources from the mantle and a possible geo-reactor. We expect that the calculation for Hawaii will be more or less indicative for Curaçao.

An underground detector array is made by drilling a vertical shaft to a depth of several kilometres. With modern drilling technology a set of branches pointing in various directions can be drilled from the end point of the vertical drill hole. Each branch points into a certain direction of the interior of the Earth and may have a length of several hundred metres. The branches will be filled up with a chain of tubular detectors. Directional sensitivity is obtained from the requirement of delayed coincidence between positron and neutron signals and can be optimised by choice of the detector diameter with respect to the distance the neutron will travel before thermalisation and capture.

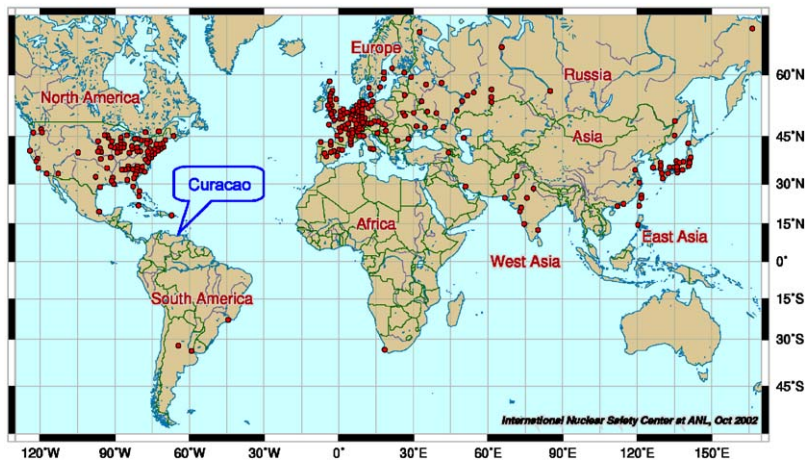


Fig. 5. World map with nuclear power stations. The stations at Cuba and Puerto Rico, are not operational. (Figure taken from the International Nuclear Safety Center at Argonne National Laboratory <http://www.insc.anl.gov>).

The project will have a number of technological challenges. One of them is drilling into basalt. The other is the development of low-energy dissipating electronics. Despite Curaçao being a plume sticking out of the ocean floor and cooled by ocean water at a depth of about 1 km, high temperatures are expected. In the underground detector set-up we expect a high density of electronic devices. Low-energy dissipating electronics will be required; their development is of direct interest to the telecommunication industry.

It should be noted that the geological formation of the island of Curaçao would allow calibration of an antineutrino detector with the aid of nuclear power driven vessels, which could be positioned at various locations and at variable distances from the detector.

Such a project exceeds the capacity of a single institution because of its inter- and intradisciplinary character; geophysics, plasma physics, nuclear physics and high-energy physics, plus several branches of geosciences and technology are embraced. As initial steps the re-examination of the surface rock formation and a deep drill are foreseen. This includes the location of the centre of the magma plume. Already in each of the stages valuable information is expected from the analysis of the cores, such as $^3\text{He}/^4\text{He}$ and $^{10}\text{Be}/^9\text{Be}$ ratios as well as ratios of stable isotopes and other radionuclides like ^{26}Al . These results will already help to test the physics and geochemistry aspects of the various models. In the meantime the design of the antineutrino detector tuned to the detection of antineutrinos from the natural radioactivity and the hypothetical geo-reactor will take place.

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References

- Achkar, B., et al., 1996. Comparison of anti-neutrino reactor spectrum models with Bugey 3 measurements. *Phys. Lett. B* 374, 243–248.
- Anderson, O.L., 2002. The power balance at the core-mantle boundary. *Phys. Earth Planet. Int.* 131, 1–17.
- Bercovici, D., Karato, S.I., 2003. Whole-mantle convection and the transition-zone water filter. *Nature* 425, 39–44.
- Birch, F., 1952. Elasticity and constitution of the earth's interior. *J. Geophys. Res.* 66, 227–286.
- Buffett, B.A., 2003. The thermal state of Earth's core. *Science* 299, 1675–1677.
- Dunai, T.J., 2000. Helium diffusion in apatite revisited: is the high temperature diffusion mechanism an artefact or a reality? *J. Conf. Abstracts* 52, 364.
- Fiorentini, G., Mantovani, F., Ricci, B., 2003. Neutrinos and energetics of the Earth. *Phys. Lett. B* 577, 139–146.
- Georgen, J.E., Kurz, M.D., Dick, H.J.B., Lin, J., 2003. Low $^3\text{He}/^4\text{He}$ ratios in basalt glasses from the western Southwest Indian Ridge (10° – 24°E). *Earth and Planetary Science Letters* 206, 509–528.
- Gutenberg, B., 1914. Über Erdbebenwellen VIIA. *Göttinger Nachr.* 166, 218.
- Herndon, J.M., 1980. The chemical composition of the interior of the earth. *Proc. Roy. Soc. London A* 372, 149–154.
- Herndon, J.M., 1992. Nuclear fission reactors as energy sources for the giant outer planets. *Naturwissenschaften* 79, 7–14.
- Herndon, J.M., 1993. Feasibility of a nuclear fission reactor at the center of the earth as the energy source for the geomagnetic field. *J. Geomagn. Geoelectr.* 45, 423–437.
- Herndon, J.M., 1994. Planetary and protostellar nuclear fission: implications for planetary change, stellar ignition and dark matter. *Proc. Roy. Soc. London A* 445, 453–461.
- Herndon, J.M., 1996. Substructure of the inner core of the Earth. *Proc. Natl. Acad. Sci. USA* 93, 646–648.
- Herndon, J.M., 2003. Nuclear georeactor origin of oceanic basalt $^3\text{He}/^4\text{He}$, evidence, and implications. *Proc. Natl. Acad. Sci. USA* 100, 3047–3050.
- Hofmann, A.W., 2003. Just add water. *Nature* 425, 24–25.
- Hollenbach, D.F., Herndon, J.M., 2001. Deep-earth reactor: nuclear fission, helium and the geomagnetic field. *Proc. Natl. Acad. Sci. USA* 98, 11085–11090.
- Hoyng, P., 2003. Private communication.
- Klaver, G.Th., 1987. The Curaçao lava formation: an ophiolitic analogue of the anomalous thick layer 2B of the mid-Cretaceous oceanic plateaus in the Western Pacific and Central Caribbean. *GUA Papers of Geology, Series 1, #27*, Ph.D. Thesis, University of Amsterdam.
- Kurtz, M.D., Geist, D., 1999. Dynamics of the galapagos hot spot from helium isotope geochemistry. *Geochim. Cosmochim. Acta* 63, 4139–4156.
- Lay, T., Williams, Q., Garnero, E., 1998. The core-mantle boundary layer and deep Earth dynamics. *Nature* 392, 461–468.
- Lehmann, I., 1936. P. *Publ. Bur. Centr. Seism. Internat. Serie A* 14, 87–115.
- Oldham, R.D., 1906. The constitution of the interior of the earth as revealed by earthquakes. *Quart. J. Geol. Soc. London* 62, 456–473.
- Raghavan, R.S., 2002. Detecting a nuclear fission reactor at the center of the Earth, Hep-ex/0208038.
- Raghavan, R.S., Schoenert, S., Enomoto, S., Shirai, J., Suckne, F., Suzuki, A., 1998. Measuring the global radioactivity in the earth by multidetector antineutrino spectroscopy. *Phys. Rev. Lett.* 80, 635–638.
- Rama Murthy, V., van Westrenen, W., Fei, Y., 2003. Experimental evidence that potassium is a substantial heat source in planetary cores. *Nature* 423, 163–165.
- Seifritz, W., 2003. Some comments on Herndon's nuclear georeactor. *Kerntechnik* 68, 193–196.
- Seta, A., Matsumoto, T., Matsuda, J., 2001. Current evolution of $^3\text{He}/^4\text{He}$ ratio in the Earth's mantle for the first 2Ga. *Earth and Planetary Science Letters* 188, 211–219.
- Stuart, F.M., Lass-Evans, S., Fitton J, G., Ellam, R.M., 2003. High $^3\text{He}/^4\text{He}$ ratios in piritic basalts from Baffin Island and the role of a mixed reservoir in mantle plumes. *Nature* 424, 57–59.