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ARCHAEOMAGNETISM

AIMS

Study of ancient geomagnetic field (direction and intensity) during archaeological periods of time.
Archaeomagnetic dating

J. Hus (2003)

This document is intended for those who want to take archaeomagnetic samples for geomagnetic field studies or archaeomagnetic dating and those who will become involved with archaeomagnetism. The thread of these loose notes is the procedure of archaeomagnetic sampling, measurement and data treatment followed by the archaeomagnetic team of the Centre de Physique du Globe in Belgium. The purpose is to inform and to share our experience gathered during several years of archaeomagnetic research. We stress on points that the collector of samples for archaeomagnetic research should keep in mind. This is a first draft, and our intention is to extend the contents of these notes, to add illustrations and to treat other aspects of archaeomagnetism so that it can be used as a document for training courses in archaeomagnetism. The list is far from exhaustive and other methods and procedures practised by other teams as well as comments are welcome.

Abbreviation

CPG = Centre de Physique du Globe

FIELDWORK

ARCHAEOMAGNETIC SAMPLING SHEME

Sampling strategy is the first crucial step to a successful archaeomagnetic study

Sampling scheme is hierarchical

Site

Samples

Specimens (option)

Site = spot reading of field (kiln, fireplace etc.)

Sample = basic collection unit (independently oriented*)
A sample is an **independent observation** of the **same** spot reading of the palaeomagnetic field. (* discussion possible)

Specimen = subsample that has appropriate dimensions and shape for measurement of natural remanent magnetisation (NRM) and treatment in demagnetisers and that fits eventually other measuring equipment's; is not necessarily independently oriented.

Sampling scheme depends on:

-aim of study (direction and/or intensity)
-accessibility of site, authorisation and restrictions imposed by site responsible
-statistical properties of magnetisation
-logistics and skill of collector or sampling labourer
-time allocated and meteorological conditions

Why many samples, many specimens?

Why many samples?

Different samples from a single site yield different directions because of:

-errors in sample orientation
-measurement errors
spatial variation of magnetisation direction and intensity within the site
-vagaries of the magnetisation process
-movements of site
-magnetic anisotropy and magnetic refraction
-presence of secondary magnetisation components such as viscous remanent magnetisation (VRM)
temporal variation of geomagnetic field and hence of magnetisation

Many samples are taken in order to average out variations in magnetisation direction from sample to sample, in particular to average out errors involved in the sampling process itself, and finally to allow an estimation of their statistical properties. In general the cooling time of the fired structure was short (estimated at hours, days, maximum weeks) and there is no need to average for field variations during cooling period (maximum variation of a few minutes of arc in direction and a few tens of Nanoteslas in intensity).
Many samples allow to determine **within-site or between-sample** scatter and hence **within-site** homogeneity of the natural remanent magnetisation (NRM). Many oriented samples (N) are taken also to improve the precision in orientation with square root of N.

Why many specimens?

- field samples may have dimensions that do not fit the remanence measurement equipment and auxiliary equipment's.
- magnetisation of samples may be inhomogeneous (not evenly distributed temperatures during heating, not evenly distributed remanence carriers)
- samples may be only partly heated
- samples may be partly weathered

Large field samples can be cut into several sub-samples or specimens, keeping the original orientation marks.
Specimens are taken to determine **within-sample or between-specimen** scatter and permits control of homogeneity of NRM and experimental procedures.

Large samples may increase homogeneity but the risk to include non or partially fired materials increases.

SAMPLING

Who?
What?
How?
How many samples?

Who?

- Archaeomagnetic team
- Others (if trained)

What?

- Baked materials (clays)
- Sediments
- Volcanic rocks

In the following we will limit ourselves to baked materials (clays).

Baked materials

The most suitable materials are baked clay, baked loam or baked soils, if possible homogeneous and free of foreign materials (free of pieces of rocks, organic material, charcoal or cultural inclusions such as shards, pieces of iron, ashes, slag's and trash). The material should be sufficiently baked, at least at about 400°C, so that a substantial thermoremanent magnetisation (TRM) is present. Stones, baked *in situ*, (limestone, sandstone, silex etc.) may yield good results in some cases. In the field, the quality of the baked material is often judged after its degree of burning, magnetic mineral content, texture, homogeneity and hardness. It is difficult to determine the degree of burning as well as the magnetic mineral content in the field. When fired in an oxidising atmosphere (air), magnetic minerals such as iron-oxyhydroxides in soils turn orange, pink or brown-red to red, due to the formation of iron-oxides especially hematite-like minerals and maghaemite. However, one should not overlook the high staining and pigmenting power of very fine-grained iron oxides due to an increase of the surface to volume ratio with a decrease of the dimensions of the grains. Clays with high calcium-carbonate content turn yellow during heating. When heated in a reducing atmosphere, magnetite-like minerals will form and the materials will become grey to black coloured. These should be distinguished from charcoal-stained materials. Materials containing clay and/or silt will become hard during baking; very sandy materials on the other hand will remain crumble and friable.

Baked and burnt materials for magnetic direction (and intensity) Determinations

In Situ

Fireplaces for heating and/or preparing food

- hearths (isolated or in settlements or buildings)
- campfires
- domestic heating systems (hypocauste, praefurnium, hearths)
- domestic cooking ovens

Kilns and fireplaces

To produce wares
- pottery
- glass
- lamps
- tobacco pipes

To produce construction materials
- roof and floor tiles and imbrices
- bricks
- lime

Metal melting and working sites
- brass, bronze, iron, silver, gold
- forgery ovens
- moulds (ex. bell)
- roasting areas

Fuels and chemicals
- charcoal
- chemical products

Food and beverages
- salt
- bread
- beer
- roasting areas (malt)
- drying and smoking areas (meat, fish)
- burnt walls of seed and cereal storage pits

Cultural
- statues
- music instruments

Cultic, worship
- cremation

- votive statues

Burnt places

- accidental (lightning, spontaneous combustion)
- intentional (war, criminal)

Displaced materials for inclination

- bricks, tiles (roof and floor), pottery, statues etc.

Displaced materials for intensity

- bricks, tiles, pottery, statues, cooking stones, burnt plaster and daub, displaced pieces of kilns and fireplaces etc.

How?

Type of sampling

Random sampling

Purposive sampling

Sampling procedure

Can not be generalised. Some sampling methods are time consuming or need heavy logistics. Choice of material is often restricted and materials are often fragile and friable.

Block samples

Are cut in any convenient direction with cutting tools (by knife when soft or sawed when hard with the aid of a portable sawing tool).

Cores

When very hard, burnt materials are present, these can be cored with a portable gasoline or electric powered corer.

Orientation procedure

Block samples

Capping and realising horizontal surface:
In CPG, gypsum and an aluminium or plexiglas plate with cross spirit levels is used to realise horizontal plane.
Azimuth determination of horizontal reference line:
In CPG, by measuring zenithal distance of sun with theodolite or determination of local hour angle with sun compass.

Cores

Aluminium or brass tube with slot, equipped with clinometer and solar compass.

Accuracy of orientation

Better than 1° in direction

Determination of dip

1. Clinometer
2. Plate with cross-levels or bull's eye level

Spirit levels accurate to better than 30' of arc should be used.

Determination of geographic azimuth

1. Magnetic compass

Must be adjusted to local magnetic declination, use:

- topographic map
- national magnetic maps
- international reference field, IGRF or DGRF
- if site position is known on map one can sight a remarkable point such as a building, tower, church etc. recognisable on the map and hence with known geographic azimuth
- or do single reading with solar compass.

Disadvantage: geomagnetic field near the site may be disturbed and strongly magnetised baked structures may cause compass deviations. In CPG we use magnetic compass only to avoid large orientation errors and to control for lightning impacts.

2. Solar compass or local hour angle method

Tool: vertical needle (wire) or gnomon
To be determined:
Date and local time or UT (GMT)
Latitude and longitude of site (from map or GPS)
Declination of sun (from Astronomical or Nautical Almanac)
Main uncertainty: reading of shadow angle, reading of angle between shadow line and +X sample (measurement) axis.

3. Theodolite or zenithal distance of sun

Tool: theodolite (can measure angles in local horizontal and vertical plane)
When shooting the sun use sunglasses! In CPG we use Wild T2 with prism designed by Prof. Roeloffs and manufactured by Wild.
To be determined:
Date and local time or UT (GMT)

Height of sun (vertical circle) and bearing of sun (horizontal circle)
Latitude of site (map or GPS)
Declination of sun (almanac)
Main uncertainty: reading of angle between reference line and +X.

How many samples ?

Even when the geomagnetic field was not disturbed and homogeneous, and perfectly recorded by the baked material, errors inherent to orientation and measurement cannot be completely avoided. The application of statistics in order to calculate the error of the average magnetisation direction requires at least 7 to 8 independently oriented samples. We remind that statistics may only be applied in case of a large number of observations. Only a little will be gained in precision when increasing the number of specimens beyond 8. However, in reality, the record is never perfect due to inhomogeneities, for instance because of anisotropy and refraction, and hence a large number of specimens well distributed in the fired structure is to be preferred

FIELDWORK ARCHAEOMAGNETIC SAMPLING

Description of site
Drawing of site
Sampling

1. Description of site

1.1 General

Date: d,m,y
Place name: country, locality name and province or state, name of excavation site
Co-ordinates site: longitude and latitude (from map or determined with GPS)
Name and address of site responsible: tel., fax, e-mail address

1.2 Site

Archaeological code of site
Archaeomagnetic code of site
Archaeological code of site area or excavation area or trench
Archaeological guess age of site
Nature of site
Baked materials present in site
Traces of repairing or rebuilding of site
Form of site
Dimensions of site
Context: -isolated
-inside building
-inside or outside settlement
Depth: depth below top surface
Parts accessible: site is completely accessible or only partly
Parts preserved: also total height preserved
Traces of disturbances:
-mechanical: tectonic, subsidence, compaction, disturbance due to excavation, cracks
-bioturbation: fauna: burrows, traces of rodents, worms
flora: traces of roots
-cryoturbation: fissures, exfoliation

2. **Drawing of site**

Ask copy of site drawings to archaeologist in charge.
If not available: make schematic drawing of site in plan and of vertical cut (scale: 1/10 or 1/20) with indication of:

- -position of samples
- -direction of magnetic north
- -depth below surface
- -height of structure

3. **Sampling**

3.1 **Project**

Determine parts of site that are indicated to be sampled

- -well baked parts
- -non-perturbed parts
- -thickness of burnt parts
- -hard, soft
- -small or big samples

Consultation with archaeologist

- -parts that may be sampled, parts that must be preserved
- -drawings that must still be made or photographs or other records that must still be taken by archaeologist.

3.2 **Preparation of site parts to be sampled**

The parts to be sampled are cleaned thoroughly, all foreign materials (dust) and all materials that have been displaced are removed by brush or knife. In some cases the material to be sampled is very fragile so that consolidation with gypsum or lacquer is necessarily before cutting. Use well-sorted, sieved, quick-hardening, non-magnetic gypsum (plaster) that is normally used for moulding purposes. In CPG we use BGB, MOLDA 3 Normal gypsum available in most European countries. Use very soft (liquid) gypsum for first consolidation (layer less than 1mm thick). The part to be taken is cut all around by knife, hand saw or even electric circular saw when material is very hard, but leave the bottom part of the stump (pedestal) attached. Non-baked materials are cut away as much as possible. When the pedestal is not very thick, leave some unbaked material that will be removed afterwards in the laboratory, but enough, so that it is convenient to put the plexiglas plate with cross spirit levels on its upper part. Cover the stump with gypsum (layer >1mm thick). Prepare liquid gypsum by filling a rubber bowl with water, add gypsum (about one part water and 1.5 part gypsum) and stir with non-magnetic tools (copper or brass trowel, wood or spatula). When mixed, the gypsum should have the consistency of a very soft cream that can be poured easily on the sample. Put some grease or oil (we prefer vaseline) on all the sides of the plexiglas plate equipped with cross spirit levels that will be used to realise a horizontal surface. Press the plexiglas plate in the gypsum when the latter is still soft and adjust until a horizontal surface is realised. After a few minutes the gypsum has become solid and the levelling plate can be removed.

3.3 Orientation procedure

Install and level theodolite on tripod a few meters away from the site (not too far and not too close), so that all the samples to be taken can be sighted and that at a certain moment during the sampling period also the sun can be sighted from the theodolite. If sun is not visible during the sampling period, make reading of a remarkable, fixed point (building, church, etc.) and leave mark (nail) indicating theodolite station before removing it. Inform responsible of site that the mark (nail) should not be removed unless the height of the sun has been measured. The azimuth of the line from the theodolite to the fixed point can be determined by shooting the sun at any time, even several years afterwards.

Relationship archaeomagnetic team and archaeologists

It is important to develop a good relationship between the archaeomagnetist and archaeologist. The final output and success of an archaeomagnetic analysis and interpretation depends on the quality of communication and mutual understanding between both. In general, the archaeologist expects an archaeomagnetic date from the archaeomagnetist, while the latter is more interested in the properties of the ancient geomagnetic field and consequently prefers to examine fired structures that have been dated independently. **The fundamental datum or result of an archaeomagnetic analysis is the field direction and intensity, corresponding to the characteristic remanent magnetisation of the examined, fired structure.** An achaeomagnetic date, obtained after comparison with standard or master curves of the secular variation, under certain assumptions, is a temporal interpretation that may change as master curves are refined or made more regionally specific. The determined field direction however will not change. Often, an archaeomagnetic analysis yields more than one possible date and only independent information about the chronological context of the site, given by the archaeologist, allows us to choose a preferred interpretation.

Archaeomagnetic data can be exploited optimally when the archaeologist provides archaeological context information.

Archaeomagnetic sampling like archaeologic excavation is a destructive activity. Archaeologists become often much attached to a particular unearthed kiln and don't want to see it destroyed immediately; they may have in mind its conservation or preservation *in situ* or in a museum.

Archaeomagnetists are very sensitive concerning the cleanliness of the excavation site. Hence, when sampling is finished, clean up the site in consultation with the site responsible and if gypsum was used see that no traces are left, as they are responsible for unaesthetic white spots on photographs taken afterwards.

LABORATORY WORK

Preparation of specimens
Determination angle between reference direction and sample axis +X
Measurement of NRM
Stability tests
Cleaning, ChRM

1. Preparation of specimens

Cutting of samples
Samples are in some cases too large to fit the remanence measuring equipments and must be trimmed to suitable dimensions. Samples are also cut into specimens to study the within-sample scatter. This is in general done with the aid of a diamond-impregnated disc or wire saw.

Moulding of specimens
Some measuring equipments require well-shaped samples (cubes or cylinders). Oriented pieces of baked clay can be moulded into a convenient shape with plastics, epoxy or gypsum. Use a cold setting plastic or epoxy. In case gypsum is used, the mould and fixing screws should be non-magnetic. The mould can be made of nonmagnetic stainless steel, brass, aluminium or plexiglas. The mould should be treated with a demoulding agent: oil, grease or vaseline.

2. Determination angle between reference direction and +X sample or measuring axis

A graduated protractor is used to measure angle between reference direction and +X or cube edge (precision 1°, reading 0.2°)

3. Measurement of NRM

- Spinner magnetometer
- Fluxgate magnetometer
- Cryogenic magnetometer

4. Stability tests

- Field tests
(Fold test, baked contact test?)
- Viscosity test
(Thellier storage test)
- Alternating field (AF) demagnetisation
- Thermal demagnetisation
- Chemical demagnetisation

5. Cleaning, ChRM

- AF and thermal demagnetisation
Single step or multiple steps
- **Combination of methods, successively or simultaneously**
- Principal component analysis (PCA)
Line through measuring points, origin as measuring point, line anchored to origin?

ORIGIN OF ERRORS AND RELIABILITY OF FIELD RECORDS IN BURNED AND BAKED SITES

Factors responsible for deviations between field record and inducing field can be classified according to their origin:

-internal or external

-natural or man-made

1. Internal origin

- **magnetic refraction**
  - increases with magnetic susceptibility and remanence
  - depends on geometry
- **anisotropy**
  - magnetostatic (form)
  - magnetocrystalline
- **demagnetising fields**
- **differential contractions during heating and cooling**
- **heterogeneity of baked materials**
- **presence of foreign materials in baked clay**
  - shards, scoria, stones, pieces of metal, charcoal
  - roots, shells etc.

2. External origin

- **movements**
  - kiln fall-in: displacements towards the interior due to loading or pressure of surrounding earth.
  - kiln fall-out: displacements towards exterior due to pressure of filling material
  - bioturbation, cryoturbation and other climate-related disturbances (wetting-drying cycles and cooling-heating cycles, drying cracks, frost cracks).
  - earthquake- and tectonically- induced movements (subsidence, uplift etc.)
  - loading due to overburden.
- **local and regional magnetic anomalies, exposure to strong electromagnetic fields**
  - natural: geomagnetic field anomalies
  - man-made: presence of ferro-metals during heating, man-made magnetic disturbances due to tools and constructions in immediate surroundings of baked structure
- **weathering, chemical changes**
- **effects on remanence of pressure, vibrations in situ, during sampling and sample preparation**

- natural (seismic tremors)
- induced during sampling and sample preparation in lab (drilling induced remanence)

- **incomplete removal of secondary magnetisations**
  - viscous remanence
  - crystalline or chemical remanence (weathering)
  - partial thermoremanent magnetisation (reheating)
  - lightning induced remanent magnetisations (IRM or ARM)
  - depositional remanence due to (re)alignment of particles inside porous baked materials
- **incomplete removal of unbaked materials**

3. <u>**Orientation errors**</u>

- **dip**
- **azimuth**

4. <u>**Measurement errors**</u>

DATA TREATMENT

Statistical methods

Determination of site average magnetisation direction, its confidence, precision and accuracy

Specimen average
Sample average

Sample magnetisation directions differ from one sample to the other due to errors. We need a way to calculate the average direction and its confidence (and error) and to estimate the scatter or dispersion of individual directions around the mean direction.

Errors

-Temporal variations in the variates being measured (in general negligible in archaeomagnetism).
-Spatial variation in the variates being measured.
-Choice of co-ordinate system (D more difficult to determine in high latitudes, I more difficult in low latitudes).

Sampling is hierarchical and average magnetisation directions are calculated at different levels.

Magnetisation directions of specimens are combined to yield sample mean.
Sample means are combined to yield site mean.

Fisher distribution

Two methods to obtain average magnetisation direction
Parametric methods: based on a statistic→→ average, errors, statistical tests are possible

Non-parametric methods: no statistic needed→→ errors not known, statistical tests not possible.

To describe the spatial distribution of magnetisation directions two variables (D,I) are needed→→ bivariate distribution.

The statistical distribution commonly used is a bivariate normal distribution, which describes two orthogonal normally distributed variables. Unit weight is given to each individual direction regardless its magnitude. The ends of the vectors are represented as points on the surface of a unit sphere.

The Fisher distribution is a bivariate normal distribution when the concentration parameter κ is sufficiently large ($\kappa > 4$).

$$\text{The density of points is} \propto e^{\kappa \,\mathrm{Cos}(\psi)}$$

κ = concentration or shape parameter of the total population
The higher κ, the tighter the directions are clustered about the mean direction.
ψ = angle between an individual magnetisation direction and true mean direction

The density $P_{\delta A}$ of points on the unit sphere is given by:

$$P_{\delta A} = \kappa/4\pi \sinh(\kappa).e^{\kappa \,\mathrm{Cos}(\psi)}$$

Where the constant factor $\kappa/4\pi\sinh(\kappa)$ is chosen such that the density is equal to unity when integrated over the whole unit sphere. The mean direction corresponds to ψ=0, where the density is a maximum.
The probability for an observation falling in a small element δA at an angular distance ψ from the true mean direction is given by:

$$P_{\delta A} \,.\, \delta A = \kappa/4\pi \sinh(\kappa).e^{\kappa \,\mathrm{Cos}(\psi)}.\delta A$$

The element of area is $\sin(\psi).d\psi.d\phi$, where ϕ is the azimuth (or longitude) of the observation about the mean direction and ψ is the co-inclination (or co-latitude).

Goodness-of-fit test of Fisher's model. Is the data set Fisher distributed?

The Fisher distribution suggests that the declinations are randomly distributed about the mean and that the inclinations are exponentially distributed. There are several methods (graphical and formal) to test if the data are Fisher distributed and how well they fit a Fisher distribution.

Quantile-Quantile (Q-Q) test
Chi-square test (Watson and Irving, 1957)
Discordant observations or outliers?

Graphical procedures

-co-latitude plot
-longitude plot
-two-variable plot

Formal testing procedures

-co-latitude test
-longitude test
-two-variable test

Concentration or shape parameters

-k

The true concentration parameter κ is unknown and can only be estimated.

Standard Fisher estimate k for κ (Fisher, 1953), when the true mean is unknown, is given by:

$$\kappa \cong k = (N-1)/(N-\mathbf{R})$$

Where **R** is the modulus of the vector sum of all the unit vectors.
Maximum likelihood estimate of κ (McFadden, 1980): is a solution of coth (k^)-1/ k^ and when **R**/N is nearly 1, given by: $\kappa \cong k\hat{} = N/(N-\mathbf{R})$
Unbiased estimate of κ (McFadden, 1980): $\kappa \cong k = (N-2)/(N-\mathbf{R})$

Precision parameter

The mean is distributed with a precision k**R**.

Reliability of mean direction or confidence

$$\alpha_{1-P} = \cos^{-1}\{1-(N-\mathbf{R})/\mathbf{R}[(1/P)^{1/N-1}-1]\}$$

In archaeomagnetism 5% confidence (P=0.05) or 95% probability is used. As there is 95% probability that the true mean direction lies within a cone with half opening angle α_{95} around the observed mean direction (cone of confidence), the smaller α_{95} the more reliable is the observed mean direction. If $k \geq 7$ then: $\alpha_{95} \cong 140/(k\mathbf{R})^{1/2}$. The angular standard error of the mean α_{63} is given approximately by: $\alpha_{63} \cong 81/(k\mathbf{R})^{1/2}$.

Scatter estimate

For a given population of unit vectors distributed according to a Fisher distribution, a certain number will lie within a specific distance from the true mean.
The angular radius of the circle containing 63% of the observations is $\theta_{63} = 81k^{-1/2}$ that is called Wilson's estimated angular standard deviation (also called angular dispersion).
The angular radius of the circle containing 95% of the observations is $\theta_{95} = 140k^{-1/2}$.

The precision increases with k and **R** and hence in general also with N The scatter is independent of N and decreases with an increase of k and hence k is also a measure of the scatter

Combining concentration parameters
If samples from the same site are taken from different physical groups (n) of materials and when each group is Fisher distributed around its mean, but when the concentration parameters of the different groups are very different, according to the propagation of errors, a better estimate for the concentration parameter k of the whole group of samples is obtained by:
$k^{-1} = \sum k_i^{-1}$, where ki is the concentration parameter of group i.

Accuracy of archaeomagnetic results

Random errors determine **precision** **Systematic errors** determine **accuracy** **Accuracy expresses how close the observed mean direction is to the true mean.**

The **precision** of the mean archaeomagnetic direction is affected by random errors, while systematic errors affect the **accuracy** of the mean archaeomagnetic direction. Finally, the accuracy of an archaeomagnetic result will depend on both random and systematic errors. The Fisher statistic and normal Gaussian statistic can be used to treat random errors. The only way to deal with systematic errors is to keep them as small as possible during sampling and measurement, taking into account the accuracy of the result we are striving at. Unfortunately, there may be systematic errors inherent at the site at the moment it is sampled (movement "en masse" for instance). In some cases it is possible to correct for them.
However, systematic errors are difficult to trace:

-movements "en masse" of site
-systematic error in orientations (faulty levels and compass, non-verticality of gnomon)
-systematic errors in measurement (misalignment of calibration standard and samples in sample holder of measuring equipment; systematic variation of measuring equipment with time or drift causing serial association between consecutive measurements)
-not complete removal of secondary components of magnetisation
-not complete cancellation of direct fields during demagnetisation

Warning!
In textbooks there are often typing errors in the formulas given.
In some textbooks there is confusion between N and **R**.
Misleading old terminology is sometimes used (κ is not a measure of precision and should be termed concentration or shape parameter).

Other methods

Other methods such as Bootstrap and Jackknife require a very large number of samples.

Books

With chapters on archaeomagnetism

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-Geophysical Research Letters (American Geophysical Union)
-Geophysics (Society of Exploration Physics)
-Journal of Geomagnetism and Geoelectricity (Terra Scientific Publishing Company, Tokio)
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-Journal of Archaeological Science
-Journal of Geophysical Research (American Geophysical Union)
-Physics and Chemistry of the Earth (Pergamon)
-Physics of the Earth and Planetary Interiors (Elsevier)
-Physics of the Solid Earth (Izvestia, Academy of Sciences, USSR)
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-Reviews of Geophysics and Space Physics (American Geophysical Union)
-Surveys in Geophysics (European Geophysical Society)
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