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On Distinguishing Self-Reversed from Field-Reversed Rocks

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During the last ten years the work of groups studying the magnetism of rocks in many countries has established the following results.

(1) Rocks of ages up to 10 or 20 million years are magnetized, on the average, roughly along the direction of the field of an axial dipole.

(2) Much older rocks from a given continent are often magnetized in a direction making a large angle with the direction of the field of an axial dipole and this mean angle tends to increase with age.

(3) About 50% of all rocks whether igneous or sedimentary are magnetized in the opposite direction to the other 50% of the rocks of given age from a given continent (Fig. 1).

Result (1) above leads to the deduction that during the last 10 or 20 million years or so the earth's mean magnetic field has had the character of an axial dipole. Result (2) could be explained either (a) because the field in ancient times was not that of a dipole or (b) that the present direction of magnetization of an ancient rock does not represent the direction of the ancient ambient field or (c) that the continents in ancient times were in different positions relative to each other and to the poles.

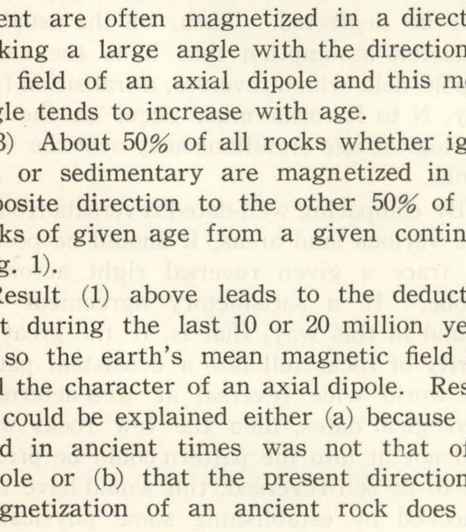

Fig. 1.

The first possibility (a) is made unlikely by the rough agreement between the direction of magnetization of igneous and sedimentary rocks, which have widely different magnetic and physical properties. The second possibility (b) is made unlikely, and the third one (c) likely because it has been shown that the magnetic latitudes, as deduced from the magnetic inclinations on the third assumption do agree in general with the latitudes deduced from the ancient climates of the continents.

In general one can conclude that among workers in rock magnetism there is wide, but not universal agreement, that the correct explanation of results (1) and (2) is that during at least the last 500 My the earth's field has been that of an axial dipole, but that the continents have drifted very markedly. Though vastly more work is needed to check these semi-qualitative conclusions and to obtain reliable quantitative estimates of the ancient latitudes and orientations of the continents, the observational and analytic methods to do this seem rather well understood.

The situation with regard to result (3) is less clear. What exactly can we deduce about the history of the earth's field from the study of the reversely magnetized rocks? This will be the main concern of this lecture. From the pioneer work of Graham, Néel and above all, that of Nagata and his colleagues in Japan, it is known that a very few of the rocks which are reversely magnetized in nature show self-reversal properties in the laboratory on suitable physical treatment and so in all probability acquired their reversed magnetization by physical and chemical processes at or after formation. A rather larger proportion show partial self-reversal in the laboratory, and some of these show full reversal after heat treatment. On the other hand, the great majority of the rocks which are reversely magnetized in nature do not show self-reversal properties when subjected to simple thermal and demagnetization tests in the laboratory. Such rocks are generally held to indicate that the earth's dipole field, when they were formed, was in the opposite direction to its normal direction. One of the main arguments for field reversal has been that systematic differences of magnetic or petrological properties have not been found between many series of normal (N) and reversed (R) lava flows. However, the published results which allow detailed comparison between the N or R lavas to be made are definitely rather slight and further work is urgently needed. As will be emphasised later, a reliable comparison will need a large number of measurements because of the great variability of the magnetic and petrological characteristics of the rock specimens from a given set of flows: the results have therefore to be treated statistically.

Perhaps the strongest evidence for field reversal at present available is found by studying rocks which have been baked, subsequent to formation, by igneous lavas, sills or dykes. It has been found by many workers that the direction of magnetization of a baked rock is generally the same as that of the baking rock, whether this is normal or reversed, and that this is so whether the baked rock is sedimentary or igneous. Such observations are hard to explain except by field reversal.

The only conceivable alternative, assuming the data to be statistically significant, is to suppose that the R or N character of the baked rock is due to the influence of chemical agents, hot liquids or gases, emanating from the igneous intrusion: for instance, a self-reversed dyke might emit, say, an oxidising atmosphere which could produce self-reversal in the baked rock: alternatively, a normal dyke might emit a reducing atmosphere which might produce a normally magnetized baked rock. Such an explanation, though possible, cannot be considered very probable. Clearly, to obtain an accurate picture of the history of the earth's field, reliable laboratory methods of distinguishing a field-reversed from a self-reversed rock are required.

The history of the reversals of the earth's dipole field can also be approached from a study of the field evidence. Instead of seeking methods of distinguishing, by means of physical and magnetic tests in the laboratory, a field-reversed from a self-reversed rock, one can seek to correlate the distribution of N and R rocks at all geological ages all over the globe, with the hope that one will thereby be enabled to deduce which rocks are truly field-reversed. The method in practice rests essentially on the assumption that the fraction of rocks which are self-reversed in nature, but which do not show self-reversal in the laboratory, is small: so that, as a *first approximation*, the few self-reversed rocks can be neglected. Then, on the usual and plausible assumption that it is the central dipole field which reverses, a transition from, say, N to R rocks must occur at the same geological age simultaneously over the whole globe.

By comparing well-dated reversals from all the various land areas, it should be possible to trace a given reversal right across the globe. If a satisfactory agreement were found in this way, that is, if the great majority of rocks fell into a consistent pattern of world wide reversal at well-determined geological dates, then the few rocks which did not fit into the pattern could be presumed to be self-reversed: this would have to be checked by establishing some physical difference from the rest. This method may become misleading if the fraction of undetected self-reversed rocks is too great. Moreover the method needs rather good dating of all the measured rocks, which is not yet generally available.

There are some other possible uncertainties with the method. For instance, it is not, in principle, impossible to suppose that some global terrestrial event could take place, such as a change in the composition of the atmosphere due to volcanic gases, or to a change in the nature of the igneous rocks produced, or to a change of climate, which could produce self-reversal in, at any rate, some types of rock simultaneously over most of the globe. However improbable such an occurrence is not physically impossible.

If one assumes that the great majority of reversely magnetized rocks already studied are field reversed, then the history of the earth's dipole field during the last 500 My appear to be somewhat as follows.

Going backward in time from the present day, the dipole has been normally directed for the last 1 My, then reversed at roughly 1 My intervals back to about 20 My. The reversals then seems to have been somewhat irregular in time, with longish periods, up to 10 My or more, when the dipole remained in the same direction. For instance, the dipole seems to have been reversed for long periods both in the Cretaceous and Eocene (about 50 to 110 My) and in all Permian time (225–270 My). However, earlier in Carboniferous and Devonian times (300–400 My), a series of reversals at about 1 My intervals, as in recent geological times, seems to have taken place (Fig. 2).

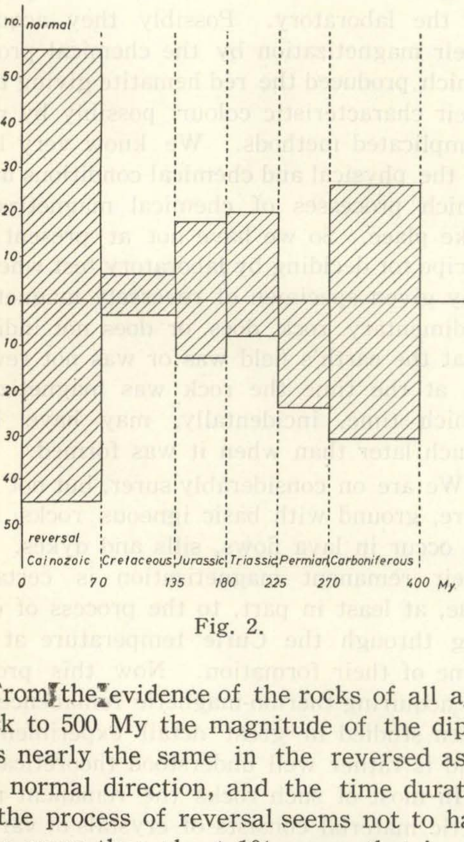

Fig. 2.

From the evidence of the rocks of all ages back to 500 My the magnitude of the dipole was nearly the same in the reversed as in the normal direction, and the time duration of the process of reversal seems not to have been more than about 10^4 years, that is, not more than 1% of the 1 My period between reversals in recent geological time.

Such, roughly, is the history of the earth's dipole as deduced from our present knowledge of the magnetism of the rocks, on the assumption that self-reversed rocks can be statistically neglected. If this is a correct account of the history of the earth's dipole, then the earth's core must contain a three-dimensional self-exciting dynamo, with the above mentioned irregular reversing properties. If theorists can construct such mechanisms, their conclusions may be of great importance also in the study of the magnetism of the sun and stars. So this conclusion that the earth's field has reversed is of such importance that it is vital that the data on which it is based should be reliable.

Now it is clear that the more refined the laboratory methods of analysis, the stronger the evidence for field-reversal if no physical differences could be found in the laboratory between R and N rocks.

On the other hand, if future work were to demonstrate physical differences between N and R rocks, then one would have to come to one or other of two very important conculusions.

The first hypothesis is that the earth's field has reversed, but that a correlation in time exists between the types of igneous rocks erupted at a given geological epoch and the occurrence of reversals of the dipole in the core. The only likely link between these two spatially separated phenomena would seem to be the system of convection currents in the earth's mantle which seem required by the facts of heat flow and mountain building. However, the time scale of these convection currents is much longer (100 My) than that of the apparent dipole reversals (1 My).

If the existence of a coupling between the motions in the core and the igneous activities at the earth's surface were to be demonstrated, this would be a geophysical discovery of the highest importance. In more general terms, one notes that any correlation in time or geographical position of any property of the core and any property of the earth's surface would indicate the existence of a coupling between core and mantle. If, as is generally accepted, the secular variation is due to motions in the core, then any correlation of the special properties of the secular variation at the surface with geographical features, as oceans or continents, would indicate such a coupling.

The second possibility is that the earth's field has never reversed (or not since 500 My ago) but that physical and chemical processes have so changed the nature of the rocks as to obliterate nearly or completely the mechanism by which they acquired their reverse magnetization. If a statistical difference between N and R rocks is found, then the second hypothesis would seem the most likely, though the possibility of the first being correct must be borne in mind.

The inadequacy of the hitherto used testing methods is revealed by the fact that cases are known where N and R specimens are found in a single block of rock, so indicating that one or other is self-reversed, but where no differences of property between the N and R specimens has so far been found.

It is important to emphasise that to maintain the field reversal hypothesis as an explanation of a series of N and R rocks, it is necessary that there shall be no statistical correlation between the N or R property and *any other* property of the specimens, including the prevalence of the various non-ferromagnetic minerals, such as the various complex silicates. If, for instance, all the N rocks of a series of lava flows were found to have a statistically significant difference in the amount of any component whatever, compared with R rocks, this would necessitate either denying that this series of flows gave any evidence for reversals, or affirming a coupling between the motions of the core and the type of igneous activity.

Returning now to the major objective of building up a reliable estimate as to how the earth's dipole moment P has varied in magnitude and sense over geological history, it is clearly necessary to make very detailed studies of the present magnetic, physical and petrological properties of the rocks and to bring these properties into relation as far as possible to the conditions of initial formation and magnetization of the rocks. The ideal method of procedure would be to repeat in the laboratory the identical conditions under which a particular rock was formed and magnetized. Then one would be able to deduce with certainty both the sense and magnitude of the ambient field when the rocks were formed. Unfortunately this is at present impossible. We do not know well enough what these conditions were: and if we did, it would be very difficult to reproduce them in the laboratory. Even if we knew what the temperature, pressure and ambient gaseous or liquid environment were, and could reproduce them in the laboratory, one could not reproduce the possibly very long time durations of the magnetization process, which certainly must often have amounted to tens of years for a cooling intrusive magma. Moreover, in cases of deep burial and so partial metamorphosis, the period may have been many millions of years.

One can rule out at present the use of laboratory tests of sedimentary rocks of the red sandstone type, as certainly reliable indicators for or against field reversal, since we are rather ignorant as to how they were magnetized and so cannot repeat the process in the laboratory. Possibly they acquired their magnetization by the chemical process which produced the red hematite giving them their characteristic colour: possibly by more complicated methods. We know very little of the physical and chemical conditions under which processes of chemical magnetization take place. So we have not at present any recipe for deciding by laboratory test whether any given specimen of reversely magnetized sedimentary rock does or does not indicate that the earth's field was or was not reversed at the time the rock was magnetized—which time, incidentally, may have been much later than when it was formed.

We are on considerably surer, but not very sure, ground with basic igneous rocks, such as occur in lava flows, sills and dykes. For their remanent magnetization is certainly due, at least in part, to the process of cooling through the Curie temperature at the time of their formation. Now this process of acquiring thermo-magnetic remanence has been studied in great detail experimentally and is rather well understood theoretically.

In most of such rocks the remanent magnetic material consists of crystals of varying sizes of mixed oxides of iron and titanium, often of great complexity with complicated intergrowths, so very seldom has one to do with a single magnetic material with simple physical properties. Two or more ferromagnetic materials with differing magnetic properties may be found in a single specimen.

As is well-known, one of the basic mechanisms of self-reversal arises from the negative magnetic interaction, either magnetostatically or by exchange forces, between one crystalline component A with high Curie temperature and low magnetization at room temperature, and a second one B with a lower Curie temperature and a higher magnetization at room temperature.

In general, an intimate mixture of two or more magnetically dissimilar substances will show normal or reversing properties according to their shape, spatial distribution and nature of the magnetic materials. When the interaction is magneto-static, and when the magnetization of component B, in the reverse field H_A of component A, increases linearly, or faster with the field, then reverse magnetization can only occur when A and B form some kind of lamella structure, when the grains of A are much elongated, or when the grains of B are spatially asymmetrically distributed with respect to the grains of A. If however, the magnetization of B increases less fast than linearly with H_A, i.e., approaches saturation, then self-reversal can occur for a wide variety of shapes for instance, when the grains of component A are spheres and component B is in the form of a spherical shell surrounding each sphere. Oxydation or reduction of the outer layer of near spherical grains could produce such geometry, as envisaged by Graham. Whether or no reversal of such shaped grains does occur will depend on whether, when B is cooled below its Curie temperature, the reverse field of A is large enough nearly to saturate B.

When the negative interaction between A and B is of the super-exchange type, then self-reversal can occur with a much wider range of geometrical configurations.

As clearly recognised by Néel, rocks, in which the properties of the A and B components are not such as to cause self-reversal at formation, might become reversed in later geological time by reason of subsequent changes in the two components due to alteration, recombination, weathering, metamorphism, relaxation phenomena and phase transformation in the solid state. Recently we have rocks owing their magnetizations to pyrrhotite liable to show self-reversal properties, which appear to result from chemical or phase changes in the solid state at temperatures below the Curie point. Moreover simple magnetic ageing, as is well-known in many magnetic materials may occur and might reduce the remanent intensity of component A below that of B, so that the net magnetization becomes reversed.

Néel also showed that self-reversal could occur under certain conditions in a single phased substance: that is, when it contains two dissimilar sub-lattice A and B with rather special properties. Gorter showed that synthetic specimens of lithium-chromium-ferrite of certain composition showed the behaviour expected of such an N-type ferrimagnetic: with other compositions, partial self-reversal occurred as for a P-type ferrimagnetic.

Néel also thought it likely that even with such a single phased substance differential physical or chemical change of the two sub-lattice over geological time could conceivably bring about the reversal of an initially normally magnetized rock.

As far as I know, no natural rock has been proved to have been self-reversed by means of having the structure of a N-type ferrimagnetic.

The various possible mechanisms for self-reversal mentioned above relate either to a single phase substance containing dissimilar sub-lattices or to two phase systems containing two dissimilar substances: in both cases one is primarily considering pure substances with well defined compositions and properties. When one considers hypothetical mechanisms for self-reversal in real rocks the possibilities become legion. For real rocks are essentially *dirty*, using this word to imply the opposite of *pure*. Consequently real rocks are often very variable in magnetic behaviour.

For instance, when specimens from a typical system of basaltic lavas, such as have provided so much valuable data on the directions of magnetization, are heated in the laboratory, the Curie temperature θ_c on first heating may lie anywhere between 100 and 500°C. Some specimens show two, or occasionally more, Curie temperatures, indicating two or more different ferromagnetic components. A very few of the rocks with two Curie temperatures show self-reversal under laboratory test, but a considerably larger fraction show partial self-reversal: some of the latter show full self-reversal after heat treatment. However, the great majority show no evidence of self-reversing properties.

The basaltic lavas are also very variable in natural intensity J_n and so also in the ratio

$$K \equiv \frac{J_n}{J_H}$$

where J_H is the thermomagnetic remanence acquired on cooling in the earth's field. In a pure and stable substance K equals unity, but for actual rocks may range 0 to 1, with a few higher values. Some of the latter specimens may have been magnetized by lightning. The low values of K are often due to changes in the rocks while being heated. Not only may the original ferromagnetic materials responsible for J_n change with heating, due to chemical change, exsolution or homogenisation etc. but some constituents of the rocks, which in nature are paramagnetic, may change on heating into new ferromagnetic substances. One common material which so changes is the complex and glassy ferro-silicate chlorophaeite. On heating to 500°C this substance seems to transform into an impure hematite. In part, the wide range of K values found in specimens from a given suite of lava flows may be attributed to the presence of varying amounts of such unstable and complex silicates.

So in general one finds that a set of specimens of basaltic lavas will show under laboratory test a wide range of both θ_c and K. Thus, any comparison, say, of the magnetic properties of a set of normally magnetized with a neighbouring set of reversely magnetized rocks, must essentially be of a statistical character. This implies that the task of demonstrating no significant difference between a set of N and R rocks, or alternatively of establishing such a difference, must be a long and arduous one.

This great variability of magnetic properties of natural basalt rocks must reflect differences (a) of the initial composition of the magma, (b) of the rate of cooling and (c) of the physical and chemical changes which take place during the various stages of the process of solidification. In addition, there must also be taken into consideration the undoubted slow changes in the rocks, which may occur subsequently during the geological history due to metamorphic changes of various kinds.

More attention should be directed by workers in rock magnetism to the complicated nature of process by which a hot magma cools to form an igneous rock. For instance, many lavas contain two quite distinct generations of titano-magnetite grains: large, well-grown crystals, often with ilmenite intergrowths, clearly formed during a period of very slow cooling: on the other hand the small grains of similar material must have been formed at some probably later period of rapid cooling. This second generation is often associated closely with certain of the complex silicates forming the ground mass of the rock. The complexity of the cooling process is also revealed by the detailed study by petrologists of ferromagnetic minerals. For instance, some rocks show evidence that large crystals of titano-magnetite with ilmenite intergrowths may be corroded away at some later stage so as to leave little of the original crystals but the skeletal remains of the more resistant ilmenite laths. Of particular significance may be the later hydrothermal stages of the consolidation of the magma, in which the minerals formed at, say, the early pyrogenic stages may be radically transformed by the chemically active liquids and gases by which they are later surrounded. Clearly the close collaboration between petrologists and rock magnetists is essential for progress in this field.

A general conclusion of a negative character can be drawn from these facts. On many occasions it is likely to prove very difficult to deduce with certainty from laboratory measurements of a particular rock whether its present direction of magnetization is in the direction of, or is opposite to, the earth's field at the time it was magnetized. However, since it is essential to attempt this, thus new and refined methods of testing and diagnosis are required, and these must be applied to a large number of samples of different ages and from different lands.

The results of such measurements of the properties of real rocks must be compared with laboratory results on the magnetic behaviour of synthetic substances, treated in the light of our growing theoretical knowledge of ferromagnetism. Real rocks are usually so complicated that any exact theoretical treatment of their properties is almost impossible and one often has to content oneself with accurately describing phenomena which one cannot explain in full molecular detail. However, the greater our knowledge of the behaviour of pure substances, the greater the range of facts about actual rocks which one will be able to interpret. Eventually the two approaches will converge and one may hope that the more important characteristics of the rocks will become explicable in terms of molecular behaviour.

An analogy might perhaps be drawn with the early decades of biochemistry, when the complexities of the behaviour of living organisms were far beyond the limited range then covered by organic chemistry: and of course even now, with the vast developments of organic chemistry of the last half century, it is only a fraction of the behaviour of living organisms which can be given a precise explanation at the molecular level. In fact, for some purposes a rock specimen may be usefully thought of as having some of the properties of a living organism. For instance, when studying the natural remanence of an igneous rock, by thermal or field demagnetization methods, one can never repeat the same experiment on the same specimen, for we do not know how to bring the specimen back to its initial state. All such tests alter the rock irrevocably, as do lethal experiments on living organisms.

In addition to laboratory and theoretical work on pure substances, together with a greatly extended phenomenological study in the laboratory of rock specimens, a wide extension of field work is essential, particularly in relation to the distribution of normal and reversed rocks in space and time. By combining all three methods one may hope to be able before long to derive a reliable history of the earth's magnetic dipole. Possibly some unexpected experimental discovery will be made which will facilitate this task.

At the present time one might perhaps sum up cautiously the state of the evidence for reversal of the earth's dipole. The evidence for reversal having occurred is quite impressive, and it is possible that the dipole did make an irregular series of reversals much as deduced from the present known distribution of N and R rocks. However, it is almost certain that some of the R rocks which are now held to indicate a reverse dipole will be found, either by further field or laboratory evidence, to be self-reversed. On the present evidence, it is not possible to exclude completely the possibility that all the R rocks are self-reversed, so implying that the earth's dipole has had its present sense at any rate for the last 400 My.

DISCUSSION

T. Nagata: Are you inclining to believe that a fair amount of reversely magnetized rocks *in situ* might be due to known and unknown mechanism of self-reversal of remanent magnetization?

P. M. S. Blackett: Yes. I am sure the fraction of reversed rocks which are self-reversed is larger than the fraction which now show full or partial self-reversal in the laboratory. However I feel that the weight of evidence is slightly on the side of field reversal sometimes in the past.

D. S. Rodbell: I did not understand the properties of chlorophaeite that you mentioned — in particular once you have heated a sample above 500°C and achieve a new and larger magnetization is that a stable (i.e., reversable) state with further temperature or pressure cycling?

P. M. S. Blackett: After heating the magnetic material appears to be mainly hematite with some titanium. On further heating and cooling it behaves quite normally, so it appears to be stable chemically and magnetically.

G. W. Rathenau: Would it be helpful to make Kerr-effect observations on natural rocks in order to see whether in some parts the magnetization points to the right and in others to the left?

P. M. S. BLACKETT: I do not think this would be possible with the natural magnetization of a rock as this is too weak.

E. W. GORTER: 1. Several ferrimagnetics show P-type behaviour in low fields (like 3500 Oe), but ordinary P type in saturating field of e.g. 30000 Oe is due to large anisotropy at low temperatures. Since P type develops at $M_A/M_B<1+\beta$, and β is small, the sublattice magnetizations must be almost equal. Verhoogen has given reason why this will probably not occur when only Fe^{3+}, Ti^{4+} and Fe^{2+} are present.

2. All saturation magnetization data on rocks are given in arbitrary units. It would be very important to be able to determine real saturation magnetization e.g. by selective chemical dissolution.

3. You showed a micrography of titanomagnetite with exsolved ilmenite. The latter could not play a rôle in the reversed because the ilmenite is non-magnetic. If the two-phase reversal mechanism plays a rôle, is it possible that a ferrimagnetic ilmenite may have caused reversal, and have later undergone chemical change to give non-magnetic ilmenite?

S. AKIMOTO: We have also found the P-type-like thermomagnetic curve in the synthetic magnetite-ulvöspinel system ($x Fe_2TiO_4\cdot(1-x)Fe_3O_4$) around $x=0.6$.

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Magnetic Properties of FeO-Fe_2O_3-TiO_2 System as a Basis of Rock Magnetism

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Magnetic properties of the ferromagnetic oxide minerals in rocks can generally be well interpreted as characteristic of the FeO-Fe_2O_3-TiO_2 ternary system, in which there exist the three fundamental solid solution series with different crystal structure, i.e., spinel, rhombohedral and orthorhombic phases. Changes of the Curie temperature, saturation moment and the cell dimension with the composition were examined in detail with respect to the spinel phase minerals in the ternary system including not only ideal titanomagnetite (Fe_2TiO_4–Fe_3O_4 series) but also titanomaghemite with varying vacancy in the metal ion site of the crystal structure.

Magnetic properties of rocks are principally attributable to those of the ferromagnetic minerals scattered with a very small proportion among the practically non-magnetic silicate minerals. The chemical analyses made hitherto reveal that the majority of the ferromagnetic mineral contained in rocks are the metallic oxides which are composed mainly of FeO, Fe_2O_3 and TiO_2 involving small quantities of MnO, MgO, Al_2O_3 and V_2O_3 as minor components. Consequently, the magnetic properties of the ferromagnetic oxide minerals can generally be well interpreted as characteristic of the FeO–Fe_2O_3–TiO_2 ternary system, in which almost all the simple oxide minerals of interest in rock magnetism, viz. wüstite (FeO), magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), hematite (α-Fe_2O_3), ilmenite ($FeTiO_3$), ulvöspinel (Fe_2TiO_4) and pseudobrookite (Fe_2TiO_5) are included.