Possible causes of abnormal polarizations of magnetic formations

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Mit der Ad. Schmidtschen Feldwaage sind in den letzten drei Jahren in den Vereinigten Staaten recht ausgedehnte magnetische Lokalvermessungen angestellt worden. Das vermessene Gebiet umfaßt mehr als eine Million Quadratkilometer, wovon der größte Teil für die Zwecke der Ölgeologie untersucht wurde. Die Anwendbarkeit der magnetischen Methode in der Ölgeologie beruht darauf, daß Ölantiklinalen häufig von Erhebungen des kristallinen Untergrundes begleitet sind. Die Antiklinalen entwickeln sich entweder durch Zuschüttung alter Gebirgsrücken („buried ridges") und durch den größeren Druck der an den Flanken mächtigeren Sedimente, oder durch Auffaltung des kristallinen Untergrundes zusammen mit den Deckschichten, oder endlich durch vulkanische Intrusionen in die Sedimente. — Das sowohl bei diesen wie auch bei den zu bergbaulichen Zwecken angestellten Messungen zutage geförderte Material hat sehr zur Erweiterung unserer Erfahrung in der Deutung magnetischer Resultate beigetragen und vor allen Dingen gezeigt, daß die reine Induktionstheorie längst nicht in so ausgedehntem Maße anwendbar ist, wie es in manchen neueren Veröffentlichungen in vielleicht zu orthodoxer Weise behauptet wird. Die Bedeutung mechanisch-geologischer Kräfte ist bisher im allgemeinen unterschätzt worden. Experimente haben gezeigt, daß eine vereinte Anwendung von Zug- und Torsionskräften im normalen Erdfelde unter Umständen eine umgekehrte Magnetisierung hervorzubringen imstande ist; die Schwankungen in der Größe der permanenten Magnetisierung des Magnetits kann plausibel ebenfalls nur auf die Verschiedenheiten von Druck- und Temperaturverhältnissen bei seiner Entstehung zurückgeführt werden; die umgekehrte Magnetisierung von Erzkörpern läßt sich in vielen Fällen durch eine Überkippung der Lager nach ihrer Magnetisierung erklären; der Wechsel von positiven und negativen Anomalien an Basaltergüssen steht wahrscheinlich auch mit der Erstarrung einzelner Teile und ihrer Überkippung während des plastischen Fließens der Decken im Zusammenhang. Es erscheint daher hoffnungslos, aus der gegenwärtigen Magnetisierungsrichtung geologischer Formationen die Richtung der Inklination des Erdfeldes in früheren geologischen Perioden ableiten zu wollen. — Auf der anderen Seite läßt sich zeigen, daß ein großer Teil der negativen Anomalien, die über Hochpunkten paramagnetischer Formationen beobachtet werden, auch durch normale Induktion erklärt werden kann. Dies ist der Fall: 1. wenn Erzkörper, oder 2. Intrusivgänge oder Magnetitbänderung längs der Textur, in Störungskörpern mit unregelmäßiger Oberfläche, flach nach Süden einfallen; 3. wenn der Magnetitgehalt, wahrscheinlich infolge unterschiedlicher Abkühlung, innerhalb ein und derselben (meistens vulkanischen) Formation starken lokalen Schwankungen unterworfen ist; 4. wenn entgegengesetzter Magnetismus in einer kleinen durch eine benachbarte größere Lagerstätte induziert wird, oder endlich 5. wenn z. B. im Grundgebirge Granit in stärker magnetischen Glimmerschiefer intrudiert und der letztere später erodiert wurde, wodurch die Dicke der magnetischen Formation über dem Zentrum der Intrusion reduziert wurde.

Among geophysical methods of prospecting the magnetic method has gained great practical importance. It combines speed with simplicity and slight cost of operation; it is equally well applicable in mining and in oil geology. It shares this advantage only with the electrical method on a comparable scale.

The applicability of the magnetic method in oil and mining rests upon the fact that virtually all magnetic effects of formations are due to the presence of magnetite and some due to pyrrhotite. Magnetite is a mineral which not only forms independent orebodies of commercial value by magmatic segregation, pyrometasomatic replacement or regional metamorphism, but is also associated, together with pyrrhotite, with commercial orebodies of non- or little magnetic ore as for instance sulphides, iron-oxides and placer-deposits. Furthermore, magnetite occurs in crystalline igneous rocks and volcanic flows, the configuration of which can thus be determined by magnetic measurements and furnish data on the general geologic structure of the area. The association of magnetite with igneous or dynamo-metamorphic rocks is the reason for the widespread application of the magnetic method in petroleum geology. The structure of sedimentary formations in which the oil occurs, can frequently be determined by magnetic measurements as it generally bears some relation to the topography of granite ridges, or the general configuration of the basement-rock and igneous intrusions.

While magnetic exploration has been used in this country and Canada in mining for a long time, its application in oil geology is of comparatively recent age; magnetic surveying on such a scale as it is done at present was not begun before 1926. Extensive experience has been gathered but it has been found that the relation between the geologic structure is not nearly as simple as it was originally thought.

The magnetic anomalies bear a simple relation to the configuration of the magnetic formations only under certain favorable conditions. Such conditions exist: when (1) a component of the earth's magnetic field is selected for the observation which has the simplest relation to the position and shape of the disturbing mass. In high magnetic latitudes, this is the magnetic vertical intensity and near the magnetic equator it is the horizontal intensity because the anomalies are of maximum magnitude above bodies magnetized by induction in the earth's magnetic field. In intermediate latitudes, the vertical component should be given preference, especially if the depth-extent of the formations is great as compared to their width. (2) When the distribution of magnetic substances in the magnetic formation is uniform; (3) when the magnetic formation owes its magnetization to induction in the earth's field only and not to other, primarily mechanical influences, which may produce abnormal polarizations.

One object of this paper is to inquire into the possible causes of this abnormal polarization of magnetic formations.

The question arises immediately: how can we recognize such abnormal polarizations in the field data? The answer to this question is rather disappointing. We cannot recognize such abnormal polarizations without having an approximate conception of the geologic conditions. The least we have to know is whether there exists a high point in a magnetic formation below the location where there is a negative anomaly in the magnetic vertical intensity in order to come to a provisional conclusion that there may be an abnormal polarization. A further study of the dip of the magnetic formation or of parts of it, and of the distribution of magnetic material in it (in horizontal and vertical direction) may then convince us that the anomaly may be explained by normal induction and arrangement of magnetic matter within the formation. Actually, then, there will be only a very few cases left, where we can speak of abnormal polarization. However, such process of elimination will only be possible under favorable conditions, that is, if we have an access to the magnetically disturbing bodies.

It has been stated before that abnormally magnetized formations cause negative disturbances in the magnetic vertical intensity. The question comes up if the reverse of this statement holds, namely that a negative anomaly always means an abnormal polarization? The answer is: certainly not. In connection with the study of the abnormal polarization we will, therefore, have to investigate negative anomalies in more detail in order to determine which negative anomalies correspond to such abnormal polarization. This will be the second object of this paper.

As a basis of all further considerations it should be noted that all statements about maxima or minima in magnetic vertical intensity apply to the northern hemisphere and to high magnetic latitudes, as only in that case a strong negative magnetic vertical intensity above the magnetic body would be something extraordinary. All these conditions become totally different near the magnetic equator provided we deal with induction only. Let us consider for a moment two extreme cases. If the inclination of the earth's magnetic field is 90^0 (near the Poles), the vertical intensity would be at its maximum directly over the center of a magnetic sphere; the horizontal intensity would be at its minimum above the northern boundary, zero above the center, and at its maximum above the southern boundary of the sphere. If the inclination is zero (near the magnetic equator), the horizontal intensity will have the maximum negative anomaly above the center of the sphere and the vertical intensity will be at its minimum over the northern boundary, zero above the center, and at its maximum above the southern edge. In other words, horizontal and vertical intensity are reversed at the poles and equator above the sphere. In intermediate latitudes the maxima of the vertical intensity will become asymmetrical as referred to the center of the sphere and there will be a negative anomaly in vertical intensity on the north side of the maximum positive anomaly. The ratio of negative divided by positive anomaly will increase from 0 to 1 as we go from the pole to the equator. If the magnetic body is not spherical but extends in some horizontal direction, the strike of the body and furthermore, its dip and its thickness in the vertical direction (in terms of depth to its surface) become of decided influence upon the behavior of the magnetic anomaly. Conditions, then, become very complicated. Magnetic anomalies which one may obtain in Venezuela will look different from what they are in Kansas on the same granite ridge. Fortunately, the influence of the strike in high magnetic latitudes is not very pronounced. In other words, not to make matters unnecessarily intricate, we will confine our considerations to the higher northern magnetic latitudes. A maximum in the magnetic vertical intensity above or near the highpoint of a magnetic formation then is the normal, and the adjacent small minima are nothing abnormal. Only if the greatest disturbance above the structure has a negative sign, conditions are abnormal and are made the object of further investigation.

It is clear that one type of such negative anomalies can be dismissed immediately from further consideration for the inquiry into the nature of abnormal polarization. Those are negative anomalies due to diamagnetic formations such as observed on salt domes and their caprocks or on supposedly diamagnetic formations such as synclines with a great thickness of sediments (carboniferous and salt basins). Whether the latter negative anomalies are actually due to diamagnetic effects has not been definitely established because the negative signs of these anomalies would disappear if the normal value of the intensity would be chosen numerically lower. The normal value is something for which a proper physical and numerical definition cannot be given; it is derived from a least square adjustment of magnetic vertical intensities obtained on a number of widely scattered magnetic stations as a function of latitude. All depending on the average location of these stations relative to the depth of the basement, this normal value may correspond to so great a depth of the basement where its influence has vanished (this would then be a true normal value), but it may just as well correspond to onley an average depth of the basement so that in basins where the basement rock drops below this average depth, negative anomalies will be observed. As it is not definitely known as yet if the magnetic anomalies on sedimentary basins are due to the diamagnetic effect of the sediments or the submergence of the paramagnetic basement, I have proposed the term pseudodiamagnetic for such formations in the tabulation of negative anomalies that is given herewith.

Classification of negative anomalies
which occur in higher northern magnetic latitudes.

A. Anomalies on diamagnetic (or pseudodiamagnetic) formations.
  a) Local anomalies (on salt domes and caprocks)
  b) regional anomalies (in sedimentary basins, as carboniferous synclines and salt basins).

B. Anomalies on or near highpoints of paramagnetic formations.
  I. Induced magnetization predominant cause of magnetic effects. Negative anomaly due to
    a) Southdip of the formation at less than critical angle.
    b) Magnetic zone, in geologic body of irregular shape, dipping south at less than critical angle.
    c) Non- or less magnetic material imbedded in magnetic media. Effects of differential cooling.
    d) Opposite magnetism induced in smaller by larger magnetic bodies.
    e) Decrease in thickness of magnetic formation.

II. Permanent magnetization predominant cause of magnetic effects. Negative anomaly due to
  a) Overturning of formations as a whole.
  b) Overturning of solidified portions in plastic lavas.
  c) Lightning.
  d) Mechanical stresses
    1. three-pole effects.
    2. torsional effects.

While the types of negative anomalies just discussed are of no significance for our problem, we will now investigate the second type of negative anomalies, those occurring above paramagnetic formations. In accordance with what has been said before, the small negative anomalies that are due to the effect of a lower end of a formation are not considered; but only negative anomalies that are observed above the upper end or the high point of a magnetic formation where generally positive anomalies are expected, will be taken into account.

Analyzing the cause of such negative anomalies as observed on orebodies (in mining) and on extended formations (in oil geology) we find, first, that their majority may be explained by the normal induction of the earth's magnetic field and by the distribution of the magnetic substances. If an orebody dips to the north and its magnetic effects at the surface are due predominantly to the induction in the earth's magnetic field, the anomaly is positive above the upper end. If the body dips to the south, the anomaly is positive only if the angle of the south dip exceeds the "critical angle" [or the complement of the inclination of the earth's magnetic field; at right angles to the direction of the total intensity, the induction is zero (if the strike is magnetic east-west)]. For south dips smaller than the critical angle, therefore, a negative anomaly will be observed above the upper end. The range of south dips producing negative anomalies increases the more the magnetic equator is approached. This phenomenon is not only observed on iron ore deposits but it occurs in buried mountain ranges of irregular shape composed of granite or schist if dikes are intruded, or magnetite banding developed, dipping to the south at angles smaller than the critical angle. — Very irregular magnetic conditions are usually observed on lava flows. Negative anomalies alter with positive anomalies. A number of explanations may be given for the variability of the disturbances; only those resting on differential induction will be considered in this paragraph, while those resting on overturning of permanently magnetized portions in the plastic lava, etc., will be discussed in the next paragraph. It is very probable that the amount of magnetite segregated in a magma depends on the rate of cooling. As there are great differences in the temperatures at the surface of a magma flow, great horizontal differences in the distribution of magnetite must result. As a fairly magnetic substance if imbedded in a strongly magnetic medium acts as diamagnetic substance, it is possible that the variability of negative and positive anomalies on magma flows is due to differential cooling. Non-magnetic inclusions in igneous magmas, as for instance metamorphosed limestones, or magnetic material still in the liquid state, may give rise to local, or regional negative anomalies. Negative anomalies observed on orebodies are often due to induction of opposite magnetism in a smaller by a larger orebody. Lastly, negative anomalies on basement uplifts seem to be rather frequently caused by intrusions of less magnetic granite into more magnetic schists, which would be equivalent, if erosion of the schist took place, to a decrease of the thickness of the magnetic formations under the magnetic minimum. It is not necessary, of course, that this decrease in the thickness of the magnetic schist is produced by a granitic intrusion, but there exist a number of other geologic factors that may bring about such a decrease in thickness, not only of magnetic members of the basement, but also of other magnetic formations on highpoints of geologic bodies.

It is quite evident that thus far we have been unsuccessful in this discussion to discover the cause of abnormal polarities of magnetic formations. The negative anomalies which we have considered could be explained by the normal induction of the earth's magnetic field, differences in the distribution of magnetic substances or in thickness of the magnetic formations. The question arises whether all or most magnetic anomalies are due to induction as it is generally assumed. There are certainly a great number of magnetic deposits which exhibit anomalies of such magnitude that their magnetization cannot be explained by induction only. It has been shown by experiment for a number of ferromagnetic substances that not only very high positive, but in certain cases, negative magnetizations, can be produced by mechanical influences in the presence of a weak magnetic field. As the retentivity of magnetic substances is proportional to the greatest intensity of magnetization attained in its magnetic history (saturation is probably never reached by combined earth's magnetic and mechanical causes), the permanent magnetization of formations that have been subjected to the discussed influences will be greater than the residual magnetism which would remain if the induction in the earth's field had been the only magnetizing cause. Then the "apparent" magnetic susceptibility (induced plus permanent magnetization divided by intensity of the earth 'smagnetic field) is, therefore, much greater than the "true" susceptibility (induced magnetization divided by strength of earth's magnetic field*).

If magnetic formations are overturned by dynamic geologic processes and if the permanent component of the magnetization is stronger than the inductive component, a negative magnetic anomaly will be observed above the upper end of it. Such cases may be observed on orebodies. It is also possible to explain the irregular conditions on lava flows by similar factors; certain portions of the lava flow which were apt to be solidified earlier than others, were magnetized and overturned in the movement of the plastic lava. Furthermore, it is known from experiments and observations on exposed formations that all kinds of magnetizations and polarities can be produced by lightning. This factor may also be of influence in

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*) L. B. Slichter, Certain Aspects of Magnetic Surveying. A. I. M. E Tech. Publ. **120**.

causing the irregular magnetic conditions on lava flows, but it is not at all certain whether lightning can produce a negative magnetization of several square miles in area on peaks of buried mountain ranges. Only for the sake of completeness the locally limited negative anomalies may be mentioned which are observed occasionally above the north poles of short and narrow bodies of magnetite (shortbar effects), the strength of which can only be explained by permanent magnetization.

It seems to me that a great deal of attention must be given to the influence of mechanical stresses upon the magnetization of geologic formations. Not only the pressure in such depths in which basement rocks occur, but also the mechanical stresses which produce folding, faulting and twisting in the progress of dynamic geologic processes, are so great that their influence cannot be neglected; where differences in such stresses occur, differences in magnetization must result. In manufacturing magnets, it has been found that it is possible to pruduce three poles in a bar instead of two. The ends may be south poles and the middle a north pole (or vice versa). While the differences in magnetization caused by varying mechanical influences are probably not sufficient to cause pronounced polarities in straight sheets of magnetic formations, it seems possible that such irregular polarities may occur on the crest of a magnetic sheet if it is bent. As theoretically the sum of free magnetism of a magnetic bar is zero, it follows that the pole strength of the negative center pole must be double that of each of the positive end-poles. Provided the abnormal polarities on basement uplifts are due to this cause, it would be readily explainable why the negative anomalies are frequently so strong as compared to the adjacent positive disturbances.

Lastly, it is very likely that abnormal polarization of magnetic formations may be produced by effects of twist. H. Nagaoka*) could show experimentally that in the earth's magnetic field the positive or normal magnetization of a nickel wire could be changed to an abnormal negative magnetization by applying torsional and pulling stress at the same time after the latter had passed a critical point Similar experiments have not been made to my knowledge on rocks or ferromagnetic minerals; if they also show the same or similar phenomena, we would be able to explain satisfactorily a considerable num berof abnormal polarizations of magnetic formations.

Summing up the discussion of negative anomalies and abnormal polarities given above, I realize that I could not present much definite information. All this paper is meant to be, is a general discussion of the possibilities of explanation. Such discussion has at least one advantage, that of the elimination of a number of factors which from our present knowledge of magnetism cannot be considered as the cause of abnormal polarizations. In this connection it may be stated that one type of negative anomalies has been purposely omitted which may be classed as "terrain anomalies" and which are obtained if the magnetometer is set up on the foot of a basalt plug, or in a quarry etc., that is, when part of the magnetic formation is above the instrument. — I believe that the most frequent and most

*) Magnetization of Nickel. Imp. Coll. of Science, Tokyo, 1889.

plausible causes of the negative vertical intensity anomalies observed above highpoints in the basement or intrusions, etc., are those stated under Ib, e, and IIb, d in the classification given herewith. Whether or not that is so can only be decided by extensive experiments, both in the laboratory on mineral specimens and on known geologic conditions in the field. The discussion just given has been greatly handicapped by the lack of these data.

One will have come to the conclusion from the above discussion that very likely not one, but a number of causes, may produce negative anomalies above the uplifts of magnetic formations. The nature of these causes is intimately associated with the mechanical, and therefore, the geologic history of the formations. In the interpretation of a negative anomaly in virgin territory we are now nearly at a loss, as such a minimum, theoretically, may be produced either by a low in the basement (if normally magnetized) or by an uplift of the same (if abnormally polarized). Doubts may often be eliminated by considering the magnitude (in gammas) of the anomaly, its horizontal extent and its shape. However, a fundamental improvement of our interpretation methods can only be hoped for if we can definitely determine the geological causes for such abnormal polarizations and can thus state for unproven territory, from a consideration of the regional geology, that definite types of negative anomalies can only be due to uplifts and not to depressions.

Die geologische Bedeutung der Schaffung einer Isanomalenkarte der magnetischen Vertikalintensität von Deutschland

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Es werden eine Reihe von Gründen mitgeteilt, die die große Bedeutung demonstrieren, welche für die geologische Forschung die Schaffung einer magnetischen Isanomalenkarte des Deutschen Reiches besitzt. Bei dicser Gelegenheit wird auch darauf hingewiesen, daß schon jetzt auf Crund der neuen magnetischen Untersuchungen in Holstein und Mecklenburg die Mittelmeer-Mjösenzone Stilles zwischen Mitteldeutschland und dem Kristianiagraben in ihrer Lage schärfer bestimmt werden kann. Auch werden einige Vorschläge für dic Durchführung einer solchen Vermessung gemacht.

Als ich vor etwa einem Jahrzehnt von dem Gedanken erfüllt, magnetische Messungen der geologischen Forschung im Flachland dienstbar zu machen, hilfesuchend zu dem großen Gelehrten Adolf Schmidt nach Potsdam kam, da fand ich nicht nur durch wertvolle Ratschläge reiche Unterstützung, sondern A. Schmidt stellte mir auch ein von ihm neu konstruiertes Instrument, eine magnetische Feldwaage für Vertikalintensität, bereitwilligst zur Verfügung. Allein diesem Umstand ist es zu danken, daß dann mein erster tastender Versuch nicht ganz erfolglos war und viele andere zu ähnlichen Versuchen anregte. Auf die Erfahrungen aber, die seitdem gewonnen wurden, gründet sich der Plan, über den im nachstehenden gesprochen werden soll. Daß es möglich ist, heute einen solchen Plan zu entwickeln und mit Zuversicht voraussagen zu können, daß er in irgendwelcher Form trotz der Not der Zeit in absehbarer Zeit verwirklicht werden wird,