The Paleomagnetics of Deep Sea Sediments and Continental Drift

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PART I

INTRODUCTION

Probably as long as man has thought, he has wondered about the sky, its planets, sun and stars. It would be foolish to think otherwise. For in them probably lie the secrets of life itself. The day, the night, the air we breath, the very ground we walk on all are linked together in a constantly thriving organism of creation and decay. It seems the only permanent yardstick we have is time and even now physicists are trying to bend it. Yet still the eons before us have been witness to events on the surface of the earth which will astound the mind. Erosion alone has cut and carried away millions of years. But even more dynamic have been the motions of the surface itself.

It is now, more than probable, that the surface of the earth is composed of large plates or crustal slabs which have reoriented themselves to produce the large scale features so obviously present. Continental and oceanic mountain chains, the ocean basins, the deep ocean "trenches" all may have been related to one general mechanism, continental drift.

Paleomagnetism, as a form of evidence, is as interrelated with this as strata are related to structural geology. One might say that a new branch of science becomes accepted when attempts are made to break it down into separate segments which are striving for their own recognition. Such is the case with paleomagnetism. It has been subdivided into a newer field, archeomagnetism. One of the forms of paleomagnetism, sediment magnetism provides geologists with almost irrefutable evidence for continental drift. One is not to be mislead to think that continental drift is the final answer; for the theories employing geosynclines and epiric seas without large scale crustal movements have survived the abuse of time until very recently. This alone establishes reason for their acceptance for as it is with many theories which do not lend themselves to direct proof, time will tell.

HISTORY

Probably the first investigations of the earth's magnetism should be attributed to the ancient Chinese. By 100 A.D. they had realized the "directional properties" of floating magnets (J. Foster personal communication). But it was not until 1600 that Gilbert related this to the earth's magnetic field (Chapman and Bartels, 1951). In 1797, Alex Humboldt began to focus attention on "the disturbing effect country rock could have on a compass needle". He proposed that this effect is due to the impact of lightning, a postulate which was generally accepted until the perfection of better laboratory tools. (Stonecipher senior thesis, 1970). Slightly later, Folgerhaiter in 1896, did some archaeologic studies dealing with the paleomagnetism of baked artifacts. There appears to be some debate in the determination of the pioneer for archaeomagnetism. At least two, G. Folgerhaiter (Stacey, 1969) and E. Thellier (R.M. Cook, 1970), appear to be most popular. These 1896 studies led Bruhnes and David to make geologic studies on lava baked clays in 1901.

Shortly following this, in 1912, Alfred Wegner was the first to present a scientific theory with supporting data suggesting continental drift in his book Die Entstehung der Kontinente. Although there were some enthusiastic promoters of this theory, A. L. Du Toit of Johannesburg University in South Africa, (with some slight differences, he wanted two primordial continents instead of one as with Wegner) the theory still gained no significant support or notice (Stoneciepher, 1970). Following this, the so called "classical early work" in paleomagnetism was done by Chevallier in 1925 who was followed by Matuyama in 1929. Then, with a stroke of almost occult forsight, Mercanton in 1926 predicted that paleomagnetic data could provide the evidence by which the concepts of continental drift and polar wandering could be tested. He also suggested the possibility that the earth's magnetic field had undergone reversals.

Paleomagnetism then became more widely accepted. Graham, in 1949, revived the suggestions of Mercanton. He also (in 1949) established valuable field methods for determining the stability of remanent magnetism. With the development of a sensitive magnetometer by Johnson and McNish in 1938 (spinner) and by Blackett in 1952 (static), paleomagnetism became a better equipped field of research.

Advances in the mineralogy of rock magnetism by Haigh, Nicholls, Kobayashi, Akimoto and especially the enthusiastic investigations by Nagata and the awe inspiring theories of magnetic domains and the four mechanisms for self-reversals by Louis Neel generally established the field of paleomagnetism as we have it today (Cox and Doell, 1960).

The theories of continental drift remained essentially unchanged until 1939. At this time Griggs suggested patterns for mantle convection. The concept of mantle convection was soon incorporated into the concept of continental drift. According to L. R. Sykes (Phinney, 1968) evidence involving the use of magnetic anomalies and large scale ocean floor displacements "has added strong support to the hypothesis of ocean floor spreading as postulated by Hess (1962) and Dietz (1961)". The foregoing hypothesis was incorporated into a single hypothesis which suggested that continental crust and oceanic crust moved as a unit, the conveyor belt hypothesis.

THE DRIFTING CONTINENTS

Holmes (1945) was wary of accepting the concept of continental drift:

> ...purely speculative ideas of this kind, specially invented to match the requirements, can have no scientific value until they acquire support from independent evidence.

Nonetheless, by more recent times, Holmes' opinion had changed since Blackett found one of Holmes' statements a compelling argument for at least considering the possibility of continental drift. In discussing the problems of Permian glaciation in which the glacial ice-sheet covered large portions of the continents of the Southern Hemisphere, Blackett referred to one of Holmes' statements:

> I remember the impression made on me by Holmes' remark that there was just not enough water in the world to produce a large enough ice-cap if the continents were then in the same relative position to each other as they are today.

Today, there are three new kinds of evidence which independently support the plate tectonic theory of continental drift. The following describes each, with emphasis on deep-sea cores.

In 1963, Vine and Mathews suggested that the magnetic anomalies observed on the seafloor were evidence of seafloor spreading because, if the anomalies were parallel to the oceanic rises, the anomalies were evidence that new oceanic crust was forming at the rises. If the sea floor is spreading and the polarity of the earth's magnetic field has reversed, any parts of the earth's crust which have cooled from a molten state (or from their curie point) will record or "freeze in" the earth's magnetic field as they find it at that time. Thus, if the sea floor, cooling from a molten state, spreads outward from a ridge with some reasonably constant velocity, there will be strips parallel to the ridge of widths corresponding to intervals of time similar to those shown in figure one. The magnetism of one strip may enhance the strength of the present magnetic field while an adjacent strip may detract from the present field. A magnetometer on the surface of the sea for instance, would detect fluctuations in the present magnetic field which really are the results of interference from the magnetized rocks in the sea floor. If the rocks were formed at the ridge, their age implies a length of time in which the rocks were moved from their creation point, the ridge, to their present location. The distance from their creation point to their present location divided by their absolute age yields a velocity corresponding to their motion from the ridge. These velocities, although different for each ridge and along each ridge, permit us to predict the age of any rock or

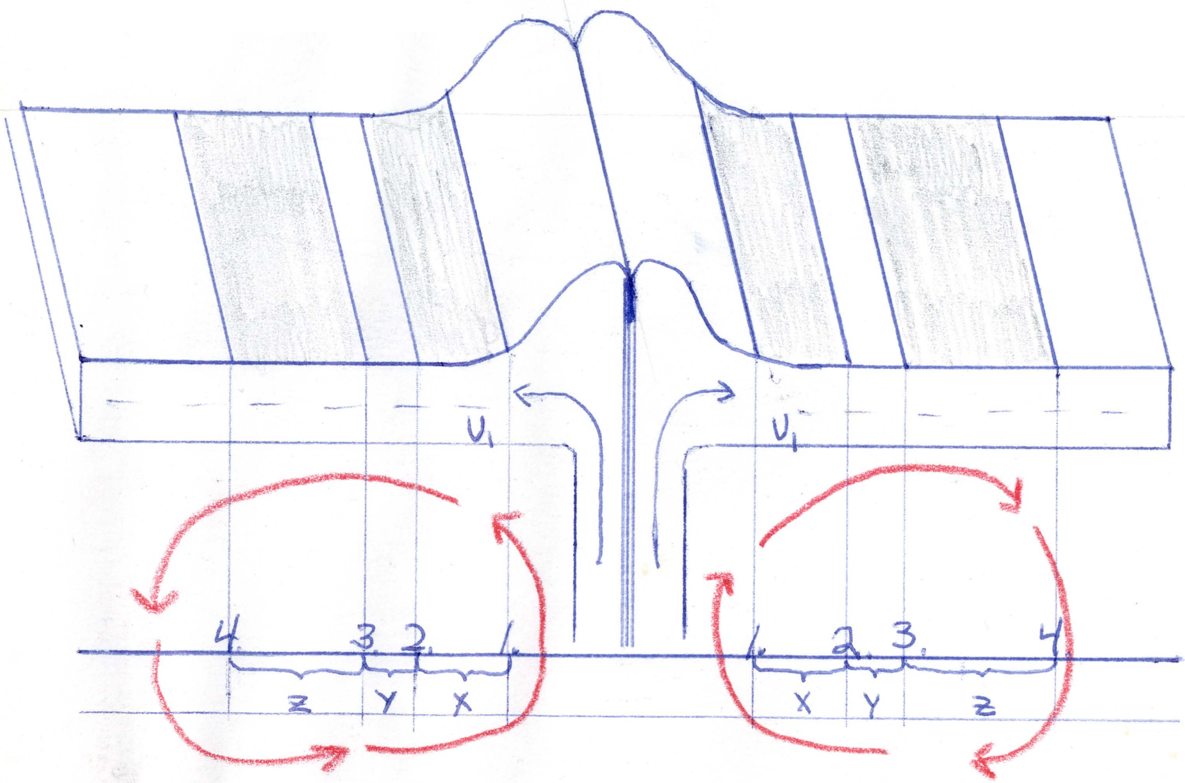

Fig. I

A sample of ocean crust spreading from a rift (ridge) in two directions with velocity V_1. The shaded areas of width z and x represent frozen magnetic formations which are negative or reversed and detract from the present magnetic field. The non-shaded strips are compatable with the present magnetics. If V_1 is reasonably constant, the widths of anomalous strips imply the length of time the magnetic field was in that particular orientation. The four boundary lines of the contiguous strips by the same reasoning imply the time required for the field to reverse. The red arrows indicate the direction of motion required for convection currents in the mantle to initiate such motion.

reversal point if we know the distance of the point from the ridge. It has been possible to identify a number of the anomalies on either side of the oceanic rises. At present numerous magnetic traverses have been made across oceanic rises and the similarity of pattern is considered to be sufficiently good to provide firm evidence for the hypothesis of sea-floor spreading.

The next one of these measurements is found in undisturbed horizontal lava flows. If we predict the age of reversal number three in figure one by the sea-floor spreading method and then locate a similarly aged section of a core of horizontal lava flows, the frozen magnetics of each should be similar. Although the location of magmatic intrusions and surface volcanics have been explained in terms of plate tectontics, the timing of the intrusions and lava flows is independent of field reversals and of tectonics (Dewy, 1969; Dewy & Bird, 1970; Dewy & Horsfield, 1970; Isacks, Oliver & Sykes, 1968). Thus we may ac cept the age relations of the magnetics of horizontal lava flows, independently, as evidence to support continental drift.

The third and last major type of evidence is in the magnetics of deep-sea sediment cores. If one travels along the sea floor away from the edge of the creating ridge and records the ages of sediments, there would be a constantly increasing age for the bottom-most sediments. Imagine the Atlantic ocean when it was first being created. The continental margins were first being exposed over top of the spreading ridge. Here were the first sediments to be deposited. As the ocean's width increased, the first sediments were covered by later ones until we reach the present. If the sea floor is spreading as illustrated in figure one, one would expect to find a thin veneer of present day sediments covering the entire ocean floor equal in thickness to the total layer over the ridge of spreading (taking into account various rates of sedimentation). As we approach the conti-ental margins however, we find older bedrock and consequently older sediments directly overlying the bedrock and at the bottom of the sediment sequence. In essence then, the oldest sediments would be not at the center of the oceans but at the continental margins, contrary to the original model proposed in 1915 by Wegener of continents pushing their way through the crust. This is exactly what is found. Not only are the older sediments found away from the ridges but their cores, if complete, exhibit the same geographic, chronologic and magnetic direction correlations in support of the model as do the horizontal lava flows. If the hypothesis of sea-floor spreading adequately explains the opening of an oceanic area, we should be able to estimate the time at which spreading began. We have three checks: 1) the average velocity of spreading divided by the width of the ocean should yield the age of the ocean and consequently the time of opening, 2) the magnetic direction of the outer, lower sediments and their bedrock basalts should correlate with the magnetic polarity of continental rocks of a similar age, and finally, 3) the bedrock and oldest sediments on the sea floor must be the correct distance and age from the spreading rift. In the Atlantic ocean, the evidence gathered to date appears to be compatable with these three criteria. According to Bullard (1969) "it is virtually certain that the Atlantic did not exist 150 million years ago".

There is, however, one aspect of the original premises of this argument which was conveniently ignored. One of the "if's" originally mentioned was "if" the polarity of the earth's magnetic field has reversed. Investigations by Nagata and his co-workers located the Haruna dacite which shows "self-reversal". That is the final magnetic direction of the rock is 180 degrees away from the ambient field in which the rock cooled. About the same time Neel predicted four conditions under which self-reversal could occur. The problem this interposes is naturally what percent of all the other rocks have undergone similar changes. Recent studies of the geometric, chronologic, and thermal histories of many geologic structures has nearly confirmed the existance of geomagnetic reversals. As stated by Cox et al, "Never in the course of collecting several thousand samples from several hundred lava flows and intrusive bodies have we encountered both normal and reversed polarity in the same ingenous cooling unit". Since their samples have been taken from a large geographic area and correlated with samples from the world over, it has been established that field reversals are a reality (Cox et al, 1964).

PART II

DEEP SEA SEDIMENTS

Near the continents, sedimentary material reaching the ocean floor is primarily derived from the continents. A good deal of this material is probably brought to the depositional site by turbidity currents. The final deposit of each turbidite is the fine grained material which continuously rains down on the sea floor and is similar to the thinner deposits which accumulate beyond the range of the turbidites. These thinner deposits and those of far offshore deep-sea origin are generally classed as pelagic sediments. Pelagic sediments comprise the bulk of open ocean sedimentation (Riedel, 1963).

There are three main lithologies for pelagic sediments, calcareous oozes, siliceous oozes and red clays. The first two are generally of organic origin while the last, red clay, is considered inorganic (Fairbridge, 1966). Of the calcareous oozes, there are two prevelent types, Globigerina and Pteropod ooze. A recent study by Friedman, (1967) has made general depth classifications for each of these. Pteropod ooze covers the ocean floor to a depth of nearly 2200 meters where it is joined by Globigerina ooze. At approximately 4200 meters the Pteropod ooze goes into solution, thus below this depth there is essentially no aragonite or aragonitic organic structures (shells, tests, etc.). With increasing depth the remaining carbonates generally go into solution. The general scheme for deep-dea stability of the carbonate minerals from weakest to strongest is aragonite followed by high magnesium carbonates with the most stable being low magnesium carbonates.

Below these depths increasing to 25,000 feet the siliceous oozes dominate. The silicate tests of diatoms and Radiolarians accumulate in enormous numbers to form deep-sea oozes. Somewhat overlapping with these sediments and in the deeper regions lie the red clays. The clays are found generally deeper than 4500 meters and at depths where "even opaline skeletal debris appears to have dissolved" (Fairbridge, 1967). The clays are commonly composed of grains of 1u in diameter or less but frequently contain coarser material. Their color is due to "the presence of ferric hydroxide or oxide, and a small amount of manganese oxide minerals" (Fairbridge, 1967). The so called "manganese nodules" are frequently associated with the pelagic red clays.

This description brings up one interesting point, what exactly in these sediments is magnetic? What serves to record the history of the earth's magnetic field? The answers to these questions are essential to the validity of the paleomagnetic work. In measuring the age of a sediment sample with magnetism one must know when the sample recorded the earth's magnetic field. If the field was recorded during the deposition of the sediment then the magnetic dating implies the time at which the sediment was deposited. However, if the earth's field was recorded by some chemical reaction which happened at a much later date then the time of deposition is still in question. This latter mode of recording the magnetic field is referred to as chemical remanent magnetization (CRM) and is not dealt with in this discussion. The first method is termed depositional remanent magnetization (DRM) and is the main topic at hand.

In providing a mechanism for DRM, the use of the term deposition is critical. For this discussion the sediment is deposited when the fabric elements of the future sedimentary rock have come in contact with the depositional interface, in this case the sea floor. Here, the fabric elements that are most important are the magnetic particles which accumulate with the sediment during deposition. Thus, by defining the specific process affecting the sediments, one of the previous questions has been answered. The magnetic grains serve to record the history of the earth's magnetic field.

Small detrital magnetic grains may be included in the construction of calcareous and siliceous tests. As the tests fall to the depths and dissolve, the detrital grains are released to become individual fabric elements of the sediment. Also, terrigenous sediments may be directly introduced by winds and volcanic eruptions. Such is the case with the volcanic islands of the Pacific and "especially in an area such as that in the eastern Atlantic, off the Sahara Desert, where the hot harmattan winds blow dusts up to 1000 miles out" (Fairbridge, 1967). Another probable source of magnetic material is extraterrestrial debris, particularly micrometeorites. Sizes range from 300u (.3mm) to 1u and less (Fairbridge, 1967). Estimates for the accumulation of extraterrestrial debris range from 35,000 to 5 million tons per year (Fairbridge, 1967; Mason, 1962).

THE MAGNETIC INFLUENCE

The aquisition of a detrital remanent magnetization is dependent upon size of detrital particles and conditions of deposition. As the size of the magnetic particle decreases the orienting effects of the magnetic field increase and become large relative to the effects of gravity and currents (Runcorn, 1956). The size range of these detrital magnetic particles may vary from 0.10mm in sandstone to as small as 30 to 0.1u in glacial varves (Graham, 1949). As generalized by Potter and Pettijohn (1963) "the smaller the particle the more sensitive it is to magnetic forces". This, however, is not strictly true as pointed out by King and Rees (1966) in that "detrital magnetism is not likely to be important in a sediment whose magnetic particles are less than 0.1u or greater than 50u or so in diameter". Here again it must be emphasized that the discussion is limited to detrital magnetization. King and Rees (1966) define DRM as a "result from a process in which the magnetic particles, already possessing a remanent magnetization by reason of their past history, are deposited from suspension and during deposition acquire a resultant orientation because of the tendency to be aligned with their remanant in the direction of the earth's field. This process is confined to sedimentary rocks".

The process by which a particle becomes aligned is relatively simple. One general technique is applied to first a spherical model then to a disk-shaped model; natural particles are assumed to have values somewhere in between. The simpler case of a spherical particle will be shown here to illustrate the technique. For a particle of diameter D in a magnetic field of strength H, intensity J, the maximum magnetic couple Cm is expressed by:

$$Cm = (\quad D^3 J H) / 6$$

If the same particle is rotating in a viscous fluid, where viscosity = v, and angular velocity = w, the viscous dampening couple Cd is:

$$Cd = \quad v D^3 w$$

For the particle to remain at rest, aligned in the field, these couples must be equal Equating and solving:

$$J = 6 v w / H$$

Brownian Movement, inhomogenity and other factors are taken into account with considerable more treatment (King & Rees, 1966).

This permits the alignment of the grains during their fall. Upon impact the grains may fall over and around other grains. As a grain gets buried compaction plays an increasingly important role. In a quiet water environment (i.e. one of low energy), the floor of the depositional basin regardless of its chemical makeup consists of two physical layers. The upper one is made up of sea bottom "soup" or ooze which is considered as "unconsolidated sediments" while below this lies the consolidated sediments. It is in the zone of the "unconsolidated sediments" in which mechanisms are taking place which permit magnetic grains to become oriented in the earth's field and thus to give rise to a DRM. This discussion deals only with the case of a low energy environment and with the acquisition of a DRM.

The unconsolidated layer can be subdivided into a mixing layer and a horizontal layer (Fig. 2). The upper portions of the unconsolidated layer are in active contact with the water above. These portions are constantly stirred and churned by the mixing efforts of the above moving water. The mixing layer is subjected to the disturbing force of the water above. In the mixing layer and the regions slightly above and below it, a grain of sediment is subjected to three main forces. Gravity affects all grains equally, the disturbing force depends on the viscosity of the disturbing medium (in most cases sea water), the size and shape of the sediment grains and the manner in which the disturbing medium is directed towards the grains (i.e. wave action, turbidity currents, etc.), and finally the force of the magnetic field at that location on the earth's surface. Gravity is unidirectional and serves generally as a compacting force. The disturbing force is generally complicated, irregular, and inconsistent. The magnetism is similar to gravity but weaker and specific to certain grains, for only minerals that have a magnetic moment will respond to the earth's magnetic field. As a grain decends to the bottom of the mixing layer (the motion is relative, in effect, the boundary of the mixing layer is migrating upward through the sediments as they begin to consolidate), the motion of the grain gradually decreases because the energy of the disturbing force decreases to 0 at the base of this layer. Soon the grain is merely vibrating within a small radius and begins to align itself with the earth's magnetic field. Here the grain begins a transitional process in which it moves from the unstable mixing layer into the stable horizontal layer.

Although the horizontal layer is not a consolidated sediment, it is considered to be the zone in which, in most cases, the rock fabric and the magnetic alignment become locked into the rock. It is this magnetic direction that is measured.

It is possible that under certain circumstances a reversal of the earth's field might give rise to a "fuzzy" transition zone. In order to describe the process a hypothetical case is presented in which specific minerals are named, although the processes may apply to other mineral assemblages as well.

It is assumed that the minerals reaching the depositional interface fall into two shape-groups: platy minerals and equidimentional minerals. The platy minerals consist of clay minerals and members of the mica group. It is further assumed that some of the mica grains have magnetite interleaved between the mica plates and that this relationship of the magnetite and mica developed in the source rock. As the clay minerals and mica reach the depositional interface they form a framework of self-supporting interlocking grains. In as much as the direction of the magnetic moment of the mica-borne magnetite is probably randomly oriented relative to the crystallographic axes of the mica, it is possible that the net depositional moment of the minerals forming the framework will reflect the ambient field at the time of deposition. The equidimensional grains are considered to include some individual grains of magnetite. These along with the other equidimensional minerals will settle into spaces between the framework minerals where they may be free to move even after the framework minerals become physically locked into a permanent orientation. In the event that a field reversal occurred while the equidimensional minerals were still free to rotate, the equidimensional magnetite would respond by physically rotating so that the magnetic moment would reflect the new magnetic field-direction. As a result, there would be a "fuzzy" zone in which the rock magnetization retained the record of two magnetic field directions.

If these deductions are correct, then the overlap zone in a core sample should, from the bottom up (depending on the relative amounts of each grain type and the strength of the ambient field) exhibit a magnetization which weakens to some minimum (which may possibly be related to the dominating grain size) and then begins to increase, the direction of magnetization now being reversed (Fig. 3).

Other factors may also play a role. It is possible that the local magnetic field of the minerals forming the framework influence the orientation of the equidimentional magnetic grains and the activity of burrowing organisms have been cited as a factor in displacing or confusing the stratigraphic record of the level at which reversal occurs. Neither problem has been adequately investigated and there are a few instances in which sharp reversal boundaries have been observed despite evidence of burrow tracks which cross the boundary (Foster personal communication, 1970).

CONCLUSIONS

A record of the recent polarity history of the earth's magnetic field has been found (1) in the magnetic pattering of the oceanic crust, (2) in deep-sea sediments and (3) in lava piles. Sedimentary units and igneous rocks, now accessible near the surface of the earth in the continental areas, also retain a record of the earth's magnetic field. Investigations of these units have permitted paleopole positions to be calculated. It is observed that the pole positions calculated on the bases of Recent-Pleistocene sediments and igneous rocks group about the present geographic north pole. However, older rock units give pole positions that do not coincide with the present pole position. Furthermore the calculated pole positions differ from one continent to another. This intercontinental scatter is greater for Paleozoic rocks than it is for early Cenozoic rocks.

These observations provided the impetus to re-examine the hypotheses of Continental Drift. The result has been to re-evaluate the tectonic features of the earth in the light of plate tectonics (i.e. Dewy & Bird, 1971). Many investigations must still be carried out. However, so many of the data are explained by this new theory that one may safely predict that geologic concepts can no longer be restricted to the evidence recoverable from continental areas only.

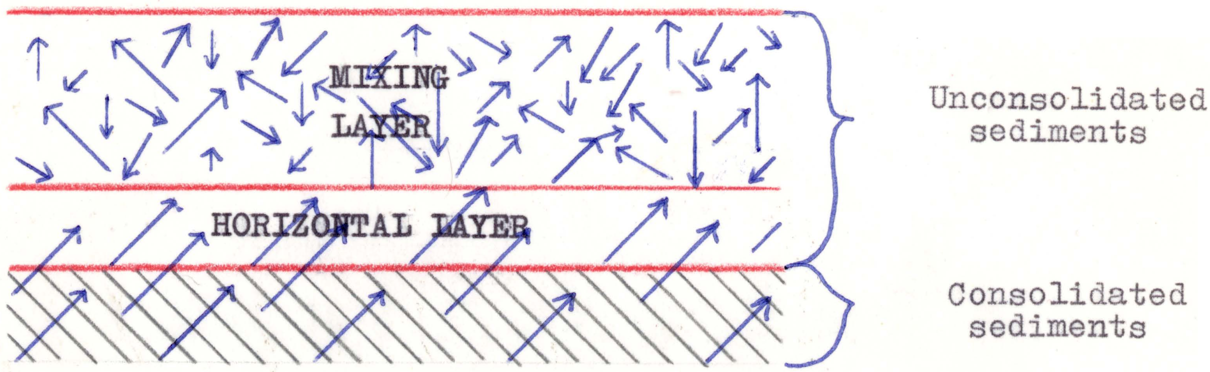

Figure 2.

The blue arrows indicate the direction of the magnetic field of the sediment particles. Those of the horizontal and consolidated areas agree with the earth's magnetic field at the time of deposition.

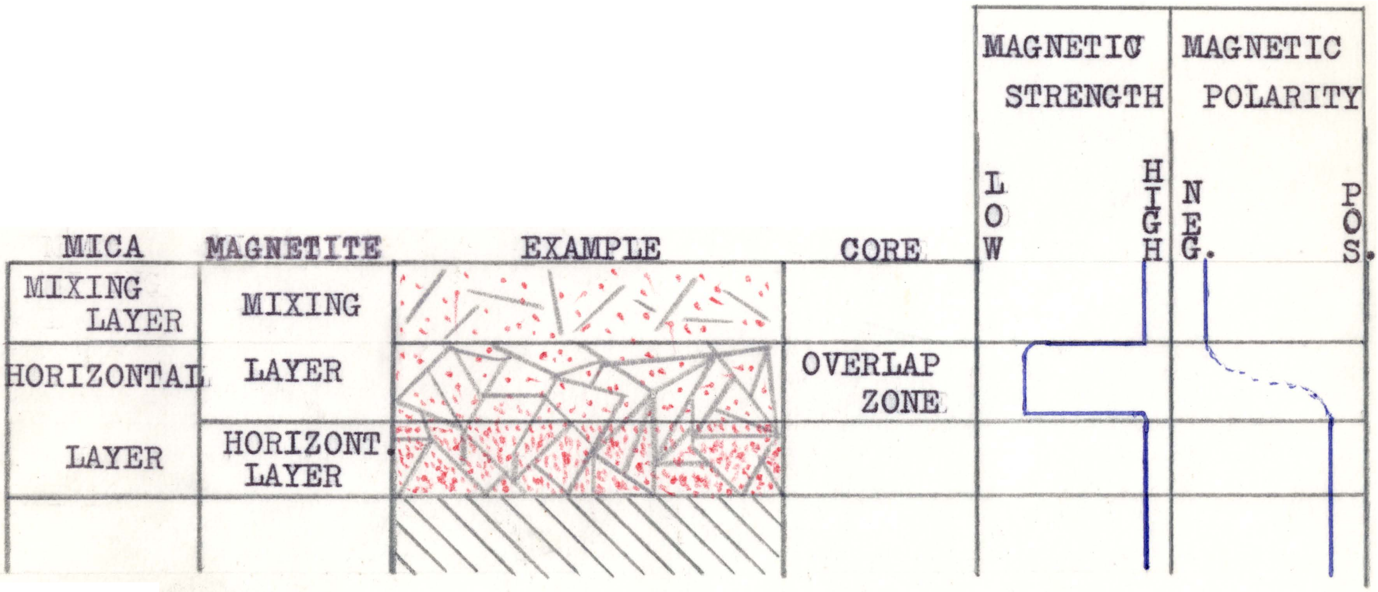

Figure 3.

Differential settling between mica plates (gray) and quartzite grains (red dots). The hatched area represents consolidated sediments as in figure 2. The overlap zone and magnetic graphs refer to the example after it has become completely consolidated and sampled as a core which experienced a reversal at the time shown. The dotted section of the polarity curve is the "fuzzy" zone.

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