Mammals and Magnetostratigraphy

Donald R. Prothero

Department of Geology
Occidental College
Los Angeles, California 90041

ABSTRACT

Magnetic polarity stratigraphy has become one of the most important tools for correlation of fossiliferous terrestrial deposits. Since 1975, many of the suitable fossiliferous terrestrial vertebrate-bearing sequences in North America, Eurasia, South America, and Africa, have been correlated with the magnetic polarity timescale. These correlations have not only improved our understanding of the temporal sequence of vertebrate evolution, but have also been used to test the synchroneity of biostratigraphic events and the timing of migrations, and to calibrate rates of evolution and sedimentation. Only magnetostratigraphy allows direct correlation of most marine and non-marine sequences, so that correlation of global oceanographic climate events with the land record are also possible.

Key words: Geochronology; geophysics – solid earth; review article; stratigraphy, historical geology, paleoecology.

INTRODUCTION

One of the most rapidly growing techniques for interpreting earth history is magnetic polarity stratigraphy. The method was first applied to sedimentary sequences with the correlation of deep-sea cores, beginning with studies by Harrison and Funnell (1964) and Opdyke and others (1966). By the early 1970s, the use of magnetostratigraphy was widespread in the geological sciences. Johnson and others (1975) and Lindsay and others (1975) were the first to study paleomagnetism in sediments bearing fossil vertebrates. In the last thirteen years, its application to fossiliferous terrestrial sections has grown explosively, so that many of the classic areas have now been studied.

It is not surprising that magnetic stratigraphy was so rapidly embraced by vertebrate biostratigraphers. Terrestrial sections, particularly those of Cenozoic age, can be ideal for magnetostratigraphy. They typically contain fine-grained sediments that are well exposed and rarely deformed or metamorphosed. More importantly, they rarely contain datable volcanic rocks or any other method to provide a numerical age of the deposits. The biochronology of land vertebrates was painstakingly worked out from complex correlations of many fossil localities (first codifed by Wood and others, 1941). Numerical ages did not become widely available until the advent of potassium-argon dating of Cenozoic localities (Evernden and others, 1964). For most areas, however, the numerical age can only be approximated based on the biochronology of the mammals. Magnetic polarity stratigraphy has made it possible to correlate these sections with the global magnetic polarity timescale, and thus provide some of the first numerical dates for critical faunas.

STRENGTHS AND LIMITATIONS

The basics of rock magnetism and the earth's magnetic field behavior have been discussed in books such as those by McElhinny (1973), Merrill and McElhinny (1983), Collinson (1983) and Tarling (1983), so I will not give the complete background here. Instead, I will concentrate on aspects that are particularly crucial to the understanding of the magnetic stratigraphy of fossiliferous terrestrial sections. Although many of these ideas and problems have been discussed in the literature for years, and are well known to magnetostratigraphers, only a few articles (see, for example, Channell, 1982) have attempted to summarize them for the general geologist. Some of the points covered in this article were summarized by Lindsay and others (1987), but that article appeared after this paper was written and reviewed.

All stratigraphic methods have their strong points and their weaknesses (reviewed in Prothero, 1989). Magnetic stratigraphy is no exception. Carefully applied, it can provide answers that were never before possible. Without proper caution, however, serious mistakes can be made. Since the method of magnetic stratigraphy has grown so rapidly in the last decade, few geologists have had enough training to properly evaluate published paleomagnetic data. In this article, I will try to outline some of the important caveats that the informed geological consumer should keep in mind when citing paleomagnetic studies. Paleomagnetism has become so important in so many areas of geology that few can afford to ignore it and avoid learning how to read such studies critically.

STRENGTHS

The nature of the reversal of the earth's magnetic field results in several unique aspects of magnetic stratigraphy that are not true of any other method of correlation. Magnetic polarity reversals are:

1. *Worldwide.* No other geological event that is recorded in sediments takes place on a worldwide basis, and most (such as ashfalls, geochemical, or biostratigraphic events) are local or regional in extent. A possible exception to this are unique geochemical signatures, such as the Cretaceous-Tertiary iridium anomaly, but even this can be missing in any section with an unconformity at the boundary.

2. *Geologically instantaneous.* High-resolution studies of magnetic polarity reversals recorded by dated lava flows and deep-sea cores show that they take about 4000-5000 years to change from one polarity state to the other (Opdyke and others, 1973; Clement and others, 1982). For most geological events older than the Holocene, this interval is too short to be resolved, since even subtle hiatuses can wipe out the record of that much time. Very few sections record this short interval of polarity transition, so for most studies, the abrupt polarity changes occur between sampling levels and can be treated as geologically instantaneous. By contrast, lithostratigraphic boundaries are notoriously time-transgressive (Shaw, 1964), and some biostratigraphies are facies-controlled and therefore time-transgressive as well (McDougall, 1980).

3. *Independent of facies or lithology.* With the exception of huge volcanic eruptions and possibly geochemical events, no geologic event is recorded in both terrestrial and marine sediments like polarity reversals. This is particularly important since there are few places in the world where fossiliferous terrestrial and marine sequences interfinger, allowing direct correlation. Polarity reversals can be recorded in deep sea muds and limestones as they are in terrestrial floodplains muds, circumventing the problem of facies changes that plague lithostratigraphic correlation.

4. *Constant resolution regardless of age.* Flynn and others (1984, Figure 1) have shown that the resolution for magnetic polarity intervals is in the order of 300,000-500,000 years, and this remains true for very ancient rocks (except during periods with few polarity changes). This is because polarity transitions are not only geologically instantaneous, but have apparently always been so in the geological past. In contrast, the inherent

analytical error in most radiometric dates is a fixed percentage of their numerical age, so the error gets worse in older and older rocks. For a 10 Ma sample, an error of 5 percent gives a resolution of 1 million years, but for rocks of 100 Ma, the resolution is about 10 million years. Thus, the resolution of most radiometric dating is superior to magnetostratigraphy only in the Quaternary, and gets progressively worse with more ancient records. New Ar-Ar dating techniques are currently pushing the limits of precision down to 1-2 percent, so that this radiometric method may resolve events of less than a million years back to the Miocene. Biostratigraphic resolution is usually on the order of one million years or more (Berggren and Van Couvering, 1978; House, 1985), so rarely does it offer better resolution than magnetostratigraphy.

LIMITATIONS

Along with all the great advantages of magnetostratigraphy come some unique drawbacks that prevent its application in many instances. Magnetostratigraphic correlations:

1. *Must be calibrated by some other means of time control.* The magnetic polarity of a given rock sample does not give a unique "age" by itself. Its polarity is either normal or reversed, and both of these states have occurred frequently in the geologic past. Correlation is based on the total magnetic pattern of a relatively thick sequence of rock. Since rates of sediment accumulation are variable, this pattern rarely can be matched to the magnetic polarity timescale (MPTS) without additional information. Instead, the age of the magnetic polarity sequence must be approximated by associated radiometric dates or biostratigraphy so that the possible matches with the MPTS can be narrowed down to a few or hopefully one solution. The more such calibration points, the more confident the magnetic correlation. By contrast, both radiometric dating and biostratigraphy are based on unidirectional, irreversible processes (radioactive decay and evolution) that permit a unique age determination from a single sample.

2. *Are limited prior to the Jurassic* (since the MPTS is based on the sea-floor spreading record, which is no older than Jurassic (185 Ma at the maximum)). There are more and more pre-Jurassic polarity records now available, but the absolute spacing of polarity events is uncertain, since rates of sediment accumulation are so variable. Older rocks are also increasingly subject to secondary overprinting by diagenetic minerals, so their polarity signal can be difficult to extract. Nevertheless, studies of the Paleozoic rocks of the Siberian Platform (Molostovsky and others, 1976) have provided a first approximation of the pre-Jurassic MPTS. By contrast, the spreading of the sea floor is a relatively constant "tape recorder" that provides the true lengths of polarity intervals from the Jurassic onward (Heirtzler and others, 1968; LaBrecque and others, 1977; Ness and others, 1980; Berggren and others, 1985).

3. *Are vulnerable to unconformities.* Since correlation depends upon a complete pattern with relatively consistent thicknesses of polarity zones, any significant loss of sedimentary record will either shorten a polarity zone or eliminate it altogether. The best way to avoid this problem is to seek sections with no apparent unconformities, and with good biostratigraphic control that would reveal cryptic unconformities by truncated biostratigraphic ranges. The possible effects of stratigraphic completeness on magnetic polarity records have been discussed by May and others (1985). Despite these reservations, however, several large-scale studies of terrestrial sections have shown that the relative thickness of polarity intervals can be remarkably consistent over wide areas and long periods of time (Tauxe and Opdyke, 1982; Prothero, 1985d).

4. *Are limited by the nature of rock magnetization.* Not all rock types are good recorders of the earth's magnetic field. In addition, there are many ways that the original signal can be distorted or destroyed. Rock magnetic studies have long shown that a stable magnetic remanence can only be carried by very small grains that are too tiny to have more than one magnetic domain within them. Above a certain size (in the order of tens of microns), the magnetic grain is large enough to have two or more magnetic domains within it. Once this happens, the domains will interact in complex ways, so that its remanence may not reflect the applied field of the earth. This means that siltstones, claystones, and limestones are typically suitable for magnetic studies, but coarser sandstones seldom hold a stable remanence.

Even if the lithology is suitable, there may be other problems with extracting the primary, or characteristic, remanence. All rocks have been influenced by the current normal polarity of the earth's magnetic field, which has persisted for the last 730,000 years. As a consequence, they have acquired some secondary remanence which results in a normal overprinting of almost all samples, including reversely magnetized rocks. After the natural remanence of the sample is measured, the first step is to demagnetize the sample with higher and higher alternating fields and/or higher and higher temperatures to remove the less stable (and presumably younger secondary) components of the total natural remanence. Without some sort of demagnetization studies to determine the nature of the remanence, paleomagnetic data is worthless.

After careful demagnetization studies on the right types of sediments, however, there can still be problems. One of the most serious is a chemical remanence acquired by diagenetic growth of iron oxides and hydroxides long after the sediment was deposited. Since this diagenesis can occur at any time after the sediment was formed, its polarity may have no relation to the primary magnetization of the sample. Unfortunately, such chemical remanence is often produced by minerals such as hematite, which are nearly impossible to remove by normal demagnetization techniques. Hematite has both a higher coercivity and a higher blocking temperature than more common magnetic minerals such as magnetite. If the primary remanence is carried by magnetite and a secondary chemical remanence by hematite, then demagnetization studies will eliminate the signal and leave the overprint. It is then very difficult to extract the desired information. This means that rocks with a high content of iron oxides, especially redbeds, can be very difficult and often impossible to get good results from.

PREFERRED CONDITIONS

Most magnetostratigraphers have been approached by researchers who are eager to have their area sampled, but don't know what is suitable for study. The discussion above should give a hint about which conditions are ideal for magnetostratigraphic analysis, and which ones are risky or hopeless. Ideally, the magnetostratigrapher needs *thick, continuous, undeformed, well exposed sections* of *fine-grained* (mudstone, siltstone, or limestone, but NOT coarse sandstone) rocks with *biostratigraphic or radiometric dates* for independent time control of the magnetic pattern. If the section is too short, too poorly exposed, too coarse, or has obvious unconformities, then there is an obvious risk that no interesting results can be obtained. It may not be worthwhile to invest the time and effort to sample it and do the laboratory work. If there is no existing time control on the section from either biostratigraphy or numerical dating, then it is probably not worth even starting such a study.

FIELD SAMPLING

If a section looks promising, the first step is sampling. Some rock types, such as limestone, can be sampled with a rotary coring drill (long used to sample basalts). Most fossiliferous sections are made of soft sedimentary rocks that cannot be sampled by the coring drill. For this reason, most sampling is carried out with simple hand tools. After digging below the weathered horizon, the sampler uses simple chisels and scrapers to plane off a smooth (usually horizontal) surface. With a compass, the orientation of the sample is then recorded on the surface, and then the sample can be removed (often the most difficult step), wrapped up, and transported to the laboratory. Because individual samples can often give spurious results, the standard procedure since the pioneering study of Johnson and others (1975) has been to collect a minimum of three samples at each level, or site. Three samples are the minimum necessary to calculate the statistics of the clustering of the sample magnetization directions, and to determine if the mean direction is statistically random or significant. With three samples per site, the paleomagnetist must decide how many sites can be sampled, given the logistical constraints of crew size, time available, sampling rate and difficulty, and many other factors (Johnson and McGee, 1983). If the section is relatively thin and there is good reason to suspect several polarity reversals, then sites may be taken every meter, or every few meters. For reconnaissance sampling, on the other hand, ten-meter or greater sampling intervals are not unusual. Sampling intervals may also be determined by suitable lithologies, and there may be sampling gaps through long sections of unsuitable sandstones or conglomerates.

LABORATORY ANALYSIS

Once all the samples have been taken, along with the necessary data about their stratigraphic position and field orientation, they must be analyzed in the laboratory. The first step is to take the irregular blocks of rock out of their field wrappings and trim them down to one-inch cubes with the oriented face on one side. This is usually done on a rock saw or a band saw with a long-lasting tungsten carbide blade. If the rock is hard enough, then a coring drill can be used in the lab to extract cores from the hand sample.

The samples are measured in a magnetometer, which senses both the direction and intensity of the magnetic vector in the sample. In the 1960s and 1970s, most of the work was done on a *spinner magnetometer* (Molyneaux, 1971; Collinson, 1983). This device spins the sample within a pickup coil (commonly a ring fluxgate), which then carries an electrical signal that the microcomputer can process into a magnetic vector. The disadvantage of the spinner magnetometer is that it is slow (2-20 minutes or more per sample), hard on the samples (fragile samples may fall apart, and liquids cannot be spun), and not very sensitive. Basalts can be measured easily, but most sediments have remanences that are 3-5 orders of magnitude weaker, and just at the limit of sensitivity of the machine. The newest fluxgate magnetometers, however, are becoming increasingly more sensitive, and some are even portable. Since the late 1970s, however, most larger paleomagnetic labs have been equipped with a *cryogenic magnetometer* (Goree and Fuller, 1976; Collinson, 1983). This device lowers the sample into a region surrounded by a superconducting quantum interference device (known as a SQUID), which is kept superconducting with liquid helium at 4 degrees K. Since it is superconducting, it has almost no resistance to electrical current. The presence of even a weakly magnetized specimen in the sensing area will induce an electrical current that can be converted to a magnetic signal.

Cryogenic magnetometers have several advantages over most spinner magnetometers. First, they are very fast. Each measurement typically takes only a few seconds to stabilize and be read by the computer. Since the specimen is not spun, any sample can be measured, including liquids and living animals. Most importantly, cryogenic magnetometers are 2-3 orders of magnitude more sensitive than most spinner magnetometers, so they can measure even the most weakly magnetized siltstone or limestone. Their main drawbacks are their great cost and their maintenance. They are notoriously sensitive and temperamental, and most successful labs have someone skilled in electronics on hand to maintain them. The expense of operating them is greater, since they require liquid helium (typically \$300-600 a shipment, which may last only a few weeks). If they are allowed to warm up, then they have to be cooled down again with liquid nitrogen. As a consequence, some labs keep the machine cooled down continuously. With the new breakthroughs in high-temperature superconductors, we can expect magnetometers in the near future which are smaller, cheaper, and use liquid nitrogen, which is considerably less difficult to handle.

The first sample measurement is the *natural remanent magnetization*, or NRM, which is a measure of the remanence of the sample before any treatment. Typically, the NRM is composed of several different magnetic directions acquired at different times in the history of the sample. Only the original, or primary, remanence records the field direction at the time the sample was deposited, and this is the "signal" that is often overprinted by "noise" of remanences acquired in younger magnetic fields. As discussed above, the sample must be demagnetized to get rid of less stable, and presumably younger, magnetic fields.

There are two primary methods to accomplish this. The sample can be placed inside a magnetically-shielded coil and subjected to stronger and stronger alternating fields (AF). These rapidly fluctuating fields destroy the domain walls of less stably magnetized components and randomize their remanence. The other approach is to subject the sample to higher and higher temperatures in a field-free space (thermal demagnetization). The less stable components usually have lower blocking temperatures, so they are often eliminated first.

After each demagnetization step, the specimen must be remeasured in the magnetometer. In most studies, each sample is demagnetized in several steps, and the changing vectors are plotted on a stereonet to determine the change in direction. Paleomagnetists also use vector demagnetization, or Zijderveld plots (As and Zijderveld, 1958; Kirschvink, 1980), to get a simultaneous display of both direction and intensity changes. From these plots, the best combination of AF and/or thermal cleaning for the rest of the samples can be determined.

Because of the problem with chemical remanence discussed above, both methods of demagnetization are typically employed. In the past, the faster AF method was often the only method used. In recent years, it has become apparent that a high-coercivity mineral, such as goethite or some other iron hydroxide can impart a secondary chemical remanence in specimens that have no visible indication of diagenetic alteration. These minerals do not respond to AF demagnetization, but are dehydrated and oxidized at 200-300 degrees C, so thermal demagnetization can eliminate the problem. Nevertheless, some paleomagnetists (see, for example, Butler and Lindsay, 1985; Prothero, 1985a) have had to revise their polarity interpretations when spurious normal polarity intervals disappeared after thermal demagnetization. The geologist who uses paleomagnetic data should always check for mention of thermal demagnetization studies, and treat data with great caution if only AF treatment has been employed.

Once a stable, characteristic direction is acquired for each sample in the study, then all sample vectors at a given site are averaged to get a mean vector. If there are three or more vectors, then the statistical significance of this mean vector can be calculated, using the spherical vector methods of Fisher (1953), Watson (1956), and Irving (1964), described in Tarling (1983, p. 117). The precision parameter, k, and the circle of confidence, $\alpha95$, are both used as measures of the statistical scatter of the vectors. With increasing precision, the value of k increases and the radius of the circle, α 95, decreases. For a given number of samples there is a critical cutoff value of α 95. If the site value is greater than the cutoff value, it means that the site clustering cannot be distinguished from a random clustering at the 95% confidence level. With weakly magnetized samples, however, it is not unusual for the sample directions to cluster poorly, even though they may give a clear polarity indication. Hence, paleomagnetists will often show such data, although they will use different symbols to indicate sites which did not pass the significance test (see, for example, Opdyke and others, 1977).

All of this information is then plotted on a polarity log adjacent to the stratigraphic section. All available biostratigraphic and/or radiometric data is used to correlate the polarity pattern to the polarity timescale. Ideally, there will be an unusually and characteristically long interval of normal or reversed polarity which occurs during the time as constrained by fossils and/or radiometric dates. Once this "key" interval is matched, then the rest of the shorter and less distinctive polarity intervals can be matched to the MPTS (see, for example, Johnson and others, 1982, Figure 13; Prothero, 1985a, Figure 8). In some cases, however, there is no unique interpretation of the polarity record, and several alternatives must be given (see, for example, Barghoorn, 1981). In other cases, the section may be entirely of one polarity. If the biostratigraphic and/or radiometric data are very good, then the section may be placed within a known polarity interval, but this does not offer much more resolution than the original stratigraphic data (see, for example, Prothero, 1984). However, it does constrain the total duration of the section to one polarity interval, which is not possible with radiometric dates alone.

Most complete paleomagnetic studies include other elements to determine the reliability of the data. As the samples are demagnetized, it is usually apparent what mineral is the carrier of the remanence. However, a complete study includes an analysis of the magnetic mineralogy. Analysis of the *Curie point*, or the temperature below which the mineral locks in a stable remanence during cooling, can be used as an indicator of the chemical composition of the magnetic mineral. Petrographic studies of the magnetic minerals, particularly under reflected light, are also widely used.

Even more important is some sort of test for field stability. The circle of confidence of the mean direction of the site should include the paleomagnetic pole for the locality at the appropriate interval of geologic time. The mean direction of the normal samples should be 180 degrees away from that of the reversed samples (*reversal test*). If the samples come from tilted or folded rocks, then correction for the folding should improve the clustering of the samples (*fold test* of Graham, 1949; see McFadden and Jones, 1981). If not, then the samples were magnetized after the folding, and the remanence is probably not depositional. The presence of conglomerates (Graham, 1949) or baked contacts around intruded dikes (Everitt and Clegg, 1962) can also be used when available (Cox and Doell, 1960; McElhinny, 1973, p. 84). The more of these tests that can be used, the greater the confidence that the magnetic directions are recorded during the original deposition of the sediment.

APPLICATIONS TO UNDERSTANDING VERTEBRATE HISTORY

Improvements in Correlation

Magnetic stratigraphy has been used for many purposes in the last decade. The most obvious of these is improved correlation of the stratigraphic record. Since most terrestrial vertebrate-bearing sequences lack radiometric dates, the only previous means of correlation was based on the biochronology of the mammals themselves (Wood and others, 1941). In the last fifteen years, however, many of the classic sections that have suitable characteristics have been tied to the MPTS (Figure 1, Table 1). These improvements, along with many of the newer radiometric dates, have been incorporated into the latest revision of Cenozoic mammalian biochronology (Woodburne, 1987). It is now possible to infer numerical ages for much more of the terrestrial vertebrate record than was ever possible in the past.

Most of these new correlations have refined the previous estimates based on vertebrate biochronology. In a few cases, however, the magnetics have radically realigned the timescale. For example, MacFadden and others (1985) found that the

Figure 1(right). Temporal spans of selected magnetostratigraphic studies of North American terrestrial sections bearing land vertebrate fossils. Numbers indicate studies cited in Table 1. The North American Land Mammal "Ages" follow this sequence from Paleocene to Pleistocene (abbreviated by first letter): Puercan, Torrejonian, Tiffanian, Clarkforkian, Wasatchian, Bridgerian, Uintan, Duchesnean, Chadronian, Orellan, Whitneyan, Arikareean, Hemingfordian, Barstovian, Clarendonian, Hemphillian, Blancan, Irvingtonian.

Oligocene Deseadan Land Mammal "Age" of South America was about ten million years younger than previous estimates, and mostly Miocene in age. Marshall and others (1986) found that most of the Miocene Land Mammal "Ages" of South America were considerably younger and shorter than previously thought. As a consequence, virtually everything that has been said about rates and correlation of changes in South American faunas must be recalculated and rethought.

Global Correlation

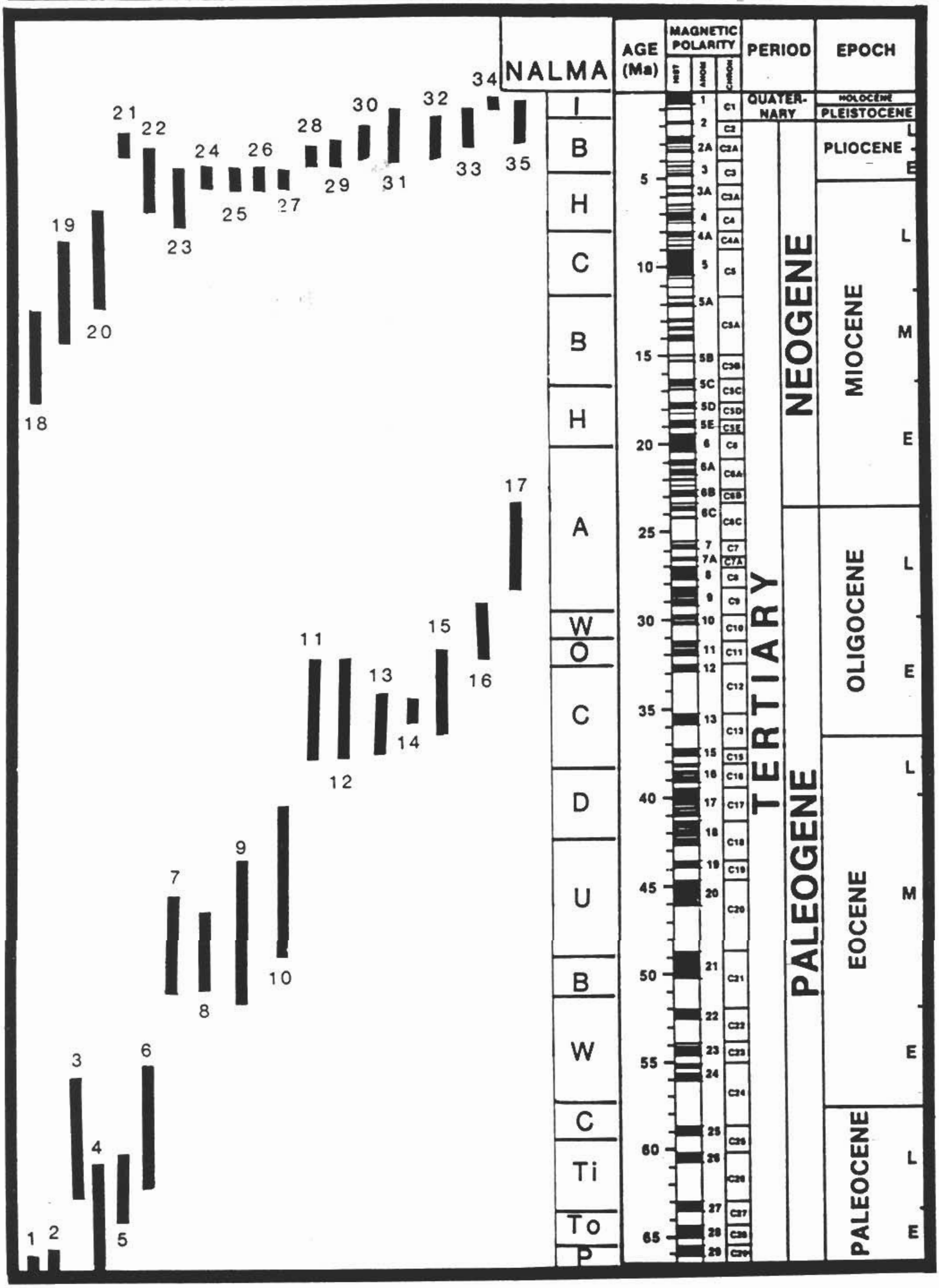
The improvements in correlation go beyond tying together terrestrial sequences. Once the local magnetic record is matched with the global MPTS, then it is possible to match terrestrial and marine chronologies. Since fossiliferous terrestrial deposits seldom interfinger with fossiferous marine deposits, this represents the first such opportunity to determine the timing and synchroneity of terrestrial and marine events. There are many interesting problems that can be solved with this improved correlation network. For example, Prothero (1985b, c) correlated changes in terrestrial Eocene and Oligocene faunas with the global marine climatic record, and showed that terrestrial extinction events were closely associated with pulses of Antarctic glaciation and global cooling.

The terrestrial record, in turn, has proven important in calibrating the MPTS. Since marine deposits rarely contain datable volcanic layers, the timescale of Berggren, Kent and Flynn (1985) relies heavily on the terrestrial magnetostratigraphy of Flynn (1986) and Prothero (1985a). Although there is still considerable controversy about the Cenozoic timescale, the discovery and dating of marine biotites directly associated with pelagic marine fossils and magnetics in the Gubbio section in Italy (Montanari and others, 1985) has provided striking confirmation of the Berggren, Kent, and Flynn timescale. The timescale controversy continues, but no matter how it is resolved, terrestrial magnetostratigraphy and the associated high-temperature radiometric dates have proven to be crucial.

Testing Biostratigraphy

Since polarity reversals serve as geologically instantaneous *time planes, they can also be used to test the timing of other* events that are supposed to be time-significant. Prothero (1982) used magnetic stratigraphy to test the synchroneity of mammalian biostratigraphic events in the Oligocene, and found they were consistently within the same polarity intervals. Flynn (1986) did a similar study for middle Eocene faunas, with similar results. Flynn and others (1984) and Tauxe and Clark (1987) reviewed the claims made for faunal heterochrony by Hickey and others (1983) and Butler and others (1981). In both cases, they found no evidence for true faunal heterochrony. Bad magnetic data which had been interpreted to indicate heterochrony had to be reinterpreted.

However, Flynn and others (1984) did show that individual faunal datum planes, such as the notorious *Hipparion* datum in the Old World (Woodburne and others, 1981) or the *Lepus* datum in the American Southwest (Opdyke and others, 1977), can show significant heterochrony. This indicates that biostratigraphic events based on a single taxon must be interpreted with caution.


NALMA
AGE (Ma)
MAGNETIC POLARITY
PERIOD
EPOCH
QUATERNARY
TERTIARY
NEOGENE
PALEOGENE
HOLOCENE
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE

NORTH AMERICA

Cretaceous

[1] Red Deer area, Edmonton, Canada	(33N-29N)	Lerbekmo and others, 1979; Lerbekmo and Coulter, 1985
[2] Hell Creek Fm., Montana	(30N-29N)	Archibald and others, 1982
Raton Basin, New Mexico-Colorado	(29R)	Payne and others, 1983

Paleocene-Eocene

[3] Clark's Fork Basin, Wyoming	(26R-24N)	Butler and others, 1981
Crazy Mountains, Montana	(27R-26R)	Butler and others, 1987
[4] San Juan Basin, New Mexico	(31R-26R)	Butler and Lindsay, 1985; Butler and others, 1977; Lindsay and others, 1978; Taylor and Butler,1980
[5] Dragon Canyon, Utah	(28N-26R)	Tomida and Butler, 1980
[6] Big Bend area, Texas	(26R-24N)	Rapp and others, 1983
Baja California	(24N-23R)	Flynn and Novacek, 1984; Flynn and others, 1988
[7] San Diego, California	(21R-20N)	Flynn, 1986
[8] East Fork Basin, Wyoming	(22R-20R)	Flynn, 1986
[9] Washakie Fm., Wyoming	(22N-19N)	Flynn, 1986
[10] Devil's Graveyard Fm., Texas	(21N-17R)	Walton (in press)
Uinta Basin, Utah		Prothero (in preparation)
Dell Beds, Sage Creek, Montana		Prothero (in preparation)
Ellesmere Island, Canadian Arctic		Hickey and others, 1983; Tauxe and Clark, 1987

Oligocene

[11] Vieja Group, Texas	(15N-12N)	Testarmata and Gose, 1979; Prothero, 1985a
[12] Flagstaff Rim, Wyoming	(15N-12N)	Prothero and others, 1982, 1983; Prothero, 1985a
[13] Ledge Creek, Wyoming	(15N-12R)	Prothero, 1985a
[14] Pipestone Springs, Montana	(13N-12R)	Prothero, 1984
[15] Dilts Ranch, Wyoming	(13R-10R)	Prothero, 1985a
[16] Brule Fm., ND-SD-NE-WY-CO	(12N-9R)	Prothero and others, 1983; Prothero, 1985d
Cook Ranch, Montana	(11R)	Prothero and Tabrum (in preparation)
[17] John Day Fm., Oregon	(8R-6CN)	Prothero and Rensberger, 1985
Arikaree Group, Nebraska	(8R-6CN)	MacFadden and Hunt (in preparation)

Neogene

[18] Barstow Fm., California	(5D-5AA)	MacFadden and others, 1987
[19] Tesuque Fm., New Mexico	(5AR-4AR)	Barghoorn, 1981
[20] Ricardo Fm., California	(5AR-4N)	Burbank and Whistler, 1985, 1987
[21] 111 Ranch, Arizona	(2N-12A)	Galusha and others, 1984
[22] Verde Fm., Arizona	(2A-4N)	Bressler and Butler, 1978
[23] Chamita Fm., New Mexico	(3R-4AN)	MacFadden, 1977
[24] Coffee Ranch, Texas	(3AN-3AR)	Lindsay and others, 1975
Mount Eden, California	(3R)	May and Repenning, 1982
[25] White Cone-Bidahochi, Arizona	(3A-3AR)	Lindsay and others, 1984
[26] Wickieup-Big Sandy Fm., Arizona	(3A-3AR)	MacFadden and others, 1979
[27] Redington, Arizona	(3AN-3AR)	Lindsay and others, 1984
[28] Yepomera, Chihauhau, Mexico	(3N)	Lindsay and others, 1984
[29] Ringold Fm., Washington	(2AN-2AR)	Lindsay and others, 1984
[30] Glenns Ferry Fm., Idaho	(2R-2AR)	Neville and others, 1979; Lindsay and others, 1984
[31] Anza-Borrego, California	(1R-3R)	Opdyke and others, 1977
[32] San Pedro Valley, Arizona	(2AN-2AR)	Johnson and others, 1975
[33] Mt. Blanco/Cita Cyn./Red Cone, Texas	(2R-2AN)	Lindsay and others, 1975
[34] Irvington, California	(1R)	Lindsay and others, 1975
[35] Kansas Pleistocene (Borchers, Rexroad,etc.)	(1R-2AN)	Lindsay and others, 1975

(Continued on next page.)

SOUTH AMERICA	
Salla, Bolivia (late Oligocene)	MacFadden and others, 1985
Santa Cruz, Argentina (Miocene)	Marshall and others, 1986
Type Uquian, Argentina (Miocene)	Marshall and others, 1982
Type Friasian, Chile (Miocene)	Flynn and Marshall (in progress)
La Venta, Colombia (Miocene)	Flynn and Marshall (in progress)
Catamarca, Argentina (Mio-Pliocene)	Butler and others, 1984
Tarija, Bolivia (Pleistocene)	MacFadden and others, 1983
AFRICA	
Baringo Basin, Kenya (Miocene)	Tauxe and others, 1985
Koobi Fora Fm., Kenya (Mio-Pliocene)	Hillhouse and others, 1986
Shungura-Usno Fms., Ethiopia (Mio-Pliocene)	Brown and others, 1978
EURASIA	
Italy and France (Pliocene)	Lindsay, 1979
Siwalik Hills, Pakistan-India (Miocene-Pliocene)	Lindsay and others, 1980; N. Johnson and others, 1982, 1985; Keller and others, 1977; G. Johnson and others, 1983; Opdyke and others, 1979; Opdyke and others, 1982; Tauxe and Opdyke, 1982; Barry and others, 1982, 1983; Behrensmeyer and Tauxe, 1982

Table 1. Recent paleomagnetic studies on vertebrate-bearing terrestrial sections, arranged by age and locality. Studies shown in Figure 1 are indicated by the number in brackets [].

Migrational events are also used widely in terrestrial biostratigraphy. Lindsay and others (1980) used magnetostratigraphy to show that the there were three different migrational first appearances of *Equus* in the Old World during the Pliocene. Lindsay and others (1984) used magnetic stratigraphy to calibrate many different migrational events in the last seven million years. In addition to calibrating many of the exchanges between the Old World and North America, Lindsay and others (1984) were able to show that the Great American Interchange between North and South America over the Panamanian filter bridge took place about 2.5 million years ago.

Rates of Evolution

Magnetic polarity reversal boundaries provide not only time planes, but a succession of dated horizons. Terrestrial sections rarely contain more than one marker that provides a numerical age, so sections with several magnetic reversals are unusually good for calculating rates of sediment accumulation. This has been utilized a number of times (see, for example, Badgely and others, 1986; Tauxe and Opdyke, 1982; Behrensmeyer and Tauxe, 1982). Once these rates have been calculated, then rates of change in the fossils contained in those sediments can also be calculated. Several such studies have already been done with marine invertebrates. Prothero (1985b, 1985c) found that the rates of change of mammals at the Chadronian-Orellan extinction event were fairly slow. Dwarfing in the oreodont *Miniochoerus* may have taken as little as 300,000 years. These data will continue to be important in the longstanding controversy over the tempo and mode of evolution.

CONCLUSION

Magnetic polarity stratigraphy has become one of the most important tools of vertebrate biochronology since it was first introduced in 1975. Although there are many pitfalls in the method, it is the only one which provides global, geologically-instantaneous time planes that have constant resolution regardless of age and are independent of facies or lithology. It is particularly useful in correlating terrestrial and marine sections, where such correlations were impossible before. It has been used to greatly improve the chronology of Cenozoic land mammals in North America, and to a lesser extent in Eurasia, Africa, and South America. Magnetostratigraphy has radically rearranged our understanding of South American Oligocene and Miocene terrestrial chronology. It has also provided time planes for testing the timing of biostratigraphic events and the timing of migrations. Magnetic "time planes" provide the tie points on which estimates of rates of sediment accumulation, and rates of evolution, can be based. Finally, by connecting marine and terrestrial records, it is possible to examine the effects of global changes in climate on terrestrial faunas much more precisely than in the past.

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About the Author

Donald R. Prothero received his BA in geology and biology from the University of California (Riverside), and his MA, M Philosophy, and PhD from Columbia University. His primary research interest is in the evolution and extinction of fossil mammals from the Eocene and Oligocene, and the correlation of these events with global climatic changes. He has published over 30 scientific papers and a textbook, *Interpreting the Stratigraphic Record*, which will be out early in 1989. He will be a Guggenheim Fellow in 1988-1989.

Food for Thought

An important reason for the dominance of crystal silicon in electronics is the quality of its natural oxide. Silicon dioxide forms a glass film on the crystal, with an atomically abrupt interface between them. At the ordinary operating temperatures of the devices, it is mechanically stable, electrically insulating and chemically protective. . . . Silicate materials are ubiquitous in computer and communications technology. In addition to SiO_2 films in integrated circuits, crystalline SiO_2 (quartz) is used for self-resonant oscillators and filters (watches, clocks and frequency standards), and bulk glassy SiO_2 is used to form optical fibers. While some dielectric materials other than silica are important in [very large-scale integrated circuits] . . . SiO_2 is by far the most used and most studied material . . .

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