

The Paleomagnetism of Sediments and Sedimentary Rocks: Importance and Reliability

THE IMPORTANCE OF SEDIMENTARY PALEOMAGNETISM

Sediments and sedimentary rocks, both lacustrine and marine, are important targets for paleomagnetists who want to answer questions about global and regional tectonics, about paleoclimate, and about the behavior and history of the Earth's magnetic field. Of the 9259 results reported in the Global Paleomagnetic Database in 2009, 4971 (54% of them) were attributed to sedimentary rocks. Although estimates indicate that sedimentary rocks make up only about 8% of the total volume of the Earth's crust (Buchner & Grapes 2011), they are ubiquitous in the thin veneer of crustal rock available to geologists.

There are two significant reasons why sedimentary rock is an important target for paleomagnetic studies. The first is that sedimentary rocks give a nearly continuous record of the geomagnetic field. This is critically important to paleomagnetic studies because it allows undisputed time averaging of the secular variation of the geomagnetic field and the application of the geo-

magnetic axial dipole (GAD) hypothesis. The GAD hypothesis, that the Earth's magnetic field has been a dipole at the center of the Earth oriented parallel to the Earth's rotation axis, is central to the widespread and successful use of paleomagnetism in the Earth sciences. Without it, paleomagnetism would probably not be a subdiscipline of geology. Using the GAD hypothesis, paleomagnetists can calculate the paleolatitudes of rocks and the amount of vertical axis rotation that may have occurred in an area. The amount of time needed to adequately average the effects of secular variation is not easily determined. In fact, some paleomagnetists would argue that the departure of the time-averaged field from the GAD field is caused by a bias in secular variation that persists for millions of years, particularly back in the Paleozoic or Precambrian. Based on the behavior of the Earth's field over the past 5 million years, when plate motions would not be large enough to affect the observation of geomagnetic secular variation, averaging over several thousand years is generally considered a long enough time to ensure that a GAD field is observed.

The paleomagnetism of igneous rocks is much stronger than that of sedimentary rocks, so it is more robust and withstands the effects of remagnetization more easily than that of sedimentary rock paleomagnetism. However, just averaging the magnetizations of a pile of lava flows is no guarantee that enough time has passed to adequately average the effects of geomagnetic secular variation. For instance, data from the Hawaiian Volcano Observatory (Kauahikaua *et al.* 1998) show that the number of flows erupted in Hawaii per thousand years over the past 12,000 years varies from 1 to 11 in any given 1000 year period. Based on the sequence of flows erupted over the past 12,000 years and assuming that about 3000 years is needed to adequately average secular variation and obtain the GAD field, anywhere from 6 to 17 flows should be measured for a paleomagnetic study that can be reliably used to reconstruct paleolatitude or for other tectonic applications. Since the volcanic history in any particular region isn't known in detail, most workers use the amplitude of the circular standard deviation of virtual geomagnetic poles (VGPs) derived from lava flows to estimate whether secular variation has been adequately averaged. The behavior of the geomagnetic field over the past 5 million years is the only guide to the amount of secular variation, i.e. the amplitude of the circular standard deviation, expected if a sequence of igneous rocks has faithfully recorded secular variation.

Although there can be unrecognized unconformities and hiatuses in any sequence of sedimentary rocks, collecting samples from a thick stratigraphic section gives confidence that enough time has been sampled to average paleosecular variation. Knowing the average sediment accumulation rate from magnetostratigraphy, rock magnetic cyclostratigraphy, fossils, or from radiometric control can give assurance that secular variation has been averaged; even without this information, knowing the typical sedimentation rate for different lithologies can however guide sampling strategy and data interpretation (Table 1.1).

There is another reason why the continuity of sedimentary paleomagnetic records is important to paleomagnetists. Recent sediments (marine and lacustrine) and high-fidelity records from ancient sedimentary rocks allow the detailed observation of geomagnetic field behavior. A continuous record of Earth's magnetic field behavior is critical for understanding the generation of the geomagnetic field and for providing constraints on models of the geodynamo. The best constraints on geodynamo models come from records of transitional field behavior during polarity transitions (Merrill *et al.* 1996). There is a rich array of data from marine sediments showing the behavior of the field during the most recent polarity transition, the Brunhes-Matuyama, some 780,000 years ago. Clement (1991) was the first to show preferred longitudinal bands of virtual geomagnetic pole paths during the Brunhes-Matuyama polarity transition using the paleomagnetism of marine sediments. The accuracy of this result was questioned and then modified by observations from igneous rocks, but it was the continuity of the sedimentary paleomagnetic record that was critical to the Clement's initial observation. Recent work on sedimentary records of secular variation of the geomagnetic field at high latitudes (Jovane *et al.* 2008) shows field behavior close to the so-called tangent cylinder (latitudes $>79.1^\circ$), a cylinder parallel to the Earth's rotation axis that includes the inner core of the Earth. These workers collected 682 samples from a 16 m long marine core at 69.03°S in the Antarctic showing that the dispersion of secular variation was high (about 30°) during the past 2 myr suggesting vigorous fluid motion in the outer core. This kind of record would be nearly impossible to obtain from igneous rocks.

Finally, continuous records of geomagnetic field paleointensity variations from marine and lacustrine sediments not only allow another constraint on geodynamo models, but they can also provide a way to correlate and date marine sediments globally. The best example of this is Valet's work (Guyodo & Valet 1996, 1999; Valet *et al.* 2005) on constructing stacked rela-

Table 1.1 Typical sediment accumulation rates for sedimentary rocks

Sedimentary environment of deposition	Average sediment accumulation rate	Sampling thickness to average secular variation
Deep marine	1 cm/1000 years	~3 cm
Near-shore marine	0.1–1 m/1000 years	~0.3–3 m
Continental lacustrine	1 m/1000 years	~3 m

tive paleointensity records $S_{\text{int}200}$, $S_{\text{int}800}$ and $S_{\text{int}2000}$ over the past 200 thousand, 800 thousand and 2 million years, respectively.

The second important reason for the large number of sedimentary paleomagnetic results in the Global Paleomagnetic Database is that paleohorizontal can be unequivocally determined from sedimentary rocks. Knowing the paleohorizontal may seem trivial, but it is not always straightforward to determine for igneous rocks and it is absolutely critical for determining the paleolatitude of the rocks from the paleomagnetic vector, assuming a GAD field. Only the bedding of sedimentary rocks unambiguously gives the ancient horizontal. Intrusive igneous rocks provide no record of the paleohorizontal; it must be detected indirectly, sometimes by the rare occurrence of layered early crystallized minerals (Cawthorn 1996) or by techniques like the aluminum-in-hornblende paleobathymetric technique (Ague & Brandon 1996). One example of this approach comes from the paleomagnetic study of the Cretaceous Mt Stuart batholith. The paleomagnetism of the Mt Stuart batholith provides an important paleomagnetic data point in the argument for large-scale translation of Baja British Columbia along western North America's continental margin (Cowan *et al.* 1997). However, its anomalous paleomagnetic inclination could just as easily be explained by wholesale tilting of the batholith after it was magnetized. The small amount of tilt of the batholith, 7° according to the aluminum-in-hornblende paleobathymeter (Ague & Brandon 1996), argues for tectonic transport. It is not as convincing as paleohorizontal obtained from sedimentary bedding however, thus leaving the tectonic transport interpretation ambiguous. Another example of how the paleohorizontal of intrusive igneous rocks can only be determined indirectly comes from a paleomagnetic study of the Eocene Quottoon plutonic complex in the Coast Mountains of British Columbia. In this case, $12\text{--}40^\circ$ tilting of the pluton is inferred from a regular decrease in exhumation age from west to east across the pluton determined by a transect of K–Ar ages (Butler *et al.* 2001). In the Quottoon study the amount of tilting has a large effect on the interpretation of the paleomagnetic inclination of the rocks.

Extrusive igneous rocks of course have a much better control on the paleohorizontal, either from direct measurement of the layering in the lava flows or from the bedding of sedimentary rocks intercalated between the flows, but there can still be ambiguities.

One concern to paleomagnetists is the problem of initial dip of extrusive igneous rocks, particularly of highly viscous volcanic flows such as andesitic rocks. Strato-volcano edifices can have initial, non-tectonic dips up to $35\text{--}42^\circ$. Even low-viscosity basaltic flows can have dips as large as 12° (MacDonald 1972; Francis 1993; Gudmundsson 2009). These unrecognized dips contribute error to the measurement of the paleohorizontal for extrusive igneous rocks and hence in the paleolatitude determined from these rocks. One good example of the possibility of unrecognized tilt in igneous rocks comes from the work of Kent & Smethurst (1998) in which the frequency distribution of inclinations from the Global Paleomagnetic Database are binned into different time periods (Cenozoic, Mesozoic, Paleozoic and Precambrian) to see if they are consistent with the GAD hypothesis throughout Earth's history. The Cenozoic and Mesozoic data have inclination frequency distributions consistent with the GAD, but the Paleozoic and Precambrian bins have more low inclinations than predicted by random sampling of the GAD. Even sedimentary inclination shallowing is ruled out as the cause because exclusively igneous results show the effect. While Kent and Smethurst speculate that octupolar geomagnetic fields contributed to the dipole in these distant times, Tauxe & Kent (2004) point out that uncorrected and unaccounted-for dips of igneous rocks, both extrusive and intrusive, could also explain the effect.

Sediments and sedimentary rocks therefore have an important role to play in paleomagnetic studies because of the continuous record they provide and because their bedding planes give an unequivocal record of the ancient horizontal.

ENVIRONMENTAL MAGNETIC RECORD FROM SEDIMENTS AND SEDIMENTARY ROCKS

The continuity or near continuity of the sedimentary record, particularly when compared to igneous rocks, also makes sedimentary rocks an important target for paleoenvironmental studies. In environmental magnetic studies, the magnetic minerals of sedimentary rocks can record paleoenvironmental conditions. While sedimentary paleomagnetism uses directional and intensity records of the geomagnetic field for correlation, dating, and paleolatitude information, environmental magnetism uses parameters that measure

the concentration of magnetic minerals, magnetic particle grain size, and magnetic mineralogy of sedimentary rocks as proxies of the paleoenvironment. Several important books have been written on environmental magnetism (Thompson & Oldfield 1986; Evans & Heller 2003) and the reader is referred to them for a more complete treatment. Chapter 8 will however introduce and cover rock magnetic cyclostratigraphy in detail, which uses environmental magnetic principles. Rock magnetic cyclostratigraphy is an exciting new use of mineral magnetic measurements that provides high-resolution chronostratigraphy for sedimentary rock sequences.

Astronomically driven climate cycles are known to be recorded by sedimentary sequences lithologically (Hinnov 2000), but the environmental magnetism of the rocks can be a very sensitive detector of Milankovitch-scale climate variations. The rock magnetic record becomes particularly important when climate-driven lithologic changes are difficult to identify in sedimentary rocks (Latta *et al.* 2006). Ultimately, rock magnetic cyclostratigraphy can provide 20 kyr resolution, much better than even the best magnetostratigraphy that records even the shortest geomagnetic polarity chrons. Pioneering efforts by Ellwood (e.g. Ellwood *et al.* 2010, 2011) looking at magnetic susceptibility variations in stratigraphic type localities have not focused exclusively on the magnetic response to astronomically driven climate cycles. Measurements that examine the concentration variations of only depositional remanent magnetic minerals (magnetite or hematite) can be more straightforward to interpret than susceptibility measurements that respond to concentration variations of diamagnetic (calcite, quartz), paramagnetic (iron-bearing silicates), and remanent magnetic minerals. Concentration variations of remanent magnetic minerals therefore have the potential to provide cleaner records of global climate cycles, either run-off variations from the continents or global aridity.

THE EVIDENCE FOR HIGH-QUALITY PALEOMAGNETIC DATA FROM SEDIMENTARY ROCKS

A main focus of this book is the accuracy of sedimentary paleomagnetic records, including some processes that can cause inaccuracies and biases in sedimentary paleomagnetism. The starting point of this discussion must however be the understanding that sediments

and sedimentary rocks can and do provide very high-quality and accurate records of the Earth's magnetic field throughout geologic time. The intent of this book is not to give the impression that there are insurmountable problems with sedimentary paleomagnetic data. Rather, the aim is to discuss some of the very important inaccuracies that can arise in sedimentary paleomagnetic data. These inaccuracies tend to be essentially second-order effects, but prevent paleomagnetism from achieving its full potential as an important tool for the Earth sciences.

The evidence that young sediments can provide a good record of the geomagnetic field is plentiful. I will show some examples, but it is by no means an exhaustive list. In doing so I will also give an estimate of the repeatability of these sedimentary records of the geomagnetic field; this is not so much a rigorous measure of the accuracy of the sedimentary paleomagnetic recorder, but a way of estimating the precision of the very best sedimentary paleomagnetic recorders. This is probably the only way to understand the accuracy of the paleomagnetism since, for most cases, the true direction and intensity of the geomagnetic field is not known. In this approach I will rely on studies in the scientific literature that report on multiple records from cores that sample sediments, both lake and marine, of the same age. The best records come from the most recent sediments which have not yet been appreciably affected by post-depositional processes, chemical and physical, that can affect the magnetization's accuracy and precision. Some of these studies report the scatter in inclination and declination down-core, others simply show plots of the agreement between multiple records of the field from which the scatter can be estimated. I do not calculate statistical parameters from these records but simply show, from digitizing the plots, the range of scatter in inclination and declination. The point of this exercise is to give the reader a better feeling for the repeatability of paleomagnetic records of the field and hence an estimate of their accuracy.

Before embarking on an examination of multiple records of the recent geomagnetic field, we will briefly consider how sediments become magnetized parallel to the Earth's field. The process by which sediments become magnetized is called the depositional or detrital remanent magnetization (DRM) process. In this process individual iron oxide, sub-micron-sized magnetic particles, typically magnetite (Fe_3O_4), become oriented so their magnetic moments are statistically biased toward

the ambient Earth's magnetic field during deposition. There is one basic theory for how this process occurs in nature, and all modifications of this theory will be covered in detail in Chapter 2. Geologists typically sample finer-grained sedimentary rocks, e.g. siltstones, very fine sandstones, mudstones, and shales, because it ensures a quiet depositional environment that should enhance the accuracy of the DRM recording process. Geologists avoid (as much as possible) sampling rocks that have obviously been affected by significant alteration, early diagenesis, recent weathering, hydrothermal events, significant metamorphism, or heating by nearby igneous bodies. Organic-rich lake and coastal marine sediments can be affected significantly by sulfate reduction diagenesis, and should be studied paleomagnetically with this possibility in mind. Rusty stains on the outcrop could indicate production of secondary Fe oxide/hydroxide magnetic minerals such as limonite by surface weathering, so samples should be taken from as fresh a subsurface as possible to avoid recent secondary magnetizations. The growth of secondary magnetic minerals by hydrothermal or tectonic fluids can be quite subtle to see in outcrop. Petrographic observation of the rock combined with field tests of age of magnetization (fold tests, contact tests, conglomerate tests; e.g. McElhinny & McFadden 2000; Tauxe 2010) may therefore be needed to determine if these processes could have affected the paleomagnetism of a sedimentary rock.

As we look at recent sedimentary records of the geomagnetic field, another point to remember is that there has been natural variability in the direction and intensity of the Earth's magnetic field due to secular variation. The secular variation of the field, particularly the field over the past 5 Ma, has been the focus of intense study in order to better understand the processes that generate the field. Five million years is the cut-off because plate tectonic motions will not be large enough over this time period to contribute to the variability of the geomagnetic directions. Typically, data from igneous rocks are used since igneous rocks tend to yield strong, reliable paleomagnetic directions while giving nearly instantaneous readings of the field. The data are usually reported in terms of the angular standard deviation of the dispersion of virtual geomagnetic poles (VGPs). The angular standard deviation S is defined:

$$S^2 = \frac{1}{N-1} \sum_{i=1}^N \Delta_i^2$$

where N is the number of samples and Δ_i is the angular distance between a sample's direction and the mean direction. The angular standard deviation includes 63% of the samples about the mean. A VGP is simply the position of the north magnetic pole that would produce the observed paleomagnetic direction, assuming that the field has been a dipole at the center of the Earth. For a suite of directions that record secular variation it is a good way to compare data from different places on the Earth's surface, essentially normalizing for the differences expected for a dipolar field observed at different site latitudes. For a collection of 3719 lava flows and thin, quickly cooled dikes, the angular standard deviation for the VGPs from samples collected at different latitudes is seen to increase from about 11° at the equator to about 20° at the poles (McElhinny & McFadden 1997).

But what does this mean for the directional dispersion of geomagnetic field directions? Constable & Johnson (1999) provide statistical models of geomagnetic field secular variation recorded by McElhinny and McFadden's dataset, and show that the dispersion of VGPs is consistent with directional angular dispersion that ranges from about 17° at the equator to about 10° at the poles (opposite to the latitudinal dependence observed for VGPs). Furthermore, as Tauxe has shown in her elongation–inclination work on inclination shallowing corrections (see Chapter 5), while VGP dispersions are nearly circular for the recent geomagnetic field, directional distributions are elongated in a north–south orientation. The elongation of the elliptical directional distribution is greatest at the equator (nearly 3:1) but close to circular at high latitudes. These observations of the geomagnetic field set the context for appreciating the evidence for accurate DRMs in recent sediments and sedimentary rocks.

EVIDENCE OF ACCURATE EARLY DRMs

One example of how fine-grained marine sedimentary rocks can provide a reproducible record of the intensity variations of the Earth's field comes from the pioneering work of Guyodo & Valet (1996). This work has gone through several iterations, but in the first study Guyodo and Valet took relative paleointensity records derived from marine sediments and stacked them to remove the effects of noise in the recording process, thus obtaining a master relative paleointensity curve over

the past 200 ka. Subsequently, this work has been extended to the last 800 ka and then to the past 2 Ma (Guyodo & Valet 1996, 1999; Valet *et al.* 2005). In the 200 ka study, they used 18 normalized paleointensity records from the world ocean and produced the $S_{int}200$ record of geomagnetic field intensity variations. They have normalized their stacked record to have a mean intensity equal to unity and can therefore report a running standard deviation for $S_{int}200$. The average value of the standard deviation is about 0.37 and gives a good sense of the repeatability of relative paleointensity DRM records. Some of this variability is due to non-dipole field effects because the records were collected globally and the non-dipole field is expressed locally, and some variability is due to errors in the recording process. It is not possible to separate the two effects in the $S_{int}200$ record, but Brachfeld & Banerjee's (2000) relative paleointensity work on Lake Pepin sedi-

ments offers some insight into the relative importance of non-dipole and recording error effects.

Directional accuracy of the paleomagnetism of recent sediments can be assessed in Lund & Keigwin's (1994) record of paleosecular variation of the field (PSV) from North Atlantic Ocean Bermuda Rise marine sediments (Fig. 1.1). Lund and Keigwin compare the natural remanent magnetizations (NRMs) of two adjacent gravity cores. Digitization and evenly spaced sampling of the inclination and declination records plotted by Lund and Keigwin show that the inclination records differ by a minimum of 0.04° to a maximum of 12.9° , while declination records differ by a minimum of 0.4° to a maximum of 15.2° . The median difference in either inclination or declination for these two marine cores is about 3° . Lund and Keigwin also collected a box core from the top 50 cm of marine sediment and sampled it with four subcores. These data showed

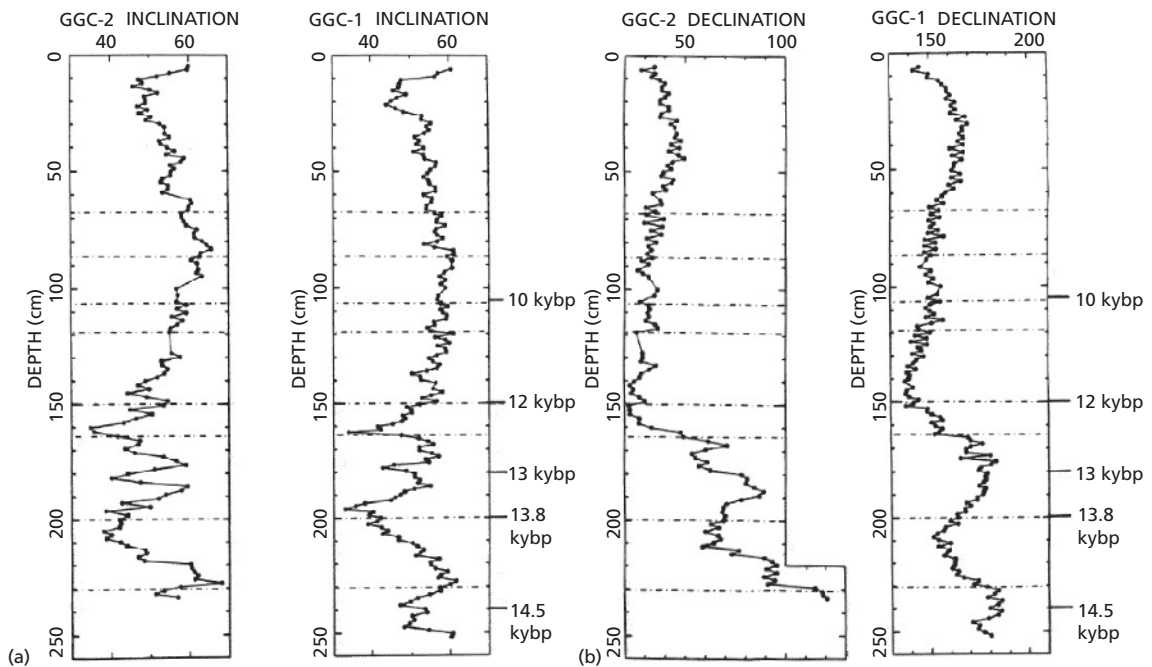


Fig. 1.1 Paleomagnetic records from the marine sediments of the Bermuda Rise showing reproducibility of paleomagnetic directions from two adjacent gravity cores: (a) inclination and (b) declination. Reprinted from *Earth & Planetary Science Letters*, volume 122, SP Lund and L Keigwin, Measurement of the degree of smoothing in sediment paleomagnetic secular variation records; an example from late Quaternary deep-sea sediments of the Bermuda Rise, western North Atlantic Ocean, 317–330, copyright (1994), with permission from Elsevier.

greater scatter in their recording of the Earth's field, probably because of the high water content of these sediments and ease with which their DRM could be disturbed by sampling. The inclinations of the subcores differed by 3.1–8.5° with a median difference of 5.6°; declinations differed by 3.6–15° with a median difference of 7.2°.

Another good example of the directional reproducibility of DRM records of paleosecular variation of the geomagnetic field comes from the data of Channell *et al.* (2004) from Ocean Drilling Program (ODP) Site 983 in the North Atlantic. In this study the authors report the Fisher mean and α_{95} confidence intervals for the averaged DRMs from multiple u-channel sampling of the core. The α_{95} of inclination varies from as little as 9° to as great as 31° with an average of 19°, while the $\alpha_{95}/\cos I$ for declination varied from 18° to 38° with a mean of 28° over the same interval in the core. Since the 95% confidence limit is twice the estimated standard error of the mean, these confidence limits for Site 983 inclinations and declinations are equivalent in magnitude to that observed for the Bermuda Rise box core.

Quite a few paleosecular variation records have been measured from both wet and dry lake sediments and all show good repeatability of DRM records of the geo-

magnetic field. The multiple records of the Mono Lake geomagnetic excursion in the dry lake sediments of the Wilson Creek Formation show good reproducibility, even when the geomagnetic field is moving very quickly during the excursion (Liddicoat & Coe 1979). Before and after the excursion, the four independent records of the field differ by up to about 10° in declination and by 5–10° in inclination. During the excursion the scatter increases somewhat; one inclination record differs from the other three by 15–20° (Fig. 1.2).

More recent work on the stacked multiple paleosecular variation records from Lake El Trebol sediments in Mexico show variations at a given horizon that are about 8.5° for inclination and about 11° for declination (Irurzun *et al.* 2006). Creer & Tucholka (1982) calculate standard errors around stacked PSV curves from North American lakes and from lakes in the British Isles. Their point is to show how repeatable the DRM is in these wet lake sediments. For central North American lakes, the standard error for declination is typically 3° to as much as 23°, but averages about 8°. The standard error in the inclination record is much better, averaging only 2°. When the PSV records from Lake Windermere are compared to those from Loch Lomond the standard error is even less (about 2° for declination and 1° for inclination). Stockhausen

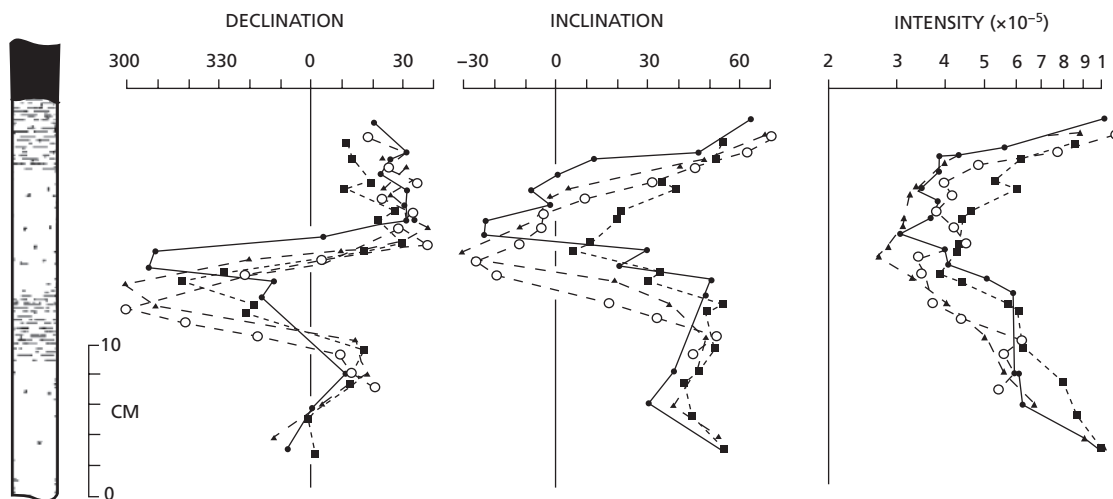


Fig. 1.2 Mono Lake geomagnetic excursion showing reproducibility of the geomagnetic field direction by sedimentary rocks, when the geomagnetic field was moving fast. JC Liddicoat and RS Coe, Mono Lake geomagnetic excursion, *Journal of Geophysical Research*, volume 84, 261–271, 1979. Copyright 1979 American Geophysical Union. Reproduced/modified by permission of American Geophysical Union.

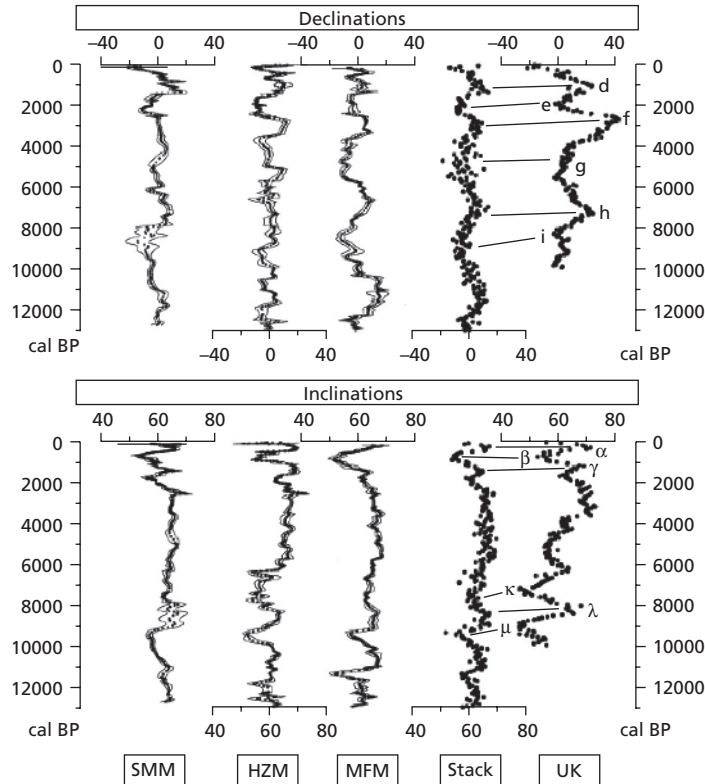


Fig. 1.3 Paleosecular variation records from the sediments of three maar lakes in Germany. The declination and inclination records of the three lakes (Schalkenmehrener Maar: SMM; Holzmaar: HZM; Meerfelder Maar: MFM) are shown with 95% confidence intervals drawn around them from multiple cores collected from each lake. The stack shows the data stacked from all three lakes, compared to the master secular variation curve from the UK. H Stockhausen, *Geomagnetic paleosecular variation (0–13000 yr BP) as recorded in sediments from three maar lakes from the West Eifel (Germany)*, *Geophysical Journal International*, 135, 898–910, 1998, John Wiley & Sons, Ltd.

(1998) stacks the PSV records from three maar lakes in Europe and sees very good reproducibility in declination ($\pm 2.5^\circ$) and inclination ($\pm 1.5^\circ$) (Fig. 1.3). This very low scatter and high reproducibility of the field is one reason for the detailed study of maar lake paleomagnetism. Maar lakes have a very quiet depositional environment with no streams bringing in sediment loads, thus allowing the most accurate records of the geomagnetic field (Merrill *et al.* 1996).

In their study of the secular variation recorded by the DRM of wet sediments from Lake Pepin in the Mississippi River, Brachfeld & Banerjee (2000) compare the Lake Pepin secular variation record to that of nearby Lake St Croix. They report good agreement of

the inclinations with differences typically less than 5° , but in some cases they indicate that the records deviate by up to 10° . Brachfeld and Banerjee also look at anhysteretic remanent magnetization (ARM)-normalized relative paleointensity records from Lake Pepin and compare them to both relative paleointensities from Lake St Croix and variations in absolute paleointensity observed in the archeomagnetic database for the past 3000 years. The variability between these paleointensity records is reported as a standard deviation of about 0.38 around a normalized mean of unity (Brachfeld & Banerjee 2000). This is amazingly similar to that reported by Guyodo & Valet (1996) for S_{int200} . Since non-dipole effects are less likely to

explain differences in paleointensity for these geographically proximal records, it would argue that a standard deviation of 0.38 is the best that can be expected for the reproducibility of relative paleointensity variations of the geomagnetic field; this is mainly due to recording errors.

Based on this admittedly limited, but representative, survey of the repeatability of DRM records of paleosecular variation in recent wet and dry lake sediments and wet marine sediments, DRM inclination and declination appear to be repeatable within 5–10° for either inclination or declination; the very best records show reproducibility from the same lake in the range 2–3°. Clearly this shows that recent lake and marine sediments have the capability of providing highly reproducible records of the geomagnetic field. In all these records, magnetite is the primary depositional magnetic mineral. Given the observed directional variability of the geomagnetic field over the past 5 Ma with angular standard deviations of 10–17°, the DRMs of recent sediments clearly have the resolution to discern the secular variation of the field.

DRMS IN RED, CONTINENTAL SEDIMENTARY ROCKS

The source of the paleomagnetic signal in red, continental sedimentary rocks, i.e. red beds, is quite controversial. While most geologists would agree that the magnetite carrying the paleomagnetism of recent marine and lake sediments is a primary depositional mineral, the hematite in red beds could be either depositional or a secondary magnetic mineral that grows chemically after deposition. This controversy consumed paleomagnetists in the 1970s and early 1980s and was denoted the 'red bed controversy'. Butler (1992) gives an excellent summary of the arguments for and against a DRM in red beds, as outlined during the height of the red bed controversy. In fact, red beds do carry a complicated paleomagnetic signal. Although it has been quite clearly demonstrated that the hematite in the Siwalik continental sediments in Pakistan carries a depositional remanence (Tauxe & Kent 1984), petrographic examination of some red sedimentary rocks (e.g. the Moenave Formation, Molina-Garza *et al.* 2003 or the Moenkopi Formation, Larson *et al.* 1982) of the Colorado Plateau would argue that all the hematite grains are chemically produced rather than depositional grains.

Some interesting observations about red beds add to the controversy. Most red beds sampled by paleomagnetists are Paleozoic and Mesozoic in age. Most of them are interpreted to have been deposited in fluvial environments (the molasse red beds of the Appalachians: Andreas Formation, Bloomsburg Formation, and Mauch Chunk Formation; the Colorado Plateau Paleozoic red beds: Chinle Formation, Moenave Formation), coastal marine environments (deltaic rocks: Catskill Formation), or large lake environments (Passaic and Lockatong Formations of the Newark basin), yet rocks currently forming in these depositional environments are not typically red in color. In the Global Paleomagnetic Database the youngest sediments reported to be red in color are typically of age at least 2 Ma. Therefore, the red pigmentary hematite in classic red continental sediments is most likely secondary and carries a post-depositional chemical remanence. But what about specular hematite grains that are interpreted to be detrital? As shown in the previous section, the most recent lake and marine sediments generally have magnetite as their primary magnetic mineral. There are no (or at least not many) good modern examples of detrital hematite grains being deposited in red sediments, particularly in the depositional environments usually associated with Mesozoic or Paleozoic red beds.

However, there is some very good evidence from the geologic record that continental sedimentary rocks that have micron-sized hematite grains carrying their paleomagnetic signal have been magnetized by a DRM. The presence of relatively large-grained, specular hematite is often used as evidence for a DRM (Passaic Formation; McIntosh *et al.* 1985). The best way to determine if specular hematite is present in a rock is by petrographic examination of a magnetic extract, but indirect methods such as a square-shaped thermal demagnetization intensity plot can also be used. Classic red bed units such as the Carboniferous Mauch Chunk Formation often show a very steep decrease in intensity at the highest demagnetization unblocking temperatures (Fig 1.2; Chapter 6). This behavior can be interpreted to mean that there is a very narrow grain size distribution of the hematite carrying the highest unblocking temperatures. Since hematite has a low spontaneous magnetization, its grains do not become multi-domain until relatively large grain sizes are reached (15 microns; Dunlop & Ozdemir 1997) and so all the hematite observed during thermal demagnetization of fine-grained continental sediments is typically single domain. The highest-unblocking-temperature

magnetization of red beds is therefore carried by the largest single-domain hematite grains. The steep decrease in intensity during thermal demagnetization of some red beds then can be interpreted as evidence for specular hematite carrying the paleomagnetism of the red bed.

Other evidence used to argue for a DRM in red beds came during the heyday of the red bed controversy from the measurement of red bed paleomagnetism on the topset, bottomset and foreset beds of crossbedding (Steiner 1983). A difference in the inclination carried by the flat-lying bottomset or topset beds and the initially dipping foreset beds would suggest a DRM affected by an initial bedding slope by magnetic grains rolling down the slope. Another powerful argument that the magnetization of red beds is primary (and therefore a DRM) comes from the observation that many red beds record a magnetostratigraphy, in which geomagnetic field polarities are constrained to stratigraphic horizons. More recent evidence that red beds are magnetized by a DRM come from what is interpreted to be records of paleosecular variation in red sedimentary rocks. Kruiver *et al.* (2000) report records of paleosecular variation (PSV) in Permian-age red beds from Dome de Barrot in southeastern France. They even go as far as to analyze the characteristics of secular variation in the Permian and observe looping of the geomagnetic field vector, behavior suggesting paleosecular variation. Much earlier, Evans & Maillol (1986) measured red bed samples taken from unoriented cores and interpreted the directional variations as due to PSV. They modeled the PSV with dipole wobble plus shorter non-dipole variations, an approach typically used with the secular variation recorded by recent marine and lake sediments. Finally, depositional magnetic fabrics carried by the anisotropy of magnetic susceptibility (AMS) and magnetic remanence (AMR) of red beds suggest that their paleomagnetism is carried by depositional magnetic minerals (Kodama & Dekkers 2004). This evidence will be covered in more detail in Chapter 5.

An interesting conundrum about the accuracy of red bed remanence arises from the different possibilities for the manner in which a red continental sedimentary rock becomes magnetized. If the red bed is magnetized primarily by a post-depositional chemical remanent magnetization (CRM), then the direction carried by the red bed may be an accurate record of the geomagnetic field direction when the secondary hematite grains grew. The age of the magnetization will not

however be the age of the rock, and it will be difficult to determine accurately. If on the other hand the red bed is magnetized by a DRM, then the timing of magnetization is exactly the age of the rock and will be accurately known. The direction of the magnetization will most likely not accurately record the direction of the geomagnetic field at deposition, however. The low spontaneous magnetization of hematite will cause detrital hematite grains in red beds to be more easily affected by gravity and other misorienting forces at deposition (water currents, initial slope). Tauxe & Kent (1984) showed this beautifully with their pioneering work on the Siwalik River sediments of Pakistan. Redeposition of these hematite-bearing sediments in the laboratory revealed a large inclination error as did observation of naturally redeposited sediments on the river floodplain. Tan *et al.* (2002) also redeposited red sedimentary rocks in the laboratory, in this case rocks from western China. They found a large compaction-caused inclination error for the finest-grained sediments and a large syn-depositional inclination error for the coarser-grained sediments. Therefore, accurate red bed directions will probably not have their age well known, and accurately dated red bed magnetization ages will probably not be an accurate record of the Earth's field direction at the time of deposition.

POST-DEPOSITIONAL PROCESSES THAT AFFECT THE MAGNETIZATION OF SEDIMENTS AND SEDIMENTARY ROCKS

Even though it's quite clear that the DRM acquired by recent sediments is reproducible when multiple coeval records are compared, this still begs the question of how accurately the DRM records the Earth's magnetic field. Chapter 2 will examine the accuracy of DRM in detail. However, even if it turns out that the DRM of recent sediments is not only reproducible but accurate, there are post-depositional processes that occur in sediments and sedimentary rocks that can either totally obliterate, distort, or bias the direction and intensity of the initial DRM acquired by the rock. These processes are: post-depositional remanence acquisition, burial compaction, reduction diagenesis, secondary growth of magnetic minerals, and tectonic strain. Not all of these processes, and in some cases none, occur in any given sediment or sedimentary rock, but we need to be cognizant of them all to be aware of their potential

effects. Each process will be covered in a separate chapter in the book, along with an estimate of the magnitude of its effect on the paleomagnetism of the rock. For now, we'll give a brief overview of each.

Post-depositional remanence

An underlying assumption of post-depositional remanence, based on laboratory experimental work and field observations, is that when sediments are first deposited the pore spaces between the non-magnetic grains in the rock are larger than the submicron-micron-sized magnetic mineral particles that give the rock its magnetization. The magnetic grains can therefore remain mobile and realign their magnetic moments with Earth's magnetic field, thus becoming more accurate in their recording of the field if they became disoriented during touchdown on the sediment-water interface. As the sediment is buried and becomes dewatered by compaction the pore spaces decrease in size, trapping and immobilizing the magnetic mineral particles. Any sediment will have a grain size distribution of magnetic particles, and the largest magnetic particles in the sediment will become trapped at shallower depths below the sediment-water interface than smaller magnetic particles.

There are several results of this vision of post-depositional remanence. First, the acquisition of the sediment's magnetization, its post-depositional remanent magnetization (pDRM), will occur lower in the sediment column than where it was deposited. So even though the pDRM was acquired after the sediment was deposited, by locking in at a finite depth (typically several centimeters to 20 cm according to some work; deMenocal *et al.* 1990; Tauxe *et al.* 1996) the magnetization acquisition time will appear to precede the depositional age of the sediment. Second, it has been argued by some (see review by Verosub 1977) that pDRM is more accurate than a syn-depositional DRM because the grains have been able to reorient after touchdown to be parallel to the ambient magnetic field, and lessen the disturbance that occurs at touchdown. Finally, in this model of post-depositional remanence, different-sized magnetic mineral grains are immobilized or locked in at different depths. The result is that the paleomagnetic recording of the field is smoothed over the depth range in which all the magnetic grains are locked into place by decreasing pore size (see summary in Tauxe *et al.* 2006).

If pDRM is important in a sedimentary rock, the rock's magnetization is therefore more likely to be an accurate record of the geomagnetic field. It will however appear to occur earlier in the sediment column than its actual depositional age, so its timing will be inaccurate. It is also highly likely that the paleomagnetic record of the field will be smoothed, and the record of high-frequency changes in the geomagnetic field will be lost. The degree of smoothing will depend on the sediment accumulation rate; fast rates will minimize the effect of smoothing.

Burial compaction

At greater depths in the sediment column (from tens to hundreds of meters) than depths which would cause the lock-in of a pDRM, the dewatering due to burial compaction can cause a bias in the magnetization direction of sediments and sedimentary rocks. Experimental data from our laboratory shows that burial compaction can cause a shallowing of paleomagnetic inclination of the order 10–20°, particularly for clay-rich sediments. This effect was not fully appreciated in the early days of paleomagnetism and even during its highly productive middle age, because observations of the DRM and pDRM of recent marine and lake sediments did not typically demonstrate any bias in the recording of the geomagnetic field inclination. One of the classic experiments that informed paleomagnetists was the observation by Opdyke & Henry (1969) that cores collected at different latitudes from the world ocean recorded inclinations entirely consistent with their latitudes, following the dipole equation for the GAD:

$$\tan(\text{paleomagnetic inclination}) = 2 \times \tan(\text{latitude}).$$

The cores sampled for these measurements were only about 1–2 m in length however, so the effects of burial compaction were not evident or important for these recently deposited marine sediments.

Another reason that inclination shallowing caused by compaction was not considered important by many paleomagnetists is that it doesn't become obvious unless the sedimentary rocks were deposited at intermediate latitudes. Inclination shallowing follows a tangent-tangent relationship (King 1955):

$$\tan(\text{observed inclination}) = f \times \tan(\text{inclination at deposition})$$

where f is the amount of shallowing between 0 and 1, with typical values between 0.45 and 0.7 for compaction-caused inclination shallowing (Bilardello & Kodama 2010b). At mid-latitudes inclination shallowing may be as much as 15–20°, whereas the effect can be 10° or less and is closer in magnitude to the resolution of typical paleomagnetic data, making the shallowing harder to detect, at high or low latitudes. This was the case for the paleomagnetic data from tectonostratigraphic terranes from western North America or central Asia. In both cases the expected paleolatitudes for the terranes, if they had not moved with respect to the craton, were intermediate in magnitude: 30–40°N for the Cretaceous Peninsular Ranges terrane and near to 45°N for the central Asian sites with anomalous paleomagnetic directions from late Mesozoic to early Cenozoic sedimentary rocks. In both cases, interpretation of the paleomagnetic data without taking account of the effects of compaction-caused inclination shallowing led to the misinterpretation that about 1000–1500 km (approximately 10–15° of paleolatitude) of northward tectonic transport had occurred.

The problem of inclination shallowing also became evident in the so-called Pangea B problem. Paleomagnetic data from the latest Paleozoic and earliest Mesozoic requires an overlap between Laurasia and Gondwana in their equatorial regions. Rochette & Vandamme (2001) have suggested that this is the result of inclination shallowing forcing both Laurasia and Gondwana closer to the equator in paleogeographic reconstructions than they actually were, thus requiring the Pangea B reconstruction in which Gondwana is shifted eastward with respect to Laurasia. A counter-clockwise 'twist' along the Tethys seaway is needed to bring the continents into their Pangea A configuration later in the Mesozoic, although there is scant geological evidence for this megashear zone (Van der Voo 1993; Torcq *et al.* 1997). Inclination shallowing as an explanation for the Pangea B problem would be reasonable if the size of the inclination bias were greater than the typical 95% confidence limits for the apparent polar wander path used for the paleogeographic reconstruction. In Torsvik & Van der Voo's (2002) analysis to determine the highest-quality Gondwana paleopoles at about 250 Ma, when the Pangea B overlap persists, 11 of the 12 paleopoles are from sedimentary units. Five of these sedimentary units with paleopoles closest to the mean Gondwana paleopole for 250 Ma were all deposited at intermediate latitudes in India, Pakistan,

and South America (Kamthi and Mangli beds and Panchet beds of India, Wargal and Chhidru Formation of Pakistan, and the Amana Formation of South America). In fact, Bilardello & Kodama (2010a) showed that if the Carboniferous sedimentary paleopoles for Gondwana are corrected for inclination shallowing and compared to an inclination-corrected paleopole for North America, then a Pangea A configuration is possible (Fig. 1.4).

Reduction diagenesis

In organic-rich marine and lake sediments iron-sulfur reduction diagenesis causes iron oxide minerals to dissolve and be replaced by a sequence of iron sulfides, some of which are ferromagnetic (Karlin & Levi 1983, 1985; Canfield & Berner 1987). The mineral at the end of the sequence of iron sulfides produced is pyrite (FeS_2), which doesn't carry any remanence but is paramagnetic. Both pyrrhotite (Fe_{1-x}S) and greigite (Fe_3S_4) are important ferromagnetic minerals formed during reduction diagenesis and will contribute a secondary chemical remanent magnetization (CRM) to the sediment. These secondary minerals are of course formed at the expense of the primary depositional magnetic mineral, magnetite, as it dissolves. Because the smallest magnetic grains have the largest surface area to volume ratio, they are preferentially destroyed in the process. The magnetic grain size is therefore seen to coarsen during reduction diagenesis and the magnetic hardness, or coercivity, of the magnetic particles of the sediment decreases.

One good example of the reduction diagenesis process comes from Lake Ely in northeastern Pennsylvania where the concentration of fine-grained biogenic magnetite is seen to decrease downcore between 30 cm and 75 cm depth in the sediment column in organic-rich lake sediments with a loss-on-ignition (LOI) of 25%. Secondary Fe sulfide magnetic phases are produced during the dissolution of the primary biogenic magnetite. The evidence is however indirect, mainly from SIRM/ χ ratios (the ratio of saturation isothermal remanent magnetization, the highest magnetization acquired by a sample in a strong magnetic field, to magnetic susceptibility) that are high when Fe sulfides are present (Peters & Dekkers 2003). The depth of reduction diagenesis in marine sediments is inversely dependent on the organic carbon flux and ranges from as deep as several meters for very low fluxes of milli-

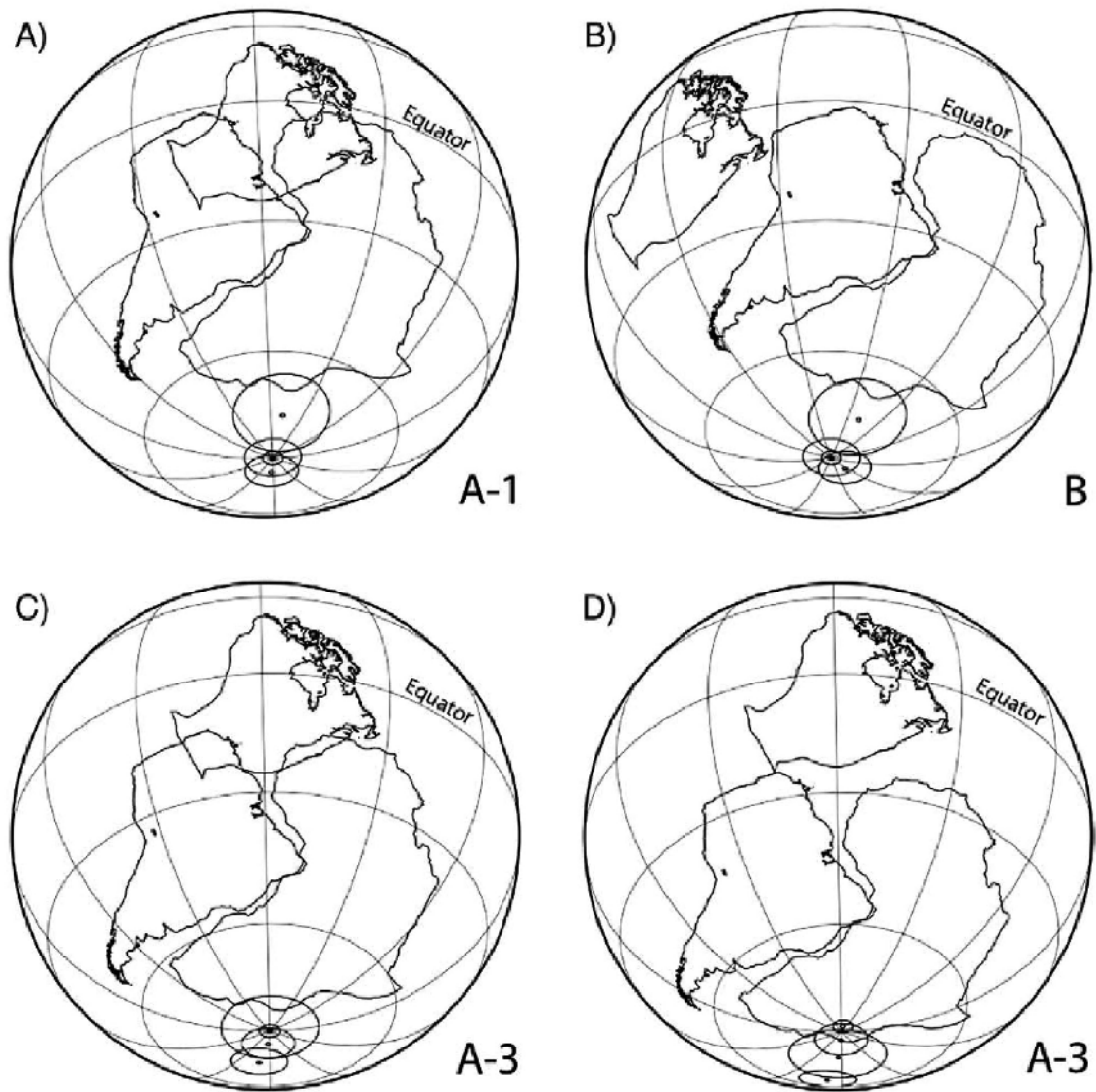


Fig. 1.4 Different Pangea configurations at 310 Ma. (a) Pangea A-1, uncorrected paleomagnetic data; (b) Pangea B, corrected North American data but uncorrected Gondwanan data; (c, d) Pangea A-3, inclination-corrected data showing the range in continental positions allowed by the paleopoles' 95% cones of confidence. Reprinted from *Earth & Planetary Science Letters*, volume 299, D Bilardello and KP Kodama. A new inclination shallowing correction of the Mauch Chunk Formation of Pennsylvania, based on high-field AIR results: Implications for the Carboniferous North American APW path and Pangea reconstructions, 218–227, copyright (2010), with permission from Elsevier.

grams of C/m^2 yr to depths of only 1 cm for tens of grams of C/m^2 yr (Schulz & Zabel 2006). The secondary ferromagnetic iron sulfide minerals that are formed essentially give a delayed NRM acquisition for the sediments affected, and the sediments are no longer magnetized by a DRM but by a CRM. Since this CRM is typically formed very early in the post-depositional history of the sediments, it could be affected by subsequent burial compaction inclination shallowing even though it will probably have an accurate directional recording of the geomagnetic field when the secondary minerals form. Efforts to use an early CRM in marine sediments for relative paleointensity measurements will be complicated by changes in paleoenvironmental conditions, causing more or less organic carbon to be deposited in the sediments (Schulz & Zabel 2006).

Later secondary CRMs

Of course, the formation of secondary magnetic minerals can occur at any stage in the post-depositional history of a rock. A rock can then have both a primary magnetization, typically carried by depositional magnetite, and a secondary magnetization, usually carried by iron sulfides or hematite. If the secondary magnetic minerals have the appropriate grain size distribution they may have higher coercivities or unblocking temperatures than the primary magnetic minerals and their remanence will be isolated by demagnetization as the characteristic remanence of the sedimentary rock. In some cases, the primary magnetization of the rock may be destroyed during the growth of the late stage magnetic minerals or the primary magnetization may be so weak initially that it is swamped by the secondary CRM. The best example of this is the nearly ubiquitous Late Paleozoic remagnetization of rocks throughout eastern North America that occurred during the Alleghanian orogeny (McCabe & Elmore 1989). This remagnetization has totally reset the remanence of Paleozoic carbonates throughout eastern North America, but it is also present as one of several components of magnetization in red clastic sedimentary rocks from the Appalachians. One possible explanation for the formation of the secondary magnetization is that fluids squeezed through the rocks of North America during the Alleghanian orogeny, causing the growth of secondary magnetite in the carbonate rocks (Oliver 1986). These fluids also apparently caused the

growth of secondary fine-grained, perhaps pigmentary, hematite in clastic sedimentary red rocks.

If late stage secondary CRMs occur in sedimentary rocks, the direction of the remagnetization will most likely be an accurate record of the geomagnetic field direction. It is unlikely that a late stage CRM will be affected by burial compaction; however, the remagnetization age will be difficult to determine. Field tests such as the fold test may help constrain the age of remagnetization, but it will not be accurately known. Because the paleohorizontal cannot be determined at the time the CRM formed, particularly if the rock has been in a tectonically active area, paleopoles or paleolatitudes determined from the CRM will be dubious.

Tectonic strain

Tectonically deformed regions are important targets for paleomagnetists, primarily because folded rocks allow them to constrain the age of magnetizations in a rock using the fold test (Graham 1949). Paleomagnetic results can also provide important insights about the tectonic events that occurred in a region. Most paleomagnetists only remove the tilt of folded strata in Graham's fold test and not the effects of grain-scale strain that may have occurred during the folding. It is interesting that in his landmark paper suggesting the fold test, Graham (1949) considered that both rigid and grain-scale rotations could affect the paleomagnetic remanence. Rock deformation can indeed affect the accuracy of a sedimentary rock's paleomagnetism. Rotation of a rock's remanence can be caused by bedding-parallel simple shear strain during flexural flow/slip folding (Kodama 1988). The geometry of the simple shear not only causes an inaccuracy in the direction of remanence, but an inaccurate estimate of the age of magnetization in that the simple shear rotation can make a pre-folding magnetization appear to be syn-folding in age. This has been demonstrated in folded red beds (Stamatatos & Kodama 1991a) and shows that magnetic grains can rotate as active particles. If the remanence behaves as a passive line, then pure shear during buckle folding will rotate the remanence. Sense and magnitude of rotation will however be case specific, depending on the relative angles between the strain ellipsoid and the remanence.

Grain-scale strain in a deformed rock can cause secondary remagnetizations since secondary magnetic

minerals can be formed during strain events. In some cases, the primary magnetic minerals can be destroyed when the rock is strained. Strain may preferentially affect magnetic grains of different coercivities, and the response of sedimentary rock magnetizations to strain can be quite complicated. Experimental deformation work has also shown that the domain walls of the magnetic particle can be affected by strain, thus preferentially affecting low-coercivity multi-domain magnetite grains. In other work, laboratory strain has randomized the orientation of small high-coercivity hematite grains.

When deformation causes remagnetization or scatter of directions, the effect will be easy to detect and disregard. When a subtle bias is caused however, as in flexural flow/slip folds, then independent strain measurements (in addition to paleomagnetic measurements) are needed to detect and account for the inaccuracies.

SUMMARY

In conclusion, I'd like to end with this thought: the more you know about the paleomagnetism of rocks, the more amazed you are that paleomagnetism works so well (Allan Cox, pers. comm., *c.* 1975); and it does work, quite well. Despite all the topics we'll cover in this book, the paleomagnetism of sedimentary rocks does do a very good job of recording the geomagnetic field. The goal of this book is to help geoscientists who rely on paleomagnetic data become cognizant of the possible pitfalls in understanding their data, so that the most accurate interpretations will result.