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Magnetic Mineralogy of Continental Deposits, San Juan Basin, New Mexico, and Clark's Fork Basin, Wyoming

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Magnetic concentrates were obtained from nine bulk samples from the Late Cretaceous through middle Paleocene continental sedimentary section in the San Juan Basin, New Mexico, and from two bulk samples from the late Paleocene and early Eocene section in the Clark's Fork Basin, Wyoming. Strong-field thermomagnetic (J_s-T) curves of almost all the San Juan Basin concentrates show only a single Curie temperature in the 175°–195°C range, indicating that the dominant ferrimagnetic mineral is detrital titanomagnetite ($Fe_{3-x}Ti_xO_4$) of composition $0.51 \leq x \leq 0.54$. The Clark's Fork Basin concentrates exhibited Curie temperatures of 200°C and 580°C, indicating a mixture of $x = 0.5$ titanomagnetite and magnetite, respectively. No evidence of hematite (or other ferric oxides or oxyhydroxides) was observed in the J_s-T data. Isothermal remanent magnetization (IRM) acquisition curves were determined for 56 samples from the Clark's Fork Basin and 114 samples from the San Juan Basin. Although dominated by IRM acquired in magnetizing fields of $\leq$300 mT, additional IRM was acquired in magnetizing fields from 300 to 700 mT. The IRM acquired above 300 mT is attributed to hematite (or other ferric oxides or oxyhydroxides) and is thought to be the result of minor oxidation, probably during recent weathering. These results indicate that IRM acquisition behavior may be used to monitor the hematite content in continental sedimentary rocks and may indicate stratigraphic intervals within which the natural remanent magnetization (NRM) could contain significant chemical remanence overprints. Although minor hematite content is indicated, the detailed sampling of IRM acquisition behavior for the San Juan Basin and Clark's Fork Basin sedimentary sequences did not reveal any significant correlation of IRM behavior with polarity of the characteristic NRM. These data thus support the previous conclusion, based on paleomagnetic data, that the characteristic NRM is a depositional remanence which provides a valid recording of the geomagnetic polarity sequence during deposition of these continental sedimentary sequences.

INTRODUCTION

Paleomagnetic polarity stratigraphy has recently been applied to geochronologic problems in a variety of continental sedimentary environments. Several studies have employed polarity stratigraphy of late Tertiary fluviatile and lacustrine sedimentary rocks in order to provide geochronologic calibration of North American land mammal ages [e.g., *Johnson et al.*, 1975; *Opdyke et al.*, 1977; *MacFadden et al.*, 1979]. Polarity stratigraphic studies of early Tertiary, dominantly paludal sedimentary sequences have been undertaken in the San Juan Basin, New Mexico [*Butler et al.*, 1977; *Lindsay et al.*, 1981] and in the Clark's Fork Basin, Wyoming [*Butler et al.*, 1981]. Given the potential importance of polarity stratigraphic studies to paleontology, stratigraphy, and geochronology, a thorough knowledge of the paleomagnetism and rock magnetism of these sedimentary rocks is desirable.

Although the above mentioned polarity stratigraphic studies have not generally been accompanied by detailed rock magnetic studies, the previously available data indicate that detrital magnetite or titanomagnetite is the dominant ferrimagnetic mineral. Attempts to prepare polished sections of the San Juan Basin and Clark's Fork Basin sedimentary rocks have been largely unsuccessful, yet those samples which have been prepared contain magnetite (or titanomagnetite) as the dominant opaque mineral. As pointed out by *Vugteveen et al.* [1981], the paleomagnetic pole position obtained from the Nacimiento Formation in the San Juan Basin is displaced from the pole positions obtained from coeval North American formations. The sense of displacement strongly suggests that the characteristic natural remanent magnetism (NRM) of the Nacimiento Formation contains an inclination error indicative of a depositional origin of the characteristic NRM. Also, the progressive demagnetization studies generally reveal two components of NRM. A viscous remanent magnetization (VRM) is commonly observed and is almost invariably aligned approximately parallel to the present geomagnetic field at the sampling locality. In most samples, this VRM can be removed by alternating field (af) demagnetization to a peak field of between 10 and 30 mT. Alternating field demagnetization usually reveals a more stable characteristic remanence which has a large portion of its coercive force spectrum between 20 and 80 mT. This characteristic magnetization is interpreted as a depositional remanent magnetization (DRM) acquired at the time of deposition. Thus polarity stratigraphic studies of these Tertiary continental sedimentary sequences are not faced with the uncertainties of timing of acquisition of the stable NRM which are the focus of the controversy regarding magnetization of red beds [*Elston and Purucker*, 1979; *Walker et al.*, 1981]. However, some important rock magnetic problems have arisen and are worthy of more thorough research.

A major concern is the possibility of magnetic overprints by minor amounts of hematite, goethite, or other ferric oxides or oxyhydroxides. These ferric minerals can form in response to oxidizing groundwater or during recent weathering. Several attempts to establish the polarity stratigraphy in Tertiary sedimentary rocks have revealed the presence of

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normal-polarity overprints with high coercivity. These overprints usually make interpretation of the polarity stratigraphy very difficult [e.g., *Hillhouse et al.*, 1977; *Lerbekmo et al.*, 1979]. They are almost certainly the result of acquisition of a chemical remanent magnetization (CRM) residing in ferric minerals which are the products of oxidation. If significant oxidation has occurred, the CRM acquired could obscure the original DRM.

Evidence of high-coercivity components of NRM with normal polarity has occasionally been observed in the paleomagnetic data from the Clark's Fork Basin and San Juan Basin [*Lindsay et al.*, 1981; *Butler et al.*, 1981]. These components are recognizable in stratigraphic intervals where the primary depositional remanence is of reversed polarity. The typical manifestation of these components is that during af demagnetization the NRM direction rotates toward, but does not reach, the expected reversed-polarity direction. This type of behavior is most common in samples collected from outcrops where the rate of denudation is low and where weathering is consequently deep. Accordingly, these normal-polarity, high-coercivity components of NRM are interpreted as chemical remanent magnetization components formed by weathering during the Brunhes normal-polarity chron.

When present as minor components of the NRM, Brunhes chron CRM overprints are not difficult to recognize, but more extensive normal overprints may be more difficult to identify. In Tertiary sedimentary rocks it is not possible to distinguish between the present axial dipole field direction and the normal-polarity direction at the time of deposition because of the lack of sufficient apparent polar wander since the rocks were deposited. Also, the low NRM intensities (10^{-4}–10^{-3} A/m for the San Juan Basin and Clark's Fork Basin sedimentary rocks) make detailed progressive af demagnetization studies to peak fields above 50 mT very difficult. Because of the chemical changes that occur while these clay-rich rocks are heated, it is also difficult to perform useful progressive thermal demagnetizations. In addition, Tertiary continental sedimentary sequences are commonly devoid of sedimentary or tectonic structures, so that field tests of NRM origin are not usually available. It is ironic that present field (or Brunhes chron) CRM components in the NRM of Tertiary sedimentary rocks can be more difficult to detect than are these components in Mesozoic or Paleozoic rocks.

It is clear that alteration with attendant oxidation represents a serious obstacle to polarity stratigraphic studies of sedimentary rocks in which the original NRM is a DRM carried by magnetite or titanomagnetite. Although extensive oxidation may be easy to recognize, mild oxidation may be difficult to detect. Thus one objective of studies of magnetic properties of these rocks should be the detection of hematite (or ferric oxyhydroxides) which is the likely product of oxidation and carrier of recently acquired CRM components. Paleomagnetic polarity studies should be accompanied by thorough documentation of the magnetic mineralogy. As a step toward this objective, this rock magnetic study of latest Cretaceous to early Eocene continental deposits from the San Juan Basin, New Mexico, and Clark's Fork Basin, Wyoming, was undertaken.

These sedimentary sequences have previously been the subject of detailed paleomagnetic and biostratigraphic study [*Lindsay et al.*, 1981; *Butler et al.*, 1981]. The paleomagnetic and preliminary rock magnetic studies indicated that the dominant ferrimagnetic minerals were most likely magnetite or titanomagnetite. The present study was undertaken with two main objectives: (1) determination of thermomagnetic behavior of magnetic concentrates and (2) determination of isothermal remanent magnetization (IRM) acquisition behavior of samples from numerous stratigraphic levels. Desired information for the first objective included Curie temperature and reversibility of the thermomagnetic curves. The obvious primary goal of these experiments was to determine the exact composition of the dominant ferrimagnetic minerals. These data were desired not only to document the depositional origin of these minerals but also to examine any evidence of postdepositional oxidation. The experiments for the second objective were undertaken in order to evaluate the use of IRM acquisition behavior in the detection of stratigraphic levels where postdepositional oxidation and resultant CRM overprints may be significant.

THERMOMAGNETIC ANALYSES

Sample Collection and Experimental Technique

Bulk samples (~2 kg) were collected from nine levels within the paleomagnetic sections in the San Juan Basin. These sections extend from the Late Cretaceous Fruitland and Kirtland formations and Ojo Alamo Sandstone into the Nacimiento Formation of Paleocene age (stratigraphic nomenclature of *Bauer* [1916]). Detailed descriptions and locations of these sections are given by *Lindsay et al.* [1981]. The bulk samples were distributed stratigraphically and with respect to geographic locality so as to correspond approximately to the paleomagnetic sampling. The formation and locality from which each bulk sample was collected are listed in Table 1. The lithologies within the paleomagnetic section in the Clark's Fork Basin [*Butler et al.*, 1981] are much less variable than those in the San Juan Basin. Accordingly, only two bulk samples were collected from the Clark's Fork Basin section.

The bulk samples were disaggregated by placing them in water. A slurry was then made by agitating the resultant mixture of sediment and water. This slurry was poured through a flexible transparent plastic tube which passed just

TABLE 1. Curie Temperatures of Magnetic Concentrates

Sample	Formation (Locality)	T_c, °C
	San Juan Basin	
SJ050	Fruitland (Hunter's Wash)	175
SJ171	Kirtland (Alamo Wash)	180
SJ177	Kirtland (Alamo Wash)	180
B004	Nacimiento (Kutz Canyon)	irreversible 570 cooling
SJ312	Nacimiento (Kutz Canyon)	195
SJ331	Nacimiento (Ojo Encino)	580 (185)
SJ347	Nacimiento (Ojo Encino)	180
SJ536	Nacimiento (Tsosie Arroyo)	175
SJ538	Nacimiento (Tsosie Arroyo)	175
	Clark's Fork Basin	
PB035	Willwood (Big Sand Coulee)	180 (550)
PB292	Willwood (Big Sand Coulee)	565 (170)

T_c is Curie temperature determined from strong-field thermomagnetic experiment. Curie temperatures in parentheses are those of a less abundant phase in samples showing two ferrimagnetic phases. Descriptions of stratigraphic sections and maps showing locations of exposures from which these samples were collected are given by *Lindsay et al.* [1981] and *Butler et al.* [1981].

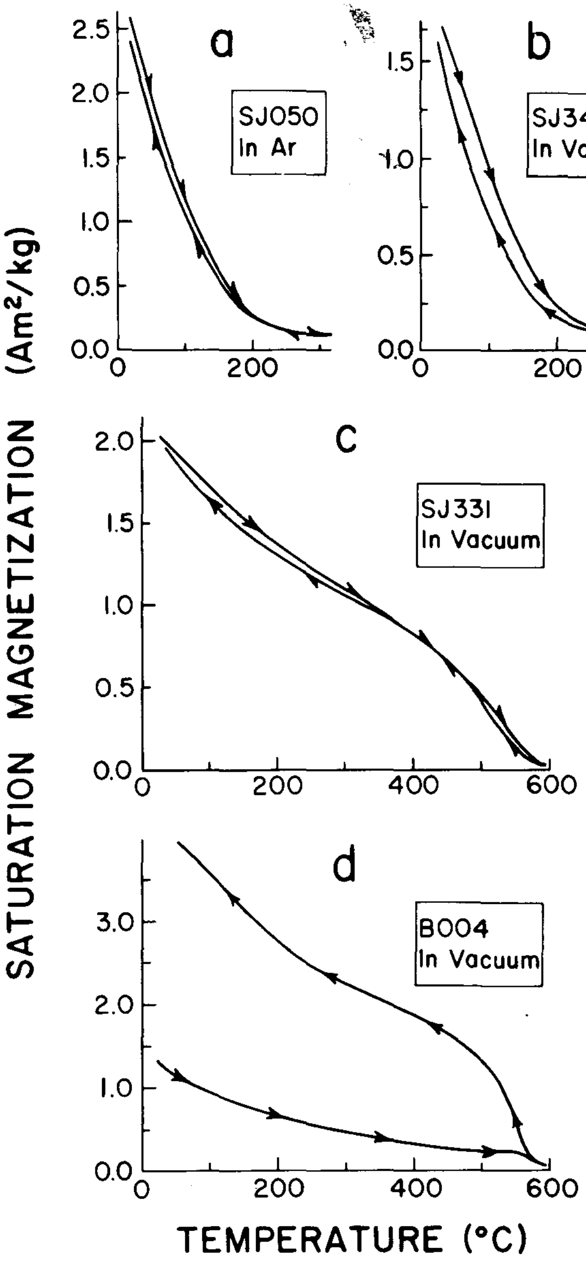

Fig. 1. Examples of strong-field thermomagnetic (J_s-T) curves for magnetic concentrates from the San Juan Basin sedimentary rocks. Arrows indicate heating and cooling curves. The atmosphere of heating is listed in each figure with sample number (see Table 1). Magnetic field strengths used are (*a*) 150 mT, (*b*) 200 mT, (*c*) 250 mT, and (*d*) 300 mT.

under the bottom edge of the pole caps of an electromagnet with a magnetic field of 300 mT. Because of the magnetic field gradient, strongly magnetic particles experienced an upward translational force and adhered to the upper part of the tubing. This magnetic concentrate was then collected by removing the tubing from the electromagnet and sluicing it with fresh water. The resultant magnetic concentrate was then dried at 80°C to yield a powder for use in the thermomagnetic experiments.

Approximately 70 mg of magnetic concentrate powder was packed in an open-ended quartz vial for thermomagnetic experiments. Continuous initial magnetization curves (magnetization versus magnetizing field) were determined up to a maximum field of 800 mT. These curves were then used to determine the magnetizing field to be used in the thermomagnetic experiment. The initial magnetization curves generally indicated that saturation of the ferrimagnetic constituents occurred in fields of 300 mT, and fields of 200–500 mT were used in the thermomagnetic experiments. Strong-field thermomagnetic (J_s-T) curves were obtained using the recording balance described by *Doell and Cox* [1967]. All samples were heated in an argon gas atmosphere after repeated evacuation to 10^{-4} torr and backfilling with argon gas. Some samples exhibited reversible J_s-T behavior in the argon gas atmosphere. However, many of the J_s-T curves in argon gas atmosphere showed evidence of oxidation during the thermomagnetic experiment. Accordingly, fresh samples of these concentrates were heated in a vacuum of 10^{-4} torr, which proved sufficient to eliminate oxidation during the experiment. Most samples were heated to 600°C, but samples with single Curie temperatures less than 200°C were heated only to 350°C. The rate of heating and cooling was 10°C/min.

J_s-T Results

Examples of J_s-T curves are shown in Figures 1 and 2, and a summary of Curie temperatures (T_C) is given in Table 1. With only two exceptions, samples from the San Juan Basin exhibit a single Curie temperature ranging from 175°C to 195°C and showed no evidence of chemical changes during the experiment. Except for a small amount of thermocouple lag resulting from heating the samples in vacuum, the J_s-T curves for all low-T_c samples are reversible.

Curie temperature and cell edge determinations on stoichiometric titanomagnetite are provided by *Akimoto et al.* [1957] and *Ozima and Larson* [1970]. *Grommé et al.* [1979] performed regression analysis of these data from which the compositional parameter x of a titanomagnetite, $Fe_{3-x}Ti_xO_4$, can be determined for the range $0.35 \leq x \leq 0.70$. Curie temperatures ranging from 175°C to 195°C are indicative of titanomagnetite with composition range $0.51 \leq x \leq 0.54$. In order to confirm this titanomagnetite composition, X ray analysis was attempted on several of the magnetic concentrates. Initial attempts failed to reveal clearly defined X ray diffraction peaks because the magnetic concentrates contained impurities. However, separation of grains using heavy liquids did succeed in providing one sample of sufficient purity to allow clear identification of the (311), (422), and (400) reflections. Using a spinel standard and Cu$K\alpha$ radiation, the cell edge was found to be 8.467 Å, indicative of $x = 0.54$ titanomagnetite. Thus Curie temperature and X ray data clearly indicate that the dominant ferrimagnetic mineral in the majority of San Juan Basin samples is a titanomagnetite of composition $0.51 \leq x \leq 0.54$.

The thermomagnetic behavior of the two samples that did not exhibit $T_C \cong 180$°C are illustrated in Figures 1*c* and 1*d*. J_s-T behavior of sample SJ331 (Figure 1*c*) from the Nacimiento Formation shows a minor inflection at 180°C and a dominant Curie temperature at 580°C. This behavior indicates the presence of a mixture of a small amount of titanomagnetite ($x = 0.53$) with a much larger proportion of magnetite. Sample B004 (Figure 1*d*) from the middle part of the Nacimiento Formation was the only sample to yield irreversible J_s-T behavior. The heating curve does not reveal a well-defined Curie temperature, and J_s increases slightly between 500° and 550°C. The cooling curve shows a sharp Curie temperature at 570°C and indicates a large increase in room temperature J_s. This type of J_s-T behavior indicates the

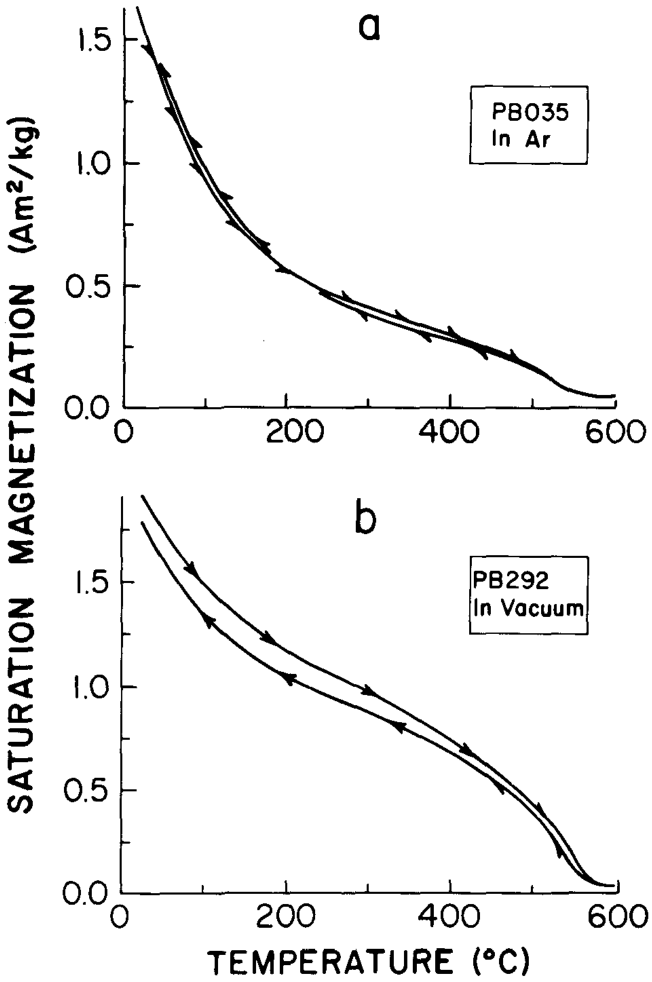

Fig. 2. Strong-field thermomagnetic (J_s-T) curves for magnetic concentrates from Clark's Fork Basin sedimentary rocks. The atmosphere of heating is listed in each figure with sample number (see Table 1). Heating and cooling curves are indicated by arrows. Magnetic field strengths used are (*a*) 400 mT and (*b*) 200 mT.

presence of cation-deficient titanomaghemite and is commonly observed in oceanic pillow lavas that have undergone low-temperature oxidation [e.g., *Marshall and Cox,* 1972]. Although the low-temperature oxidation of the titanomagnetite in sample B004 could have occurred in the source area or during transport prior to deposition, I suspect that oxidation occurred after deposition but before burial.

The strata from which sample B004 was collected are maroon brown rather than the more common gray of the claystone and siltstone of the Nacimiento Formation. In addition, this stratigraphic level is an important mammalian fossil locality known as Big Pocket [*Taylor and Butler,* 1980]. The unusual color of these strata and the occurrence of mammalian fossils could indicate that these materials were subaerially exposed before subsequent burial. A short period of subaerial exposure could have produced low-temperature oxidation of the detrital titanomagnetite to yield the observed titanomaghemite.

J_s-T curves showing 175°C $\leq T_c \leq$ 195°C were observed in samples collected from throughout the paleomagnetic section in the San Juan Basin. Samples from the Late Cretaceous Fruitland and Kirtland formations as well as samples from the upper part of the Paleocene Nacimiento Formation exhibit these low Curie temperatures indicative of $0.51 \leq x \leq 0.54$ titanomagnetite. This observation implies several important conditions regarding the source terrane for these sedimentary materials as well as depositional and postdepositional conditions.

The observation of stoichiometric titanomagnetite of $x = 0.55$ composition throughout the stratigraphic section in the San Juan Basin would require a volcanic source terrane that was continuously supplying mafic volcanic detritus to the basin. Titanomagnetite with high Ti content is common only in andesitic to basaltic volcanic rocks [*Buddington and Lindsley,* 1964]. The rapid oxidation of titanomagnetite in oceanic pillow lavas [e.g., *Irving,* 1970; *Marshall and Cox,* 1972; *Grommé et al.,* 1979] demonstrates that these high-Ti titanomagnetites are quite susceptible to low-temperature oxidation. Thus a volcanic terrane capable of supplying stoichiometric $x = 0.55$ titanomagnetites would probably not be much older than the derived sedimentary materials. A source terrane supplying fresh mafic volcanic detritus to the San Juan Basin in latest Cretaceous and Paleocene time is required.

The only area in which volcanism of this age is likely to have occurred is the San Juan Mountains, north of the San Juan Basin. Along the Animas River in the northernmost San Juan Basin, *Reeside* [1924] found andesite cobbles within conglomerates of the Animas Formation. Sedimentary rocks of the Animas and Kirtland formations were also found to be rich in andesitic debris. *Cobban and Reeside* [1952] consider the Animas Formation to be correlative with the Late Cretaceous through Paleocene continental sedimentary rocks of the central San Juan Basin. *Fassett and Hinds* [1971] cite the occurrence of bentonitic shale in the lower part of the Fruitland Formation in the southeastern San Juan Basin as evidence of volcanism during deposition of the Fruitland and Kirtland formations. *Larsen and Cross* [1956] interpreted Reeside's observations as evidence for a considerable pile of volcanic rocks of Late Cretaceous age which were largely eroded in the Paleocene. Direct evidence for a volcanic episode of Late Cretaceous age is presently limited to a small outcrop of rhyodacite flows, flow breccia, tuff breccia, and associated conglomerates which constitute the Late Cretaceous Cimarron Ridge Formation in the northwestern San Juan Mountains [*Dickinson et al.,* 1968]. Potassium-argon age determinations indicate an age of ~66 Ma. for these volcanic rocks. Thus although the actual volcanic rocks have been almost entirely eroded, evidence of volcanic activity of Late Cretaceous age in the San Juan Mountains does exist, and this area was almost certainly the source of the stoichiometric titanomagnetites found in the San Juan Basin sedimentary rocks.

In addition to the source terrane requirements, erosion and transport of the source material to the San Juan Basin must have occurred without oxidation. Because of the susceptibility of fine-grained stoichiometric titanomagnetites to oxidation, subaerial exposure for any length of time is precluded, and transport was likely quite rapid. Furthermore, the titanomagnetite must have been effectively shielded from postdepositional oxidation by inclusion in clays and silts of low permeability. Thus it appears that the only major oxidizing conditions to which these titanomagnetites have been exposed are the conditions of present weathering and erosion.

The J_s-T curves for the samples from the Clark's Fork Basin are given in Figure 2 and are summarized in Table 1. Both samples show Curie temperatures at both 180°–200°C and 550°–580°C. However, the relative amplitudes of these two phases are different in the two samples. These J_s-T data indicate the mixture of two ferrimagnetic phases. Curie temperatures of 200°C indicate the presence of a titanomagnetite of $x \sim 0.5$ composition. The Curie temperature of 500°–580°C indicates the presence of magnetite with little or no Ti. The source terrane for the Clark's Fork Basin sedimentary rocks evidently contained mafic volcanic material with stoichiometric titanomagnetites as well as more oxidized volcanic rocks with magnetite. The Clark's Fork Basin and the Crazy Mountain Basin of southwestern Montana occupy parts of a continuous structural depression into which Late Cretaceous and early Tertiary sedimentary materials were deposited. *Roberts* [1972] has found that the Late Cretaceous and Paleocene Fort Union Formation in the Crazy Mountain Basin contains a large proportion of volcanic detritus. Thus evidence of a mafic volcanic source terrane for the Clark's Fork Basin sedimentary rocks is quite reasonable.

The most important result of the thermomagnetic experiments is the observation that the dominant ferrimagnetic minerals are detrital titanomagnetites. The high Ti content of the titanomagnetites from the San Juan Basin sedimentary rocks is quite surprising. The detrital origin of the dominant ferrimagnetic minerals in both the Clark's Fork Basin and the San Juan Basin rocks is thus confirmed, and a detrital origin of the stable NRM is supported. In addition, the thermomagnetic data do not show evidence of hematite, goethite, or other ferric minerals which would be the anticipated products of postdepositional oxidation.

POLISHED GRAIN MOUNT OBSERVATIONS

Previous attempts to prepare polished sections or polished thin sections of rock samples were largely unsuccessful. The difficulty in preparing polished sections is primarily the result of the hardness contrast between the opaques and the clay/silt matrix. Even when impregnated with epoxy resins, the opaque grains tend to roll or to be plucked from the section when the surface is polished. However, polished grain mounts of several of the magnetic separates were successfully prepared. Microscopic examination of these polished grain mounts under reflected light yielded several interesting observations.

Polished grain mounts were prepared from the magnetic concentrates of San Juan Basin samples SJ050, SJ331, and SJ347. J_s-T experiments on magnetic concentrates from samples SJ050 and SJ347 exhibited Curie temperatures of 175°C and 180°C, respectively, whereas the dominant Curie temperature of sample SJ331 was 580°C. Almost all opaque grains in the polished grain mounts from SJ050 and SJ347 are optically homogeneous and isotropic. These observations are consistent with the J_s-T and X ray data, which indicated a stoichiometric titanomagnetite composition of the dominant ferrimagnetic phase in these samples. Although not common, a few grains in both of these polished grain mounts exhibited magnetite-ilmenite intergrowth structures. Grains composed of magnetite-ilmenite intergrowths are quite common in the polished grain mount from sample SJ331, consistent with the 580°C Curie temperature indicating magnetite as the dominant ferrimagnetic phase. In all three grain mounts of San Juan Basin magnetic concentrates, most grain boundaries are very sharp with little or no rimming of grains by hematite or titanomaghemite. No martite grains were observed.

Polished grain mounts were also prepared from the magnetic concentrates of the two Clark's Fork Basin samples. These grain mounts contain mixtures of optically homogeneous and isotropic grains along with grains exhibiting magnetite-ilmenite intergrowths. These microscopic observations are consistent with the J_s-T data, which indicates a mixture of magnetite and titanomagnetite. Again, almost all grain boundaries are sharp with no rimming by hematite or titanomaghemite. An interesting feature of these grain mounts is the mixture of grains with very different oxidation states. The same grain mount commonly contains homogeneous, unoxidized titanomagnetite grains along with grains which have suffered significant dueteric oxidation. These observations imply a source region(s) which was heterogeneous in degree of deuteric oxidation.

ISOTHERMAL REMANENT MAGNETISM

Although the strong-field thermomagnetic experiments clearly demonstrate that titanomagnetites are the dominant ferrimagnetic phase, the presence of minor amounts of hematite or other ferric oxides (or oxyhydroxides) would not be observed in the thermomagnetic experiments. (For convenience, all ferric oxides and oxyhydroxides, such as hematite, goethite and limonite, will hereafter be referred to as hematite, although the data available may not be sufficient to discriminate between the various ferric oxides and oxyhydroxides.) The J_s-T curves would fail to reveal minor amounts of hematite because its saturation magnetization is a small fraction of that of titanomagnetite. Thus although the J_s-T results indicate that hematite is not a major ferrimagnetic constituent, the failure to observe hematite in the thermomagnetic experiments cannot be taken as evidence that hematite is absent. In addition, the magnetic concentration technique might fail to extract hematite from the sample, even if it were present in a significant amount (see discussion below). Thus we require a technique with the capability to detect a minor hematite content in the presence of a significant amount of titanomagnetite.

As shown by *Dunlop* [1972], the mode of acquisition of isothermal remanence can allow detection of a small amount of hematite in the presence of a larger amount of titanomagnetite. IRM is measured after a direct magnetizing field H is applied to the sample and the field is then removed. Progressively higher field strengths are then used; a maximum magnetizing field of 700 mT was used in this study. Titanomagnetite does not exhibit coercive force greater than 300 mT. Therefore an IRM acquisition curve (IRM versus H) which shows no increased IRM above 300 mT magnetizing field indicates the presence of titanomagnetite, and increased IRM above 300 mT magnetizing field must be attributed to hematite or other ferric minerals with high coercivity.

Samples for IRM acquisition experiments were selected from 114 paleomagnetic sites throughout the San Juan Basin section and from 56 paleomagnetic sites in the Clark's Fork Basin section. This sample distribution provided detailed coverage of both stratigraphic sections. The primary objective of such a detailed sampling was to investigate whether IRM acquisition could be related to paleomagnetic properties such as NRM demagnetization behavior. Of special interest was the possibility of using IRM acquisition to detect the presence of high-coercivity hematite. Because this hematite could carry CRM overprints, IRM acquisition

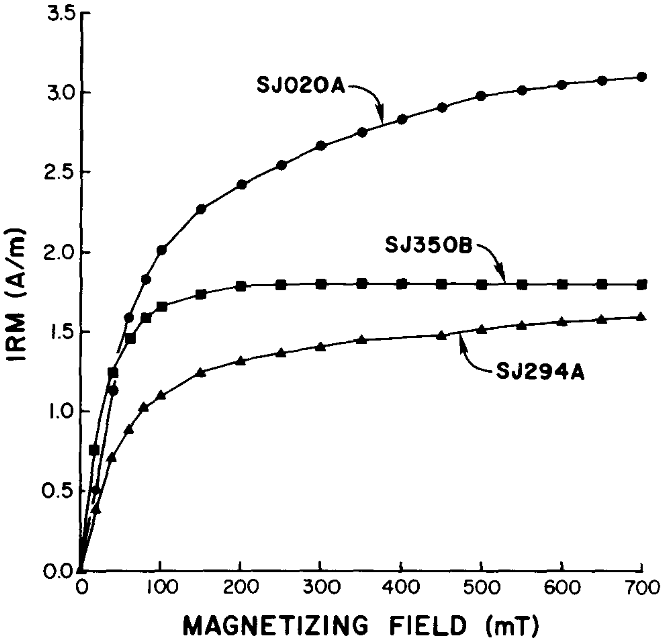

Fig. 3. Examples of isothermal remanent magnetization acquisition curves for San Juan Basin samples. Remanent magnetization was measured following removal of the direct magnetizing field. The strength of the magnetizing field was progressively increased.

behaviors could be useful in detecting stratigraphic intervals in which CRM overprints are likely.

Examples of IRM acquisition curves are given in Figures 3 and 4. These examples were chosen to illustrate the range of behaviors observed. Many samples, such as SJ350B (Figure 3) and PB133A (Figure 4), acquire little or no additional IRM in magnetizing fields greater than 300 mT. This behavior indicates that these samples contain only titanomagnetite. However, samples such as SJ020A (Figure 3) and PB206A (Figure 4) show increased IRM in magnetizing fields greater than 300 mT. These samples evidently contain appreciable amounts of high-coercivity hematite. Average IRM acquisition behaviors are illustrated by samples SJ294A (Figure 3) and PB095A (Figure 4). These samples yield IRM acquisition curves that are dominated by IRM acquired in $H < 300$ mT but exhibit small additional IRM acquired in $H > 300$ mT. This average behavior suggests that the titanomagnetite observed in the J_s-T curves also dominates the IRM acquisition but that a minor amount of hematite is also present.

In order to investigate the stratigraphic distribution of IRM acquisition behaviors and the possible relation of IRM acquisition to properties of the NRM, it is desirable to define a parameter which in some way quantifies the IRM acquisition behavior. Specifically, a parameter that can reflect the ratio of high-coercivity (>300 mT) to low-coercivity (<300 mT) fractions of the IRM acquisition curve is needed. Let

$$\delta = [\mathrm{IRM}(600\ \mathrm{mT}) - \mathrm{IRM}(300\ \mathrm{mT})]/\mathrm{IRM}(300\ \mathrm{mT})$$

where IRM(600 mT) is the IRM acquired by exposure to a magnetizing field of 600 mT and IRM(300 mT) is the IRM acquired by exposure to a magnetizing field of 300 mT. A $\delta = 0$ value would indicate an IRM acquisition curve in which no additional IRM is acquired for $H > 300$ mT. Such a curve would indicate the absence of hematite. However, a sample of pure hematite would not have a δ value of infinity but would probably have $\delta \sim 1.0$. It is not possible to derive a volume ratio of hematite to titanomagnetite from the δ value. The relatively small J_s for hematite and the uncertainty of the relative efficiency of IRM acquisition between hematite and titanomagnetite belie the use of δ as a quantitative measure of the hematite:titanomagnetite ratio. However, the δ value is useful as a parameter which characterizes the shape of the IRM acquisition curve and thereby provides at least a qualitative measure of the hematite:titanomagnetite ratio.

Of major concern is the stratigraphic distribution of δ values and the relation of δ values to polarity zones defined by the af demagnetized NRM. A systematic distribution of δ, especially a correlation of δ with polarity of a characteristic NRM, would suggest that hematite is of major importance to the NRM. Such an observation would obviously jeopardize the validity of the magnetic polarity stratigraphy. At the worst, if normal-polarity zones were the result of overprinting during present weathering, high δ values would be observed in the normal-polarity zones.

If no systematic variation of δ is observed, the likelihood would be minimal that the minor hematite content has significantly influenced the NRM. The absence of any systematic δ variation would suggest that the minor hematite present has only slightly influenced the NRM. Although the NRM may contain a small component of high coercivity carried by hematite (as is observed at some sites), the NRM properties would be dominated by the titanomagnetite. In such a case the characteristic NRM with coercivities in the 20- to 80-mT range would quite clearly be the depositional remanence carried by the titanomagnetite. The polarity of that characteristic NRM would be a valid recording of the geomagnetic polarity at the time of deposition. Obviously, this is the desired result and would be consistent with the hypothesis that the small hematite content present has been produced by slight oxidation during present weathering of the outcrop at sampling sites which are randomly distributed throughout the stratigraphic section.

Figures 5 and 6 illustrate the stratigraphic distribution of the δ values derived from the IRM acquisition experiments on Clark's Fork Basin and San Juan Basin samples, respectively. Table 2 lists mean δ values ($\bar{\delta}$) and standard deviations for all samples examined. Mean δ values were calculated for the entire sample population as well as separately for the populations of normal- and reversed-polarity sites. In addition, mean δ values were determined for each formation in the stratigraphic sections.

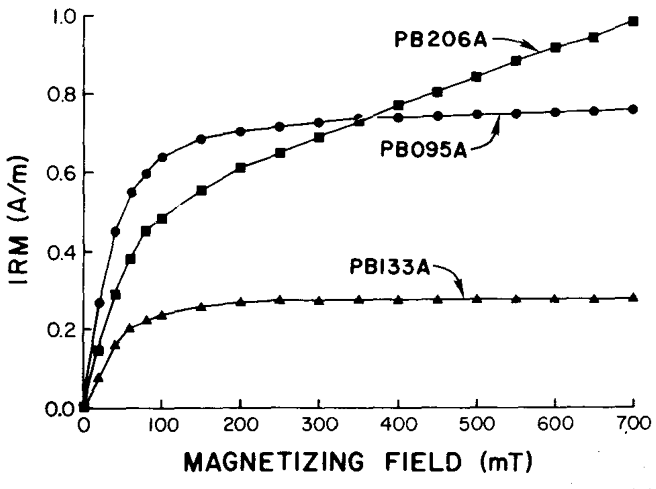

Fig. 4. Examples of isothermal remanent magnetization acquisition curves for Clark's Fork Basin samples.

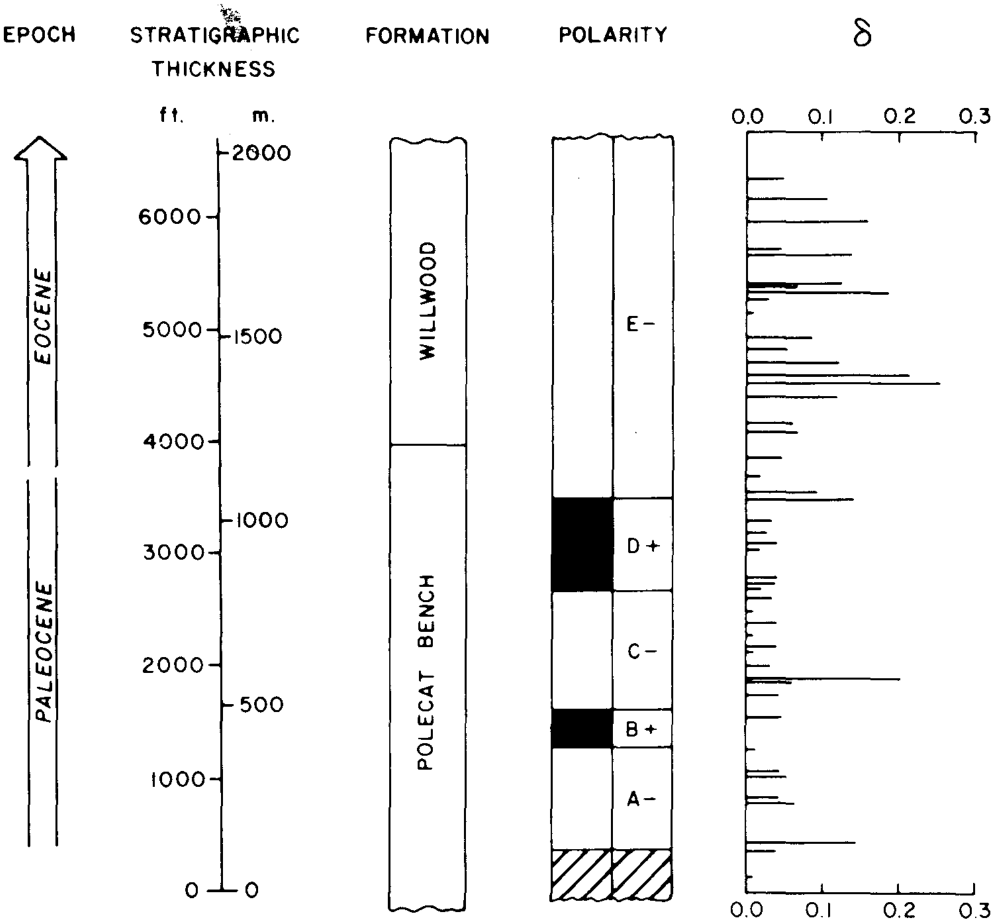

Fig. 5. Stratigraphic distribution of δ values determined from IRM acquisition curves for the Clark's Fork Basin samples. The stratigraphic section and definition of polarity zonation are described by *Butler et al.* [1981].

As illustrated in Figure 5 and summarized in Table 2, no clear variation of $\bar{\delta}$ exists in the Clark's Fork basin section. No significant correlation of $\bar{\delta}$ with polarity of the characteristic NRM is observed, although δ values tend to be higher in the upper part of the section. This observation is consistent with common NRM demagnetization behavior which indicates the presence of small normal-polarity components of high coercivity in the upper part of the Clark's Fork Basin section [*Butler et al.*, 1981]. However, the NRM vector of sites in the upper part of the section commonly moved toward but failed to reach the anticipated Eocene reversed-polarity direction. These observations support the interpretation that the minor hematite content evidenced by the IRM acquisition experiments was produced during recent weathering and does contribute a small normal-polarity CRM component to the NRM. However, this component is not of sufficient magnitude to obscure the polarity of the characteristic NRM carried by the titanomagnetite. The IRM experiments thus substantiate the hypothesis that the characteristic NRM is a DRM carried by titanomagnetite and that the Clark's Fork Basin polarity zonation provides a valid recording of the geomagnetic polarity sequence during deposition of this stratigraphic sequence.

Figure 6 illustrates the stratigraphic distribution of the 114 samples and the resulting δ values from the San Juan Basin for which IRM acquisition curves were determined. The δ values are comparable to those observed in the Clark's Fork Basin. However, a few samples in the San Juan Basin section exhibit $\delta > 0.3$, whereas no samples in the Clark's Fork Basin section exhibited such high δ values. Most of these San Juan Basin samples with high δ values appear to be randomly distributed throughout the section, and no correlation with polarity of the characteristic NRM is evident. As indicated in Table 2, no significant correlation of $\bar{\delta}$ with polarity of the characteristic NRM is observed in any of the formations in the San Juan Basin section.

The Ojo Alamo Sandstone does seem to exhibit δ values larger than the adjacent formations. One sample from each paleomagnetic site in the upper part of the Kirtland Shale and the Ojo Alamo Sandstone were subjected to the IRM acquisition experiment in order to investigate this stratigraphic interval. The heavy bars in Figure 6 represent the average δ values obtained from sites within normal-polarity zone $\gamma+$ and from reversed-polarity sites underlying and overlying $\gamma+$. Although the mean δ value from sites within this normal-polarity zone is higher than the overall mean value, the sites in the underlying reversed-polarity zone also have a high mean δ value. Close inspection showed that these high mean values are dominated by a small proportion of sites with anomalously high δ values. The δ values are not, in fact, uniformly high in this stratigraphic interval. Also, the sites exhibiting the anomalously high δ values are not confined to the normal-polarity zone ($\gamma+$), as would be expected if that polarity zone were the result of a large CRM overprint. Although the presently available evidence does not indicate a CRM overprint origin for the characteristic NRM within normal-polarity zone $\gamma+$, the IRM data have prompted further study of this stratigraphic interval.

As with the Clark's Fork Basin section, the absence of any systematic correlation of $\bar{\delta}$ with polarity of the characteristic

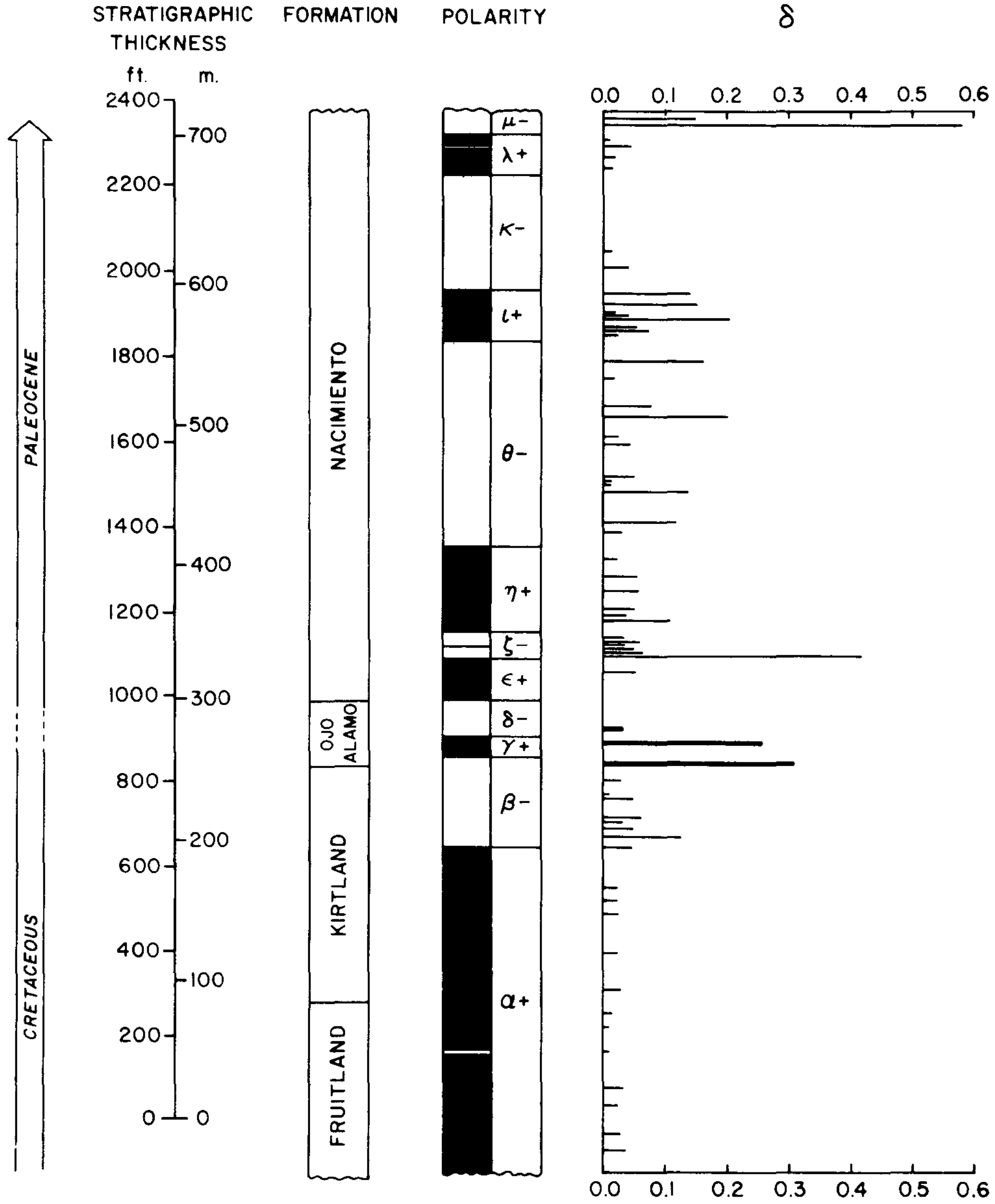

Fig. 6. Stratigraphic distribution of δ values determined from IRM acquisition curves for San Juan Basin samples. Bold lines in and adjacent to normal-polarity zone $\gamma+$ represent average δ values ($\bar{\delta}$) for sets of samples from paleomagnetic sites within this stratigraphic interval. Number of samples (N), $\bar{\delta}$, and standard deviation (s.d.) for the mean values are as follows: upper part of reversed-polarity zone $\beta-$ in Kirtland Formation, $N = 12$, $\bar{\delta} = 0.31$, and s.d. $= 0.40$; sites in Ojo Alamo Sandstone within $\gamma+$, $N = 14$, $\bar{\delta} = 0.28$, and s.d. $= 0.31$; sites in Ojo Alamo Sandstone above $\gamma+$, $N = 8$, $\bar{\delta} = 0.03$, and s.d. $= 0.01$. Descriptions of stratigraphic sections and polarity zonations are given by *Lindsay et al.* [1981].

NRM in the San Juan Basin section indicates that the minor hematite content has not influenced the polarity of the characteristic NRM. Thus the IRM acquisition experiments again substantiate the hypothesis that the characteristic NRM is carried by the titanomagnetite and is a depositional remanence. The observed polarity zonation thus provides a record of the geomagnetic polarity sequence during deposition of the San Juan Basin sedimentary rocks.

Two additional experiments were performed to gain information about the hematite content demonstrated by the IRM experiments. Microscope slides of each magnetic concentrate were prepared by dispersing a small amount of concentrate in immersion oil on a glass slide and placing a cover glass over the dispersion. These slides were examined under the microscope in transmitted light to investigate nonopaque grains in the concentrate. Although rare, some reddish translucent grains were observed in almost all slides. These grains are thought to be silicates containing ferric oxides and may contain regions of precipitated hematite.

Prior to preparation of the magnetic concentrates, an IRM acquisition experiment was performed on a specimen from each bulk sample. For three of these specimens the IRM curve exhibited significant increases above H = 300 mT (kOe) indicating the presence of significant hematite in the bulk sample. For two such samples, sufficient magnetic concentrate remained after the J_s-T experiments to allow preparation of a sample for IRM analysis by dispersing ~100 mg of concentrate in ~10 cm^3 of plaster. A blank plaster sample was also prepared, and the IRM acquired by the blank sample was <0.1% of the IRM acquired by the plaster

TABLE 2. Summary of Isothermal Remanence Acquisition Results

Polarity	N	$\bar{\delta}$	s.d.
Clark's Fork Basin			
All	56	0.083	0.080
Normal	9	0.035	0.011
Reversed	47	0.092	0.085
Polecat Bench Formation			
All	30	0.047	0.043
Normal	9	0.035	0.011
Reversed	19	0.055	0.046
Willwood Formation			
Reversed*	26	0.104	0.065
San Juan Basin			
All	114	0.120	0.209
Normal	45	0.111	0.200
Reversed	54	0.137	0.236
Fruitland Formation			
All	9	0.025	0.012
Normal	8	0.028	0.010
Reversed	1	0.005	
Kirtland Formation			
All	26	0.126	0.214
Normal	5	0.024	0.002
Reversed	19	0.159	0.243
Ojo Alamo Sandstone			
All	22	0.242	0.355
Normal	13	0.266	0.324
Reversed	8	0.181	0.434
Nacimiento Formation			
All	57	0.084	0.107
Normal	18	0.063	0.055
Reversed	26	0.115	0.141

N is the number of samples, $\bar{\delta}$ is the mean of δ values, and s.d. is the standard deviation of the mean δ value. In some cases the sum of the normal and reversed polarity sets is less than the total sample population because samples of intermediate or ambiguous polarity were not included within the normal- or reversed-polarity sets.

*Willwood Formation is entirely of reversed polarity.

plus concentrate samples. IRM acquisition curves for the plaster plus concentrate samples showed no increase in IRM for magnetizing fields above 300 mT. These results indicate that the magnetic concentration procedure had failed to extract the hematite from the sediment. It is quite likely that the magnetic concentration technique would be much less efficient for silicate grains containing hematite than for titanomagnetite grains with hematite rimming. Thus both the microscopic observations of the magnetic concentrates and results of the IRM experiments on the plaster plus concentrate samples suggest that the hematite present in these sedimentary rocks is the result of oxidation of iron-bearing silicates rather than the result of oxidation of the detrital titanomagnetite.

CONCLUSIONS

Results of the strong-field thermomagnetic experiments on magnetic concentrates from the sedimentary sequences in San Juan Basin and Clark's Fork Basin provide important information regarding the nature of the dominant ferrimagnetic minerals. Samples from throughout the Late Cretaceous to middle Paleocene sedimentary sequence in the San Juan Basin have Curie temperatures ranging from 175°C to 195°C, indicative of stoichiometric titanomagnetite in the $0.51 \leq x \leq 0.54$ range. Only a single sample showed evidence of low-temperature oxidation. These observations require a volcanic source terrane capable of supplying fresh mafic volcanic detritus without oxidation during erosion, transport, or deposition. Significant postdepositional oxidation was apparently prevented by the low permeability of silt and clay in these rocks. Such source materials and depositional conditions are likely to have led to the formation and preservation of a depositional remanence, as the consistency of the paleomagnetic data implies.

J_s-T results from the Clark's Fork Basin samples indicate that the dominant ferrimagnetic constituents are mixtures of magnetite and titanomagnetite of $x \sim 0.5$ composition. Conclusions reached for the San Juan Basin sedimentary rocks regarding sediment source and depositional conditions also apply to the Clark's Fork Basin rocks.

Results of the experiments on isothermal remanence acquisition yield two major conclusions:

1. Evidence of high-coercivity hematite was detected by experiments on IRM acquisition when no evidence for hematite was observed in the strong-field thermomagnetic results. This result indicates the potential use of IRM acquisition to monitor minor hematite content in sedimentary rocks that also contain a larger titanomagnetite content. Normal-polarity overprints are one of the major problems that arise in polarity stratigraphic studies of continental sedimentary rocks. Because hematite is a potential carrier of CRM overprints, monitoring the hematite content by IRM acquisition provides an indirect method of detecting stratigraphic levels in which the NRM could contain a significant CRM overprint. Any correlation of hematite content evident from the IRM acquisition behavior with polarity of the characteristic NRM should be carefully examined. Such correlations could be an indicator that CRM overprints, rather than stable NRM components of depositional origin, are producing the polarity zonations observed. It is not yet possible to prescribe a critical test based on IRM acquisition that is sufficient to assure that the polarity zonation observed is free from normal-polarity overprints. Examination of the stratigraphic distribution of IRM behavior does, however, seem to be a worthwhile supplement to studies of paleomagnetic polarity stratigraphy.
2. Detailed sampling of IRM acquisition behavior for sedimentary rocks from the San Juan Basin and Clark's Fork Basin did not reveal any systematic variations suggestive of significant CRM overprints. Although minor hematite content is indicated, no correlation with polarity of the characteristic NRM exists in either stratigraphic sequence. These results indicate that the minor hematite content present may contribute a small CRM component to the NRM. However, this component has not obscured the polarity of the depositional component carried by the titanomagnetite. The observed polarity sequences of characteristic NRM determined by *Lindsay et al.* [1981] and *Butler et al.* [1981] thus provide records of the geomagnetic polarity sequence during deposition of these sedimentary sequences.

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