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MINERALOGY OF MAGNETIC MINERALS AND REVISED MAGNETIC POLARITY STRATIGRAPHY OF CONTINENTAL SEDIMENTS, SAN JUAN BASIN, NEW MEXICO

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ABSTRACT

Detailed paleomagnetic and rock-magnetic analyses have been performed on samples from multiple sections through the Cretaceous/Tertiary (K/T) boundary and throughout a 750 m thick sequence of late Cretaceous through middle Paleocene continental deposits in the San Juan Basin, New Mexico. Curie temperatures have been determined for magnetic separates from 52 levels and, with only two exceptions, they range from 180 to 300°C. Along with microprobe and X-ray analyses these data indicate that the detrital ferrimagnetic mineral is titanomagnetite with composition 0.45 < x < 0.60. This magnetic mineralogy indicates derivation of the continental San Juan Basin sediments from a volcanic (probably dacitic or andesitic) source. These mineralogical data, along with other geological data and the pattern of magnetic polarity zonation in multiple sections across the basin, argue strongly for deposition of the late Cretaceous and Paleocene continental deposits in the San Juan Basin as a clastic wedge derived from a source to the north or northwest. Demagnetization experiments, coupled with the mineralogy of the magnetic minerals, indicate that revision of our previous correlation of the San Juan Basin stratigraphic sequence with the magnetic polarity time scale is required. This revision indicates that the K/T boundary (recognized above the highest stratigraphic occurrence of dinosaur fossils) occurs within a reversed polarity zone correlative with magnetic polarity chron 29R. This correlation is consistent with the K/T boundary in the marine sedimentary sequence at Gubbio, Italy. Puercan (early Paleocene) fossil mammals occur within a normal polarity zone correlative with chron 29N and Torrejonian (middle Paleocene) fossil mammals occur within polarity zones correlative with chron 27N, 27R, and 28N. With this revision, consistent and sequential placements within the magnetic polarity time scale have been accomplished for all North American land mammal ages in the Paleocene through early Eocene interval.

INTRODUCTION

Paleomagnetic study of the continental deposits in the San Juan Basin was originally undertaken to determine the placement of Puercan (early Paleocene), Torrejonian (middle Paleocene), and Tiffanian (late Paleocene) land mammal ages with respect to the independent chronologic framework provided by the magnetic polarity time scale. Several publications (Butler et al. 1977; Taylor and Butler 1980; Lindsay et al. 1978, 1981) have reported paleomagnetic data and interpretations of the polarity zonation from the late Cretaceous and Paleocene continental deposits. The stratigraphic succession includes the Fruitland and Kirtland Formations, Ojo Alamo Sandstone, and Nacimiento Formation. An initial study of the magnetic mineralogy was published by Butler (1982). The pattern of resulting polarity zonation showed quite good correspondence to the pattern of polarity intervals in the magnetic polarity time scale between magnetic polarity chron 31N and chron 25N. This correlation is illustrated in figure 1. Several objections to this correlation were raised (Alvarez and Vann 1979; Fassett 1979; Lucas and Schoch 1982), and our own subsequent research has led to additional studies and a reevaluation of the magnetostratigraphic results from the San Juan Basin. In this paper, we report the results of recent additional rock-magnetic and paleomagnetic investigations.

Magnetic polarity stratigraphic study of continental deposits in the Clark's Fork Basin, Wyoming (Butler et al. 1981) was undertaken subsequent to the original San Juan Basin study. The Clark's Fork Basin section contains fossil mammal assemblages assigned to Tiffanian (late Paleocene), Clarkforkian (transitional Paleocene/Eocene) and Wasatchian (early Eocene) land mammal ages. Given the age constraints provided by these fossils, the two normal polarity zones in the Clark's Fork Basin section could be firmly correlated with chron 26N and 25N of the
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FIG. 1.—Correlation by Lindsay et al. (1981) of San Juan Basin magnetic polarity zonation with the magnetic polarity time scale of Ness et al. (1980). The San Juan Basin polarity column was scaled to make the stratigraphic thickness between the top of zone a+ and the base of zone i+ match the interval between the younger boundary of chron 30N and the older boundary of chron 26N.

magnetic polarity time scale. Comparison of the original San Juan Basin and Clark’s Fork Basin results implied a significant overlap between Tiffanian fossils of the Clark’s Fork Basin and Torrejonian fossils of the San Juan Basin. Although a minor overlap might be explained by paleogeographic or paleoenvironmental mechanisms, the magnitude of the apparent overlap seemed excessive, because land mammal ages are traditionally thought to occupy distinct and successive intervals of geologic time (Wood et al. 1941). Thus, the unexpected overlap of Torrejonian fossils from the San Juan Basin with Tiffanian fossils from the Clark’s Fork Basin could indicate that the magnetozones containing the Torrejonian fossils in the San Juan Basin had been incorrectly correlated to the magnetic polarity time scale (Lucas and Schoch 1982).

The initial study of the rock-magnetism of the San Juan Basin sediments (Butler 1982) indicated only minor oxidation of magnetic minerals overall. However, some indications of oxidation were found in samples from the upper Kirtland Formation just below the Ojo Alamo Sandstone. Because this is the stratigraphic level from which the normal polarity magnetozone γ+ in the San Juan Basin composite section was determined (fig. 1), we became concerned that this magnetozone could have suffered post-depositional remagnetization. This concern prompted a detailed re-collection of that stratigraphic interval coupled with a more detailed examination of the mineralogy of the magnetic minerals. The results of these studies are presented below.

MINERALOGY OF MAGNETIC MINERALS AND PALEOMAGNETIC DATA

Results of a detailed study of the magnetic mineralogy of continental sediments from the San Juan Basin are described below. These results establish that the dominant ferrimagnetic mineral in these sediments is titanohematite with composition intermediate between hematite and ilmenite. Paleomagnetic and rock-magnetic data from re-collected sections in the Kirtland Formation and Ojo Alamo Sandstone are then presented. These data indicate that magnetozone γ+ (fig. 1) is a normal polarity viscous overprint on a primary component of reversed polarity. This magnetozone must be removed from the polarity zonation of the San Juan Basin. Paleomagnetic data are also presented from two additional sections not included in our original magnetostratigraphic study. The resulting data indicate that the stratigraphic interval below the Ojo Alamo Sandstone is of reversed polarity in all sections studied.

Magnetic Minerals.—Paleomagnetic data from numerous stratigraphic sections in the San Juan Basin have been published by Taylor and Butler (1980) and Lindsay et al. (1981). The limited rock-magnetic studies which accompanied those paleomagnetic investigations indicated that alternating-field (AF) demagnetization seemed to be effective in removing secondary components of the natural remanent magnetization (NRM). Progressive AF demagnetization were performed on a small proportion of the total sample collection (~5%). These experiments revealed the presence of two components of
NRM. A low coercivity viscous remanent magnetization (VRM) was often observed and was erased by AF demagnetization to peak fields of about 20 mT. A “primary” component of NRM was observed to have coercivity dominantly between 20 and 60 mT. Several observations led to the conclusion this component was a depositional remanent magnetization (DRM) carried by magnetite.

Although few detailed studies of magnetic mineralogy of continental sediments have been published, magnetite (or titanomagnetite with low Ti content) is most commonly observed as the dominant detrital magnetic mineral. This generalization is probably accounted for by the occurrence of magnetite as the dominant ferrimagnetic mineral in many igneous and metamorphic rocks. Thus magnetite is likely available from a wide variety of source terranes from which continental sediments are derived. The a priori expectation would be that the dominant magnetic mineral in the San Juan Basin sediments would be magnetite. This expectation seemed to be confirmed by two preliminary experiments on the rock-magnetism of these sediments. Isothermal remanent magnetization (IRM) was predominantly acquired in magnetizing fields up to 300 mT, with only a small further increase of IRM in higher magnetizing fields. This behavior is common for rocks in which the dominant magnetic mineral is magnetite or titanomagnetite (Dunlop 1972; Butler 1982). In addition, a single strong-field thermomagnetic experiment on a sample from the San Juan Basin (Shive pers. comm.) indicated a dominant Curie temperature \( T_c \) of 580°C, the Curie temperature of magnetite. Thus, we felt confident that the primary component of the NRM was a DRM carried by detrital magnetite. As described below, it is now known that this initial strong-field thermomagnetic result is not typical thermomagnetic behavior for the late Cretaceous through Paleocene continental sediments of the San Juan Basin. Subsequent, more detailed work has revealed a much more complex mineralogy of magnetic minerals in the continental sediments of the San Juan Basin.

In the earlier paleomagnetic studies, some progressive thermal demagnetization experiments led to confusing results. Whereas we expected that thermal demagnetizations would reveal blocking temperatures of the NRM distributed below the 580°C Curie temperature of magnetite, the NRM was nearly completely demagnetized at the initial temperature of 200°C used in the thermal demagnetization. At the time, this observation was rationalized by presuming that the heating of these clay-rich sediments in air had led to oxidation of the detrital magnetite. As described below, the proper explanation of the low blocking temperatures for thermal demagnetization is the low Curie temperature (~200°C) of the detrital ferrimagnetic mineral.

An initial study of the mineralogy of magnetic minerals was undertaken by Butler (1982). That study was initiated primarily to provide additional evidence for the detrital origin of the primary NRM and to investigate the possibility of post-depositional remagnetization of the continental sediments in both the San Juan Basin and the Clark’s Fork Basin. Magnetic separates were obtained from nine stratigraphic levels in the San Juan Basin section. Strong-field thermomagnetic experiments revealed Curie temperatures of ~200°C for seven of these magnetic separates. One separate had a Curie temperature of 580°C while the remaining samples revealed the irreversible thermomagnetic characteristics indicative of titanomagnetite. A dominant Curie temperature of ~200°C was unexpected and was taken to indicate that the dominant magnetic mineral was detrital titanomagnetite \( (\text{Fe}_3-x\text{Ti}_x\text{O}_4) \) with composition intermediate between magnetite and ulvospinel \((0.51 < x < 0.54)\). Intermediate composition titanomagnetites are much less common than is magnetite, except in rapidly cooled maﬁc volcanic rocks. In an attempt to conﬁrm that the dominant magnetic mineral is indeed titanomagnetite, X-ray analysis was performed on one of the magnetic separates. A spinel standard was added to provide internal calibration peaks for determination of the cell edge. Even after puriﬁcation of the magnetic separate by heavy liquid separation, only three X-ray peaks from the magnetic separate were sufﬁciently sharp and close to the peaks of the spinel standard to be of use for determination of the cell edge. The value of 8.467Å was interpreted to be indicative of \( x = 0.54 \) titanomagnetite, “conﬁrming” the Curie temperature results (Butler 1982). The additional mineralogic data collected for the
present study clearly indicate that the dominant magnetic mineral is titanohematite rather than titanomagnetite. In retrospect, it is clear that many of the previous conclusions about the magnetic mineralogy were strongly influenced by the common belief amongst paleomagnetists that intermediate composition titanohematite is rare. However, results of the present investigation indicate that intermediate composition titanohematite may not be as rare as previously believed.

For the present study, oriented paleomagnetic samples and bulk samples for magnetic separation were collected from 52 sites distributed throughout the entire late Cretaceous to middle Paleocene continental sedimentary section in the San Juan Basin. Magnetic separations were performed on the bulk samples using a technique similar to that described by Butler (1982) but with the addition of pumps for circulating the sediment/water slurry. This technique produced much more concentrated magnetic separates than were previously obtained. Even with the improved separation technique, significant amounts of quartz and clay particles are also entrained in the magnetic fraction during separation. Strong-field thermomagnetic experiments were performed on all magnetic separates, X-ray diffraction analysis was performed on eight magnetic separates, and polished grain mounts were prepared from five representative magnetic separates. The polished grain mounts were used in the microprobe and reflected light microscopic studies.

The thermomagnetic experiments were similar to those described by Butler (1982) with the exception that a recording microbalance interfaced to a microprocessor was used. The heating chamber was evacuated to 10^-2 torr, then backfilled with ½ atmosphere of argon gas. Heating and cooling rate was 10°C/min. Sample weight with the magnetic field turned off was automatically monitored during the thermomagnetic experiment. This base-level weight was measured approximately every 30°C. Changes in the base-level weight were removed from the data by linear interpolation between base-level readings.

Typical results of the thermomagnetic experiments are shown in figure 2. Calibration tests using CrO_2 (T_c = 120°C) indicate that the thermocouple temperature leads the sample temperature by about 10°C during heating and cooling in the 100 to 200°C range. The apparent irreversibility of the heating and cooling curves in figure 2 is a result of this thermocouple lead. Curie temperatures were determined by: (1) fitting a straight line between the low temperature portions of the heating and cooling curves, (2) fitting a straight line to the high temperature portion of the thermomagnetic curve, then (3) projecting the intersection of these two lines to the temperature axis. This procedure is illustrated in figure 2 and is a useful technique for Curie temperature determination from concave thermomagnetic curves (Gromme et al. 1969).

All but two magnetic separates exhibited a single Curie temperature in the range 180 < T_c < 300°C. No other Curie temperatures were evident, even when samples were heated to 620°C. The remaining two separates both exhibited single Curie temperatures of 580°C. In the absence of other data, these Curie temperatures could be accounted for by either intermediate composition titanomagnetite or intermediate composition titanohematite.

Figures 3 and 4 illustrate the results of the microprobe and X-ray analyses. Microprobe analyses were done on a number (≥7) of individual grains in each of five polished grain mounts. Analyses were performed on the larger (>10 μm) grains so that the microprobe

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**FIG. 2.—Examples of strong-field thermomagnetic behavior for magnetic separates from San Juan Basin continental sediments. Arrows indicate heating and cooling curves. Curie temperatures were determined by intersection of high and low temperature segments projected to the temperature axis. See text for details.**
beam could be focused entirely within the opaque grain. The grains were analyzed for 10 elements including Al, Mg, Mn, Cr, Fe, and Ti. Concentrations of all elements other than Ti and Fe were always <2%. Microprobe data were used to determine the Ti:Ti + Fe ratio for each grain. The mean and standard deviation of this ratio were computed for each polished grain mount. As can be seen in figure 4, the Ti contents determined from the microprobe data are too high to be accounted for by titanomagnetite and indicate that the opaque grains are most likely intermediate composition titanohematites. Accordingly, the compositions determined from the microprobe analyses were plotted on the titanohematite series.

An example of the X-ray diffraction data is presented in figure 3. Diffraction patterns for ilmenite and magnetite standards are also illustrated for comparative purposes. X-ray peaks due to the quartz included in the magnetic separate were used for internal calibration. The alignment of the X-ray peaks of the Fe/Ti oxide in the magnetic separate with the peaks of the ilmenite standard clearly indicate a rhombohedral crystal structure for the Fe/Ti oxide in the magnetic separate. Thus the magnetic mineral is indeed an intermediate composition titanohematite (Fe$_{2-x}$Ti$_x$O$_3$) rather than titanomagnetite. The peaks of the Fe/Ti oxide in the magnetic separate were then used to calculate the rhombohedral unit cell dimension. This dimension is a function of composition and can be used to determine the compositional parameter x (Akimoto 1957). The unit cell dimensions and implied composition are illustrated in figure 4, as are the compositions implied by the Curie temperatures. Reflected light microscope observations of the opaque grains in the polished grain mounts indicate homogeneous grains with anisotropic reflectance. The reflected light microscopic, microprobe, Curie temperature, and X-ray data are very consistent in indicating that, at almost all stratigraphic levels in the late Cretaceous through middle Paleocene continental sediments of the San Juan Basin, the detrital ferrimagnetic mineral is titanohematite with composition 0.45 < x < 0.60. The implications of these results will be discussed below.

**Normal Overprint of Magnetozone y+.**—In the initial study of the rock-magnetism of the San Juan Basin sediments, IRM acquisition was used to determine the ratio of high coercivity (>300 mT) phases to low coercivity (<300 mT) phases. The IRM acquired above 300 mT is most likely carried by hema-
The high coercivity component was generally minor. Thus, for most of the stratigraphic column, the data support the contention that the NRM is primarily a DRM carried by detrital titanohematite. This DRM was acquired at the time of deposition and would provide a reliable magnetic polarity zonation. However, systematically higher concentrations of high coercivity phases were evident in the IRM acquisition experiments for samples from the Kirtland Formation just below the contact with the Ojo Alamo Sandstone. Because this is the stratigraphic level from which the normal polarity zone γ+ of the San Juan Basin composite section was determined (fig. 1), we became concerned that this magnetozone could have suffered post-depositional remagnetization. Thorough study of the paleomagnetic and rock-magnetic properties of samples from multiple sections through this stratigraphic interval has borne out this concern.

The three sections used to define magnetozone γ+ are on the south side of South Mesa (Lindsay et al. 1981). These are the upper portion of the Hunter Wash-Alamo Wash section (referred to here as South Mesa section), the Barnum Brown Amphitheater section, and the Barrel Spring Arroyo section (fig. 5). These sections were re-collected in detail. Eight oriented samples and a bulk sample for magnetic separation were collected from each of 13 sites in these three sections. In addition, similar recollections of 39 sites (including bulk samples) were distributed amongst the remaining 13 normal polarity zones in the other magnetostratigraphic sections of Lindsay et al. (1981). Curie temperatures were determined for each magnetic separate and, with the two exceptions noted above, were all found to be in the range 180 < Tc < 300°C. Detailed progressive AF demagnetization was performed on three oriented samples from each site. Progressive thermal demagnetizations were performed on three samples from each site at closely spaced temperature intervals below the Curie temperature determined from the magnetic separate. Representative results of these experiments are illustrated in figure 6. In addition, IRM acquisition experiments were performed on one sample from each site.

If the primary component of the NRM is a DRM carried by the detrital titanohematite,
the primary NRM should have coercivity predominantly within the 20 to 80 mT interval. Blocking temperatures in the thermal demagnetization experiments should be distributed below the Curie temperature determined from the magnetic separate. Data from one reversed polarity and one normal polarity site exhibiting these desired characteristics are illustrated in figures 6A and 6B, respectively. However, sites with strong evidence for overprinting of the DRM were also found in the three sections mentioned above. Data from a representative overprinted site are illustrated in figure 6C. The AF demagnetization reveals that a considerable portion of the NRM has coercive force >80 mT and blocking temperature >320°C. Thus, the NRM for this site is dominated by a component which cannot be a DRM carried by the detrital titanohematite. IRM acquisition for this site also indicates the presence of a high proportion of the phase with coercive force >300 mT. The NRM of this site is almost certainly dominated by a normal overprint carried by hematite. It is thus quite clear that overprinted (remagnetized) sites do exist in the three sections used to define magnetozone $\gamma^+$. Demagnetization behaviors of overprinted sites were analyzed by vector subtraction techniques for evidence of reversed polarity components. However, no statistically significant evidence of such components was evident.

Of obvious importance to the evaluation of magnetozone $\gamma^+$ is the stratigraphic distribution of sites with primary NRM of depositional origin as opposed to overprinted sites. For each site, the AF and thermal demagnetization results were analyzed and the “best” demagnetization level was selected. For sites such as illustrated in figure 6A and 6B, selection of the best demagnetization level is not critical since the direction of the primary NRM is stable over significant ranges of demagnetizing fields and temperatures. For all such sites, no significant difference in primary NRM direction was observed between the AF and thermal demagnetizations. Many sites with evidence for overprinting behaved erratically during the progressive demagneti-
Fig. 6.—Example vector demagnetization diagrams illustrating progressive AF and thermal demagnetization results. Bar indicates scale of each diagram. Numbers adjacent to data points illustrating AF demagnetization results indicate peak demagnetizing field in mT while numbers adjacent to data points illustrating thermal demagnetization indicate temperature (°C). Site SB008 is in the Barnum Brown Amphitheater section and is labeled “8” in figure 7. Site SB010 is in the Barrel Spring Arroyo section and is labeled “10” in figure 7. Site SB046 is in magnetozone D+ of the Kutz Canyon section of Lindsay et al. (1981).
zations, and the choice of demagnetization level was somewhat arbitrary. This is largely irrelevant, however, because the NRM is clearly secondary. The final site-average virtual geomagnetic pole (VGP) latitudes are plotted against stratigraphic position in figure 7. Sites showing evidence of overprinting erratic demagnetization behavior, coercivity dominantly >80 mT, or high coercivity phases evident in IRM acquisition experiments are shown with lines through the data points.

Two features of the data are crucial to the interpretation. First, all sites for which the primary NRM is a DRM carried by titanohematite are of reversed polarity. Second, these reversed polarity sites occur throughout the stratigraphic interval from which $\gamma^+$ was originally defined. The observation of reversed polarity sites in these re-collected sections where no reversed polarity sites were found in the original collections is in part due to experience in collecting lithologies in which secondary components are minimized and in part due to the detailed demagnetization procedures employed on the re-collections. Lithologies with even slight red or rusty mottling were found to be prone to normal overprinting, although avoidance of lithologies with visible mottling does not guarantee that such overprints are avoided. The data from the re-collections clearly indicate that the normal polarity zones (C+ of the three sections of Lindsay et al. (1981)) originally used to define normal polarity zone $\gamma^+$ in the composite section are not viable indicators of normal polarity at the time of deposition. We conclude that the geomagnetic field was of reversed polarity during deposition of this stratigraphic interval and that magnetozone $\gamma^+$ should be removed from the composite section.

Experiments were also performed on acquisition of viscous remanent magnetization (VRM). Results are illustrated in figure 8. Samples 4D, 7F, and 10G are from sites with significant overprinting, while the remaining samples are from sites where the NRM is primarily a DRM. Acquisition of VRM is much more rapid for overprinted sites. The rates of VRM acquisition in the overprinted
sites are such that a large portion of the total NRM, if not the entire NRM, could have been acquired during the Brunhes normal polarity epoch. These data indicate that the normal polarity overprint observed in the three sections at South Mesa is a VRM overprint. For some sites in these sections, the normal polarity VRM dominates the NRM whereas for other sites the reversed polarity DRM component dominates. This VRM is probably carried by hematite which could have been present during deposition or perhaps was precipitated post-deposition. VRM components carried by fine-grained hematite are known to be resistant to AF demagnetization and can have wide distributions of blocking temperatures (Dunlop and Stirling 1977).

Progressive demagnetization and IRM acquisition experiments were also performed on the 39 additional sites distributed throughout all the sections of Lindsay et al. (1981). In no case was any evidence of normal overprinting of the NRM found. Thus all normal polarity zones other than $\gamma^+$ are viable recordings of normal polarity of the geomagnetic field during deposition. Data obtained from the re-collection of the upper portion of the section in Kutz Canyon did, however, indicate that polarity zone $\lambda^+$ is thinner than indicated by the original collection.

In order to progress in terms of techniques or recommended practices in magnetic polarity stratigraphy, it is worth asking whether this normal overprint could have been recognized during analysis of the original collections. We believe the overprint could have been recognized by a more thorough study of the rock-magnetism, particularly the progressive demagnetization behavior. Had progressive demagnetizations been done on samples from even one or two sites in the overprinted zone, the presence of that overprint would have become evident. However, since the overprinted zone represented a very small percentage of the total section sampled, no sites from that zone happened to be selected for progressive demagnetization studies. In selecting a "representative" small portion (~5%) of samples from the total sample population for progressive demagnetization experiments, it is important to ensure that the chosen samples are closely spaced in a stratigraphic sense. In a study such as in the San Juan Basin where there were a total of 26 polarity zones distributed amongst the six major sections collected, it would be good practice to subject two sites in each polarity zone to progressive demagnetization experiments. In practice, this will be difficult to do because the polarity zonation is a priori unknown and only evident after the appropriate magnetic cleaning technique determined from the progressive demagnetizations has been employed on the entire section. Perhaps the only practical solution is to subject samples from about 10 or 20% of the sites (evenly spaced stratigraphically) to progressive demagnetization. This procedure would ensure that considerable fidelity would be maintained in monitoring demagnetization behaviors. As regards normal polarity overprints, we would stress that the critical point is that the primary nature of the NRM in any normal polarity zone which is of significance in the interpretation should be adequately documented by thorough progressive demagnetization experiments on samples from that normal polarity zone.

Moncisco Mesa and Eagle Mesa Sections.—Paleomagnetic samples were collected from two stratigraphic sections not included in our original studies. A sequence of 19 paleomagnetic sites was collected from a 150 m thick stratigraphic section below the Ojo Alamo Sandstone at Moncisco Mesa. A section of 85 m thickness containing 16 paleomagnetic sites was collected at Eagle Mesa. The locations of these sections are shown in figure 9. Detailed progressive AF and thermal demagnetizations, as well as examinations of the mineralogy of the magnetic minerals, were performed on samples from four sites within the Moncisco Mesa section and three sites within the Eagle Mesa section. Demagnetization behaviors were similar to those illustrated in figure 6A and 6B indicating that the primary NRM is a DRM carried by the detrital titanohematite. AF demagnetization to 20 mT was found to remove the secondary viscous components isolating the primary NRM.

Data from three sites within the Moncisco Mesa section were rejected on the basis of very weak NRM ($<2 \times 10^{-4}$ A/m) and scattered directions of NRM. The remaining 16 sites in the Moncisco Mesa section define two polarity zones in that section. The data are illustrated in figure 10. A basal normal polarity zone is over lain by a reversed polarity zone which extends to the Ojo Alamo Sand-
stone. This reversed polarity zone has a minimum thickness of 100 m. The normal
and reversed polarity zones are labeled Moncisco A+ and Moncisco B−, respectively.

The paleomagnetic data from Eagle Mesa are illustrated in figure 11. A basal normal
polarity zone with thickness at least 40 m is overlain by 45 m of reversed polarity extend-
ing to the Ojo Alamo Sandstone. The normal and reversed polarity zones are labeled Eagle
Mesa A+ and Eagle Mesa B−, respectively.

DISCUSSION

The discussion is presented in three parts. Implications of the intermediate composition
titanohematites are presented first. The major

implication is that a persistent provenance,
including a major fraction of dacitic or an-
desitic volcanic rocks, is required for the late
Cretaceous and Paleocene continental depos-
its. The source was almost certainly in the
San Juan Mountains region. A discussion of
competing depositional models for these sedi-
ments is then presented. The rock-magnetic
and paleomagnetic data are much more easily
explained by the clastic wedge model of Dane
(1936) than by the tilting and erosion model of
Fassett and Hinds (1971). Finally, the impli-
cations of revision to the polarity zonation by
removing magnetozone γ+ are presented.

The K/T boundary in the San Juan Basin is
found to occur within a reversed polarity

Fig. 9.—Location map for Moncisco Mesa and Eagle Mesa paleomagnetic sections. Bold straight lines indicate the locations of the sections. Solid lines in southern portion of Eagle Mesa map are paved roads. Stippling on index map indicates the outcrop limits of the Ojo Alamo Sandstone. Section numbers and major drainage are shown along with the 6300 ft elevation contour at Moncisco Mesa and the 6900 ft elevation contour at Eagle Mesa.
zone correlative with chron 29R. Within the resolution provided by magnetic polarity stratigraphy, the K/T boundary in the San Juan Basin is synchronous with the K/T boundary in the marine sequence at Gubbio, Italy. Revised placements within the magnetic polarity time scale are presented for the Peurcan and Torrejonian land mammal ages.

**Magnetic Mineralogy and Source Terrane.**—The observation of intermediate composition titanohematite as the dominant ferrimagnetic mineral has some important implications regarding the lithology of the source rocks from which these sediments were derived. The titanohematite series exhibits complete solid solution only at high temperatures (>1000°C), and exsolution of intermediate composition titanohematite is quite rapid (Uyeda 1958; Carmichael 1961). Thus, intermediate titanohematites have only been encountered in rapidly cooled volcanic rocks usually of dacitic composition, although some occurrences from andesitic rocks are known. Because of the high-temperature solvus, the intermediate composition titanohematites must be detrital and cannot be of diagenetic origin. Accordingly, observation of intermediate titanohematites in the San Juan Basin sediments requires that the source rocks were volcanic rocks, probably of dacitic or andesitic composition.

Substantial evidence for nearby Laramide volcanism close to the San Juan Basin exists only for the region of the San Juan Mountains on the northern perimeter of the basin. Andesite cobbles have been found in the McDermott member of the Animas Formation in the northernmost San Juan Basin (Reeside 1924). The Animas Formation has been correlated with the late Cretaceous through Paleocene continental sediments of the central San Juan Basin (Cobban and Reeside 1952). These observations have been interpreted by Larsen and Cross (1956) as evidence for a late Cretaceous volcanic field in the San Juan Mountains which was eroded in the Paleocene. Remaining late Cretaceous volcanic rocks in this region are limited to the Cimarron Ridge Formation in the northwestern San Juan Mountains containing rhyodacite flows, tuff breccia, flow breccia, and associated conglomerates (Dickinson et al. 1968). Armstrong (1969) dated dioritic laccoliths in the San Juan Mountains area and found late Cretaceous and early Tertiary ages for laccoliths which occur along a southwestern projection of the Laramide mineral belt of Colorado. Dacitic or andesitic volcanic rocks certainly could be expected to occur as the extrusive counterparts of these laccoliths. While the volcanic rocks have been almost entirely eroded or covered by subsequent Tertiary volcanic rocks, there is abundant evidence for a late Cretaceous volcanic field in the San Juan Mountains region.

The requirement, implied by the observed titanohematite, that a source terrane include volcanic rocks and the evidence for such rocks in the nearby San Juan Mountains region implicate this area as the probable
source area for the late Cretaceous through Paleocene continental sediments in the San Juan Basin. The presence of titanohematite throughout the sequence implies a persistent provenance of similar character for all the late Cretaceous and Paleocene continental sediments rather than a change in source terrain at the Cretaceous/Tertiary boundary. Based on sandstone petrography and sedimentology of the Kirtland Formation and Ojo Alamo Sandstone, Klute (pers. comm.) has also argued for a constant source of the continental deposits adjacent to the K/T boundary. The implications regarding the sedimentologic model for the San Juan Basin and the issue of the unconformity at the K/T boundary within the basin will be discussed below.

**Depositional Models.**—Controversy regarding the stratigraphy of the late Cretaceous and early Tertiary continental deposits in the San Juan Basin is longstanding. The stratigraphy has been studied by Bauer (1916), Reeside (1924), Dane (1936) and Fassett and Hinds (1971). Different placements of the K/T boundary within the stratigraphic section have been made by these various stratigraphers. In addition, interpretations regarding the placement and duration of (or even presence of) a significant unconformity at the K/T boundary have varied. A full review of these various interpretations will not be included here. Instead, a brief description of the competing stratigraphic/sedimentologic models will be given prior to discussion of the paleomagnetic data.

An observation which must be accounted for by any model of the late Cretaceous-early Tertiary geologic history of the San Juan Basin is the decrease in combined thickness of the Fruitland and Kirtland Formations from northwest to southeast across the Basin. In turn, interpretation of this decreased thickness influences conclusions regarding an unconformity at the K/T boundary. Two fundamentally different interpretations exist. The clastic wedge model of Dane (1936) implies little or no unconformity at the K/T boundary, while the model of Fassett and Hinds (1971) implies a significant unconformity which increases in magnitude from northwest to southeast across the basin.

Dane (1936) proposed that the southward thinning and pinching out of the late Cretaceous continental deposits plus decrease of coarse clasts toward the south resulted from deposition farther from the source area. He considered the Kirtland Formation and related sediments to be a clastic wedge with a northern or northwestern source. He further concluded that no important hiatus occurred between deposition of the late Cretaceous and early Tertiary continental deposits of the San Juan Basin.

Fassett and Hinds (1971) proposed a model for the late Cretaceous-early Tertiary geologic history of the San Juan Basin which depended heavily on interpretation of electric logs from over 2000 oil and gas wells. They interpreted the subsurface data to demonstrate northeasterward retreat of the Cretaceous seaway associated with stratigraphic rise of the Pictured Cliffs Sandstone. This final marine regression was followed by inferred deposition of a uniform thickness of Fruitland-Kirtland continental deposits from a southwestern source. They proposed tilting of the basin toward the north with subsequent erosion of Fruitland-Kirtland strata more intense in the southern part of the basin prior to the end of the Cretaceous. According to their model, up to 640 m of late Cretaceous strata were eroded from the southeastern part of the basin. Tertiary continental sediments were then deposited on the eroded Cretaceous surface. According to this model, the K/T boundary in the San Juan Basin is an erosional unconformity below which the late Cretaceous continental sediments become older from northwest to southeast. A further implication of the Fassett and Hinds (1971) model is that even the youngest Cretaceous continental deposits in the San Juan Basin are no younger than late Campanian to early Maastrichtian in age, with no late Maastrichtian continental deposits present.

The most direct test of these two opposing depositional models would be accurate age determination of the Fruitland and Kirtland Formations. The clastic wedge model of Dane (1936) predicts the existence of late Maastrichtian continental deposits while the model of Fassett and Hinds (1971) predicts formations that are no younger than late Campanian to early Maastrichtian. However, the available fossil record and radiometric dates are too equivocal to resolve the age of the Fruitland and Kirtland Formations. Given the wide range of ages interpreted from
the radiometric and fossil data, it is hardly surprising that interpretations regarding correlation of the magnetic polarity zonation with the magnetic polarity time scale have also varied. As shown in figure 1, we have interpreted magnetozone a+ in the Fruitland and Kirtland Formations to be correlative with chron 31N and 30N (Lindsay et al. 1981). This interpretation has been challenged (e.g., Alvarez and Vann 1979; Fassett 1979; Lucas and Schoch 1982), and we have replied to those criticisms (Lindsay et al. 1979a, 1979b, 1982). These differing interpretations have not changed substantially since publication of the above listed comments and replies. Thus we will not reiterate those arguments here. Instead, we discuss below the implications of the newly acquired paleomagnetic data from Moncisco Mesa and Eagle Mesa. We believe that the magnetic polarity zonation in the Fruitland and Kirtland Formations and in the overlying Nacimiento Formation argue strongly for the clastic wedge model of sedimentation in the San Juan Basin during the late Cretaceous and early Tertiary. However, we will also discuss how the paleomagnetic data could be made to fit the Fassett and Hinds (1971) model. We believe there are severe difficulties in doing so.

In figure 12, paleomagnetic polarity columns from the Nacimiento Formation at Kutz Canyon and Ojo Encino (Taylor and Butler 1980) are illustrated along with polarity columns from the Fruitland and Kirtland Formations at Moncisco Mesa, Alamo Wash-Barrel Spring, and Eagle Mesa. Solid lines are shown tying what we interpret to be equivalent polarity zone boundaries. A dashed line connects the stratigraphic levels of the base of the Ojo Alamo Sandstone. The correlations between Kutz Canyon and Ojo Encino are very strongly supported by the biostratigraphy. Abundant, diagnostic Torrejonian fossil mammals occur within Kutz Canyon zones C− and D+ and within Ojo Encino zones B− and C+. Ojo Encino is the location of the type section of the Torrejonian land mammal age (Taylor and Butler 1980). The thickness of correlative polarity zones clearly decreases from Kutz Canyon to Ojo Encino. This decrease in thickness of correlative polarity zones indicates a general thinning of the Nacimiento Formation from northwest to southeast across the San Juan Basin. Such a thinning is consistent with deposition of the Nacimiento Formation as a clastic wedge derived from a source terrane to the north or northwest.

In the three sections through the Fruitland and Kirtland Formations at Moncisco Mesa, Alamo Wash-Barrel Spring, and Eagle Mesa, the stratigraphic interval below the Ojo Alamo Sandstone is always of reversed polarity. We interpret the basal normal polarity zones in all three sections (Moncisco A+, Alamo Wash-Barrel Spring A+, and Eagle Mesa A+) to be correlative. If correct, this correlation indicates that the stratigraphic interval of reversed polarity below and adjacent to the Ojo Alamo Sandstone decreases in thickness from Moncisco Mesa to Eagle Mesa. The decrease in thickness is progressive with distance from northwest to southeast across the San Juan Basin. We interpret the decrease in thickness of this reversed polarity zone to indicate a decrease in rate of sediment accumulation of the Fruitland and Kirtland Formations from northwest to southeast. Note that the rate of decrease in thickness of the correlative polarity zones with distance is virtually identical between the Fruitland and Kirtland Formations and the overlying Nacimiento Formation. We consider these observations of northwest to southeast thinning of correlative magnetic polarity zones to be strong evidence for a general thinning of the entire continental sedimentary sequence from northwest to southeast across the San Juan Basin. This thinning is easily explained by a clastic wedge model of deposition for the late Cretaceous and Paleocene continental deposits in the San Juan Basin. If the above correlations of magnetozones in the Fruitland and Kirtland Formations are correct, an additional implication is that the overprinted zone (γ+) at South Mesa is not present at Moncisco Mesa or Eagle Mesa. The sedimentary and/or post-depositional conditions responsible for the overprinted zone at South Mesa evidently did not occur at Moncisco Mesa or Eagle Mesa.

In the Fassett and Hinds (1971) model, the Fruitland and Kirtland Formations are derived from a source to the southwest with a major change in source taking place at, or near, the K/T boundary. The K/T boundary is an erosional disconformity which cuts down into older Fruitland-Kirtland deposits from
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northwest to southeast across the basin. From Hunter Wash-Barrel Spring to Eagle Mesa, approximately 300 m of Fruitland-Kirtland strata are predicted to have been eroded (Fassett and Hinds 1971, fig. 11). The following scenario would be required in order for the pattern of magnetic polarity zones in figure 12 to be consistent with the Fassett and Hinds (1971) model.

Proceeding from northwest to southeast, the erosional disconformity at the K/T boundary would have to cut down into reversed polarity zones which would be cor-

relative with successively older reversed polarity intervals of the magnetic polarity time scale. The disconformity would also have to erode into these successively older reversed polarity zones such as to produce reversed polarity zones beneath the disconformity which are progressively thinner from northwest to southeast. Furthermore, the rate of erosional thinning would have to equal the rate of northwest to southeast depositional thinning observed in the overlying Nacimiento Formation. We find this requirement highly unlikely. The pattern of polarity zones

Fig. 12.—Comparison of thicknesses of correlative magnetozones between Kutz Canyon and Ojo Encino in the Nacimiento Formation and between Moncisco Mesa, Hunter Wash-Barrel Spring, and Eagle Mesa in the Kirtland Formation. Locations of magnetostratigraphic sections are at origins of arrows which point to the respective polarity columns derived from those sections. Stippling outlines the outcrop limits of the Ojo Alamo Sandstone.

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in figure 12 is very simply explained by the clastic wedge model of Dane (1936) but requires a very complicated, ad hoc scenario in order to be consistent with the model of Fassett and Hinds (1971). Taken together with the mineralogy of the magnetic minerals and sandstone petrology which argue for constancy of source terrane, we believe the polarity zonation in the late Cretaceous through Paleocene continental deposits strongly favors the clastic wedge model.

Revised Magnetic Polarity Zonation.— Arguments for correlating magnetic polarity zone a+ with chrons 31N and 30N of the magnetic polarity time scale (fig. 1 and fig. 13) have been advanced by Lindsay et al. (1981). Our interpretation of the available paleontologic, radiometric, and paleomagnetic data pertaining to the age of the Fruitland and Kirtland Formations leads us to maintain that this correlation is by far the most parsimonious. The reader is referred to Lindsay et al. (1981) for a detailed discussion of this issue. The above referenced comments and replies outline counterarguments and our replies regarding this correlation. The above discussion of the polarity zonation and depositional models for the late Cretaceous and Paleocene continental deposits strengthen our belief that sediment accumulation was relatively continuous across the K/T boundary in the San Juan Basin and that polarity zone a+ is correlative with chron 31N and 30N.

In the discussion below, we have correlated polarity zone a+ with chron 31N and 30N. Given the differing interpretations of that correlation, however, it is worth mentioning the effects on the following discussion which would ensue from correlation of a+ with an older polarity chron. We believe that the correlations between polarity zones in the Paleocene Nacimiento Formation with the polarity time scale would be largely unaffected by alternative correlations of polarity zone a+ with the polarity time scale. In fact, Lucas and Schoch (1982) have argued previously for the Paleocene correlations given below. They argued (and we now concur) that, in conjunction with the results from the Clark’s Fork Basin (Butler et al. 1981), the biostratigraphic and magnetostratigraphic data from the Nacimiento Formation are sufficient to establish the correlations given below for the Paleocene portion of the San Juan Basin section. Thus the major conclusions regarding geochronology of Paleocene land mammal section are not affected significantly by alternate correlations of the polarity zones in the Cretaceous portion of the section.

Conclusions regarding the magnetostratigraphy of the K/T boundary in the San Juan Basin are severely affected by alternate correlations of polarity zone a+ with the magnetic polarity time scale. If zone a+ is, in fact, correlative with a polarity chron older than chron 31N, some of the conclusions regarding the placement of the K/T boundary in the San Juan Basin within the magnetic polarity time scale are invalidated. Whereas correlation of zone a+ with chron 31N and 30N leads to placement of the K/T boundary within chron 29R, correlation of zone a+ with an older chron would only allow the conclusion that the K/T boundary in the San Juan Basin is older than chron 29N. The precise correlation to the K/T boundary at Gubbio, Italy (which we argue for below) would be invalid. In that case, the results from the San Juan Basin would be of very limited use in the debate regarding the global synchronicity of the terminal Cretaceous extinctions (e.g., Officer and Drake 1983; Alvarez et al. 1984a, 1984b). We strongly prefer correlation of zone a+ in the Fruitland and Kirtland Formations with chron 31N and 30N of the magnetic polarity time scale, and the following discussion employs that correlation.

Based upon the data presented above, it is concluded that magnetozone γ+ of Lindsay et al. (1981) should be removed from the composite magnetic polarity zonation of the San Juan Basin. The effect of removing this magnetozone is illustrated in figure 13. Magnetozones ε+, η+, and i+ are correlated with polarity chron 29N, 28N, and 27N, respectively. Correlation of magnetozone λ+ with the magnetic polarity time scale is uncertain but is of little consequence since this stratigraphic interval contains no diagnostic fossils. The important effects of the revised correlation on the biostratigraphy are that the highest stratigraphic occurrence of dinosaur fossils is now recorded from the reversed polarity magnetozone correlative with chron 29R. Puercan (early Paleocene) fossils are found within the normal polarity magnetozone correlative with chron 29N. Thus,
the Cretaceous/Tertiary boundary in the San Juan Basin occurs within the upper half of the reversed polarity magnetozone correlative with reversed polarity chron 29R. Torrejonian (middle Paleocene) fossils occur within polarity magnetozones correlative with chron 28N, 27R, and 27N.

The revised placement of the Cretaceous/Tertiary boundary in the San Juan Basin also has implications for the magnetic polarity and biostratigraphic results from sections through the K/T boundary in northeastern Montana (Archibald et al. 1982). The reversed polarity magnetozone within which replacement of Lancian faunas by early Paleocene Puercan faunas takes place can now be correlated confidently with chron 29R. This reversed polarity magnetozone also contains the formal boundary between the Hell Creek and Tullock Formations (which is placed at the base of the "Z" lignites). The apparent time transgression of the "Z" lignite concluded by Archibald et al. (1982) between the Billy Creek and Snow Creek sections was recently identified by the authors of that paper as an error in placing the magnetic polarity data with respect to the lithostratigraphic column from the Billy Creek section. When this error is corrected, no time transgression of the "Z" lignite is evident between these two sections. (However, these lignites could still be time transgressive between Garfield and McConel counties.) Thus the K/T boundary in the continental deposits of both the San Juan Basin, New Mexico and in northeastern Montana occurs consistently within reversed polarity chron 29R.

It is also worth noting that an iridium anomaly has been observed within the "Z" lignites (Alvarez et al. 1984a, 1984b). Although various interpretations of the cause of the iridium anomaly found at the K/T boundary in numerous stratigraphic sections have been advanced, and debate continues regarding the biological effects of proposed causes, it seems quite clear that the iridium anomaly at the K/T boundary approximates a global chronostratigraphic horizon. Since the iridium anomaly at the K/T boundary in the pelagic limestone section at Gubbio, Italy occurs within a reversed polarity zone which is securely correlated with chron 29R, the observation of an iridium anomaly in the "Z" lignites would also indicate that the reversed
polarity zone containing the K/T boundary in the continental deposits of northeastern Montana is correlative with chron 29R.

As shown in figure 14A, the revised correlation of the San Juan Basin composite to the magnetic polarity time scale removes the apparent temporal overlap between Torrejonian fossils in the San Juan Basin and Tiffanian fossils in the Clark’s Fork Basin. Torrejonian fossils in the San Juan Basin are found to extend into the normal polarity magnetozone correlative with chron 27N while Tiffanian fossils in the Clark’s Fork Basin are found no lower than the reversed polarity magnetozone correlative with chron 26R. This revision of the San Juan Basin magnetostratigraphy is thus consistent with exclusive placements of Torrejonian and Tiffanian land mammal ages in geologic time. Thus, consistent and sequential placements within the magnetic polarity time scale have now been accomplished for all North American land mammal ages in the Paleocene through early Eocene.

Figure 14B illustrates the correlation of the revised San Juan Basin composite with the magnetic polarity sequence at Gubbio, Italy. The apparent diachronity evident from previous interpretations of dinosaur extinction in the San Juan Basin with foraminiferal extinctions at the K/T boundary in the Gubbio section is removed. Both extinctions occur within the upper part of the reversed magnetozones correlative with chron 29R. Occurrence of both extinction events within magnetozones correlative with chron 29R does not prove synchrony of the extinctions, but does allow the conclusion of synchrony within the resolution provided. There is certainly no evidence for diachronity as we had previously concluded. Since chron 29R has a likely duration of 0.5 m.y., dinosaur extinction in the San Juan Basin must have occurred within 0.5 m.y. of the foraminiferal extinctions marking the K/T boundary at Gubbio. Given the stratigraphic positions of the extinction levels within these correlative reversed polarity magnetozones,

Fig. 14.—A. Correlations of magnetic polarity columns in the Clark’s Fork Basin, Wyoming (Butler et al. 1981) and in the San Juan Basin, New Mexico with the magnetic polarity time scale. Stratigraphic intervals of fossil mammals and dinosaurs are shown adjacent to the polarity columns. B. Correlation of magnetic polarity zones in Scaglia Rossa Limestone at Gubbio, Italy (Alvarez et al., 1977) with revised polarity zonation in the San Juan Basin. Numbers in the center of the figure indicate the magnetic polarity chron with which the normal polarity zones in each column are correlated. Highest stratigraphic occurrence of dinosaur fossils in the San Juan Basin is at the base of the vertically barred interval. The lowest stratigraphic occurrence of Puercan fossil mammals is at the top of the vertically barred interval. Thus the Cretaceous/Tertiary boundary in the San Juan Basin occurs within that interval.
the time difference between the extinctions is almost certainly <0.5 m.y. and the extinctions could, indeed, be synchronous. The San Juan Basin magnetostratigraphic results are thus no longer in conflict with the terminal Cretaceous event proposed by Alvarez et al. (1980, 1984a, 1984b).

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