RICE UNIVERSITY

A Paleomagnetic Study of the Permian Basalts at Las Delicias, Coahuila, Mexico

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Arts

Thesis Director's signature:

Houston, Texas

May, 1970
ABSTRACT

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The Permian lavas and pyroclastics near Las Delicias, Mexico were measured for their natural remanent magnetism in the attempt to obtain a thermoremanent magnetic pole determination for the Permian period from North America. Samples having an original remanent intensity greater than $10^{-5}$ emu/cc were subjected to AF demagnetization. Three separate directions of NRM were resolved, none of which are similar to previous results for the Permian. Field tests for reliability and a mean direction parallel to the present field indicate that one of the three directions is due to a recently acquired magnetization. However, a preliminary investigation of titanomagnetite grains in a sample with this low-temperature chemical remanence has revealed a predominance of high-temperature oxidation features. No signs for low-temperature alteration were found. It is concluded that high-temperature oxidation in titaniferous minerals may not always be a reliable indication of stability. The two other directions of NRM probably represent ancient fields. Member samples of one have an unusually high coercivity together with obvious weathering effects and low-temperature oxidation. No explanation is presently
available for the source of their NRM. The third direction is possibly Permian. If so, this implies a post-Permian counterclockwise rotation of the section at Las Delicias of about 70°. An additional basement fracture zone in the eastern Sierra Madre Oriental is proposed in order to account for such a movement.
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Acknowledgments

The writer would like to thank Drs. H.C. Clark, R.L. Wilson and J.C. De Bremaecker for their patience and assistance during this project. Dr. Wilson's knowledge of the geology of Northern Mexico was particularly helpful. Dr. D.R. Baker also provided invaluable assistance during thin and polished section examinations. My field assistants were Mr. W.P. Leeman and Mr. J.Z. Tomich. They both contributed long hours in the field, and their help is gratefully acknowledged.
Part 1 - INTRODUCTION

The Importance of Permian Paleomagnetic Data

Permian paleomagnetic pole locations from the various continental masses display several consistent and unique features. These may be leading to a better understanding of the past behavior of the earth's magnetic field and the movement of large crustal blocks. An important piece of evidence for continental drift between Europe and North America is the increased match between Permian poles for the two continents (Wells & Verhoogen, 1967) as the Atlantic is re-closed by the method of Bullard, et. al. (1965). A long period of an apparently quiescent magnetic field, reversely oriented to the present field, is also indicated by the world-wide data. This has been named the "Kiaman" magnetic interval by Irving & Parry (1963). It was present for an approximately $50 \cdot 10^6$ year duration (McMahon & Strangway, 1968) for which no positive evidence for a field reversal has yet been found. The relatively small scatter of remanent directions from many Permian rocks also suggests a magnetic field of reduced secular variations during Kiaman time.

The Need for a Thermoremanent (TRM) Pole Determination for North America

The North American data contains one possible weakness. Most of the pole positions determined to date for Permian time
on this continent are from studies of red beds, because of a lack of unmetamorphosed volcanic rocks. The paleomagnetic studies of red beds, although highly consistent and most probably reliable in the picture they present, contain certain inherent difficulties. An accurate stratigraphic age is often impossible to assign to such sediments since they are usually nearly unfossiliferous. Furthermore, the source of the chemical remanent magnetism (CRM) in red beds is still somewhat uncertain. This has been discussed recently by Collinson (1967, 1968). He shows that the magnitude of induced magnetization in any one sedimentary unit results primarily from the ferric iron content. However, whether the ferric iron resides in interstitial crystals of minerals such as ilmenite or titanhyematite, or in iron bearing clay minerals, is as yet unknown. With this uncertainty of the source mineral, the time and rate of formation of chemical magnetic domains is also an inaccurately determined factor. Consequently, the length of time after deposition necessary to acquire a stable CRM is still a problem in paleomagnetism. In addition, Krs (1967) has pointed out that factors such as porosity can profoundly affect the magnetic character of sedimentary rocks, and that porous sandstones can be partly or even totally remagnetized at any time during their history.

Much of the stable TRM found in igneous rocks is currently believed to be free from these difficulties. In recent years studies of high-temperature oxidation levels in the iron-titanium oxide minerals of igneous rocks show a clear relationship between
high-temperature oxidation states and a stable remanent magnetism (Larson, et. al., 1966; Wilson, et. al., 1968; Ade-Hall et. al., 1968). The easily recognized textures in these minerals are thought to indicate the temperatures at which the rocks crystallized. When known high-temperature mineral phases are present in an unmetamorphosed rock, therefore, a stable magnetic remanence should date from the time of the rock's emplacement and initial cooling. The recent papers propose that with increased temperature and water vapor pressure in a melt, sub-solidus oxidation occurs in titanomagnetite followed by aggregation of ilmenite along the octahedral planes of the magnetite structure. Further increases in temperature produce rutile, pseudobrookite and titanohematite phases. According to Lindsley (1962, 1965) these higher classes can only develop at temperatures exceeding approximately 600°C. This implies that the high-temperature alteration must have been deuteric; that is, the oxidation took place soon after the emplacement of the lava. Because of the close correlation between high-temperature oxidation phases and remanent magnetic stability, a stable remanence found in rocks with such features should be a valid representation of the earth's magnetic field at the time determined by the rock's age. Alternatively, if an outcrop has been reheated or subjected to low-temperature chemical alteration since its emplacement the mineral composition should provide an adequate indication of this.

However, proof is still lacking that the stable high-temperature remanence derives from the microscopically visible iron-
Fig. 1. Sampling sites at Las Delicias, Mexico. After R.E. King, et al. (1944).
titanium mineral grains. The possibility remains that the
source is in groundmass grains of the micron range. Larson,
et al. (1968) have discussed this suggestion. If this is the
case, a chemical replacement of the initial TRM would be unde­
tectable under the petrographic microscope. In such a rock a
stable remanence accompanied by high-temperature mineral phases
may not represent the field orientation at the time of cooling.
Results from this study may indicate that the stable remanence
found in many of these samples does not derive from the unweath­
ered high-temperature titanomagnetite grains, but rather from
an undetermined groundmass source.

Procedures for the Study

The series of Permian igneous rocks and volcanic clastics
located near Las Delicias, Mexico (Fig. 1) was sampled during this
study. Because of controversy in the literature as to the exact
nature of the igneous materials at Las Delicias, a re-examination
of field relationships and considerable thin section studies were
necessary. King, et al. (1944) interpret the units that were
sampled here as hypabyssal intrusions, whereas Newell (1957) lists
no primary igneous rocks other than tuffs in his Las Delicias
section. Evidence that a lava flow does indeed exist at these
outcrops (Fig. 2) is discussed in part 2 of this study.

Following the examination of field evidence related to the
Las Delicias igneous rocks, the source and time of acquisition of
the remanent magnetism is considered. Procedures described by
Irving (1964) are utilized to determine NRM stability. Progressively-
stepped alternating field (AF) demagnetization of all specimens having sufficient initial remanent intensity has been the primary technique for evaluating stability in this study. The tendency to undergo only small changes in intensity and direction in the range of the 100 oersted applied peak field is taken as an indication of a stable direction at that point in the demagnetization process. Additionally, if demagnetization produces alignment of directions for a number of samples of like lithology and field occurrence, a single direction for an entire rock unit is assumed. Such an NRM would be stable if it were significantly displaced from the direction of the present field.

In order to define the time of NRM acquisition, thin sections for most specimens were examined. These outcrops were apparently exposed to weathering and erosion for a considerable span of time in the early Mesozoic. The late Tertiary exposure has also been of sufficient duration for possible chemical alteration and remagnetization. The thin sections were searched for signs of temperatures and pressures which could create alterations in the titaniferous minerals. Evidence of this sort would indicate an unreliable remanent vector.

A preliminary polished section examination was undertaken in order to evaluate high-temperature oxidation phases in the opaque mineral grains. The presence of such textures should be strong evidence for a reliable NRM. According to Ozima & Larson (1970), "a basic rock affected by this mode of alteration will generally possess a stable, intense, and original TRM".
Certain paleomagnetic field criteria are available to establish the reliability of an NRM (Irving, 1964). For folded rocks, Graham's (1949) bedding tilt test is particularly applicable. This requires that a single direction of NRM, acquired in a rock unit before folding, should resolve itself as the limbs of the folds are returned to the horizontal. If the scatter of directions increases as bedding attitude is removed, the NRM was acquired after the tectonism occurred. Application of this test has yielded unexpected results with regard to indications of stability by the presence of high-temperature titaniferous minerals.

Part 2 - THE LAS DELICIAS VOLCANICS

Geology of the Sampling Locality

The Las Delicias Permian outcrops are located 70 miles north-northeast of Torrøen, Coahuila, Mexico (see inset, Fig. 1). They were first discovered in 1913 by Haarmann and later described by Bøse (1921), R.E. King (1934), Kelly (1936), King, et. al. (1944), Humphrey (1955) and Newell (1957). The outcrop area is presumably a structural syncline, represented by two limbs of a north-south trending synclinal fold. The axial region of the fold is covered throughout most of the area, allowing little certainty in correlation between east and west limbs. Dip on both limbs varies from less than 10° to vertical, but averages about 45° over the entire section. Nearly flat-lying Middle Cretaceous limestones and evaporites overlie the Permian beds with sharp
angular unconformity.

Volcanic clastics comprise most of the approximately 10,000 feet of section, possibly deposited in a southern continuation of the Ouachita-Marathon geosyncline of West Texas, or in a foredeep basin comparable in position to the Marfa Basin and Sheffield Channel. Poorly sorted, variegated graywackes, occasional limestone reef-like masses, and at least one series of volcanic extrusives form the resistant outcrops in the area. According to Newell (1957), most of the graywackes were mistakenly identified as pillow-weathering basalts by King (1934) and King, et al. (1944). Newell's re-interpretation was substantiated during the field measurements and hand sampling for this study. The numerous strata of basalt included by King et al. (1944) in the geologic section of the western, or Difunta, synclinal flank could not be found in the field. Instead, pillow-weathering layers of resistant fine-grained clastics, easily mistaken for igneous rocks, are abundant. This difference from the originally described section has considerably reduced the usefulness of the Las Delicias area for paleomagnetic investigation.

In the west flank of the syncline near the uppermost portion of the exposed Permian section is a short sequence of spilitic basalts and pyroclastics. These are the rock units sampled for their paleomagnetic character. They consist of several flows of green and purple porphyrytic spilites, tuffs containing angular inclusions of the porphyry and one blue-black aphanitic basalt that grades locally into a flow breccia. Outcrops occur either
along the east-west striking arroyo banks that dissect the upper valley floor (Fig.1) or along a line of small conical hills between the arroyos. Interbedded within the lavas are layers of dark, fissile shales, which become slaty at places, and resistant, fine to medium-grained graywackes. Total thickness of the sequence, including the detrital and tuffaceous materials, is about 600 feet. Although contacts are difficult to find, none of the individual lava flows is believed to be in excess of 50 feet thick, and probably no more than five or six discrete flows are represented.

Interpretations of these igneous outcrops have also differed widely. King et. al. (1944) describe them as late or post-Permian hypabyssal intrusions. On the other hand, Newell (1957) found only pyroclastic conglomerates, shales, and graywackes throughout the Difunta flank. Newell shows a complete absence of flows and intrusions in his geologic section. Either or these conclusions would eliminate the possibility for a paleomagnetic determination of the earth's field at the time the Las Delicias sediments were deposited. Fortunately, however, both field observations and thin section study have provided conclusive evidence that these outcrops do indeed include lavas extruded contemporaneously with the surrounding Permian sediments.

Following examinations of thin sections the writer classifies these flows as spilites. Petrographic descriptions are given in the following section. Nevertheless, the strongest evidence that they are extrusive derives from their intimate association
Fig. 2. Outcrop of spilitic porphyry and aphanitic basalt at Cerro San Pedro. View is across Arroyo la Difunta looking south. Dark, upper half of outcrop is the fine-grained basalt. To the left of the vehicle is green porphyry, grading to a purple color behind and to the right of the vehicle.

Fig. 3. Bouldery tuff, slightly higher in the section than outcrop of Figure 2. Angular pebbles and boulders in the tuff are the basalts of Figure 2.
with coarse tuffs which are obviously extrusive. Figure 3 is of such a tuff, about 50 feet higher in the section than the outcrop of green and purple porphyrytic shown in Figure 2. The angular inclusions visible in the photograph are of this same basaltic material. This is ample proof that the rocks of Figure 2 must be extrusive. This outcrop, at Cerro San Pedro beside Arroyo la Difunta, is included within bed 3 from the Difunta flank of King et al. (1944). Above and below this horizon are layers of dark shale having well documented Late Permian fauna (King et al., 1944). These igneous outcrops, therefore, should reliably represent a Permian-aged extrusion.

Newell's (1957) omission of any large igneous bed near the top of the Difunta section implies one of two interpretations. Either he does not consider the extensive outcrop shown on Figure 2 to be Permian, and consequently not belonging in the Permian section, or else he believes this, too, to be a large slump feature in the surrounding detritus. The field relationships just described demonstrate that if this was once a continuous molten zone, it is undoubtedly Permian. On the other hand, the interpretation as a large erratic seems difficult considering the size of the outcrop alone. Paleomagnetic results described in part 4 of this study provide additional evidence that this is more likely one of a series of small lava flows.

**Petrographic Descriptions**

Two types of lavas with distinct textural differences were found in the upper Difunta flank section. One of these
Fig. 4. Zoned phenocryst from the spilitic basalt of sample 8D061. The interior of the crystal is highly twinned labradorite. Sodium enrichment from deuteric alteration has created an untwinned oligoclase rim on the phenocryst.
directly overlies the other with a sharp, undulating contact, yet they display completely dissimilar NRM characteristics. In thin section, their groundmasses appear to be nearly identical. One of the two types is the purple and green porphyry shown at the base of the outcrop of Figure 2. The other is aphanitic and is dark, almost black, on a fresh surface. It is pictured in the same photograph at the uppermost portion of the outcrop. This relationship, the dark aphanitic basalt lying in direct contact above the brightly colored porphyry, is also found at several points further south in the Difunta flank.

The groundmass of each type shows a sub-ophitic texture of euhedral laths of plagioclase surrounded by pigeonite and augite. Micro-fractures and amygdules filled with calcite are common in both, but they are more prevalent in the porphyrys. Some serpentine and occasionally iddingsite can be found in pseudomorphs of former olivine crystals. In a few samples, small blebs of epidote, none exceeding a tenth of a millimeter in length, are visible. Opaques are common as tiny grains scattered rather evenly throughout the groundmass. The phenocrysts in the porphyrys are subhedral to euhedral crystals of plagioclase. They commonly show a significantly more sodic outer shell and a calcium-rich interior. The phenocryst of Figure 4 is typical. A twinned interior of labradorite is bordered by untwinned oligoclase.

This mineral assemblage is typical of a spilitic basalt (Williams, et. al., 1954). As with numerous other spilite occurrences,
the presence of undeformed amygdules and flow lines in the groundmass indicate that remineralization products such as epidote are deuteric rather than due to low grade metamorphism. Such features would be considerably distorted under conditions of high stress. The same is true for the sodium enrichment of the plagioclase phenocrysts. These alterations probably occurred late in the initial cooling period of the lavas, and may have been due to contamination by sea water (Amstutz, 1968; Turner & Verhoogen, 1960). The classification of these lavas as spilites is logical in light of the most common occurrence of such sodium rich basalts. They are often found with early stage eugeosynclinal deposits similar to those at Las Delicias (Turner & Verhoogen, 1960).

Thin section study has not revealed any indication of high temperatures or directed stresses in these rocks since their initial crystallization. Additionally, where evidence of low temperature alterations due to weathering was present, it was quite apparent both in thin section and on a fresh surface of the hand sample. Samples possessing these obvious weathering features have a unique and as yet unexplained remanent magnetic character. This will be discussed in section 5. Thin and polished sections for the remainder of the samples showed no signs of low temperature oxidation.

Stratigraphic and Absolute Ages of the Lavas

The series of lavas and sediments used in this study is directly above the fusuline zone of Polydiexodina and the ammonoid zone of Timorites in the Difunta section (King, et. al., 1944), and is therefore of Late Guadalupian age. It correlates with the Bell
Canyon and Altuda formations in the Guadalupe and Glass Mountains of West Texas, and may be from the same volcanic source as the bentonites and ash beds which occur in those formations (King, 1942). Above the lavas, King, et. al. (1944) have found the cephalopod *Kingoceras kingi* and fusuline *Polydiexodina mexicana*, neither of which is found in the Texas Permian strata. These authors suggest that the uppermost portion of the Difunta flank may correlate with the Ochoan series, which is nearly unfossiliferous in the West Texas Permian.

One whole-rock potassium argon date has so far been determined for a sample of the porphyrytic basalt. Sample 8D064 was measured, yielding an age of 200.04 m.y. (no estimate of the accuracy for this date is available). According to Kulp (1961), this should correspond to middle Triassic. However, very little absolute-age data is available from the western hemisphere for Late Permian or Early Triassic times. At present, the significance of this determination cannot be evaluated.

**Geologic History of the Site Since Permian Time**

At some time between middle or late Permian and Upper Jurassic (Portlandian) the Las Delicias rocks were subjected to compressive forces and subsequently uplifted and exposed to erosion. There is some evidence that the present top of the Difunta section represents approximately the final history of Permian sedimentation before folding began. King (King, et. al., 1944, p.25) writes, "on the west side of Cerro la Difunta the imbricated limestones override the underlying shales, and obviously do not continue
downward into those shales • • • Along the Arroyo la Colorada, which cuts against the south side of Cerro la Difunta there is no evidence of thrusting, and in the lower land to the south the sequence is perfectly normal. Possibly the imbrication took place only near the land surface at the time of folding, whereas at lower levels only bedding slip occurred." This suggests that the strata at what is now the top of the section were also near the top when folding took place. An Ochoan age for compression and uplift is compatible with the regional uplift that culminated after Ochoan time throughout the south-western United States. The additional implication is that the lavas and tuffs were never subjected to burial greatly in excess of the approximately 1000 feet of sediments now above them in the section. This could explain the lack of thin section evidence for at least low grade metamorphism in spite of the fact that these rocks have been tightly folded.

During the early Mesozoic the Las Delicias area was a positive zone, forming what Kellum, et. al. (1936) have designated the Coahuila Peninsula. These authors and Murray (1961) describe the numerous geologic indications for the existence of this land mass. Limestones of a deep water facies were not deposited over the site until Late Cretaceous, and, again, the total depth of burial never exceeded several thousands of feet. Uplift and erosion occurred again during the Laramide revolution, and the final exposure of the Permian sequence probably dates from some time in the Late Tertiary.
The state of Coahuila is bordered to the north and south by two great fracture zones which probably were active during much of the existence of these rocks. The Texas Lineament to the north (Fig. 14) has been described by Baker (1934), Moody & Hill (1956), Albritton & Smith (1957) and Muehlberger (1965). Baker (1934, p. 212) has called it "probably the greatest single structural line of the western hemisphere". It probably is the landward extension of the great Murray fracture zone, which passes 1800 miles across the eastern Pacific to the center of the Hawaiian Island chain. Included in its lineation is the California Transverse Range and numerous lesser ranges in Arizona and New Mexico, cross-cutting the northerly trends of the basin and range fault blocks. South of Las Delicias is the Saltillo-Torreon fault zone (Fig. 14). Murray (1961, p. 130) places great emphasis on his conclusion that this is the landward projection of the Pacific Molokai fracture zone (Smith & Menard, 1965). These two great east-west structural trends quite possibly have played a part in the deformational history of the Permian rocks at Las Delicias. In part 5 of this report a translation along these basement fractures has been called upon to explain some of the paleomagnetic results obtained here.

Part 3 - SAMPLING SITES AND LABORATORY PROCEDURES

Field core-drilling was not feasible in the Las Delicias area because of the lack of drilling water and inaccessibility of outcrops. Oriented hand samples were collected using the procedures
described by Girdler (1967). Site locations are depicted on Figure 1. Sampling was, of necessity, limited to fresh exposures, and these are not abundant. For this reason, no regular spacing of samples within a sampling site was possible. In Arroyo Wencelau where the most complete and undisturbed section was found, sampling sites were designated on the basis of what appears to be separate flows. Thus, sites 4 & 5, 5 & 6 and 7 & 8 are separated by thinly bedded shales, on which, for the latter two intervals, bedding attitude was measured (Table 1). Sampling sites 6 & 7, however, are both of the green porphyry grading into a pale green tuffaceous and scoriaceous material, and separated apparently only by a bouldery tuff breccia. These two sites probably represent the same extrusive event. Sites 9 & 10 in Arroyo Wencelau and portions of sites 1 & 2, further north between Arroyos la Colorada and la Difunta, are of the blue-black aphanitic basalt and breccia. Sites 1 & 2 contained so few workable outcrops that separate flows could not be distinguished. Site 1 was determined to be a small overthrust after the samples had been taken, and therefore not in place in the section.

Only one outcrop area of primary igneous rocks was found in the east limb, and since no differentiation into separate flows was possible, this was designated in its entirety as site 3. Twenty oriented samples were collected here, but only a few have yielded a measurable NRM (Table 1).

Following field data collection, hand samples were cored at the laboratory, set to the horizontal with plaster bases and
re-oriented to true north. Specimens cut from the cores are 2.49 cm. in diameter and 2.28 cm. in length. One specimen, usually the deepest within the hand sample, was selected for measurement from each sample, giving unit weight to the samples in the analysis. NRM was measured on a spinner magnetometer similar in design to that described by Doell & Cox (1967), but modified to employ precision lock-in amplifier detection. The orientation accuracy is estimated to be $\pm 3^\circ$ for all specimens. Errors due to measuring techniques and equipment are estimated at less than $\pm 3^\circ$ in direction and $\pm 5\%$ in intensity.

Alternating field (AF) demagnetization was performed in a two-axis tumbler, which rotates the specimen in an alternating field, smoothly reduced to zero from progressively increased peak values (Doell & Cox, 1967). Steps of 25, 50, 100, 150, 200 and 300 oersteds were applied, followed by increasing increments of 100 oersteds until large and erratic changes in direction and intensity indicated that non-random components of the demagnetization field were introducing anhysteretic remanence (ARM) into the specimens.

Part 4 - ANALYSIS OF PALEOMAGNETIC RESULTS

Remanent Directions After Elimination of Unreliable Data

Of the 81 oriented hand samples gathered from the various site localities shown on Figure 1, 30 were found to be unsuitable for paleomagnetic measurements. Most of these were determined during laboratory coring attempts to be so highly fractured and
Fig. 5. Directions of original magnetization for all samples from the Las Delicias area. Open circles, upper hemisphere; closed circles, lower hemisphere.

Fig. 6. NRM after elimination of weak and unstable specimens and following demagnetization at a peak field of 100 oersteds. Circles of confidence from the $a_{95}$ values in Table 2 are illustrated. 8D015 is a reversed vector in class I; 8D077 a normal vector in class III.
weathered that the presence of an ancient remanence was considered unlikely. Some were identified as fine-grained clastics rather than primary igneous rocks after thin section examination. The remaining 51 samples were measured with the spinner magnetometer and plotted on a Lambert equal area projection. Figure 5 shows all of the directions of original magnetization before demagnetization. Of these, 21 specimens had an original magnetization less than $10^{-5}$ emu/cc. This value represents the approximate limit of resolution of the magnetometer used, therefore no demagnetization was possible for these samples. Most of the very weak specimens were subjected to demagnetization attempts at low alternating field strengths on the chance that opposing vectors might happen to be present in the rock, but in no instance did this prove fruitful. The plot of the weak specimens on the equal area projection displays no significant alignments. Therefore, they too were dropped from further consideration.

The specimens rejected for weak original remanence are predominantly either the more tuffaceous materials or the pale green, calcite-rich porphyrys. Five samples of this greenish porphyry were taken at site 6. All are fresh, resistant igneous rocks, yet none contained an NRM of sufficient magnitude for demagnetization. For some the original NRM was too weak to measure. Many of the tuffs, particularly in the east flank, are also of a greenish hue. A close spatial relationship between occurrences of the green porphyry and the tuffaceous material was noted in the field. These may represent the rapidly cooled and more highly contaminated outer
<table>
<thead>
<tr>
<th>Site Number</th>
<th>Specimen Classification</th>
<th>Strike Dip</th>
<th>Original Magnetization $I_D$ (emu/cc $\cdot 10^{-4}$)</th>
<th>100-oersted Demagnetization $I_D$</th>
<th>Stability Factor $J_{100}/J_0$ ($S_{a-b}$)</th>
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<td>1</td>
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<td>N70E 36°E</td>
<td>34.1 104.2 0.11</td>
<td>23.5 128.4 80.4</td>
<td>.846</td>
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<td>2</td>
<td>flow brecc.</td>
<td>**</td>
<td>-0.9 255.2 7.28</td>
<td>12.1 206.6 19.5</td>
<td>.375</td>
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**NOTES**

* Data for demagnetized samples having J₀ greater than 10⁻⁵ emu/cc.

** Bedding attitude unobtainable

Lithologies: pu. porph. - purple porphyrytic spilite
gr. porph. - green
aph. bas. - black aphanitic basalt
flow brecc. - basaltic flow breccia

I, specimen inclination
D, specimen declination
J₀, original NRM intensity
edges of the flows.

Stability Tests: AF Demagnetization and the Stability Factor, $S_a - b$

Natural remanent magnetism for the 30 samples with original magnetization greater than $10^{-5}$ emu/cc is given on Table 1. Directions and intensities before and after demagnetizing are shown. Considerable initial scatter before demagnetization is apparent. At the 100 oersted level in the demagnetization procedure, however, one distinct group and two other sparsely populated groupings appear in the data. The groups are designated classes I, II and III. Demagnetized NRM directions for the samples within these three categories are shown on Figure 6. These 23 samples are related not only on the basis of their near parallel directions after demagnetization, but also either by a characteristic lithology and stratigraphic position in the field (classes I & II), or by an unusually high coercivity (class III).

Stability of the grouped and ungrouped directions has been established for this study by the specimen demagnetization behavior. One indication of a single stable direction in a rock unit is the tendency for the remanent directions from a number of specimens to align after demagnetization. This suggests a stable NRM if the cleaned direction is significantly different from that due to the present field. Figures 7c & 7d illustrate two demagnetization curves for representative specimens from classes I & II. Each contains an initial soft magnetization. The remanent directions show considerably improved alignment after cleaning at the 100 oersted level.
Fig. 7. Remanent directions during demagnetization and demagnetization curves for the three samples of class III (a & b) and representative samples from classes I and II. The directions of classes I and II show a tendency to group after demagnetization at about the 100 oersted level.
Another criterion for stability is the tendency to undergo only small changes in direction or intensity or both during demagnetization. Once the field strength has reached a value many times greater than the rocks would have been subjected to by the earth's field through geologic time and only small changes have occurred, stability can be assumed. Figure 7 also illustrates this behavior. 7c & 7d show that unstable components are removed by demagnetization at 25 and 50 oersteds, after which changes both in intensity and direction are typically small at the 100, 150 and sometimes as high as the 200 oersted level. The remanent direction at which these two parameters change the least during demagnetization is probably the most stable component present. Figures 7a & 7b illustrate the high stability of the class III directions.

Wilson, et. al. (1968) have devised a quantitative expression for stability, in an attempt to relate the extent of changes both in direction and intensity over an interval of demagnetizing levels to a "stability factor". They compare the non-dimensional resultants of the vector of original magnetization and the vectors at the 200 oersted and intermediate levels with the intensity at 200 oersteds, for their "$S_{200}$". However, any specimen having a soft secondary magnetization superimposed on a stable primary component would yield a small $S_{200}$ by their procedures. It would probably be considered as unstable by the criteria mentioned in Ade-Hall, et. al. (1968). When soft components are obviously present, a better approach seems to be to compute a
stability factor for an interval of the demagnetization procedure other than that including the first several steps. The interval from 50 to 150 oersteds has been used in this study, since for most specimens only minor vectorial changes occur near the 100 oersted level. Similar to the method of Wilson, et. al. (1968), the $S_{a-b}$ values in Table 1 were calculated with the formula

$$S_{a-b} = \frac{R_{100}}{R_{100} + (r_1 + r_2)}$$

where $R_{100}$ equals the vector of remanent magnetism after demagnetization at 100 oersteds peak field; and $r_1$, $r_2$ are the non-dimensional resultants between the vectors at 50 and 100 oersteds, and 100 and 150 oersteds, respectively, for $a = 50$, $b = 150$. $r_1$, $r_2$ can be calculated from the formula

$$r_1^2 = J(50)^2 + J(100)^2 - 2J(50)J(100)(\cos \Delta D + \cos \Delta I - 1)$$

where $J(50)$, $J(100)$ are the vectors of NRM after 50 and 100 oersted demagnetization, and $\Delta D$ and $\Delta I$ are the differences between declination and inclination for these vectors. $S_{a-b}$ varies from zero to one, with possible instability indicated for values less than about .500. As an example, $S_{a-b}$ ($a =$ original magnetization, $b =$ 50 oersteds) has been calculated for specimen 8D064 over the initial demagnetizing intervals, for which an unstable component has obviously been removed (Figs. 4c & 4d). This gives an $S_{a-b} = .337$. Thus, a stability factor, $S_{a-b}$ of less than .400 indicates that little or no confidence can be assigned a remanent direction determined in the interval $a$ to $b$ if no other evidence
for stability is present. Conversely, Table 1 shows that the extremely hard remanent magnetism of specimen 8D01l (Figs. 4a & 4b) gives \( S_{a-b} = 0.881 \). Judging from the behavior during demagnetization of this specimen, this must represent very nearly the upper limit for NRM stability in these rocks.

The above criteria and the calculated \( S_{a-b} \) for each specimen have been applied to evaluate the stability of the grouped directions. Interval stability factors in excess of about 0.500 are probably indicative of dependable stability. Six specimens show stability factors less than this. Of these, 8D030, 8D080 and 8D090 (Table 1) are in the class I category. Elimination of the first and last of these does not change the mean NRM of the group significantly, therefore they are maintained in the calculations. 8D080, however, not only has a low \( S_{a-b} \), but also a widely divergent direction both before and after demagnetization. It is considered unstable for this combination of reasons and has not been used in the calculations. 8D006 and 8D025 are also highly displaced from any characteristic grouping. 8D006 is of class II lithology, but it is from the site 1 locality which field study has shown to be thrust out of the section and probably overturned (part 3, this study). It was not possible to determine the amount of rotation that was involved during the overturning. Specimen 8D026 shows no alignment with the remanent directions of samples and no vector component of the present field. It and 8D025 are from a tuffaceous outcrop in the east limb. The best conclusion possible is that they represent large boulders included in the tuffs.
Because of these considerations, all of the samples from site 1, plus 8D025 and 8D026, are deemed unreliable whether or not they show a stable demagnetized NRM. Although the stability factor for 8D067 is low, it is of the same lithology as the remainder of the class II samples, and its NRM aligns with the class II grouping. It is therefore included in the group calculations.

Analysis of Grouped Directions

Figure illustrates the grouping of directions of NRM in most specimens after soft components of remanent magnetism were removed by demagnetization. These secondary magnetizations did not indicate any tendency of streaking toward a single direction, so a random source is suggested. They are removable at room temperature by a low intensity AF demagnetization. They are probably isothermal remanent magnetism (IRM) caused by lightning strikes. The grouped directions that remain after IRM components have been eliminated represent a particular orientation of the earth's total magnetic field at some time in the past.

All three classes of grouped directions shown on Figure 6 contain vectors from samples widely distributed in the section, and all classes can be characterized either by a distinct lithology of samples or an unusual hardness of the remanent magnetism. For this reason, statistical calculations for confidence factors and mean directions have been carried out on a class level rather than the site level analysis common in many paleomagnetic
investigations.

Several mechanisms of acquisition can be postulated to explain the correlation between lithology and the grouped directions. One possibility is that the different lithologies represent unique volcanic events, so widely separated in time that the earth's dipole field had changed its orientation. A second explanation could be that three distinct volcanic events have occurred over a relatively short span of time, but their cooling period was so brief that secular variation has not been averaged out. A third possibility is that remagnetization could have occurred for some, or all, of the different lithic types, the time and extent of the NRM alteration having been controlled either by the differing mineral assemblages or the time and duration of the exposure to weathering. In order to evaluate these different possibilities each class will be considered separately.

Class I Data

Of the 30 samples having a measureable NRM, 14 fall into the class I grouping shown on Figure 6. All but two samples in this class were collected from the spilitic flows in the west limb of the syncline. Nearly all have the characteristic porphyrytic texture, every sample being obviously very closely related in texture and lithology. Two of the class I samples, significantly, are from site 3 in the east limb. As Table 1 shows, the angles of dip at the opposing synclinal flanks are approximately 90° apart. Since stable directions of NRM from both sides coincide before bedding attitude is removed, application of the
Graham (1949) bedding tilt test establishes that the class I direction was acquired after deformation. It cannot be a Permian vector. Additionally, the component of the present axial dipole field for the Las Delicias locality falls within the circle of confidence for this group. In fact, Table 2 shows that the calculated mean of the group determines the present rotational pole position to within eight degrees. This group, therefore, is most likely due to a low temperature CRM acquired in the late Tertiary. The duration of acquisition is at least in the order of hundreds of years, because secular variation appears to have been averaged out. One sample in the class, 8D015, has a reversed direction, so the time of acquisition possibly began as early as 700,000 years ago, late in the paleomagnetic Matuyama reversed epoch (Cox, et al., 1963). We cannot be certain yet whether it is most logical to assume that exposure to oxidizing conditions has occurred only in the past half million years, or if remagnetization gradually sets in with each polarity reversal.

Thin sections of these class I samples were examined, but no obvious mineralogic alterations caused by weathering were found. Deuteric alterations are present: serpentine, iddingsite and titanomagnetite from occasional pseudomorphs of olivine. Minor epidote and chlorite development occurs on the feldspars and pyroxenes. In all cases, however, beneath the weathered surface there are no inward progressive changes in alterations toward the interior of the rock. The same is true for individual mineral grains. The ferrous opaque minerals, in particular, when examined
Fig. 8. Photomicrograph of typical titanomagnetite mineral grain from sample 8D064. Lamellae of ilmenite and other high-temperature oxidation phases are well developed along 010 planes.

Fig. 9. Enlargement of top center portion of Figure 8. Internal reflections from rutile are evident in ilmenite laths. This grain was treated with a 30 second application of concentrated HCl to verify magnetite phases and accentuate ilmenite lamellae.
Fig. 10. Another titanomagnetite mineral grain from 8D064. The edges of the grain are well defined and show no signs of low temperature alterations.

Fig. 11. Enlargement of top center portion of Figure 10. Titanohematite and hematite (white) are visible as central cores in magnetite (gray) zones. The oxidation has occurred internally in the crystal during cooling rather than due to weathering alterations.
both in thin and polished section show no sign of peripheral alterations (Figs. 10 & 11). Therefore, although the NRM of the lavas plainly demonstrates that recent remagnetization has taken place, there is a complete lack of evidence in thin and polished section for oxidation caused by weathering. The microscopic examination of the thin sections has apparently not told the entire story, for the only possible way that a recent CRM could have been acquired is through the effects of oxidizing agents which have somehow permeated these rocks.

Titaniferous Mineralogy of Class I Samples - Reflected Light Studies

It was immediately noticed when polished sections of class I samples were examined that the predominant titaniferous mineral grains are of the high-temperature oxidation classes described in several recent studies (Wilson, et. al., 1968). A statistical analysis of the titaniferous mineralogy of the lavas, using the procedures of Ade-Hall, et. al., (1968), is still in progress, but preliminary observations lead to some conflicting conclusions. Figures 8, 9, 10 and 11 are photographs of opaque mineral grains for the class I sample 8D064. The high-temperature mineral phases of ilmenite, rutile and titanohematite are all abundant. Rutile is particularly easily identified by its red and yellow internal reflections in the ilmenite lamellae. Yet sample 8D064 obviously groups with the class I vectors (Figs. 4c & 4d), and has therefore a recently acquired NRM. This is the same sample that has been dated at about 200 m.y. (part 2, this study).
If a stable TRM was once present in this sample, as the iron titanium mineral assemblage suggests, it is certainly now missing. In its place is a low temperature CRM. As previously mentioned, the titaniferous mineral grains show no signs of chemical alteration at their boundaries as would be expected for changes due to the external environment. Although the conclusion is tentative and preliminary, it would seem that in this instance the stable initial TRM once presumably present did not arise from the optically visible titanomagnetite mineral grains as Strangway, et. al. (1968) have proposed. If it did, it would either still be present to some degree because of initial stability or there would be signs of chemical alterations on the rims of the opaque mineral grains. Rather, the stable NRM must occur co-existently with such an opaque mineral texture, but due to sub-microscopic ferromagnetic grains in the groundmass of the rock. Strangway, et. al. (1968) have also discussed this second possibility. The opaque mineral content of this suite of rocks is presently under further investigation.

**Class II Data**

All samples are also of like lithology, strikingly distinct from that of the class I rocks in hand specimen, but with a mineral content obviously related to them. The characteristic rock type is the blue-black aphanitic aphanitic basalt and breccia. The member samples are from only two sampling positions along strike, and no rocks of this type were found on the east side. The mean remanent direction of this group is so far displaced from
the present field orientation that it is most likely due to some ancient field. Recent, large-scale rotation of these outcrops is unlikely. During demagnetization there was no evidence for streaking along the great circle cutting the present field direction. The change in the mean direction for this group during demagnetization from zero to 100 oersteds amounts to only 10° in azimuth and is nearly normal to the direction toward the present dipole field vector. Therefore, no component of the Tertiary field has been resolved. Thin sections again produced no signs of chemical alteration. Comparison of the calculated pole positions for this group with previous results, before and after bedding attitude correction, follows in part 5. Because it possesses a stable NRM and derives from a Permian extrusive, this class may represent a Permian vector. The alignment of directions from widely separated sampling sites and the lack of indications of chemical alteration strongly argues against Newell's (1957) possible implication that these are large boulders in a tuffaceous matrix.

Class III Data

The three samples in the class III group are quite distinctive on the basis of the extremely high coercivity of their remanent magnetism. 8D011 was collected from the south side of a small prominence between the Arroyos la Difunta and la Colorada. The other two are from the series of outcrops along Arroyo Wencelau. All have the porphyrytic texture, but are lighter in color on a fresh surface than the class I rocks.
Fig. 12. Plagioclase phenocryst from sample 8D011. The surrounding matrix is bright red in refracted light due to hematitic oxidation in the groundmass. The phenocryst is peripherally zoned, also from low temperature alterations.
As in class I, this group has a mixed polarity. 8D077 is normally oriented, whereas 8D011 and 8D062 are reversed. The hardness of the NRM of the three is notable (Figs. 4a & 4b and Table 1). The mean inclination for this group is so divergent that secular variations in excess of 40° from the rotational pole would have to be assumed for it to be considered due to the present field. Therefore this class, too, is possibly ancient. Class III folded and unfolded pole determinations are also discussed in part 5.

The source of the extremely hard magnetism of these samples is apparent in thin section. The entire groundmass of 8D011 shows the bright red color of hematite, and feldspar phenocrysts are zoned around their boundaries, presumably also due to low temperature alterations (Fig. 12). The coloration in the groundmass of 8D011 associated with an unusually high coercivity may be evidence that domains of critical grain size (Néel, 1955) for stability are located here rather than in the larger titanomagnetite grains with high-temperature oxidation features.

Part 5 - COMPARISON WITH PREVIOUS RESULTS

Following AF demagnetization, the remanent directions of classes II and III show a tendency to group in directions well removed from that due to the present field. Therefore, by the criteria for stability for this study, these are stable directions. The mean vectors for both are completely dissimilar to
Fig. 13. Virtual poles calculated from the mean remanent directions for classes II and III. IIb, class II virtual pole before bedding attitude correction; IIa, after bedding attitude correction. The same symbols are used for class III. Point 0 is the Permian north pole determined by Helsley (1965) and Farrell & May (1969); point X is the south Permian pole. Lines A-A' and B-B' are the loci of virtual pole positions for rotation of the section at Las Delicias about a vertical axis.
any previous results for Permian time, so they cannot be used
to verify or evaluate the earlier studies. Table 2 lists the
calculated virtual pole positions for these remanent directions.
The poles are plotted on Figure 13, both for before and after
corrections for bedding attitude were applied. None of the four
pole calculations falls even close to the post-Permian polar
wandering curve for North America. Accordingly, they probably
represent a tectonic displacement of some ancient field direct-
on. Class II samples show no signs of remineralization since
their original crystallization, therefore this category can be
most logically analyzed in terms of a Permian-derived NRM.
Class III samples show obvious indications of alterations. The
time of acquisition of the NRM for these should be post-Permian,
or at least later than that for class II.

Evaluation of a tectonic displacement for the class II
rocks is possible only if the location of the magnetic pole
relative to the site is assumed to be a known factor. Recent
Permian pole determinations are those of Helsley (1965) for the
West Virginia Dunkard series and Farrell & May (1969) for the
Grand Canyon series in Arizona. The results of these two studies
are in good agreement. In Figure 13 the median position be-
tween the north Permian poles from Arizona and West Virginia is
shown as point "O". The Permian south pole is depicted as point
"X".

The following assumptions are required: 1) There has been
no large-scale relative movement between the Las Delicias
### TABLE 2. NRM of Grouped Directions on Figure 6, and calculated Virtual Pole Positions.

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<th>Class II</th>
<th>Class III</th>
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<tr>
<th>NOTES</th>
<th>N - Number of samples.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Im</td>
<td>Class mean inclination.</td>
</tr>
<tr>
<td>Dm</td>
<td>Class mean declination.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>k</th>
<th>Class precision parameter (Fisher, 1953).</th>
</tr>
</thead>
<tbody>
<tr>
<td>a95</td>
<td>Radius of 95% circle of confidence (Irving, 1964).</td>
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</table>
locality and the West Virginia and Arizona sites since Permian time. "Large-scale" is taken to mean translations in excess of several hundred miles. Movement along lines of paleo-latitude would have had less effect on this analysis than meridian translations. 2) The displacement at Las Delicias has been primarily one of rotation about a vertical axis. This follows from the above condition. Because the dipole field is assumed axially symmetric, providing the latitude of the site is fixed displacement of the virtual pole position can only take by site rotation. These lavas can be returned to their original horizontality, using bedding attitude from the shales. Once this is done, only rotation about a vertical axis is possible.

On Figure 13, the angular distance from Las Delicias to either "0" or "X" is the Permian paleo-latitude for this site under the first assumption. The line A-A' represents all of the permissible pole locations for rotation of a normally oriented NRM following the second assumption. B-B' is the loci of all possible pole locations for a reversely oriented NRM. For a normal field polarity the paleolatitude is 99°. A reversed polarity gives a paleolatitude of 81°. Nearly all prior investigations of Permian paleomagnetism have yielded a reverse field (McMahon & Strangway, 1968), so the line B-B' is more likely representative of the correct path of rotation. Removal of bedding attitude (Table 1) from the class II cleaned directions increases the fit of the IIa pole to either lines A-A' or B-B'. Table 2 shows that the latitude computed from the mean class II directions before
Fig. 14. Generalized tectonic map of Northern Mexico, after P.B. King (1942). The proposed Coahuila fracture zone is delineated by trends of the north-eastern Sierra Madre Oriental. Postulated post-Permian translation along the Coahuila and Torreon-Saltillo fracture zones may have caused a sizeable sinistral rotation of the section at Las Delicias.
bedding attitude is removed is 67.6°. After correction for bedding tilt, class II directions show a latitude of 89.3°. This fits either of the north or south paleolatitudes shown on Figure 13 about equally well. Bedding attitude correction for class III gives ambiguous results. Pole IIIa is approximately the same distance from the loci of rotated poles as is IIIb.

The result of this comparison is readily seen to provide yet another ambiguity. If the class III mean direction is reliable and represents a post-Permian vector and class II is reliably Permian, then clockwise rotation is required. The amount of rotation would be 111° for a normal field or 291° for a reverse field. Neither of these seem likely. If class II is indeed Permian and a reverse field is assumed, a counterclockwise rotation of 69° results. This leaves the class III directions unexplained.

Because a sinistral rotation is the most likely of all the possibilities, this is pictured on Figure 14 along with the major fracture zones north and south of Las Delicias. Murray (1961) asserts that the sense of movement along the Saltill-Torreon fracture is left lateral. This could explain a counterclockwise turning of areas to the north due to a drag mechanism. Albritton and Smith (1957) review the articles concerning the Texas Lineament and conclude that it also has left lateral displacement. However, Muehlberger (1965) believes the displacement here to be right lateral. Because of the conflict, the sense of
movement is shown in Figure 14 as uncertain for the Texas Lineament. It seems unlikely that drag along the Saltillo-Torreón fracture zone alone could cause a rotation of 69° at Las Delicias. This fault line manifests itself in one way by the strong east-west folds between Torreon and Saltillo. Another lineation of tight folds exists in the Sierra Madre Oriental of Eastern Coahuila. It is proposed here that this alignment describes an additional major left-lateral fracture zone. Las Delicias, lying near the apex of the union of these two systems, is postulated to have been rotated about 70° in a sinistral sense due to drag along these faults.

Part 6 - CONCLUSIONS

The previous quote from Ozima and Larson (1970) that basic rocks with the high oxidation classes of titaniferous minerals "will generally possess a stable, intense and original TRM" may have to be considered conditional if the preliminary results of this study are sustained. The evidence here suggests that the stable NRM in such rocks may arise from submicroscopic groundmass mineral grains. In one specimen of this study, alteration of the original TRM has obviously occurred, but no alteration can be seen in the large opaque grains having high-temperature oxidation features. Thus high temperature oxidation in titaniferous minerals may not always be a reliable indication of stability. Final conclusions will have to await a complete statistical survey of oxidation classes in these rocks.
Two of the directions of NRM resolved here are well removed from the present field direction at Las Delicias. They do not approximate any position along the North American polar wandering curve between Permian time and the present. Considerable tectonic rotation of these outcrops seems to be implied. More data is obviously required before any conclusions as to either orientation or mode of acquisition of the class III directions can be drawn. The class II vectors, on the other hand, may be of Permian origin. Their considerable displacement from any previously derived Permian or post-Permian orientation may eventually provide valuable insight into the tectonic history of Northern Mexico. An investigation of Mesozoic remanent directions for this same general locality is presently in progress. This could possibly verify or disprove the postulated large-scale sinistral rotation at Las Delicias since Permian time.
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