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THE MAGNETIC ENVIRONMENT OF TEKTITES

APPROVED BY

DISSERTATION COMMITTEE

THE MAGNETIC ENVIRONMENT OF TEKTITES

TO DAD

The last thing you said to me was to go back and finish up.

This is for you.

THE MAGNETIC ENVIRONMENT

OF TEKTITES

ABSTRACT

Magnetic properties of tektites from the four strewn fields along with certain impact glasses were analyzed through paleomagnetic techniques and measured with highly sensitive superconducting magnetometers.

The results revealed that tektites have a stable natural remanent magnetization arising from a thermo-remanent magnetism which was acquired at the time the glasses cooled through the blocking temperature of the ferromagnetic phase.

Scanning electron microprobe studies in conjunction with thermal and alternating field demagnetization indicated that the magnetic carrier of the natural remanent magnetization is magnetite on the sub-microscopic level.

Based on the accumulated magnetic data, it was concluded that the natural remanent magnetization of tektites was reliable and could be used for ancient magnetic field estimations. Paleointensity determinations on interior cores of

ablated tektites, as well as other forms, demonstrated that tektites cooled in a field similar in amplitude to that of the earth. This data refutes the lunar hypothesis.

In addition, on the basis of particular magnetic properties, the preliminary findings suggest that there may be a genetic relationship between certain strewn fields and large impact sites.

ACKNOWLEDGMENTS

This research was conducted at the paleomagnetic laboratories of the University of Oklahoma, the University of California at Santa Barbara, and the University of Texas at Dallas. The facilities of Superconducting Technology Inc., at Mountain View, California were also employed. I am grateful to these institutions for permitting me to use their equipment for the studies on tektites presented in this paper.

Without the training I have received over the years from my advisor, Dr. Robert Dubois, this paper would not have been possible. He along with Dr. Virgil E. Barnes made this research enjoyable and well worth the effort.

I thank Dr. Robert Fowler of the OU physics department for his consideration and time in constructing the electrical discharge unit used in this research. Assistance was also rendered by Dr. Michael Fuller and Dr. Charles Helsey along with their respective paleomagnetic staffs. Appreciation is also extended to Dr. Dean Chapman, Mr. Leroy Scheiber, and Mr. Frank Centolanzi at Ames Research Center. I also express gratitude to Dr. Aurellio deGasparis for his comments.

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FOREWORD

Five years ago I became interested in small natural glasses known as "tektites". Initially my interest was confined mostly to readings and to collecting these fascinating objects. It was three years ago, upon meeting Dr. Virgil E. Barnes, that my interest was directed towards joining the many researchers who have sought to contribute to the tektite problem.

My personal contacts with noted individuals since this time have been most rewarding, more so than I could ever attain by researching a different topic with limited implications. Tektites have brought together geologists, geophysicists, geochemists, aerodynamicists, and other discipline groups in a concerted effort to arrive at an origin for these glasses. I consider myself very fortunate to have been able to contribute what little I could to solving this enigma.

INTRODUCTION

For over one-hundred years, tektites have been studied in an effort to determine their origin. No other rock has been examined more closely and subjected to the most sophisticated devices and techniques, not even the lunar samples. A thorough discussion of the "tektite enigma" as I would refer to it, would take-up many times the length of this paper, and it is for this reason that one should consult the many papers that have been written on this subject. O'Keefe (1963) and more recently Barnes and Barnes (1973) have edited an excellent collection of research papers relative to tektites.

Suffice it to say, that the origin of these glasses still remains in doubt. No one theory can fully explain all of their physical and chemical properties as well as their limited geographical distribution patterns. Each theory of formation encounters at least one factor which cannot be adequately explained. Some of these problems will be discussed in conjunction with the magnetic evidence during the course of this paper.

Purpose of Research

The purpose of this research is to investigate the magnetic properties of tektites from the four strewn fields and to arrive at a theory which can assist in studying the controversy of their origin. Under "magnetic properties" I include such entities as natural remanent magnetism, susceptibility, nature of the magnetic carriers, and estimation of the inducing field intensity. The investigation will utilize mostly standard paleomagnetic techniques and will be directed at answering the following:

1. Are tektites resistant to shock?

2. Can magnetic susceptibility be of any use in determining the phenomenon which created the tektite strewn fields?

3. What is the origin of the NRM (natural remanent magnetization) in tektites? Is the NRM a primary magnetization or is it due to secondary causes?

4. Can the behavior of tektite NRM be used to determine the composition and size range of the magnetic carriers of the remanence? If so, then what does this information reveal about the stability of the NRM ?

5. Do impact glasses share any of the magnetic properties of tektites?

6. How can the magnetic data for tektites be used to determine if they are terrestrial or extra-terrestrial?

PREVIOUS MAGNETIC RESEARCH

After the initial magnetic susceptibility findings of Sentfle and Thorpe (1959), it was believed by certain researchers that the magnetic properties of tektites were somewhat insignificant to their origin. The literature is replete with petrologic and chemical data, much in duplication, but few publications discuss the significance of tektite magnetic properties.

Friedman *et al.* (1960) melted soils from tektite strewn fields in a solar furnace, recording the changes in ferric-ferrous ratios. Their data suggested that tektites were not formed by heating of surface material *in situ*.

Booker and Harrison (1966) in a limited study of tektite magnetic intensity, found that most of the glasses examined were below 10^{-7} emu/gm. By heating tektites to temperatures in excess of $700^{\circ}C$ in a controlled field of 0.5 oersted, it was found that the magnetization increased. Earlier Dubois (unpublished data) found that in similar heating experiments, that the moment increased between one and two orders of magnitude. This suggests that tektites were formed in a magnetic field of low intensity.

Ostertag *et al.* (1969), after analysis of tektite magnetic susceptibility, concluded that they were formed above $1,500^{\circ}C$, and that the iron oxidation state can be duplicated by heating at surface atmospheric conditions. This is in direct conflict with the partial atmospheric pressure findings of Friedman et al. (1960).

Some of the other magnetic research conducted over the years has invariably been restricted to susceptibility analysis of microtektites and tektites containing nickel-iron metallic spherules. The reason for the emphasis on this particular magnetic property was undoubtedly one of available instrumentation. It was not until technological advances had produced more sensitive magnetometers that additional research on tektite magnetic properties other than susceptibility was made possible.

Degasparis (unpublished data, 1973) was the first to use the cryogenic magnetometer on certain tektites. During the summer of 1975 at the University of California, Santa Barbara, I was fortunate in being able to work briefly with some of the individuals associated with his research. He had used the earliest cryogenic magnetometer developed by Superconducting Technology Inc., for his work on tektites. Because of the aperature size and associated electronics, the sensitivity was such that his research was mostly restricted to a detailed magnetic analysis of the Muong Nong type tektite. This is the layered variety of tektite, formed at a relatively lower temperature than others (Barnes, 1971) and contains sufficient crystalline inclusions to render a magnetic moment measurable with the particular cryogenic unit utilized. Layered tektites are shown in Plate 12.

His findings on the Muong Nong tektites will be discussed along with my research during the course of this paper. I did not duplicate any of the research on layered tektites, as the intention was to use more sensitive equipment to attempt a study on other tektite groups.

LABORATORY PREPARATION

Source of Samples

Figure 1 shows the source of tektites used in this research. Care was taken in requesting that all samples not have been subjected to any laboratory testing since being collected. In the case of tektites from Tektos, these were only used for destructive tests and not natural remanent magnetization determinations. With any other samples, it was recognized that natural fires at the collection sites were a potential problem. It was possible to eliminate a few tektites whose appearance and moment suggested that secondary heating had occurred.

Contamination and Selection

The contamination problem is well illustrated on 3 uncleaned tektites selected for intensity measurements. These were first washed in water, measured, re-washed in a strong detergent, placed in an ultrasonic vibrator for 30 minutes, and then re-measured. Results are shown in Table 1.

Many tektites are found associated with laterite deposits and their surface configurations of cracks, etch and ablation marks provides a suitable resting place for oxidized iron particles. On many samples, it was not possible to entirely remove these deposits and consequently they were eliminated from the study. To preclude the possibility of an inaccurate

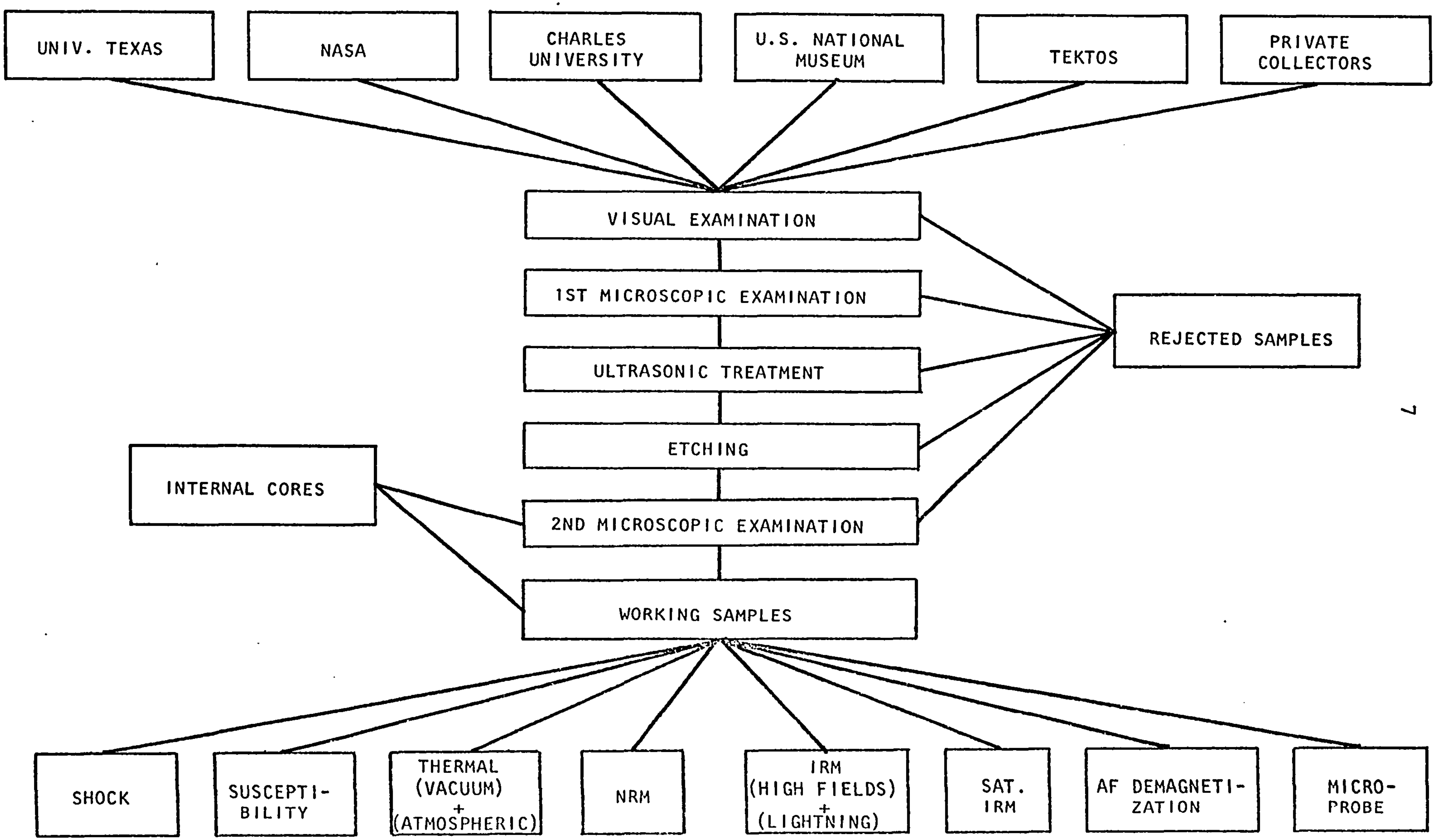

Figure 1. Tektite project flow chart.

Tektite	Intensity after 1st cleaning (emu/gm)	Intensity after ultrasound (emu/gm)
Moldavite 28.3 gm	2.4×10^{-8}	$1,0 \times 10^{-8}$
Australite 21.6 gm	5.9×10^{-7}	5.0×10^{-7}
Indochinite 30.4 gm	6.2×10^{-6}	not detectible

Table 1. Intensity changes after cleaning.

moment due to adventitious matter within minute cracks, any tektite having this feature was also eliminated. The specimens used in this research therefore, were limited mostly to tektites having smooth surface features or ablation and etch areas that were readily cleanable. A few internal cores were taken on expendable specimens.

Several thousand tektites were examined over a period of four years for use in this research. The usual examination process is shown in Figure 1. After the inspection procedure, approximately 400 tektites remained as working samples.

Related Glasses

In addition to tektites from the four strewn fields, several impact glasses (Plate 14) were also studied to determine if they possess any of the magnetic properties of tektites. Libyan Desert Glass, first reported by Clayton and Spencer (1934), is included in this category although Barnes and Barnes (1973) and other authorities consider it a Muong Nong type of tektite.

The other impact glasses studied were from the Ries, Bosumtwi, Wabar, Aouelloul, and Henbury craters. Darwin glass from the island of Tasamania was also examined. Most of these samples were cleaned in the same manner as were the tektites.

Sample Identification

Rather than assign arbitrary numbers, most samples in this research are identified according to their weight and collection area. In some cases, a photograph of particular samples is also provided. Fragments of glass, as well as those tektites used for destructive tests do not have weights listed.

INSTRUMENTATION

The Superconducting Magnetometer

Until recently, the measurements of magnetic moments smaller than 10^{-6} emu were difficult. Reliance for accurate measurements were made on either the spinner, flux-gate or astatic magnetometers. Some of these units were modified for greater sensitivity, but associated problems rendered measurements tedious and variable. Research in the area of superconductivity led to development of the cryogenic magnetometer, an instrument capable of measuring magnetic moments within seconds and with several orders of magnitude greater sensitivity. The theoretical and operating principles of these devices can be found in Goree (1970, 1973).

In addition to the astatic and spinner magnetometer, four cryogenic magnetometers were used in this research. The unit shown in Plate 1 has a 6.3 cm aperature (A) and was used for measurements on large tektite samples. Because of the access diameter, the liquid-helium cooled coils in the jacket (B) are farther apart than with a smaller unit. This restricts the maximum sensitivity to approximately 10^{-7} emu. All three orientation axes are measured simultaneously (C) so that the sample need not be rotated. The Helm-Holtz coils (D) are for regulating the magnetic field within the unit before it becomes superconducting. For instance, if something other than zero field is desired,

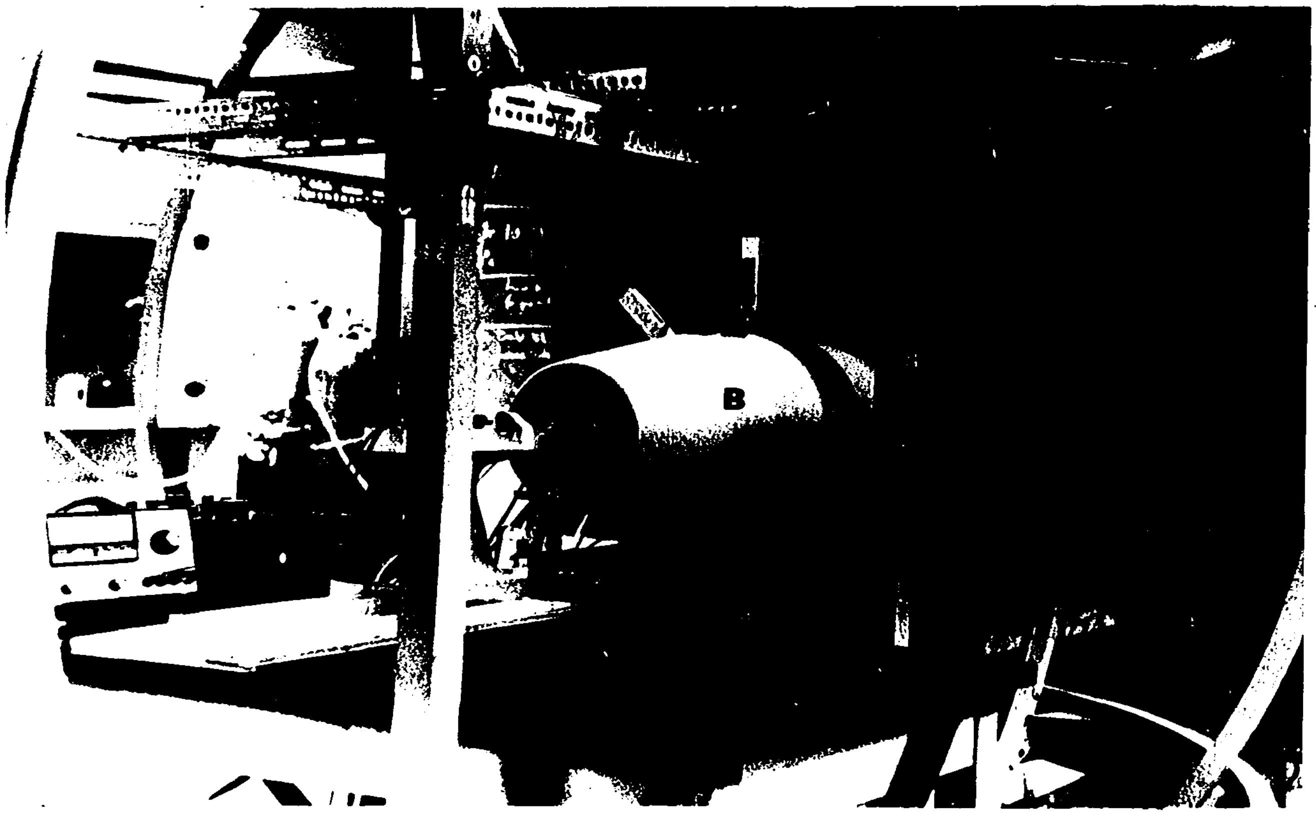

Plate 1. The 6.3 cm superconducting magnetometer.

the voltage in the coils is set accordingly, and the magnetometer is moved into the central coil area. Internal heating devices are activated within the magnetometer to raise the shield temperature slightly above the superconducting state ($4.2^{o}K$). Once this is attained the heaters are deactivated and the ambient field at the time becomes "trapped" within the unit when it returns to the superconducting temperature. This fluctuation-free field is now shielded from further changes in the external environment and will remain within the magnetometer as long as it is superconducting. Using this "trapped field" method permits studies on induced moment, susceptibility, and anistropy. This particular magnetometer was refilled with 19 liters of liquid helium every 96 hours.

Plate 2 shows the recording devices for the above discussed unit. The digital display (a) shows the X, Y, and Z magnetic vector components. To the left of this display are recorder graphs (b & c).

Plate 3 illustrates the vertical 3.8 cm access cryogenic magnetometer, two of which were used in this research. This type of magnetometer was used for smaller tektites and had a sensitivity to 10^{-8} emu. Measurements with these instruments were done at Superconductiong Technology Inc., Mountain View, California, and the University of Texas at Dallas.

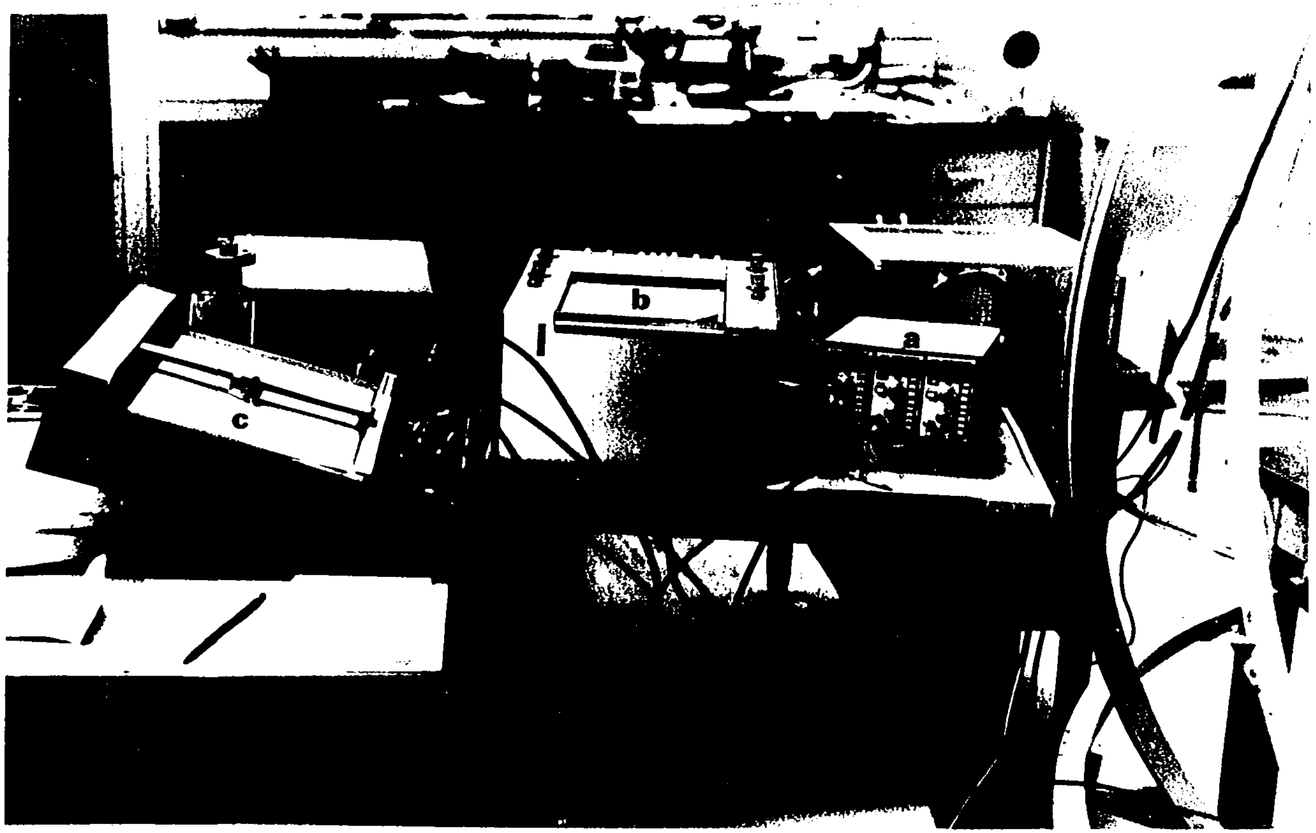

Plate 2. Recording devices.

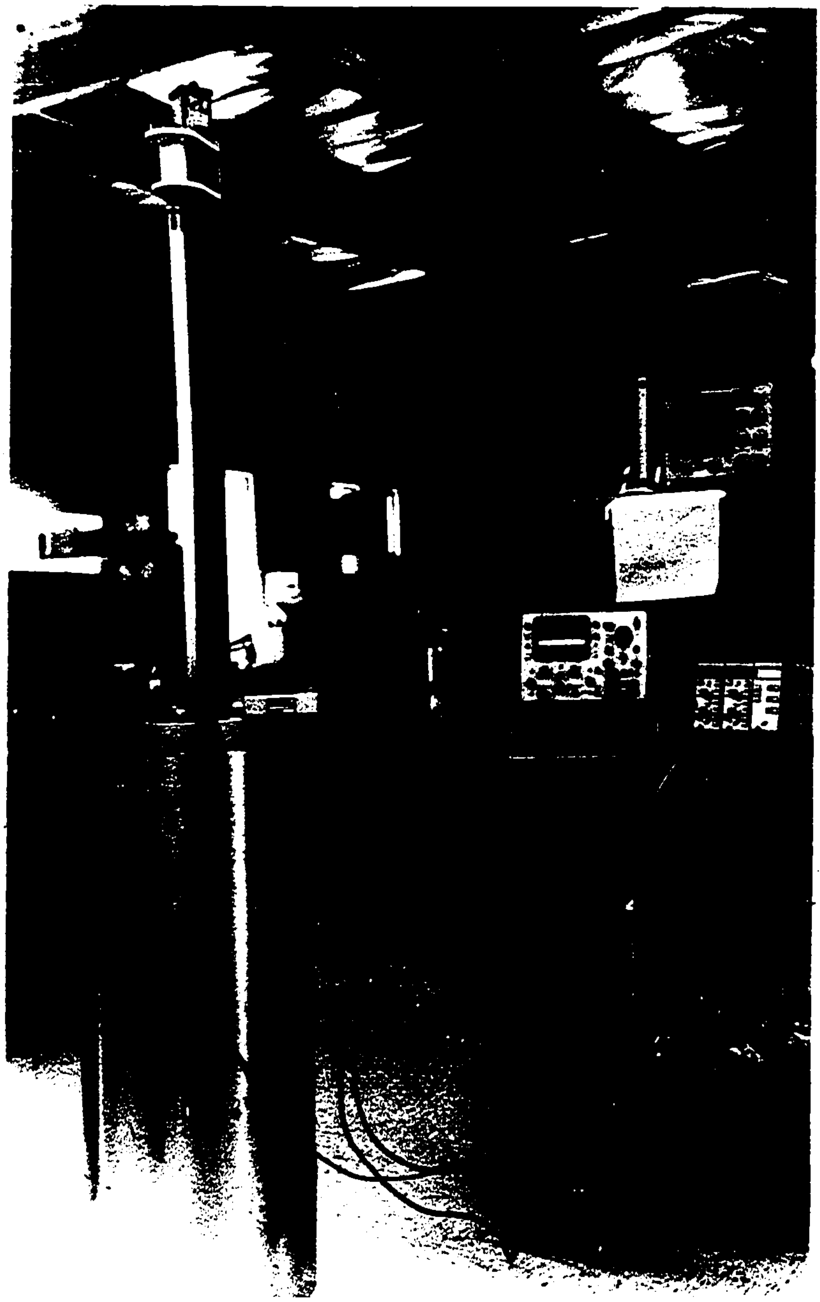

Plate 3. The 3.8 cm cryogenic magnetometer.
The mylar sample holder can be seen in the elevated position. Shielding is provided by a large μ metal cylinder similar to that used on the 0.3 cm superconducting unit.

Plate 4 shows the third type of superconducting unit. The maximum diameter of the sample access on this is 0.3 cm, which has a sensitivity of better than 10^{-10} emu. The upper portion of the magnetometer (A) contains a build-in AF demagnetization unit. After recording the intensity of a specimen, the sample rod (B) can be elevated into the demagnetization area without having to remove the sample from the magnetometer. Measurements with this unit as well as the 6.3 cm magnetometer, were done at the University of California, Santa Barbara.

It was apparent from the beginning, that despite the excellent equipment available, sample measurement for intensity would present somewhat of a problem. Because of the low magnetic moment of tektites, the more mass the sample possessed, the better was the probability of getting a high reading. Such intensity was especially important for continued NRM demagnetization analysis. If a large sample's moment was below the noise level of the 6.3 cm instrument, it wouldn't fit into the more sensitive 3.8 cm unit. Some expendable tektites were cut to accommodate the smaller opening, but this resulted in a mass loss which often offset the greater sensitivity of the smaller access units. This was especially noted with the highly sensitive 0.3 cm magnetometer. Ideally, an operating sensitivity of the 0.3 cm unit for all samples would have been desired, but this has not yet been attained in cryogenic technology.

Plate 4. The 0.3 cm cryogenic magnetometer.

Ovens

Sample heating was carried out in two ovens, each enclosed within a set of Helm-Holtz coils for ambient magnetic field control. The oven at the University of Oklahoma (Plate 5) was capable of heating samples in air as well as being large enough to contain a vacuum bomb. Heating at the University of Texas at Dallas was conducted only in air because of the restricted size of the oven. Thermal studies at the University of California at Santa Barbara were limited, but some were done in a portable oven placed within the Helm-Holtz coils utilized by the 6.3 cm cryogenic magnetometer.

Magnets

Three sets of magnets were used for saturation isothermal remanent magnetization studies. The larger set (Plate 6) was used at the University of Oklahoma and was actually part of the vibrating sample magnetometer. Its diameter was such that it could accommodate the largest tektites.

Two other smaller magnet sets were used at the other two institutions. While the larger magnets mentioned above were capable of achieving fields around 10,000 OE, the smaller ones were restricted to a maximum of around 4,000 OE. This did not present any problem relative to the samples.

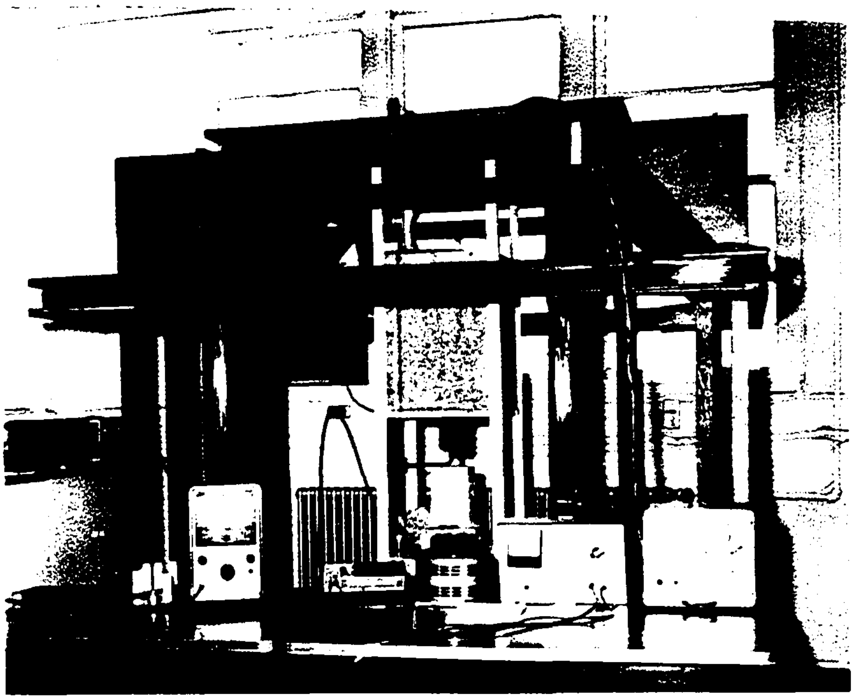

Plate 5. Field controlled oven. A vacuum bomb can be seen emerging from the base of the oven. The angled tube leads to a pump assembly.

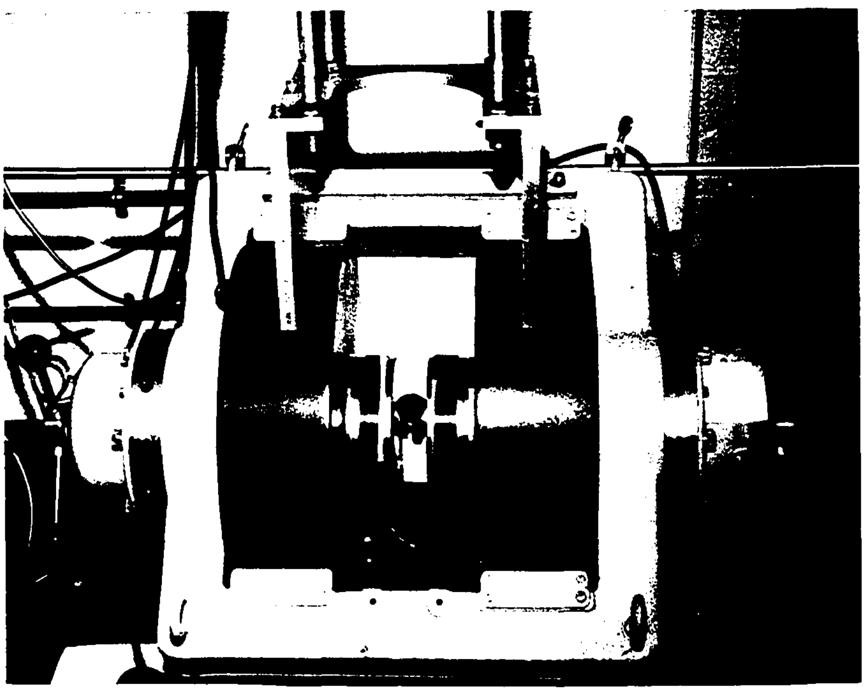

Plate 6. Magnet assembly used for saturation studies. A 4 cm tektite can be seen within the unit.

Demagnetization Equipment

AF demagnetization was accomplished be single, double, and triple axis units at the Universities of California, Oklahoma, and Texas respectively. External field shielding was provided by u-metal for the single and triple axis units, while a set of Helm-Holtz coils was used for the double axis system. One of these is shown in Plate 7.

Other Equipment

In addition to the paleomagnetic units used for the tektites, investigations were also performed on the probable magnetic carriers in tektite glass by other devices.

Elemental X-ray scans were carried out with an Applied Research Laboratories scanning electron microprobe. This instrument was also used for scanning electron photomicrographs. The entire elemental distribution spectra was also determined by use of a Qanta Metrix energy dispersive unit. All of this work was conducted at the University of Texas at Dallas.

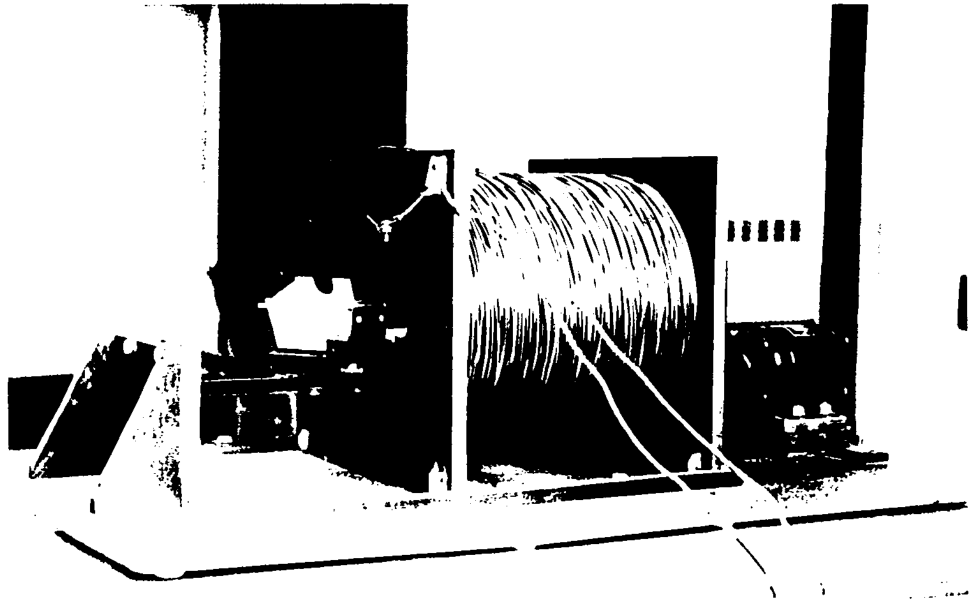

Plate 7. Double-axis AF demagnetization unit. Sample cup diagonal is approximately 6.25 cm.

MEASUREMENT PROBLEMS

An example of the extremely low moment of the average tektite is shown in Figure 2. For comparative purposes a 10 gram piece of obsidian was also recorded (Fig. 3). These measurements were taken on the 3.8 cm access unit at Superconducting Technology Inc. The graph trace shown is that from an X-Y recorder attachment similar to the one illustrated in Plate 2. The trace from "a" to "b" is the instrument noise level at 10^{-8} emu. At "b" an empty mylar sample holder has been inserted, and withdrawn at "c". It will be noted that the holder itself has a moment at this level. The trace from "c" to "d" is noise, during which time a 32 gram tektite is being attached to the mylar tube. At "d" the tektite has been inserted. As can be seen, the holder noise is masking or cancelling the tektite moment.

Numerous sample holders were used in an effort to find one with a lower intensity. Once this was located it was demagnetized further by an instrument assembled for the purpose. After these corrections, it was possible to get the maximum limit of sensitivity from the magnetometer. Figure 4 shows the tektite intensity after these corrections. Despite these obstacles, some intensity measurements were made on the samples, although the truly reliable ones were less than had been originally anticipated. During these particular readings it was fortunate to have the designers of the

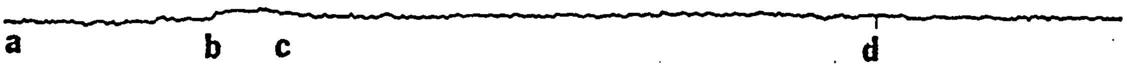

Fig. 2. Sample holder and tektite moment.

Fig. 3. Obsidian trace.

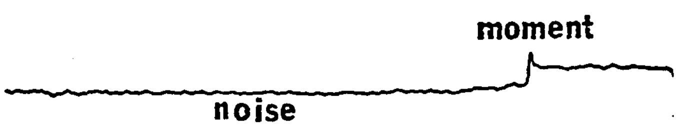

Fig. 4. Corrected tektite moment.

magnetometer present, as they offered assistance and advice relative to measurements on samples of this nature.

These readings were later re-checked on the 3.8 cm unit at the University of Texas at Dallas. Helm-Holtz coils were not used for "zero" field control when the instrument was initially being cooled to the cryogenic limit. Instead, the entire room containing the magnetometer was shielded by μ metal, somewhat like a walk-in safe. Only two compartments of this nature are presently in operation, and are considered to be more efficient in maintaining "zero" ambient magnetic field control than are the Helm-Holtz coils. The measurements on the tektites therefore, represent the most accurate readings possible with available equipment.

STABILITY OF TEKTITE NRM TO SHOCK

The configuration of the vast majority of tektites indicates that they had been in motion at the time of solidification. Plates 8 to 12 show some of the more common forms of these glasses from the Indochina and Australian areas. Based on the Fe^{+3}/Fe^{+2} ratios, an atmospheric pressure one-fifth that of normal is believed to be present at the time of high temperature fusion (Schnetzler and Pinson, 1963). This corresponds to an altitude of approximately 12,000 meters above sea level. Ostertag et al. (1969) pointed out however, that the Fe^{+3}/Fe^{+2} ratio in tektites is influenced by several independent variables. These are the melting temperature, the nature of the atmosphere, melting time, and, possibly, the rate of cooling. Proper combination of these parameters can lead to more than one condition that may have accounted for the origin of tektites.

The oxidation state can also be duplicated by a large surface detonation, since a low pressure area is created at the immediate blast site. This is followed by a high pressure shock wave (USAF lecture, 1966). All of this information is capable of demonstrating that tektites need not have fallen from high altitudes. However, the ablation features found on some tektites, or the remains of these ablation features, clearly indicate atmospheric entry (or re-entry). Examples of these features

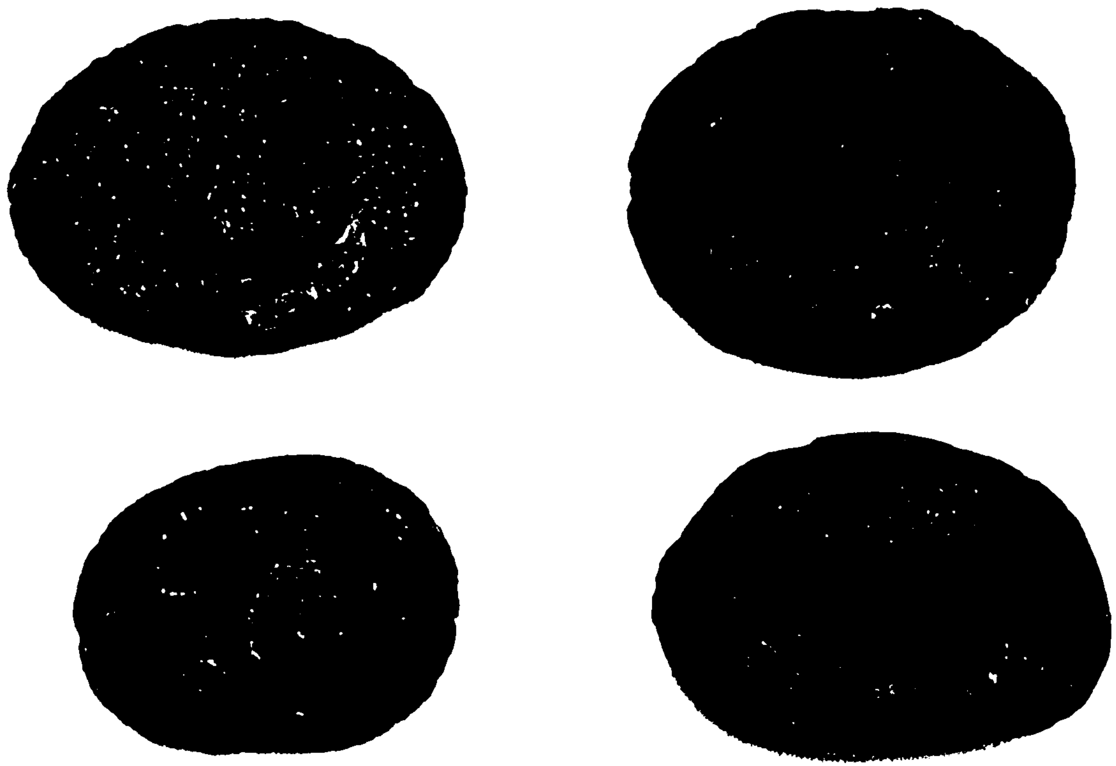

Plate 8. Indochinites

Disc and plate forms are shown. Most of the larger tektites belong to this category. (X 0.7)

Plate 9. Indochinites.

Progressive flattening of dumbbell shape is shown from left to right. Solidification occurred during rotation of molten glass phase. (X 0.7)

Plate 10. Indochinites.
Variations of teardrop forms due to differences in viscosity and cooling rate during formation. (actual size)

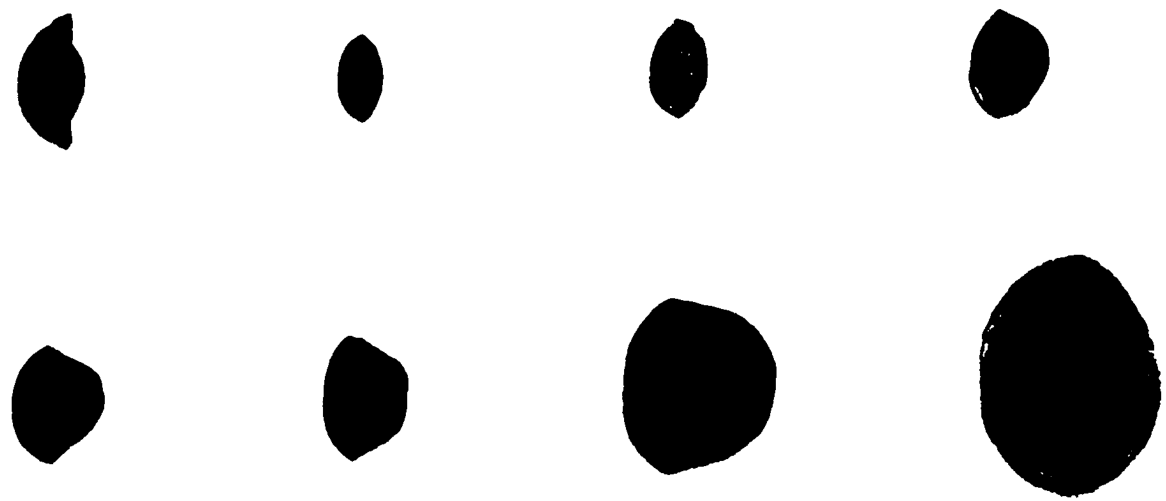

Plate 11. Australites.

Side view illustrating variations in core size and effects of ablation. Only the tektite at the upper left has its ablation flange intact. The others have been spalled during atmospheric transit. (actual size)

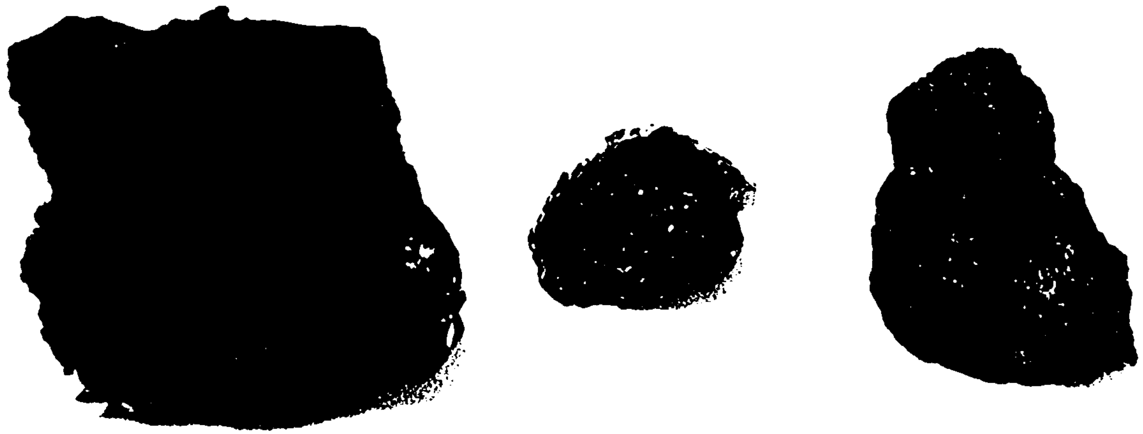

Plate 12. Comparison of layered tektites with a philippinite.

The center specimen shows the typical surface features found on most tektites formed at high temperatures while the samples to the left and right are the relatively low temperature layered variety. Aerodynamic sculpturing is absent on these and other layered tektites. (actual size) are shown in plate 11.

For the purpose of determining the stability of the magnetic carriers to impact shock it was assumed that all tektites had dropped from high altitudes. The question then arises as to exactly how fast they were moving at the time of surface contact. Determining this was deemed essential for any adequate magnetic analysis. If the NRM could be effectively influenced by the shock of landing, then little could be determined from their original magnetic properties.

The terminal velocities of small and large tektites used in this study were calculated through a modified Reynolds Number equation. This was done via computer calculations in conjunction with the National Severe Storms Laboratory. A complete derivation of the equation and associated parameters can be found in Mason (1957). Briefly however, the equation was originally utilized in determining raindrop terminal velocities and is of the form

$$\frac{C_d \ Re^2}{24} = \frac{4}{9n^2} r^3 p' p \ g$$

where: C_d = drag coefficient

p = density of object

r = radius of object

p' = density of medium

n = dynamic viscosity of medium

g = gravitational acceleration

Re = Reynolds Number

After the dimensionless Reynolds Number (Re) is obtained from the preceeding equation it is then inserted into the equation below to yield the terminal velocity (V_t).

$$V_t = \frac{n}{2rp'} Re$$

The only difference in applying this to tektites was to use 2.4 as the mean specific gravity, and hold the drag coefficient constant. In the case of raindrops, the latter changes as the liquid becomes distorted with increasing resistance of air at lower elevations, hence it must be considered. The point could be made that perhaps molten tektites behave in the same way, thus the drag coefficient should likewise be considered. This will not be argued. However, by holding the coefficient constant it will give a slightly higher velocity which is still applicable to the study.

The restriction on the use of this equation for tektites is to assume either spherical or teardrop forms, for which computations can be made. Any other shapes, such as dumbbells, cores, discs, etc., are not applicable and must be tested empirically. It is worth noting however, that sphere and teardrop forms give the highest terminal velocities of all shapes considered.

For tektites with diameters ranging from 1 to 6 centimeters, the terminal velocity was determined to range from 30 to 50 meters per second. For the smaller diameter tektites (1 to 3 centimeters), this terminal velocity could be attained by dropping them from approximately 140 meters; the larger ones would reach their terminal velocity from a drop at approximately 180 meters. Thus regardless of where tektites are formed, even considering that they are entering or re-entering the upper atmosphere, their impact velocity has a definite limit. It is recognized however, that if tektites are produced by the detonation of some extra-terrestrial body above the surface, accurate impact velocities are difficult to determine. Those tektites possibly emitted from the lower hemisphere of the blast would have a substantial initial velocity component in addition to their freefall velocity. While at NASA's Ames Research Center, I had the opportunity to discuss the terminal velocity data with Dr. Dean Chapman, Director of Astronautics. All of the figures and computations were found to be in agreement, as well as the problems associated with an air burst.

To study the effect of impact shock on the NRM of various tektites, several specimens were selected, measured for NRM with the superconducting magnetometer, and then impacted at the corresponding velocities. Initially, an attempt was made to procure the vertical-ballistics gas gun at NASA for this purpose, but velocitites could not be sufficiently reduced to the desired level.

Since a fifty-story building or helicopter was not immediately available, another method was used. This consisted of a sling and stopwatch. Timing the span between release and impact gave a rough estimate of the impact velocity. By trial and error the proper tension on the sling was arrived at. Several tektites were then fired into soil, water, and various rock surfaces.

The values of NRM after the tests were then compared with those before and found to have no difference; higher velocities produced the same results. In comparison, a piece of Wabar impact glass (from Saudi Arabia) was subjected to the same experiment and found to differ in its NRM by as much as 30 percent The NRM of this particular specimen constantly altered with each impact. Apparently this glass must have an extremely low coercivity for this to occur.

Shock tests were then performed on several tektites by impacting them into a granite slab at the highest velocities possible with the sling. It took several firings before one of the tektites ruptured, the others resisted breakage, This obvious resiliency can mostly be attributed to the lack of microlites in the glass and is probably the reason why many tektites are found unbroken in differing environments. The tektite that had broken was taped together and measured for NRM change. None was evident. One tektite was given a low IRM (60 OE) and also impacted. Although it did not rupture, the magnetization did show a decrease in intensity of approximately 16 percent.

To gain additional information on the resistance of tektites to severe shock, some of these glasses were destroyed by an M-16 rifle. Due to the paucity of samples, an Ivory Coast tektite was not included.

The M-16 fires a relatively light 5.56 mm projectile in excess of 960 meters per second, which produces a 1,660 joule impact force mostly expendible on the "surface" of a proper target and not in deep penetration of that target. By using projectiles of lighter mass, it was possible to push the velocity over 1,200 meters per second with impact forces exceeding 1,870 joules. In comparison, a 20 gram tektite in free-fall will attain a terminal velocity which will produce approximately 25 joules at impact.

The projectiles used for the tests are shown in Plate 13. A 7.62 mm cartridge (.30-06 caliber) is also shown for comparative purposes. Only projectiles having "soft noses" or "hollow points" were employed. Characteristically these types of bullets expand upon impact and expend their kinetic energy within a relatively short penetration depth. Again, when used in conjunction with an M-16, the shock effect is enhanced to an even greater degree.

To contain the impact energy within and around the tektites as much as possible, each tektite was suspended in a small can filled with water. These were later destroyed by point-blank

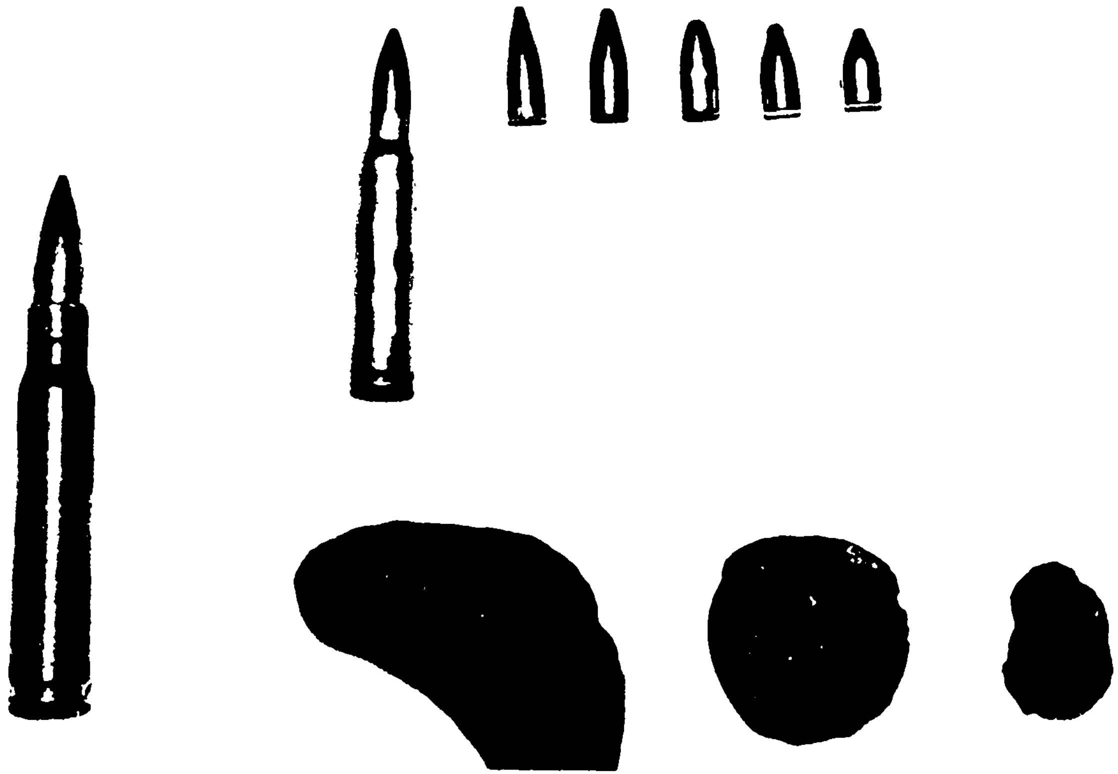

Plate 13. Projectiles used for destructive shock tests.

5.56 mm (.223 caliber) projectiles are shown. Cartridge at left is that of 7.62 mm (.30-06 caliber). Some tektites used for experiment are also shown. (actual size) shots. Some of the firings had to be repeated because of the difficulty in finding the remains.

The fragments from each of the tektites were then measured for changes in magnetic moment. Due to the reduction in mass, it was not possible for the cryogenic unit to record the magnetization from the smaller pieces of each tektite. The larger fragments produced moments which generally ranged from 0 to 9.0 percent higher than the moments before destruction. The differences are most likely due to metallic contamination by the projectiles and not to alteration of the ferromagnetic inclusions; experimental error is also a possibility.

One tektite was demagnetized and then given an isothermal remanent magnetization (100 OE) to return the moment to the approximate NRM value. After destruction, the moment showed a decrease between two and three orders of magnitude. Another test was conducted on a tektite given an artificial thermoremanent magnetization in a 2.0 OE field. The measured changes were less than several percent. With a demagnetized sample, there was no measurable change after impact.

The destruction of these tektites represents an extreme testing procedure as it is difficult to visualize under what circumstances a tektite could experience such shock in the natural environment. Excepting those tektites possibly emitted from the lower hemisphere of an air burst of some phenomena, there appears to be nothing that could alter their moment by shock. It is undoubtedly correct to state that even an air burst and subsequent terrestrial impact would not substantially alter the magnetization. Complete results of the impact studies are shown in Table 2.

It was therefore concluded that the NRM of tektites is impervious to shock, and that a paleomagnetic study of these glasses need not be restricted to undamaged specimens. If any magnetization is lost on impact, it is not the original NRM, but probably a secondary moment. Impact tests performed on the tektite given an IRM lend support to this contention.

The most important corollary of the experiments is that a tektite landing in the earth's magnetic field cannot take on the intensity of that field. Therefore, if the paleointensity of tektites reveals a magnetization similar to the earth's, the argument that it was acquired by shock is not valid.

Tektite	NRM Before Destruction emu/gm (X 10^{-6})	Impact Force (joules)	NRM After Destruction emu/gm (X 10^{-6})
Moldavite	0.095	1,660	0.100
Australite	0.140	1,660	0.145
Indochinite	0.211	1,870 - 2,000	0.219
Bediasite	0.009	1,870 - 2,000	0.010
Indochinite*	0.800	1,870 - 2,000	0.006
Philippinite**	not detectible	1,870 - 2,000	not detectible
Philippinite***	0.850	1.870 - 2,000	0.816

* IRM (100 OE)

** demagnetized

*** TRM (2.0 OE)

Table 2. Comparison of NRM before and after destructive tests.

SUSCEPTIBILITY MEASUREMENTS

Previously, the most notable susceptibility research on tektites was done by Sentfle and Thorpe (1959), Sullivan et al. (1969), and Ostertag et al. (1969). These older measurements were made on a Curie-Cheneveau balance and utilized small tektite fragments. Destruction, or partial destruction of specimens was a necessary part of this procedure.

In using this balance, measurements were conducted in a controlled helium atmosphere under a field strength sometimes exceeding 3,900 OE. Another method was that using the Gouy and Faraday technique, which was relatively accurate, but at the same time, more complex. With this method, the associated power units were numerous, and it was necessary to use field strengths from 0 to 14 kG (kOE). Complete descriptions of these procedures can be found in Sentfle and Thorpe (1959), and Ostertag et al. (1969).

The essential difference between these techniques and that using the superconducting magnetometer is that the balances are indirect methods involving parts of specimens and mathematical extrapolation, whereas the superconducting unit can be considered a direct approach. By using the cryogenic magnetometer for susceptibility, an entire tektite up to a diameter of 6.3 cm could be utilized. Measurements were made without the use of graphs and without the usual problems associated with subjecting specimens to high magnetic fields and delicate balances under highly controlled conditions. It was not necessary to damage any of the tektites in the process and there was no permanent magnetic moment imparted to the specimens during the study.

At superconducting temperatures, the shield of the magnetometer cannot be penetrated by any external magnetic or electric field. In this sense, the unit is a closed system, not subject to any adjustment to compensate for changes in the external environment, including temperature, pressure, etc. No other susceptibility measuring device has these properties.

Furthermore, since the balance described could not accommodate an entire tektite, the measurements proceeded on the assumption that a minute particle extracted from the tektite, was representative of the entire mass. This is questionable, especially since tektites are not completely homogeneous (Chao, 1963). The differences between the readings on the cryogenic unit and those reported by Sentfle and Thorpe (1959), and other researchers could well be attributed in part, to this.

Procedure

The cryogenic unit was moved into the Helm-Holtz coils and the temperature within the internal shield raised above $4^{O}K$. The ambient field in the vertical direction was raised from 0 to 0.28 OE (28,000γ). This was held until the shield temperature had returned to the superconducting state and resulted in a field contained within the unit in the (Y axis) direction. A tektite now inserted within this field experiences an induced moment in addition to its NRM. This is then recorded from the Y axis digital readout at 0^{O} and 180^{O}. The following equation is then applied:

$$\frac{\frac{\theta + \theta'}{2} - H_m}{S \times M_I} = \text{Susceptibility (emu/gram)}$$

where θ = Y axis moment at 0^{O} (x 10^{-6} emu)

θ' = Y axis moment at 180^{O} (x 10^{-6} emu)

H_m = moment of sample holder

S = sample weight (grams)

M_I = induced moment of internal field (0.28 OE)

Sample rotation did not generally present any difficulty provided that the tektite was capable of being fitted into the U-shaped holder apparatus. On many of the specimens however, due to weight and elongation, it was necessary to modify the holder with various mylar attachments. At first the 180^{O} rotation often caused a slight movement on the larger samples, but through practice and proper attaching procedures, this was usually overcome. Those tektites which continued to exhibit a slight shift during testing were eliminated from the study. Although many large disc-form tektites had been obtained, it was not possible to measure them intact since they would not clear the aperature.

One hundred and fifty-eight tektites were examined for susceptibility. The speciments exhibited many of the aerodynamic forms and were representative of most collection areas. Additional Ivory Coast tektites would have been desired, especially ones with specific collection sites rather than the usual "Ivory Coast" designation. An attempt was made to obtain more of these tektites from the three-hundred thousand tektite collection at NASA's Moffett Field facility. Surprisingly, out of this vast number of samples only four were from the Ivory Coast, and none of these were complete specimens. This has much to say about collecting procedures. Suffice it also to say, that in any tektite collection, the indochinites will invariably outnumber any other group. Recent political changes within this area will undoubtedly affect future collecting by foreigners, and perhaps lead to discovery in other areas. The Ivory Coast region has long been ignored in preference to more "hospitable" locations, but hopefully future collecting ventures will rectify this.

Discussion of Susceptibility Data

The magnetic susceptibility of a glass is a function of the percentage of dissolved iron, the oxidation state (Fe^{2+}, Fe^{3+}), and the dimensions and amount of ferromagnetic inclusions (Sentfle and Thorpe, 1959). The susceptibility is independent of the ambient magnetic field intensity at the time a material cools through the Curie point. This information by itself is not effective in distinguishing between a terrestrial or extra-terrestrial origin for tektites, but like other physical and chemical properties, it is another entity which can be used to group glasses into various categories.

In table 3 a comparison of magnetic susceptibility and intensity is given for certain natural glasses. The figures shown are for individual specimens and are not means. It will be noted that while some of the susceptibility figures for the various glasses are similar, a considerable difference is evident in the intensity of magnetization, as much as five orders of magnitude. This arises because of the nature of tektite glass.

The variations are not due to lower iron content, but are the result of high temperature fusion and rapid cooling which essentially left mostly all of the iron in solution. The fact that a moment is present is evidence that some of the iron, however little, exists as superparamagnetic, single domain, or

Sample	Weight (grams)	Magnetic Susceptibility emu/gm (X 10-6)	Magnetic Intensity emu/gm (X 10-6)
Tektites			
Philippinite	44.8	6.1	0 .003
Australite	35.8	5.9	0 .051
Bediasite	29.8	5.3	0 .019
Moldavite	23.4	2.5	0 .190
Ivory Coast	6.7	7.9	not detectible
Impactites			
Libyan Desert Glass	8.6	0.050	0.016
Aouelloul	20.2	3.1	0.10
Ries	14.1	1.5	1.8
Bosumtwi	2.6	5.8	46.0
Henbury	4.1	900.0	270.0
Darwin Glass	1.2	1.6	0.090
Wabar	3.1	variable	variable
Other			
Obsidian (S. America)	18.4	1.8	224.0
Obsidian (California)	15.2	0.62	481.0
Obsidian (Philippines)	16.0	8.8	177.0
Obsidian (Hawaii)	30.6	9.5	560.0
Power Line Fusion	7.0	5.2	0.21

Table 3. Typical magnetic properties of some natural glasses.

Plate 14. Impact glasses and power line fusion.

multidomain particles. Without these phases, or a combination of them, there would be no ferromagnetism.

Despite the geological ages of tektites and the different geographical areas where they are found, the susceptibility differences between strewn fields, while distinct, are nevertheless quite restricted. Although the five tektites shown were selected at random, the susceptibility they manifest might just as well have been the mean for each group as the range is not large (Table 4).

Impact Glasses

The impact glasses differ considerably from tektites in physical and chemical properties. There are also marked differences in the magnetic properties as Table 3 indicates. Their range in susceptibility is much greater than tektites which undoubtedly arises because of the random nature of surface impacts. The intensity of magnetization also differs from tektites owing to the crystalline nature of impactites and the frequent contamination by metallic particles from the impacting bodies.

Libyan desert glass appears to be in a class by itself relative to susceptibilty. This is to be expected since it is virtually all SiO_2 with a total iron content less than 0.34 percent (Barnes, 1967). Additional magnetic experimentation suggested that this glass can be grouped with tektites.

Strewn Field	No. of Specimens	Magnetic Susceptibility emu/gm (X 10^{-6}) range	mean	standard deviation
Moldavite	31	1.2 - 4.8	2.1	0.5
Bediasite	12	3.9 - 7.0	5.6	1.8
Ivory Coast	4	7.9 - 8.5	8.2	0.3
Australasian	111	4.3 - 7.5	6.3	0.5

Table 4. Susceptibility data of the tektite strewn fields.

Applications of Susceptibility Data

Susceptibility appears to be useful to separate strewn fields from one another, and also provides a further separation of tektites within individual strewn fields. Thus, during the investigation it was possible after practice, to determine what strewn field and often what part of a strewn field a sample was from merely by noting the magnitude of the susceptibility. The moldavites and Ivory Coast tektites are quite distinct while the susceptibility of the bediasites appear to range mostly throughout the australasian susceptibility figures. The mean susceptibilities however, can delineate the australasian area into a rather interesting geographical "plot" and warrents some speculative comments.

Table 5 gives a breakdown of the australasian strewn field according to susceptibility determinations. These means are then plotted in Figure 5. It will be noted that some order appears to be present in the groupings. Excepting the south-eastern area of Australia, the susceptibility changes are essentially of the same magnitude from the Wharton Basin outward. From the samples measured, and from the microtektite data, the highest mean is at the Wharton Basin while the lowest is placed at the periphery of the strewn field. Because of the religious significance attached to tektites, transport by tribes in Indochina and Australia is a potential problem and cannot be ruled out.

Location	No. of Specimens	Magnetic susceptibility emu/gm (X 10^{-6}) range	mean
Viet Nam	4	6.1 - 6.4	6.3
S.E. Thailand	6	6.4 - 6.6	6.5
Cent. Thailand	3	6.0 - 6.3	6.2
Hainan	3	5.3 - 5.4	5.3
Malaya	2	6.6 - 7.0	6.8
Billiton	4	7.1 - 7.5	7.4
Wharton Basin*	10	5.1 - 14.3	9.8
Java	2	7.3 - 7.5	7.4
N. Borneo	3	6.7 - 7.5	6.7
Cagayan, Philippines	2	5.6 - 5.9	5.8
Anda Tara "	4	6.0 - 6.3	6.2
Santa Mesa "	7	6.3 - 6.9	6.5
Panay "	3	5.9 - 6.1	6.0
Pugad Babuy "	3	6.6	6.6
S. Australian Basin*	9	1.8 - 11.7	5.4
Monger, Australia	2	6.2 - 6.3	6.3
Lake Cowan "	2	6.1	6.1
S.W. Coastal "	4	5.8 - 6.2	6.0
Lake Erie "	2	4.7	4.7
N. Lake Erie "	3	4.3 - 4.4	4.4
S. New South Wales "	3	4.9 - 5.4	5.2
S.E. New South Wales "	2	5.3	5.3
N. New South Wales "	4	5.6 - 6.1	5.9
W. New South Wales "	2	5.4 - 5.7	5.6
<u>Unknown Specific Locations</u>			
Indochinites	10	6.2 - 6.3	6.3
Philippinites	12	5.9 - 6.7	6.4

* Microtektite data from oceanic cores (Sullivan _et al._, 1969)

Table 5. Susceptibility of tektites from the australasian strewn field.

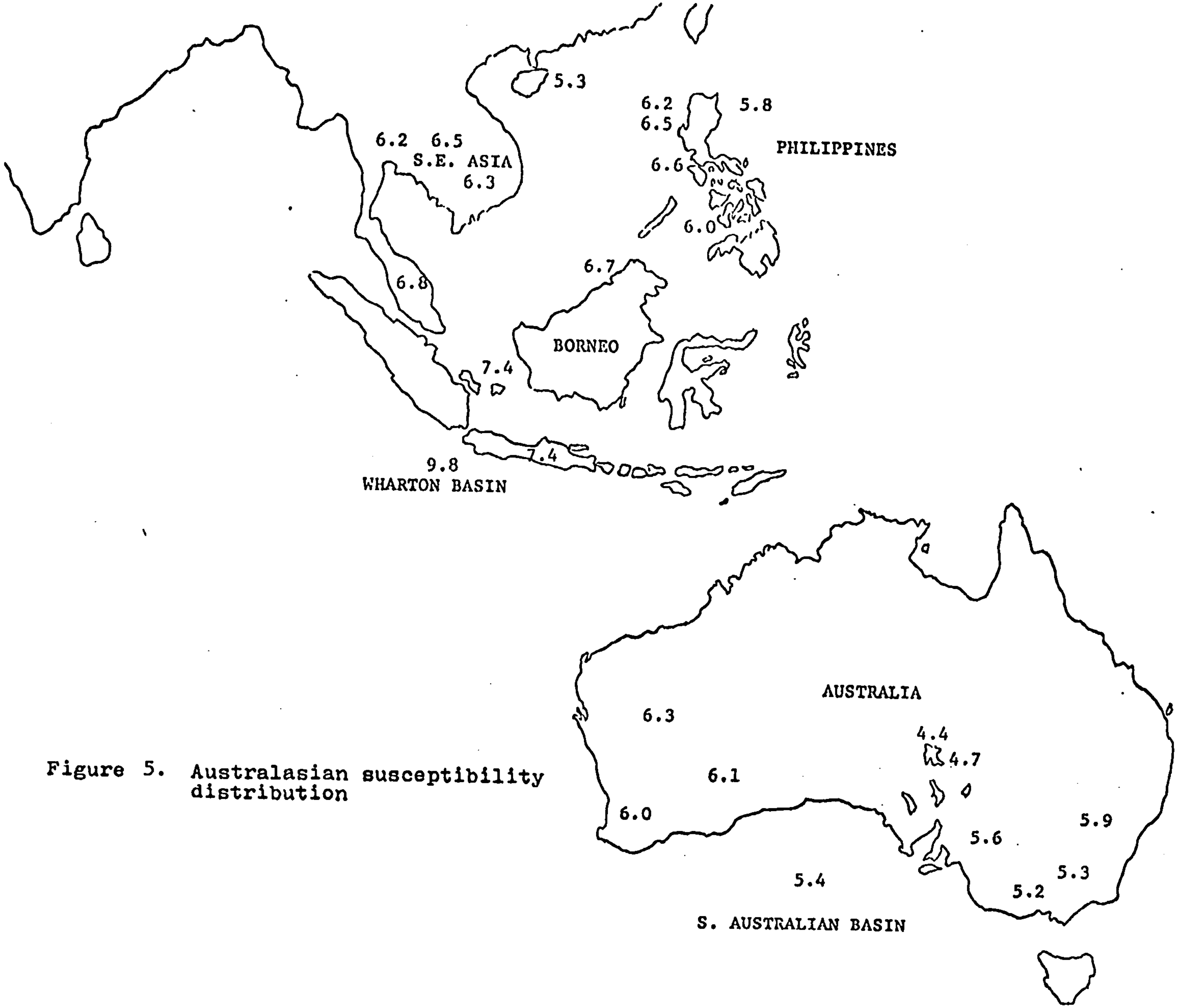

Figure 5. Australasian susceptibility distribution

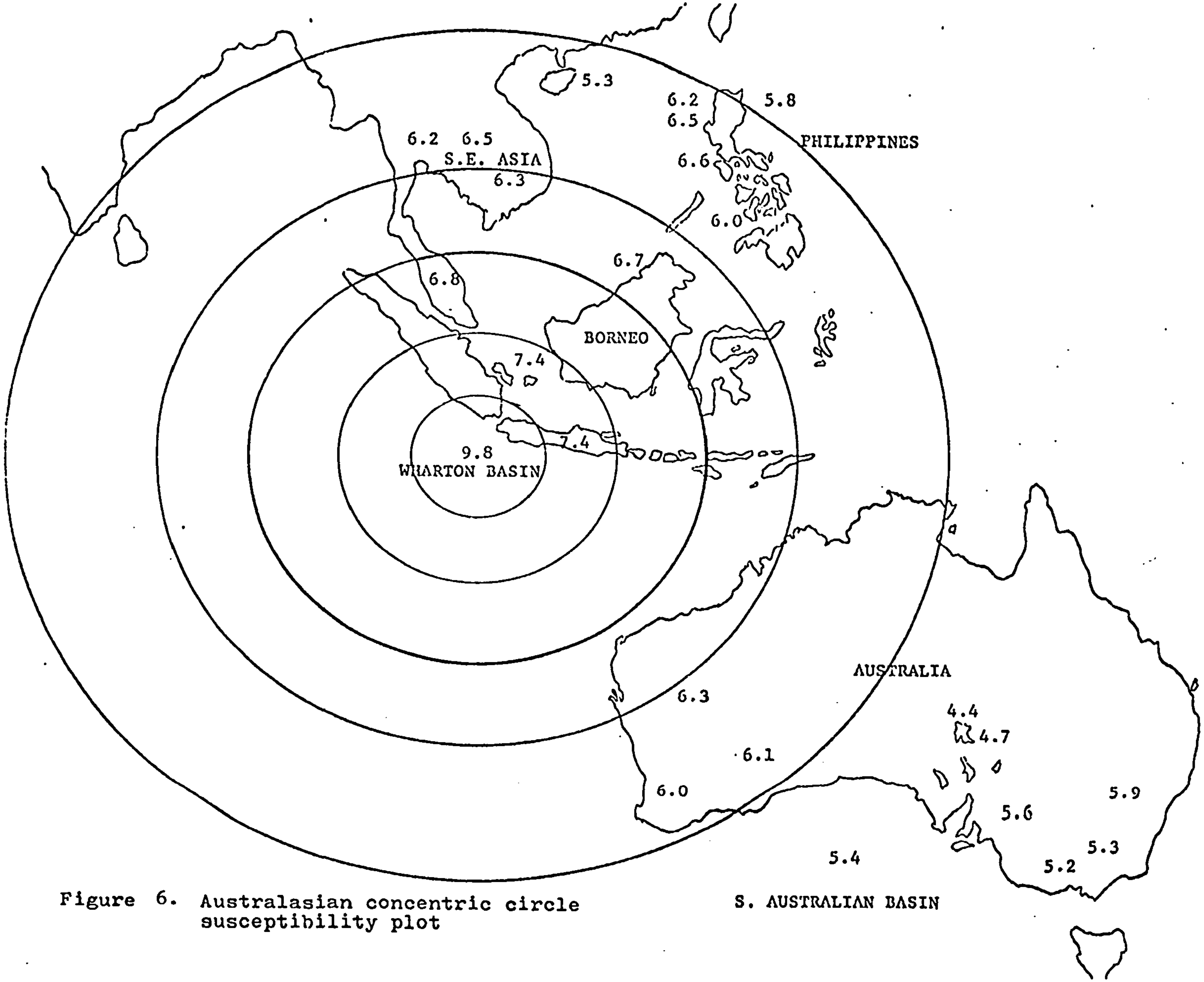

Figure 6. Australasian concentric circle susceptibility plot

Figure 6 overlays concentric circles over the strewn field area. If the samples tested are truly representative of the collection sites, then there might be an explanation as to why this "pattern" exists. Admittedly, the figures are means, and "patterns" are usually subjective, but some general order does appear to be present.

Microtektites

The microtektites can be accepted as true tektites with some reservations, the main one being their actual impact site. The size of these glasses are, by definition, less than one millimeter. The ones from the oceanic area around Austrialia range from .038 to 0.707 mm (Cassidy *et al.*, 1966), and hence they are far more mobile in an aqueous medium than are their land macrotektite counterparts. That they are part of the same event as are the other tektites in this area is supported by their depositional position in a zone associated in time with a geomagnetic reversal approximately 700,000 years ago (Glass, 1967). Macrotektites from the australasian region have been dated at about 700,000 years by the K/Ar method (McDougall and Lovering, 1969).

Another reservation with respect to the microtektites has to do with susceptibility data. Since a superconducting unit was not used for this, there could be some error in the measurements or a difference in readings due to the base standard utilized.

However, if the microtektite data were to be eliminated the "pattern" would not differ that drastically since the "center" of the plot would remain about the Java region.

A Possible Formation Model

Since it was previously shown that the susceptibility is a function of the oxidation state, percentage of dissolved iron, and dimensions and amount of ferromagnetic inclusions, the tektite producing event must somehow account for these changes across the strewn field.

Temperature can influence the susceptibility and hence in looking at Figure 6, one is tempted to put a detonation point of some parent body over the Wharton Basin with a subsequent spray of tektite glass moving radially outward. If temperature is not the prime cause of the susceptibility differences, then oxidation state might also explain the "pattern". During an explosion there is a marked change in atmospheric pressure symmetrically within and about the detonation area. Thus, a glass solidifying at points through 360° around the shock wave emission could conceivably take on the same atmospheric conditions resulting in a similar susceptibility. If the tektite event is of some unusual nuclear or electrical phenomenon, there should be no effect on the susceptibility since this magnetic property is independent of magnetic and electrical activity. The susceptibility readings should therefore only depend on the factors mentioned previously, and could not detect anything out of the ordinary.

One entity which was surprising relative to the susceptibility data, was the intensity of magnetization. Although there were exceptions, the tendency was for the intensity to increase as the susceptibility decreased. The layered indochinites were the most intense, followed by the philippinites and the australites. There were relatively strong samples in the range of 10^{-7} to 10^{-8} emu/gm as well as weak ones $< 10^{-8}$ emu/gm. Most likely, the higher intensity tektites were either formed at a lower temperature and/or possibly cooled for a longer period of time. The effect of cooling rate on intensity will shortly be discussed.

Barnes and Pitakpaivan (1962) present chemical and petrological evidence that within the Indochina area, there was a high and low temperature region. This evidence comes from the abundance of lechatelierite particles (fuzed quartz) and the occurrence of "fingers" -- small areas on tektites having concentrations of silica due to vaporization of iron at temperatures around 3,000°C. These "fingers" are also found extensively in australites and in some philippinites.

In tests on viscosity of tektites Chapman (1964) determined that primary forms which fell over Australia, were heated to approximately 2,600°C while those that fell over Indochina reached about 2,100°C. Thus, according to Barnes and Pitakpaivan, high temperature tektites are found mostly in Australia with scattered areas of Indochina and the Philippines yielding some, while Chapman restricts the high temperature specimens to Australia. Based on bubbly lechatelierite, Barnes (1967) puts the overall cool area in Indochina with the Philippines and Java having intermediate temperatures, followed by Australia at the hotter end.

Implications of Susceptibility and Intensity Data

The tektites that were not measurable were exposed to a 7,000 OE field and remeasured. Almost all of these samples remained below the detection level of the magnetometer. This indicates that the iron content is virtually totally ionic, which strongly suggests formation temperatures higher than for other tektites. This could possibly indicate "hot spots" within the field, and could mean that there might not be one center of the event, but possibly several.

Attempting to determine what condition could have produced the observed susceptibility values by re-heating or remelting australasian tektites is questionable. As soon as the tektites have re-melted, there will be changes in the iron oxides, ferromagnetic inclusions, etc. All of these changes would not be the same that the original melt would undergo during solidification.

Difficulty also arises in attempting to interpret what the tektite event was because one has to equate it with some known phenomenon. In particular, blast effects are usually symmetrical relative to shock wave, ejection of material, and rise and fall in temperature. All these factors could determine the phases of the dissolved and undissolved iron, and hence could be manifested by the values of susceptibility.

It would appear that susceptibility measurements on synthetic tektite glass under differing atmospheric and cooling conditions, could assist in clarifying many of the unanswered questions. Outside of the limited experiments by Ostertag et al. (1969), practically no research has been done in this area.

Nothing in the literature could be found relative to magnetic studies done on natural glasses formed in nuclear explosions. Evidently this research has never been conducted and without something of this nature, it is difficult to determine exactly how the susceptibility and intensity would vary. In view of this, the interpretation of the data from the australasian strewn field must remain essentially speculative.

In conjunction with further magnetic work done on tektites in this paper, additional comments relative to the event will be later discussed.

SUSCEPTIBILITY AND INTENSITY CHANGES ACROSS A TEKTITE

Plate 15 shows a 23.5 gram philippinite that was examined for susceptibility and intensity changes from the exterior to the interior. The discs show the approximate place where the tektite was cut. Sentfle and Thorpe (1959) completed a similar experiment on an indochinite and found that the susceptibility was essentially constant throughout. However, they were unable to measure the intensity on any tektite or tektite fragment during their study. The reason for repeating this experiment was to determine if a variation in intensity existed across the specimens.

The data presented on Plate 15, while indicating an essentially constant susceptibility, suggest a variation in the intensity. The moment is higher towards the interior, and most likely is due to variations in the solidification rate.

At formation, a tektite is cooling at a rapid rate. Greenland and Lovering (1962) estimate that for tektite spheres of 1-cm radius, the decrease in temperature from 2,000°K to 1,000°K would require about 35 seconds; a 5-cm radius tektite would take about 175 seconds. The size of the tektite in Plate 15 is approximately 3.5 cm, so the cooling time will be somewhere between the stated values. Additional time would be required for the temperature to fall below the Curie point of the carriers.

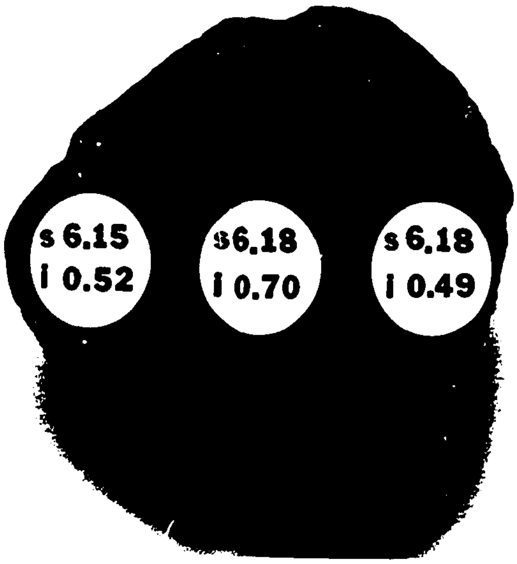

Plate 15. Susceptibility and intensity changes across a philippinite. (x 10^{-6} emu/gm) Photo =2X

Plate 16. Intensity changes across a volcanic bomb. (x 10^{-3} emu/gm) Photo = actual size

The longer the interior takes to solidify, the better will be the chance of ferromagnetic grains forming. Considering the differences in cooling rate of the exterior and interior, a tektite tends to resemble a volcanic bomb. Of course there will be some contrasts in thermal conductivity depending upon structural properties. To determine if the differences in moment could be attributed to the cooling rate, the same cutting procedure and intensity tests were performed on this type of material.

Plate 16 shows the intensity changes across a sectioned volcanic bomb. Measurements were made with the spinner magnetometer since the moments were too intense for the superconducting unit. It will be noted that although the intensity is much higher, the changes in moment are similar to that of the tektite. Since this volcanic bomb cooled within the geomagnetic field at, or partly at, a relatively low altitude above the surface, it would not be correct to reason that the intensity differences are due to variations in the inducing field. Stated another way, the intensity changes are not caused by exposure of one area to a different field strength than the other.

The corollary of this is that one cannot conclude from the intensity variations alone across a tektite, that primary solidification occurred somwhere in the solar system where the inducing field differed from the earth's, the latter of which could have been induced in the tektite upon atmospheric entry.

The variations therefore, as with the volcanic bomb are, in all probability, due to differences in cooling rate and associated physical changes.

Some individuals upon noting the low value of NRM of tektites take this as indicating that they are extra-terrestrial. While the intensity of magnetism is related to the intensity of the magnetic field in which it was acquired, this is not the only factor.

The other variable factors are: (1) the amount and type of magnetic material present, (2) its magnetic stability, (3) the process in which the remanence was acquired in the first place, and (4) the later history of the rock (Irving, 1964).

In the case of tektites, the amount and type of magnetic material present is quite important for a proper interpretation as to what their intensity suggests. Tektites have an extremely low moment not because they necessarily formed in some extra-terrestrial environment, but simply because of the paucity of ferromagnetic material. The ferromagnetic phase is so minute that if tektites had solidified in a field intensity several thousand times greater than the earth's, they would still be hundreds of times less intense than a typical basalt.

SUSCEPTIBILITY OF SPECIMENS FROM THE MOLDAVITE STREWN FIELD

Ever since concordant K/Ar ages of approximately 14,000,000 years were found for moldavites and impact glasses from the Ries (Gentner *et al.*, 1963), various researchers have attempted to find a genetic relationship between the two. Previous research by Adams and Huffaker (1962) in aerodynamics, had demonstrated that tektites could not have been driven upwards for more than a few hundred meters regardless of the force or velocity given to them. Despite this, the hopes of a genetic relationship continued.

Various papers in O'Keefe (1963) and Barnes and Barnes (1973) reveal that while considerable petrological and chemical differences exist between the two, the presence of certain trace elements could suggest a possible relationship. Since the moldavites used for susceptibility measurements in this research had their specific collection sites listed, it was decided to observe how these changed relative to distances from the Ries crater. Like the australasian field, all tektites examined were measured with the cryogenic magnetometer.

The four susceptibility numbers appearing in Figure 7 resulted from arbitrarily selecting distance widths of approximately 25 KM and averaging the susceptibility of the moldavites within these. The specific distances of the tektite localities and the

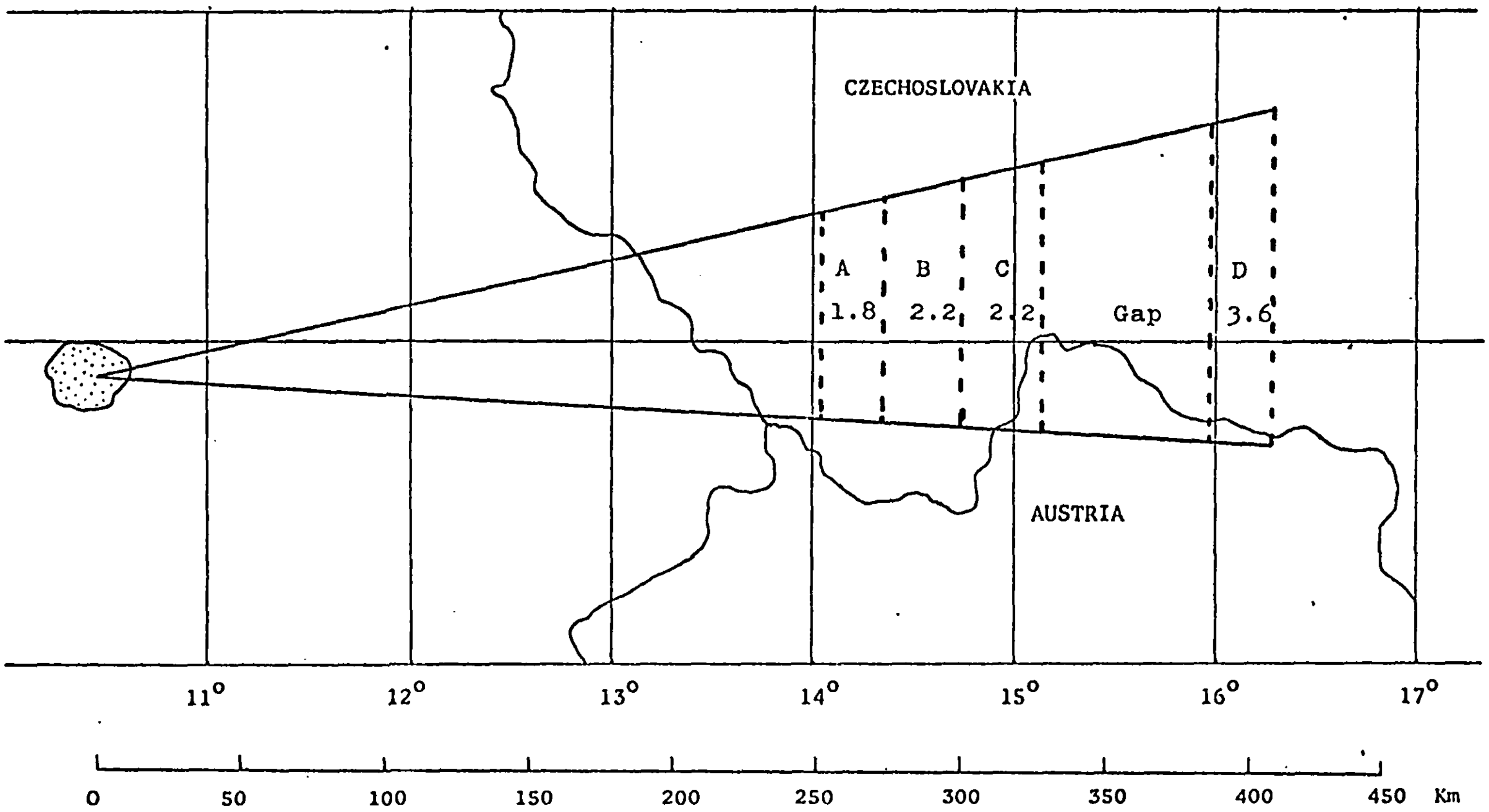

Figure 7. Susceptibility as a function of distance from the Ries Crater. (The drawing is from Cohen, 1958, to which has been added the susceptibility data $\times 10^{-6}$ emu/gm.)

Zone	No. of specimens	Magnetic susceptibility emu/gm (x 10^{-6}) range	mean	std dev
A	8	1.3 - 2.0	1.8	0.3
B	6	1.2 - 2.4	2.2	0.2
C	5	2.0 - 2.5	2.2	0.3
Gap	0			
D	12	1.7 -4.8	3.6	0.7

Zone Description

A - Moldavites first appear in Trebanice at a distance of 256 km from the Ries. This zone includes from Trebanice (256 km) to Slavce (274.5 km).

B - from Slavce (274.5 km) to Soběslav (303.0 km)

C - from Soběslav (303.0 km) to Jindřichův Hrade (322.0 km)

Gap - no moldavites have ever been found between Jindřichův Hradec and Teruvka, a distance of over 60 km.

D - from Teruvka (386.0 km) to Senohrady (413.0 km).

Table 6. Moldavite susceptibility results.

associated susceptibilities are discussed in Table 6.

As with the australasian strewn field, the susceptibility values do not appear to be random. The reference point for the australasian area was centered over Java, and the susceptibilities appeared to decrease outward from this point. With the moldavites however, this pattern is reversed. Also, the tektites in this case are relatively restricted in geographical area.

Table 6 shows that the mean susceptibility of the Bohemian tektites (zones A,B,C) is different from that of the Moravian tektites (zone D). But the values of intensity of magnetization were not distributed in a similar way. Rather, within the Bohemian and Moravian area, there were relatively high and low intensity samples which ranged from 1.2 X 10^{-7} emu/gm to below the interference level of the magnetometer. These specimens were independent of distance from the Ries crater. Susceptibility of the moldavites varied inversely with the intensity.

As with tektites from the australasian field, the samples that were unmeasurable were exposed to a 7,000 OE field. Again, it was found that the samples were still undetectible, suggesting the possibility of "hot spots" caused by some phenomenon within the Bohemian and Moravian regions.

Chapman (1971) explains the relationship between the Ries crater and moldavite strewn field according to his "conate crater theory". He advocates a burst of composite ejecta from a lunar impact consisting of tektites with one or more large fragments from the original meteoritic projectile. When this material lands on the earth, the fragment excavates a crater "conate" with, but not the parent of the tektites. The restriction of tektites to one side of the Ries crater is explained by the forward position of the tektite spray relative to the projectile fragment during transit from moon to earth. Thus, the differences in chemical and petrological characteristics between glasses in the crater and moldavites are explained.

This model tends to favor the change in susceptibility values from the Ries crater. However, the returned lunar samples have mostly refuted a lunar origin for tektites (Taylor, 1975). If it is assumed that the ages of impactites from the Ries Crater and moldavites are a coincidence, then another coincidence occurs with the Ivory Coast strewn field.

As with the moldavite strewn field, the Ivory Coast tektites are also "associated" with a large impact feature. In this case, it is the Ashanti crater (Lake Bosumtwi) in Ghana which lies approximately 300 KM to the east of the strewn field (Fig. 8). Cohen (1963) and Gentner _et al_. (1963) found that the impact glasses from the crater bottom have essentially the same K/Ar age as the Ivory Coast tektites (1,300,000 years). Once again, the impactites show little in common with the tektites, but trace element abundances suggest a relationship. With some trace elements, the relationship is much stronger than with the Ries

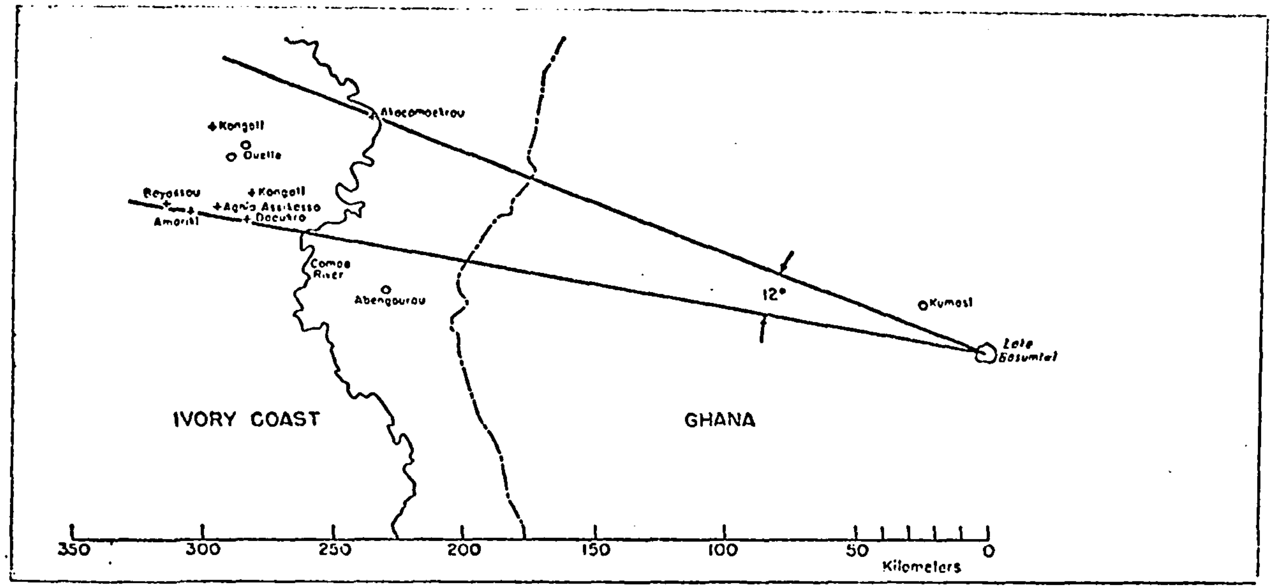

Figure 8. The Ivory Coast strewn field and Bosumtwi crater. (from Cohen, 1963)

impactites and moldavites (Rybach and Adams, 1969; Schnetzler et al., 1966; Taylor and Epstein, 1966).

Unfortunately, it was not possible to study the changes in susceptibility as a function of distance from the Ashanti crater. The samples were too few and lacked locality data. Therefore, little could be stated relative to their susceptibility and intensity measurements. With the bediasites found in Texas and Georgia, there is also little that can be stated because most of the samples did not have collection areas identified. The intensity of magnetization was found to vary inversely with the susceptibility, but unlike other tektite groups, those samples exposed to a 7,000 OE field were all detectible on the magnetometer.

Having presented the results of these studies on the magnetic intensity and susceptibility of tektites, other magnetic properties of these glasses and impactites will now be investigated to determine a possible relationship.

ORIGIN OF THE NATURAL REMANENT MAGNETIZATION

During a paleomagnetic investigation it is important to determine how the NRM originated. In addition to processes related to thermal remanent magnetization (TRM), which usually produces a very stable magnetic moment, the NRM can have its origin through other means. For example, an isothermal remanent magnetization (IRM) can be imparted to a tektite if it were from an area hit by lightning, or exposed to a high magnetic field sometime after collecting. Heating at elevated temperatures but below the Curie point can produce a partial thermal remanent magnetization (PTRM). This could arise, for example, if the sample were exposed to a natural fire or sustained low heating through burial for long periods of time.

Magnetization can also result from chemical changes, and results in a chemical remanent magnetization (CRM). Basically, this involves an increase in grain size or percentage or change in the ferromagnetic phase due to various reactions occurring in different geological environments.

Shock remanent magnetization (SRM) considered by certain researchers to be a potential source of magnetization has been shown in this research to be ineffective relative to tektites and hence is dismissed. Regardless how tektites had been shocked in the natural environment, the NRM would be invariably preserved intact.

Since tektites range in age from 700,000 to 33,000,000 years (Fleischer and Price, 1964) the possibility exists that they may have acquired a magnetic component by exposure to the earth's magnetic field for these long periods. This type of magnetization is called viscous remanent magnetization (VRM). Thus it is apparent that the NRM could have originated in many ways, and it must be determined which process is the most probable origin.

Isothermal Remanent Magnetization

IRM is a potential source since some tektites have probably been exposed to a magnet or struck by lightning during their past history. To test for the former, a tektite was selected from each of the strewn fields and demagnetized by AF methods. An IRM was then given to the samples to return their intensity to approximately where it had been before demagnetization. The artificial IRM was then demagnetized and the curves compared (Fig. 9). The resulting data shows that a given percentage of the IRM was erased at lower fields than that of the NRM. This indicates that the IRM is less stable than the NRM and cannot be the primary source of the NRM.

Lightning is another source of the IRM, and its effects are noticeable in samples collected from certain surface outcrops. Graham (1961) in studying the Robinson dike in South Africa found that not only the intensity varied in different surface samples,

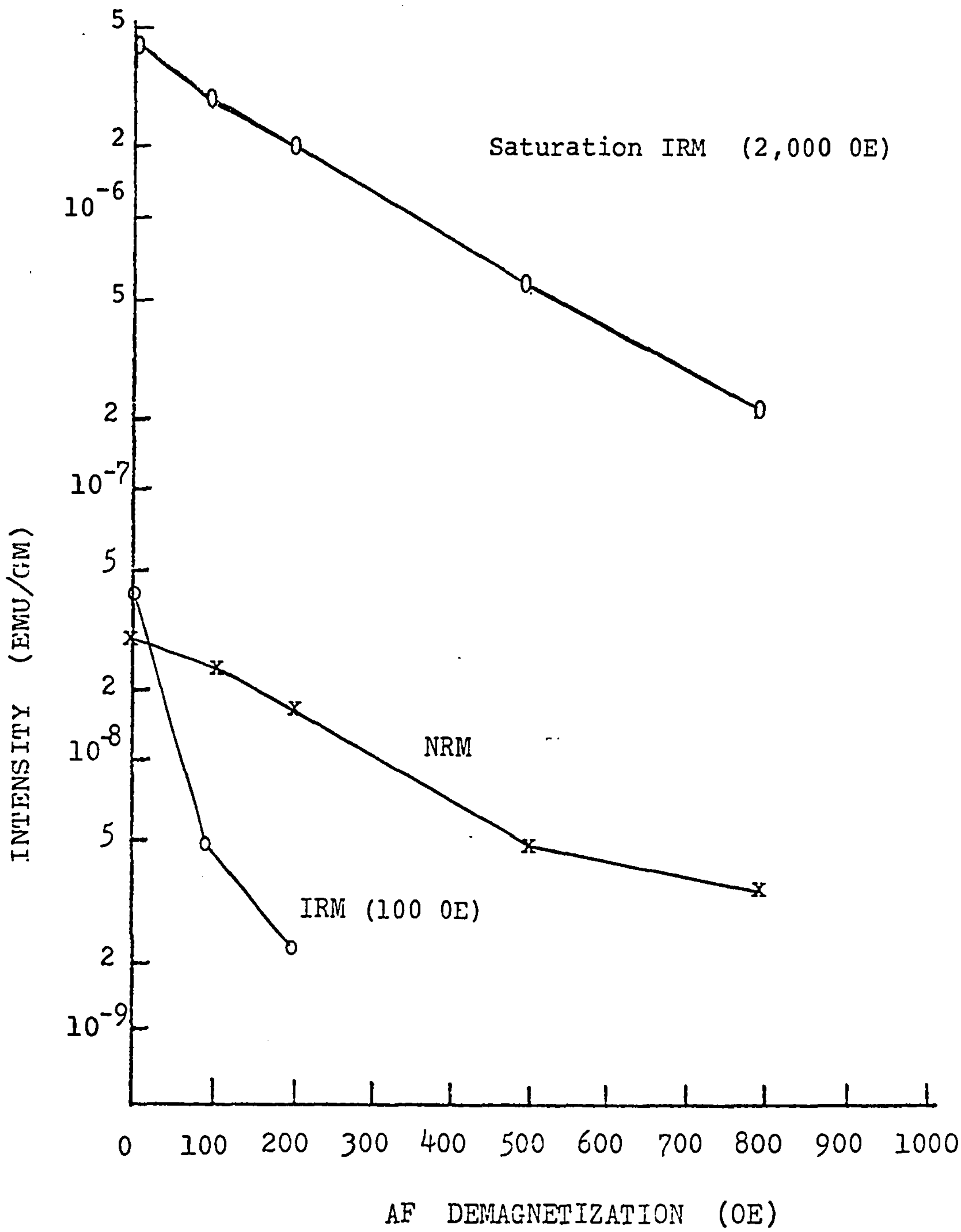

Figure 9. Comparison of NRM and IRM curves on a 30.8 gm indochinite.

but also the directions of magnetization. As one proceeded deeper into the mine associated with the dike, the NRM decreased about an order of magnitude and the magnetization directions rotated into a preferential plane i.e., the natural directions.

With proper AF demagnetization, it is possible to "clean" the effects of lightning from samples and obtain the primary directions of magnetization. The alternating field is applied until there are no further changes in the directions of magnetization and it is then assumed that all of the effects have been removed (Irving, 1964). Since demagnetization of IRM may have a tendency in many cases to remove also some of the NRM, it is difficult to estimate what the true NRM intensity was before the remagnetization.

Since all tektites, except possibly the Muong Nong variety, have solidified while airborne, and consequently were transported in various magnetic environments, their directions of magnetization are exceedingly difficult, if not impossible to estimate. Fortunately relative to this research, magnetic directions of *in situ* specimens are not necessary. However, the possible effect of lightning on the NRM presents a problem in that a strike might be capable of completely masking the NRM with a magnetic component that could not in part be distinguished from the NRM itself. This could present problems relative to the paleointensity determinations which are to follow.

On the basis of probability, all of the examined tektites in this paper certainly have not been hit by or been in proximity to a lightning strike. Then again, an argument, however weak, could be put forth. For example, suppose that tektites have arrived from a place in the solar system where the magnetic field was low compared to the earth's. Further suppose that this NRM remained intact during atmospheric entry. Now, subject those tektites to a lightning strike and problems arise as to what the true NRM was.

It was previously mentioned that the majority of tektites examined in this research, were beyond the detection level of the magnetometers. The question that arises because of this is that perhaps the tektites that were measurable, were in fact measurable not because of their greater ferromagnetic content, but because their moment had been increased by an IRM. This is a valid argument, and having previously removed one possible IRM cause (Fig. 9) the other must now be determined.

Surprisingly, no quantitative data relative to lightning strikes on rocks of differing compositions could be found in the literature. Apparently, the actual effects have not been experimentally determined.

It was therefore decided to empirically subject tektites to lightning strikes. However, rather than attach several of these glasses to a lightning rod and wait for Oklahoma's weather to live up to its reputation, another route was sought.

The apparatus shown in Plate 17, was constructed by Dr. Robert Fowler of the OU physics department to test the tektites in this research. Referring to Plate 20, "A" are capacitors, "B" is part of a power regulating control, and "C" an electrical discharging unit. Several tektites can be seen clustered about the latter. The blocks on top of the assembly are lead weights, whose function was to keep the device on the ground during discharge. Several shields were also positioned around the equipment before proceeding with the tests.

The power of the electrical discharge was calculated at about 10^5 amperes with an arc duration of approximately 10^{-6} seconds. This represents a "super" lightning stroke occurring in roughly 1 out of 100 discharges in nature (Fowler, personal communication). Along with the tektites, cores from baked clays and redbeds were also tested for comparison. All of the cores showed a significant increase in intensity after the discharge.

Results from a baked clay core are shown in Figure 10. It will be noted that the intensity of the NRM before AF demagnetization was 3.0×10^{-3} emu/gm and decreased to about 2.5×10^{-4} emu/gm as a result of demagnetization. The smoothness of the demagnetization curve will be noted.

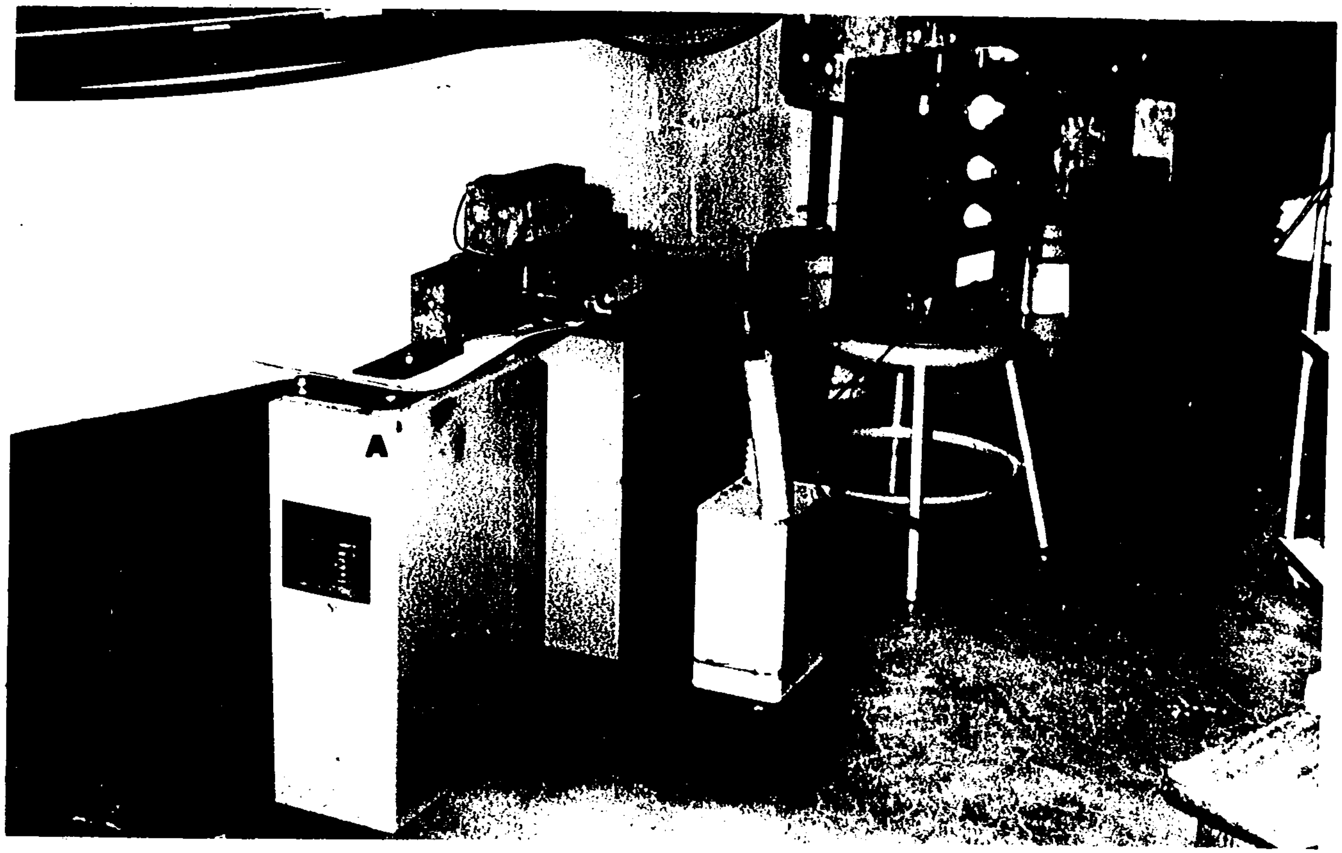

Plate 17. Lightning simulation apparatus.

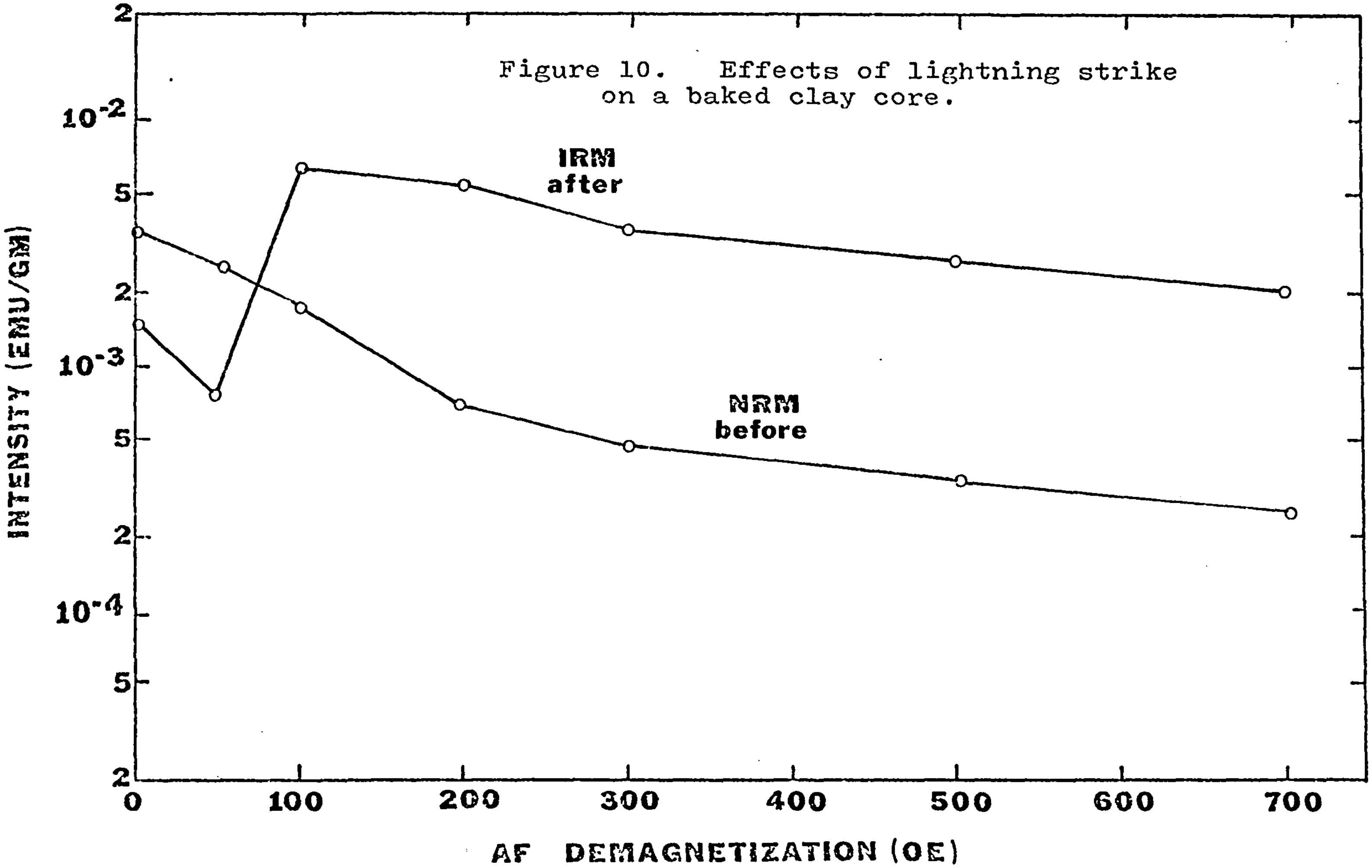

Figure 10. Effects of lightning strike on a baked clay core.

After the discharge, the intensity gained almost an order of magnitude, and the demagnetization curve was spurious out to 100 OE. After this, the curve was essentially parallel to the NRM curve. It is apparent that the effects of a lightning strike can mask the NRM, but not necessarily the directions (inclination and declination). These rotated into the NRM directions after demagnetization in a 200 OE field. When this same core was subjected to another strike, the moment again increased, though less than half an order of magnitude. The demagnetization curves of this were essentially the same as Figure 10. This suggests that a single strike might not be capable of saturating a sample of this nature.

With the tektites, only one sample (an indochinite) showed any measurable change before and after discharge. The demagnetization curve of this particular tektite is illustrated in Figure 11. This sample had been demagnetized out to 300 OE before being tested. After the discharge, it showed a slight gain in intensity, much lower however than with the clay. When this specimen was demagnetized out to 500 OE, the intensity was about what would have been expected for the NRM under similar conditions. The dotted line shows the probable path that would have been followed by the NRM. These conclusions are based on the demagnetization properties of other tektites.

Actually, the intensity of this sample remained the same

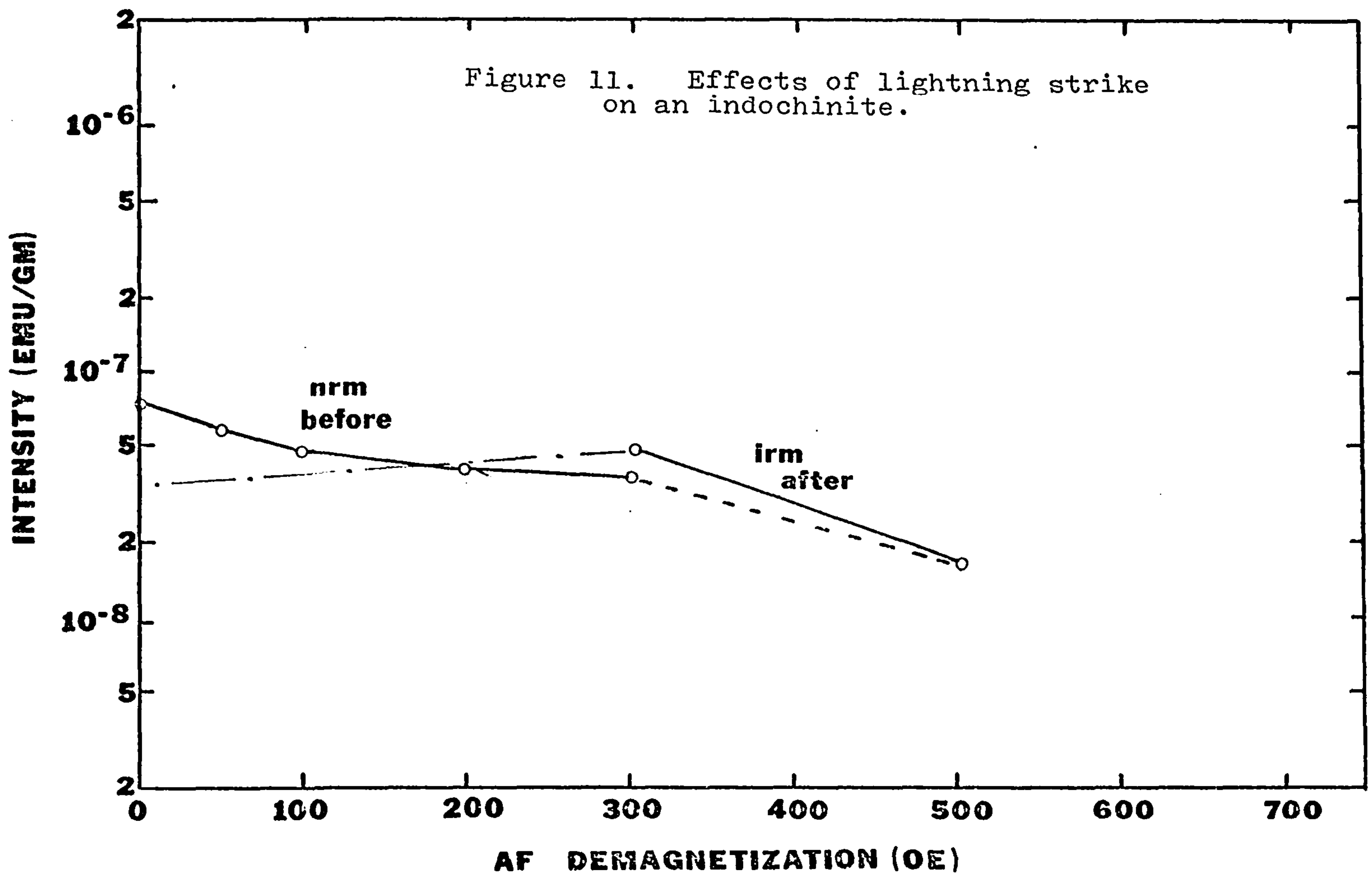

Figure 11. Effects of lightning strike on an indochinite.

during demagnetization at 50, 100, 200, and 300 OE. Had the complete curve been drawn, the part up to 300 OE would have been almost parallel to the X-axis. This suggests that practically no IRM was imparted to the tektite, and that perhaps what was observed was a function of instrument error. This could be due to a difference in calibration of the magnetometer during the time readings were taken or perhaps to reading error itself.

Thus, while the baked clay was noticeably altered by lightning strikes, tektites were not. Even repeated strikes produced no changes. Apparently their extremely low ferromagnetic content within a non-conducting glass matrix, negates any reaction of the domains to the instantaneous discharge. Again, as with the shock tests, this represents an extreme testing procedure. In this case, the tektites were subjected to a direct pulse of current much higher than normally present in the natural environment. From these experiments it was concluded that the source of the NRM in tektites is not due to an IRM of this nature.

Partial Thermoremanent Magnetization

The general stability of the NRM thermal demagnetization curve (Fig. 45) up to the blocking temperature region indicates that this sample had not received a PTRM. Had it previously been reheated to a point below 550°C, the curve would have had a pronounced irregularity in it. PTRM can be recognized because the magnetization is lost at the same temperature it was acquired.

With tektites, to substantially alter the NRM, the temperature would have to enter the blocking temperature region (refer to page 121). Natural fires are not usually this intense and have a tendency to impart a discoloration on a tektite which is easily recognized. The primary source of the magnetization in tektites cannot be due to a PTRM.

Chemical and Viscous Remanent Magnetization

In experiments on tektite glass, deGasparis et al. (1975); personal communication (1976) determined that CRM and VRM are not primary sources of the NRM. These types of magnetization were simulated on a laboratory time scale using elevated temperature to approximate the effect of the true time. Three Muong Nong tektites were first subjected to a 1 OE field for 10 days at a temperature of 100°C and later for the same time at 200°C. It was found that the first experiment did not cause changes in the moment larger than the experimental error. The second heating produced changes of 10 percent of the measured NRM for one tektite, and smaller changes in the other two.

I did not repeat these experiments in this research, but can add that about the only way an effective CRM or VRM could be introduced into a tektite is through natural devitrification of the glass. This commonly occurs in obsidian within the natural range of environmental temperatures. The water content of a rock can induce changes in the NRM with time through alteration of the glass matrix itself. However, the water content in tektites is so low that this does not appear to be possible. It is extremely rare to find a tektite with appreciable devitrification. Those few that do display it have been involved in fires of some nature.

Friedman (1958) found that tektites average less than 50 parts per million in water content which is several orders of magnitude lower than any terrestrial glasses known, either natural or artificial, including atomic-bomb produced glasses. Clearly, the NRM in tektites is due to a cause other than those previously mentioned.

Thermoremanent Magnetization

The other cause considered is that due to a TRM created when the tektites cooled from their high fusion temperature through the blocking temperature range of the magnetic carriers. This seems to be the best explanation for the relatively strong behavior of the magnetization during AF demagnetization (Figs. 15 - 19). In tests on the Muong Nong tektites, deGasparis et al. (1975) were led to the same conclusion. As soon as a tektite is examined magnetically it becomes apparent that it resembles igneous material relative to TRM. It was desirable in this research however, to try to remove any doubt relative to the nature of the magnetization. Additional tests with artificial TRM's and a study of their demagnetization curves were completed to support the TRM origin. An example is shown in Figure 51.

Although the evidence indicates that the major part of the magnetization was acquired by TRM, this should not be interpreted as implying that it is the only method of acquisition. Perhaps it is best to state that the TRM is dominant, and to recognize that minor magnetic components could have contributed a few percent to the intensity.

PROPERTIES OF THE NRM

Having established that the NRM is dominantly a TRM, its magnetic behavior will now be examined. To give a better illustration, a typical tektite curve (Fig. 12) is compared with those of a lunar sample (Fig. 13) and a basalt (Fig. 14). The latter two are not always typical of these specimens but are used here to show some of the extreme properties that NRM can manifest.

In the case of Figure 13 , it will be noted that much of the NRM is lost in a relatively low alternating field. This is followed by a slower decrease in the intensity as the demagnetization is increased. According to Fuller (1974) many of the lunar rocks exhibit this type of demagnetization curve. It arises mostly because of a relatively large IRM component in the samples. Nagata (1961) mentions that certain terrestrial rocks exhibit similar curves also. Only a few of the tektites from certain goegraphical regions exhibited curves of this nature.

Figure 14 shows an example of an NRM which is highly resistant to demagnetization. Some terrestrial rocks behave in this manner (Irving, 1964) and at least one rare lunar sample is comparable to this "curve" (Fuller, 1974). No IRM is evident here. A TRM with the proper ferromagnetic size range could yield a demagnetization curve like this. None of the tektites examined where this resistant to demagnetization.

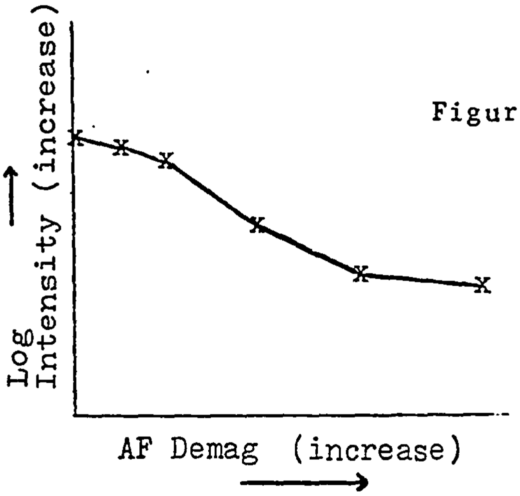

Figure 12 . Tektite

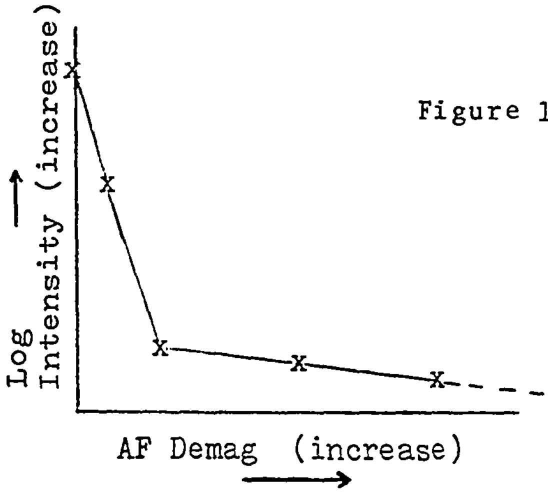

Figure 13 . Lunar sample

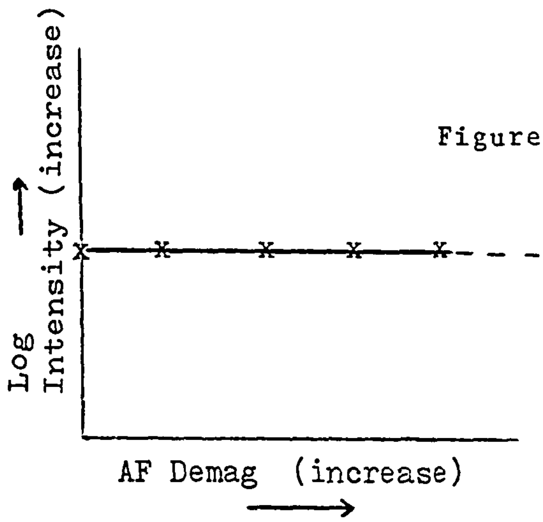

Figure 14 . Basalt

As can be seen in Figure 12 the tektite demagnetization curve lies somewhere between the two extremes. However, the NRM can be considered to be quite stable despite the slight slope of the curve. While the lunar samples, terrestrial rocks, and impactites show a wide range in demagnetization behavior, tektites generally do not.

Relationship of Carrier Size to NRM

The ability of tektites to retain a stable NRM is mostly related to the size and composition of the ferromagnetic inclusions, as well as the manner in which the NRM is acquired. It was previously shown that tektite NRM is dominantly thermal in origin and hence the importance of the magnetic phase size needs mentioning.

Very fine particles may be so small that although their constituent individual atoms are exchanged-coupled below the Curie Point, the relaxation time of the magnetization of the particle as a whole is so short that the particle is in magnetic equilibrium with the environment and cannot exhibit stable remanence. Such samples exhibit magnetic viscosity or time dependence of magnetization. Neél (1949) described the process by which ferromagnetic particles change with increasing time:

$$J_r = J_o \exp(-t/\tau)$$

where

$$\frac{1}{\tau} = f_o \exp(-KuV/kT)$$

The first equation expresses the remanence (J_r) in the absence of a field where J_o is the original remanence, t is the time since J_o and τ is the relaxation time. The second equation expresses the relaxation time, where f_o is a frequency factor not strongly dependent upon temperature (Neel, 1949), Ku is the magnetic anisotropy, V is the volume of the particle, k is the Boltzman constant, and T is the absolute temperature. Thus, the strong effect of the volume of the particle (V), on the relaxation time (τ) defines times short when compared with experimentally observed times (Fuller, 1974). The Wabar impactite is a good example of time dependence of magnetization, and illustrates the effect of an abundance of superparamagnetic magnetic carriers. These fine particles are found extensively in the many of the lunar samples.

The single-domain state covers a range of grain sizes in which the relaxation time is extremely long compared with experimently observed time. A dispersion of such grains can carry remanence that is stable at room temperature for times even comparable with the age of the solar system. The remanence is also generally stable against AF demagnetization and hence is termed "hard". Individual particles carry a remanence equal to their saturation magnetization; they are homogeneously magnetized (Fuller, 1974; Nagata, 1961).

With multidomain particles, the material is inhomogeneously magnetized, which reduces the demagnetization energy of the particle and gives a remanence small compared with the saturation magnetization. Multidomain magnetization is demagnetized by relatively weak alternating fields. Between the range of truly multidomain behavior, exhibited in the presence of a large number of domain walls in the particle, and the range of single-domain behavior, there is a transition region in which the particle has only a small number of walls and carries a remanence comparably stable to that of single-domain particles (Fuller, 1974). A more detailed discussion of magnetic carrier sizes can be found in Nagata (1961), Irving (1964), and Banerjee and Stacey (1974).

During an investigation of the magnetic properties of various specimens, it is desirable to obtain as many parameters as possible relative to the characteristics of the ferromagnetic particles. This includes determining the amount of superparamagnetic, single-domain, and multidomain carriers. To do this involves a detailed study of the initial susceptibility, saturation magnetization, saturation remanence, coercive force, and remanent coercive force. Ratios of these then lead to fairly accurate estimates of the ferromagnetic contributions of differing carrier sizes.

While the saturation magnetization was determined with the cryogenic magnetometer, a complete and reliable hysteresis curve was not. For this, one has to resort to the vibrating sample magnetometer. Preparing a sample for this analysis involves placing a fragment about the size of a pencil point at the end of a sapphire rod and vibrating it within the magnets shown in Plate 6. This equipment is not superconducting and hence its noise level surpassed the most intense tektite glass attempted; even a Muong Nong sample was not detectible. The sizes of the magnetic carriers in tektites therefore, had to be inferred. As will be seen later in this paper, some were visually detected.

Tektite Demagnetization Curves

Examination of the demagnetization curves in Figures 15-19 can assist in determining the probable sizes of the magnetic carriers along with their relative abundances. Generally, the moldavites were the hardest followed by the bediasites, australites, indochinites, Ivory Coast tektite, and particular philippinites. This should be qualified since the NRM of the Ivory Coast sample (Fig. 16) was not detectible and hence it was the saturation IRM that was used. A comparison of saturation IRM and NRM demagnetization behavior in other tektites showed that the former is relatively softer than the NRM, and considering this, the Ivory Coast curve would probably be harder

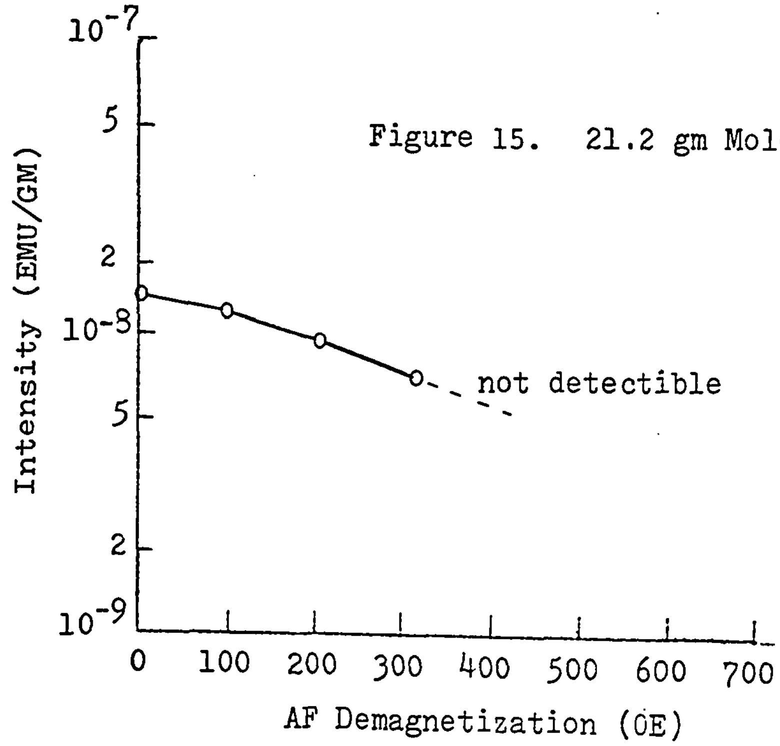

Figure 15. 21.2 gm Moldavite.

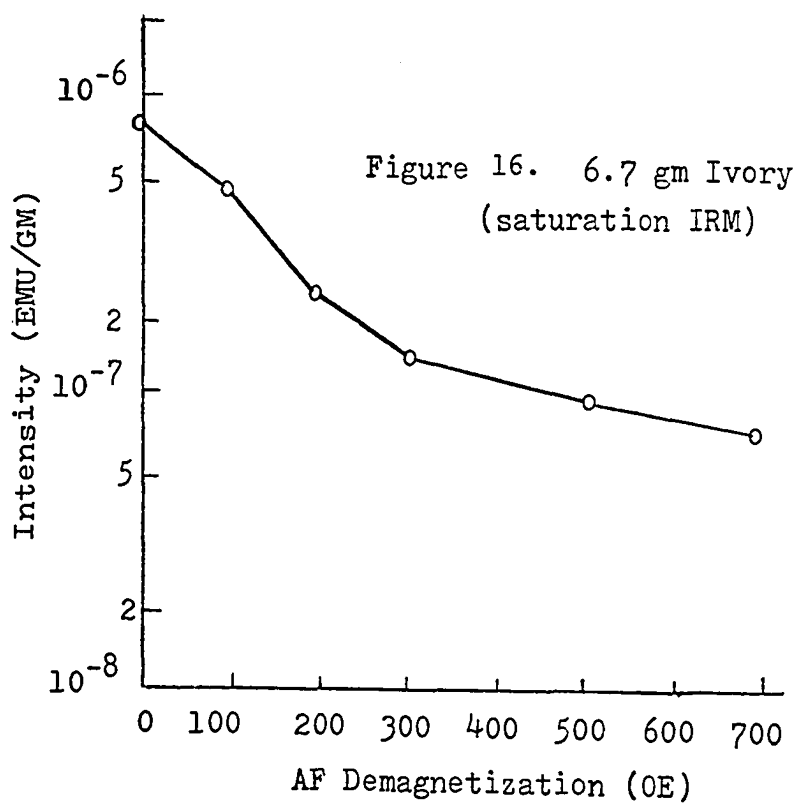

Figure 16. 6.7 gm Ivory Coast.
(saturation IRM)

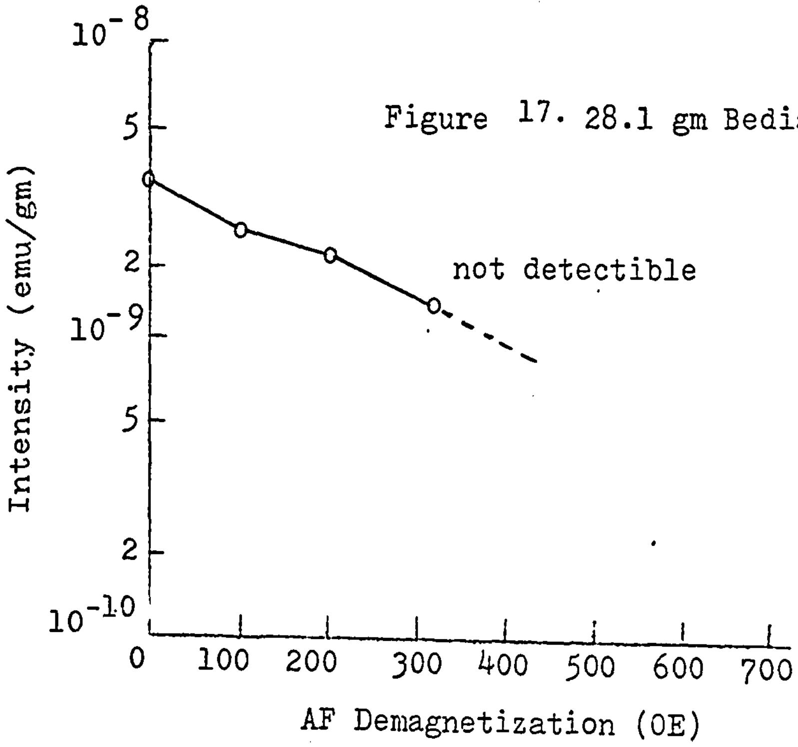

Figure 17. 28.1 gm Bediasite.

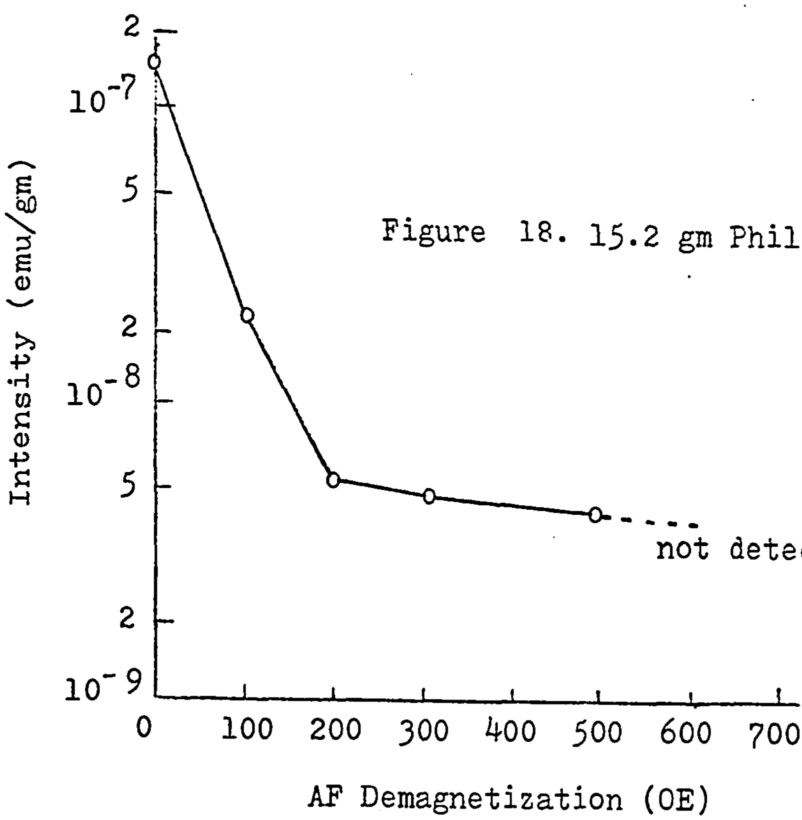

Figure 18. 15.2 gm Philippinite.

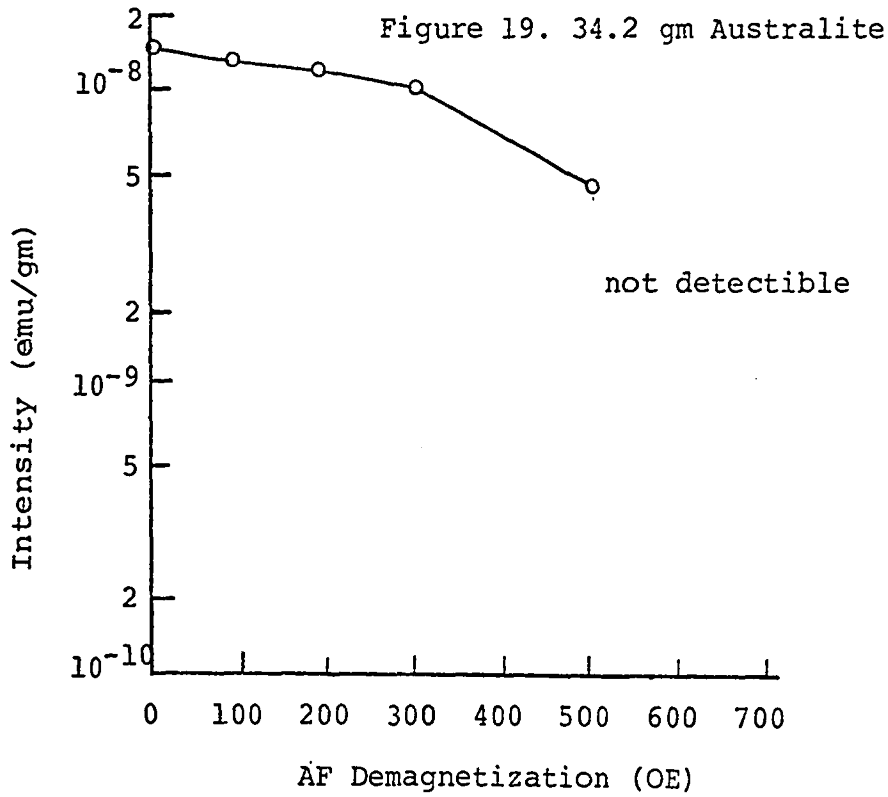

Figure 19. 34.2 gm Australite
not detectible
Intensity (emu/gm)
2
10^{-8}
5
2
10^{-9}
5
2
10^{-10}
0
100
200
300
400
500
600
700
AF Demagnetization (OE)

had it been the NRM which was demagnetized.

The philippinite (Fig. 18) consists of a low coercivity component which is removed in an alternating field of about 200 OE. After this, the slope of the curve is somewhat comparable to other tektites. This behavior appears to be typical of tektites from certain areas of the Philippines and is unique since it was not observed in tektites from other strewn fields, even from other areas of the Philippines as well. This was further investigated and will be later discussed.

Australites as well as other tektites from the australasian area were also demagnetized and their curves are comparable to the bediasites. It should be mentioned that the majority of the samples were either initially unmeasurable, or not detectible after some demagnetization. It appears as though at least another order of magnitude in sensitivity from the 3.8 cm magnetometer would be necessary to obtain sufficient measurements.

Estimation of Magnetic Carrier Sizes

In comparison with the Wabar impactite and many lunar samples, tektites show practically no viscosity. If a superparamagnetic contribution is present, it is an extremely minor one as it has little, if any, effect on the slope of the demagnetization curves.

Lowrie and Fuller (1971) developed a test to distinguish multidomain and single-domain carriers of remanence. The test makes use of the distinctive AF demagnetization characteristics between the two and involves comparing the NRM with saturation IRM. The saturation IRM is used as an equivalent of strong-field TRM because their stability characteristics are identical, and using IRM avoids the necessity of heating the sample. The characteristics of single-domain and multidomain demagnetization then give the following two possibilities:

(1) For single-domain carriers, the saturation IRM is relatively less stable than the weak-field TRM.

(2) For multidomain carriers, the saturation IRM is relatively more stable than the weak-field TRM.

In the case of tektites, the weak-field TRM is the same as the NRM. Figure 9 shows the typical demagnetization characteristics between tektite NRM and saturation IRM. No measurable exceptions to this were found during the course of this research. Comparison of the curves suggests that the dominant magnetic carriers are mostly single-domain, or lie somewhere between the single and multidomain state. Curves similar to Figure 9 were also observed in studies on the Muong Nong tektites (deGasparis, personal communication).

Impactite Demagnetization Curves

Demagnetization of impactites reveals a wider range of behavior than with the tektites. Some curves were relatively soft while others were relatively hard. The physical appearance of the glasses, specifically their oxidized nature or the lack of it, had little in common with the demagnetization curves. Sufficient data on Libyan Desert glass and the power line fusion could not be obtained, and thus it wasn't possible to determine how their NRM demagnetization curves would compare with the other impactites. These samples were saturated however, by exposure to a 4,000 OE field, and then demagnetized. Both had curves parallel to the obtained NRM demagnetization portions.

Three curves for the Ries impactite are shown. By cutting samples from different parts of the unhomogeneous crater glass the demagnetization curves would vary. Curve A shows a similarity to the moldavites, or rather that portion of the curve which was demagnetized out to about 300 OE. Both the Ries impactite and moldavites were exceptionally hard, more so than with other tektites and impactites.

The Bosumtwi impactite was harder than the Ivory Coast tektite, but this was not surprising since it wasn't the NRM which was demagnetized on the Ivory Coast sample. If a large enough tektite from this area is found, it could yield a moment detectible on a cryogenic magnetometer. Demagnetization of this could then be compared with the impactite. In general however, there appears to be a similarity between the two curves.

Actually, the Bosumtwi impactite in Figure 25 is not the one shown in Plate 14 . This one resembled a vesicular quartzite and was from a different part of the crater rim than was the suevite-type. Demagnetization of the suevite-type (Fig. 28) revealed an erratic behavior which resembled an ARM. Like the Ries impactite, the demagnetization curves changed when different sections of the material were tested.

The demagnetization curve of Darwin glass behaved in somewhat of an unusual manner in that it began with a hard component, which was followed by a softer one. Only one sample was available and it couldn't be determined if this was typical of these glasses from Tasmania.

Demagnetization curves by themselves cannot establish a definite relationship between or among specimens. As an example, the Henbury curve (Fig. 24) is very similar to the tektites, but this is about all that they have in common. However, particular demagnetization curves of the Ries and Bosumtwi impactites do show a similarity to their nearby respective tektites, and this information can be added to the evidence for a genetic relationship.

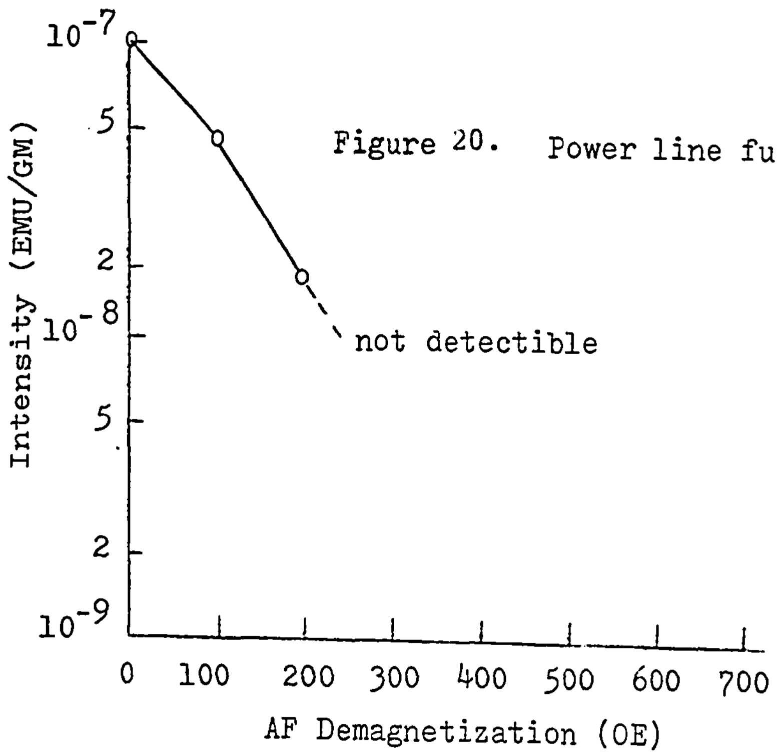

Figure 20. Power line fusion.

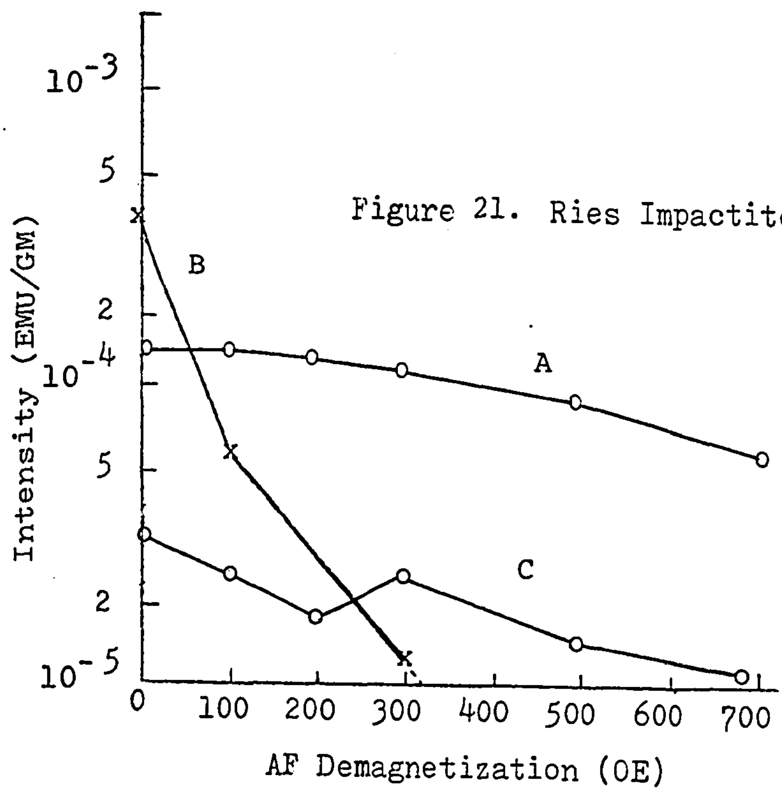

Figure 21. Ries Impactite.

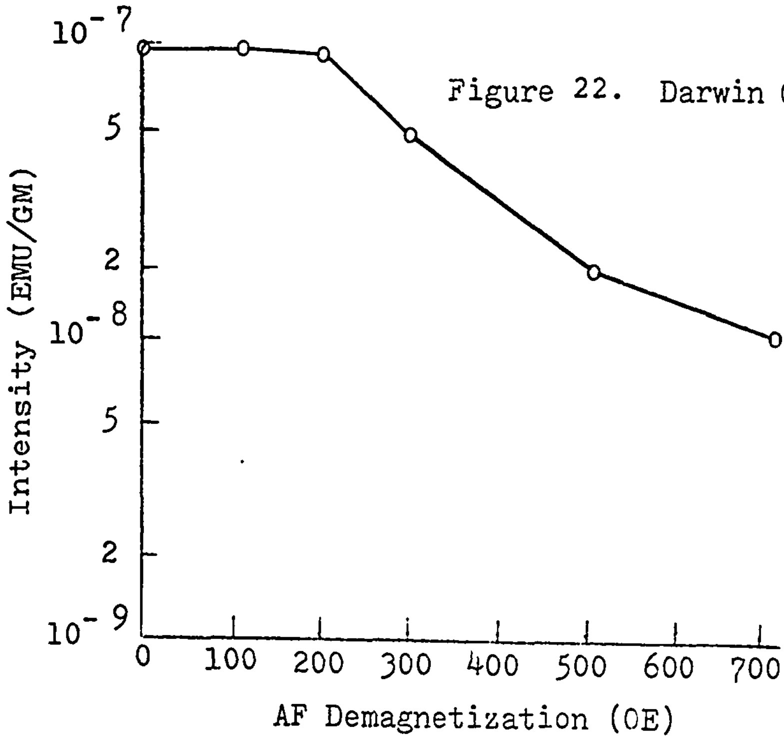

Figure 22. Darwin Glass.

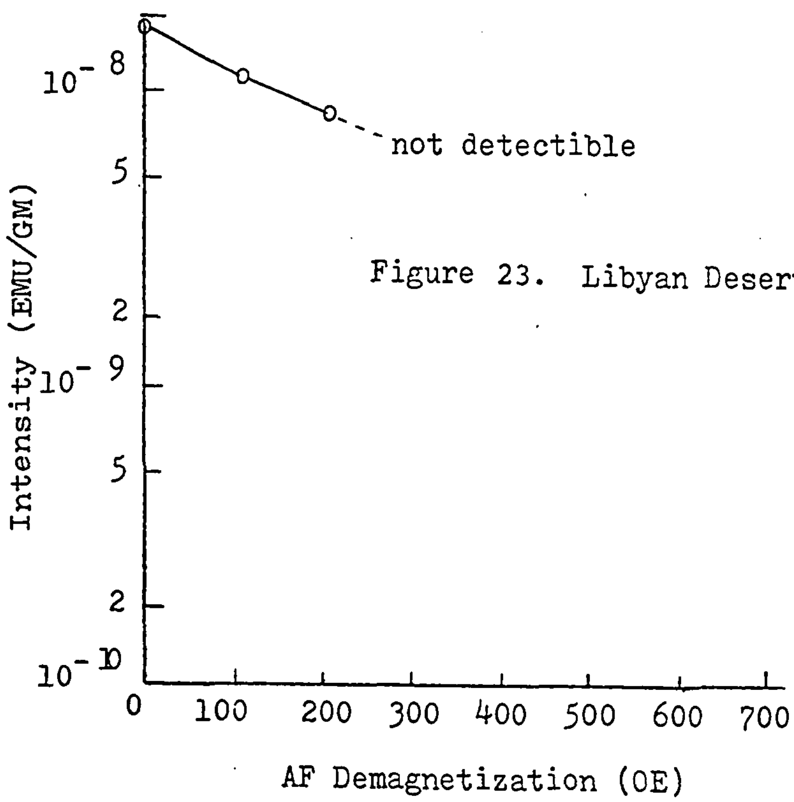

Figure 23. Libyan Desert Glass.

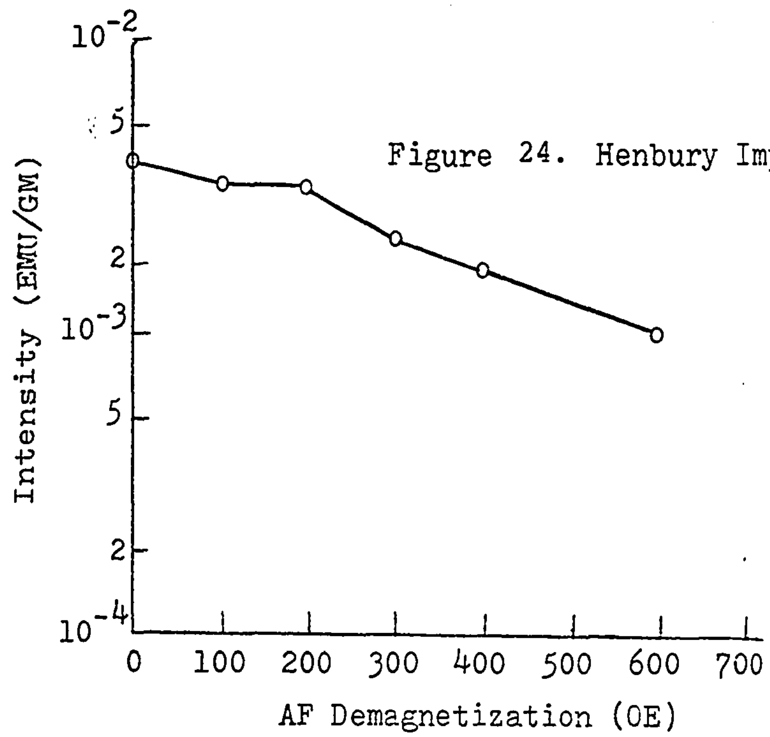

Figure 24. Henbury Impactite.

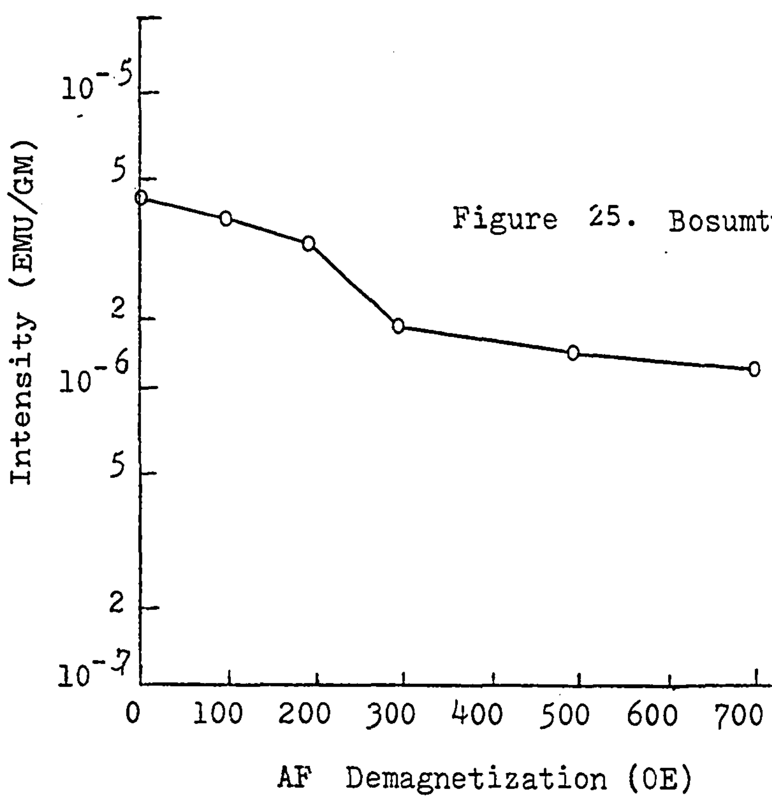

Figure 25. Bosumtwi Impactite.

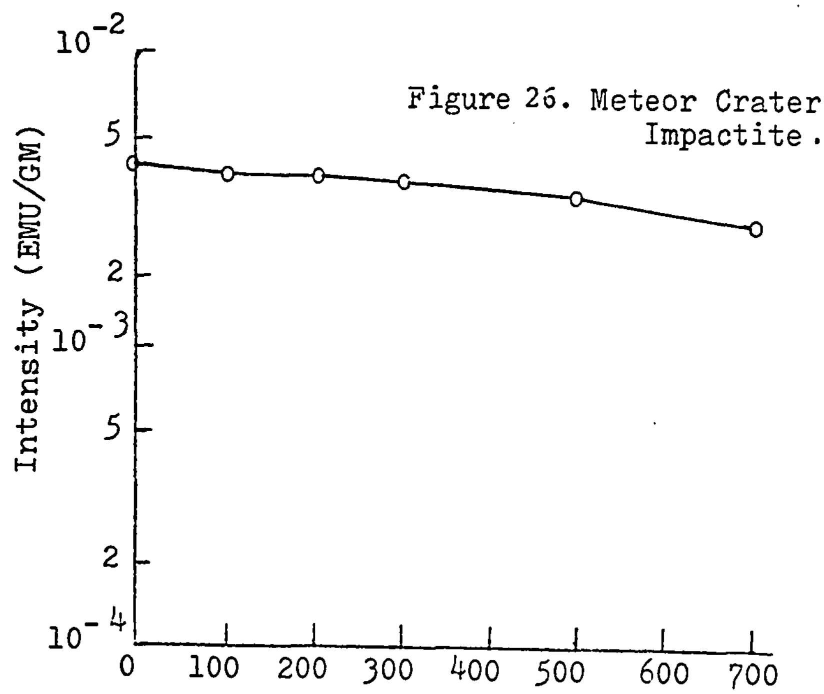

Figure 26. Meteor Crater Impactite.

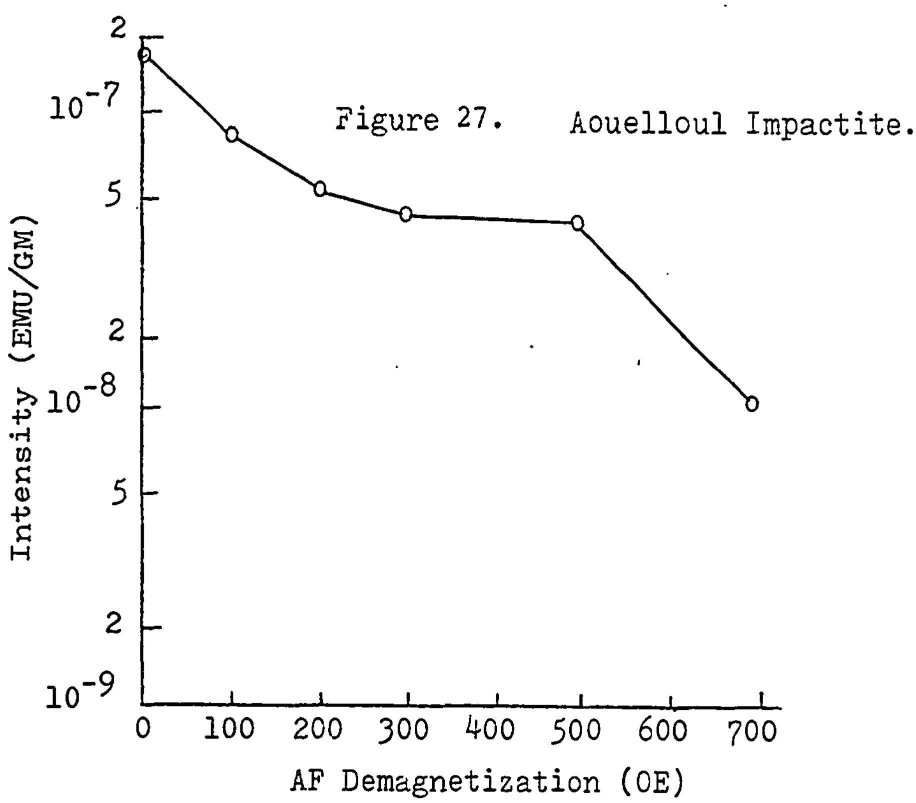

Figure 27. Aouelloul Impactite.

Figure 28. Bosumtwi Impactite (suevite-type)

SATURATION STUDIES

Tektites from the four strewn fields as well as the impactites were given a saturation IRM to determine if there was any way of comparing the curves. When possible, several samples from each group were tested. The main device used for saturation was the magnet system on the vibrating sample magnetometer. A smaller set of magnets was also employed at other laboratories.

The theory of domain wall movement is given in Irving (1964). In brief, the procedure used for the tektites and impactites was to first measure the sample on a magnetometer, then place the sample between two electromagnets. A field is then applied across the magnets of some particular strength. After each increase in field magnitude, the samples are then remeasured. This procedure continues until the readings stablize. The ferromagnetic particles in the sample are reacting to the magnetic field and adjust their domains accordingly. As the field is increased, the domains will reach a point at which no additional "rotation" is possible. When this occurs, the domains have aligned themselves along the longitudinal axis of the applied field and the sample is said to be "saturated". Figure 29 illustrates domain movement in the presence of an applied magnetic field.

Both spinner and cryogenic units were used for measurements. This was necessary because the moment of some of the samples was too intense for the superconducting magnetometer to measure.

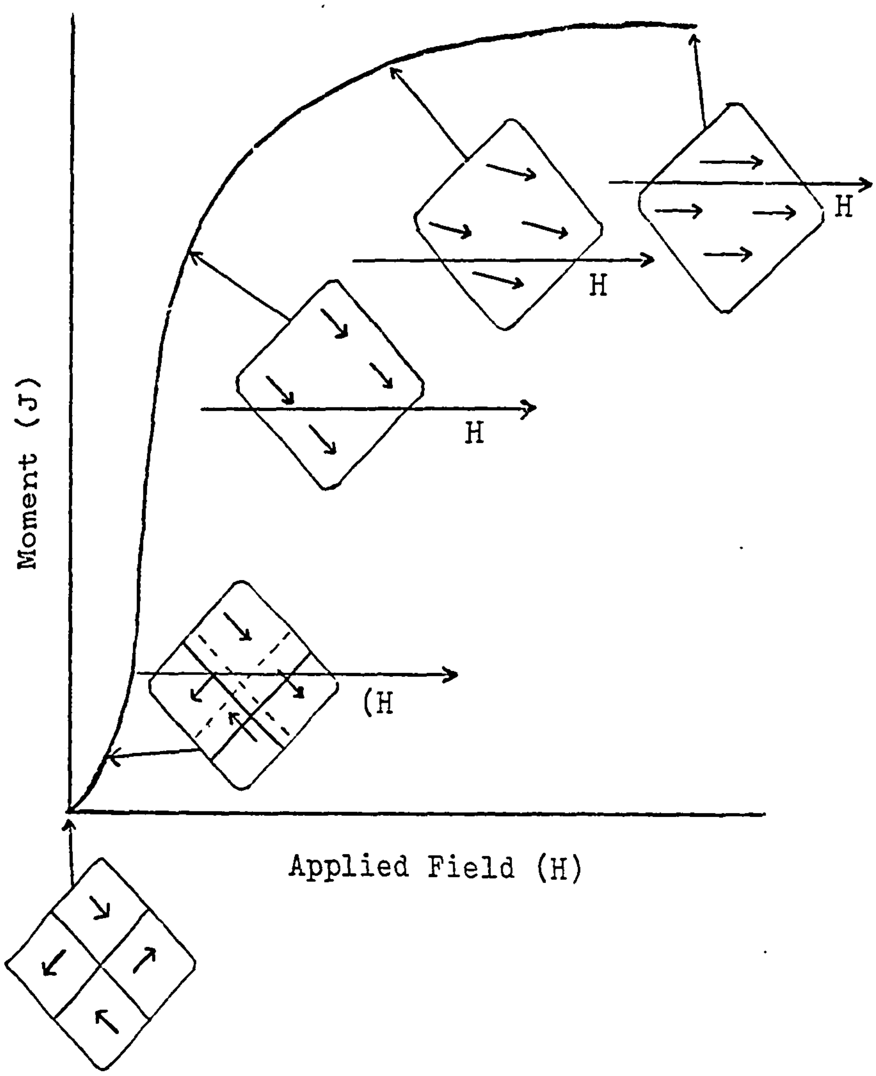

Figure 29. Magnetization process according to domain theory. (modified from Irving, 1964)

Calibration among the cryogenic units was essentially identical whereas the spinner recorded about a 10 percent lower moment. This is considered insignificant since changes in orders of magnitude were dominant.

Figures 30 to 34 show the saturation curves and values of tektites from each of the four strewn fields. It will be noted that, excepting the bediasites, tektite saturation IRM is about two orders of magnitude greater than their NRM. Saturation occurs within an applied field strength of between 1,000 and 2,000 OE. The only exception to this were the moldavites which continued to demonstrate a slight gain in intensity out to 4,000 OE. Additional moldavites were tested, with two showing a similar behavior while the others became saturated at around 2,000 OE. It was noted during the investigation, that several tektites remained below the noise level of the magnetometer even when a field up to 10,000 OE was applied. This suggests that the iron content is totally ionic, implying extremely high temperatures and abrupt cooling conditions.

With the Ivory Coast tektite (Fig. 31) the NRM could not be measured and hence the intercept is shown coming from somewhere at or below 10^{-8}. Judging from the general two order of magnitude increase in intensity with saturation, the NRM of this sample is probably not much lower than the noise level.

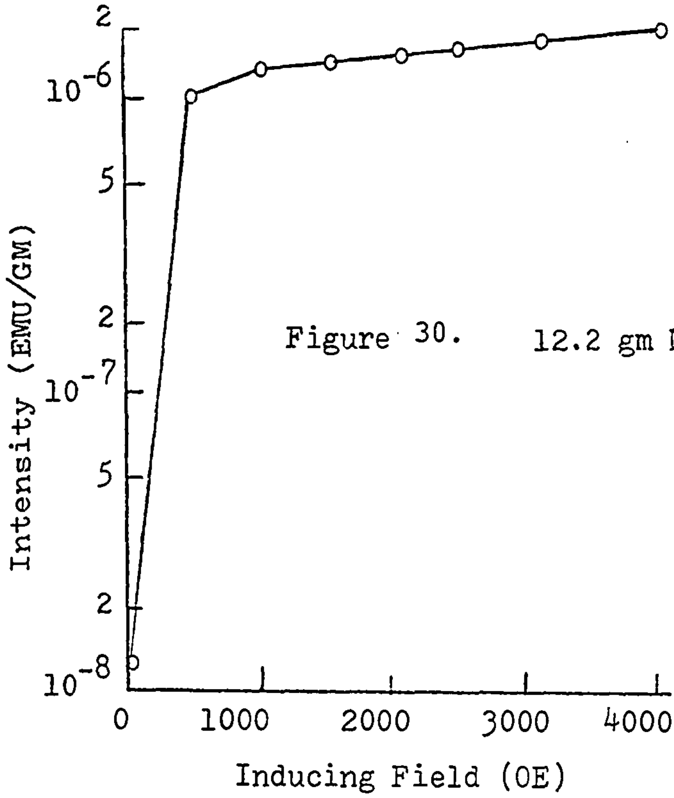

Figure 30. 12.2 gm Moldavite.

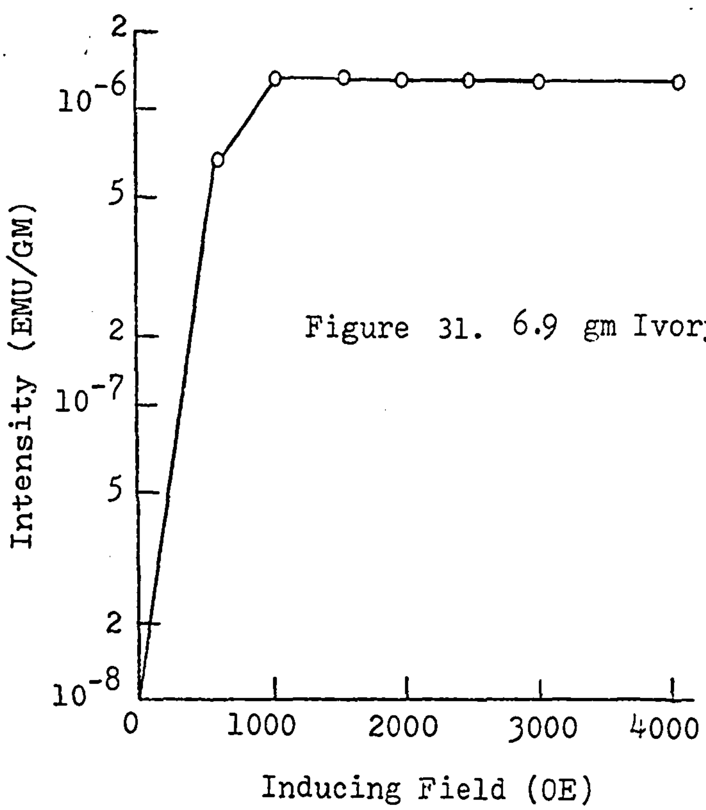

Figure 31. 6.9 gm Ivory Coast.

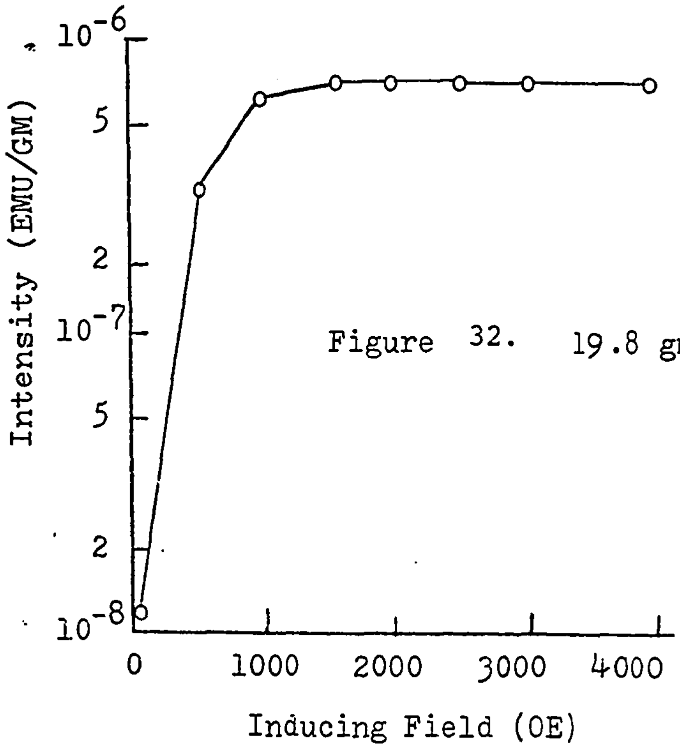

Figure 32. 19.8 gm Australite.

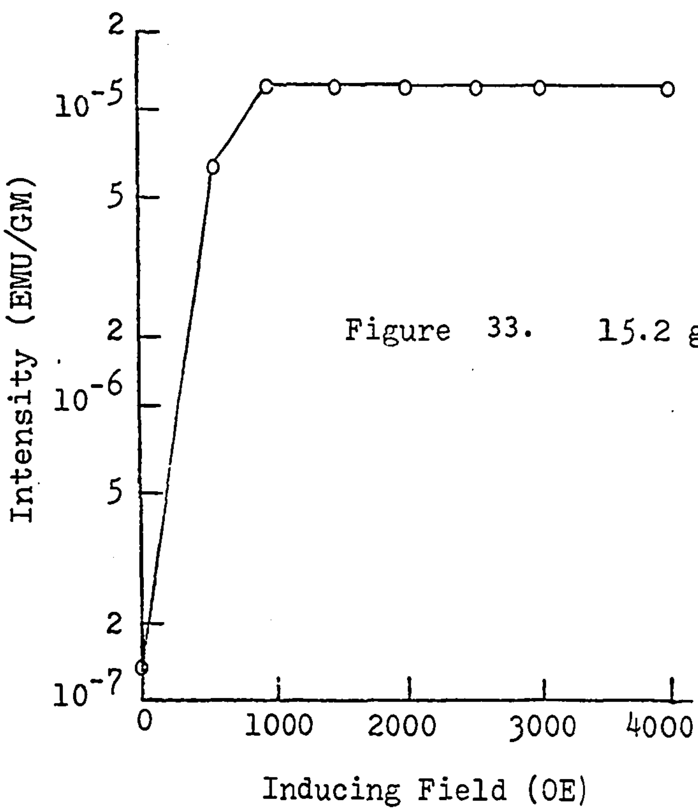

Figure 33. 15.2 gm Philippinite.

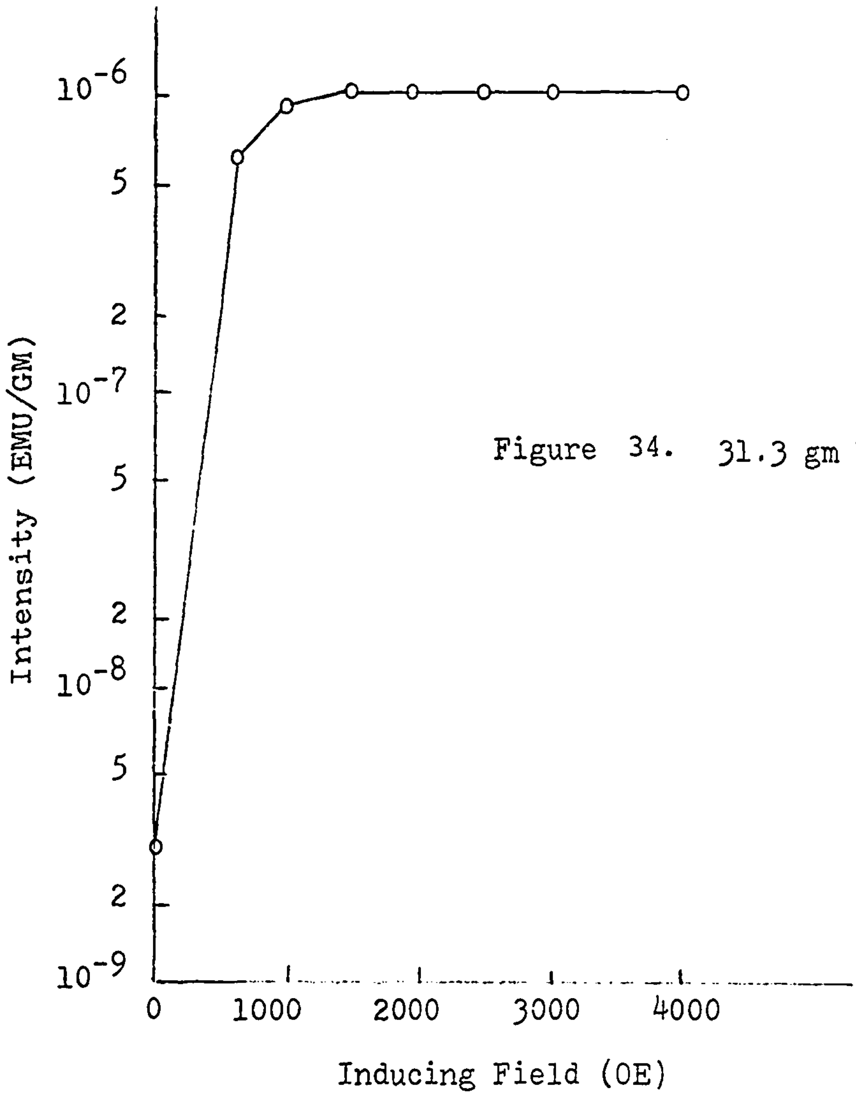

Figure 34. 31.3 gm Bediasite.

Impactites

The impactites display a wider range of behavior than do the tektites. If the second derivative is considered (curvature) the differences are also apparent.

Some similarity between the Ries and Bosumtwi impactites along with their possible "associated" tektites appears to be evident. In the case of the Ries impactite, two out of four samples showed a saturation curve like that illustrated (Fig. 36). The other two became saturated between 2,000 and 3,000 OE.

The Bosumtwi impactite also shows a saturation curve similar to the Ivory Coast tektites. This was the glassy material and not the suevite-type; the latter had a saturation curve similar to the Henbury impactite. However, the curve could be made to vary when saturation tests were performed on different sections of the same sample. Actually, with the curve in Figure 38, the intercept does not represent the NRM. Only one sample of this type was available and it had been demagnetized (Fig. 25). However, even considering plotting the NRM at slightly below 5.0 X 10^{-6}, the curvature would not be affected that drastically.

Again, demagnetization curves as well as saturation curves by themselves cannot establish a definite relationship between tektites and possible source material. Some similar magnetic properties do tend to emerge relative to tektites themselves and also with tektites and certain impactites.

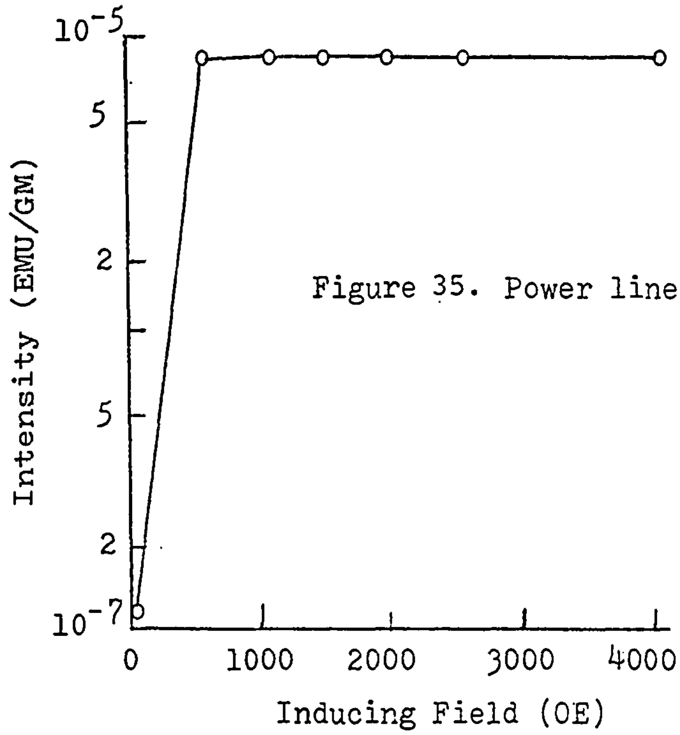

Figure 35. Power line fusion.

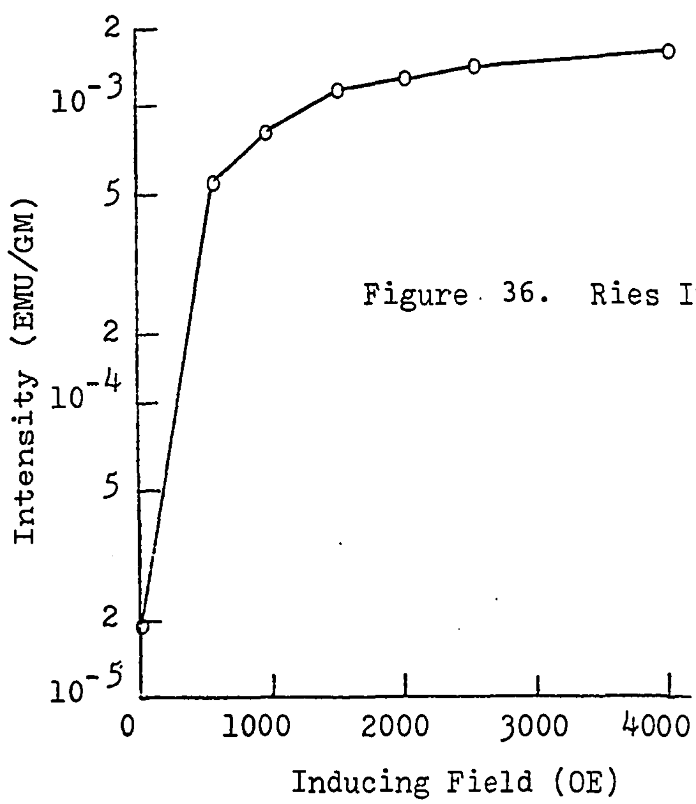

Figure 36. Ries Impactite.

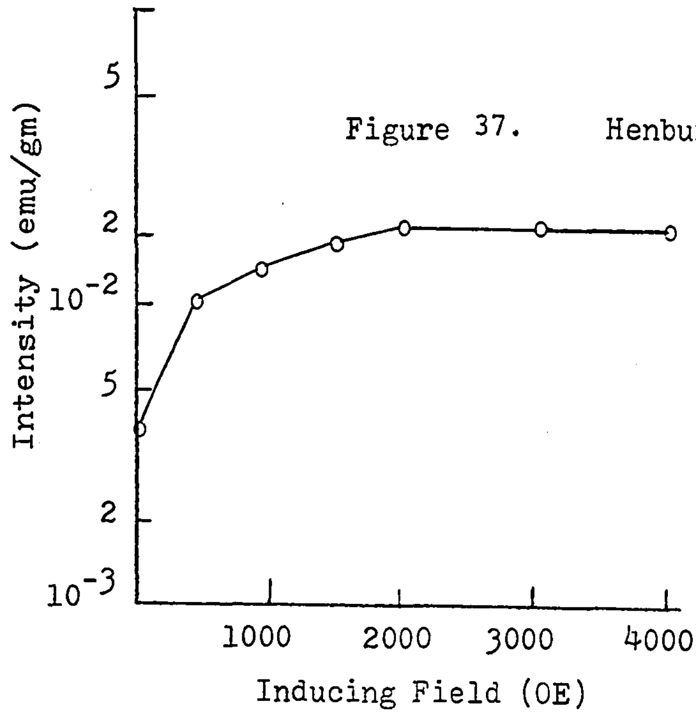

Figure 37. Henbury Impactite.

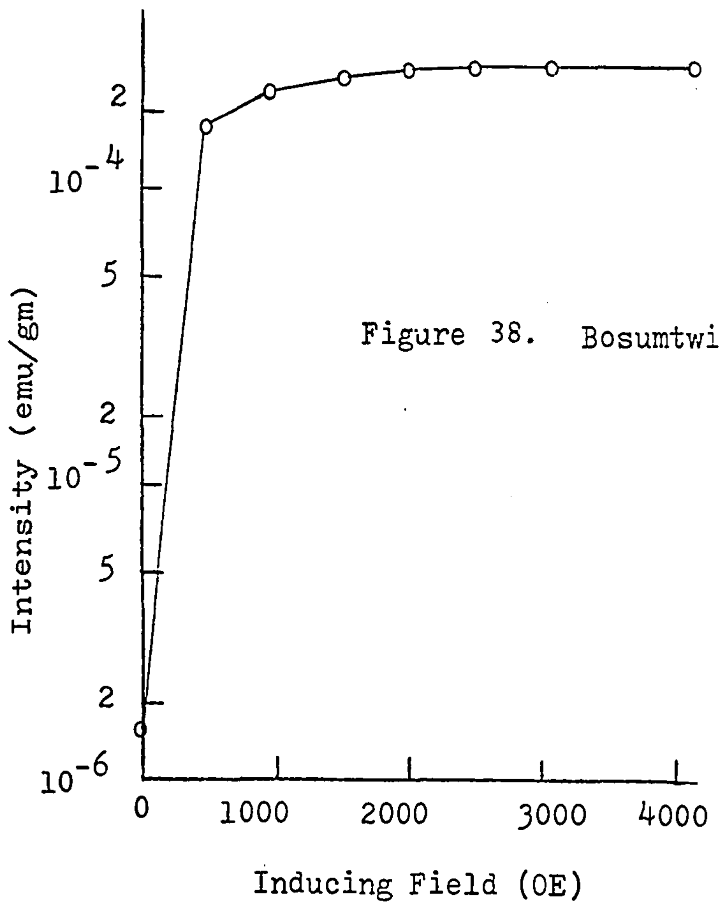

Figure 38. Bosumtwi Impactite.

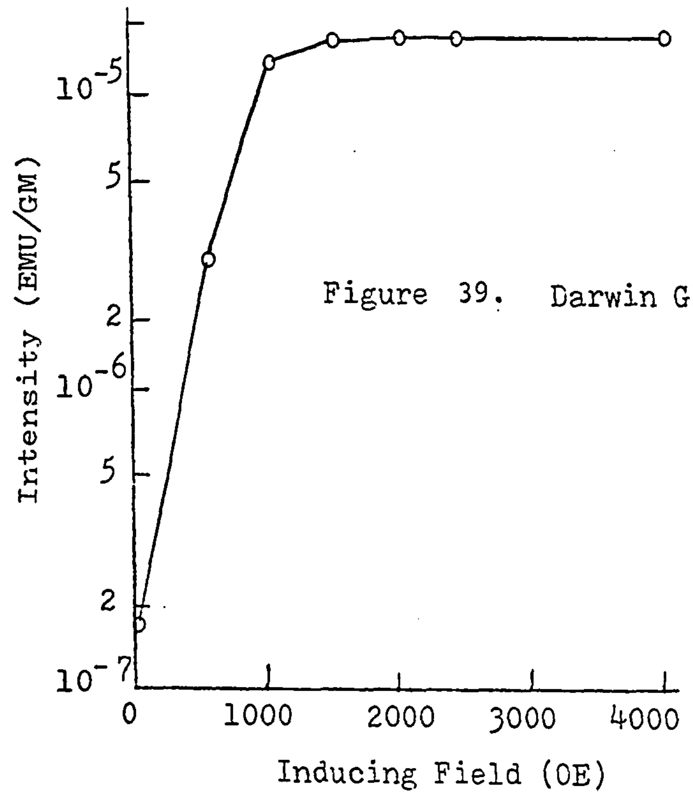

Figure 39. Darwin Glass.

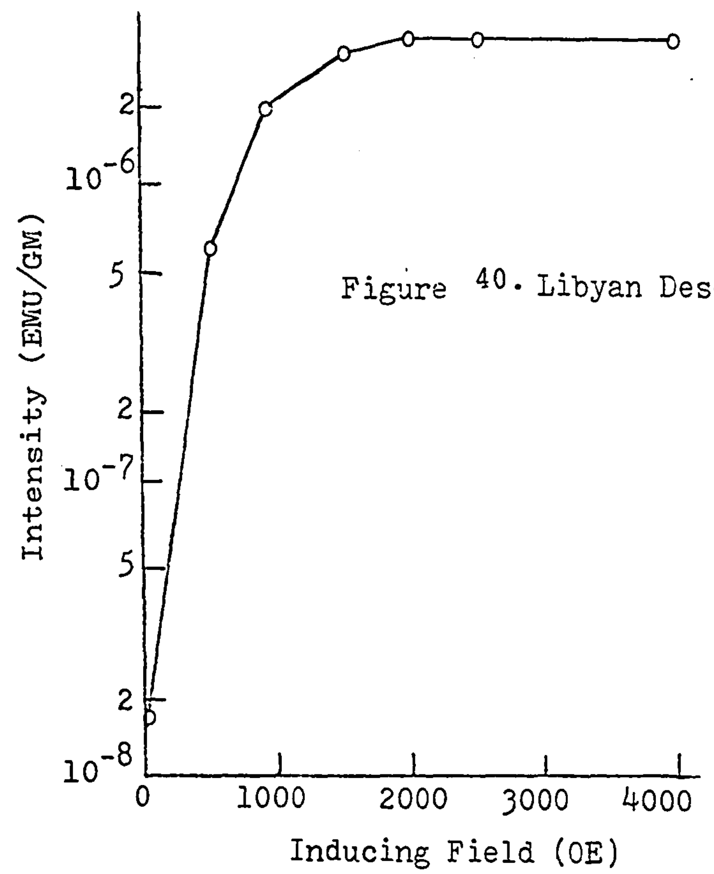

Figure 40. Libyan Desert Glass.

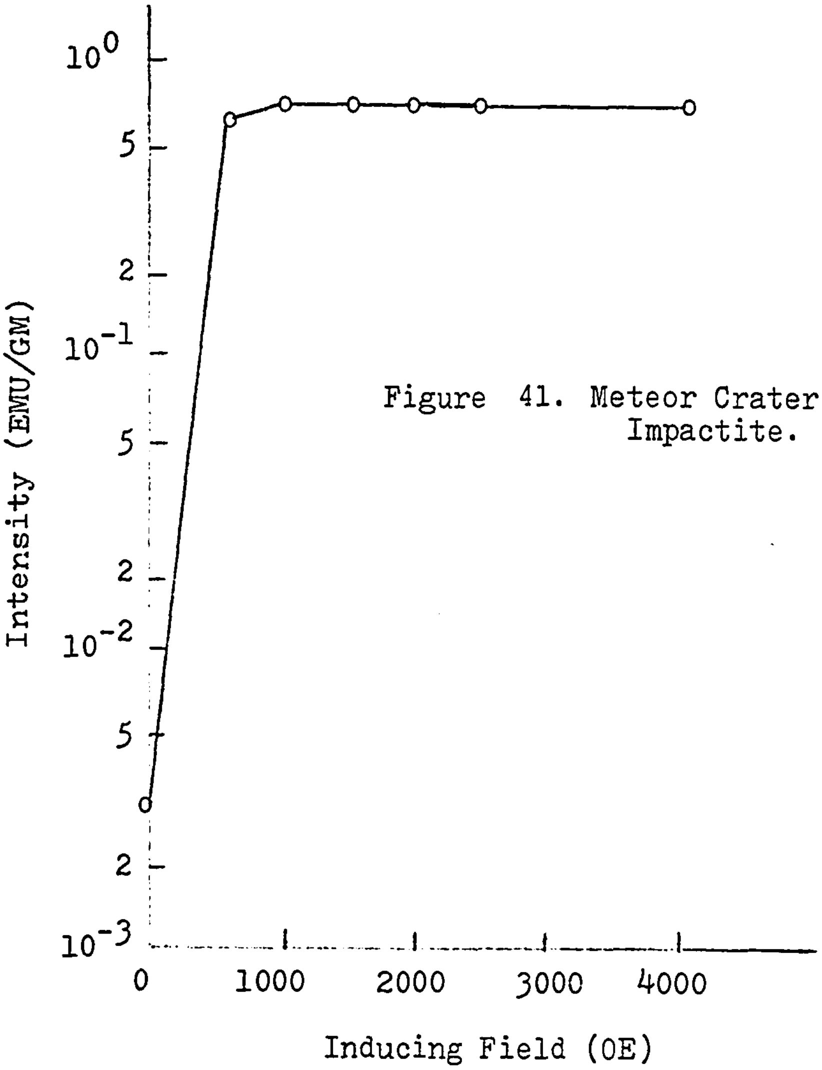

Figure 41. Meteor Crater Impactite.

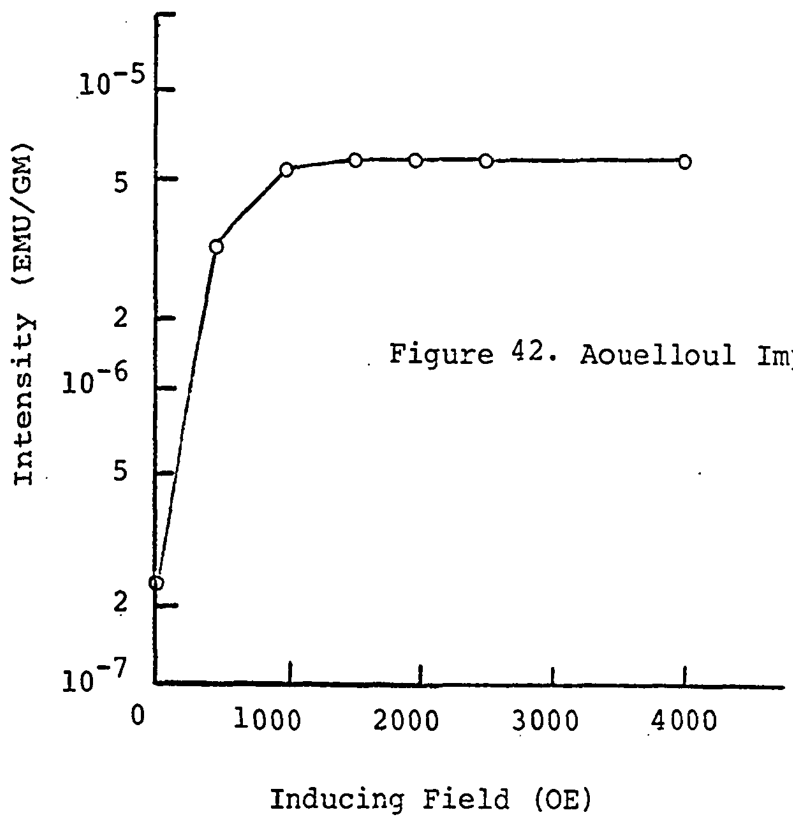

Figure 42. Aouelloul Impactite

Implications of Saturation Studies

A significant factor relative to the tektites is that of the differences in magnitude between the NRM's and the saturation IRM's. Since the NRM has been invariably established as that arising from a TRM, the saturation values suggest something about the paleointensity of the inducing field.

According to Fuller (1974; personal communication), the TRM of rocks acquired in a field of a few tenths of an oersted is approximately 2 orders of magnitude smaller than the saturation IRM of the same material; the earth's present field strength is approximately 0.45 OE. This should not be taken as indication of a terrestrial origin any more than considering the low NRM of tektites as indicative of an extra-terrestrial one. Rather, it is another factor to consider and add to the coming paleointensity data.

As previously mentioned and shown in Plates 8 - 12, the majority of tektites have experienced aerodymanic sculpturing. If tektites are extra-terrestrial, the thermal conditions during atmospheric entry may have erased the original NRM. The saturation data then could only be reflecting the earth's magnetic field strength acquired during elevated temperatures to the Curie point of the magnetic carriers during ablation.

It will be demonstrated shortly that there is a way to circumvent the potential problem due to secondary heating during atmospheric transit.

CARRIER CHANGES IN OXIDIZING AND NON OXIDIZING ENVIRONMENTS

The stability of the magnetic carriers to thermal energy was determined by changes in the intensity measurements before and after heating. This phase of the study was essential both for learning about the carrier reactions as well as determining the potential of various heating and non-heating methods for the paleointensity analysis.

Six tektites were selected for testing. The four strewn fields were represented as well as other major parts of the australasian area. These samples were given a saturation IRM to 9,000 OE, measured, then sealed in a vacuum bomb and placed in an oven with an ambient magnetic field intensity of zero. The equipment can be seen in Plate 5. The vacuum bomb pump ran continually during heating to 700°C and return to room temperature. Sustained vacuum level was approximately 0.001 atmospheres. Following the cool-down period, the tektites were removed, given another saturation IRM and remeasured.

The same procedure was repeated once again only this time the heating was conducted under normal atmospheric conditions. Results are shown in Table 7. Two of the tektites had been put through a demagnetization process and are shown in Figures 43 and 44.

It will be noted that when heating was conducted under normal atmospheric conditions, that the magnetic intensity was greater before heating than after. This was reversed when heating was conducted in a vacuum. This means that the ability of the magnetic carriers to retain magnetization is affected because of changes in their physical and/or chemical properties after heating in air or in a vacuum. Stated another way, the magnetic carriers are being partially destroyed by oxidation in air but are coalescing in the vacuum. The results are similar to those obtained by deGasparis _et al_. (1975) on the Muong Nong tektites.

This heating procedure was also conducted on the impact glasses and power line fusion (Table 8). It will be noted that in contrast to the tektites, some of these glasses behave in an opposite manner. An impactite from Meteor Crater (not shown in Table) was later tested and found to behave like the Henbury impactite and power line fusion. Had additional impact glasses been examined, the results would undoubtedly have been more random, owing to the nature of the source material.

Of particular interest are the Ries, Bosumptwi and Darwin Glass specimens. These three impactites are usually related to tektites on the basis of age (Gentner _et al_., 1969; Fleischer _et al_., 1965). In other words, they have the same K/Ar and fission track ages as the moldavites, Ivory Coast and australasian tektites respectively. The similarity in magnetic carrier

SAMPLE		INTENSITY ($X\ 10^{-6}$ EMU/GM)		
		Before Heating	After Heating (vacuum)	After Heating (air)
Moldavite	16.8 gm	0.8	1.8	not detectible
Australite	19.1 gm	6.0	9.0	4.5
Philippinite	15.3 gm	1.4	2.1	1.0
Indochinite	24.6 gm	12.5	16.0	7.5
Bediasite	18.4 gm	3.8	5.1	3.0
Ivory Coast	6.9 gm	2.7	7.5	not detectible

Table 7. Saturation moment changes after heating for tektites.

SAMPLE		INTENSITY (X 10^{-6} EMU/GM) Before Heating	After Heating (vacuum)	After Heating (air)
Libyan Desert Glass	8.6 gm	14.1	17.5	8.0
Aouelloul	9.5 gm	10.2	82.4	45.1
Ries	6.8 gm	760.0	1010.0	680.0
Bosumtwi	7.3 gm	1600.0	2300.0	1800.0
Henbury	6.0 gm	7300.0	5600.0	13000.0
Darwin Glass	1.2 gm	20.0	40.0	not detectible
Wabar	3.1 gm	Variable		
Power Line Fusion	7.0 gm	60.8	55.1	100.0

Table 8. Saturation moment changes after heating for impactites and power line fusion.

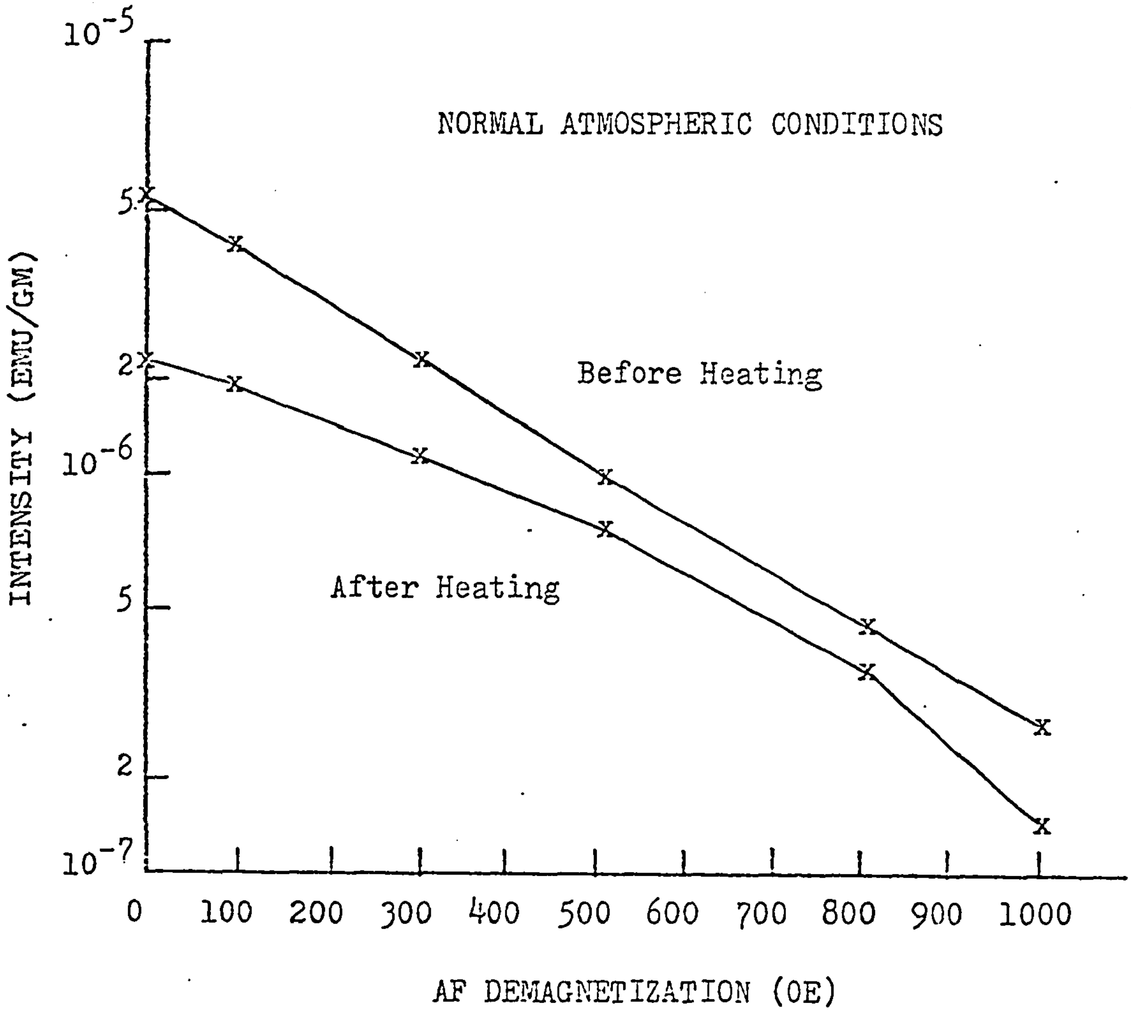

Figure 43. 24.1 gm philippinite (Saturation IRM)

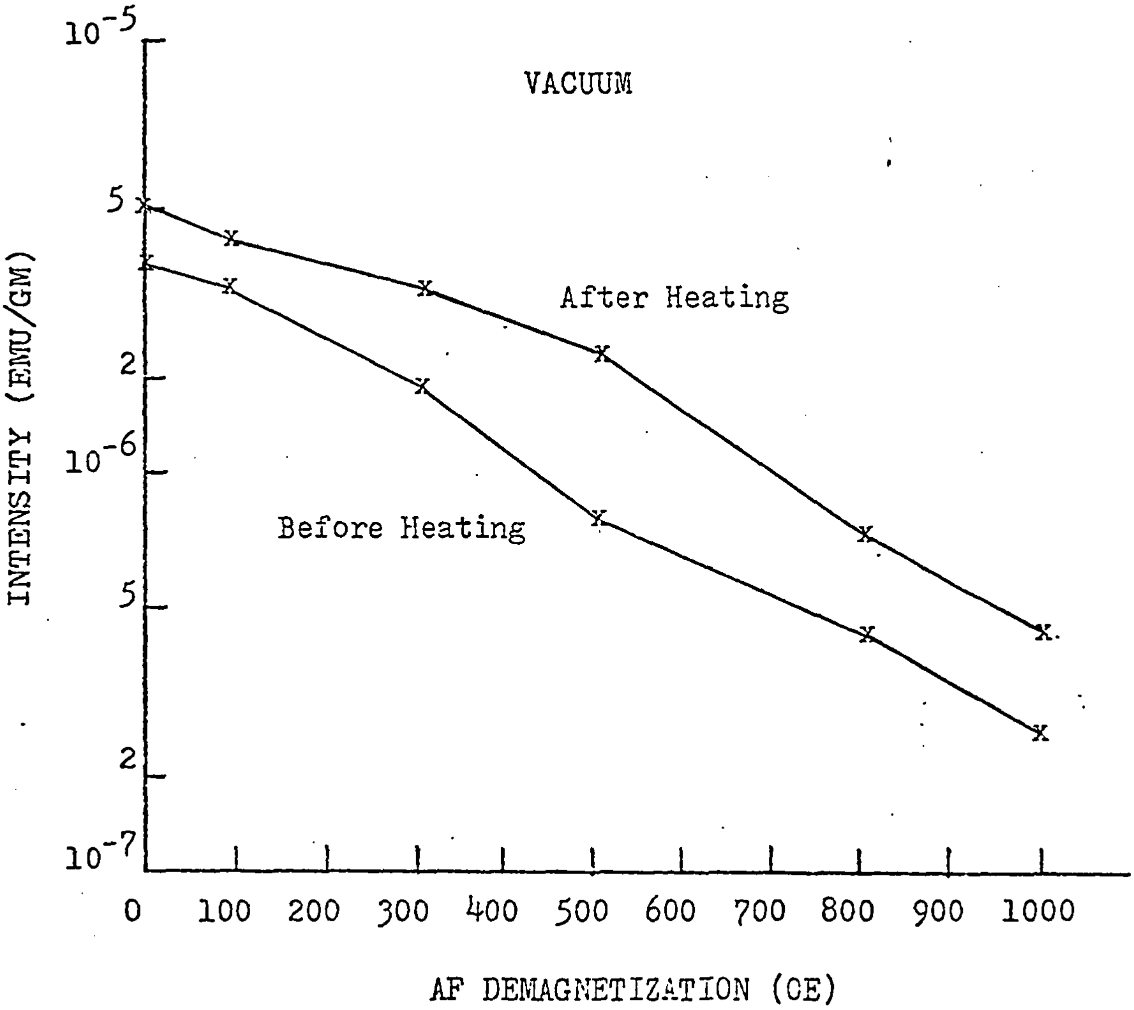

Figure 44. 28.1 gm bediasite (Saturation IRM)

behavior also suggests a possible relationship, even though the physical and chemical differences between impactites and tektites is substantial.

More than possessing a genetic relationship to tektites, Libyan Desert Glass is actually considered to be one (Barnes, personal communication). Like other tektites and the particular impactites just mentioned, the behavior of its magnetic carriers is the same. Thus, this magnetic property, while showing no uniform behavior among all impactites or other igneous materials on the earth's surface, does display a similar behavior among tektites and their genetically related counterparts.

THERMAL DEMAGNETIZATION AND SEM STUDIES

After IRM saturation to 9,000 OE, selected tektites from the four strewn fields were subjected to thermal demagnetization. Heating was conducted in air in zero field. Due to the availability of equipment in conjunction with the oven, an astatic and spinner magnetometer were utilized. These units are not as sensitive as the cryogenic devices and hence this was the reason for boosting the tektite intensity with a saturation IRM. This procedure does not affect the Curie point of the magnetic carriers.

The samples were heated in steps of 300°, 500°, 550° and 600°C. After each temperature elevation, the tektites were cooled to room temperature and then remeasured. Strict zero field control was maintained during all heating and cooling to preclude giving the tektites an unwarranted TRM.

After heating to 600°C no detectible magnetism was evident in any of the samples. The typical thermal demagnetization curve is shown in Figure 45. It will be noted that the blocking temperature (the region where the slope is the steepest) lies between 550° and 600°C. Between these temperatures the magnetization is being affected the most rapidly. In this particular case, since heating is being conducted in zero field, the greatest loss in moment occurs in this region. Therefore, a tektite cooling down from its high fusion temperature in an ambient magnetic field of

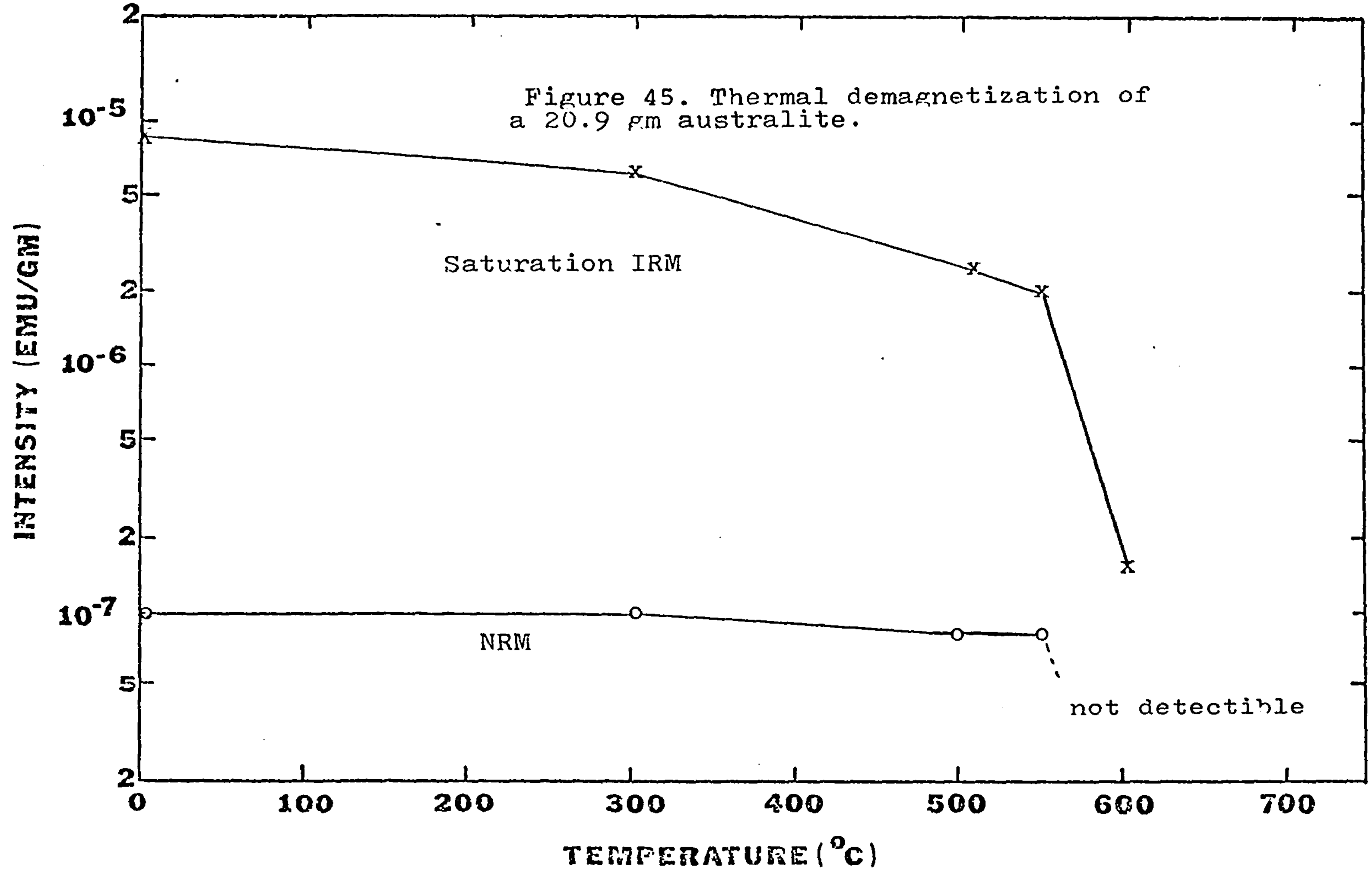

Figure 45. Thermal demagnetization of a 20.9 gm australite.

some intensity would acquire almost all of its magnetization through this narrow temperature range. As defined by Nagata (1961) the Curie point would be the theoretical upper limit of the blocking temperature. In the case of tektites, this is approximately 600°C.

This particular temperature is too low for hematite but is compatible with Curie points for magnetite (Irving, 1964) or a nickel-iron alloy (Hoselitz and Sucksmith, 1943). One is now left with attempting to distinguish between these two possibilities.

Kleinmann (1969) described black magnetic spherules 30 to 150 u in diameter, extracted from crushed indochinites, moldavites, and Ivory Coast tektites. On the average, each tektite contained 2 to 5 spherules, although one indochinite contained 50. The spherules were variable in number from tektite to tektite and seemed to be independent of strewn-field area. X-ray powder diffraction revealed that three kinds of spherules were evident, consisting of skeletons, intergrowths, and idiomorphic crystals of magnetite.

One of these magnetite spherules is shown in Plate 18. This sample was cut from a 25.5 gm indochinite. With the assistance of Dr. Yeming Wu, it was possible to isolate this spherule and study its magnetic properties on the 0.3 cm superconducting unit.

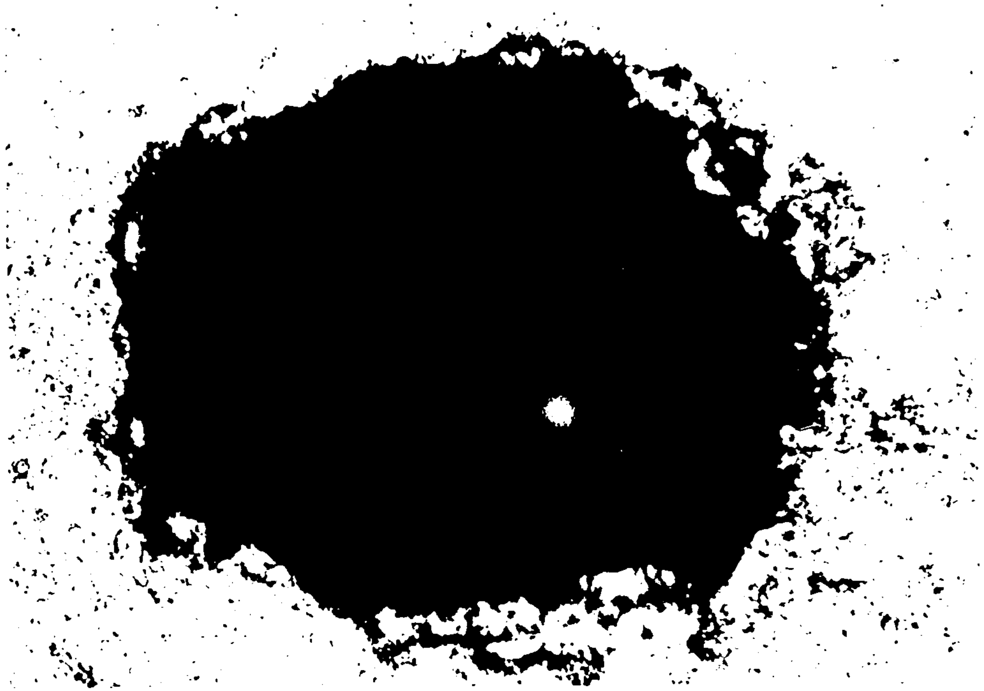

Plate 18. Nonmetallic spherule. Black filament structure is an optical effect. (particle diameter = approx. 140μ)

Clearly, this non-metallic particle is multidomain, but unlike the magnetic properties that distinguish this size range, the NRM is relatively stable, though slightly viscous (Fig. 46). It will also be noted in Plate 18 that no diffusion gradient is evident, nor should one be expected since the total iron content in tektites is below their saturation level. However, while there is no evidence to indicate that this spherule originated from within the tektite glass itself, the AF demagnetization curve on "clear tektite glass" (no spherules) suggests just this.

Generally, the stability of the spherule is comparable to tektite glass having no spherules (Fig. 47). Clear tektite glass in turn exhibits a demagnetization curve similar to previously shown demagnetization curves on "whole" tektites. The use of "whole" in this instance refers to tektites which have not been cut or examined for these particular spherules. This evidence suggests that the spherules are visual aggregrates of their sub-microscopic counterparts. Kleinmann (1969) discussed the probable origin of these by impact or by factors involving liquid immiscibility. Exactly what their origin is attributed to has been debated.

An attempt was made to detect the sub-microscopic carriers under a scanning electron microscope, but nothing was evident. deGasparis (personal communication) had previously used the million volt SEM instrument at the U.S. Steel Laboratories in an unsuccesful effort to detect the magnetic carriers in Muong Nong tektites.

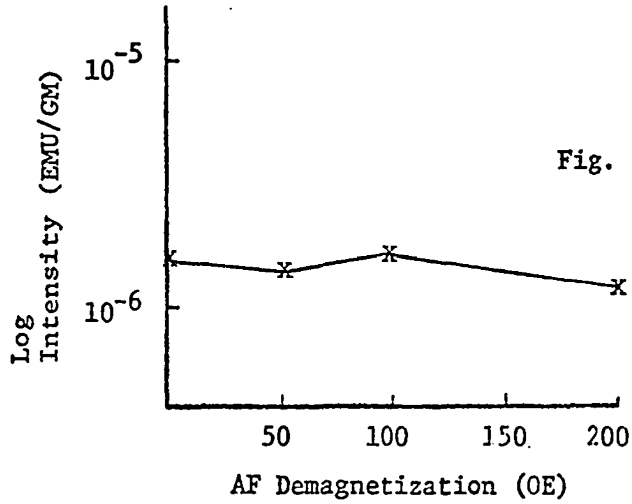

Fig. 46. Magnetite spherule (Wu, unpublished data)

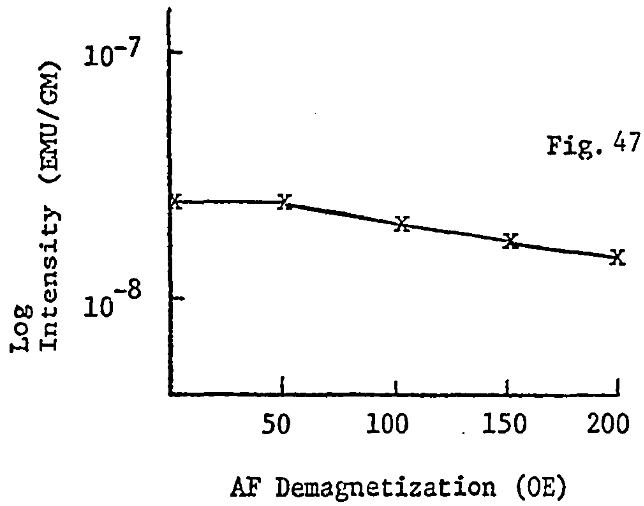

Fig. 47. Clear tektite glass

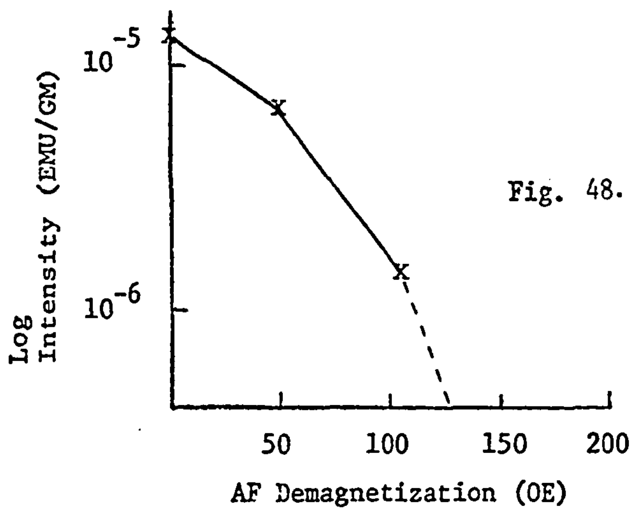

Fig. 48. Ni-Fe spherule

If these layered samples, with their crystalline inclusions and greater ferromagnetic content could not be detected then it is understandable why the other groups could not.

Plate 19 shows an SEM photomicrograph of another type of spherule. This one was found in a 9.8 gm specimen from Kubao in the Philippines. It had been cut and polished for microprobe analysis. It should be mentioned that all of the magnetic data was collected before the microprobe analysis to preclude the possibility of moment alterations.

Like the other spherule, this one is also multidomain, but consists of a virtually pure metallic iron phase, which the other lacked. The elemental-iron-wave-length-emission pattern can be seen in Plate 20. These particles are commonly referred to as "nickel-iron", even though in this particular case the composition was about 99.5% Fe and less than 0.2% Ni. Like the previously examined spherule, no diffussion gradient was evident. This can best be seen in examining Plate 20. This also could not have "condensed" from the glass for the same reasons given for the magnetite spherule.

The intensity of the metallic spherule was between 3 and 4 orders of magnitude higher than the surrounding glass, but its AF demagnetization curve (Fig. 48) was unlike that of clear tektite glass. As can be seen, most of the magnetization was lost in low AF. It can be expected that inclusions of this nature would

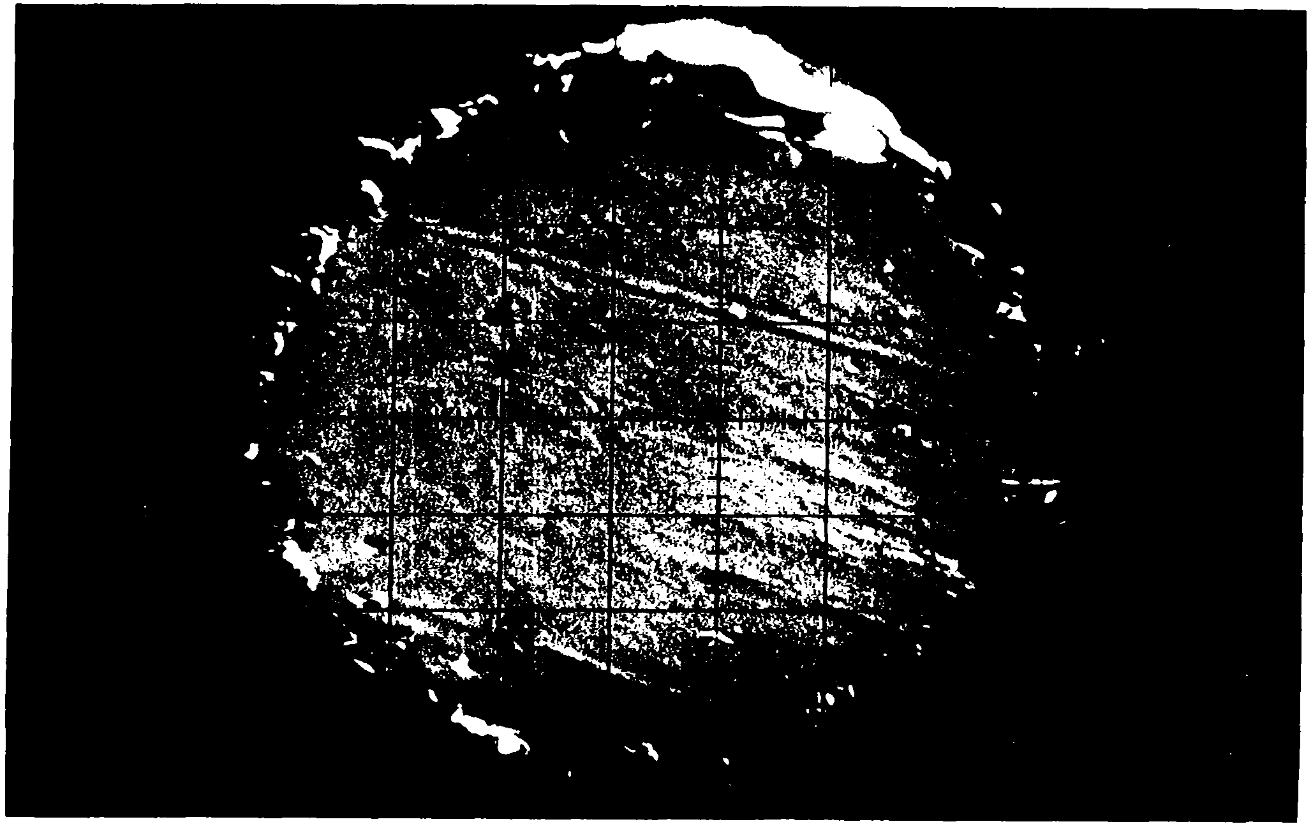

Plate 19. Scanning electron photomicrograph of metallic spherule. Each large scale division is 70 μ .

(Courtesy of E. Padovani)

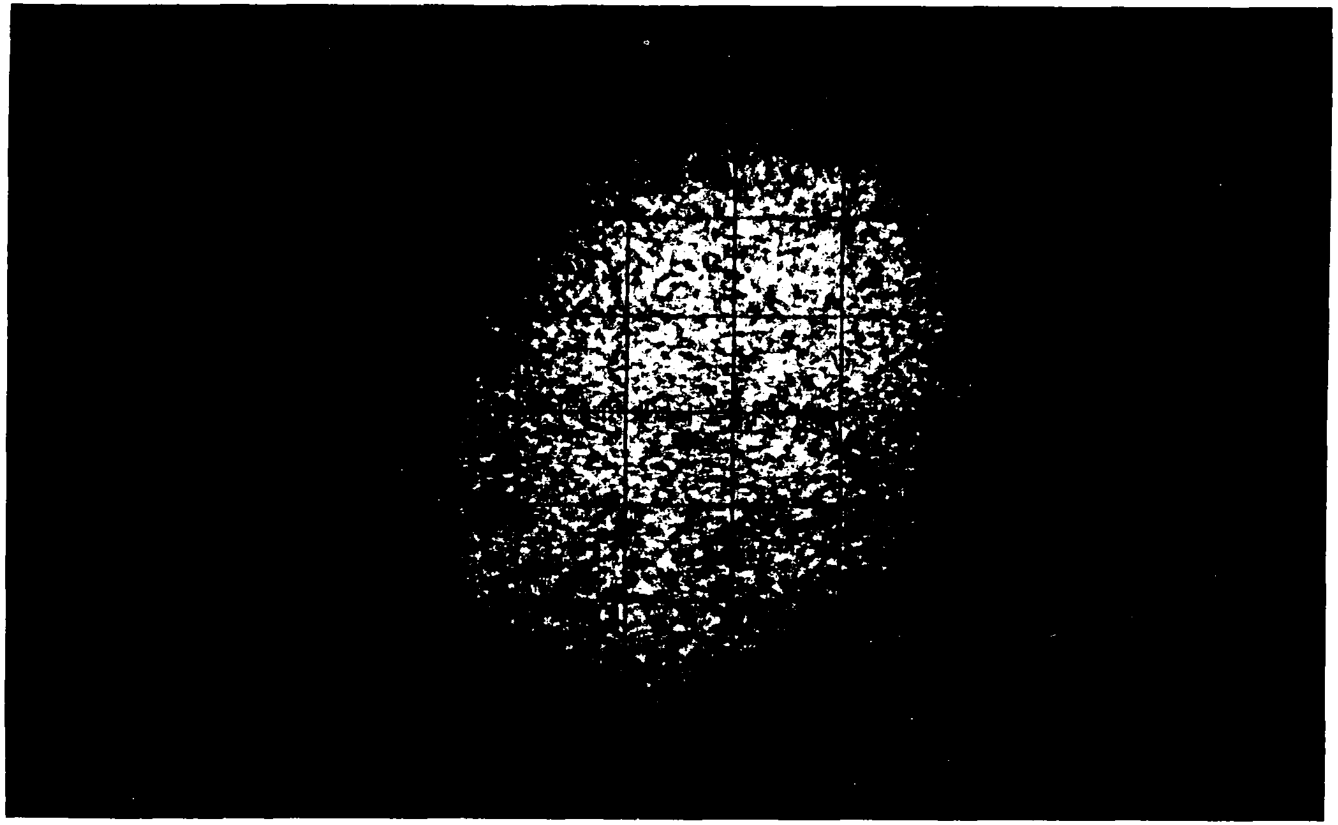

Plate 20. Metallic spherule elemental iron λ emission pattern. Scale is same as Plate 19.
(Courtesy of E. Padovani)

contribute to the NRM of tektites from this geographical area; this was observed in tektites that contained these particles. These multidomain inclusions explain the unique demagnetization curve on the "whole" philippinite in Figure 18. The relatively soft component that is removed around 200 OE is undoubtedly due to these particles. After their effect has been erased, the curve renders a slope that is usually typical for tektites. Exactly why these metallic spherules are restricted to only this area and are not found in other strewn fields isn't known.

Thus while the blocking temperature of these metallic nickel-iron spherules is the same for magnetite, the former's AF demagnetization curve in addition to their rarity in tektites tends to eliminate them as the prime NRM carrier. Relative to the paleointensity determinations, it is quite fortunate that the major NRM carriers are not due to particles of this nature since they cannot be considered that reliable for NRM preservation.

Dunn and Fuller (1975) in using a furnace attachment on the 6.3 cm cryogenic magnetometer, found that the magnetic carriers in layered tektites exhibited evidence of high-iron titanomagnetite. It was not possible to use this procedure on any tektite other than the relatively high-moment Muong Nong type, because the thermocouple would only accommodate small tektite fragments. Because of the reduced mass with these small fragments, they were not detectable on the instrument.

However, even without this information, the combined data on the Muong Nong types and the tektites examined in this research strongly suggest that the magnetic carriers are magnetite in composition and not nickel-iron. If this information, as well as Kleinmann's determination on the magnetite composition of the spherules is correct, then a lunar origin for these tektites is placed further in doubt. According to Fuller, (personal communication) magnetite has not been detected in any of the Apollo samples.

Impact Glasses

Blocking temperatures for the impact glasses are given in Table 9. It will be noted that on most samples tested, the region of 550° to 600°C appears to be dominant, suggesting either magnetite or a nickel-iron alloy. Some derviations are present however, again owing to the diversity of the parent bodies and composition of the impact area.

By itself, this information would not suggest much. But when combined with other magnetic data, a possible genetic relationship between tektites and the particular impactites previously mentioned, is again evident.

Most notable of these similarities is probably with Libyan Desert Glass. Although its water content is higher than tektites by about an order of magnitude (Friedman, 1958) all of its magnetic properties appear to be the same. It seems to be somewhere

SPECIMEN	BLOCKING TEMPERATURE (°C)	PROBABLE MAGNETIC CARRIERS
Tektites (all strewn fields)	550 - 600	magnetite/nickel-iron
Aouelloul	550 - 600	magnetite/nickel-iron
Bosumptwi	550 - 600	magnetite/nickel-iron
Libyan Desert Glass	550 - 600	magnetite/nickel-iron
Henbury	$>$700 *	hematite
Meteor Crater	600 - 700	hematite transition
Ries	550 - 600	magnetite/nickel-iron
Power Line Fusion	550 - 600	magnetite/nickel-iron
Darwin Glass	550 - 600	magnetite/nickel-iron

Table 9. Blocking temperatures for tektites and impactites

* Possible instrumentation error due to position of thermocouple.

between impactites and tektites, almost like an incomplete formation of a tektite, or perhaps a glass resulting from impact of some body in the Libyan Desert where it is found.

However, just using the magnetic data to group it, it can be classified along with the tektites. No crater is found associated with this group of glasses. This would be understandable though since the pertetual motion of sand would obscure any impact scar in a relatively short period of time.

SUMMARY OF RESULTS

Thus far, the research presented in this paper has revealed many of the magnetic properties of tektites and impact glasses. The shock studies have shown the resistance of tektites to impact. This demonstrated that a magnetic analysis of these glasses was feasible and unrestricted to whole specimens.

Measurements on tektite susceptibility revealed that the cryogenic magnetometer could delineate strewn fields to a greater degree than is currently possible with standard chemical techniques. The interpretation as to why certain "patterns" exist is open to speculation.

Comparison of magnetic intensity across the interior of a tektite with that of a volcanic bomb, provided information as to why these differences occur. This can assist in clarifying what other researchers have interpreted as evidence of an extra-terrestrial origin.

Various paleomagnetic techniques applied to tektites further demonstrated that the NRM was dominantly a TRM; this TRM was shown to be stable. The dominant magnetic carriers were identified as magnetite having dimensions mostly in the single-domain range, or between the single and multidomain state. Their behavior in oxidizing and non-oxidizing environments was studied and compared to various impactites. Saturation IRM and demagnetization studies were also done among tektites and impactites. Considering all the magnetic data, the "related" impactites have more in common with their associated tektites than they do with other impactites.

The intention now, is to attempt to settle the much-debated question as to the terrestrial or extra-terrestrial origin for tektites.

THE QUESTION OF TEKTITE ORIGIN

The greatest objection to a terrestrial origin for the australasian strewn field has been the absence of a massive crater in this area, as well as the aerodynamic argument. These factors provide the prime argument for those researchers who favor an extra-terrestrial origin. Whatever the event was, and wherever it originated, it spread a mass of tektite glass, estimated at 100 million tons over the australasian area (Cassidy, et al., 1969).

Urey (1957) had proposed an impact by a comet, suggesting that the diffuse nature of this body would not leave a recognizable crater, yet could fuse terrestrial material and impact with such force that the ensuing explosion could remove the atmosphere above the blast site. During this removal, small droplets of tektite glass would be ejected into the upper atmosphere, cool into spherical primary forms, and then re-enter. This could account for the ablation flanges found mostly on australities. The other material which did not reach such high elevations would have formed the other common tektite forms after, or during the fall to earth.

Ablation research by Chapman et al., (1962) has shown that tektites were rigid bodies before experiencing atmospheric ablation. Therefore, if a tektite melt is originating on the earth, it must somehow be moved to an area where the gas phase pressure is below 2×10^{-7} atmosphere (Chapman and Larson, 1963).

Only here will the dynamic pressure be less than 200 dynes/cm^2, a requirement to avoid flattening or disruption of liquid droplets of australite size.

To remove the atmosphere above a meteoritic impact site requires approximately 10^{23} ergs of energy, an amount sufficient to excavate a crater several hundred kilometers in diameter (Lin, 1966; Chapman and Gault, 1967). Also, according to Chapman (1971), the concept of cometary impact of underdense material appears to be "hopeless". At cometary velocities (20 to 30 km/sec) the impact pressure is so high ($\sim$30 mb) and shock heating so great ($\sim 10^{4}$°C) that the comet head would be vaporized and therefore incapable of survival and ejection of material.

This data then, tends to favor an extra-terrestrial origin for tektites. Tektite glass could be formed by the impact of some body on another planet where the atmospheric pressure was more conducive to the aerodynamic requirements. If the planet in question had a lower escape velocity than the earth, ejection of tektites into space would be facilitated. This material would probably eventually come under the influence of the earth's gravitational field and produce the tektite strewn fields. Despite the appeal of this hypothesis over the years, it has many limitations.

Cosmic-ray-induced isotopes, of ^{26}Al, ^{3}He, ^{21}Ne, and ^{10}Be, indicate a space exposure time of less than 20 years (Fleischer, *et al.*, 1965b). The time necessary for objects to work their way into various planetary areas is believed to be on the order of hundreds of thousands or millions of years. Furthermore, Paddack (1969), suggests that radiation pressure, acting asymmetrically because of albedo or geometry variations would cause tektites to rotate and eventually rupture under centrifugal stresses. For tektites having dimensions of a few centimeters, the maximum survival time by this mechanism is given at 6 X 10^4 years.

Ballistics tests by Gault and Wedekind (1969), combined with estimates for the flux of micrometeoroids at 1 AU, indicate that the mean survival time before the complete destruction of tektites in circular heliocentric orbits is of the order of 10^3 and 10^4 years for, respectively, objects 1 to 10 cm in diameter. Partial fragmentation and loss of physical identity as tektites would occur in much shorter periods of time. Thus, any tektite that did manage to survive this period of time in space would not possess an unaltered primary shape, and also would show evidence of cosmic-ray exposure.

Another problem of the extra-terrestrial origin, seldom stated, has to do with the ablation flanges produced upon atmospheric entry. Why don't all tektite groups exhibit ablation features? Even in the australasian strewn field, the intact ablation features are restricted to the south east area. Cores, which unequivocally have been spalled, are not found in the northern areas. In fact, only a small percentage of tektites from this part of the world show evidence of ablation. None of these features has been found in any other strewn field. The aerodynamicists contend that this can be explained on the basis of entry angle, viscosity, weathering, and other factors.

Formation of Teardrop Tektites

While at NASA's Ames Research Center, I was impressed by the extensive ablation studies that had been done on synthetic tektite glass. Every tektite shape had been duplicated in their experiments, including the ones shown in Plate 21. The original conditions under which these particular tektites formed is crucial to the extra-terrestrial hypothesis.

The variation of the form shown in Plate 21 is termed a "sagged teardrop". It appears to be caused by a viscous mass hitting a surface and sagging in a gravitational field. If this is correct, then it discounts the hypothesis of a "solid" tektite swarm entering the upper atmosphere from a place beyond the earth-moon system.

To produce this shape by settling on the surface, the tektite glass would have to be already molten at the time of atmospheric entry. The reason for this is in the thermal data presented by Centolanzi (1969; personal communication, 1975). It is not possible for rigid tektite glass to liquify or even

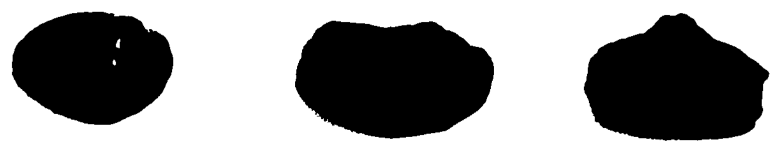

Plate 21. Sagged teardrops from Thailand.

soften during atmospheric heating, only a few tenths of a centimeter of the exterior would ablate. Even an iron meteorite which is a far more efficient conductor of thermal energy than glass, can be handled almost immediately upon descending to earth (Dubois, personal communication).

The sagged teardrop shapes were duplicated in experiments by first having a mass of soft tektite glass rotated, which produced a dumbbell, followed by separation and collision with other tektites. If this occurred in an extra-terrestrial environment, the ablation flange produced upon entry was completely spalled (Scheiber, personal communication). Thus, while Occam's razor would suggest terrestrial impact of some body with the resulting splash of glass, this need not necessarily be the case. As will shortly be mentioned, the layered Muong Nong tektites (Plate 12) which show evidence of having flowed into depressions in Thailand (Barnes, 1971) have also been explained by the NASA group, without requiring a solid mass to melt during atmospheric transit.

Tektite Formation According to the Lunar Hypothesis

To reconcile all of the data therefore, and explain the various shapes and not just the australites, it is necessary for the proponents of an extra-terrestrial source to postulate that all tektite shapes originated by impact on some other planetary body and subsequently arrived on earth either as solid bodies, or partly solid and partly molten bodies. There could be many mechanisms producing the tektite event, but the emphasis here is on the physical condition of the tektites at entry.

The "solid" swarm, as I shall refer to it, appears to have difficulty explaining the lack of ablation features, or the lack of remains of ablation features on the majority of tektites. When this is combined with the cosmic-ray and micrometeorid data, and the detection of atmospheric gas bubbles inside some tektites (Zahringer and Gentner, 1963), it faces rather rough going to say the least. This is not to mention the isotopic and petrologic data supporting the contention that the Muong Nong tektites formed from local soil (Barnes, 1971).

On the basis of paleomagnetic evidence, deGasparis *et al.* (1975) have also demonstrated that the Muong Nong tektites acquired their magnetism in a field of comparable intensity to the earth, and at a similar latitude to the collection site. In order to explain this finding in addition to the australites, the believers in the extra-terrestrial origin would have to assume that part of the incoming tektite mass was solid, while part was molten. This way, after entering the upper atmosphere some of the soft mass would splash to earth and form the Muong Nong type, thereby explaining the similarity with the local soil (mixing), while cooling *in situ* could account for the magnetic properties. The australites would be explained and the atmospheric gas found in some tektites could be due either to capture by molten droplets, or diffusion.

The conditions just stated represent the usual approach taken by individuals who support a lunar origin. A lunar source appears to be the only explanation for the lack of cosmic induced isotopes and the only place where a mass could be ejected and remain partially molten during transit to earth.

Centolanzi (1969, personal communication 1975), has shown that molten glass spheres above approximately 1 meter radius, could survive the 2.5 day transit time from moon to earth; the fate of such a mass at entry however, would be difficult to predict. Chapman (1971) then proposed that the source of the australasian strewn field was the Rosse ray of the lunar crater Tycho. With NASA's trajectory computers at his disposal, he successfully demonstrated that the ejecta from this ray would match the tektite landing pattern for the australasian area.

Results of the lunar exploration program have shown that little comparable to tektite glass has been found (King *et al.*, 1970). All evidence thus far is against a lunar origin, unless one assumes that the samples are not representative of the lunar surface, or that some unknown differentiation process is occurring in the lunar interior with an occasional eruption of siliceous mass, eventually landing on earth. The latter appears to be a return to the lunar ejection model proposed by Verbeek in 1897. But despite the negative evidence, the lunar origin is still supported by certain individuals on the basis of the terrestrial aerodynamic argument and the lack of a source crater. This appears to be a reasonable argument.

Let us assume that the lunar hypothesis is still valid because the Apollo samples are not representative of the lunar surface. Chapman's proposal (1964; 1971), is given below:

> From a synthesis of the overall evidence a picture of the event and the processes which produced the australasian tektites has been reconstructed as follows: The event was initiated by the impact of a large meteoroid on the lunar surface which formed a crater estimated from total tektite mass and probability considerations to be in the range from several to the order of 100 km diameter. Two separate stages involving different physical processes are envisioned, both of which are relevant to the formation of tektites. The first stage is one of violence and intense pressure, in which various component rocks of the lunar crust are mixed, compressed, heated, and fused as they forcibly are moved in the same manner as a fluid is moved when subjected to extremely high pressures. During this stage the fused mass is bounded on one side by a compressional wave propagating into the lunar crust, and is accelerated en masse to high velocities before leaving the crater. Judging from impact experiments, masses of fused material are spewed in discrete jets at various places around the circumference of the crater, with each jet being confined to a small azimuthal dispersion. The time scale of this intense pressure stage is the order of seconds. It is pictured that the heating is the greatest in the early portions of this stage, wherein the propagating wave is strongest, and that, as the propagating wave decays and moves material outward from the impact center, the intensity of heating, and the velocity of injection progressively decrease. As soon as the fused material is jetted from the surface of the moon, however, a second stage

> of physical processes begin, since this material is then suddenly exposed to the vacuum of space. In the absence of external forces the masses of molten material disrupt into myriads of blobs through their own internal eddying motions coupled with the disrupting processes of boiling, outgassing, and perhaps the shattering experience of passing for a brief instant through a feeble blast of gasses produced by volatilization in the earliest stage of impact. Once launched into space, surface tension is the only constraining force tending to maintain the shape of a given mass of glass. The duration of this second stage -- the stage of blob formation and reshaping -- would last the order of several to tens of minutes, depending upon the size of the blob. This stage would be terminated in space when the material solidified to a rigid glassy state. The process taking place in this second stage determine the character of the primary shapes of the tektites. Since the reshaping process takes place in a vacuum, it is possible for essentially perfect spheres, as well as other very delicate hollow forms, to be produced. It is pictured therefore, that the jet of material leaving the moon is comprised of a trail of progressively varying shapes and sizes. At the head would be clusters of nearly spherical shapes which were heated to the highest temperatures and given the highest velocities of ejection. This would be followed by clusters which were broken up at a somewhat higher viscosity and formed thereby less regular shapes that generally were larger than the spherical objects. These, in turn, were trailed or partially intermixed with the teardrop forms, and the large chunky tektite material, which represent the portion with the lowest temperature and highest viscosity of formation of the group.

While I was at Ames Research Center, part of this hypothesis had been modified in view of what was stated relative to deGasparis' data. Specifically, the "large chunky tektite material" has been altered by assuming that part of the ejecta remained molten during its transit and impact on earth.

To assist in settling the controversy, the approach now will be to attempt to determine the intensity of the inducing field for tektites which, because of their viscosity, had solidified at or near the impact site. According to Chapman's (1963; 1964; 1971), and Centolanzi's (1969) data, the primary tektite forms could not have arrived at earth in a molten state, nor could they have been produced by the breakup of a large molten mass during atmospheric entry. Thus, the primary forms possess the NRM of the original inducing field.

Before proceeding with the paleointensity analysis, it would be well at this point to examine the ablation data relative to the flanged australites, or "buttons" as they are commonly referred to. Their past thermal history is an important aspect of magnetic experimentation.

Aerothermal Stress Shell

As can be seen from Table 10, the thickness of the stress shell is inversely proportional to the entry angle from the horizontal. For $y_i = 90^{\circ}$, this yields a stress shell thickness of 1.8 mm and represents the minimum transit time from the upper atmosphere to the surface. For $y_i = 6^{\circ}$, the stress shell would have a maximum thickness of 4.0 mm. An entry angle $< 6^{\circ}$ is not possible for $v_i = 11$ km/sec. A tektite entering under these conditions would skip out of the atmosphere.

Entry angle γ_i, deg	Thickness of stress shell, t_s, mm	Cooling rate of front face in annealing range (dT_s/dt), deg/sec
6	4.0	21
20	2.7	49
30	2.4	58
45	2.1	80
90	1.8	120

Table 10. Thickness of aerothermal stress shell relative to atmospheric entry angle (computed for entry velocity, V_i = 11 km/sec). (from Chapman, 1964)

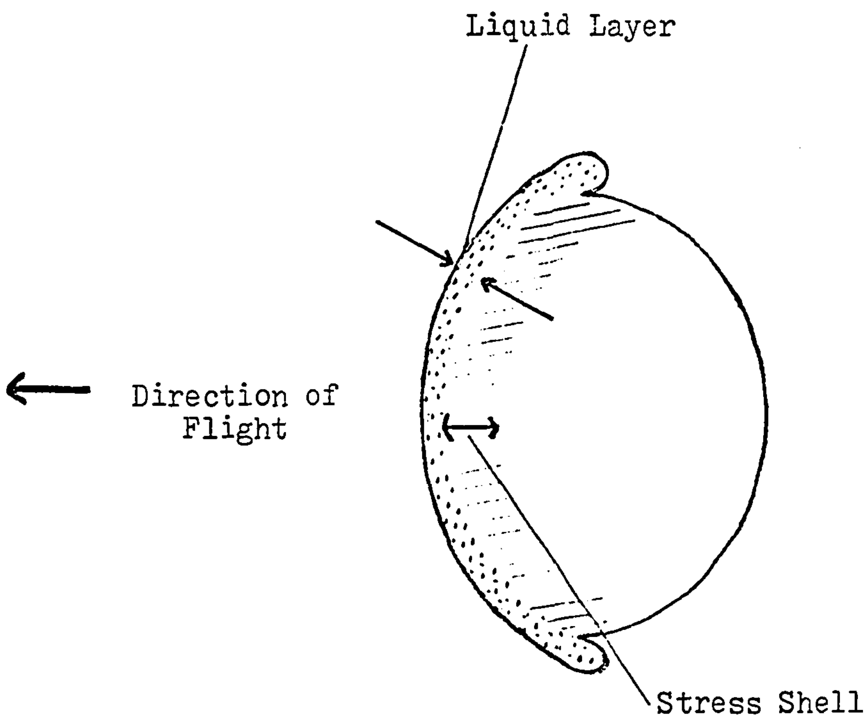

Figure 49. Australite cross-section (Modified from Chapman, 1964)

Based on the percentage of mass loss on various button tektites, the possible entry velocities will range from 7 to 11 km/sec (Chapman, 1964). Thus, for an entry velocity of 7 km/sec at low y_i, the transit time will increase, resulting in an increase in thermal penetration into the core, which will also produce a thicker stress shell. Since the preservation of the original NRM in the core is dependent upon its thermal history, it becomes imperative to know how deep the ablative heating (which can exceed 2,000°C on the surface) has penetrated.

Strain Pattern

According to Chapman (1964), for tektite glass of density $\rho = 2.40$, the strain temperature is approximately 650°C and the annealing temperature, about 700°C. On an ablating tektite, the front-face surface temperature is cooling at about 58°C/sec, which induces pronounced thermal stresses within a shell under the front surface (Figure 49). The strain temperature represents the temperature up to which a glass may be heated and rapidly cooled without inducing residual strain. Since the front layer is heated above the annealing temperature and solidifies at dimensions commensurate with the relatively cool and rigid interior, it develops tensile stresses as it further cools to ambient temperature.

Fortunately, the thermal stress patterns resulting from ablation are easily discernable when a tektite thin-section is viewed through crossed polars. Remembering that the strain temperature is produced at about 650°C, it then becomes possible to determine to what extent the core area has been heated.

Strain Effects on Synthetic and Natural Tektite Glass

Plate 22 illustrates thin sections of natural and synthetic tektite glass as viewed in cross-polarized light. The upper three photographs show the results of aerodynamic ablation experiments on synthetic tektite glass spheres. The clear areas indicate that the stress temperature of $650^{\circ}C$ has been attained, while dark areas mean that temperatures this high have not penetrated into these regions. In "C", the entire glass has been mostly heated through while "A" and "B" show a minimum of thermal conduction.

The natural tektite thin sections (D, E, F) resulted from virtually identical ablation conditions as did their synthetic counterparts. Thus, the exterior heating of "D" and "E" was such that their entry angle and velocity left the posterior internal areas unstressed. Immediately inward and adjacent to the stress shell, the temperature began to approach $650^{\circ}C$, while further into the core it was several hundred degrees below the stress point; this sharp drop in temperature results from the low thermal conductivity of tektite glass. In "F", the stress temperature was attained or exceeded throughout the tektite.

It was previously shown that thermal demagnetization of tektite saturation IRM revealed a blocking temperature of between 550° and $600^{\circ}C$. Whatever the exact magnetic carrier is, for the

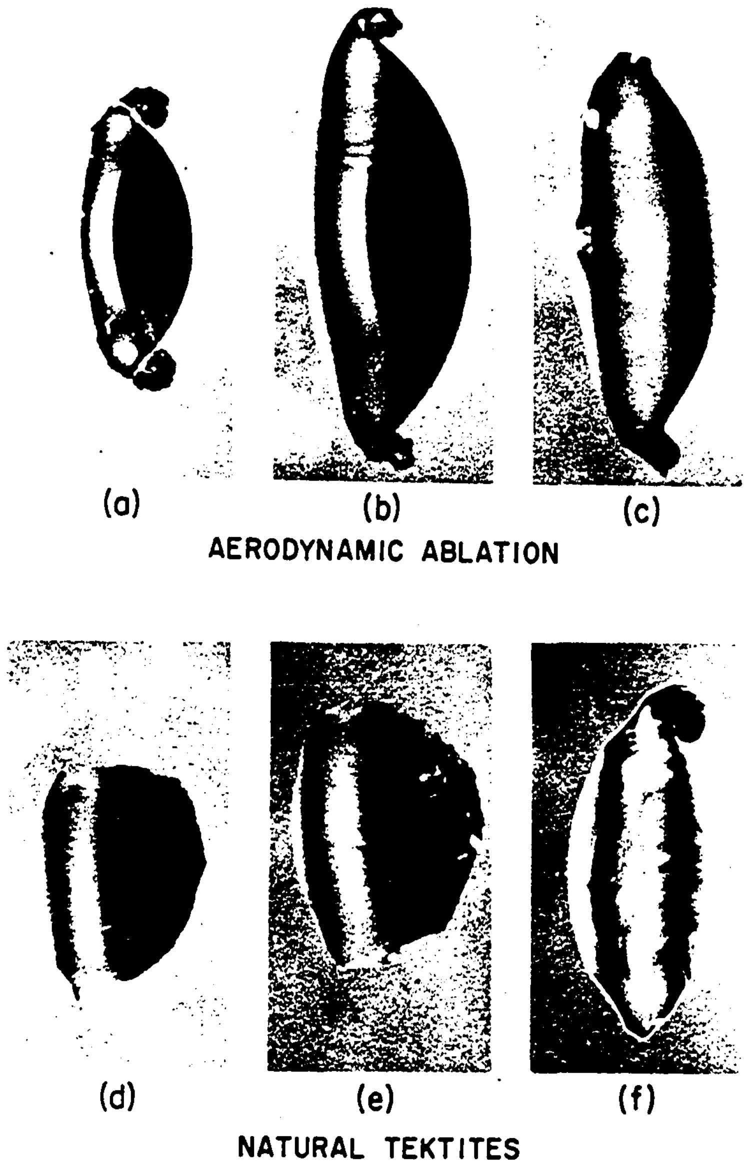

Plate 22. Strain patterns in ablated tektites. (from Chapman, 1964)

purpose of this phase of the research it will be assumed that the Curie point is approximately 600°C. Since Fig. 45 reveals that almost 90 percent of the magnetization is acquired within 10° or 20°C of this temperature, 580°C then, represents the maximum point that the interior core area can withstand before losing the primary magnetization and taking on a secondary moment.

Selection of Cores

The core selection was done at Ames Research Center after I had thoroughly discussed the temperature requirements with several researchers. Based on size and curvature of the core, it was possible to locate two particular tektites which probably were not heated through-out to the stress point. These two cores were previously shown along with other australites in Plate 11. They are shown again in Plate 23. The lower core is a 19.5 gram specimen from Williams Creek, Australia, while the upper one is from Pagranayan in the Philippines and weighs 41.9 grams.

To remove any doubt relative to interior stress temperatures, both tektites were thin sectioned off-center and viewed through crossed polars. One of these is shown in Plate 24. It will be noted that the posterior appears dark, and remains so during rotation through 360°, indicating that the stress point was not attained; these petrographic properties were identical to the other core. Again, owing to the low thermal conductivity of

Plate 23. Cores used for paleointensity study.

Upper core is 41.9 gm specimen from the Philippines. Lower is 19.5 gm specimen from Australia. (X 2.0) tektite glass, these dark regions were well below the 580° critical temperature.

Preparation of Cores

Removal of the interior unstrained glass region from the rest of the tektite was a potential problem. Not only did the cut have to be precise, but retaining as much usable mass as possible was imperative. Without a relatively substantial mass, the cryogenic magnetometer would not have been able to detect the NRM. The moment of many australites is quite low when compared to tektites from other strewn fields, and hence the bigger the glass specimen, the better the chances were of obtaining an accurate moment.

The off-center thin sections of the selected cores were accomplished by using a diamond saw with a thickness of about 1.0 mm. Once the unstrained glass areas could be detected in these thin sections, an outline of the usable areas was inscribed on the cores, slightly inward towards the area of maximum unstrained glass. Excising this called for somewhat of an unorthodox procedure, as both the thickness of the diamond saw and standard cutting positions were unacceptable.

Plate 25 shows how the cut was accomplished. A hand held dental instrument powered by a variable RPM motor and fitted with a diamond abrasive disc was employed. This proved to be ideal as the cut could be made with precision and under complete

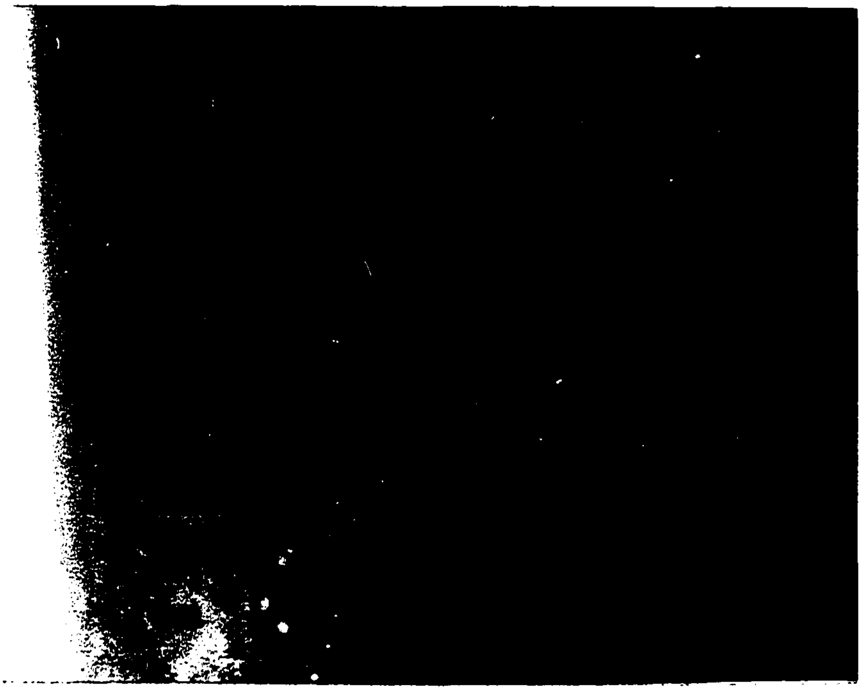

Plate 24. Photomicrograph of core thin section in crossed polarized light. Width of weathered and fractured aerothermal stress shell to left is about 1.0 mm.

Plate 25. Interior core removal.

control at all times. A minimum mass of glass was lost as the thickness of the diamond disc was less than 0.30 mm.

After the sectioned glass had been cut, the interior pieces were washed in warm nitric acid for 20 minutes to remove any contamination due to metallic fragments from the diamond's carbide-supporting frame. The samples were then placed in an ultrasonic vibrator for 10 minutes; this was followed by a 10 minute etching in a dilute solution of hydrofloric acid.

Experimental Procedure

It was previously shown that the magnetic carriers are affected by heating in both air and in a vacuum. Once heating to the Curie point has been done, the carrier alteration presents somewhat of a problem with regards to the paleointensity determinations.

For a direct ancient magnetic field calculation, the normal procedure is to first demagnetize the NRM of a sample, then heat that sample to above the Curie point in a controlled ambient magnetic field of some magnitude. This is followed by another demagnetization and comparison of the curves. Since heating is involved, carrier changes can be expected to introduce some inaccuracy into the calculations.

The Thellier-Thellier process as described by Fuller (1974) involves a stepwise heating method which ideally tends to correct for some of the carrier changes. Unfortunately, none of the laboratories used in the research had the proper instrumentation to apply this technique.

The newer anhysteritic remanent magnetization method (ARM) is conducted mostly at room temperature and this tends to circumvent the heating problems associated with other methods (Banerjee and Mellema, 1974). However, even this procedure requires one heating to the Curie point.

Another method, which was used by deGasparis et al., (1975) on the Muong Nong tektites and by Fuller (1974) on certain lunar samples, is that of comparing the NRM and saturation IRM ratios. No heating is necessary here, thus eliminating the problem with irreversible carrier changes. However, Dubois (personal communication) considers it a potentially invalid method of paleointensity analysis.

The question of determining the paleointensity then, becomes essentially one of necessary accuracy. Because of the low NRM of tektites and the reaction of the carriers to thermal energy, no method can give a precise value of the ambient magnetic field intensity at the time these glasses cooled through the blocking temperature. The best that can be expected therefore, is to accept the inevitable changes that occur and attempt to compensate for them. Certainly, if one were trying to estimate the paleointensity within a few percent, it would not be possible.

however, the margin for error would have to exceed several orders of magnitude for an erroneous conclusion to occur.

The objective is to distinguish between primary magnetism acquired in the vicinity of the moon, or on earth. The present lunar field intensity ranges from 100 to slightly over 1,000 gammas (Fuller, 1974). Based on various Apollo studies, it is believed that it has not deviated much from these values in the past. None of the lunar samples have yielded sufficient evidence to the support of an internally generated magnetic field as the earth's. For the purposes of this study, an ancient lunar field intensity of several thousand gammas is assumed, although the more reasonable estimate should be several hundred.

Estimation of the Paleointensity Field

Based on paleointensity studies, estimates of the earth's inducing field approximately 700,000 years ago is about 45,000 gammas (Lee, personal communication). While the australasian tektite event appears to have occurred near or during a reversal the decrease in field intensity would be insignificant. Black (1971) estimates that during a reversal, "zero" field is not even approached; it is estimated that the earth's magnetic field would decrease approximately 15 percent of its normal value. Thus, even if the tektite event did occur during a reversal or perhaps cause the reversal, as some researchers suggest, a substantial field intensity would still remain.

To get a direct estimate of the earth's magnetic field intensity at the time of the australasian tektite event, a dated basalt from the Philippines was obtained and put through standard paleointensity procedures. The results gave a field intensity of approximately 0.40 OE., which is close to additional published and unpublished data.

To estimate the intensity of the primary inducing field in the two core sections, they were measured for NRM, demagnetizated, then given a TRM of comparable intensity to the basalt (0.40 OE). Because of the availability of equipment at the time, heating was conducted in air. Some carrier destruction was to be expected, but according to Table 7, the expected changes were not considered significant.

After the cores had cooled to room temperature under continuous field control, they were remeasured and demagnetized. Results are shown in Figs. 50-51. Both the initial demagnetization measurements and those following the TRM were done at the limits of the 3.8 cm cryogenic magnetometer. While complete curves could not be obtained, the NRM and TRM values along with their demagnetization reactions were. Even considering the possibility of a substantial change in the magnetic carriers, it is apparent that primary magnetization occurred in an inducing field of several tens of thousands of gammas and not several hundreds or thousands.

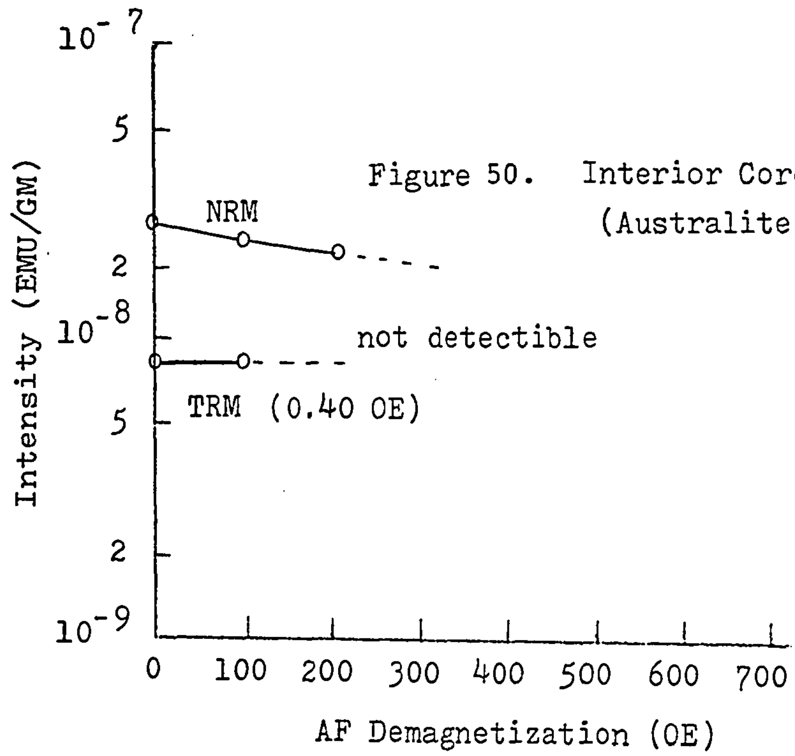

Figure 50. Interior Core (Australite)

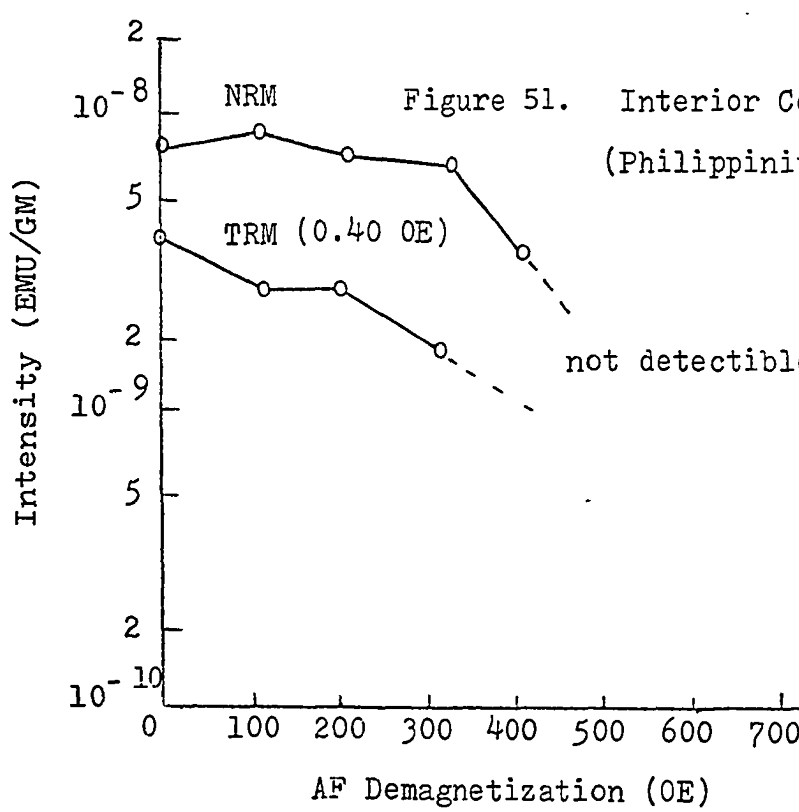

Figure 51. Interior Core (Philippinite)

For an additional check on this, a tektite was given a TRM in a field strength of around 1,000 gammas and then measured for NRM. This was followed by another TRM in a field strength of 0.40 OE. The increase was from below the detection level of the magnetometer to above 10^{-7} emu/gm, a gain of between at least 2 and 3 orders of magnitude. This strongly suggests that the cores solidified in a field strength of comparable magnitude to the volcanic.

The argument could be raised that these tektite cores had acquired their moment as the result of secondary heating after falling to earth. For instance, perhaps a natural fire erased the original TRM and recorded a secondary one, specifically the earth's intensity. This is highly doubtful, especially considering the environment where these cores are commonly found.

To circumvent this however, it had previously been decided to check the samples for alteration in their fission tracks. Before conducting the paleointensity experiments on these glasses, a small fragment had been removed from each core and forwarded to Dr. Robert Fleischer at the General Electric Research Laboratories. Details of the exact fission track method can be found in Fleischer and Price (1964). Briefly, the method is capable of detecting secondary heating events to the annealing temperature through visual examination of tracks produced in the glass by the spontaneous decay of ${}^{238}_{92}U$.

The track densities of the two samples were 410 ($\pm$ 56) and 282 ($\pm$ 43)/cm^2 as compared to 350 and 250 for tektites that were not heat-affected. This means that the likelihood of important heating throughout the volume is small (Fleischer, personal communication).

It was previously shown in this paper that tektite NRM is almost certainly not due to a SRM, CRM, IRM, PTRM, or VRM. Since this left a TRM and since the fission-track evidence has invariably eliminated a secondary TRM, this can only indicate that the measured NRM was acquired at the time these glasses initially solidified into primary forms.

The inescapable conclusion one is led to is that the button australites have a terrestrial origin. Had they formed at or near the lunar surface, the paleointensity would have been orders of mangitude different from that indicated.

PALEOINTENSITY MEASUREMENTS ON OTHER TEKTITES

Australasian Tektites

Various tektites from the australasian area are shown along with those from other strewn fields in Table 11. The same procedure was used for these as for the australites. Considering the changes in the magnetic carriers, the conclusion is that all of these tektites also cooled in the earth's magnetic field.

It is recognized that initial solidification could have occurred in a low intensity field, with subsequent ablation in the earth's magnetic field. This is an argument that can be used against magnetic data on whole tektites. As previously mentioned, even the data of deGasparis et al., relative to the Muong Nong tektites has a potential weakness in that masses of glass of the proper size could have survived the earth-moon transit in a liquid state, and solidified in Thailand.

Arguments of the above nature however, can not be directed towards the primary forms. Since it has been shown that they are terrestrial in origin, this means that all other tektites associated with the same australasian event are also terrestrial in origin. Thus, the findings of deGasparis et al., relative to the Muong Nong types are confirmed. In addition, the sagged teardrops (Plate 21) are not due to any special aerodynamic conditions in an extra-terrestrial environment, but simply represent tektite glass which hit the ground in a semi-molten condition. Their magnetization reflects solidification within the earth's magnetic field and one need not hypothesize any further than this.

Origin of Moldavites, Bediasites, and Ivory Coast Tektites

As can be seen from Table 11, the differences between the NRM and TRM for tektites other than those from the australasian field indicates that solidification also occurred within the earth's mangetic field. As can be noted, some tektites showed a slight increase in intensity when heated in the 0.40 OE field. This could be due to variations in the magnetic field strength were they cooled or additional chemical changes in the magnetic carriers, even though the latter showed evidence of partial destruction in air by previous tests.

Some of the early researchers had reported that tektites showed a high increase in magnetization when heated in the earth's field. Most of this data could not have been very accurate because of the types of magnetometers available at the time. And although some tektites did increase, the magnitude of the change was relatively small. The increases should not be interpreted as indicative of an extra-terrestrial origin. It is not uncommon to find terrestrial igneous material which behaves in a similar manner.

Nothing aerodynamically comparable to button australites are found in other strewn fields, nor do any tektites from these

Strewn Field	No. of Samples	Magnetic Intensity emu/gm (x 10^{-6})	
		NRM	TRM (0.40 OE)
Moldavite	2	0.018	0.010
		0.011	not detectible
Bediasite	2	0.150	0.090
		0.009	0.005
Indochinite	4	0.253	0.382
		0.165	0.087
		0.070	0.105
		0.095	0.095
Ivory Coast	2	not detectible	

Table 11. Comparison of NRM and artificial TRM for various tektites.

other areas retain any readily identifiable ablation remains. Thin-sections of these tektites reveals a strain pattern unlike the australities, i.e., only one heating appears to have taken place. Sections from the interiors of tektites from these areas reveals a similar NRM as the entire tektite itself.

The probable reason for this is that none of them entered or re-entered the atmosphere. The magnitude of the event that produced them was apparently far less than that for australasian area.

FORMATION MODELS

The event which created the australasian strewn field must be capable of explaining, among other entities, the different tektite forms found in widely separated areas. The Muong Nong tektites in Thailand show no evidence of aerodynamic shaping, but rather properties attributed to flowage on the earth's surface (Barnes, 1971). As one proceeds from Indochina across the strewn field, the formation viscosity decreases, until only the spherical primary forms are found in Australia (Chapman, 1963).

DeGasparis *et al.* (1975) propose the jetting model. At impact, the target and projectile are subjected to high temperatures and pressures creating a liquid jet of material. It is suggested that a large enough blast could create a liquid jet that would penetrate the upper atmosphere. Once above 100 km, the atmospheric pressure would permit the formation of undistorted primary forms. The differences in shapes can thus be explained by this model as one proceeds across the strewn field. The australites could have gone into orbit or fallen soon after ejection. This could account for the ablation forms, while those tektites shown in Plates 10 and 12 represent tektite glass that was at the lower end of the jet. Once again, since no crater is evident however, this model is difficult to substantiate. In addition, little is known about the jetting phenomena, so that it is difficult to arrive at any quantitative data on this (Chapman, personal communication). Another problem is that jetting occurs at a low angle, which means that a greater distance of atmosphere would have to be traversed to attain the proper altitude where the primary forms could be produced (French, personal communication). Some of the susceptibility and intensity data also suggest that there could be several "hot spots" within the strewn field which the jetting model might not be able to explain. However, recognizing that much research needs to be done in this area, it should not be dismissed.

Almost certainly, if not definitely, the australites have re-entered the atmosphere after being blown upwards from either a surface or air burst of some nature. The aerodynamicists contend that an impact capable of removing the atmosphere and ejecting material into orbit cannot occur without excavating a crater of tremendous proportions. Most geologists have tended to accept this. Then again the aerodynamicists should not be considered to be infallible, since it is also their calculations to the present-day which can demonstrate that the bumblebee is incapable to flight -- to which the insect responds by doing it anyway.

The point is not to be facetious, but to recognize the limits and imperfections that arise in the applications of the laws of physics and chemistry to idealized (simplified) models of actual physical situations. Since the magnetic data now joins the list of evidence supporting a terrestrial origin for tektites, it would appear that the hopes of a lunar origin should be abandoned, and the intentions directed towards finding a suitable mechanism for tektite formation on earth.

Since some trace elemental determinations and now the magnetic data tends to possibly link some tektites with "associated" impactites, an explanation, however speculative, is in order as to why there is such a petrologic difference between the two.

A thorough perusing of the literature will reveal that tektites are not simply high-temperature equivalents of impactites. Yet with the impactites "associated" with the Ivory Coast tektites and moldavites, some similarity is present in trace elements.

The magnetic data have shown that while impact glasses have a wide range of behavior tektites do not. However, impact glasses "associated" with tektite events share many of the magnetic properties of tektites, more so than with other impactites. Owing to the diversity of terrestrial source material, it is highly doubtful that random impacts on the earth could produce four strewn fields practically indistinguishable on the basis of particular magnetic properties. Taylor and Epstein (1969) were led to the same conclusion relative to the O^{18}/O^{16} ratios. Yet this is exactly what is observed. The suggestion is that the "associated" impactites show magnetic similarities to tektites not because the source material at the impact site is similar (which unequivocally it is not), but because the iron phase of some impacting phenomena is being fuzed into the crater glass and ensuing liquid jet.

The implication is that the liquid jet creating the tektites is mostly composed of material from the parent body, while the impactites are formed mostly from material at the impact site. During the cratering process, some material is invariably incorporated into both types of glass, but not enough to alter the distinct physical and chemical properties of each. Thus from one impact, it appears possible that two different types of glasses can be formed.

Since all known tektites also have a narrow range in physical and chemical properties, this implies that the impacting body cannot be meteoritic, but rather some recurring phenomena of uniform composition. In addition, as the magnetic data have shown the possibility of "hot spots" within two strewn fields, this further suggests that tektite events can be multiple in nature.

Considering all information, it appears as though the cometary hypothesis of Urey (1957) is the best explanation for tektite formation. Comets have been observed to travel in multiples and are believed to have originated from a single mass during formation of the solar system (Chapman, personal communication).

Although meteorite impacts have been observed and studied, cometary ones have not. As the geologic record has shown the immense magnitude of tektite events, we should not be too eager to witness a cometary impact to support the proposed hypothesis. Far more would be lost than would be gained.

While the phenomena responsible for tektite events will undoubtedly be debated in the future, one point appears to have been settled.

The hypothesis of a lunar origin for tektites has been assigned its final resting place, earth.

CONCLUSIONS

The magnetic research conducted on tektites and certain impactites in this paper revealed the following:

(A) Tektite magnetism (NRM) is impervious to terminal velocity shock. Not only is the moment unaffected, but a tektite cannot take on the intensity of the ambient mangetic field at the time of impact.

(B) Magnetic susceptibility is a useful entity which can be used to group tektites and delineate strewn fields. When done with a cryogenic magnetometer, the procedure becomes rapid and more accurate than with other existing methods. Sufficient samples from the Ivory Coast and bediasite strewn fields should be examined for susceptibility in the future should these tektite measurements continue. Additional research into the exact susceptibility changes that occur for tektite glass under different heating and cooling conditions is needed. This in addition to susceptibility measurements on debris around conventional and nuclear detonation areas should provide a clearer interpretation of why the previously mentioned "patterns" exist.

(C) In contrast to the impactites, the magnetic properties of tektites strongly suggest that the impacting body is of a unique nature, almost to the extent that the body is coming from the same source.

(D) Certain impact glasses that are genetically related to tektites on the basis of age, have similar magnetic properties to tektites.

(E) On the basis of overall magnetic data as well as petrological data mentioned in the literature, Libyan Desert Glass can be classified with tektites.

(F) The NRM of tektites is due to a TRM. All evidence also indicates that the primary magnetic carrier is magnetite having a size range between and including single and multidomain. The magnetization is considered to be hard and reliable for paleointensity determinations. In the case of tektites containing metallic iron spherules, the NRM is more intense, but is not considered reliable for paleointensity studies.

(G) The preliminary magnetic data indicates that there may be a genetic relationship between the Ries impact glasses and moldavites. This is also the case with the Bosumtwi crater and Ivory Coast tektites. However, both the tektite and impact samples are far too few to conclude anything at this point. In the case of the impactites, since their magnetic properties tend to vary from different parts of the crater , a good statistical sampling and testing program is in order. Once sufficient data has been accumulated, the combined magnetic data may yield reliable information.

(H) Tektites have a terrestrial origin, not a lunar one.

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PERSONAL COMMUNICATIONS

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APPENDIX A

SOURCE	TEKTITE TYPE	SAMPLE WEIGHT (gms)	NUMBER OF TEKTITES WITH UNLISTED WEIGHTS
Univ. Texas at Austin	Indochinites	24.6, 25.5	42
	Australites	19.8, 19.1, 34.2, 20.9	19
	Philippinites	44.8, 15.2, 15.3	6
	Other austral-asian tektites	21.4	23
	Ivory Coast	6.9, 6.7	2
	Bediasites	29.8, 28.1, 18.4, 31.3	8
	Moldavites	23.4, 16.8	13
	(all impactites)		
Charles University (Czechoslovakia)	Moldavites	21.2, 12.2	14
National Aeronautics and Space Administration	Philippinite	9.8	4
	Australites	41.9, 19.5	20
Tektos (Commercial)	Indochinites	fragments	19
	Australites		16

Table A. Source of samples.

Table A (cont)

SOURCE	TEKTITE TYPE	SAMPLE WEIGHT (gms)	NUMBER OF TEKTITES WITH UNLISTED WEIGHTS
U.S. National Museum	Australites	fragments	3
	Philippinites		1
R.L. Dubois (Univ. Okla)	Indochinites	mostly fragments	13
	Australites		16
R.R. Donofrio	Philippinites	mostly fragments	12
	Australites		6
	Indochinites		10