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Abstract
This thesis study investigates two individual projects to determine the paleomagnetic records from sediment core NBP0502-1B from Maxwell Bay Antarctica and SNC Martian meteorite Yamato-908459. Core NBP0502-1B from Maxwell Bay, South Shetland Islands, recovered a 108 m sedimentary record dating between 14.1-14.8 ka. The core has a silty-clay lithology and a calcite based radiocarbon chronology, making this an ideal site to reconstruct an independently dated record of paleosecular variation (PSV) and relative paleointensity (RPI). The interval 0-72 mbsf displays a normal sedimentary fabric, with $K_{\text{min}}$ inclination values nearly vertical and $K_{\text{int}}$ and $K_{\text{max}}$ distributed within the bedding plane. Below 72 mbsf, we observed fabrics with shallow $K_{\text{min}}$ axes, which may have been caused by deposition on an inclined seafloor. Samples were analyzed for magnetic hysteresis ratios: saturation remanence normalized by saturation magnetization ($M_r/M_s$) and coercivity of remanence normalized by coercivity ($H_{\text{cr}}/H_c$). The samples plot in the pseudo-single domain (PSD) region and to the right of the PSD region of the Day Plot. There were no differences in the hysteresis ratios between normal AMS fabrics and those from below 72 mbsf. Curie point analyses have identified four different features in the heating curve; these features have been tentatively identified as titanium-rich titanomagnetite, a magnetic iron sulfide, and two titanomagnetites, with moderate Ti and poor Ti content. Scanning electron microscope analysis supports the Curie point measurements. Samples were also subjected to stepwise alternating field (AF) demagnetization. A low coercivity overprint, likely a drilling or storage overprint was removed at 10-15 mT. The sediments recorded a strong, stable remanent magnetization. Inclinations values between the u-channels and paleomagnetic cubes range from 36.6° to -89.9°, with shallow inclinations often correlating with but not
limited to AMS fabrics with non-vertical $K_{\text{min}}$ values. The maximum angular deviation (MAD) values between the u-channels and paleomagnetic cubes range from $0.2^\circ$ to $25^\circ$ and do not correlate with AMS fabric. A preliminary RPI is presented in this thesis.

The study of natural and synthetic Martian meteorite assesses the magnetic recording assemblage and remanence properties of the SNC meteorite Yamato-980459 (hereafter Y-980459), a primitive member of the shergottite group of Martian meteorites, which was formed under IW +1 $fO_2$. This study is the fourth in series to understand the origin, intensity, and long-term stability of the Mars crustal anomalies detected during the Mars Global Surveyor mission (Acuña et al., 1999). Here we examine samples of natural and synthetic Y-980459 to gain a more representative picture of the magnetic and remanence-carrying abilities of the Mars crust. Our $\chi$ values are similar to values reported by Hoffman et al., 2010. The NRM and ARM results suggest that there is heterogeneity within the natural Y-980459 and this basaltic shergottite is not a likely carrier of intense crustal anomalies. The synthetic samples lack S, and some chromites adhered to the FePt wires, which affects the $\chi$, ARM, IRM and hysteresis parameters. The lack of sulfides in the synthetic samples resulted in lower $\chi$, ARM and IRM measurements than their natural counter parts. The combination of this study and previous studies indicate that samples synthesized under $fO_2$ close to IW have the ability to record only, moderate remanences and are not capable of producing the anomalies. Thus, samples synthesized under more oxidizing conditions may be the key to understanding the origin of the Martian magnetic anomalies.
Investigating planetary magnetic fields:
1. Paleosecular variation and relative paleointensity curves from Maxwell Bay, Antarctica
2. Rock magnetic and remanence properties of natural and synthetic Martian basalts

by
Deepa Shah
A Master’s Thesis Submitted to the Faculty of Montclair State University
In Partial Fulfillment of the Requirements For the Degree of Master of Science
May 2013
Investigating planetary magnetic fields:

I. Paleosecular variation and relative paleointensity curves from Maxwell Bay, Antarctica

II. Rock magnetic and remanence properties of natural and synthetic Martian basalts

A THESIS
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Paleosecular variation and relative paleointensity curves from Maxwell Bay, Antarctica

1 Introduction

Cruise NBP0502-1B was the first field season of the Shallow Drilling (SHALDRIL) Program (Anderson et al., 2005), conducted on the northeastern Antarctic Peninsula, an area experiencing dramatic climate change (Anderson et al., 2005; Milliken et al., 2009). Core NBP0502-1B was drilled from the center of a small basin in Maxwell Bay, South Shetland Islands (62° 16.931' S, 58° 45.230' W) in a water depth of 488 m (Figure 1). The core recovered a very high resolution, thick post-glacial section consisting of homogenous silty-clay lithology, preserving abundant shells, thus allowing the construction of a calcite based radiocarbon chronology (Milliken et al., 2009). The shallow water depth in Maxwell Bay likely places the core site above the local carbonate compensation depth (CCD), decreasing the rate of calcite dissolution and allowing the preservation of biogenic calcite. This enables the construction of an independently-dated climate record and paleomagnetic record, the latter of which can be used as a regional reference curve for the Antarctic Peninsula. Moreover, this site has the potential to fill a spatial gap in the distribution of paleomagnetic records that are used in geomagnetic field models.

The goal of SHALDRIL was to penetrate through the glacial strata and acquire older deposits that will elucidate the changes in climate, cryosphere, biosphere and evolution of the Antarctic Peninsula. The drilling technology available at the conception of SHALDRIL restricted the total depth of drilling to 1000m including both the water column and sediment column. This technology was to be installed on the RV/IB Nathaniel B. Palmer (NBP). The objective of the SHALDRIL project is to acquire a
representative sampling of the upper Paleogene (65.5-23.03 Myr) and Neogene (23.03-2.588 Myr) strata on the shelf.

1.1 Maxwell Bay

King George Island is a volcanic island located in a subduction zone, which generates volcaniclastic sediment containing an abundance of Fe-oxides, making this an ideal site to collect sediments that would recover a good and stable recording assemblage. The base of King George Island is composed of rocks from the upper Jurassic and Cretaceous-Tertiary Andean intrusive suite (Barton, 1965), (Figure 2). The sub-bottom profile displays a series of three basins that are separated by sills; each basin contains up to 100 m of acoustically laminated sediment (Anderson et al., 2005). The SHALDRIL program wanted to drill at a soft sediment site and Maxwell Bay was target site because of a thick section in shallow water with a potential to generate a Holocene climate record, described in detail by Milliken et al., 2009.

2 Methods

Core NBP0502-1B was collected in 43 individual 3-m sections. The sedimentary record is 108 m long with 87% recovery (Milliken et al., 2009). Core NBP0502-1B was sampled using a combination of u-channels and paleomagnetic cubes. U-channels were collected from the archive halves of the core in long sections (75-150 cm) free of air gaps and disturbances, and extend down to 60.44 mbsf. Cubes (6.5 cc volume) were collected from the working halves where air gaps or disturbances created short sections (<75 cm). Paleomagnetic cubes were collected every 10-15 cm for Anisotropy of Magnetic
Susceptibility (AMS), Natural Remanent Magnetization (NRM), and Anhysteretic Remanent Magnetization (ARM). Unoriented samples for rock magnetism, hysteresis parameters, and scanning electron microscope (SEM) were collected every 50-75 cm throughout the entire core.

AMS measurements were done on AGICO KLY-4 Kappabridge at Montclair State University using an applied field of 300 A/m, with a frequency of 920 Hz. Each paleomagnetic cube was measured in 15 directions to acquire the orientation of the principal susceptibilities ($K_{\text{max}}$, $K_{\text{int}}$, $K_{\text{min}}$). NRM, and ARM of U-channels were subjected to stepwise alternating field (AF) demagnetization from 0 to 80 mT in 5-10 mT increments on a 2G model 755 Cryogenic Magnetometer with in-line AF demagnetization unit. Measurements were conducted at the Institute de Sciences de la Mer de Rimouski (ISMER) at the Université du Québec à Rimouski. ARM acquisition was imparted in a peak alternating field of 100 mT, and a DC field of 0.05 mT. NRM and ARM measurements of the paleomagnetic cube samples were conducted on an AGICO JR6 Spinner Magnetometer and subjected to AF demagnetization from 0 to 100 mT in 5-10 mT increments with varying decay rates of 0.0025 mT (for 5 mT to 60 mT) and 0.005 mT (for 80 mT and 100 mT) on a D-tech D-2000 AF Demagnetizer at Montclair State University. ARM acquisition was acquired in a peak alternating filed of 100 mT and a DC field of 0.05 mT.

Hysteresis parameters saturation magnetization ($M_s$), saturation remanence ($M_r$), coercivity ($H_c$), and coercivity of remanence ($H_{CR}$) were measured using a Princeton Measurements Corp. 3900-04C Vibrating Sample Magnetometer (VSM). Hysteresis loops were obtained using a 1T peak field. Induced magnetization was normalized by
mass and the paramagnetic and diamagnetic contributions were subtracted using a high field slope calculated between 0.7 – 1 T.

Temperature dependence of magnetic susceptibility was measured on an AGICO KLY-4 Kappabridge. The samples were measured during heating from room temperature to 700°C and back to room temperature. The measurements were conducted in a flowing argon gas environment and aluminum oxide was used as space filler to ensure contact between small samples and the temperature sensor.

Selected intervals were targeted for SEM analysis. Samples were treated with Calgon® and then placed in a sonicator for 5-10 minutes to disaggregate the sample. The samples were sieved at 63 microns, dried and embedded in epoxy. Grain mounts were polished, carbon coated and analyzed on a Hitachi S3400N scanning electron microscope (SEM) with a Bruker X-flash energy dispersive spectrometer. Nine intervals were selected throughout the core (Figure 3 and Table 1). In each interval, 20-50 Fe-oxides were analyzed at 15 kV in order to evaluate the magnetic mineral assemblage. Only those grains larger then 10 microns and that contained no Si (used here a measure of x-rays generated by neighboring grains) were used to calculate a mineral formula.

3 Results

3.1 Core Description

Core NBP05-02 1B contains 3 main sedimentary units. Unit I (0-58.3 mbsf) is a greenish-grey diatom-bearing silty mud. Unit II (58.3-105.2 mbsf) consists of alternating dark grey clay layers with silty mud layers. This unit has low diatom abundance and higher terrigenous content. Unit III (105.2-108.2 mbsf) is a clay-rich diamicton (Milliken
et al., 2009). The three sedimentary units are further subdivided into seismic facies (units A through F) and lithologic units (unit 1 through 9) (Table 2) on the basis of sub-bottom profiles and seismic records as described by Anderson et al., 2005, Milliken et al., 2009, (Figure 1). The % recovery is affected by air gaps in the core, slurry at the tops of the core sections, and occasionally disturbed at the base of the core barrel (Anderson et al., 2005). The air gaps average one per core, and range from a few cm to 20-cm in length. The shipboard party logged all intervals of gaps and obvious disturbances. The potential for core disturbance to impact paleomagnetic work is a serious consideration, and was the motivation for conducting anisotropy of magnetic susceptibility measurements.

3.2 Radiocarbon chronology

The radiocarbon chronology for Core NBP0502-1B is based on 29 samples, derived from carbonates including mollusks, gastropods, and shell fragments (Figure 4a). Accelerator mass spectrometry ages were determined at the Woods Hole NOSAMS facility (Milliken et al., 2009). The radiocarbon dates show a smooth progression of ages with depth from 0 to 94 mbsf (Figure 4a). The sedimentation rates varies by two-orders of magnitude from 0.7 mm/a to ~30 mm/a (Milliken at al., 2009). The base of Unit II is dated at 10.1 ka.

3.3 Anisotropy of Magnetic Susceptibility

Within sedimentary Unit I (0–58.3 mbsf), K_{min} inclination values are generally steeper than 55° and K_{max} inclination values are generally shallower than 15°. Within sedimentary Unit II (58.3–105.2 mbsf) K_{min} inclination fluctuates between values that are
steeper and shallower than 55°, and the $K_{\text{max}}$ inclination values are generally shallower than 20°. In sedimentary Unit III (105.2–108.2 mbsf) $K_{\text{min}}$ inclination values hover around 55°, and $K_{\text{max}}$ inclination values hover around 20° (Figure 4c and 4d). The AMS orientation parameters are independent of the amplitude of susceptibility, which is fairly uniform throughout the core. Steep and shallow $K_{\text{min}}$ inclination values are observed in samples with similar bulk susceptibilities.

3.4 Remanent Magnetization

3.4.1 Natural Remanent Magnetization (NRM)

This study presents two sets of data for NRM; one set belongs to the u-channel samples (Figure 5) and the other belongs to the paleomagnetic cube samples (Figure 6). Measurements from 0 to 86 mbsf are presented here. Both the cube and u-channel measurements for NRM record a strong, stable remanent magnetization with an easily-isolated characteristic component. Principle component analysis (PCA) on paleomagnetic cubes was performed using the 20-50 mT AF demagnetization steps, with a few exceptions. The intervals where the PCA measurements were calculated from 30-60 mT were sometimes, though not always characterized by diatomaceous mud, silty mud, and mottled intervals. In certain intervals, 30 mT was necessary to remove the drilling overprint (Figure 7). PCA on the u-channels samples was performed using 20-50 mT AF demagnetization steps. PCA inclination for both the u-channels and paleomagnetic cubes values are steeply negative and fluctuate around the geocentric axial dipole (GAD) field value of -75°, though a few samples have shallower and steeper values (Figure 5b and 6b).
The PCA inclination for u-channels and paleomagnetic cubes range between 2.9° to -89.9° and 36.6° to -87.7° respectively, prior to cleaning the dataset for u-channel edge effect, turbidites, ash layers, gravel grains, or other non-field influences responsible for excessively shallow and positive inclination values. Between 0 to 71.5 mbsf, intervals of shallow PCA inclinations sometimes correspond with $K_{\text{min}}$ inclinations less than 55°. MAD angle values for u-channels and paleomagnetic cubes range between 0.2° to 15.8° and 0.6° to 25° respectively, though the values for u-channels are generally less than 3° and for paleomagnetic cubes, the values are generally less than 5°. The paleomagnetic cubes have a volume of 6.5 cm$^3$, however, the sample may not fill the entire cube, and hence the samples move in the spinner magnetometer as the measurements are being conducted, leading to higher MAD values. The MAD values that result from the u-channel data have a smaller variability than the MAD values for paleomagnetic cube measurements (Figure 9). However, the changes during alternating field demagnetization are similar for both cubes and u-channels. Further, the resulting PCA inclination values for the u-channels and paleomagnetic cubes are similar.

NRM median destructive field (MDF) values for u-channels and paleomagnetic cubes range between 3.2 and 34.8 mT and 2.9 and 40 mT respectively. The u-channel MDF values display a decrease in intensity from 30 mT at the top of the core to 20 mT at 40 mbsf. The intensity then increases to approximately 25 mT from 40 mbsf to 60 mbsf. Intervals affected by drilling overprints have MDF value less than 10 mT. In Unit I, the paleomagnetic cubes display a decrease in intensity from 35 mT to 30 mT. At the base of Unit I, the MDF decreases to less than 10 mT. Through Unit II the MDF values for paleomagnetic cubes are fairly stable at 25 mT.
The u-channel data measured at the Institut des Sciences de la Mer de Rimouski (ISMER) Université du Québec à Rimouski (UQAR) was "cleaned" to remove edge effect; 6 data points (6-cm) were removed from the top and the bottom of each u-channels. In addition to removing intervals for edge effects, intervals that were identified as volcanic ash, turbidities and air gaps were also removed because they would be local phenomenon and are not good recorders. Figure 8 displays the progression of the removal of these intervals. After the removal of intervals indicated above, there are 2 intervals remaining that display a sudden increase in NRM intensity, which are no longer present at 20 mT AF demagnetization, suggesting that those intervals represent drilling overprint that has been successfully removed at the 20 mT AF demagnetization level. These intervals also display high MAD values and low MDF values. The completed RPI and PSV will have a combination of u-channels and paleomagnetic cube measurements.

3.4.2 Anhysteretic Remanent Magnetization

ARM intensities from the paleomagnetic cube and u-channel samples display a steady decrease during AF demagnetization. The 0 mT ARM values of the u-channels and paleomagnetic cubes are very close to each other. The ARM measurements for paleomagnetic cubes are still in progress; hence there is limited amount of data available. The u-channel 0 mT ARM intensities vary between 0.3 and 1.3 A/m (Figure 10a). The 0 mT ARM intensity for paleomagnetic cubes varies between 0.4 and 1.2 A/m (Figure 10b). There is an interval that displays near 0 A/m, this interval has been identified as diatomaceous silty mud with drilling disturbance, and may contain an air void. The close proximity of values in both the paleomagnetic cubes and u-channels indicates that the
samples are capable of retaining intense remanences, and the two different sampling and measurement methods yield comparable values. ARM is used as the normalizing parameter to construct an RPI record, where $RPI = \frac{NRM}{ARM}$ at a given AF demagnetization level (Figure 11).

### 3.5 Hysteresis parameters

Hysteresis parameters (Figure 12) $M_R / M_S$ values vary from 0.06-0.12 and $H_{CR} / H_C$ values vary from 3.36-6.10. The samples plot primarily in the lower left hand corner of the pseudo-single domain (PSD) field, with a small number of samples plotting to the right of the PSD field of a Day Plot (Day et al., 1977) (Figure 12a). We observe no difference in hysteresis parameters between samples with steep vs. shallow $K_{min}$ inclination values (Figure 12b). Most of the clay rich intervals display a higher $M_R / M_S$ ratio and a lower $H_{CR} / H_C$ ratio, however the greatest variability is present in clay with green laminations. Diatomaceous silty mud intervals display a smaller variability than silty mud, though both sample types plot close together (Figure 12c).

### 3.6 Curie temperatures

Thermomagnetic curves display 4 features at approximately 150°C, 300°C, 450°C and 550°C (Figure 13). We interpret these features to represent titanium-rich titanomagnetite or ilmenite, an iron sulfide such as pyrrhotite, and two titanomagnetites with moderate Ti and Ti-poor compositions, respectively. Some of the samples exhibited a strong sulfur smell during heating, suggesting the presence of sulfides. No difference is seen in thermomagnetic curves between samples with steep vs. shallow $K_{min}$ inclination
values. All of the samples tested yielded higher amplitude of susceptibility for the cooling curve, suggesting some alteration of the sample that generated magnetic material during heating.

### 3.7 Scanning Electron Microscope

The amount of measurements for this study is limited by the iron oxide grain size. Most of the grains observed in the intervals measured were smaller than 5 μm, hence were not used for analysis (Figure 14). Most of the grains analyzed were less than 15 μm in diameter, which falls within the PSD range for titanomagnetite. The data indicates that there is variability in the elemental Fe wt% and Ti wt% in Unit I. This variability decreases towards the middle of the core in Unit II (Figure 15). The distribution of Fe wt% vs. Ti wt% displays three clusters; the greatest variability is in the upper right hand corner, the other two clusters plot at lower Fe and higher Ti content (Figure 16). The largest cluster primarily corresponds to moderate Ti titanomagnetite, consistent with the Curie temperature measurements. Even though there are 3 clusters, the data forms a single trendline. The range of elemental Fe wt% and Ti wt% are roughly constant regardless of the value of magnetic susceptibility (Figure 16b and 16c). The range of grain size decreases down core in Unit I and increases down core in Unit II (Figure 17). Overall, a very similar Fe-Ti-oxide assemblage is present throughout the core (Figure 18).

SEM data is supported by Curie temperature data, indicating titanomagnetites (Fe$_{3-x}$Ti$_x$O$_4$) are present in all of the intervals measured. Titanomagnetites are separated in 3 ranges, Ti poor titanomagnetite ($X < 0.1$), moderate Ti titanomagnetite ($0.1 < X <$
0.6) and a Ti rich titanomagnetite (X > 0.6). A moderate Ti titanomagnetite is the only oxide mineral that is present in all of the intervals examined. Ti-rich titanomagnetite abundance is variable down core. Ti-poor titanomagnetite is fairly constant down core.

When restricted to grains > 10 μm, the number of grains for which a quantitative mineral formula can be calculated is significantly decreased. In some cases, only 1 grain per horizon was available for this calculation (Table 3). Therefore, these formulas are not entirely representative of the interval and the data should be viewed with scrutiny.

4 Discussion

Anisotropy of magnetic susceptibility (ASM) data was used to assess whether the SHALDRIL drilling system introduced core disturbance, as has been seen with some coring systems (Anderson et al., 2005). The SHALDRIL shipboard party observed slurry at the tops of core sections, which likely resulted from cave-ins of the drill hole walls, or coring-induced disturbances that caused material to accumulate at the bottom of the hole between successive “pushes,” similar to the slurry that exists at the top of each Ocean Drilling Program 9.5-m hydraulic piston core. The shipboard party observed air gaps that were speculated to be caused by gas expansion, some of which were amplified when dragging the cutting wire through each section to separate the archive and working halves. Therefore, AMS measurements were used to assess the presence or absence of coring-induced disturbance that would affect the paleomagnetic signal in the core.

From 0 to 72 mbsf, the $K_{\text{min}}$ inclination values are steeply oriented, indicating no drilling disturbance. From 72 to 108 mbsf, the $K_{\text{min}}$ inclination values vary between steep and shallow orientations. Seismic facies B contains inclined discontinuous, downlapping
seismic reflectors, interpreted as sediment-gravity flows (Milliken et al., 2009). Therefore, stereonets were generated to assess the evolution of the AMS fabric in the base of Unit I and top of Unit II, and better define the top of the inclined seismic reflectors (Figure 1 and 19). Samples from section 26E (beginning 66.57 mbsf in Unit II) show “normal” sedimentary fabrics, with near vertical $K_{\text{min}}$ inclination values. $K_{\text{max}}$ and $K_{\text{int}}$ inclination values are shallow and randomly distributed within the girdle of the stereonet, which is interpreted to coincide with the bedding plane. Samples from section 28E (beginning at 72 mbsf in Unit II) display a steady decrease in $K_{\text{min}}$ inclination values towards horizontal, the $K_{\text{int}}$ inclination values show no clear pattern, and $K_{\text{max}}$ inclination values make two clusters within the bedding plane. Samples from section 30E (beginning at 75.73 mbsf in Unit II) display no preferential orientation for $K_{\text{max}}$, $K_{\text{int}}$, $K_{\text{min}}$ inclination values. Section 36E (beginning at 91.57 mbsf in Unit II) display three distinct clusters of $K_{\text{max}}$, and $K_{\text{int}}$ inclination values.

The Flinn diagram, which plots lineation ($L = K_{\text{max}}/K_{\text{int}}$) vs. foliation ($F = K_{\int}/K_{\text{min}}$) shows that samples with $K_{\text{min}}$ inclinations greater than 55° plot in the oblate field (Figure 20). Samples with $K_{\text{min}}$ inclination less than 55° fall in both the oblate and prolate fields. Ellipsoid shape indicates sediment fabric, which corresponds at times with bulk grain size distribution. The majority of the samples plot in the oblate faction, even though the samples with $K_{\text{min}}$ less than 55 plot in the prolate faction, the deviation from a sphere is less than 8%, which suggests minimal deformation of the grains. On the basis of these observations, we speculate that the non-vertical $K_{\text{min}}$ inclinations below 72 mbsf and clustering of $K_{\text{min}}$, $K_{\text{int}}$, and $K_{\text{max}}$, values result from either fabrics imparted during sediment-gravity flow emplacement, or deposition and subsequent rolling of grains on an
inclined surface. We therefore interpret the top of the sediment-gravity flow unit to be at 71.5 mbsf, which corresponds to 9.1 ka. Due to the presence of the sediment-gravity flows, the paleomagnetic inclinations and declinations below 71.5 mbsf must be viewed with caution. Below 71.5 mbsf, shallow $K_{\text{min}}$ inclination values do not correlate with shallow PCA inclinations, and the MAD values remain low, indicating that the RPI values from this interval can be reliable; likely at the top of sediment gravity flows where the fine particles have settled out of suspension.

The PCA inclinations from u-channels and paleomagnetic cubes vary from moderately positive values to steeply negative values. However, they do dwell within $\pm 10^\circ$ of the present-day field value of $-55^\circ$ and the GAD value of $-75^\circ$ (Figure 5b and 6b). A preliminary relative paleointensity (RPI=ARM/NRM) was calculated for both the u-channels and paleomagnetic cubes (Figure 11). Further refinement of RPI will be done using multiple AF demagnetization levels and via comparison with IRM-normalized RPI.

5 Conclusions

NBP0502-1B possesses a uniform magnetic recording assemblage. Down-core hysteresis parameters plot predominantly in the pseudo-single domain field of a Day Plot, with a few outliers to the right of the PSD field on a Day Plot. Curie temperature data suggests the presence of three titanomagnetites with Ti-rich (or possibly ilmenite), moderate-Ti and a Ti-poor composition. A magnetic iron sulfide may also be present. The SEM oxide mineralogy data supports the presence of Ti-poor, moderate Ti and Ti-rich titanomagnetites, with some magnetite, rutile, and pyrite.
AMS data shows normal sedimentary fabrics from 0-72 mbsf, where $K_{\text{min}}$ inclination values are near vertical and $K_{\text{max}}$ and $K_{\text{int}}$ values are within the bedding plane. The majority of the samples plot in the oblate field of a Flinn Diagram. This provides confidence in the fidelity of the paleomagnetic record within this interval. Between 72-95 mbsf, $K_{\text{min}}$ values are shallower than 55°. Below 95 mbsf, the $K_{\text{min}}$ inclination values are primarily vertical. Core sections below 72 mbsf display clustering of $K_{\text{min}}$, $K_{\text{int}}$, and $K_{\text{max}}$ inclination values. As indicated by the stereonets, shallow $K_{\text{min}}$ inclination values and axis clustering is likely due to deposition on an inclined surface and/or fabrics controlled by sediment-gravity flows.

NRM measurements indicate that core NBP0502-1B records a strong, stable remanent magnetization with low MAD values, and whose inclination values are consistent with expectations for a high southern latitude site. Samples from within Seismic Unit B, characterized by sediment-gravity flows, will receive extra scrutiny. Our data suggest that paleomagnetic inclination and MAD values within Seismic Unit B are similar to the upper 72-m of section. Post-depositional realignment of magnetic grains in the fine-grained tops of the sediment gravity flows may have allowed the finer titanomagnetite grains to properly reorient with the ambient field. U-channel and cube data will be merged to construct a Holocene record of paleosecular variation and relative paleointensity, which can then be used as a reference curve for tuning other un-dated sedimentary records in the Antarctic Peninsula region.
6. References
II Rock Magnetic Analyses of Natural and Synthetic Martian Basalts

1 Introduction

In the presence of an external magnetic field, the total field measurement is composed of 3 components: the local field at the measurement location, the component of magnetization that the local field induces in the sample and the remanent magnetization carried by the sample. The smallest contribution to the magnetic field of a planetary body is provided by the remanent magnetization of crustal rocks and sediment. These remanent magnetization features located at the surface and within the shallow crust are termed "magnetic anomalies." The magnetization depends on the composition of the recording material, the intensity of the planetary magnetic field at the time of the material's formation, and the type of magnetic recording process.

The goals of this project are to better understand the origin, intensity, and long-term stability of the Mars crustal anomalies detected during the Mars Global Surveyor (MGS) mission, and to determine the magnetic mineral assemblage of the Martian crust. This project is the fourth project in a series to investigate igneous origin for Martian crustal anomalies. This study builds on previous work using synthetic analogs of the Mars crust (Hammer, 2006; Brachfeld and Hammer 2006; Bowles et al., 2009, 2012). These studies found that samples synthesized under moderately oxidizing quartz-faylite-magnetite (QFM) conditions acquired intense thermoremanent magnetizations (TRM) even in relatively weak applied fields. This study investigates samples generated at more reducing conditions, specifically iron wüstite (IW) +1, a value common for the Mars SNC meteorites, using a combination of natural and synthetic analogues of shergottite meteorite Yamato-980459.
1.1 Mars Global Surveyor Missions

The MGS, magnetic field experiment/electron reflectometer (MAG/ER) observed a lack of a magnetic field that has an internal origin but did observe distinct, intense remanent magnetization located in the southern hemisphere (Acuña et al., 1999). This was surprising, as Mars does not possess a dynamo field of internal origin. The magnetized region is south of the crustal dichotomy, which marks the boundary between the younger northern lowlands and the older southern-cratered highlands (Figure 21) (Acuña et al., 1999). Based on the absence of crustal magnetism in the northern lowlands, the Martian dynamo is hypothesized to have been active during the early history of the planet, and shut off during the early Noachian (4 Ga). This date is determined by the impact crater size-frequency distributions that help estimate the age of the crust surrounding the crustal anomalies. This suggests that the crust of the northern lowlands formed and cooled in the absence of an external magnetic field. Several variables contribute to the observed intensity of the Martian crustal anomalies, which include remanence acquisition process, intensity of the magnetizing field, efficiency of magnetic recording assemblage, thickness of the magnetized layer and subsequent alternations of the remanent magnetization (Brachfeld and Hammer 2006).

The observed anomalies are oriented east-west, they extend 1000–2000 km in length and 200 km in width, and alternate between positively and negatively magnetized strips. This dwarfs the sea-floor spreading anomalies on Earth that are 10-100 km wide (Connerney et al., 1999). The crustal magnetic signal measured on Mars is entirely remanent since Mars currently does not possess a geodynamo field that could induce a magnetization within the crust. The crustal magnetic anomalies are more than 10 times
the intensity of the observed terrestrial anomalies (Acuna et al., 1999 and references therein). The Thermal Emission Spectrometer (TES) aboard MGS helped generate the first global mineral map of the Martian crust, which is dominated by primary volcanic minerals (plagioclase feldspar, pyroxene, and olivine) along with high silica, and poor crystalline material. The differences in abundance of the minerals grouped the rock composition into two categories, basalt and basaltic andesite.

Proposed remanence acquisition processes and remanence carriers include thermoremanent magnetization (TRM) carried by titanomagnetite, TRM carried by multi-domain hematite (Dunlop and Kletetschka, 2001), lamellar magnetization in which exsolution lamellae subdivide an initially homogenous multi-domain grain into stable single domain regions, (McEnroe et al., 2004), and a chemical remanent magnetization (CRM) acquired during decomposition of siderite to magnetite (Scott and Fuller, 2004). While this study does not explore all of the processes, all of the processes listed above are strongly influenced by the composition of the magnetic mineral assemblage.

1.2 Previous Studies

This thesis project builds on previous experimental studies that employed synthetic basalts to investigate the igneous origins of Martian crustal anomalies. The goal is to evaluate the mineralogy, texture, and magnetic properties of natural and synthetic samples as a potential source of Mars magnetic anomalies. Previous studies by Brachfeld and Hammer, 2006 and Bowles et al., 2009, employed basalts synthesized at the University of Hawaii Experimental Petrology Laboratory. The Shergotty-Nahkla-Chassigny (SNC) meteorites can be used as compositional guides to elucidate the origin
and compositional information about the Martian crust. Some of the SNC meteorites that were originally part of Mars' lithosphere but were ejected during large impact events and may have recorded the ancient mars filed. The SNC data suggests intensities similar to the current terrestrial magnetic field (Weiss et al., 2002). If the intensity of the ancient Mars field was similar to Earth's current field, then an exceptionally efficient carrier of remanence is required to produce the observed intense anomalies (Weiss et al., 2002).

Brachfeld and Hammer, 2006 experimented with basalts that were synthesized at 4 oxygen fugacity (fO₂) buffers from iron-wustite (IW), which is 3.44 log units below the quartz-faylite-magnetite (QFM) buffer to 5 log units above the QFM buffer. The study indicated that samples synthesized under the IW buffer display a low concentration of remanence carrying grains, whose sizes are likely near the superparamagnetic (SP) and stable-single domain (SSD) boundary. Samples that were synthesized under the QFM and nickel-nickel oxide (NNO) buffer displayed a slightly higher concentration of remanence carrying grains, acquired strong TRM's and were within the SSD and pseudo-single domain (PSD) regions of a Day Plot. The highest concentration of remanence carrying grains were generated by the manganese oxide (MNO) buffer and ranged up to 100 μm in diameter. However, MNO conditions are likely restricted to the Martian surface and are unrealistic for the interior of Mars. Results indicated that titanomagnetites that crystallize from Fe-rich melts can acquire intense remanent magnetizations even in the presence of a weak applied field. The QFM sample set carried the highest anhysteretic remanent magnetization (ARM)'s and TRM's, thus can account for the intense anomalies detected on Mars (Brachfeld and Hammer, 2006).
Bowles et al., 2009 experimented with two distinct compositions, meteorite type (M-type) and terrestrial-type (T-Type). These samples were generated at \( f/O_2 \) conditions between IW+2 and QFM. The goal of this study was to understand how varying bulk melt compositions (primarily Fe/Al ratio), \( f/O_2 \), and cooling rates affect magnetic assemblages in rapidly cooling basalts. The M-Type basalt is Fe-rich and Al-poor, with Fe/Al = 1.5, and represents SNC parent melts with small amounts of Mn and Cr. T-Type composition is Al-rich and Fe-poor with Fe/Al = 0.4, is slightly richer in Ca and resembles terrestrial type basalts. The samples in this study are most applicable to models in which the Martian crust is generated through volcanism. This study determined that samples generated under IW+2 to QFM conditions results in intense magnetization in both compositions, but the presence of Cr also results in an increase in magnetic grain size, which can affect the long-term stability of the remanence in QFM samples.

Cuomo, 2010 studied T-type and M-type synthetic compositions that were annealed between 21 to 158 days to study the properties of slow cooled shallow intrusions of Martin composition. All samples acquired intense remanences during synthesis, which is assumed to be a thermoremanent magnetization (TRM) acquired from the laboratory field. The low coercivity of the samples suggests that these materials would be quickly demagnetized by shock demagnetization during meteorite impacts. The study concluded that despite the ability of the samples to acquire strong remanences that could account for the anomalies seen on Mars, the soft coercivity of the samples discredit these samples as carriers of the crustal anomalies.
2 Sample Description and synthesis processes

2.1 Yamato-980459 (Y-980459)

This project examines one natural and one synthetic SNC meteorite, an olivine-phyric (containing large crystals of olivine) shergottite, Yamato-980459 (Y-980459) and a sulfur-free analog of Y-980459. Based on the alkali-silica content, olivine-phyric shergottites are basalts whose elemental abundances are similar to basaltic shergottites, but they have higher MgO, Ni and Cr concentrations with lower Si content (McSween, 2008). Their launch sites on Mars consist of multiple flows through time.

Y-980459 in experimental studies can be used to represent a primary melt (Usui et al., 2009), i.e., a melt derived directly from the Mars mantle without subsequent differentiation. Y-980459 is basaltic in composition, with large olivine phenocrysts with prismatic pyroxenes that are encased in glassy groundmass that has Fe-rich olivine, chromite, dendritic olivine, chain-like augite, and iron sulfides. This sample lacks plagioclase/maskelynite, which is commonly found in meteorites (Gershake et al., 2003, Usui et al., 2009, First and Hammer 2012, First et al., 2013). Y-980459 formed under IW+1 conditions (Shearer et al., 2006). Y-980459 is of interest because it allows us to test the remanence-carrying abilities of Fe-rich basalt generated at low $f_{O_2}$ and which contains both Fe-oxides and Fe-sulfides. The sulfur-free analog of Y-980459 (hereafter referred to as Y-98*), allows us to examine the contributions of iron sulfides to the magnetic signatures of two basalts that are otherwise identical with respect to major element composition.
Four Y-980459 chips were obtained for magnetic analyses, with chip masses ranging between 3.5 and 9.0 mg. The samples were provided by the National Institute Research Program (NIPR) for Antarctic Meteorites.

2.2 Synthetic Y-98*

The composition of Y-98* was based on two previous studies done by Gershake et al., 2003 and Misawa 2010 (Table 4). Two batches of Y-98* (Y-98* f48 and Y-98* f49) were generated by Dr. Julia Hammer and Emily First at University of Hawaii at Manoa to test for reproducibility of the synthesis process and run products. Y-98* samples were held at 1384.5°C for 12 hours, cooled to 1113°C at 28°C/h, cooled to 909°C at 320.6°C/h and then quenched in water. The samples were suspended from Pt wires (Figure 22), which were electro plated with iron (Fe) to mitigate the Fe loss from the sample to the wire. Samples from Y-98* f48 went below IW conditions for the last 5 minutes, thus reduction might have taken place due to low efficiency of gas mixing. Samples from Y-98* f49 were synthetized at IW+0.8 (within 0.2 log units of IW+1). The finished bead was broken off the wires and masses determined for the largest pieces.

3 Methods

An AGICO KLY-4 Kappabridge was used to determine the magnetic susceptibility (χ) of natural and synthetic basalts in an alternating field of 300 A/m. A D-tech D-2000 AF Demagnetizer, AGICO JR6 Spinner Magnetometer, and ASC Scientific IM-10-30 Impulse Magnetizer were used to determine the natural remanent magnetization (NRM), anhysteretic remanent magnetization (ARM), and isothermal
remanent magnetization (IRM), of natural and synthetic basalts. For NRM measurements, an AF demagnetizing field from 0 to 100 mT was used with a decay rate of 0.0025 mT for (5 to 60 mT) and a decay rate of 0.005 mT for (80 to 100 mT). ARM acquisition was imparted with an alternating field (AF) of 100 mT, decay rate of 0.005 mT in a DC field of 0.1 mT. IRM acquisition was imparted at 300 volts, which produced a 1T field. The Princeton Measurements Corp. Vibrating Sample Magnetometer (VSM) 3900-04C was used to determine the hysteresis parameters saturation magnetization ($M_s$), saturation remanence ($M_r$), coercivity ($H_c$), and coercivity of remanence ($H_{cr}$). Hysteresis loops were obtained using a 1T peak field. Induced magnetization was normalized by mass and the paramagnetic and diamagnetic contributions were subtracted using a high field slope calculated between 0.7 – 1 T. Magnetic susceptibility, NRM, ARM, IRM, and hysteresis parameters were measured by encasing the samples with Fiberfrax® in a gelatin capsule to immobilize the sample while the measurements are conducted.

4 Results

4.1 Yamato-980459

The natural Y-98 samples contain iron sulfides and chromites and lack magnetite (First et al., 2013; Shah et al., 2013). Preliminary electron microprobe analyses of Y-980459 indicate an average chromite composition of $\text{Cr}_1.66\text{Fe}_{0.65}\text{Mg}_{0.39}\text{Al}_{0.27}\text{Ti}_{0.01}\text{O}_4$. Some of the chromites contain slightly more Ti and slightly less Cr (Figure 23). The average composition of the iron sulfides is 57.61 wt% Fe and 37.83 wt% S. The iron sulfides also contain 0.61 to 6.94 wt% Ni (First et al., 2013) (Figure 23).
Preliminary electron microprobe analysis of Y-98* spinels are very similar (Figure 24), with an average composition of $\text{Cr}_{1.59}\text{Fe}_{0.63}\text{Mg}_{0.43}\text{Al}_{0.29}\text{Ti}_{0.02}\text{Mn}_{0.01}\text{O}_4$. The four chips of Y-980459 are weakly magnetic with magnetic susceptibility values ranging between $5.14\times10^{-7}$ to $6.34\times10^{-7}$ $\text{m}^3/\text{kg}$, similar to values previously reported by Hoffman et al., 2010 (Figure 25).

Samples of Y-980459 display two different behaviors; Category 1 (chips 1 and 3) display a higher intensity of magnetic susceptibility, NRM, ARM and IRM than samples in category 2 (chips 2 and 4). Category 1 samples display NRM$_0$ (0-mT) intensities of 0.0354 to 0.0420 mAm$^2$/kg, ARM$_0$ (0-mT) intensities of 0.198 to 0.220 mAm$^2$/kg and IRM$_0$ (0-mT) intensities of 14.1 to 14.2 mAm$^2$/kg. Category 2 (Chips 2 and 4) display NRM$_0$ values of 0.0191 to 0.00774 mAm$^2$/kg, ARM$_0$ values of 0.175 to 0.183 mAm$^2$/kg, and IRM$_0$ values of 13.5 to 14.1 mAm$^2$/kg.

While all 4 chips acquire a remanence during alternating field (AF) demagnetization of NRM, category 2 samples display a nearly 5-fold increase above the starting NRM values (Figure 26). Chips 1, 3 and 4 display a “normal” behavior during AF demagnetization of ARM, for which ARM/ARM$_{\text{max}}$ decays steadily with peak-applied field (Figure 27). The IRM measurements for Y-980459 were all similar to each other and independent of category (Figure 27), and hysteresis parameters for all 4 Y-980459 chips plot in upper left region of the PSD region on the Day Plot (Figure 28).

4.2 Synthetic Y-98*

The four beads of the Y-98* recorded a magnetic susceptibility between $3.56\times10^{-7}$ to $3.91\times10^{-7}$ $\text{m}^3/\text{kg}$ (Figure 25). The magnetic susceptibility of FePt wires were also
tested and the values range from $1.72 \times 10^{-5}$ to $2.98 \times 10^{-5}$ Am$^2$/kg. This indicates that the FePt wires are approximately 30% more intense than their corresponding beads. The susceptibility of metal, particular one containing Fe will dwarf a collection of mostly paramagnetic material, emphasizing the need to separate the sample from the wire prior to magnetic analysis.

Y-98* samples display NRMO values of 0.0102 to 0.0261 mAm$^2$/kg. No NRM AF demagnetization was measured because the beads were broken off the wire, which resulted in several randomly oriented fragments of various size fractions. ARMo values vary between 0.0121 to 0.0244 mAm$^2$/kg, and IRMo values vary between 1.13 to 1.75 mAm$^2$/kg. The intensities recorded by the Y-98* are much weaker than those of Y-980459. ARM AF demagnetization behavior is noisy (Figure 29), reflecting the overall low concentration of magnetic grains comprised of weakly magnetic chromite.

Y-98* samples plot near to the bottom right corner of the PSD field (Day et al., 1977) (Figure 28). Hc values for Y-98* are high (43-75 mT), suggesting that a high-coercivity mineral is present in Y-98*, one that is unresponsive to the low applied field used for ARM acquisition, but that is magnetized by the 1-T pulse field used to impart IRM.

5. Discussion

Understanding the intensity and long-term stability of remanent magnetization for both the natural and synthetic samples can indicate which synthetic basalts are efficient carriers of remanence, resistant to shock demagnetization during meteorite impacts and
therefore stable over geologic time. The analyses of these parameters will allow us to improve our interpretation of the Mars crustal anomalies.

Hysteresis parameters for Y-980459 are comparable to those of rapidly cooled Fe-rich basalts synthesized at QFM (Cr-free) and IW+2 (Cr-bearing) conditions (Brachfeld and Hammer, 2006; Bowles et al., 2009), which contained Fe-Ti-Mg-Al spinels and Fe-Ti-Cr-Mg-Al spinels, respectively, and were sulfur-free. The hysteresis parameters of Y-980459 are controlled by iron sulfides. Although the iron sulfide grains observed in Y-980459 are several tens to > 100 μm, iron sulfides such as pyrrhotite and greigite have larger \( M_r/M_s \) ratios and smaller \( H_{cr}/H_c \) ratios than magnetites of the same grain size (Dekker, 1988; Roberts et al., 2011), making sulfide-bearing samples appear finer-grained when displayed on the magnetite-calibrated Day plot. Y-98*, which lacks sulfur, plots in the lower right corner of the PSD field along with other Cr-bearing Fe-rich basalts synthesized at IW through QFM conditions (Bowles et al., 2009).

Overall, Y-98* shows very similar magnetic properties to Fe-rich, Cr-bearing and Cr-free basalts synthesized at IW to IW + 2 \( fO_2 \) conditions. The major differences in behavior between Y-980459 and Y-98* are due to the presence of magnetic iron sulfides in Y-980459, which lead to higher intensities of natural and induced remanences and greater resistance to AF demagnetization. However, Y-980459 is still 1 to 2 orders of magnitude more weakly magnetic than basalts of the same composition that were synthesized at QFM \( fO_2 \) conditions.

The NRM and ARM measurements of the Y-980459 samples suggest acquisition of a gyroremanent magnetization (GRM). The increase in intensity of NRM during AF demagnetization is likely a GRM, a spurious remanence acquired perpendicular to the
applied field during AF demagnetization. GRM acquisition is a common behavior in iron sulfide greigite (Fe$_3$S$_4$) and pyrrhotite (Roberts et al., 2011 and references therein; Thompson 1990). This is consistent with the microprobe observations of Fe-sulfide grains, and Ni-bearing pyrrhotite in natural Y-980459. The ARM values and trends of chromite-only Y-98* do not replicate the behavior seen in the Y-980459 samples. The IRM median destructive field (MDF) for Y-980459 is higher (35 mT) than that of Y-98* (20 mT). Overall, while Y-908459 possesses a moderately efficient recording assemblage comprised of high-coercivity pyrrhotite, the intensity of remanence acquired suggests that basalts synthesized under reducing conditions are not capable of generating the high-amplitude anomalies detected by the Mars Global Surveyor mission.

6. Conclusions

Four chips of Y-980459, a primitive member of the shergottite group of Martian meteorites, have been analyzed for magnetic properties to better understand the magnetic recording assemblage and remanence properties of the Martian crust. Y-980459 samples have similar $\chi$ and NRM values to those reported by Hoffman et al., 2010, and similar magnetic properties to synthetic Mars basalts synthesized under IW to IW+2 $fO_2$ conditions (Brachfeld and Hammer 2006; Bowles et al., 2009). Y-980459 samples acquired a GRM during AF demagnetization of the NRM, which we attribute to the presence of ferromagnetic sulfides. The sulfur-free compositional analog Y-98* has weaker susceptibility, NRM, ARM and IRM than Y-980459. Our results suggest that basalts formed under conditions more reducing than QFM are not capable of retaining intense remanent magnetization needed to generate crustal anomalies seen on Mars.
7. References


Hoffman, V.H., Funkai, M., Torri, M., 2010, Comparing the Magnetic Signatures of MWA 5789 and Yamato 980459 Olivine Phryic Shergottites, 73rd Meeting of Meteoritical Society, Abstract# 5338, New York City, NY.


Figures and Tables

Figure 1: Study area

(a) Map of the Antarctic Peninsula. (b) Bathymetry map of Maxwell Bay. The star indicates the location of NBP05-02 core 1B. (c) Close up of bathymetry in Maxwell Bay. (d) 3.5 kHz chirp record across Maxwell Bay (Milliken et al., 2009).
Geological map of King George Island with exposed outcrops. The red star indicates the drill site. The two main units in the vicinity are uTv (Upper Tertiary volcanic rocks) and KT (Cretaceous – Triassic Andean Intrusive rocks) (Adie, 1969).
Figure 3: Unit Correlation

The asterisks indicate SEM sample horizons. The red line indicates seismic units, the green line indicates lithologic units, and the purple lines indicate seismic facies. Numbers on each line are depth in meters.
Figure 4: Lithostratigraphy, age model, Anisotropy of Magnetic Susceptibility

a) Lithostratigraphy and radiocarbon chronology (after Milliken et al., 2009). (b) Mass-normalized magnetic susceptibility ($\chi$). (c) Inclination of the minimum susceptibility axis ($K_{\text{min}}$). (d) Inclination of the maximum susceptibility axis ($K_{\text{max}}$).
Figure 5: U-channel data

U-channel data from 0 to 60.44 mbsf. (a) NRM at the 20 mT AF demagnetization level. (b) PCA inclination calculated from the 20-50 mT AF levels. The solid lines at -55° and -75° are the present day inclination and the GAD value at the core site, respectively. (c) MAD values. (d) Median destructive field (MDF) for the NRM.
(a) Cube NRM intensity at the 20 mT AF demagnetization level. (b) PCA inclination from the 20-50 mT AF demagnetization levels. The solid lines at -55° and -75° are the present day inclination and the GAD value at the core site, respectively. (c) MAD values. (d) MDF for NRM.
Figures a and d display NRM intensity vs. peak alternating field for samples with a drilling overprint for u-channels and paleomagnetic cubes respectively. Figures b and e display the normalized magnetic moment (J/Jo) after the removal of drilling overprint for u-channels and paleomagnetic cubes respectively. Figures c and f display NRM intensity vs. peak alternating field for samples without drilling overprint for u-channels and paleomagnetic cubes respectively.
Figure 8: U-channel edge effect correction

NRM vs. measurement number for u-channel samples. (a) Raw 0 mT NRM measurements. (b) 0 mT NRM profile after removal of edge effect, ash layers, turbidities and air gaps. (c) NRM at the 20 mT AF demagnetization level.
Figure 9: Comparison of u-channel and cubes PCA data

PCA inclination (left) and MAD values (right) for u-channels (red) and cubes (blue). Both data sets display similar intensities for each parameter plotted.
Figure 10: 0 mT ARM (A/m) intensities

ARM intensity for u-channels (left) and cubes (right).
Figure 11: Relative Paleointensity

Preliminary relative paleointensity (RPI) for u-channels and cubes, where (RPI = NRM/ARM).
Figure 12: Day plots

(a) Hysteresis parameters on the Day Plot. (b) Close-up of the hysteresis parameters distinguished by the $K_{\text{min}}$ inclination values. (c) Hysteresis parameters distinguished by lithology.
There are 4 features at approximately 150°C, 300°C, 450°C and 550°C. These features are interpreted as titanium-rich titanomagnetite or ilmenite, an iron sulfide such as greigite, and two titanomagnetites with moderate Ti and Ti-poor compositions, respectively.
Figure 14: Scanning electron microscope grain size images

Variations in grain morphology and composition from selected intervals. (a) An Fe-Ti oxide devoid of inclusions or intergrowths. (b) Hypermap illustrating elemental distribution. (c-e) Oxide grains within a lithic fragments. (d) Grain illustrating intergrowths within an oxide. (e and g) Oxide grains with inclusions. (f) Hypermap of Fe-oxide host with Ti-rich lamellae.
All data points are for grains > 5 μm. From left to right: Fe wt% and Ti wt%, from which Fe/Ti ratios were calculated (Figure 15c).
Figure 16: Distribution of Fe and Ti content

Fe and Ti composition of individual grains (top), and comparison with magnetic susceptibility.
Figure 17: Fe-Ti oxide grain size

Length and width of Fe-Ti oxide grains measured on the SEM.
Figure 18: Down core oxide mineralogy from scanning electron microscope

Minerals

Abundance of Ti-rich and Ti-poor titanomagnetite, rutile, and magnetite in selected horizons.
The top left is Section 26 ($K_{\min} > 55$), top right is Section 30 ($K_{\min} < 55$) and the bottom left is Section 36 (sediments on an inclined plane). The black dots are the $K_{\text{max}}$ inclination values, the blue dots are the $K_{\text{int}}$ inclination values and the orange dots are the $K_{\text{min}}$ inclination values. These stereonets indicate the variations in fabric orientation seen throughout the core. Section 26 shows a normal sedimentary fabric. Sections 28, 30, and 36 show the effects of grain rolling (sections 28 and 36) and randomization (section 30) within sediment gravity flows.
Figure 20: Flinn Diagram

Lineation ($K_{\text{max}}/K_{\text{int}}$) vs. foliation ($K_{\text{int}}/K_{\text{min}}$) diagram.
Figure 21: Map of Martian crustal magnetic anomalies

Intensity of the radial component of Martian crustal anomalies observed by the MGS (Connerney et al., 2005).
“Chandelier” set up for sample synthesis. Beads are approximately 3–4 mm.
Figure 23: Electron microprobe analysis for Y-980459 sulfides and oxides

(a) Image of Fe-sulfide from Y-980459. (b) Fe-Ni-S ternary plot of sulfides, with troilite and greigite plotted as end members. (c) Elemental wt% plot of sulfides. (d) Oxide wt% for chromites (After First et al., 2013 and Shah et al., 2013).
Figure 24: Backscatter electron images and spinel compositions for Y-98*

(a) Y-98* f48iii BSE image, (b) Y-98* f49ii BSE image (same scale as figure 5a). (c) BSE image of dendritic olivine. (d) BSE image of chromites. (e) Oxide wt% for spinels (after First et al., 2013 and Shah et al., 2013).
Figure 25: Magnetic susceptibility for the natural and synthetic Martian basalts

Magnetic susceptibility for synthetic basalts plotted with respect to the $f$/O$_2$ synthesis conditions, plotted as deviation from IW = 0.
Alternating field demagnetization of the NRM for natural Y-98, showing acquisition of a remanence during the experiment. This is likely a gyroscopic remanent magnetization (GRM) carried by pyrrhotite.
AF demagnetization of ARM (top) and IRM (bottom) for natural Y-98.
Summary of hysteresis parameters for synthetic basalts synthesized at IW to QFM conditions.
Figure 29: ARM and IRM for Y-98*

AF demagnetization of ARM (top) and IRM (bottom) for synthetic Y-98*.
<table>
<thead>
<tr>
<th>Sample (depth, mbsf)</th>
<th>Description</th>
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<tbody>
<tr>
<td>1E-91 (0.91 mbsf)</td>
<td>Medium to coarse mud</td>
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<tr>
<td>4E-171 (8.21 mbsf)</td>
<td>Medium sand layers</td>
</tr>
<tr>
<td>5E-241 (11.91 mbsf)</td>
<td>Silty mud</td>
</tr>
<tr>
<td>15E-171 (39.21 mbsf)</td>
<td>Silty mud, mottled</td>
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<tr>
<td>25E-86 (64.86 mbsf)</td>
<td>Ash, diatomaceous silty mud with black subhorizontal mottles, interbedded silt to very fine sand laminations</td>
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<tr>
<td>28E-63 (72.13 mbsf)</td>
<td>Ash, silty mud, prominent subhorizontal mottles, silt strings, diatomaceous, $K_{\text{min}} &lt; 55$, oblate flinn angle</td>
</tr>
<tr>
<td>29E-233 (76.33 mbsf)</td>
<td>Ash, silty mud, diatomaceous, faint subhorizontal mottles, silty to very fine sand strings, $K_{\text{min}} &gt; 55$, prolate flinn angle</td>
</tr>
<tr>
<td>30E-287 (78.37 mbsf)</td>
<td>Very dark gray silty mud, moderately mottled, diatomaceous, silty to very fine sand laminations, $K_{\text{min}} &lt; 55$, oblate flinn angle</td>
</tr>
</tbody>
</table>

Lithologic descriptions from the SHALDRIL cruise report (Anderson et al., 2005), along with parameters measured in this study.
Table 2: Core units and facies

<table>
<thead>
<tr>
<th>Sedimentary Units</th>
<th>Seismic Facies</th>
<th>Lithologic Units</th>
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</thead>
<tbody>
<tr>
<td>Unit I (0-58.3) mbsf</td>
<td>Unit F (0-11) mbsf</td>
<td>Units 7, 8, 9 (0-4) mbsf</td>
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<td></td>
<td>Unit E (11-30 mbsf)</td>
<td>Unit 6 (4-11) mbsf</td>
</tr>
<tr>
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<td>Unit D (30-54) mbsf</td>
<td>Unit 5 (11-30) mbsf</td>
</tr>
<tr>
<td>Unit II (58.3-105.2) mbsf</td>
<td>Unit C (54-73) mbsf</td>
<td>Unit 4 (30-54) mbsf</td>
</tr>
<tr>
<td></td>
<td>Unit B (73-104) mbsf</td>
<td>Unit 3 (54-73) mbsf</td>
</tr>
<tr>
<td>Unit III (105.2-108.2) mbsf</td>
<td>Unit A (104-108.2) mbsf</td>
<td>Unit 2 (73-103) mbsf</td>
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Units defined by (Milliken et al., 2009) based on sub-bottom profile sediment core description.
Table 3: Example mineral formulas on a 3-cation to 4 oxygen basis calculated from EDS data. (All grains greater than 10 microns).

<table>
<thead>
<tr>
<th>Interval</th>
<th>Depth (mbsf)</th>
<th>Ti poor Titanomagnetite</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>IE 91</td>
<td>0.91</td>
<td>2.96</td>
<td>0.04</td>
</tr>
<tr>
<td>4E 171</td>
<td>8.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5E 241</td>
<td>11.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15E 171</td>
<td>39.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25E 86</td>
<td>64.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28E 63</td>
<td>72.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29E 233</td>
<td>76.33</td>
<td>2.71</td>
<td>0.05</td>
</tr>
<tr>
<td>30E 287</td>
<td>78.37</td>
<td>2.74</td>
<td>0.07</td>
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<table>
<thead>
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<th>Depth (mbsf)</th>
<th>Mod Ti Titanomagnetite</th>
<th>Notes</th>
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<td>8.21</td>
<td>2.52</td>
<td>0.31</td>
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<td>5E 241</td>
<td>11.91</td>
<td>2.48</td>
<td>0.36</td>
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<td>15E 171</td>
<td>39.21</td>
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<td>72.13</td>
<td>2.39</td>
<td>0.42</td>
</tr>
<tr>
<td>29E 233</td>
<td>76.33</td>
<td>2.26</td>
<td>0.5</td>
</tr>
<tr>
<td>30E 287</td>
<td>78.37</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>Depth (mbsf)</th>
<th>Ti rich Titanomagnetite</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
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<td>0.74</td>
</tr>
<tr>
<td>4E 171</td>
<td>8.21</td>
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<td>0.68</td>
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<td>0.68</td>
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<tr>
<td>28E 63</td>
<td>72.13</td>
<td>2.07</td>
<td>0.6</td>
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<tr>
<td>29E 233</td>
<td>76.33</td>
<td>2.07</td>
<td>0.6</td>
</tr>
<tr>
<td>30E 287</td>
<td>78.37</td>
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<td></td>
</tr>
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</table>
Table 4: Oxide elemental wt% for Y-980459 and Y-98*

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Greshake et al., 2003</th>
<th>Misawa, 2010</th>
<th>First et al., 2013</th>
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</thead>
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<tr>
<td>SiO₂</td>
<td>49.76</td>
<td>48.65</td>
<td>48.07</td>
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<tr>
<td>TiO₂</td>
<td>0.48</td>
<td>0.54</td>
<td>0.54</td>
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<tr>
<td>Al₂O₃</td>
<td>6.04</td>
<td>5.26</td>
<td>5.62</td>
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<tr>
<td>Cr₂O₃</td>
<td>0.72</td>
<td>0.71</td>
<td>0.60</td>
</tr>
<tr>
<td>FeO</td>
<td>15.91</td>
<td>17.52</td>
<td>17.71</td>
</tr>
<tr>
<td>MnO</td>
<td>0.43</td>
<td>0.52</td>
<td>0.53</td>
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<td>MgO</td>
<td>18.23</td>
<td>19.62</td>
<td>18.73</td>
</tr>
<tr>
<td>NiO</td>
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<td>0.03</td>
<td>N/A</td>
</tr>
<tr>
<td>CaO</td>
<td>7.25</td>
<td>6.36</td>
<td>6.24</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.81</td>
<td>0.48</td>
<td>N/A</td>
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<tr>
<td>K₂O</td>
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<td>0.02</td>
<td>N/A</td>
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<tr>
<td>P₂O₅</td>
<td>0.31</td>
<td>0.29</td>
<td>N/A</td>
</tr>
<tr>
<td>FeS</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>100.00</td>
<td>98.04</td>
</tr>
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</table>

Greshake et al., 2003 and Misawa, 2010 report actual Y-980459 bulk composition. First et al., 2013 gives the composition of synthetic Y-98*. 