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Geophysical Logging of DUSEL Core and Geotechnical Applications

Roggenthen, W. M. and Koch, C. D.
Dept. of Geology and Geological Engineering, South Dakota School of Mines and Technology, Rapid City, SD, USA

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ABSTRACT: A well-documented coring program was conducted as part of the geotechnical characterization for preparation of the Preliminary Design for the Deep Underground Science and Engineering (DUSEL) project. A total of 1645 m of holes were drilled and cored with more than 90% recovery of the HQ core in most of the coring runs. The lithologies sampled by the cores included amphibolites, rhyolites, and phyllites. Approximately 60% of the recovered core were measured for acoustic velocities (Vp, Vs) and magnetic susceptibilities. The amphibolites had the highest acoustic velocities followed by the phyllites and rhyolites. Magnetic susceptibilities of the rhyolites were very low, and the amphibolite and phyllites values were variable. The variability may be due to fracturing and subsequent filling of the fractures by pyrrhotite. Calculated values of Poisson's Ratio and Young's modulus from the acoustic measurements are comparable to those derived from geomechanical testing. The acoustic measurements did not have a good correlation with the geotechnical logging performed on the cores, probably because the acoustic measurements were performed on intact samples whereas geotechnical logging is more sensitive to locating discontinuities.

1. INTRODUCTION

The former Homestake Gold Mine is located in South Dakota in the northern portion of the Black Hills of South Dakota and Wyoming. The site is being transformed from a closed underground mine into a leading scientific facility with the primary purpose of investigating high energy particle physics. The original science project planned for this location was the Deep Underground Science and Engineering Laboratory (DUSEL), and extensive coring of the host rock was conducted as part of the tasks associated with the development of the Preliminary Design [1] for this project. Although DUSEL was not pursued further, physics experiments continue to be developed in the underground at the Sanford Underground Research Facility (SURF). A smaller scale laboratory hosting experiments in dark matter and neutrino experiments is being developed on the 4850 Level (1478 m below the surface) at this time.

The stratigraphic section at Homestake consists of Precambrian Proterozoic metamorphosed sedimentary rocks and amphibolites [2] with the Yates unit of the Poorman Formation being the oldest followed by the upper portion of the Poorman Fm., the Homestake Fm., and the Ellison Fm. The Yates is defined as the lowermost portion of the Poorman Fm. and further discussions herein will refer simply to the upper Poorman Fm. and the Yates. The Homestake succession was originally deposited as a series of relatively fine-grained clastic sediments, and the lower part of the section exposed in the laboratory consists of a protolith of basaltic flows and, perhaps, intrusive rocks [3]. The depositional basin was active at approximately 2 Ga based upon radiometric dating of a tuffaceous unit in the lower part of the Ellison Fm, which yielded a date of 1.97 ± 0.008 Ga [4]. This section was later metamorphosed at approximately 1.84 Ga [5], and the garnet isograd runs through the central part of the underground workings. The Yates and the upper Poorman Fm. are the only Precambrian units exposed in the area of the current physics laboratories on the 4850 Level. During the early Tertiary, a series of rhyolites, which are part of an east-west trending belt of intrusive rocks along the northern edge of the Black Hills, intruded both the Yates and Poorman Formation [6].

A coring campaign was performed as part of the DUSEL Preliminary Design project and 5,400 ft of boreholes were drilled with core recovery in excess of 90% for most of the coring runs [7]. The core from the Homestake underground was logged for geotechnical parameters and lithology [8] and samples were measured for rock mechanic properties [9, 10]. The present study used the cores acquired in this project to determine relationships between P-wave velocities (Vp), S-wave velocities (Vs), magnetic susceptibilities, and geotechnical properties. The geophysical parameters were acquired on 3363 feet of core, and included all of Cores B, C, D, J, and a portion of N. Core locations are shown in Figure 1 [11].

2. GEOPHYSICAL MEASUREMENTS

P-wave velocities, S-wave velocities, and magnetic susceptibilities were acquired from approximately 3500 feet of oriented core from underground in the former gold mine Homestake in Lead SD. The P (Vp) and S-wave (Vs) measurements initially were taken with a Proceq Pundit Lab Ultrasonic Instrument using 150 kHz and 54 kHz transducers for some Vp measurements. Most of the P and S measurements were made using an Olympus 250 kHz transducer, which allowed the P and S measurements to be acquired at the same time and at the same location on the core. P-wave and S-wave measurements were recorded every ~7.5 cm when the core was intact. All the measurements that were taken were direct measurements with a transducer placed on opposite sides of the core to acquire the transit times. Two sets of P-waves and S-waves measurements were obtained at every 7.5 cm location, and the averages were used in the plots that follow. Ideally, the Vp and Vs measurements should have been taken under pressure. However it would not have been practical to acquire a sufficient number of measurements along the length of the cores with this requirement. The high strength of the amphibolite, in particular, rendered the requirement of applying pressure less necessary.

The magnetic susceptibilities were measured using a Kappameter KT-5, for the majority of Hole C, and GF instruments SM-20 for the remainder of the work. The magnetic susceptibilities were measured in a similar fashion to the acoustic measurements. Two measurements were recorded every 6.5 cm along the core, one along the oriented core line and one 90° counterclockwise to the core orientation line.

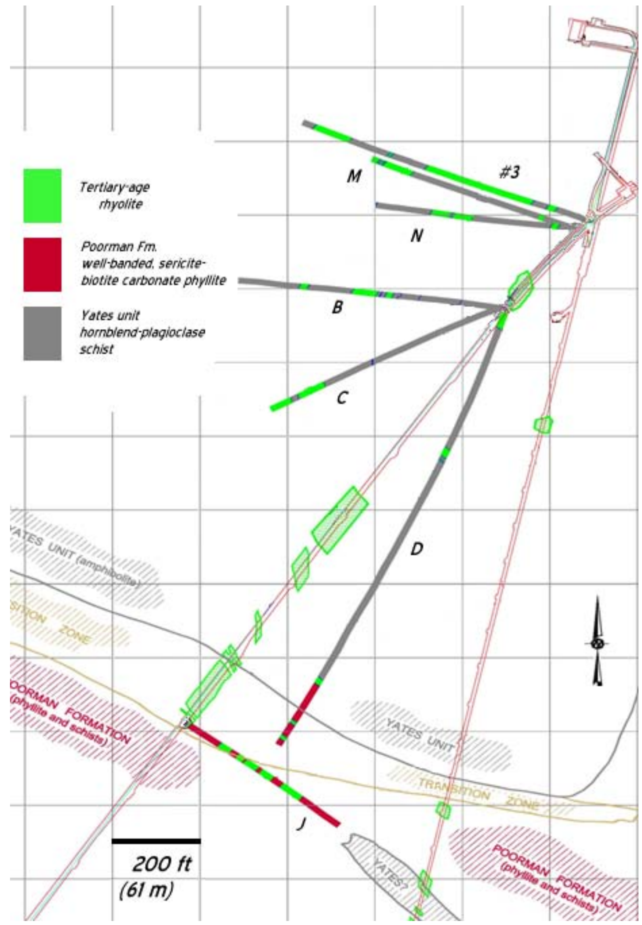
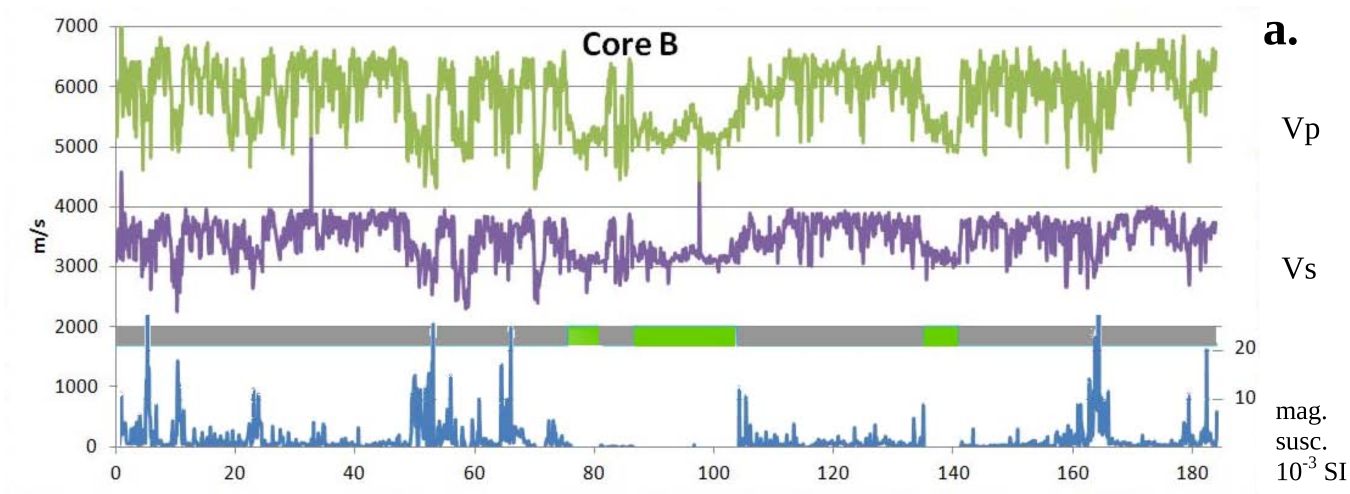


Fig. 1 Locations of drill holes on the 4850 of the Sanford Underground Research Facility (SURF). Cores from drill holes B, C, D, J, and a portion of N were used in this study that measured seismic velocities (Vp and Vs) and the magnetic susceptibility of the cored material. The units mapped during the Preliminary Design [10, 11] included the Yates amphibolite (grey), phyllite of the Poorman Formation (red), and Tertiary-age rhyolite(green).

3. DATA ANALYSIS

Examples of the Vp measurements along with the magnetic susceptibility are shown in Figures 2a (Core B) and 2b (Core J). The lithologies logged in Hole B alternate between amphibolite and rhyolite, whereas Hole J consisted of phyllites of the Poorman Fm. and Tertiary rhyolite [12]. Core locations in relation to interpreted geology are shown in Figure 1. The amphibolite Vp in Figure 2a is relatively consistent, although short zones of velocity decreases occur. Visual examination of the core in these zones of lower velocities found that many of the decreases are



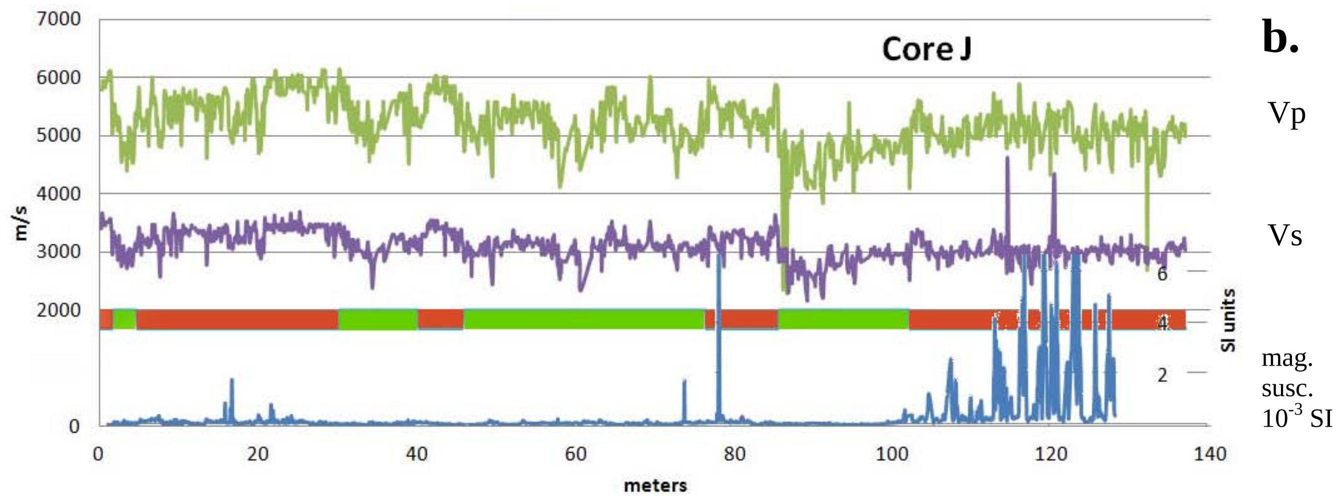


Fig. 2

a) Vp, Vs, magnetic susceptibilities, and lithologies from Core B which consists of alternating amphibolites and rhyolites.

b) b) Similar measurements of Core J, which is from the upper Poorman and consists of phyllites and rhyolites. Color bars indicate the lithologies: grey (amphibolite), red (phyllite), and green (rhyolite).

associated with healed fractures where the amphibolite fabric is clearly disrupted, but mineral precipitates in the fracture have closed any original fracture porosity. The amphibolite is characterized by seismic velocities that are greater than those of the rhyolites, making them easily identified on these plots. Vs values track the Vp values well, and a linear, well-defined relationship exists between Vp and Vs (Fig. 3). The Vp and Vs behavior of Core B is typical of the other cores measured that consist of amphibolites and rhyolites.

The Vp values from the phyllites of Core J (Fig. 2b) are not as regular as those of the amphibolite of (Core B). Although the overall Vp values are substantially lower than the amphibolites, they are still greater than the rhyolite in the same hole. Core J has velocities that are systematically lower toward the end of the core than the start of the hole, which is in the Poorman Formation. The Vp/Vs ratio for Core J is similar to that of Core B.

The magnetic susceptibilities of the cores were measured along with the velocities and are plotted as the bottom curves in Figures 2a and 2b in 10^{-3} SI units. The amphibolite susceptibilities are characterized by low, background values of that are interrupted by higher

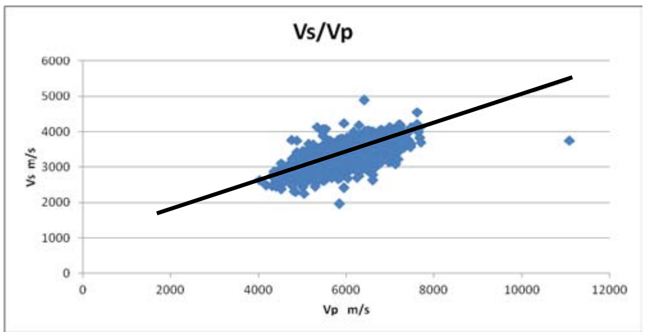


Fig. 3 Plot of Vp vs. Vs for all of the amphibolites measured in this study. The correlation between Vs and Vp is weak (R^2 = .6) but yields a relationship of Vs = .4 Vp + 1060 m/s.

spikes, which may exceed 20 times the background values. The rhyolites consistently have very low magnetic values and often reach the sensitivity limits of the instrumentation used to perform the measurements. The Poorman Formation (Core J in Fig. 2b) also shows low values of magnetic susceptibility, although the end of Core J shows higher values with intermittent spikes of magnetic susceptibilities.

Figure 4 is a section of the record from Hole C showing the relationship between Vp and magnetic susceptibility for a short part of the core. The section shows the typical response from an amphibolite, the contact between amphibolite and rhyolite, and one or more fractures in the amphibolite. Although the magnetic mineralogy of the amphibolite has not been determined in these specific samples, thin section analysis from other locations indicates that both pyrrhotite and magnetite are present in this unit [2, 5]. The amphibolite Vp is characterized by steady values with some exceptions where the velocity decreases sharply,

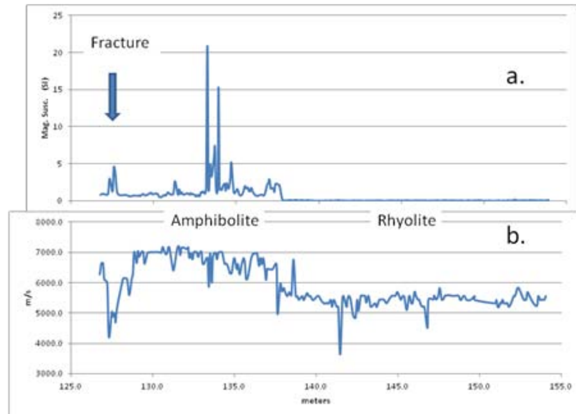


Fig. 4 a) Magnetic susceptibilities from a portion of Core C. b) Vp from the same portion of core. The rhyolite is characterized by lower velocities and magnetic susceptibilities. Healed fractures (meter marker 127 at arrow) in the amphibolite have lower seismic velocities and higher susceptibilities probably due to precipitation of pyrrhotite in the fractures.

such as at meter marker 127. The background magnetic susceptibility in the amphibolite is interrupted frequently by intermittently higher values. Amphibolite acoustic velocities quickly decrease at the contact with the rhyolite. The susceptibility drops to very low values at the contact with the rhyolite in response to the lack of magnetic minerals in the rhyolite. Examination of Figure 4 shows that decreases in Vp coincide with sharp increases in the magnetic susceptibility. For example, in the vicinity of meter marker 127, Vp decreases, magnetic susceptibility increases, and the core shows evidence of a healed fracture at that location. Visual examination of the fracture shows the abundant presence of pyrrhotite in the fracture. Figure 5 is a frequency distribution plot of $\log_2$ magnitudes of the magnetic susceptibilities. This plot shows that by far most of the magnetic susceptibilities fall in the low categories and that the high susceptibilities have a broader distribution, which is suggestive of an origin relating to fracture and fracture filling by a magnetic mineral.

The average values for the cores for the acoustic and magnetic measurements and the calculated geomechanical parameters are listed in Table 1. This includes the velocity measurements, measurements of magnetic susceptibility (SI units), Poisson's Ratio, and Young's modulus (E). Poisson' Ratio and Young's modulus were calculated using Eq. 1 and Eq. 2, respectively.

Densities for amphibolites (2.92 gm/cm^3) and rhyolites (2.54 gm/cm3) used to calculate Young's moduli (E) were derived from core subsamples as part of the geomechanical analyses for the drilling program [9].

$$\sigma = \frac{2V_s^2 - V_p^2}{2\left(V_s^2 - V_p^2\right)} \qquad (1)$$

$$E = 2\rho V_s^2\left(1 + \frac{2V_s^2 - V_p^2}{2\left(V_s^2 - V_p^2\right)}\right) \qquad (2)$$

The density used for the phyllite (2.89 gm/cm3) was determined by Nutsch [12] for phyllites of the Poorman Formation in the Homestake underground in general. The values in Table 1 compare reasonably well to those determined for amphibolite and rhyolite on the basis of geomechanical tests of core material during the evaluation program for the Preliminary Design [10].

The geomechanical testing found that Young's modulus and Poisson's Ratio (σ) for the amphibolite was 86 GPa and 0.26, and the values for the rhyolites based on the testing were 51 GPa and 0.20. The data in Table 1, which was derived on the basis of acoustic properties, show a variation between 88.5 and 94.2 for amphibolite and between 57.7 and 63.7 for the rhyolites. Table 2 is a summary of measured and calculated geotechnical parameters for the all of the rock types including amphibolite, rhyolite, and phyllite.

Table 1 Average Values of Measured Parameters: Including measurements of velocity and magnetic susceptibility and calculation of Poisson's Ratio (□) and Young's Modulus (E).

		Core B	Core C	Core D	Core J	Core N
amphibolite	Vp m/s	5998	6506	6263		6005
	Vs m/s	3537	3516	3542		3486
	σ	0.23	0.29	0.27		0.25
	E (GPa)	89.6	93.8	94.2		88.5
	mag. susc. (SI)	1.88	1.76	1.91		4.67
phyllite	Vp m/s			5558	5559	
	Vs m/s			2788	3316	
	σ			0.32	0.22	
	E (GPa)			56.5	73.1	
	mag. susc. (SI)			0.93	0.06	
rhyolite	Vp m/s	5213	5444	5171	5087	5371
	Vs m/s	3143	3093	3025	3031	3202
	σ	0.21	0.25	0.23	0.23	0.22
	E (GPa)	61.3	61.1	59.8	57.7	63.7
	mag. susc. (SI)	0.02	0.05	0.02	<.001	0.02

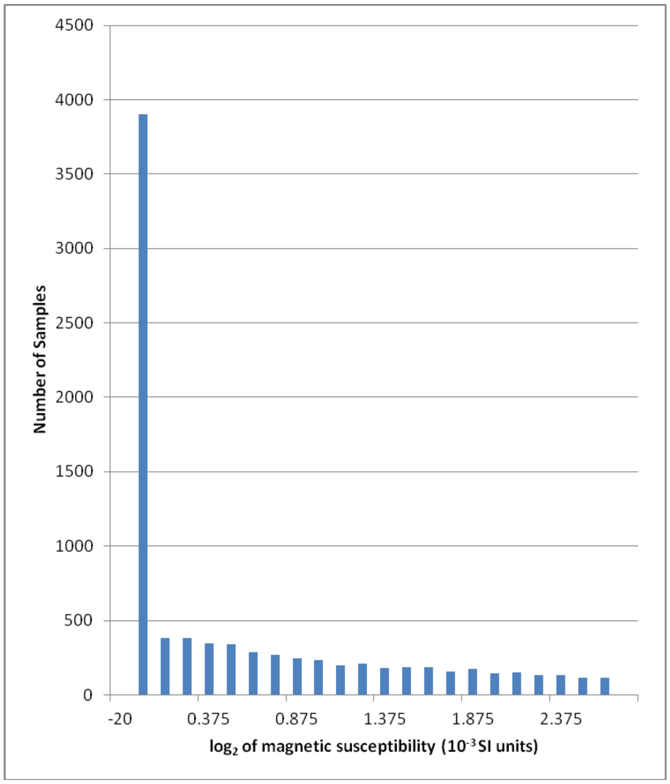


Fig. 5 Frequency distribution plot of magnetic susceptibility measurements of amphibolite samples. The results from a total of 8470 samples are shown in the plot although an additional 1158 samples plot to the left at higher susceptibilities but much lower frequency of occurrence.

Variations in Young's Modulus (E) along the length of Core B are shown in Figure 6. The core photographs from positions a) and b) illustrate the differences between the amphibolite and what are probably healed fracture zones.

Table 2 Average measured and calculated values for combined lithologies.

	n	P m/s	S m/s	σ	E
Rhyolite	1089	5189	3094	0.23	59
Phyllite	872	5571	3047	0.28	68
Amphibolite	4981	6210	3532	0.26	91

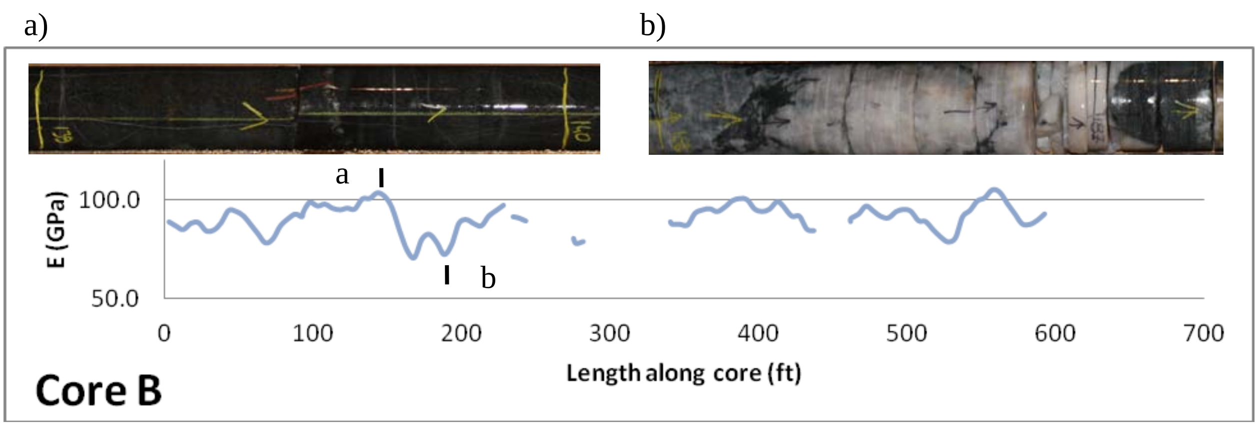


Fig. 6 Plot of E along the length of Core B for only the amphibolites showing the effect of changes in lithology. The gaps reflect the occurrence of rhyolites which are omitted from this plot. a) One foot (.3 m) core of amphibolite which represents the bulk of the rock mass shows a high value of E. b) Example of changes in lithology along the core length which may represent volumes of healed fractures.

4. DISCUSSION

The measured geophysical properties summarized in Table 1 demonstrate that, in general, the seismic velocities are consistent between cores for similar rock types as well as within the rock types taken as a group (Table 2). Amphibolites have the highest velocities, and rhyolites have the lowest velocities. The phyllites consistently have values intermediate to these two rock types. Because the velocity measurements were acquired under unconfined conditions, the direct comparison with the geomechanical measurements on the cores is not expected to be exact. The amphibolite values of Poisson's Ratio and Young's modulus based on velocities, however, compare reasonably well with those acquired through geomechanical testing. Poisson's Ratio for the amphibolites at 0.26 was the same for both the velocity determinations and the geomechanical testing. The rhyolites show a larger difference between the testing and velocity measurements although the relative values of the rhyolites with respect to the amphibolites were the same in both methods. Overall, the correlation between the calculated values using velocities and the geomechanical testing appear to be quite good. The plot shown in Figure 6 of Young’s Modulus (E) calculated along the length of the core indicates that E in this case is sensitive to the lithology, especially locations associated with healed fractures. Comparison of the measured velocities and Young’s Modulus with the geotechnical logging on the same cores does not show obvious correlations, however. This lack of correlation is not surprising in that geotechnical logging tends to be influenced more by discontinuities, such as fractures and faults, whereas the measurements of velocities are more sensitive to the properties of intact rock.

The variations in magnetic susceptibility of the amphibolite and rhyolite, shown in Figures 2a and 2b, probably depend upon relative proportions of magnetite and pyrrhotite. Both of these minerals are identifiable in both hand specimen and polished thin sections. The background level of ~0.5 SI units is likely to be related to magnetite content whereas the sharp peaks in magnetization can be correlated to visual evidence of pyrrhotite concentrations. Figure 5 shows that the bulk of the measurements consist of the background values of magnetic susceptibility whereas the larger susceptibilities have a significantly different distribution. Although the origin of these concentrations cannot be ascribed to either primary or secondary processes with absolute certainty at this time, the most likely possibility is that the background values are produced by accessory magnetite whereas the spikes in magnetic susceptibility may be caused by pyrrhotite precipitating in small fractures in the amphibolite. Core photographs in the region of 127 m of Figure 4 show a healed fracture that has macroscopic pyrrhotite precipitated in the fracture. This is consistent with the high magnetic susceptibility values and the Vp decreases, as well. Similarly, the plot of Core J shows lower velocities toward the end of the hole which also has a greater number of spikes in susceptibility than in the phyllite in other sections of this core. Visual inspection of this portion of the core shows that the rock is more highly contorted and the layering of the phyllite is disturbed and thus is consistent with higher susceptibilities being associated with fracturing and precipitation of pyrrhotite.

The Tertiary rhyolites are characterized by very low magnetic susceptibilities even though pyrite is often abundant in this rock type showing that sulfur was present. The low values of susceptibilities indicate that neither magnetite nor pyrrhotite is present in any significant quantity. Kishima [13] showed that under conditions of high sulfur fugacity magnetite is not the preferred iron-bearing phase. The absence of magnetic pyrrhotite in the rhyolites also suggests that the Tertiary intrusions are not responsible for the magnetic susceptibilities determined in the amphibolites. Therefore, this suggests that the pyrrhotite in the amphibolites formed prior to the intrusion of the Tertiary-age rhyolites, most likely during the Precambrian. In contrast to the healed, inferred Precambrian-age fracturing, Tertiary-age fracturing at SURF tends to form open spaces with vuggy mineralization. Reasons for differences in susceptibilities between the Yates and upper Poorman are not as apparent, and generally the Yates unit has higher susceptibilities than the phyllites of the upper Poorman Fm. The Yates may be more brittle than the Poorman and thus supported a higher fracturing frequency to act as an avenue for precipitation of iron sulfides during the Precambrian, although the possibility of stratigraphically controlled occurrences of pyrrhotite with the Yates cannot be eliminated for all instances.

5. CONCLUSIONS

Healed fractures can be identified in the Yates unit by acoustic measurements. The healed fractures of the Yates unit appear to have been developed prior to intrusion of the Tertiary-age rhyolites, probably during the Precambrian. The velocity measurements appear to correlate better with the geomechanical measurements as opposed to determinations from core logging. Core logging for geotechnical properties tends to be influenced by discontinuities whereas velocity measurements, and to a lesser extent, magnetic susceptibility measurements are biased toward competent parts of the core. Given these considerations, it may be better to measure velocities via sonic logging in the borehole, which would maintain the rock mass under higher *in situ* stresses and under conditions that include discontinuities such as fractures.

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