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Limits of Paleomagnetic Detection: Low-temperature, Helium-free Ultra-high Resolution Scanning SQUID Microscopy

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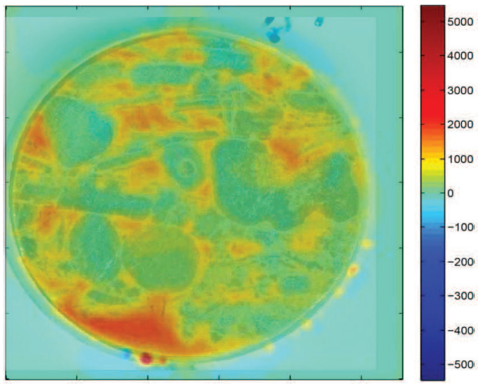
Despite the extraordinary sensitivity of helium-temperature SQUID magnetic sensors, most of their use in geophysics has been in moment magnetometers for paleomagnetic and rock magnetic studies. However, developments in the past decade at Vanderbilt University, Caltech, and at MIT have incorporated them into what is now called the Ultra-High Resolution Scanning SQUID Microscope (UHRSSM). The extreme sensitivity of these instruments ? in some cases capable of imaging the magnetic moment of a single magnetotactic bacterium ? arises from engineering that allows a superconducting sensor in a high vacuum, held at < 5 K, to come within a few tens to hundreds of micrometers from the surface of a room-temperature sample at ambient temperature and pressure. Separating these two regimes, a sapphire window thins to ˜ 25 um near the sensor, and elaborate radiation shielding blocks all but the sensor tip from background heat. By scanning samples in a micron-scale grid beneath the sensor, a map or image of the magnetic field is generated, similar to, but at much smaller scale than, those produced by aeromagnetic surveys. Unlike a magnetic-force microscope, where a magnetized needle is tapped over a small area of a sample, the UHRSSM does not expose the sample to strong magnetic fields and can operate over a much larger area ? from steps only 5 um in size to cover areas up to ˜ 5 x 5 cm. For NRM measurements, the entire assembly must be housed in a mu-metal shielded system with background fields < 10 nT.

Early versions of these instruments were cumbersome to use, requiring separate Dewars for liquid helium and nitrogen. They also needed an elaborate lever mechanism in the vacuum for adjusting the distance of the SQUID sensor from the sapphire window and sample. At Caltech we modified our UHRSSM to operate from a two-stage pulse-tube system manufactured by Cryomech, Inc., which is capable of cooling the sensor to 3.6 K in about two hours. (The same pulse-tube system now is standard on new 2G? magnetometers.) This modification freed us from use of both liquid nitrogen and helium, and minimized the thermal contraction problem to the point where the vacuum lever assembly was not needed. On the other hand, we discovered that the pulse tubes do generate an ˜ 1 Hz magnetic noise of up to 1000 nT amplitude; this is due to their use of rare-earth ferrites with paramagnetic to ferromagnetic transition temperatures < 20 K. This required the addition of a superconducting lead shield to block this noise, and for high-sensitivity measurements, the addition of a second SQUID sensor chip in a gradiometer configuration with real-time noise cancellation.

Applications of the UHRSSM are diverse. It can establish ca. 10,000 independent-grain paleointensity estimates per conventional paleomagnetic sample that offer insight into the dispersion of intra-unit, between-sample paleointensity results. It can assess a conglomerate test on a sandstone or igneous/extraterrestrial (meteoritic) breccia. It can function as a geochemical prospecting tool, discriminating the most pristine from the least-desirable among multiple sulfide paragenetic textures and phases in Archean black shales. And applied to biomagnetic problems, the UHRSSM can localize magnetocyte or magnetosomes within tissue that otherwise can be challenging to detect. The attached image shows a 2.5 cm diameter scan of pre-compaction Archean sulfide nodules that are variably magnetized by an IRM, with relatively nonmagnetic cores. Matrix, in contrast, is strongly remagnetized by pyrrhotite dating ˜500 myr after deposition of the shale.



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