GP72B-1013 1330h POSTER

A Negative Fold Test on the Lorrain Formation of the Huronian Supergroup: Uncertainty on the Paleolatitude of the Paleoproterozoic Gowganda Glaciation

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One of the major contributions of paleomagnetic studies to the field of paleoclimatology has been to provide constraints on the latitude of Proterozoic glacial intervals. As reviewed recently by Evans[1], several tightly-constrained results for the Neoproterozoic indicate the presence of tropical glaciers near the Equator which have led to the much-debated Snowball Earth hypothesis. In contrast, of the several results from the Paleoproterozoic glaciogenic units, only one[2] from the Transvaal Supergroup of South Africa is constrained directly by a paleomagnetic field test of stability. Although two recent studies of the youngest glacial interval in the Huronian supergroup of Canada [3,4] isolated high-temperature, low-latitude components, the authors did not conduct either conglomerate or soft-sediment fold tests to constrain more precisely the time that the magnetizations were acquired.

Upon examination of a large road-cut exposure of the purple siltstone member of the Lorrain formation along highway 17 near the town of Desbarats (one of the sites reported in [3]), we discovered a ductile chevron fold covering a $\sim$100-m^2 area, with an axis plunging 19° to the WSW, roughly perpendicular to the high-temperature characteristic direction reported for this unit [3]. The angular discordance between the two limbs was measured at $\sim 55^\circ$. Using a portable concrete saw, we sliced out and oriented a boomerang-shaped wedge $\sim$ 45 cm long, $\sim$ 10 cm wide, and $\sim$ 3 cm thick, which was cut perpendicular to the fold axis. From this we obtained 74 standard specimens for paleomagnetic analysis, distributed symmetrically on the two limbs. All of these were progressively demagnetized using similar techniques to the earlier studies [3,4]. Demagnetization behavior reveals the prevalence of a low-inclination northerly component isolated by high-temperature thermal demagnetization and resolved by PCA, which resembles the Lorrain D component reported previously [3], but lays within the scatter cone of the Lorrain A direction. Prior to the corrections for fold and tilt, average directions from both limbs share a common mean North and shallow direction ($p < 0.4$), whereas after correction the two means diverge by nearly 50° ($p << 0.001$), which indicates a very highly significant but negative fold test, supporting the conclusion in [3] that the Lorrain D was secondary.

However, directions similar to Lorrain D and A persist at temperatures above 580°C, the maximum temperature reported for Lorrain D in [3]. Further, we find it difficult to distinguish the high-T Lorrain components (C, B, and A) reported in [3]. Small-scale micro-conglomerates and other deformational features which are present in the exposure may provide additional constraints for testing the origin of these high-T components using scanning SQUID microscopy.

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GP72B-1014 1330h POSTER

A kinematic model for Afar Depression lithospheric thinning and its implications for hominid evolution: an exercise in plate-tectonic paleoanthropology

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We present a detailed Nubia-Arabia-Somalia (NU-AR-SOM) kinematic reconstruction based on magnetic sea floor isochrons in the Gulf of Aden and Red Sea and piercing points along the Red Sea margins. The reconstruction is combined with digital topographic and depth-to-Moho data to constrain in 4D the Late Oligocene to present-day evolution of the Afar supra-Moho crust. Opposite end-member models for crustal evolution are described. We conclude that less than 20% of the present-day Afar supra-Moho crust was constructed by magmatic processes such as diking and underplating. The reconstructions indicate that the greater percentage of crustal thinning (extension) occurred before 6.2 Ma. We model the thinning of the effective elastic lithosphere that accompanied extension, and show that the regional-scale topographic development of the Afar depression was virtually complete by Mid Pliocene time.

The plate-tectonic model has paleoanthropological implications. Prior to 6.2 Ma the proximal positions of NU-SOM, AR, and the Danakil block suggest subaerial conditions prevailed between Yemen and Ethiopia. Uninhibited Africa-Eurasia faunal exchange through Afar and Arabia (corroborated by isotopic and paleontologic data) was tectonically permissible until the time of the earliest hominids. Continued stretching caused the Afar land bridge(s) to disappear during Early to Mid Pliocene time. Primitive hominid populations living within the Afar Depression became isolated from AR sometime before 3.2 Ma. With the plateau becoming less habitable due to long-term Late Neogene cooling, hominids that remained in the Afar Depression were required to adapt to a smaller range that was effectively bounded by the already well-developed NU-SOM escarpments and the newly opened Straits of Bab el Mandeb. The combination of high quality habitat,topographic confinement, and a gradual (tectonic) reduction in range, exacerbated by potentially severe fluctuations in local climate (well documented by land and marine paleoclimate proxies) appears to have been unique to Afar in Mid Pliocene Africa, and may have caused hominids living in the Depression to undergo physical and cultural evolution more rapidly and successfully than hominids inhabiting equally productive but less confined ranges elsewhere. We suggest that plate-tectonic induced isolation caused the Afar Depression to become the cauldron within which genus Homo arose to prominence. If our interpretation is correct, continental drift played a major role in hominid-to-human evolution.

GP72B-1015 1330h POSTER

Application of Magnetic Mapping to Proterozoic Continental Reconstruction

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Models of the Neoproterozoic (1.0-0.8 Ga) assembly of the supercontinent Rodinia include the SWEAT hypothesis, which places Proterozoic eastern Australia adjacent to the Proterozoic western margin of Canada, and the AUSWUS hypothesis, which juxtaposes the Proterozoic southwestern U.S. and Proterozoic eastern Australia. The disparity between the two models is largely due to an inability to correlate different basement mapping techniques used for the two continents. A thick weathering regolith in Australia has required the use of magnetic signature maps to define the Precambrian basement. Because of abundant basement exposure in the western U.S., isotopic methods have been used to define Precambrian terrane boundaries and little magnetic mapping has been done.

The eastern margin of Proterozoic Australia is defined by magnetic mapping as the Tasman line. SWEAT places the eastern Proterozoic margin of Australia, west of the Tasman line against the northwestern margin of Proterozoic Canada. This model is mainly based on geologic piercing points and strati-graphic/isotopic correlations. The AUSWUS model connects the Tasman line to the western margin of the Proterozoic U.S., adjacent to the ^{87}Sr/^{86}Sr line. The ^{87}Sr/^{86}Sr line has been suggested to divide Proterozoic basement to the east and younger accreted terranes to the west.

Magnetic mapping of the Proterozoic margin of the southwestern U.S. through the reduction of aeromagnetic data allows comparison with the magnetically defined margin of Proterozoic Australia. Preliminary evaluation of magnetic styles (amplitude and wavelength) and linear trends of the southwestern U.S. suggest that both Proterozoic and Phanerozoic igneous rocks greatly influence the total magnetic signature. Isolation of the Proterozoic component from the total aeromagnetic signal requires understanding the character, distribution, and magnitude of the magnetism in the Proterozoic rocks.

The magnetic signatures of two suites of granites in the southwestern U.S. could provide substantial support for the AUSWUS reconstruction. First, numerous Proterozoic granites crop out in western Arizona in the boundary between the Mojave and Yavapai provinces. The AUSWUS reconstruction suggests that the boundary zone is correlative with the Broken Hill block in Australia and that Proterozoic rocks in the boundary may correlate with the Arunta arc assemblage in Australia. Understanding the magnetic signature of the Mojave/Yavapai boundary will aid in resolving possible magnetic lineaments across the AUSWUS reconstruction. Second, a band of $\sim$1.4 Ga, possibly anorogenic granites transects the continental U.S. If continued along strike in the AUSWUS reconstruction, this band may be cogenetic with rocks in the Gawler craton of Australia. Magnetic susceptibilities of both suites of Proterozoic granites will be presented and contrasted with magnetic trends from the Australian craton.

GP11A MCC: Hall C Monday 0830h

The Use of Magnetic Properties as a Petrologic Tool I Posters *(joint with OS)*

Presiding: **J Rosenbaum,** U.S. Geological Survey**; K L Verosub,** University of California, Davis

GP11A-1061 0830h POSTER

Borehole Magnetometer Data as Information Source for Internal Structure and Stratigraphic Evolution of Mauna Kea Volcano

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A quasi-continuous magnetic log has been obtained in the Hawaii Scientific Drilling Project 2 (HSDP-2), providing information down to 1800 mbsl of Mauna Kea volcano flank deposits. The HSDP borehole penetrates in this depth section series of Aa- and Pahoehoe subaerial lava flows in the upper part followed by heterogeneous submarine series of hyaloclastites with changing amount of intercalated massive flows. The borehole magnetometer was employed to measure the horizontal and vertical magnetic fields. Measurements were taken in downhole and uphole runs, with a good correlation between both runs. The logs were processed to calculate rock magnetizations from magnetic components, using a multi-disk cylindrical model for the penetrated rocks. The disk thickness corresponds to the logging sampling rate of 0.1 m. Magnetic borehole logging in the HSDP-2 hole reveals strong magnetic anomalies in the subaerial as well in the submarine part with deviations from the normal field of up to 15000 nT. Since the magnetic behavior in the subaerial basalts is mainly related to early processes of high temperature alteration of the lava flows during extrusion, the continuous borehole magnetic data provide information to the amount of high temperature affected material within single lava flows. The magnetic data of the submarine part show a heterogeneous picture with longer sections of an undisturbed magnetic field and intercalated zones with strong anomalies. These anomalies are not restricted only to massive basalt flows as it might be expected, but also appear in series described as hyaloclastic units. A detailed comparison between core information, borehole magnetic data and other downhole logs (spectral gamma-ray and electrical resistivity) allowed us to distinguish between at least two types of hyaloclastites with different genetic origin. Hyaloclastites with strong magnetization are generated from former massive lava flows, exhibiting low matrix contents, a low natural gamma ray and a fragmented, auto-brecciated appearance, while hyaloclastites with low magnetization show a more typical sedimentary character and are characterized by high matrix contents which correspond to high gamma-ray values. Taking this information into account the continuous borehole data allow to subdivide the encountered submarine deposits into several volcanostratigraphic units, as well as to detect unconformities in the volcanic deposits which are most probably produced by landslides or debris avalanches. The most prominent boundary is encountered at about 1670 mbsl. There, the log and core data strongly point to a basis of the large landslide. This hypothesis is further supported by a strong change of the magnetic inclination towards low values.

GP11A-1062 0830h POSTER

Application of Downhole Magnetic Field Measurements in the Identification of Petrological Variations in Basalts, Gabbros and Volcaniclastic Sediments

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Downhole magnetic field measurements are routinely carried out during many downhole-logging operations for spatial orientation of borehole wall images. The tools used for this purpose, like the Schlumberger General Purpose Inclinometer Tool (GPIT), were not specifically developed for geological interpretations but comparisons with measurements from precise magnetometers show very good correlations. However, systematic value shifts sometimes occur in some holes and this means that data from the GPIT should be used only qualitatively. We show examples from several holes drilled by the ODP demonstrating the potential of magnetic field logs for geologic and petrologic purposes. Variations in the magnetic field data are caused by different geologic processes in these examples.

Injections of Fe-Ti-oxide rich gabbros into olivine gabbro of the lower oceanic crust drilled in ODP Holes 735B and 1105A (SW Indian Ridge) cause distinct signals in the magnetic field logs. The vertical resolution of the tool allows detection of thin layers (10 cm minimum thickness) with small anomalies in the magnetic field logs.

Cyclicity in eruption processes at mid-ocean ridges can be revealed using the magnetic field logs. Slight petrologic differences between magmas from different eruptions and changes in the Earth?s magnetic field due to reversals, or secular variations in pauses between the eruptions cause characteristic patterns in the logs (e.g. ODP Holes 395A and 418A).

Cooling and subsequent alteration processes cause the formation of different types of Fe- and/or Ti-oxide minerals. Typical examples of the formation of secondary magnetic minerals in subaerial lava flows are seen in ODP Hole 1137A (Kerguelen Plateau). Characteristic anomalies in the magnetic field log correlate well with total gamma ray measurement, which is an indicator for alteration in this type of rocks.

Grain Size linked with crystallinity variations in basaltic volcaniclastic deposits and debris flows influence the magnetic field logs (e.g. ODP Hole 956B, Canary Islands). Large anomalies occur in basaltic breccias while hyaloclastites typically show no anomaly.

GP11A-1063 0830h POSTER

Magnetomineralogy as a tool for determination of the meteorite weathering

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In early solar system history are several electromagnetic processes expected capable of magnetizing the primitive solid particles condensating from the Solar Nebula. The signature of this magnetic events can be observed in meteorites found on the Earth. It can take a long time from meteorite fall till laboratory study. Some samples are deposited in the desert or Antarctic ice for thousands of years. In this work we used the sample of the LL chondrite found in Libya desert for weathering simulations, magnetic mineralogy and magnetic properties study. The weathering in this sample is related to the desert varnish formation. From high and low temperature magnetic susceptibility measurements we can see, that most important magnetic carriers are iron, magnetite and hematite. The influence on magnetic mineralogy can be seen from weathering simulations done by leaching the samples in different solutions. This change affects the suitability of different samples for primary magnetic record study. Acknowledgements: This work is supported by Charles University Grant Agency, Czech Republic and would not be possible without the help of following people: Jakub Haloda, Petr Jakes, Marcela Bukovanska, Jaroslav Kadlec, Libuse Kohoutova, Vladimir Kohout.

GP11A-1064 0830h POSTER

Detection and Quantification of Superparamagnetic and Multi-Domain Particles in Environmental Magnetism

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Environmental magnetism relies on the possibility to infer knowledge of subtle details about the magnetic fraction in sediments from few magnetic measurements which are easily and relatively fast performed and do not need extensive sample preparation. Besides mineralogy, the most important information which can be obtained is the magnetization state which is linked to the grain size of the magnetic fraction. Low temperature measurement of frequency dependent susceptibility over a wide range of frequencies and temperatures allows to quantify the content and size distribution of superparamagnetic (SP) particles, but hitherto is not an expeditious mean of data acquisition. A very effective method to assess the presence of multi-domain (MD) particles is the saturation initial curve $M_{si}(H)$ (Fabian and von Dobeneck, 1997) which is a hysteresis initial curve starting in the state of saturation remanence. The area between $M_{si}(H)$ and the upper hysteresis branch in relation to the total area of the loop is a robust measure of MD content which is not influenced by SP particles. Viscosity of isothermal remanent magnetization (IRM), on the other hand, is effective in detecting SP fractions which extend into the single-domain (SD) grain size region. The efficiency of the above methods is demonstrated in case studies using synthetic as well as natural samples.

GP11A-1065 0830h POSTER

Determining the climatic boundary between the Chinese loess and paleosol: Evidence from aeolian coarse-grained magnetite

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This paper proposes a new method to distinguish between interglacial deposits and pedogenically-overprinted glacial loess based on the concentration variations of coarse-grained aeolian (magnetically pseudo-single domain and multi-domain) magnetite. We apply the method to a sequence from the upper part of the loess unit L2 (marine isotope stage MIS 6) to the sub-loess unit S1L2 (MIS 5d) at the YuanBo (YB) section in the Chinese Loess Plateau. The method is based on the differences in low temperature properties between the coarse-grained (multi-domain and pseudo-single domain) detrital magnetite and the pedogenic magnetic particles including superparamagnetic (SP) particles and relatively larger maghemite particles. The former is characterized by a crystallographic Verwey transition around 120 K. In contrast, the magnetization of the latter continuously decreases in intensity with increasing temperatures. The method involves two steps: 1) calculating the first-derivative of the low temperature thermal demagnetization of the saturated isothermal remanent magnetization acquired at 20 K (LT-SIRM), which enhances the behavior related to the Verwey transition, and 2) fitting a third-order polynomial background to the data between both 50-70 and 150-300 K, and then subtracting this background from the total derivative curves. The area under the background-corrected derivative curves represents the absolute intensity drop associated with the Verwey transition (ΔJ_{TV}). This is caused by the aeolian coarse-grained magnetite, which is very sensitive to the changes in the intensity of the winter monsoon, and in turn related to the changes in paleoclimate. The results show that the sharp drop of ΔJ_{TV} at 39.44m corresponds to the climatic boundary from L2 (MIS 6) to S1S3 (MIS 5e), and not at 39.8m as thought previously. Thus, the paleosol deposits just below this boundary are in fact highly altered L2 materials instead of S1S3 accumulations.

GP11A-1066 0830h POSTER

Mechanical Model of Grain Alignment Revisited: Implications for Anisotropy of Magnetic Susceptibility Measurements.

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The anisotropy of magnetic susceptibility (AMS) has been used extensively to determine magma flow direction in dikes. Based in a partial interpretation of a mechanical model of ellipsoidal particle- alignment either the axis of maximum susceptibility or of intermediate susceptibility have been proposed as indicators of flow direction. However, a complete interpretation of the same mechanical model, applied to a large number of originally randomly oriented particles allows us to show that the susceptibility axes present different orientations as a function of time and of grain shape. A preliminary analysis of results allow us to identify four types of axes distributions: 1) mean maximum susceptibility is imbricated both to the dike plane and magma flow direction ("normal" fabric), 2) mean maximum susceptibility is not imbricated but parallel to flow direction, 3) mean intermediate susceptibility is parallel to flow direction while mean maximum susceptibility remains in the plane of the dike and 4) there is no relation between the axes of susceptibility and flow direction or the plane of the dike. Based on our modeling results, it is concluded that there is no simple rule of thumb that can be applied in every case, nor any statistical tool that can ascertain a successful interpretation of AMS measurements in dikes. Nevertheless, it is remarked that a deeper understanding of the physics involved on the process of acquisition of magnetic fabric remains the only means to extract most of the information encoded by the measurements, resulting in sounder interpretations. These results have also implications concerning the applicability of AMS as flow direction indicator not only in dikes but in lava flows and other igneous rocks.

GP11A-1067 0830h POSTER

Room- and Low-Temperature Magnetic Fabrics and Tectonic Strain in Weak- to Moderately-Deformed Mudrocks

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Pencil structures in mudrocks reflect the bedding-cleavage intersection in weak- to moderately-cleaved rocks. We have determined the Anisotropy of Magnetic Susceptibility (AMS) at both room- and liquid N-temperature (77K) in pencil structures from a sequence of mudstones of the Ordovician Knobs Fm. in the Valley and Ridge Province of the US Appalachians. Magnetic mineralogy was determined by X-ray analysis and low-temperature bulk susceptibility measurements. Distribution of the magnetic ellipsoid axes tracks with the incipient tectonic fabric of the pencil mudstones. The maximum susceptibility axes parallel the pencils' long axes, while the minimum axes of susceptibility are normal to the primary sedimentary fabric. Independent strain quantification from fringe structures shows a correlation between magnetic fabric and tectonic strain. An exponential relationship between the AMS shape parameter T and tectonic shortening has been determined for the interval of 10-25% shortening: shortening(%)=17*exp(T). This relationship appears to be supported by tectonic stains up to 40%. The T parameter (T = [lnF-lnL]/[lnL+lnF]) describes the shape of the magnetic susceptibility ellipsoid, which better correlates with strain than the magnetic intensity parameter P or P'. Low-Temperature measurements enhance the magnetic fabric (P/P'), but T remains about equal for originally oblate fabrics. In contrast, originally prolate fabrics shift toward the oblate field. This indicates that low-temperature measurements differentially affect subfabrics, likely reflecting different phyllosilicate mineralogies. These intrinsic changes in the anisotropy of susceptibility from low- to room-temperature can be used for mineralogic characterization of subfabrics, as different phyllosilicates have distinct Curie paramagnetic temperatures. Whereas the correlation between strain and AMS is only valid within a restricted range (less than 40% shortening), it establishes the magnitude and directions of tectonic strain in weakly deformed clay-rich rocks, where strain indicators are often lacking or are poorly developed.

GP11A-1068 0830h POSTER

Magnetic Fabric and Deformation of the Metasediments in the Southwestern Ogcheon Metamorphic Belt, Korea

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We have reanalyzed magnetic fabric data of low- to medium-grade metasedimentary rocks in the southwestern part of the Ogcheon belt, and synthesized magnetic fabrics, regional structure and metamorphic zonations of the study area in order to reveal the deformation history of the Ogcheon belt. The Ogcheon belt, which comprises the Ogcheon metamorphic belt (OMB) to the southwest and the Taebaeksan zone to the northeast, is a fold-and-thrust belt running diagonally (SW-NE) across the Korean Peninsula, and divides the peninsula into the Gyeonggi massif and the Ryeongnam massif. In recent years, the Ogcheon belt has been a key place in formulating the tectonic framework of the Korean Peninsula and East Asia, because the Ogcheon belt is regarded a candidate for possible eastern extension of the Qinling-Dabie-Sulu belt, the suture zone between the North and South China blocks. Magnetic fabrics of the study area show a good agreement with petrofabrics observed in the field. The shapes of magnetic anisotropy ellipsoids change from the oblate field in the biotite zone toward the prolate field in the garnet and staurolite zones as the metamorphic grade increases. Synthesis of magnetic fabrics and previously reported metamorphic evolution suggests the deformation history of the study area as follows. Penetrative NW dipping cleavages, defined by magnetic foliations, in the study area formed by prevailing NW-SE shortening event during the M1 regional metamorphism in the late Triassic-early Jurassic. We believe that this shortening event is associated with the collisional event between the North and South China blocks rather than with the closure processes of an intracontinental rift basin. Cleavages and magnetic foliations in the staurolite zone showing steep dip to the SE are due possibly to the intrusion of Jurassic granite in the northeastern area. Subsequently, a NE-striking ductile shearing in the staurolite zone caused resultant petrofabrics of the study area during the middle Jurassic. Sufficient heat high enough to cause a ductile shearing might be supplied from granite intruded in the northwestern part of the study area.

GP11A-1069 0830h POSTER

Preliminary Results of Anisotropy of Magnetic Susceptibility of Metasedimentary Rocks in the Central Ogcheon Metamorphic Belt, Korea

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An anisotropy of magnetic susceptibility (AMS) study has been carried out for 687 samples from 44 sites of low- to medium-grade metasedimentary rocks distributed in the central Ogcheon Metamorphic Belt. Stepwise acquisition and thermal demagnetization of 3-axes composite isothermal remanent magnetization (IRM) experiments and anisotropy of anhysteretic remanent magnetization (AARM) experiments were also performed for representative specimens. The study area is divided into three metamorphic zones: the biotite zone, the garnet zone and the silimanite+andalusite zone from southeast to northwest. The biotite and garnet zones were formed by intermediate pressure/temperature regional metamorphism and the silimanite+andalusite zone was a result of contact metamorphism due to the intrusion of the Jurassic granite after the regional metamorphism. The preliminary result of the AMS measurements shows that the southern part of the biotite zone is characterized by the inverse magnetic fabrics caused by single-domain (SD) magnetite, which are found by the fact that the Kmin directions are swapped for Kmax directions in the AARM experiments when they are compared with those of the AMS. On the contrary, NW dipping magnetic foliations are mainly carried by hematite and pyrrhotite grains in the central and northern parts of the biotite zone. The garnet zone shows characteristic regional patterns of AMS ellipsoids as follows. In the southeastern region, the NE-E plunging magnetic lineations, mainly recorded by pyrrhotite and hematite, show a good agreement with the mineral lineations defined by biotite grains showing preferred orientation in the outcrop and are interpreted as a movement direction of the upper block of a thrust fault. Inverse magnetic fabrics carried by SD magnetite are observed again as a representative feature in the central region. The NW-W dipping magnetic foliations recorded by pyrrhotite and hematite are the characteristic feature in the northwestern region. AMS result of the silimanite+andalusite zone shows clear magnetic foliations subparallel to a boundary between metasediments and the Jurassic granite, even though rock fabrics are rarely observed in the field. In this region, magnetic minerals contributing to the AMS results are changed from magnetite to hematite with increasing distance from the contact. The magnetic foliations subparallel to the contact, without revealing any effects of previous regional metamorphism, indicate that the emplacement of the granite was post-tectonic in origin.

GP11A-1070 0830h POSTER

Paleomagnetism and Magma Flow Direction in Dikes of the Wai'anae Volcano, O'ahu, Hawai'i Determined From Magnetic Fabric Studies

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In order to investigate the volcanic evolution the plumbing and the triggering mechanisms of the catastrophic mass wasting that had occurred in the Wai'anae Volcano, O'ahu, Hawai'i we have undertaken a paleomagnetic and anisotropy of magnetic susceptibility (AMS) study of a set of dikes from the volcano. We have drilled a set of dikes and have recovered a minimum of 8 and up to 23 samples per intrusive. The width of the dikes ranges between 0.5 to 1.5 m. In terms of the paleomagnetic results, at least 8 samples per intrusive were stepwise demagnetized by a.f. from 5 to 100 mT. Companion specimens from the same core were demagnetized at 15 temperature steps. In both cases, demagnetization diagrams obtained with each technique showed a stable characteristic direction of remanence (ChRM) with no ambiguity. The ChRM was calculated using principal component analysis for the demagnetization diagrams with a well-defined component trending to the origin. No bias or systematic departure from the origin was accepted, and in all cases the ChRM relied on a minimum of seven successive directions isolated during stepwise demagnetization. In addition, low-field susceptibility vs temperature (k-T) and SIRM experiments were performed on at least one sample per intrusive. As a result of such tests, we were able to identify magnetite (at 575^{o}C) and a low-temperature mineral phase at about 250-300^{o} C, which probably reflects the presence of titanomagnetite with low Ti content as indicated by its large susceptibility. The determined directions of the intrusives resulted in normal and reversed polarities, indicating that such dikes were emplaced at different periods of time covering a gap of 350 kyrs. AMS was determined for all the studied dikes, and statistically significant AMS clusters were found in all of them. For all the lineated dikes, the mean maximum AMS (Kmax) coincides with the macroscopic lineations to within 10 to 20^{o}. The AMS ellipsoid shape in about half of the samples is prolate, and the other half is oblate. We interpret the AMS to be determined by the shape anisotropy of the ferromagnetic grains. Our AMS measurements enable us to infer absolute magma directions for the intrusive studied. The maximum AMS axes of samples from one side of the dike form a tight cluster on an equal-area plot, and those from the other side of the dike form another tight cluster. We infer that these paired clusters are caused by imbrication of nonequant ferromagnetic crystals against each other 's margin of the dike during deposition in a velocity gradient, and hence indicated the flow azimuth, i.e. the absolute magma flow direction. All dikes gave paired AMS plots. The magma flowed up at high angles (greater than 40-80^{o}). We conclude that the emplacement mechanisms of the dikes that triggered the collapse of the volcanic edifice is totally different from other central volcanoes such as the Koolau volcano in O'ahu, Hawai'i.

GP11A-1071 0830h POSTER

Insights on the Dynamics of Silicic Lava Flows Inferred From Anisotropy of Magnetic Susceptibility (AMS) and Optical Measurements.

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Measurements of the anisotropy of magnetic susceptibility (AMS) on lavas can yield information concerning flow directions, deformation regimes, and relative shear rates. Here we report results of measurements made on samples of rhyolitic obsidian collected from Obsidian Dome, California. Comparisons of AMS measurements with previously determined 3D microlite orientation distributions in these samples serve as a calibration of the AMS technique. Despite the low values of bulk susceptibility (1.06 - 7.04 x 10^{-3} SI) found in the dome relative to typical values in basalts (10^{-2} SI), the degree of anisotropy is extremely high in all specimens (3.4 - 10.7). Furthermore, susceptibility tensors exhibit a wide range of shapes varying from prolate to triaxial and flattened ellipsoids (B parameter from -8.6 to +6.4) corresponding to various degrees of microlite dispersion. Our results also indicate that despite the tight clustering of principal susceptibility axes obtained on each site, bulk flow directions inferred from the orientations of kmax axes may be misleading because the orientation of the local extension changes from place to place within the dome. However, it is shown that the AMS of each specimen provides a good measure of the direction of local extension. Consequently, it is possible to interpret spatial variations in flow regime from systematic changes in the orientation of principal susceptibility axes. As the proposed association between the local deformation regime and AMS is strongly dependent on the aspect ratio of the crystals embedded in the flowing lava, some caution must be exerted when interpreting AMS results from other flows, and a direct comparison between different flows may not be granted in many occasions.

GP

GP11A-1072 0830h POSTER

Partial Self-Reversal of the TRM in Basalts: A Combined Rock Magnetic and Microscopic Approach

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Partial or (less often) complete self-reversal is a phenomenon occasionally occurring in basalts containing inhomogeneous ferrimagnetic mineral phases. We studied samples from Olby and Laschamp (France) and Vogelsberg (Germany) exhibiting this peculiar behaviour and present data giving evidence that in basalts the phenomenon is rather caused by partially oxidised titanomagnetites in contrast to andesitic lavas where hemoilmenite phases cause self-reversal. The partial low-temperature oxidation forms close side-by-side phase assemblages of titanomagnetite (with Curie temperatures between 190°C and 275°C) and titanomaghemite (with Curie temperatures between 440°C and 580°C) which are potentially able to interact magnetically.

In order to identify the geometry, composition and magnetic properties of these mineral phases we combined various microscopic techniques: The standard light-microscopy and Bitter pattern imaging was complemented by electron microprobe measurements to determine the variation of the chemical composition over single grains and by magnetic force microscopy to specify the domain state of the ferrimagnetic minerals. The combination of these techniques applied to individual particles allows a more concise characterisation regarding the influence of composition on domain state and internal stress.

GP11A-1073 0830h POSTER

Paleomagnetism of the Mt. Stuart Batholith Revisted Again: What Has Been Learned in the 30 Years After Beck and Noson 1972?

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Thirty years after publication by Beck and Noson (1972) of the first paleomagnetic study of the Cretaceous Mount Stuart batholith (North Cascades of Washington), the tectonic significance of its remanent magnetization is still hotly debated. Here, we review the role that paleomagnetic results from the Mt. Stuart batholith has played in debates over Cordilleran tectonics, and present results of a new paleomagnetic and rock magnetic study of these rocks. The remanence direction obtained by Beck and Noson (1972), and subsequently confirmed by Beck and others (1981) and Patterson and others (1994) is markedly discordant relative to directions expected for Cretaceous rocks from the North America craton. Taken at face value, this discordance is explained by large scale (3000 km) translation of a coastal microplate along the North America margin, and sparked what is now known as the Baja-BC hypothesis. Alternatively, the directional discordance has been explained as being due to post-magnetization tilt of the batholith. Detailed Al-in-hornblende (AH) barometry (Ague and Brandon 1996) of the Mt. Stuart batholith found only minor (ca. 6 degrees) tilt had occurred, removing some of the uncertainty in determining the Cretaceous paleolatitude of the batholith. Questions regarding the magnetization age of the Mt. Stuart batholith were raised by the paleomagnetic study of Patterson and others (1994), who reported that the northern portion of the batholith has reversed polarity directions, and that most remanence throughout the batholith is carried by pyrrhotite. If most of the Mt. Stuart paleomagnetic results come from pyrrhotite, then a significant time lag between when the AH barometer can provide paleohorizontal control and the time of remanence acquisition is likely.

We have collected 20 new paleomagnetic sites from the Mount Stuart batholith and the adjacent Beckler Peak stock. Using thermal and low-temperature demagnetization, and rock-magnetic tests, we have found that the remanence in the majority of the batholith is carried by SD magnetite. The mean of the new Mount Stuart batholith sites is D = 354.2°, I = 46.2°, k = 87.2, $\alpha95$ = 4.6°, and is similar to those of the Beck and Noson (1972) and Beck and others (1981) studies. Examination of Ar geochonology of hornblende and biotite from the Mt. Stuart batholith finds that the southern portion of the batholith cooled through the blocking temperature of magnetite at 91 Ma. The northern portion cooled through the blocking temperature of magnetite at 86 Ma, and of pyrrhotite at 83 Ma. From these combined results, we conclude that the paleomagnetic directions from the southern portion of the batholith were acquired within 0.5 to 1.0 Ma of the time at which the AH barometers cooled below their closure temperature. Use of the AH barometry to establish paleohorizontal for these rocks is thus well justified. Correcting the Mt. Stuart direction for the tilt indicated by the AH barometry, the mean becomes D = 2.7°, I = 50.5°. This result places the Mount Stuart batholith at a latitude of 31.2°+/- 3.5°N at 91 Ma. By identifying the carrier of remanence in the Mt. Stuart batholith as being SD magnetite, we have removed the major remaining uncertainty in interpreting the paleomagnetism of these rocks. The stable directions repeatedly found in the Mt. Stuart rocks clearly support the microplate tectonic model of Beck and Noson (1972), presently manifest as the Baja BC hypothesis.

GP11A-1074 0830h POSTER

Improved Isolation of High-Temperature Paleomagnetic Components by Combined Low-Temperature and Thermal Demagnetization for Plutonic Rocks with Multicomponent Magnetization

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Thermal demagnetization (THD) of magnetite-bearing plutonic rocks often results in smooth but complex demagnetization paths with scattered high-temperature paleomagnetic components. A possible explanation is that low-temperature thermoremanent magnetizations (TRMs), carried by multidomain (MD) magnetite, variably overlap high-temperature single-domain (SD) TRMs and may persist to high temperature during magnetic cleaning. Low-temperature demagnetization (LTD) has been suggested as a way of selectively removing overprints carried by MD minerals, allowing better resolution of SD components.

For this study, THD in 27 steps was applied to 41 specimens of medium-grained granodiorite to diorite from 7 sites in the Eocene Golden Horn batholith, North Cascades, Washington. Magnetic remanence measurements were made with a cryogenic magnetometer in field-free space. For each specimen, generally two paleomagnetic components were defined in a smooth demagnetization path. Typical unblocking was distributed up to as high as 510°C corresponding to a large, steeply downward component. The transition between components was complex but above 555°C, unblocking was abrupt and generally corresponded to a relatively small, steeply upward component. Within sites, high-temperature component directions included one or more outlying points or were only loosely clustered. With only 5 to 7 samples, site mean errors generally exceeded $\alpha95$ of 20 degrees. Improvement of site $\alpha95$s to a reasonable level required elimination of 16 data points using physically unjustified statistical tests for random directions and/or more complex combined component and plane analysis.

Observed unblocking behavior is consistent with respective MD and SD magnetite carriers of low- and high-temperature components with overlapping unblocking spectra. Magnetic cleaning of specimens with poorly-defined or shallower-than-expected upward directions was apparently incomplete. Dunlop and Xu (1994) have shown that MD magnetite, even with a low-temperature TRM, can exhibit high-temperature unblocking. Borradaile (1994) suggested that low-temperature treatment with liquid nitrogen could selectively demagnetize MD magnetite by passing through its low temperature transitions. Improved isolation of SD carried components with LTD has been successfully demonstrated for metamorphic rocks (Warnock et al., 2000) and limestone (Borradaile, 2001).

Sample mates of 13 of 16 Golden Horn specimens with high-temperature components, that were either statistical outliers or poorly defined, were cycled three times to low temperature with liquid nitrogen. NRM intensity was reduced on average 65%. Subsequent THD unblocking was less distributed and more abrupt at high temperature. Better defined and/or more steeply upward components were revealed for 9 specimens and substituted for non-LTD specimens in site level analysis. In addition, elimination of remaining outlying data points could now be justified. Significant improvement in site and study level k and $\alpha95$ parameters was achieved for unfiltered data. With MAD and outlier filtering, significantly more specimens were retained in the analysis with similar but more robust results. LTD preceding THD was successful in better resolving high-temperature paleomagnetic components and is recommended for demagnetization of igneous rocks with significant MD magnetite behavior.

GP11A-1075 0830h POSTER

General Purpose Inclinometry Tool in Hard-Rock Formations. Are Borehole Wall Micro-Resistivity Images Properly Oriented ?

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Although magnetically oriented microresistivity borehole wall images tools were initially developed for weakly magnetized sedimentary formations, its scientific applications to hard-rock formations, also allows imaging of the in-situ structure of oceanic crust. In the frame of the Ocean Drilling Program (ODP) such as Leg 197, quantitative structural interpretation of these images and core reorientation rely on their proper orientation. Based on magnetic measurements, we investigate here the influence of Natural Remanent Magnetization (NRM) and magnetic susceptibility on tool orientation determination.

Drilled formations at ODP Hole 1203A are characterized by alternating layers of basalts and volcaniclastic sediments having NRM in between 1 and 10 A/m and susceptibility in between 10-3 and 10-1 SI. This data set provides the opportunity to test a filtering algorithm that isolates the rotational component by comparing the raw total magnetic field records to the tabulated geomagnetic field at this site. These results are validated by comparing the computed rotational component with direct record of tool rotation measured with the oriented Goettingen Borehole Magnetometer. Next, using the previous data and data recorded in ODP Hole 735B drilled in gabbroic basement which is characterized by oxide-rich layers having NRM up to 10 A/m and susceptibility up to 10-3 SI, we compare the previously validated algorithm to the Schlumberger algorithm classically used to compute the rotational component of the tool in sedimentary formation. Considering that the oxide rich layers are thin and distant enough to produce only high frequency fluctuations in the magnetic records, rotational component of the tool, and consequently, image orientations are properly defined for structural use and core reorientation, a key-step in the paleomagnetic study of the Hawaiian hotspot motion.

URL: http://www.ldeo.columbia.edu/BRG/ODP/ODP/LEG_SUMM/197/leg197.html

GP11A-1076 0830h POSTER

Crystallographic Relationships of Silicate-hosted Magnetite Inclusions Determined with Electron Backscatter Pattern Indexing (EBSP)

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Crystallographically controlled laths of magnetite exsolved in silicates such as clinopyroxene and plagioclase are common features in gabbros and mafic granulite facies rocks. As the inclusions cool below the Curie temperature of magnetite (580°C) they record a component of the direction and intensity of the Earths ambient magnetic field. The extreme anisotropy of the inclusions aspect ratio allows them to retain an unusually stable magnetization, as exemplified by their single-domain behavior. In order to transform these magnetite inclusions into a useful paleomagnetic tool it is necessary to clearly describe the epitaxial relationship between the magnetite and its host silicate phases.

In the past the crystallographic orientation of magnetite inclusions and their host silicates were determined using single-crystal X-ray diffraction or diffraction patterns obtained with a transmission electron microscope. Although both of these techniques are ultimately successful, they are time consuming and cumbersome. The Electron Backscatter Diffraction Pattern (EBSP) technique is an alternative approach that uses diffraction patterns of Kikuchi bands generated in a scanning electron microscope. The geometric relationships between intersecting Kikuchi bands can be used to determine the orientation of a crystal. Generally the EBSP technique is used to determine preferred orientation patterns in aggregates. However, in this application we use it to investigate local crystallographic relationships. First, inclusions in a thin section are visualized on a backscattered electron image and verified chemically with an EDX signal. Then EBSPs are produced for both the host silicate and the magnetite inclusions and the orientation relationship is ascertained. The EBSP techniques straightforward sample preparation and rapid measurement time, combined with the broad accessibility of scanning electron microscopes allow scientists to more efficiently determine crystallographic relationships between microscopic mineral features.

Exsolved magnetite inclusions occur in clinopyroxenes from gabbros in the Messum Volcanic Complex of Namibia. Using the EBSP technique we were able to determine that (100) and (010) of clinopyroxene are parallel to (111) and (011) of magnetite respectively. The lattice parameters used for this analysis were a = 8.411 Å for magnetite, and a = 9.746 Å, b = 8.49 Å, c = 5.251 Å, b = 105.63°, and space group *C2/c* for clinopyroxene. This relationship produces a smooth fit between the octahedra in the close-packed oxygen layers of both minerals with the c-axis [001] of clinopyroxene parallel to [110] of magnetite. These results are in good agreement with orientations determined using diffraction patterns collected with transmission electron microscopes.

GP11A-1077 0830h POSTER

A Rock Magnetic and HRTEM Study of Nanocrystalline Goethite: Crystal Growth by Oriented Aggregation

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Goethite (α-FeOOH) is a weakly ferromagnetic mineral common in soils, lake sediments, and loess, where its formation and subsequent structural and chemical evolution depend strongly on local environmental conditions. It is therefore a mineral of primary importance for the study of iron geochemistry in modern and past environments, and impacts fields of research as diverse as paleoclimate reconstruction, paleomagnetism, or heavy-metal pollution. Magnetic measurements of bulk samples represent a tool of choice for undertaking such studies, because of their high sensitivity to the magnetic iron oxides and oxyhydroxides. These can be particularly useful when combined with measurements from other analytical techniques such as x-ray diffraction (XRD), synchrotron radiation-based techniques, and high-resolution transmission electron microscopy (HRTEM).

We present a magnetic and HRTEM study of synthetic nanocrystalline goethite. A suspension of nanogoethite particles was prepared by slow hydrolysis of dissolved Fe^{3+}, followed by microwave annealing and rapid cooling in an ice bath. HRTEM characterization of the particles revealed a bimodal particle size distribution, in which 90% of the particles were 3.5nm-indiameter isolated primary nanoparticles. The remaining particles had a needle-like morphology with an average width of 3.5nm and aspect ratio of 4.5:1. The suspension was aged at 90°C for 336 hours, and samples were taken throughout this aging period. Rock magnetic data show that the goethite nanoparticles are superparamagnetic at room temperature, with a peak in magnetic susceptibility around 35K associated with the blocking/unblocking of magnetization in these particles. All magnetic parameters are about an order of magnitude larger for these nanoparticles than for commercially available goethite (submicron-sized needles). Both magnetic and HRTEM results indicate that after 24 hours, the particles evolve into a needles-dominated system. HRTEM results show that crystal growth occurs through oriented aggregation of the primary nanoparticles, as confirmed by smooth increases in blocking temperatures.

GP11A-1078 0830h POSTER

Thermal Treatment of Clays Resulting in Magnetic Mineral Formation in a Smectite - An Analogy to low Burial Conditions

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Widespread chemical remanent magnetizations (CRMs) are common in sedimentary rocks and several mechanisms such as the migration of orogenic fluids and the presence of hydrocarbons have been proposed to cause their formation. Another possible mechanism causing magnetite authigenesis and CRMs is the low temperature diagenetic conversion of smectite to illite during burial in sedimentary rocks. Although empirical evidence supports such a connection, genetic links between low temperature diagenesis (below 100oC) and changes in the magnetic signal have not been tested. In this study, bulk magnetic susceptibility of heated clays was monitored over time under a variety of experimental conditions. Gradual increases of bulk magnetic susceptibility in a heated nontronite were identified in all experimental settings. A heated sodium-montmorillonite showed an augmentation in the bulk magnetic susceptibility signal, but with a more complex response. No changes were observed in any of the other clays, including one smectite (iron-sodium nontronite). Hysteresis measurements combined with thermal demagnetization of low-temperature saturation isothermal remanent magnetization analyses, room temperature isothermal remanent magnetization, and anhysteretic remanent magnetization analyses of the nontronite indicate that the increase in bulk magnetic susceptibility is at least partially caused by the formation of ferrimagnetic material. The authigenic phase is interpreted as magnetite and is of superparamagnetic (SP) as well as remanence-carrying grain size. X-ray diffraction indicates that illitization of the smectite may not have occurred. Visible-infrared reflectance spectra have been measured and analyses of the spectra are underway. This laboratory study provides supporting genetic evidence for a potential connection between some clay diagenetic processes and the formation of some widespread CRMs.

GP11A-1079 0830h POSTER

Paleosecular Variation, Geochronology, and Magnetic Mineralogy of Pleistocene Igneous Rocks of Ascension Island, South Atlantic Ocean

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Paleomagnetic samples were collected from 68 sites on Ascension Island between May 14 and June 18, 2001. Paleomagnetic analyses of samples were performed at the University of Puget Sound paleomagnetic laboratory. Preliminary results indicate that 32 sites yield normal directions, six sites give reversed directions, and three sites exhibit intermediate directions (VGP latitude less than 60°). Eight sites exhibit too much scatter in paleomagnetic directions to be useful and nineteen sites have yet to be analyzed as of 9/1/02. Mean directions for both normally and reversely magnetized units tend to exhibit inclinations steeper than expected for Ascension Island. Ar/Ar dating of 20 samples was completed at the University of Wisconsin, Madison. Ages range from 50.9±7.9 ka to 1086.2±15.2 ka. Ages and polarities indicate directions represent the Matuyama Chron, Brunhes Chron, and Jaramillo Subchron. Sixteen samples from twelve sites were examined using reflected light microscopy at Tarleton State University. Eight sites appear to be relatively unaltered. Three sites show moderate alteration, but appear to retain substantial primary magnetic mineralogy and record primary magnetic directions. One site is extensively altered and probably records secondary magnetism. Optical examination confirms inferences from thermal demagnetization that magnetic mineralogy is largely dominated by titanomagnetite with some units containing significant hematite. A substantial paleosecular variation (PSV) database has been compiled for the past 5 Ma, but numerous areas, including the South Atlantic are underrepresented. This study has produced enough magnetic directions from the last million years or more to fill a gap in the PSV database, which can be used to test and refine emerging geodynamo models.

GP11A-1080 0830h POSTER

Magnetic Properties of Single Crystal Clinopyroxenes: *Anisotropy* of Remanence

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Magnetite exsolved from clinopyroxene in subsolidus cooling can have robust remanence characteristics. Exsolved from the host silicate during slow cooling, the magnetite is in the form of lath-shaped needles. With clinopyroxene as a crystal-chemical template, the magnetite needles are arranged in only two directions or arrays (termed X and Z, about 75° apart). The extreme elongation of each magnetite needle produces a dominating shape anisotropy that generates anamolously high coercivities and extremely long relaxation times. The dominance of shape anisotropy also produces a complete restriction in remanence directions. Each needle can have one of the two possible remanence directions, parallel or anti-parallel to its length. Each array can be expected to produce a remanence along its axis (e.g. +X or -X), while the presence of two arrays (as in CPX) should produce a remanence that is restricted to a plane (X-Z plane in CPX). Observations of remanence directions in single crystals of CPX show these specific linear and planar restrictions. This type of intracrystalline remanence control is different from the more commonly encountered distribution anisotropy, arising from a bias of preferred orientations in populations of magnetite crystals. The term anisotropy may not be wholly appropriate for the silicate-hosted, shape restricted remanence, which has only two bipolar states within a given CPX crystal. The term *polarity* would be appropriate, except for its preemptive use in describing the state of the global field. The term *anisotropy* will be used for now as a general term for the bipolar states of magnetite arrays.

Anisotropy of IRM, Mr, Ms, and microscopic coercivity have been measured on single crystals of CPX (ca. 0.1 mg each) from gabbroic cone sheets of early Cretaceous age (Messum Complex, Namibia). IRM values have an abrupt reduction by a factor of 4 through a 30° zone in the X-Z plane. The hysteresis parameter Mr shows a more regular sinusoidal change (also by a factor of 4), reaching a minimum whenever the applied field is most perpendicular to the X and Z arrays. The saturation magnetization (Ms) is less variable, but shows 30% variations when the applied field is perpendicular to the X and Z arrays. Microscopic coercivity has been measured using the detailed hysteresis method of FORC analysis (First Order Reversal Curves). Each array of magnetites can be measured separately by applying the field perpendicular to the other array. Differences in the microcoercivity can be determined for each array, e.g. X=75-100mT while Z=85-125mT. Extreme *anisotropy* can be seen whenever the applied field is perpendicular to the plane of the arrays (Y direction), such that no microcoercivity population can be detected (up to 700mT) in the Y direction. For IRM, the remanence also appears to be null in the Y direction. The current challenge is to overcome these extreme restrictions in remanence *anisotropy*, while utilizing the equally extreme remanence stability to decode paleomagnetic field directions and intensities.

G P

GP11A-1081 0830h POSTER

Use of FORC Diagrams to Study Transformations Associated with Natural Physical and Chemical Gradients

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In many situations, determinations of magnetic properties can be more sensitive probes of geologic materials than corresponding mineralogical, chemical or physical measurements. However, like these other approaches, magnetic methods usually give results that reflect the bulk or average value of a magnetic property, rather than the distribution of that property over the magnetic grains in a sample. In contrast, FORC diagrams, which are constructed from suites of partial hysteresis curves known as first-order reversal curves (FORCs), can probe the distribution of the magnetic grains in a sample. They also provide information about interactions between magnetic grains, a phenomenon that is usually assumed to be negligible in the interpretation of magnetic data. We are presently exploring the use of FORC diagrams to characterize the transformations that take place along naturally-occurring physical and/or chemical gradients. These gradients result from various geological and geophysical phenomena, including paleoenvironmental and paleoclimatic variations, thermal and geochemical processes, and diagenetic and deformational events. Our initial results indicate that in several situations, FORC diagrams can provide insights about these phenomena that cannot be obtained by other magnetic or non-magnetic methods.