GP12A MCC: 2006 Monday 1340h

Magnetic Anisotropy and Its Applications II *(joint with T, V)*

Presiding: **W D MacDonald,** State University of New York at Binghamton**;** **B Housen,** Western Washington University

GP12A-01 1340h

Magnetic Fabric and Paleomagnetism of the Peninsular Ranges Batholith, Sierra San Pedro Mártir, Baja California.

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We summarize results of recent paleomagnetic, structural, petrologic and magnetic fabric studies along an east-west (60 km long) transect across the Peninsular Ranges Batholith (PRB) in north-central Baja California. The transect includes both magnetite rich plutons from the western sector of the PRB, and ilmenite rich plutons from the eastern sector, as well as plutons on the eastern and western side of major tectonic discontinuities. We include results for 8 plutons, included well-characterized bodies such as San Pedro Mártir (SP), San José (SJ) and La Zarza (LZ), and relatively little known plutons such as Potrero (PO), Aguaje del Burro (AB), El Milagro (MI), and San Telmo (ST). Plutons on the western sector of the PRB yield a paleomagnetic pole at 82° N-186.4° E (A95=4.8°). When rotated into a pre- Gulf of California position, the pole (79.2° -188.2°) is statistically undistinguishable from the North American reference pole. In contrast, SP, SJ and PO plutons, on either side of the NW trending Main Martir Thrust yield clearly discordant direction that can only be reconciled with results for the western plutons assuming southwestward tilt of ∼ 25° for SP and greater than 45° for SJ and PO. We find strong evidence in support of tilt of the plutons from thermochronological, structural, and geobarometric data. These data will be discussed elsewhere. Here we focus on magnetic fabric data. AMS for SJ is strongly developed with high values for degree of anisotropy (P= 1.14 a 1.40), but marked east-west asymmetry that contrasts with the general symmetry of the pluton along a north-south axis. Oblate fabrics (T∼ +0.4) with dispersed lineation directions dominate the west side of the pluton and prolate fabrics (T∼ -0.15) with steep to vertical lineations dominate on its eastern side. This fabric is interpreted to result from magma flow. SP, a much larger pluton and sensibly asymmetric, displays high degrees of anisotropy (P∼1.2) on its western side but dominantly oblate (T∼ +0.4) fabric, with foliations parallel to the pluton margins. In contrast, the eastern side of the pluton displays low P values (∼ 1.06-1.10), but markedly oblate fabrics (T∼ +0.6) parallel to the pluton margin. Fabrics in the pluton interior are weakly developed. These data are interpreted to support models of pluton emplacement that involve drag (vertical shear) along the western margin of the pluton along the Main Mártir Thrust during pluton ascent, thus facilitating tilt and deformation of the smaller plutons to the west.

GP12A-02 1355h

Anisotropy of Magnetic Susceptibility (AMS) and Remanent Magnetization Directions (NRM) determined from Intrusive Magma Flow: Volcanic Evolution of the Koolau Dike Complex.

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The Koolau volcano on the northeastern flank of the island of Oahu in Hawaii is the source area for one of the largest landslides on Earth (3,000 to 4,000 km3), the Nuuanu debris avalanche. The offshore expression of this slide is an extensive rubbly field of debris extending approximately 230 km from the island across the Hawaiian Deep and onto the Hawaiian Arch. We have studied the intrusives of the Koolau volcano by means of Anisotropy of Magnetic Susceptibility (AMS) and paleomagnetism (NRM) studies to investigate the plumbing of the Koolau volcano, the volcanic evolution and to constrain further the timing of the Nuuanu detachment (Herrero-Bervera et al., 2002). We have re-examined 71 dikes from the Knight and Walker (1988) study and 10 additional dikes sampled in the Kapaa quarry located within the deeply and perhaps the youngest collapsed part of the Koolau Volcano. The results derived from these investigations indicate that the plumbing of the Koolau volcano is characterized by a very coherent dike complex and by a high dike injection nature. The petrofabrics yielded coherent flow azimuths regardless of their time of emplacement. Nearly 50 percent of the dikes studied (30) gave paired AMS plots and were fed by lateral flow (near horizontal magma flow, Kmax between 5 to 30^o of inclination). In very few cases the magma flow was near vertical. We were able to measure the NRM of 79 dikes of which 63 dikes are characterized by a high degree of magnetic stability. At least 20 dikes were stepwise demagnetized by alternating fields from 5 to 100 mT. The demagnetization diagrams obtained showed a stable direction of remanence for most samples. In all cases, the characteristic component (ChRM) was clearly defined from at least seven successive directions isolated during stepwise demagnetization. The mean direction calculated for each intrusive revealed the existence of reversed polarities except for two dikes that are characterized by normal polarities. The overall results (AMS and NRM) indicate that the dike injection within the Koolau Dike Complex (KDC) was the main cause of the triggering of the giant Nuuanu landslide (synchronous denudation by seaward creep on normal to listric faults).

GP12A-03 1410h

Magnetic Fabric, Paleomagnetism and Rock Magnetism of Mafic Intrusive Rocks in the Shimanto Accretionary Complex in Southwest Japan

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The Shimanto Belt in Southwest Japan is unique in that a part of this accretionary complex was characterized by anomalous, post-accretion, near-trench igneous activity associated with regional folding and faulting. Our study focuses on a large intrusive body (c. 14 Ma) and nearby mafic rocks as well as surrounding sedimentary rocks near Cape Muroto of Shikoku Island. We measured remanent magnetizations, anisotropy of magnetic susceptibilities (AMS) and rock magnetic properties in order to clarify how the mafic body was intruded and settled in the present attitude, and to assess the thermal effect of volcanic intrusion on the accretionary prism. The intrusive body was sampled several meters interval from the chilled margin over about 120 m thick in total, and showed stable remanent magnetizations with moderate magnetic coercivity and unblocking temperature spectrum indicating fine-grained magnetite in the groundmass is the major magnetic carrier. The in-situ directions point moderately upward in the northwest quadrant, showing remarkable contrast from the representative direction of contemporaneous rocks in Southwest Japan. There is a systematic variation in inclinations with distance from the margin: the in-situ inclinations of 30-50 degrees near the margin appears to steepen gradually up to 70-80 degrees toward the core of the body. AMS study recognized two zones with relatively well-grouped, minimum susceptibility axes; the one zone, which has the most tightly clustered minimum axes, is located about 20-30 m away from the chilled margin, and the other one is in the central portion of the body with minimum axes much more scattered. The oblate magnetic fabric is consistent with the bedding attitude of the surrounding sedimentary strata, indicating that the body intruded nearly horizontally into the sediment. Magnetizations of the sedimentary rocks nearby show similar directions of reversed polarity as the volcanic intrusion, suggesting the sediments are likely to have been remagnetized on intrusion of the mafic rocks. These AMS and paleomagnetic results suggest that the intrusive body experienced considerable deformation as well as the host accretionary prism.

GP12A-04 1425h INVITED

The magnetic anisotropy of mantle peridotites

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Previous magnetic anisotropy studies in peridotites have shown that secondary magnetite dominates their low-field AMS. This magnetite is formed during serpentinization processes along the foliation plane and along fractures. In serpentinized peridotites from the Mid-Atlantic Ridge, the long axis of the low-field AMS ellipsoid, was reported to be parallel to the [100] olivine axis while the short axis was parallel to [001]. In extensively serpentinized peridotites of the same area, secondary pseudo-single domain (PSD) magnetite was dispersed and no relationship between olivine LPO and magnetic fabric existed. In general, the shape fabric of magnetite does not relate to either the olivine LPO or the primary silicate flow fabrics. Therefore, the low-field AMS of mantle peridotites cannot provide useful information on mantle flow fabrics. The separation of the primary silicate paramagnetic fabric component from the bulk, i.e., ferromagnetic and paramagnetic, AMS fabric is necessary for flow studies in peridotites. In a previous study of serpentinized harzburgites from an ophiolite, others proposed to isolate the ferromagnetic component from the bulk AMS by using the anisotropy of anhysteretic remanence. This approach, based on the subtraction of the AARM tensor (carried by ferromagnetic phases only) from the low-field AMS tensor, may be misleading because the AARM fabric of ferromagnetic phases does not exactly correspond to their low-field AMS fabric. This is particularly true with regards to the degree of anisotropy. The normalized AARM tensor theoretically solves this problem in the case of multi-domain magnetic fabrics. However the AARM tensor normalization cannot be easily applied to rocks with a range of grain-sizes from single domain to multi-domain. At this point the paramagnetic component of the AMS fabric can be isolated only by using torque magnetometry a technique requiring 4 to 6 hours per specimen. More recently we have developed a new magnetic fabric method, based on high-field measurements, above the saturation of ferromagnetic phases, using a vibrating sample magnetometer. This technique has been succesfully tested on the Twin Sisters dunite massif, in Washington State, which was chosen because of its petrological simplicity and moderate degree of serpentinization. The paramagnetic component of the AMS is controlled by the magnetocrystalline anisotropy of mafic silicates which, in turn, should coincide with olivine LPOs. The principal current challenge is to investigate the geometric relationship between the high-field magnetic fabrics and the olivine LPOs measured on the same specimens.

GP12A-05 1440h INVITED

How Deformed are Weakly Deformed Rocks? Insights From Magnetic Anisotropy

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Early stages of rock deformation typically involve preferred orientation of minerals or fabric elements. Magnetic anisotropy is an extremely sensitive and accurate technique that can be used to determine tectonic fabrics and thus is an ideal approach to characterize weakly deformed rocks. In mudrocks, Anisotropy of Magnetic Susceptibility resides mostly on phyllosilicate grains and the degree of preferred orientation can then be taken as a deformation intensity gauge. A number of field-based and experimental studies show that under very low strain and incipient re-orientation, phyllosilicate platy grains interact with each other to produce a rather common magnetic ellipsoid where the principal maximum axes of susceptibility lie parallel to the bedding and flattening plane intersection. Under progressive incremental strain, principal axes of maximum susceptibility eventually parallel the tectonic stretching direction, depending on the strain and both magnitude and orientation of the original (pre-deformational) fabric. This type of early fabrics is very often characterized by prolate magnetic ellipsoids with relatively low values of anisotropy degree (P). The magnetic ellipsoid evolution under increasing strain shows an initial decrease in anisotropy degree followed by an almost exponential growth. The magnetic shape factor (T) changes from oblate (primary-sedimentary fabric) to prolate and back to the oblate field for higher strains. The initial cryptofabric (prolate ellipsoid, low value of P) occurs usually before the appearance of discernible cleavage and thus indicates the first evidence for penetrative tectonic fabrics in rocks. There is an overwhelming number of studies, mostly from the Alpine realm, revealing magnetic cryptofabric in mudrocks otherwise lacking evidence for tectonic deformation (such as pressure-solution, pencil structures, cleavage). Due to the high sensitivity of magnetic anisotropy methods, we are pushing the frontiers of what is classically been called weakly deformed rocks. For example, the question of whether the appearance of cleavage in mudrocks occurs at some strain threshold or instead it builds up gradually from the earliest stages of deformation and has simply escaped noticed, has been debated for many years. Our recent advances in magnetic anisotropy of "weakly deformed rocks" not only favor the later, but also support that magnetic cryptofabric, which is typically linear, is the precursor of what we have been calling incipient cleavage in mudrocks.

GP12A-06 1455h INVITED

Contrasting Magnetic Fabrics in Sediments of Alpine and Variscan Accretionary Wedges of Central Europe

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The magnetic fabrics in sediments of the Alpine thrust sheets of the Flysch and Klippen Belts of the West Carpathians range from essentially sedimentary to mostly deformational in origin. The former magnetic fabrics are characterized by virtual parallelism of the magnetic foliations to the bedding and by close relationship of magnetic lineations to the current directions, if observable. These magnetic fabrics are typical of the thrust sheets at both margins of the Flysch Belt. The sheets were probably detached from the wedge relatively early and underwent deformations as rigid bodies (translation and perhaps rotation) without being affected by detectable ductile deformation. The latter magnetic fabrics show significant deflections of the magnetic lineations from the current directions and important deflections of magnetic foliations from the bedding evolving into girdle pattern in magnetic foliation poles. These magnetic fabrics are typical of the central thrust sheets where the magnetic fabric was relatively strongly affected by ductile deformation represented by a combination of simple shear (responsible for overthrust movements) and lateral shortening (mostly bedding-parallel), probably associated with creation and motion of the thrust sheets driven by a push from the rear side. However, the deformation was too weak to give rise to the cleavage. The Variscan thrust sheets of the Rheno-Hercynian Zone of the E Bohemian Massif show very variable magnetic fabrics and deformation fabric elements. In some areas, the achimetamorphism, ductile deformation and degree of AMS are in general weak; the magnetic fabric is oblate, the magnetic foliation is either parallel to the bedding or tends to create a partial girdle in its poles. The strata create buckle folds of long wavelength whose magnetic fabric can be unfolded geometrically. In the other areas, spaced cleavage and relatively tight buckle folds can be found. Magnetic foliation is still mostly parallel to the bedding, but the magnetic lineation is re-oriented into parallelism to the cleavage/bedding intersection lines. The magnetic fabric of the most folds can be unfolded only partially. In the other areas, cleavage folds and very well developed slaty cleavage occur. The degree of AMS is high, the magnetic foliation is parallel to the slaty cleavage and the magnetic lineation is parallel to the cleavage/bedding intersection lines. The magnetic fabric in the folds is homogeneous, the folds cannot be unfolded at all. In places, the slaty cleavage is transposed into the metamorphic schistosity. The magnetic fabric in crystalline rocks neighboring this wedge shows the same orientations as that of the wedge. This is interpreted as underplating the wedge by the detached crystalline basement.

GP12A-07 1510h

Comparing magnetic and clast fabric in gouge and breccia from the Black Mountain detachments, Death Valley, CA: Implications for the micro-mechanics and kinematics of shallow crustal shear zones.

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The Black Mountain detachments, Death Valley, CA, place Pliocene-Quaternary sediment against Miocene and older crystalline rocks. The detachments comprise sharp slip surfaces and centimeter-to-meter scale shear zones. The shear zones contain gouge and breccia that exhibit well-developed mesoscopic foliation but no evidence for deformation from crystal plasticity or penetrative pressure solution. Measurements of the anisotropy of magnetic susceptibility (AMS), partial anhysteresic remanent magnetization (pARM), and shape preferred orientation (SPO) of greater than 50 micron grains define fabric consistent with the extension direction of the faults inferred from geologic and geodetic data. Many lines of evidence including low-Temperature MS experiments, pARM, transmission and scanning electron microscopy, and optical petrography demonstrate that the magnetic carriers within the gouge and breccia are dominantly nanometer-to-micrometer scale grains that grew within the shear zones prior to the most recent deformation. In contrast, SPO was measured for populations of grains that were inherited from the wall-rock. SPO was measured on thin sections cut parallel to three orthogonal planes-of-view. Because it is not known if the SPO vectors are eigenvectors a priori the resulting SPO vectors were compared in relative length and orientation with the eigenvectors of the AMS ellipsoid. Flattened and some elongated AMS and SPO ellipsoids characterize the fabrics. The long axes of these ellipsoids are shallowly inclined to the shear plane, but in some cases are inclined out of the plane of inferred shear. The similarity of fabric defined by clasts (SPO) and matrix (AMS) is inconsistent with a plastically yielding matrix or a dispersive mode of polyphase flow. Although mechanically the gouge and breccia were/are frictional materials that deform via a complex granular flow, we find that the orientation of the SPO and AMS are best described using kinematic models rooted in Jeffery's theories for fluids. Because the magnetic carriers demonstrably grew after the larger SPO-defining clasts began rotating, we propose that the SPO records more finite strain than the AMS. This can explain most of the discrepancies between the SPO and AMS orientations.

URL: http://www.ess.washington.edu/~cowan/

GP12A-08 1525h

Rotation of Uniaxial Ellipsoidal Particles During Simple Shear Revisited: Implications for the Interpretation of AMS Measurements.

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The rotation of uniaxial ellipsoidal particles has provided the base for many studies of shape preferred orientations (SPOs) of mineral grains, including those concerned with the anisotropy of magnetic susceptibility (AMS) of a large variety of rocks. In most AMS studies, it has been customary to assume that a stable orientation is achieved irrespective either of the elongation ratio of the particle, or of the amount of shear experienced by the rock. In contrast, fabric studies other than AMS commonly have made much emphasis in the cyclic movement of the particles, concluding that no stable orientation can be achieved in simple shear. In this work we studied the evolution of a multiparticle system as a function of 1) the elongation ratio of the particles, 2) the initial particle distribution and 3) the amount of shear experienced by the rock. Our model reveals that all of these factors are important in controlling the acquisition of a stable orientation upon deformation, and can be used to establish adequate threshold values depending of the conditions of interest. The more elongated particles (r = short / long semiaxis < 0.2) will define a stable fabric in almost any situation of geological interest. Less elongated particles ($r > 0.5$) can also be considered to have achieved a stable orientation if deformation remains low ($\gamma < 3$). Consequently, it is necessary to distinguish between rocks in which the SPO is suspected to have been achieved under solid deformation and those in which the SPO may have been acquired upon magmatic deformationand for which shear can be much larger ($\gamma \sim 80$). Of particular relevance for AMS studies is the finding that it is possible to observe some systems with less elongated particles in which the mean orientations are perpendicular to the direction of shear. This implies that many "abnormal" fabrics may have been the result of the natural evolution of a simple multiparticle system, and not to turbulence or post-emplacement alteration effects. Our model results also suggest that a systematic study of samples collected at various controlled positions within the same rock can provide enough information to evaluate whether the mean SPO of the minerals (and hence the associated AMS) is parallel to the direction of shear.

GP12B MCC: 2006 Monday 1600h

Conductivity From Crust to Core II

(joint with T)

Presiding: **S Constable,** Scripps Institution of Oceanography**; S K Park,** Institute of Geophysics and Planetary Physics, University of California, Los Angeles

GP12B-01 1600h

Three-dimensional inversion of marine magnetotelluric data

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In this paper we present the results of the feasibility study of the sea-bottom array MT observations for petroleum exploration. We consider a model of an offshore sea-bottom petroleum reservoir. The resistivity of petroleum reservoir and of salt structures is usually on an order greater than those of surrounding sea-bottom sediments. That is why these structures can be considered easily detectable targets for marine MT methods. However, the interpretation of the sea-bottom MT data was based, as a rule, on 1-D or 2-D modeling. Recently, we have developed a powerful 3-D MT inversion method, which can be applied for both the ground and sea-bottom observations. This method is based on an application of the quasi-analytical (QA) approximation in the initial stage of the iterative process to speed up the inversion. However, in the final stage of the inversion we use the rigorous forward modeling to generate more accurate result. We examine several models, which represent a petroleum reservoir in the presence of a salt dome of a complex shape. The inversion results show that even in the case of complex sea-bottom geological structures, where the reservoir response is strongly distorted by the salt dome effect, the inversion generates a clear image of the reservoir. These results demonstrate that the sea-bottom MT survey can be a powerful tool for offshore petroleum exploration.

GP12B-02 1615h

Electrical Conductivity and Anisotropy in Pacific Lithosphere: CSEM Results from APPLE

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Strain associated with plate formation at mid-ocean ridge spreading centers may influence electrical conductivity at various depths in the lithosphere, and may leave an anisotropic fabric frozen in place. By measuring lithospheric electrical conductivity and anisotropy, insight may be gained regarding the formation and evolution of oceanic crust and mantle. Controlled-source electromagnetic (CSEM) sounding of 35 Ma Pacific lithosphere was undertaken as part of the Anisotropy and Physics of the Pacific Lithosphere Experiment (APPLE), carried out approximately 1000 km west of San Diego. The transmitter (DASI), with a 100 m horizontal electric dipole antenna, was deep-towed in a 30 km radius circle around an array of receivers. A radial tow to 70 km total range and a 15 km radius semicircular tow supplemented the geometry of the main tow. DASI transmitted a 4 Hz square wave throughout the CSEM phase of the experiment. Smooth (and layered) inversions of short-offset (2-20 km) data, using 1-D isotropic modeling, generate models with upper-crustal resistivities $\sim$1 Ωm, varying by about an order of magnitude across the survey area. Lower crustal resistivities are on the order of 10^3 Ωm. Smooth inversion of the long radial tow data indicates upper mantle resistivities of $\sim 10^4$ Ωm, with an increase in conductivity below 20 km depth. This may be due to thermally-activated olivine conduction, indicating that the base