**Burial Remagnetization Mechanisms**

Although the migration of externally-derived fluids is a likely agent of remagnetization for some CRMs, widespread CRMs which occur in rocks that have not been altered by such fluids need to be explained by another remagnetization mechanism. Several burial diagenetic remagnetization processes such as clay diagenesis and maturation of organic matter have received considerable attention as agents of remagnetization. The results of laboratory simulation experiments also support a connection between burial diagenesis and authigenesis of magnetite (Moreau et al., 2005).

![Depth (km) vs Temperature (°C)](image)

Burial Remagnetization processes—“simmering in their own juices”

**Smectite to illite**

Paleomagnetic and geochemical results from Mesozoic carbonates in the Vocontian Trough in SE-France support a hypothesized acquisition of a CRM during burial diagenesis of smectite and are not consistent with a connection to orogenic-type fluids (Katz et al., 1998, 2000). See Case Study 1.

Paleomagnetic, geochemical, and petrographic/SEM studies on Jurassic sedimentary rock of Skye, Scotland (Woods et al., 2002) are consistent with the hypothesized clay diagenesis and remagnetization connection. The Jurassic rocks in southern Skye contain that contain illite also contain a dual polarity early Tertiary (55 Ma) CRM that formed at approximately the same time as the Tertiary igneous rocks on Skye. This is the inferred time for illitization. In contrast, the same age rocks in North Skye which are not altered and are dominated by smectite do not contain the CRM. This presence-absence test and age of the CRM suggest that magnetite authigenesis is related to the smectite-to-illite conversion, and that clay diagenesis is a viable remagnetization mechanism.
While geochemical and petrographic studies provide important clues for establishing this relationship, the ultimate test of this hypothesis requires the application of independent dating methods to verify the paleomagnetic ages. Towards this end, we are working with Dr. Crawford Elliott at Georgia State University who does K-Ar dating of illites to directly test for a timing connection between remagnetization and the smectite to illite conversion. We have also estimated the timing of illitization by using established kinetic models (Blumstein et al., 2004).

We collected additional samples from our paleomagnetic sampling sites (mudstones, marls) on Skye for the K-Ar dating. The clay fractions of Jurassic marls in the Great Estuarine Group in southern Isle of Skye are dominated by mixed-layered illite-smectite (I-S) with large percentages (>85%) of illite layers. The marls have not been buried to the depths normally required to convert smectite to illite-rich I-S, so it is possible that the conversion was in response to heat and hydrothermal fluids from nearby early Tertiary igneous activity about 55 Ma ago. The large percentages of illite layers in I-S, the Srodon intensity ratios, and the Kubler index values are consistent with the formation of diagenetic I-S as a result of relatively brief heating caused by igneous heating. A linear extrapolation of K-Ar age vs. percentage of 2M1 polytype (detrital illite) from one marl (EL-6) yields an estimate for the age of diagenetic illite of 106 Ma (Elliot et al., 2006a). The estimated and measured age values, however, could be substantially greater than the true age of the diagenetic illite in I-S because of the presence of detrital 1Md illite that was recycled from early Paleozoic shales. Nevertheless, most of the illite in the Elgol marls (80% or more in the finest fractions) must be diagenetic and probably formed in response to the early Tertiary heating.

We are currently testing clay diagenesis as a remagnetization mechanism for CRMs by comparing results from Mesozoic strata in the Disturbed Belt of Montana where the rocks contain ordered illite/smectite that formed by moderate heating as a result of thrust loading, with equivalent strata on the adjacent Sweetgrass Arch which contain unaltered smectite-rich clay mineral assemblages (e.g., Hoffman and Hower, 1979). A presence-absence test based on comparison of the results from the Sweetgrass Arch and the disturbed belt are consistent with a spatial connection between magnetite authigenesis and clay diagenesis (Gill et al., 2002). The results of the regional fold test on carbonate concretions in the Marias River Shale, however, suggest that the CRM was acquired prior to folding (Elliot et al., 2006b). A prefolding CRM is difficult to reconcile with the inferred timing of illitization (thrust loading) because it is likely that thrust loading was coincident with partial deformation of the Cretaceous rocks. This work raises questions about the hypothesized relationship (Elliot et al., 2006).

We also collected samples from bentonites for K-Ar dating that were in close proximity to the concretions. The bentonites provide a more definitive measure of the age of diagenetic illite than the mudstones sampled on Skye. The K-Ar dates for the diagenetic illite are between 51.9-54.1 Ma which is consistent timing of thrust load burial (Elliot et al., 2006b).

**Maturation of Organic matter**
A recently completed study in the Mississippian Deseret Limestone in the mountain ranges of western Utah found a Jurassic CRM that was not related to externally derived fluids (Blumstein et al., 2004). The time of remanence acquisition for this component overlaps with the timing of the oil window based on modeling studies, and the CRM is interpreted to have formed as a result of the maturation of hydrocarbons (see Case Study 2).

Our previous studies have also provided evidence for a relationship between remagnetization and maturation of organic matter. For example, in a regional study of the Belden Formation, Colorado, Banerjee et al. (1997) reported that the timing of CRM acquisition is different across the basin and it agrees with the modeled time of maturation of organic matter for the different localities. In addition, a collaborative study with colleagues at Oak Ridge National Laboratory on the oxygen isotopes of diagenetic magnetite in the Belden indicates that the magnetite formed from water having δ18O near 0 ‰ or less, implying a meteoric or connate source rather than a highly evolved orogenic or basinal fluid (Ripperdan et al., 1998). The results of these studies are consistent with a study of a single fold in the Belden which indicates that a synfolding CRM which resides in authigenic magnetite that rims pyrite grains is not related to syndeformational orogenic fluids (Fruit et al., 1995). A study of organic-rich beds in the Old Red Sandstone (Scotland) indicates that the time of CRM acquisition agrees with independent estimates for the time of thermal maturation (Plaster-Kirk et al., 1995). Simulation experiments have also successfully produced magnetite by dissolution-reprecipitation of pyrite (Brothers et al., 1996). These experiments may simulate diagenesis at temperatures below 100°C and is one possible pathway for magnetite authigenesis. A study of organic-rich Jurassic sedimentary rocks adjacent to a Tertiary dike in Scotland, investigated as an analog for burial heating, suggest that moderate burial depth might be sufficient to cause magnetochemical changes (Katz et al., 1998).

It is important to keep in mind that the smectite to illite transformation and maturation of organic matter mechanisms for CRM acquisition are not necessarily mutually exclusive. Organic matter is intimately associated with clay minerals in black shales (Kennedy et al., 2002) and it is conceivable that the authigenesis of magnetic phases is facilitated by this interplay.

Case Study 1. Burial diagenesis of smectite, chemical remagnetization, and magnetite authigenesis in the Vocontian trough, SE-France

Results of a paleomagnetic, rock magnetic, geochemical and petrographic study on Jurassic and Cretaceous carbonates in the Vocontian trough (Fig. 1) support a hypothesized connection between burial diagenetic alteration of smectite and the widespread occurrence of a CRM carried by magnetite (Katz et al., 2000). Conglomerate tests indicate the magnetization is secondary (Fig. 2). Where smectite has altered to other clay minerals, limestones are characterized by a prefolding, secondary, normal polarity
magnetization throughout the basin (Fig. 3). The magnetization is interpreted to be a CRM based on low burial depths which can not cause thermoviscous resetting.

Where significant smectite is still present, the CRM is absent/weakly developed and where the clays show no evidence for burial alteration, the units are characterized by a primary magnetization. CRM intensity also varies with the amount of smectite and burial. The IRM, ARM, and NRM intensities increase where smectite has been altered, both stratigraphically (Fig. 4) and geographically. This is interpreted to indicate magnetite authigenesis associated with clay diagenesis. Superparamagnetic magnetite is more dominant in highly altered units based on the results of low temperature experiments. All sections away from the Alps have $^{87}$Sr/$^{86}$Sr values that are similar to coeval seawater (Fig. 5) and stable isotopes of carbon and oxygen show no sign of alteration. Orogenic-type fluids, therefore, are not a likely agent of remagnetization.

![Location Map of the Vocontian Trough](image)

**Figure 1.** Map of the Vocontian Trough, several of the sampling localities, and the level of smectite alteration.

Near the Alps, the rocks are characterized by a reversed polarity component which is interpreted to reflect acquisition of the CRM through a reversal. A postfolding magnetization is also present there and strontium isotopic ratios are higher than elsewhere in the basin and might indicate some alteration by orogenic-type fluids. We conclude that burial diagenesis of smectite is the likely cause for the development of the widespread CRM in the Vocontian trough and that this mechanism might explain widespread chemical remagnetization elsewhere.
Figure 2. Negative conglomerate test indicating the magnetization is secondary. Note grouping of the samples from the breccia clasts and the bedded micrite. Closed circles: projections on lower hemisphere.

Figure 3. Stereographic projections of magnetic directions for in situ and tilt corrected coordinates from one representative fold (open circles: projections on upper hemisphere) and the incremental fold test results. Blue line: precision parameter k at various steps of unfolding. Note that the best grouping is at 100% untilting. Also shown are the F-values (red line). A horizontal line at ~ 0.3 is the 95% confidence level (McFadden and Jones, 1981) for the common mean.
Figure 4. Results from central part of Vocontian trough near Montclus as function of stratigraphic position (left column; limestone, hachured; marl, black; breccia, spotted). The NRM as function of stratigraphic position is shown in the next column. Intensities are higher in older units where characteristic magnetization is well developed. ARM as function of stratigraphic position is also shown, indicating that older units contain more remanence-carrying magnetite. The column on the right shows percent smectite of total clay fraction (Deconick et al., 1985).

Figure 5. Coeval seawater values for the Mesozoic rocks sampled and the $^{87}\text{Sr}/^{86}\text{Sr}$ values for the samples. Note that the samples in the Berrias/center have coeval values. Results from the east may be slightly elevated.
Case Study 2. Timing of Hydrocarbon Maturation in a Source Rock: the Deseret Limestone, Utah (Blumstein et al., 2004).

The objective of this study was to test models for the origin of widespread remagnetizations in the Mississippian Deseret Limestone and to specifically test the paleomagnetic method for dating maturation of organic matter. The Delle Phosphatic Member of the Deseret Limestone is a source rock for hydrocarbons and modeling studies indicate it entered the oil window in the Early Cretaceous during the Sevier Orogeny (Hunton et al., 1999). Paleomagnetic and rock magnetic results from the Deseret Limestone and the stratigraphically equivalent Chainman Shale in western Utah indicate that the unit contains several ancient magnetizations residing in magnetite. Burial temperatures are too low for the magnetizations to be thermoviscous in origin and the components are interpreted as CRMs. Fold tests from western Utah indicate the presence of a pre-folding Triassic to Jurassic CRM (component 1; Figs. 1 and 2) that was acquired at the beginning of the oil window (Fig. 3). Geochemical analyses suggest that externally derived fluids did not alter these rocks. In some specimens, pyrite grains have been partially altered by an iron oxide, interpreted to be magnetite (Fig. 3). The time of remanence acquisition for the Triassic-Jurassic component overlaps with the oil window (Fig. 4) and the results are consistent with a connection between organic matter maturation and remagnetization. A younger CRM (component 2) in western/central Utah is apparently post-folding and is probably Late Cretaceous to Early Tertiary in age.

Figure 1: a) Equal area projection for component 1 site means in the Mountain Home Range (MG sites [one limb], circles; MH sites [other limb], squares) in both geographic and stratigraphic positions (with α95 circles for site means). The open symbols represent negative inclinations. b) Graph showing the percent unfolding versus grouping (k) for component 1 in the Mountain Home Range (Watson and Enkin, 1993). Although this test produces multiple synthetic curves, we only present the best grouping result. The best grouping is at 92% ± 9% unfolding. c) Graph showing the percent unfolding versus grouping (k) for a block rotation Fisher analysis test (Enkin and Watson, 1996). This was performed to address the possible loss of declination information as a result of block rotations. Both fold tests indicate component 1 is prefolding. The vertical dashed lines for b and c highlight the best grouping unfolding position and the horizontal dashed lines for b and c show the error bars for the fold tests.
We also tested for a connection between clay diagenesis and remagnetization by simulating the timing of the smectite-to-illite transformation in the Deseret using the
model by Huang et al., (1993). The modeling of the smectite-to-illite transformation in the Deseret Limestone suggests a mean age of illitization (247 Ma) prior to acquisition of both CRMs although the range for illitization (216-287 Ma) overlaps with the Triassic to Jurassic CRM. The results of this study support the hypothesis that pervasive CRMs can be related to burial diagenetic processes, and that paleomagnetism can be used to determine the timing of maturation of organic matter.

References at end of “Origin of Syntilting Remagnetization” section.