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DEVELOPMENT AND APPLICATION OF A PALEOMAGNETIC/GEOCHEMICAL METHOD FOR CONSTRAINING THE TIMING OF BURIAL AND OTHER DIAGENETIC EVENTS

P.I.: R. Douglas Elmore

co-P.I.: Michael H. Engel

School of Geology and Geophysics

The University of Oklahoma

Norman, OK 73019

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PROJECT SUMMARY

Studies of diagenesis caused by fluid migration or other events are commonly hindered by a lack of temporal control. Our results to date demonstrate that a paleomagnetic/geochemical approach can be used to date fluid migration as well as burial diagenetic events. Our principal working hypothesis is that burial diagenetic processes (e.g., maturation of organic-rich sediments and clay diagenesis) and the migration of fluids can trigger the authigenesis of magnetic mineral phases. The ages of these events can be constrained by comparing chemical remanent magnetizations (CRMs) to independently established Apparent Polar Wander Paths. Whilst geochemical (e.g. stable isotope and organic analyses) and petrographic studies provide important clues for establishing these relationships, the ultimate test of this hypothesis requires the application of independent dating methods to verify the paleomagnetic ages. Towards this end, we have used K-Ar dating of illitization as an alternative method for constraining the ages of magnetic mineral phases in our field areas.

INTRODUCTION

Hydrocarbon generation and expulsion, as well as the smectite to illite transformation, are diagenetic processes commonly associated with organic-rich, argillaceous rocks in foreland (e.g. Appalachian), cratonic (e.g. Illinois) basins and passive margins (e.g. Gulf of Mexico). Constraining the timing of these processes is crucial with respect to models for basin evolution which are used for oil and gas exploration. As discussed below, hydrocarbon generation and migration are directly and indirectly related to mineral authigenesis (the precipitation of magnetite and illitization, respectively), the detection and timing of which can be constrained by a combination of paleomagnetic and isotopic approaches.

Our principal working hypothesis is that burial diagenetic processes (e.g., maturation of organic-rich sediments and clay diagenesis) and the migration of fluids can trigger the authigenesis of magnetic mineral phases, the ages of which can be determined by comparing their chemical remanent magnetizations (CRMs) to independently established Apparent Polar Wander Paths. Whilst geochemical (e.g. stable isotope and organic analyses) and petrographic studies provide important clues for establishing these relationships, the ultimate test of this hypothesis requires the application of independent dating methods to verify the paleomagnetic ages. Towards this end, we have employed K-Ar dating and modeling of illitization as an independent method for constraining the ages of magnetic mineral phases in our field areas.

The smectite to illite conversion (either assuming a solid-state transformation or a dissolution-precipitation model for the conversion) is a well-known diagenetic process that is used to help determine the time-temperature history of basins and margins (e.g. Gulf Coast, Denver Basin). Organic matter in black shales is intimately associated with the surfaces and interlayers of clay minerals (e.g. Kennedy et al., 2002) and a connection between the conversion of smectite to illite and the thermal maturation of organic-rich sediments is well established (see Pevear, 1999 for a recent review). Waters released during the conversion of smectite to illite may facilitate the expulsion of oil and gas from source rocks (e.g. Burst, 1969). Saline fluids have also been implicated with respect to the migration of hydrocarbons over long distances in foreland basins (Oliver, 1992). Consequently, the measurement of the age of the smectite to illite conversion either directly or estimated by use of established kinetic models (Elliott and Matisoff, 1996; Pevear, 1999) is important to help determine the timing of hydrocarbon generation and migration, critical information with respect to frontier exploration.

We have made significant progress toward understanding the origin and timing of chemical remagnetization related to burial diagenetic processes. For example, a recently completed field study documents a relationship between remagnetization and the maturation of organic matter (Blumstein et al., 2004). Other field studies also suggest a connection between the smectite to illite transition and acquisition of a CRM (e.g., Katz et al., 2000; Woods et al., 2002; Gill et al., 2002). We have tested this hypothesized connection by conducting K-Ar dating of authigenic illites in units with CRMs (e.g., Basu et al., 2003). The results of laboratory simulation experiments also support a connection between clay diagenesis and authigenesis of magnetite. We are also developing/testing a fluid related model for alteration and remagnetization of Appalachian redbeds that involves reduction and mobilization of iron phases by hydrocarbons and precipitation of authigenic hematite as a result of the introduction of meteoric fluid recharge (Cox et al., 2003). In addition, our studies of fluid-related CRMs along faults in Scotland provide information on the timing and origin of fluid flow events along faults (Elmore et al., 2003; Parnell et al., 2004; Blumstein et al., 2005). Paleomagnetic dating is emerging as an important method for determining the age of diagenetic processes, many of which could previously only be estimated from models.

SUMMARY OF RESEARCH

During the past two years our research supported by DOE has focused on testing burial as well as fluid related diagenetic remagnetization mechanisms. Summaries of this research are provided below.

Burial Diagenetic Remagnetization Mechanisms

We have focused on two burial diagenetic remagnetization processes: clay diagenesis and maturation of organic matter. The formation of authigenic magnetite during clay diagenesis is based on the following scenario. Illite can form at the expense of smectite at burial to depths greater than 2 km by either transformation or dissolution-precipitation processes (e.g., Moore and Reynolds, 1997). If the smectites are iron-rich or contain iron in the layered structure, then iron is released as a result of the conversion to illite (Boles and Franks, 1979). In closed systems, potassium, which is needed for illitization, is derived from the decomposition of potassium feldspars (e.g., Gulf Coast, Hower et al., 1976). In open systems (e.g. where there have been migrating basinal solutions), the source of potassium may be migrating saline brines or connate basin waters (Elliott and Haynes, 2002). The relationship between CRM and smectite illitization is well established from paleomagnetic, rock magnetic and geochemical study of Mesozoic carbonates in the Vocontian Trough in SE-France (Katz et al. 1998a; Katz et al., 2000). In these studies, the hypothesized acquisition of a CRM occurred during burial diagenesis of smectite.

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 different localities. In addition, a collaborative study with colleagues at ORNL on the oxygen isotopes of diagenetic magnetite in the Belden indicates that the magnetite formed from water having $\delta^{18}O$ near $0^{o}/_{oo}$ 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). The results are also consistent with a study of organic-rich beds in the Old Red Sandstone (Scotland) where 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^{o}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 magneto-chemical changes (Katz et al., 1998b).

It is important to keep in mind, however, that the aforementioned 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. The aforementioned studies serve as the basis for the following recently completed investigation of the Deseret Limestone.

Timing of Hydrocarbon Maturation in a Source Rock: the Deseret Limestone, Utah

The objective of this study is 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 (Huntoon et al., 1999). Paleomagnetic and rock magnetic results from the Deseret Limestone and the stratigraphically equivalent Chainman Shale in western Utah indicate that the units contain two ancient magnetizations residing in magnetite (Figures 1 and 2). Burial temperatures are too low for the magnetizations to be thermoviscous in origin and they are interpreted to be CRMs. Fold tests from western Utah indicate the presence of a pre-folding Triassic to Jurassic CRM (component 1; Figures 1 and 2) that was acquired at the beginning of the oil window (Figure 4). Geochemical analyses suggest that externally derived fluids did not alter these rocks. A second younger CRM in western/central Utah is apparently post-folding and is probably Late Cretaceous to Early Tertiary in age (component 2; Figure 2). In some specimens, pyrite grains have been partially altered by an iron oxide, interpreted to be magnetite (Figure 3). The time of remanence acquisition for this component overlaps with the oil window (Figure 4). The results from these two CRMs are consistent with a connection between organic matter maturation and remagnetization.

In a new approach for our studies, the timing of the smectite-to-illite transformation in the Deseret was simulated using the model by Huang et al., (1993) to test for a connection between remagnetization and clay diagenesis (Blumstein et al., 2004). The modeling of the smectite-to-illite transformation in the Deseret Limestone suggests a mean age prior to acquisition of both CRMs although the range for illitization 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 such processes.

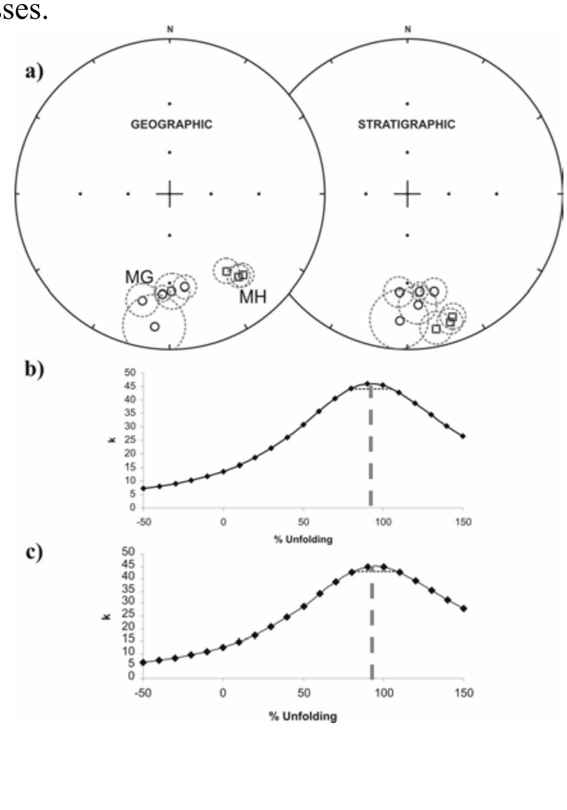


Figure 1: a) Equal area projection for component 1 site means in the Mountain Home Range (MG sites, circles; MH site, squares) in both geographic and stratigraphic positions (with α95 circles for site means). The open symbols represent negative inclinations. b) Graph showing the percent unfolding versus 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% unfolding ±9%. c) Graph showing the percent unfolding versus grouping (k) for an 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 highlight the best grouping unfolding position and the horizontal dashed lines for b and c show the error bars for the fold tests.

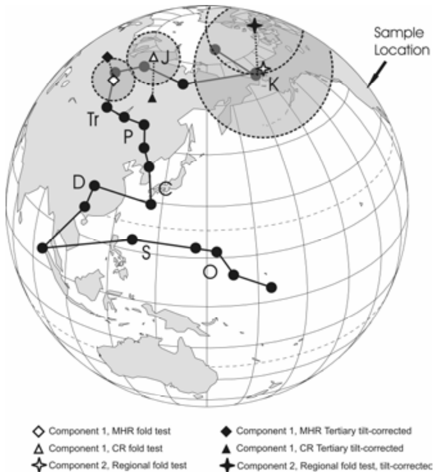


Figure 2: North American apparent polar wander path [Van der Voo, 1993] showing the poles for the fold test results. The results from the Tertiary tilt corrections are also shown. The error circles are the β95 values.

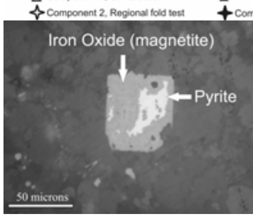


Figure 3: Thin section showing an iron oxide (magnetite?) replacing pyrite in reflected light. Sample SS2-3.

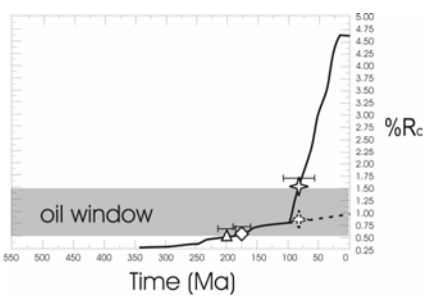


Figure 4: Time versus vitrinite reflectance curve for the Mississippian Deseret Limestone [modified from Huntoon et al., 1999] with the oil window. The triangle (CR) and diamond (MHR) represent the Late Triassic to Early Jurassic component 1 and the star represents the Cretaceous to early Tertiary Component 2. Error bars for the poles were estimated from the APWP. The dashed line represents the estimated curve for the Chainman Shale in western Utah and the dashed star represents component 2 on the estimated curve.

Remagnetization and Clay Diagenesis in Jurassic Sediments of Skye, Scotland

The hypothesized connection between clay diagenesis and magnetite authigenesis is supported by the results of paleomagnetic, rock magnetic, geochemical, and petrographic/SEM studies on Jurassic sedimentary rock of Skye, Scotland (Woods et al., 2002). In this study a presence-absence test and the timing of acquisition for the CRM suggests that magnetite authigenesis is related to the smectite-to-illite conversion, and that clay diagenesis is a viable remagnetization mechanism.

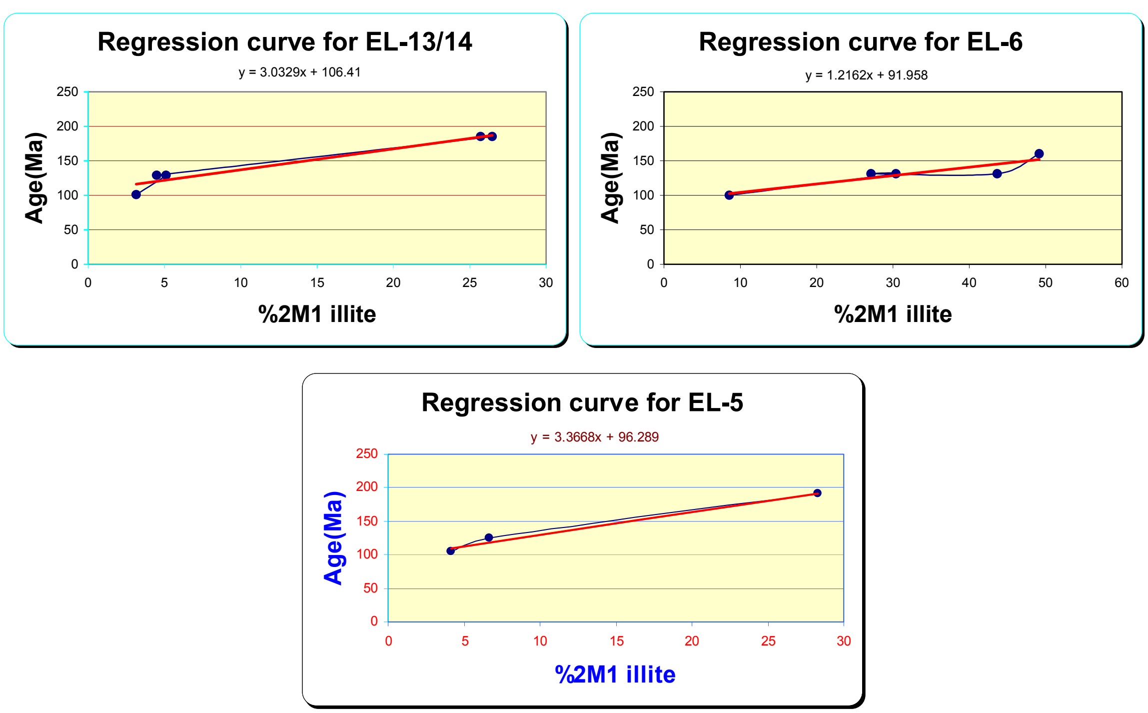
We collected additional samples from our paleomagnetic sampling sites on Skye so Crawford Elliott and graduate student Ankan Basu could perform K-Ar dating of the illites to test if there is a connection between remagnetization and the smectite to illite conversion. In Table 1 below it can be seen that the measured K-Ar dates are for the most part significantly older than the age of acquisition of chemical remnant magnetization. The K-Ar dates decrease with decreasing grain size and percentage of 2M1 illite. The dates are interpreted to be a mixture of detrital and diagenetic illite. Linear extrapolation of diagenetic illite via an Illite Analysis Approach still results in older ages (Figure 5). However, in EL 5 and El 13-14, non-linear extrapolations from the finest sample to the y-axis results in an age of diagenetic illite ca. 50-60 Ma which is in closer agreement to an early Tertiary age for CRM. These results were presented at AGU in San Francisco (Basu et al., 2003) and a manuscript has been submitted (Elliott et al., 2005).

Table 1: Clay Mineralogy and K-Ar dates of clay separates, Skye Scotland.

Sample (size fraction)	Clay Mineralogy	% K	% $^{40*}Ar_{rad}$	$^{40*}Ar$ (pmol/g)	Age (Ma)
EL 5 (1-2µm)	K, I-S (90%I), C	1.82	5.2	635	191
EL 5 (<1µm)	I-S (85%I), K	3.04	17.5	683	125
EL 5 (<1µm)	I-S (85%I), K. tr.C	3.04	16.4	712	131
EL6 (1-2µm)	K, I-S (90%I), C	1.92	54.5	558	160
EL6 (1-2µm)	K, I-S (90%I), C	1.92	23.6	55	159
EL6 (0.25-1.0µm)	K, I-S (90%I), C	2.72	23.6	662	135
EL6 (0.25-1.0µm)	K, I-S (90%I), C	2.72	27.4	641	131
EL6 (<0.25µm)	I-S (90%I), K, tr.C	3.10	37.6	554	100
EL 12 (1-2µm)	K, I-S (90%I), C	2.38	67.4	936	213
EL 12 (< 1µm)	I-S (90% I), K. tr.C	1.99	11.6	631	174
EL12 (<0.25µm)	I-S (90% I), K				
EL 13-14 (1-2 µm)	I-S (90%I), K, tr. C	3.55	88.0	1198	185
EL 13-14 (0.25-1.0 µm)	I-S (90%I), K, tr. C	4.05	23.5	941	129
EL 13-14 (<0.25 µm)	I-S (90% I), K.	4.61	88.5	831	101

Notes: K - kaolinite, I-S - illite smectite; C – Chlorite; tr. – trace amounts.

Figure 5. Illite Age Analysis Regression Curves. Note the K-Ar ages decrease with decreased % 2M1 illite and also decrease with grain size as shown in Table 1.



Thrust Loading and Clay Diagenesis, Montana

In this study we tested clay diagenesis as a remagnetization mechanism for CRMs by comparing results from Mesozoic strata (e.g., Marias and Blackleaf formations) 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). A timing test based on the comparison of the Tertiary pole position for the CRM with the timing of thrusting (Early Paleocene-Late Eocene; Mudge, 1970) is also consistent with a connection with the clay diagenesis-remagnetization hypothesis. The results of the regional fold test, however, suggest that the CRM was acquired prior to folding or perhaps during the early stages of the rock's inclusion into the folds and faults of the Disturbed Belt (Gill et al., 2002). An early synfolding CRM is consistent with the clay diagenesis model but a prefolding CRM is more difficult to reconcile with the model because it is likely that thrust loading was coincident with partial deformation of the Cretaceous rocks.

We have also collected companion samples from the paleomagnetic sites for K-Ar dating to test for a connection between the smectite to illite transition and remagnetization. These samples are currently being processed to determine the type ordering, percentage of illite layers and the dates of diagenetic separates. Bentonites collected from these sections will provide a more definitive measure of the age of diagenetic illite.

Elsewhere in the Sawtooth Mountains, we also sampled Paleozoic limestones (Devonian Jefferson and Mississippian Madison formations) on several folds as well as tilted outcrops in the Disturbed Belt. The objective is to determine the mechanism of remagnetization (burial process or fluids?) and if remagnetization trends perpendicular to the thrust fronts occur as they do in the Canadian part of the Rocky Mountains (Enkin et al., 2000). Kerry Moreland, an M.S. student, has found that the Jefferson and Madison formations contain a reversed Tertiary CRM (Figure 6) similar to that found in the Mesozoic rocks. A preliminary fold test suggests that the CRM is prefolding to early synfolding. Initial geochemical data for outcrop samples taken from the Jefferson Formation indicate the presence of light hydrocarbons that have migrated into the unit. The Jefferson dolomites and limestones are reservoirs for gas in this region (Clayton et al., 1982). We have previously demonstrated that hydrocarbon migration into carbonates can trigger the precipitation of authigenic magnetic phases (e.g. Elmore et al., 1987) and it is possible that a similar connection exists here.

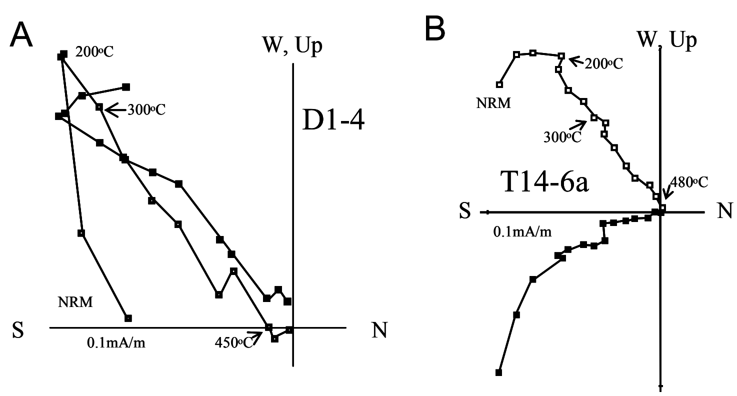


Figure 6. Orthogonal projections of the demagnetization behavior of a representative specimens from the A) Jefferson Fm. from a tilted (thrusted) outcrop and B) Madison Limestone on the Teton Anticline in Montana (eastern flank). Squares-horizontal; circles-vertical, in geographic coordinates.

Simulation Experiments: Evidence of Magnetite Authigenesis in Thermally Treated Smectites-- Analogy with Low Temperature Burial Conditions

Whilst our recent field studies provide a strong indication for a connection between clay mineral authigenesis and the precipitation of authigenic magnetite, the actual processes involved remain to be identified. To investigate this issue, we conducted laboratory simulation experiments. Our initial studies (Cogoini et al., 2002) suggested that a low temperature smectite diagenetic process other than the formation of illite can cause authigenesis of magnetite with grain sizes sufficient to carry a CRM . Because magnetite was created without a detectable change from smectite to illite, it is unlikely that the source of iron is located within the octahedral sites of smectite. Rather, iron adsorbed onto the surface of the clay is a more likely candidate. Clays such as smectite have reactive surfaces (e.g., Goldberg, 1989) that can adsorb iron (e.g., Goodman, 1978; Craciun and Maghea, 1985). The results of these experiments suggest that iron adsorbed on smectites could be a source for authigenic magnetite and that smectite diagenesis prior to illitization could be another mechanistic pathway for acquisition of CRMs residing in magnetite.

To investigate this further, we conducted additional laboratory simulation experiments in collaboration with Dr. Larry Anovitz at the University of Tennessee where we are able to control such factors as oxygen fugacity. We used the Nau-2 nontronite for these experiments, the same material we used in our preliminary experiments. In a first experiment we ran the samples at 300^0C and used a brass vessel. Oxygen fugacity was buffered by Cu/CuO although the fO_2 was probably near Ni-NiO, slightly more reducing than the copper, because of the vessel. After three days the magnetic susceptibility of the samples had increased by about 50% and after one week they increased by a factor of two ($4.57 \times e^{-6} m^3/Kg$ to $9.91 \times e^{-6} m^3/Kg$). At one week, however, the samples came out rust red and the experiment was halted. X-ray diffraction analysis revealed one predominant peak at 16.7 degrees 2Θ based on analyses of random mounts of the synthesis experiments after solvation in ethylene glycol vapor. However, we did not note a change in the structure of the smectite to an ordered illite-smectite (see Moore and Reynolds, 1997 for representative X-ray diffraction patterns of mixed layer I-S**.** It is possible, however, that a random order I-S was formed which contained up to 50% illite layers and still showed the 001 reflection at 16.7 degrees 2Θ. A second experiment, run at 200^0 C for 12 weeks did not produce a significant increase in magnetic susceptibility.

Fluids and CRMs

Remagnetization of Upper Devonian Sandstones in the Appalachian Provinces of West Virginia: A Reduction/Reoxidation Model

Samples of red and green fluvial to marine sandstones of the Hampshire Formation/Catskill Group were analyzed from regional-scale folds across the structural trend of the Valley and Ridge (VR) and Appalachian Plateau (AP) provinces of West Virginia to develop a model for remagnetization of red sandstones (Cox et al., 2003, Cox et al., 2005). The red sandstones contain a Permian magnetization with southerly declinations and shallow inclinations that resides in hematite and is interpreted as a CRM. Specimens from green sandstone have weak intensities and do not contain the component. Incremental fold tests for the component yield generally prefolding results from the AP and synfolding results from the VR, thus remanence acquisition likely occurred within the time span of structural development. Thin section analysis shows the presence of authigenic specularite cement and submicron red pigment.

Geochemical/fluid inclusion studies (Evans and Battles, 1999) indicate the rocks were exposed to mixed methane-saturated formational and meteoric fluids only with no evidence that external hot orogenic fluids altered the rocks. A working model for CRM acquisition involves 1) methane reduction of previously formed iron phases and mobilization of iron, and 2) a return to oxidizing conditions and precipitation of new authigenic hematite as a result of the introduction of meteoric fluids just prior to and during uplift (e.g., Garven, 1995). The green sandstones could be a relic of the reduction phase although they may have formed as a result of gleying which occurs in paleosols (e.g., Retallack et al., 2003).

Remagnetization and Fluid Migration along Faults in the Caledonides, Scotland

For the past several years we have investigated the role of faults as fluid conduits in Scotland (e.g., Elmore et al., 2002). Faults can act as barriers to flow or they can be conduits for flow, thereby controlling the distribution of diagenetic alteration, mineralization, and remagnetization (e.g., Knipe, 1993). For example, a study of the Highland Boundary fault (HBF) in Scotland suggests there were multiple flow events along the fault in the late Paleozoic (Elmore et al., 2002). The fluids could be related to the intrusion of Carboniferous dikes in central Scotland and/or the reactivation of the HBF in the Carboniferous-Permian. The study of the Moine Thrust Zone in the Caledonides of Scotland suggests that there were four fluid flow events along the fault between the Devonian and early Tertiary (Elmore et al., 2003; Blumstein et al., 2005). These localized CRMs coincide with post-Caledonian events such as the migration of hydrothermal fluids related to Devonian igneous activity, regional crustal extension of Scotland and NW Europe in the Permian, possible Proto-Atlantic rifting in the Triassic, and Tertiary intrusions. Preliminary paleomagnetic (Elmore et al., 2003) and geochemical results (Parnell et al., 2004) for this study are published. A detailed paper describing all the paleomagnetic results is in press (Blumstein et al., 2005).

We also sampled the folded Old Red sandstone from several areas along the Great Glen Fault. Preliminary analysis indicates that the Old Red contains a postfolding Carboniferous CRM in hematite as well as an apparently younger (Permian/Triassic?) CRM in hematite. Similar magnetizations have been reported in previous studies, generally north of the Great Glen Fault (e.g., Van der Voo and Scotese, 1981; Torsvik et al., 1983; Tarling, 1985).

The aforementioned studies are providing evidence that dormant faults or fault systems can be conduits for localized fluid flow events at different times. Since the CRMs are younger than the Caledonian orogeny, they are not necessarily related to major orogenic events (i.e. continent-continent collision; Oliver, 1992) bur can be related to more localized igneous activity as well as tectonic events such as regional crustal extension.

We also conducted a paleomagnetic study of sandstone dikes in basement rocks in Scotland which provides evidence for syndepositional faulting during the deposition of the Torridon Group (~900Ma) (Myers-Dulin et. al., 2002; 2005). Although this was not a major focus our research, it is a useful application of paleomagnetism to the study of faults.

SUMMARY

Studies of diagenesis caused by fluid migration or other events are commonly hindered by a lack of temporal control. Our research addressed this issue and provides a foundation for the development of a paleomagnetic approach to date diagenetic events. This approach can provide timing information on rocks that are difficult to date using other techniques, as well as complementing other dating techniques (e.g., K-Ar; Ur-Pb).

Clay-mineral modifications during diagenesis are important because they can reveal fundamental changes in the water and organic matter content and the potential for fluid migration (Chamley, 1994). The timing of the smectite to illite transition is commonly synchronous with the maturation of organic matter to form hydrocarbons and the determination of timing relative to trap formation can lead to successful hydrocarbon exploration models (e.g. Pevear, 1999; Kennedy et al., 2002). Our field studies and laboratory simulation experiments provide compelling evidence for a connection between clay diagenesis and magnetite authigenesis.

STUDENT PARTICIPATION

The P.I. (Elmore) and co-P.I. (Engel) for this proposal have combined their respective talents in sedimentology/paleomagnetism and stable isotope/organic geochemistry on the study of burial and fluid-related diagenetic procsses. Numerous students (10 M.S. and 4 Ph.D.) have been involved in the projects and most have gone on to work in the oil industry.

Kerry Moreland, a M.S. candidate, is completing her M.S. thesis on the paleomagnetism of the Paleozoic limestones in the Sawtooth Mountains. Vanessa O'Brien and Louise Totten are completing their M.S. theses on the geochemistry and paleomagnetism of the Mesozoic rocks that carry CRMs in the Disturbed belt, Montana. Shannon Myers-Dulin, a first year graduate student, completed the study of the Great Glen and sandstone dyke projects in Scotland, which is now in press to the Scottish Journal of Geology. Students that have completed their degrees with prior support from our DOE grants are Dr. D. Fruit (Ph.D.), L. Plaster-Kirk (M.S.), T. Campbell (M.S.), K. Brisman (M.S.), G. Bixler (M.S.), S. Banerjee (Ph.D), B. Katz (Ph.D), M. Davidson (M.S.), S. Woods (M.S.), Jeff Gill (M.S.), A. Blumstein (M.S.), R. Blumstein (M.S.), and Monika Cogoini (Ph.D.).

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