Final Technical Report

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

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PROJECT SUMMARY

This collaborative research project between Georgia State University (Prof. Elliott) and Oklahoma University (Profs. Elmore and Engle) is aimed at understanding further the measurement of the timing of geologic processes causing diagenetic events (e.g. burial metamorphism, thrust sheet burial, basinwide fluid migration, contact metamorphism) through combined application of paleomagnetic analyses and K-Ar age determination of illite. These diagnenetic events are known to heat rocks to temperatures sufficient to form crude oil and natural gas. Thus, improved knowledge of the timing of diagenetic events lead to improved burial history models for the exploration of crude oil and natural gas (e.g. Pevear, 1999). Our principal working hypothesis is that the authigenesis of magnetic mineral phases results also from the conversion of smectite to illite and the ages of these diagenetic events can be constrained by comparing the ages of chemical remanent magnetizations (CRMs) to independently measurements of K-Ar age of diagenetic illite. In this study, we have tested the hypothesized connection between smectite to illite (i.e clay diagenesis) and remagnetization by conducting K-Ar dating of authigenic illites in units in Scotland and Montana (e.g., Elliott et al., 2006a; Elliott et al., 2006b).

INTRODUCTION

Hydrocarbon generation and expulsion, as well as the smectite to illite transformation, are largely temperature-dependent processes commonly associated with the diagenesis of organic-rich, argillaceous rocks in foreland (e.g. Appalachian), cratonic (e.g. Illinois) basins and passive margins (e.g. Gulf of Mexico). The timing of these diagenetic processes leading to the generation of crude oil and natural gas are necessary to construct models describing thermal and burial history of sedimentary basins, and, in some cases where the timing of a trap is known, the timing of the generation of crude oil and natural gas also guides decisions to drill (e.g. Pevear, 1999). The stacking order of illite-smectite is a semi-quantitative geothermometer (Hower and Hoffman, 1979). The timing of these diagenetic magnetite and illite-smectite can be constrained respectfully by paleomagnetic, and geochronologic approaches to determine the time-temperature history of petroleum source rocks. As discussed below, the generation and migration of hydrocarbons generation are directly and indirectly related to mineral authigenesis (e.g. the precipitation of magnetite) and the conversion of smectite to diagenetic illite or mixed layer illite-smectite.

Our principal working hypothesis is that burial diagenetic processes (e.g., maturation of organic-rich sediments and clay diagenesis) and the migration of fluids and water rock reactions with migrating 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. The results of laboratory simulation experiments also support a connection between burial diagenesis and authigenesis of magnetite (Moreau et al., 2005). A test of this hypothesis requires the application of independent dating method(s) to verify the paleomagnetic ages. Towards this end, we have employed K-Ar dating and modeling of diagenetic illite-smectite or illite vas an independent method for constraining the ages of temperature dependent diagenetic processes which form 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 can be used as a semi-quantitative geothermometer to help determine the time-temperature history of basins and margins (e.g. Gulf Coast, Hower et al., 1976; Pollastro, 1993). Organic matter in black shales is intimately associated with the surfaces and interlayers of clay minerals and a connection between the conversion of smectite to illite and the thermal maturation of organic-rich sediments is also well established (see Pevear, 1999 for a recent review; Kennedy et al., 2002). Waters released during the conversion of smectite to illite may facilitate the expulsion of oil and gas from source rocks (e.g. Burst, 1969). The expulsion of saline fluids due to convergent tectonic activity aided the migration of hydrocarbons over long distances in foreland basins as well forming diagnetic illite basinwide (e.g Appalachian Basin, Elliott and Aronson, 1987; 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.

In this collaborative project, we have made significant progress toward understanding the origin and timing of chemical remagnetization related to burial diagenetic processes such as the smectite to illite conversion. For example, we completed a recent field study that suggests a relationship between remagnetization and the maturation of organic matter in Mississippian carbonates in Utah (Blumstein et al., 2004). Other field studies in Syke and in the Disturbed Belt, Montana also suggest a connection between the smectite to illite transition and acquisition of a CRM, and we have tested this hypothesized connection by conducting K-Ar dating of authigenic illites in units with CRMs (e.g., Katz et al., 2000; Woods et al., 2002; Gill et al., 2002; Elliott et al., 2006a; Elliott et al., 2006b). Paleomagnetic dating combined with K-Ar dating of illite 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 project period, our research supported by DOE has focused on testing burial as well as fluid related diagenetic remagnetization mechanisms in the Isle of Skye, Scotland and in the Disturbed Belt, Montana. Summaries of this research involving GSU are provided below.

Clay Diagenesis and Remagnetization in Jurassic Sediments of Skye, Scotland

The clay fractions of Jurassic marls in the Great Estuarine Group in southern Isle of Skye are composed of mixed-layered illite-smectite (I-S) with high percentages (>85%) of illite layers, kaolinite, and generally smaller amounts of chlorite (Basu et al., 2004; Elliott et al., 2006a).

These 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 high percentages of illite layers in I-S, the Środoń Intensity ratios, and the Kübler index values are consistent with the formation of diagenetic I-S as a result of relatively brief heating caused by igneous activity. The Jurassic rocks in southern Skye contain a secondary chemical remanent magnetization (CRM) that resides in magnetite and formed at approximately the same time as the Tertiary igneous rocks on Skye.

Given the presence of significant amounts of detrital illite (the $2M_1$ polytype), the age of diagenetic illite was estimated by the use of the Illite Age Analysis technique (IAA) to test the hypothesis that the CRM was acquired coincidently with the smectite-to-illite conversion. IAA assumes a linear relationship between the measured K-Ar ages of fine fractions of illite and percentage of the $2M_1$ polytype (detrital illite) (a controversy in itself, see Środoń, 1999, Środoń, 2000, Ylagan et al, 2000). The $1M_d$ illite polytype is assumed to be diagenetic in origin. As shown in Figure 1, the linear regression of K-Ar ages versus the percentages of $2M_1$ polytype (detrital illite) from one marl (EL-6) yields an estimate for the age of diagenetic illite of 106 Ma which is close to the measured age of the finest (<0.25 µm) subfraction (108 Ma). These estimated and measured age values, however, could be substantially older than the true age of the diagenetic illite in I-S because of the presence of detrital $1M_d$ illite that was recycled from early Paleozoic shales and whose importance relative to the diagenetic I-S may have been enhanced in the presence of K-poor diagenetic fluid. The presence of significant detrital illite in all size fractions made it difficult to measure the age of diagnetic illite caused by the release of fluids during early Tertiary igneous activity on Syke. This study however brought to mind the importance of detrital $1M_d$ illite which heretofore has not been well described for chronologic studies where diagenetic illite (also$1M_d$ polytype) is also believed to be present.

Thrust Loading and Clay Diagenesis, Disturbed Belt, Montana

In this study (Elliott et al., 2006b), we test a burial model for diagenetic illite and whether illitization is related to the acquisition of a chemical remanent magnetization (CRM) in the Disturbed Belt, Montana. A prefolding, reversed polarity, secondary magnetization is found in carbonate concretions in diagenetically altered Upper Cretaceous rocks in the Disturbed Belt. Stratigraphically equivalent unaltered rocks to the east on the Sweetgrass Arch do not contain

Figure 1

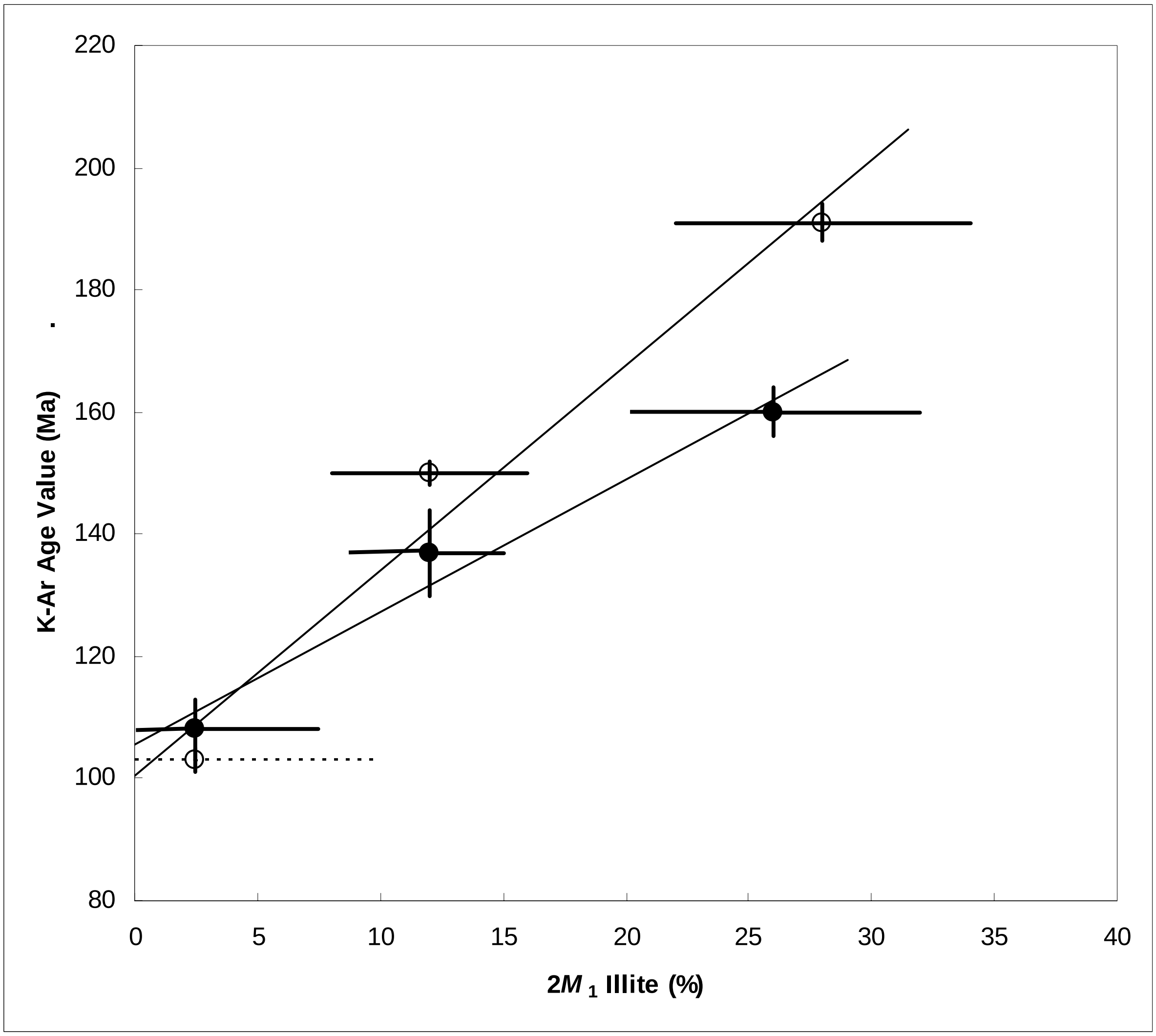

Figure 1: K-Ar age values versus percentages of $2M_1$ polytype for clay subfractions of EL-6 (filled symbols) and EL-13/14 (open symbols) showing regression lines for Illite Age Analysis. The value used in the regressions for the $2M_1$ illite polytype in the finest clay subfraction (<0.25μm) of each marl is 2.5%, but the dashed line indicates that the value for that subfraction of EL-13/14 was not measured and might be considerably larger than 2.5% or even 5%.

this magnetization. This magnetization could be a CRM or a thermoviscous remagnetization. The age derived from the pole position of the magnetization is generally consistent with the Early Tertiary K-Ar ages of diagenetic illite-smectite measured in this study. These ages are also concordant or somewhat younger that the K-Ar ages measured by Hoffman et al, (1976) who suggested that diagenetic illite formed under thrust loading. The paleomagnetic age is not constrained well enough for a precise comparison to K-Ar ages of diagenetic illite. If this magnetization is a CRM, it could be related to illitization. Alternatively, if the prefolding CRM had been acquired prior to thrust loading then the magnetization is not related to illitization. Geochemical studies are currently underway to test if the magnetization could be related to fluid alteration.

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 (e.g. K-Ar ages of illte where detrital illite is present in sizeable amounts in the finest fractions), as well as complementing other dating techniques (e.g., K-Ar; Rb-Sr, U-Pb).where diagenetic illite can be separated or is present exclusively.

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

In addition to the numerous students (10 M.S. degree students, and four Ph.D. students) supported by this project at Oklahoma University, two M.S. degree students in Geology at Georgia State University were supported by the DOE funds to Georgia State University (Ankan Basu and Stephen Osborn) during the three year period of this collaborative study. Ankan Basu completed his degree requirements at GSU in SP 2004 and he entered the Ph.D. program at Virginia Tech and State University in FA 2004. Osborn began his work on this project in FA

2004. He participated in field work in Montana last summer with Prof. Elmore, Vanessa O'Brien and he is currently writing his M.S. degree thesis to complete his M.S. degree requirements in SP 2006. Osborn has applied to several Ph.D. programs and he has received a verbal offer to enter the Ph.D. program in Geological Sciences at the University of Tennessee-Knoxville. Prof. Elmore participated on the oral exams of the M.S. thesis of Basu and he will be an examiner on Osborn's thesis.

OTHER COLLABORATION

This study benefited from collaboration with Prof. J. Marion Wampler, Georgia Institute of Technology, for the K-Ar measurements of illite. In addition, we collaborated with Prof. Georg Grathoff (Portland State University) for the measurement of illite polytypes of small amounts of illite clays (< 20 milligrams) for the Syke study.

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