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REMANENT AND ROCK MAGNETIC PROPERTIES AT THE
HANNA, WYOMING, UNDERGROUND COAL GASIFICATION
SITE: HANNA II, PHASES 2 AND 3 EXPERIMENT

By
John Wm. Geissman
Jim Callian
Alv Dan Youngberg

September 1983

Work Performed Under Contract No. AS20-81LC10694

For
Morgantown Energy Technology Center
Laramie Project Office
Laramie, Wyoming

By
Colorado School of Mines
Golden, Colorado

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ABSTRACT

Several underground coal gasification (UCG) experiments have been conducted in the Hanna No. 1 coal seam. During the fall, 1980, the Laramie Energy Technology Center performed a post-burn field study of the Hanna II, Phases 2 and 3 experiment at the Hanna UCG site. The field work consisted of high resolution seismic, drilling, coring, and geophysical logging. The Paleomagnetism Laboratory, Department of Geology, Colorado School of Mines, contributed to the post-burn study by doing remanent and rock magnetic measurement laboratory work on the core material. Funding was provided by the Laramie Energy Technology Center. The purpose of the study was to determine the nature of the remanent magnetism of the overburden Hanna Formation and changes in the remanence and magnetic mineralogy attending underground coal gasification experiments. With this information, further estimates of the thermal and chemical conditions reached during the conversion experiment could be made.

Overburden in the burn area, consisting of non-marine mudstones, sandstones, coals, and conglomerates, is characterized by very low intensities of natural remanent magnetization (10^{-3} to 10^{-4} A/m, 10^{-6} to 10^{-7} emu/cc). Demagnetization experiments suggest that the magnetization resides largely in rare detrital magnetite of variable grain size. Dispersion of magnetization directions is generally very high in overburden material and is probably due to depositional and post-depositional (diagenetic) processes.

In the vicinity of the burn cavity, overburden units immediately above the Hanna No. 1 coal seam have been subjected to high temperature pyrometamorphism during Hanna II UCG experiments. This activity caused significant changes in the magnetic mineralogy and the associated remanence characteristics of the overburden sediments. Core holes 2HP-174 and 2HP-176, drilled in the center of the burn cavity, best display the magnetization changes. For each hole, a zone approximately 10 m above the void space created during collapse, exhibits anomalous magnetization properties (NRM intensities between 10^{-1} and 1 A/m; k [dispersion parameter values] exceeding 500 [excellent grouping], initial susceptibilities exceeding 10^{-4}). Core holes at the edge of the burn chamber (e.g., 2HP-173) show very little change in magnetization properties as the chamber is approached.

The magnetization data, together with previous petrographic observations, suggest that magnetite is being formed in a reducing process at the expense of detrital ferromagnesian silicates and possible hematite and goethite in the overburden sediments. Thermal gradients immediately above the burn cavity are difficult to estimate; changes in magnetic properties of unaltered Hanna Formation overburden are activated at temperatures as low as 300°C. The magnetic expression of the burn cavity should be able to be modelled as being due to a thin slab overlying the cavity. Pyrometamorphosed material that has collapsed into the cavity, should have any magnetization which is randomized due to collapse and therefore should be able to be incorporated into a magnetic anomaly model.

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INTRODUCTION AND STUDY AREA

A series of underground coal gasification (UCG) experiments were conducted by the Laramie Energy Technology Center (LETC) at a site near Hanna, Wyoming, from March 1973, to October 1979. The study site (Figs. 1 and 2) is located approximately 4 km south of the town of Hanna in the SW 1/4, Section 29, and the E 1/2, SE 1/4, Section 30, T22N, R81W, Carbon County, Wyoming. The property is owned by the Rocky Mountain Energy Company and is under lease to LETC.

This study, in concert with the work of Craig, et al. (1982), was intended to provide information on the lithologic, mineralogic, and magnetic characteristics of overburden materials that have been thermally altered by UCG experiments. This information is of great use in evaluating the conditions present during UCG experiments. The work of Craig, et al. (1982), on the Hanna II, Phases 2 and 3 experimental burn provided data on (1) the nature and distribution of pre-burn overburden Hanna Formation sediments, (2) the mineralogical and textural characteristics of pyrometamorphosed rocks that formed during the burn, (3) the temperatures reached during the gasification experiment, and (4) the oxidation state of the burn system. The findings of the present study, which deals with the remanent and rock magnetic properties of the Hanna II, Phases 2 and 3 cores, closely corroborate the observations of Craig, et al. (1982), and provide additional data bearing on the nature of the thermal aureole formed during UCG experiments.

The work described was undertaken as part of a broader series of studies on the remanent and rock magnetic properties of pyrometamorphosed rocks in the central and southern Rocky Mountain Region. Work on clinker (baked and fused rock formed during the natural burning of coal seams) in the Powder River Basin at the Colorado School of Mines (Jones, et al., 1982a, b; Jones and Geissman, 1982, Jones 1983) has shown that clinker, in general, possesses a single component of magnetization that is nearly parallel (normal polarity, positive inclination) or antiparallel (reverse polarity, negative inclination) to the earth's present-day magnetic field direction. This magnetization was acquired during post-burn cooling of the overlying clinker and is thus called a thermoremanent magnetization (TRM). The TRM in clinker is complicated by the fact that the magnetic mineralogy of the overburden material is significantly altered during burning. Clinker formation occurs essentially at the ground surface and a relatively oxidizing environment probably exists (Herring, 1980). One fundamental aspect of the present study,

involving material altered in a relatively reducing environment (Craig, et. al., 1982) was thus to investigate the effects of the burn environment on the magnetic properties of the overburden material.

OBJECTIVES AND SCOPE OF INVESTIGATIONS

The major objectives of this study were to (1) determine whether UCG burning had any effect on the remanent and rock magnetic properties of the Hanna Formation overburden, (2) characterize these magnetic effects, and (3) utilize the magnetic data to better understand the nature of the thermal environment during UCG experiments.

The investigations included:

- (1) Measurement of the intensity and direction of the natural remanent magnetization of specimens from numerous stratigraphic intervals from all drill cores.
- (2) Determination of the mean direction of the natural remanent magnetization and associated statistics at selected stratigraphic levels from all drill cores.
- (3) Comparison of mean inclinations with expected inclinations based on the late 1970's geomagnetic field direction for the Hanna II site.
- (4) Measurement of the initial susceptibility of specimens from numerous stratigraphic intervals from all drill cores.
- (5) Characterization of thermal and alternating field demagnetization behavior in representative specimens from all drill cores.
- (6) Tests of the acquisition and backfield demagnetization of isothermal remanent magnetization in representative specimens.
- (7) Curie point determinations.
- (8) Estimations of the degree and nature of thermal alteration of overburden materials in the vicinity of the burn cavity and relations to magnetic anomalies attending magnetization changes.

GENERAL GEOLOGY

Hanna Formation Stratigraphy

Overburden in the vicinity of the Hanna II, Phases 2 and 3 experiment consists of 37 m to 152 m of non-marine mudstones, sandstones, coals, and conglomerates of the Paleocene-Eocene Hanna Formation. Craig, et al. (1982), describe in detail the stratigraphy of these units near the Hanna UCG site. The Hanna No. 1 coal bed, approximately 10 m thick,

Figure 1. Generalized location map of the Hanna Basin and surrounding uplifts and mountains, Wyoming. PM in the Shirley Mountains stands for Paleozoic-Mesozoic sedimentary rocks. Modified from Ryan (1977).

Figure 2. Location map of Hanna UCG site, SW 1/4, Section 29, E 1/2, SE 1/4, Section 30, T22N, R81W, Carbon County, Wyoming.

was the subject of the UCG experiments. Craig, et al. (1982), divide the overburden above the Hanna No. 1 coal into four local stratigraphic units (Fig. 3), consisting from bottom to top of:

(1) fine-grained sandstones and mudstones deposited as a lacustrine delta.

(2) mudstones with thin, isolated, lenticular and tabular shaped sandstone bodies deposits in a meandering fluvial system.

(3) coarse-grained, poorly sorted sandstones and conglomerates with a sheet-like geometry deposits in a braided river complex.

(4) interbedded mudstones, sandstones, and thin coals, deposited on the floodplain of a meandering river system.

UCG Experiments and Burn Effects

Youngberg and Sinks (1981) and Craig, et al. (1982), have described in detail the post-burn drilling activity and burn cavity produced. The cavity, shown in Figures 4-6, now consists of char (thermally altered coal), pyrometamorphic rock, and rubble. Craig, et al. (1982), suggested that pyrometamorphism was confined to the cavity or to the rocks in the roof of the burn cavity during gasification. Pyrometamorphosed material collapsed into the cavity during and shortly after burning. They noted that correlation of cavity rock types with stratigraphic units outside the cavity was difficult due to cavity collapse, rubble, pyrometamorphism, and poor core recovery. It is largely for this reason that the present study was concentrated on the recoverable, intact material lying above the void at the top of the burn cavity.

Temperatures of UCG burning and pyrometamorphism probably exceeded 1000 °C. The maximum temperatures measured on most wells near the hottest part of the burn were between 925 and 1056°C (Beard and Reed, 1976; Northrop, et al., 1977). Estimates from cordierite, oligoclase, and mullite melting reactions suggest temperatures in excess of 1200°C (Craig, et al., 1982), while fusibility tests of coal ash yielded temperature ranges from 1138 to 1600°C.

LABORATORY METHODOLOGY

Standard remanent magnetism measurement techniques require specimens to be of cylindrical shape with a height/diameter ratio of about 0.86 (Noltimier, 1971). The diameter of the specimen measured is approximately 2.53 cm. Specimens were prepared by drilling core pieces perpendicular to the core axis and oriented with respect to a horizontal datum assuming that the Hanna cores were drilled vertically. An attempt was made to reorient the cores with respect to the vertical by lithologic inspection, but this was not always successful. Each piece of Hanna drill core was numbered according to the drilling footage. All individual specimens prepared from the same piece of drill core were given the same sample number. For example, a particular specimen might be numbered

Figure 3. Subdivision of the overburden of the Hanna No. 1 coal bed at the Hanna UCG site into four gross lithologic units. From Craig, et al. (1982).

2HP-173-298'. Specimen data thus refer to data for a given stratigraphic level with an error of at most about 0.2 m.

Remanent magnetizations were measured with a Schonstedt SSM-1A spinner magnetometer modified with a Hewlett Packard (HEDS 5300) 500 count/rotation optical shaft encoder interfaced with a Cromemco System Two computer for on-line signal analysis and data reduction. A six spin measurement procedure (Doell and Cox, 1967) was employed for all specimens. Because of the extremely low intensities of the natural remanent magnetization (NRM), 500 counts/rotation were generally digitized and thus each NRM measurement was lengthy. NRM measurements occupied a major portion of the investigation; as will be shown below, the NRM data are quite indicative and valuable in detecting effects due to UCG burning.

Investigations of the NRM in the Hanna material were carried out using standard demagnetization techniques. Alternating field demagnetization utilized a Schonstedt specimen demagnetizer to investigate the coercivity spectra of the NRM in representative specimens. Thermal demagnetization, which provides blocking temperature spectra of the NRM, utilized a Schonstedt (TSD-1) furnace. Temperatures were monitored using the Schonstedt furnace probe itself and "synthetic" rock specimens into which thermocouple probes had been cemented and connected to an Omega 2170A thermocouple thermometer.

Chemical demagnetization experiments were attempted on representative overburden specimens. This technique involves immersing each specimen in reagent grade HCl for progressively longer periods of time (e.g., Henry, 1979). It is widely used for the removal of hematite-bearing pigment cements in terrigenous clastic rocks. As will be shown below, however, magnetite is the principal carrier of the magnetization in the Hanna Formation overburden. Chemical demagnetization is thus relatively ineffective in removing the magnetization in the Hanna Formation units. In general, the specimens decrepitated in acid before a significant portion of the magnetization is removed. The results of chemical demagnetization studies are not discussed any further.

Initial (low-field) susceptibilities were measured on a Bison susceptibility bridge. The unit is accurate to approximately 1.0×10^{-6} cgs units.

Rock magnetism experiments employed two techniques. One was the monitoring of the acquisition of an isothermal remanent magnetization (IRM) in representative specimens. In these tests, the NRM of a specimen is first measured, then the specimen is placed into a DC magnetic field of known strength for a short period of time. The field is removed and the magnetization of the specimen is remeasured. The DC field is then increased, the specimen immersed, then removed, and then remeasured. This procedure is continued until the magnetization of the specimen is saturated. The "saturation" IRM (SIRM) is then demagnetized by subjecting the specimen to oppositely directed, increasing DC fields. IRM acquisition tests are extremely useful in determining the nature of the magnetic mineralogy in rocks (e.g., Irving, 1974; Park, 1975; Lowrie and Heller, 1982).

Figure 4. Plan view and well locations for the Hanna II, Phases 2 and 3 UCG site. Locations of cross sections in Figure 5 (section A-A') and Figure 6 (section B-B') are shown. Modified from Youngberg and Sinks (1981).

Figure 5. Southwest-northeast cross-section A-A' showing the maximum height and shape of the burn cavity and the distribution of both altered and unaltered rock types. Dashed lines indicate that the position of boundaries are not accurately known. Location of line of section shown on Figure 4. Modified from Youngberg and Sinks (1981).

Figure 6. Northwest-southeast cross-section B-B' of the burn cavity. The distribution of altered and unaltered rock types are shown. Dashed lines indicate that the positions of the boundaries are not accurately known. Location of line of section shown on Figure 4.

The second technique involves monitoring the saturation magnetization (J_s) versus increasing temperature to determine the Curie point (T_c) of the predominant magnetic phase. J_s is imparted by a DC field greater than about 0.1 Tesla (1000 gauss). Curie temperatures can be used to infer the chemical composition of the magnetic phase.

REMANENT MAGNETIZATION DATA

Figures 7-14 display the natural remanent magnetization data from all specimens measured from each of the Hanna drill holes. Plotted in these diagrams are inclination deviations, NRM intensities, precision parameter of the magnetization directions, and susceptibility. Observations related to each of these data sets can be discussed in terms of three sample groups:

- 1) Pre-burn hole 2HP-133
- 2) Post-burn holes 2HP-172, -173, -175, -178, -182.
- 3) Post-burn holes 2HP-174, -176.

Directional Variations

Variations in magnetization directions cannot be totally monitored in this investigation because the Hanna cores are unoriented. Inspection of graded beds and/or cross stratification can usually aid in determining core orientation with respect to vertical (Craig, et al., 1982). Certain variations in directional data can be monitored with reasonable certainty using unoriented drill core, however, and have proven useful in the present study. If it is assumed that any magnetization acquired as a result of chemical changes and/or thermal effects during test burning is acquired parallel to the ambient magnetic field direction, then the inclination (the angle of "plunge" of the magnetization vector from the horizontal) is predictable. The declination (the angle measured from north of the horizontal component of the magnetization) cannot be predicted because the core has been rotated. As specimens have been prepared by drilling perpendicular to the core axis and the Hanna cores are oriented within 2° of vertical inclination orientations can be achieved. The expected inclination for the Hanna site in the late 1970's is approximately $+69^\circ$ (Peddie, et al., 1976; Epoch 1975.0 geomagnetic data). In Figures 7-14, NRM inclination data are plotted for all stratigraphic levels from which three or more specimens were measured and associated mean directions and statistics could be calculated. The mean inclination data are plotted in terms of positive (steeper) or negative (shallower) deviations from an expected inclination value.

The inclination deviation follows a regular pattern through two of the drill holes investigated (2HP-174, -176). Immediately above the burn cavity the inclination deviations become very small. Below and farther above the cavity, inclination deviations become extremely irregular, but the directional dispersion at each level also increases drastically (see below) and therefore inclination variations in the zone

Figure 7. Remanent and rock magnetic data plotted vs. core depth, Hanna II site, core 2HP-133. In the first column, the deviation from the expected inclination ($+69^{\circ}$, see text) of the mean inclination of the natural remanent magnetization is plotted for stratigraphic levels where three or more specimens were measured and mean NRM directions and associated statistics could be calculated. In the second column, the rock type and core nature is summarized. In the third column, the intensity of the NRM is plotted. The fourth column displays the Fisher precision parameter (Fisher, 1953). The fifth column gives the initial susceptibility. Susceptibility data given in circles refer to Hanna Formation rock specimens; square refer to fragmented char or rubble samples. The maximum sensitivity of the Bison unit used for measurements is 1.0×10^{-6} cgs units; all values less than this are plotted at 1×10^{-6} cgs units.

Figure 8.

Remanent and rock magnetic data plotted vs. core depth,
Hanna II site, core 2HP-172. Presentation of data is
as in Figure 7.

Remanent and rock magnetic data plotted vs. core depth, Hanna II site, core 2HP-173. Presentation of data is as in Figure 7.

Figure 10. Remanent and rock magnetic data plotted vs. core depth, Hanna II site, core 2HP-174. Presentation of data is as in Figure 7.

Figure 11.

Remanent and rock magnetic data plotted vs. core depth,
Hanna II site, core 2HP-175. Presentation of data is
as in Figure 7.

Figure 12.

Remanent and rock magnetic data plotted vs. core depth,
Hanna II site, core 2HP-176. Presentation of data is
as in Figure 7.

20

61.0m
200ft

91.4m
300ft

STRATIGRAPHY

INCLINATION
DEVIATION

NRM INTENSITY
(in A/m)

FISHER PRE- SUSCEPTI-
CISION PARAMETER BILITY
(log CGS)

-60 -40 -20° -20° -5 -4 -3 -2 -1 0 1 2 3 -6 -5 -4 -3

Figure 13.

Remanent and rock magnetic data plotted vs. core depth,
Hanna II site, core 2HP-178. Presentation of data is
as in Figure 7.

Figure 14.

Remanent and rock magnetic data plotted vs. core depth,
Hanna II site, core 2HP-182. Presentation of data is
as in Figure 7.

immediately above the burn cavity, in combination with extremely small dispersions of magnetization directions, strongly suggest that the present earth's field direction has been recorded with very high fidelity by overburden during test burning.

In the other holes (pre-burn hole 2HP-133 and post-burn holes 2HP-172, 173, -175, -178, -182), inclination deviations are varied throughout the sampled portion of each core, though shallower inclinations predominate.

The average inclination for late Paleocene-early Eocene time is approximately $+59^{\circ}$ (Irving, 1979; based on paleomagnetic data time-averaging the earth's field). Inclination deviations in post-burn cores 2HP-172, -173, -175, -178, -182 are very similar to deviations in pre-burn core 2HP-133. As well, directional dispersion is usually high at all stratigraphic intervals for each of these cores. These data suggest that the original, unaltered Hanna Formation contains a complicated magnetization possibly composed of several components (i.e., primary, as a result of depositional, and secondary, as a result of diagenetic processes). These findings are similar to those by Bressler and Elston (1981) from the time-equivalent Fort Union and lower Wasatch Formation.

Intensity Variations

Plotted in the second column of Figures 7-14 are the NRM intensities of all specimens measured. Each point represents a separate specimen. NRM intensities for pre-burn core 2HP-133 (Figure 7) are all very low, generally ranging between 1.0×10^{-4} and 2.0×10^{-3} A/m (1.0×10^{-7} and 2.0×10^{-6} emu/cc) and are typical of NRM intensities for such lithologies (e.g., Butler, 1982). The intensity values for hole 2HP-133 show little systematic variation with stratigraphy. Post-burn holes 2HP-172, -173, -175, -178, -182 exhibit similar intensity values and variations throughout each sampled section, suggesting that the burning did not affect the magnetic mineralogy and magnetism in these cores. Only in post-burn hole 2HP-173 is there a slight indication of an increase in NRM intensities as the burn cavity is approached.

Postburn holes 2HP-174 and -176 show a significant (greater than two order of magnitude) increase in NRM intensities as the burn cavity is approached. The intensity increase occurs over a stratigraphic interval of less than 1 m. Intensity values occasionally exceed 1.0 A/m, a value typical of intermediate composition igneous rocks!

In all drill cores investigated, Hanna Formation units below the burn cavity show normal (background) NRM intensities.

Dispersion of NRM Directions

A measure of the dispersion of magnetization directional data is the best estimate, k , of the precision parameter of a set of unit vectors dispersed on a sphere (Fisher, 1953). The value K is determined as $(N-1)/(N-R)$, where N is the number of unit vectors measured and R is the vector sum of the N unit vectors. The higher the value of k , the more well-grouped the magnetization vectors. For each stratigraphic level

where the NRM direction and intensity of three or more specimens could be measured, the value of k was determined as the mean direction of the level was calculated.

Pre-burn hole 2HP-133 is characterized by irregular, but generally low k values throughout the stratigraphic sequence sampled. Post-burn holes 2HP-172, -173, -175, -178, -182 all display the same general characteristics. Post-burn holes 2HP-174 and -176 show increases in k values of greater than two orders of magnitude as the burn cavity is approached. Stratigraphic levels below the burn cavity and far above it show low (background) values.

Initial Susceptibility

The initial (low field) susceptibility may be used as a rough estimate of the magnetite content in rocks (e.g., Lindsley, et al., 1966; Parasnis, 1973). Material from pre-burn hole 2HP-133, as well as from post-burn holes 2HP-172, -173, -175, -178, -182, is characterized by generally very low initial susceptibilities (less than 1.0×10^{-5}), suggesting very low (less than 0.05 volume %) magnetite contents. Post-burn holes 2HP-174 and -176, on the other hand, show a significant (approximately two order of magnitude) increase in susceptibility values in the zone immediately above the burn cavity, while values remain relatively constant and low farther above and immediately below the burn cavity. The increase in susceptibility signifies a major change in the magnetic mineralogy of the Hanna Formation overburden during test burning. The susceptibility values imply magnetite contents of approximately 1-5 volume %.

Only susceptibility measurements were carried out on char and rubble material, because standard specimens could not be prepared from the fragmented material retrieved from the core holes. Susceptibility values for char are all less than 1.0×10^{-5} , while some rubble/pyro-metamorphosed material exhibits values greater than 1.0×10^{-4} .

Summary of NRM Observations

The remanent magnetic data presented in Figures 7-14 thus suggest that a zone of Hanna Formation overburden immediately overlying the burn cavity has been significantly altered during UCG burning. This zone is characterized by (1) well-grouped NRM directions whose inclinations are close to the present-day field inclination in southeast Wyoming, (2) NRM intensities approximately two orders of magnitude greater than background values, and (3) initial susceptibilities approximately two orders of magnitude greater than background values. The magnetization of Hanna Formation units within this zone was presumably acquired during heating and associated geochemical/ magnetic mineralogy changes. The magnetization is in all likelihood a partial to complete thermochemical remanent magnetization (TCRM) acquired during rapid cooling of the overburden immediately above the burn cavity. The anomalous susceptibility values dictate that magnetite is produced in this zone during UCG testing, hence the chemical aspect to the magnetization.

Core from post-burn drill holes located on the margin of the burn cavity do not show significant changes in magnetic mineralogy as the burn cavity is approached. The present results imply that thermal effects were focused upward toward the center of the burn cavity, and were not distributed in a radial manner away from the cavity. This observation agrees with the findings of Craig, et al. (1982). The core material thermally affected by the UCG burn will, for clarity, be termed remagnetized.

DEMAGNETIZATION RESULTS

Thermal Demagnetization

Representative specimens from stratigraphic levels from all drill holes were progressively thermally demagnetized. Behavior during thermal demagnetization is generally straightforward and may be discussed in two general groups, for which specific examples are given. Remagnetized material from drill cores 2HP-174 and -176 displays the simple removal of a single component of magnetization up to maximum blocking temperatures of pure magnetite (approximately 585°C)(Fig. 15). The blocking temperatures of remagnetized material are distributed over a wide range of temperatures (Fig. 16), suggesting that magnetite formed during UCG burning is of varied grain sizes (e.g., Neel, 1949; McElhinny, 1973; Pullaiah, et al., 1975). The absence of blocking temperatures above approximately 585°C indicates that very little, if any, magnetization is carried by hematite. Initial susceptibilities were monitored at each demagnetization level and show either little change or slight to substantial increases with heating (Fig. 17). Constant susceptibility values during thermal demagnetization imply no changes to the magnetic mineralogy, while increases imply that even additional magnetite is being formed during heating. The significance of the latter phenomenon will be discussed below. Figure 18 shows that the direction of each specimen undergoes little change in inclination during thermal treatment and little tendency toward the predicted inclination of about +69°. Importantly, the remagnetized material does not appear to display the removal of a slight "overprint" component (acquired during UCG burning) at a particular (low) temperature and then the removal of a background component up to maximum magnetite blocking temperatures.

Response to thermal demagnetization by unaltered Hanna Formation material is variable, but quite distinct from that of remagnetized material. Blocking temperature spectra of the NRM in unaltered material are generally lower than those in remagnetized Hanna Formation (Fig. 19). By 400°C, approximately 90% of the magnetization in most specimens has been removed (e.g., Specimens 2HP-133-222, 224, 238.5, and 248 in Fig. 19a). As well, directional stability is quite erratic for most specimens. As described above, the initial susceptibilities for unaltered material are less than 1.0×10^{-5} . Monitoring of susceptibility values during thermal demagnetization shows that values remain very low to about 250°C (Fig. 20). Above this temperature, however, many specimens

Figure 15. Progressive orthogonal demagnetization diagrams illustrating the successive removal of a TCRM component in remagnetized Hanna Formation during thermal demagnetization. The endpoint of the magnetization vector is projected simultaneously onto two planes, one the N-S,E-W, the other either the N-S,U-D or E-W,U-D. The horizontal projection is depicted by filled circles, the vertical by open circles. Simultaneous linear alignments of data points on the horizontal and vertical projections signify the removal of single magnetization components (Zijerveld, 1967). Demagnetizing temperatures (in °C) are given beside the points on the vertical projection. Demagnetizations of (a) specimen of remagnetized overburden at the 262' level, 2HP-174, (b) specimen of remagnetized overburden at the 251' level, 2HP-176, (c) specimen of remagnetized overburden at the 262' level, 2HP-176.

FIGURE 15

FIGURE 15

FIGURE 15

Figure 16. Normalized magnetization intensity vs. temperature; thermal demagnetization, remagnetized Hanna Formation. (a) specimens from 2HP-174. (b) specimens from 2HP-176.

FIGURE 16

FIGURE 16

Figure 17. Initial susceptibility vs. temperature; thermal demagnetization, remagnetized Hanna Formation.

Figure 18. Inclination deviation vs. temperature, thermal demagnetization, remagnetized Hanna Formation.

Figure 19. Normalized magnetization intensity vs. temperature; thermal demagnetization, unaltered Hanna Formation. (a,b) specimens from 2HP-133.

FIGURE 19

Figure 20. Initial susceptibility vs. temperature; thermal demagnetization, unaltered Hanna Formation.

exhibit a dramatic rise in susceptibility, signifying the production of magnetite. Coincident with the rise in susceptibility is a pronounced rise in magnetization intensity (e.g., specimens 2HP-133-270, 274, and 290 in Figs. 19b and 20). Such changes are definitely not observed in remagnetized Hanna material; this phenomenon has important ramifications for the nature and origin of the magnetization in remagnetized Hanna Formation overburden immediately above the burn cavity.

Alternating Field Demagnetization

Representative specimens from stratigraphic levels from all drill holes were progressively demagnetized via alternating field demagnetization methods. Behavior during this treatment, as with thermal demagnetization, is generally straightforward and falls into two types. Remagnetized material of post-burn holes 2HP-174 and -176 again displays the simple removal of a single component of magnetization up to peak fields in excess of 40 mTesla (400 oersteds). By such fields, the magnetization has decreased by over two orders of magnitude (Fig. 21). Behavior at higher fields is generally spurious, suggesting that much of the magnetite produced during UCG burning is coarse-grained (multi-domain) in size.

The usual behavior of unaltered Hanna Formation overburden in alternating field demagnetization is distinct from that of remagnetized material. Most material examined displays the removal of a single magnetization component, but in these cases the component is considerably more "stable" or resistive to alternating field demagnetization (Fig. 22). Unaltered Hanna Formation overburden contains considerably less magnetite than remagnetized material, as evidenced by susceptibility data, and the magnetite present appears to be of a much finer grain size, leading to greater stability (higher coercivities) in alternating field demagnetization.

ROCK MAGNETIZATION DATA

IRM Acquisition Tests

Representative specimens from various stratigraphic levels all display saturation of IRM in DC fields between 0.075 and 0.15 Tesla (750 and 1500 gauss) (Figs. 23-25). Remagnetized material has extremely high saturation IRM values (greater than 100 A/m), suggestive of abundant (approximately 1-5 volume %) magnetite. Unaltered material has significantly lower saturation IRM values (approximately 2.0 A/m), indicating a much lower magnetite content. As saturation IRM values are dependent on both magnetite grain size and magnetite concentration (e.g., Dankers, 1977), exact estimates of magnetite contents are precluded. Curves for remagnetized and unaltered material below 0.2T are of noticeably different shapes. The more rounded curves for unaltered materials imply that these units overall contain finer-grained (smaller domain) magnetite grains than their remagnetized counterparts (Dankers, 1977). At fields above 0.2 T, IRM remains constant (saturated) in remagnetized material. The unaltered units display a slight increase in IRM above 0.2 T. These

Figure 21. Normalized magnetization intensity vs. peak field; alternating field demagnetization, remagnetized Hanna Formation.

Figure 22. Normalized magnetization intensity vs. peak field; alternating field demagnetization, unaltered Hanna Formation.

Figure 23. Curves showing the acquisition of IRM (positive field) and backfield demagnetization (negative field); remagnetized Hanna Formation.

Figure 2 4. Curves showing the acquisition of IRM (positive field) and backfield demagnetization (negative field); unaltered Hanna Formation, post-burn holes 2HP-174 and 2HP-176.

Figure 25. Curves showing the acquisition of IRM (positive field); unaltered Hanna Formation, pre-burn hole 2HP-133.

observations, in combination with the thermal demagnetization results, strongly suggest that magnetite is the dominant magnetic phase. The presence of slight hematite is indicated by a positive slope of the IRM acquisition curve between 0.2 and 2.0 T.

Backfield demagnetization tests result in the removal of the magnetization in DC fields of about -0.1 T (100 gauss) or less, again indicating that magnetite is the very predominant magnetic phase. The DC field required to reduce the IRM to a value of zero is called the coercivity of remanence (H_{cr}). H_{cr} values for unaltered Hanna Formation are consistently higher than those for the remagnetized material, again suggesting that the magnetite grain sizes in unaltered Hanna material are generally smaller than those in remagnetized units, supporting previous observations based on alternating field results. Multiple slopes for the backfield demagnetization curves may indicate different magnetite grain size populations (Park, 1975).

Curie Point Determinations

These tests could only be performed on remagnetized material, as attempts to separate magnetic minerals from the unaltered Hanna Formation proved unsuccessful. A saturation magnetization was imparted to representative specimens using a permanent magnet producing a peak field of 0.22 T (2200 gauss). Typical curves, shown in Figure 26, illustrate that the main magnetic phase is a titanomagnetite of variable titanium content. Specimen 2HP-174-266 exhibits a Curie temperature close to 585°C, that of pure magnetite, while specimen 2HP-176-262 exhibits a less interpretable pattern, but a Curie temperature below 500°C, suggesting a titanium content of approximately 10 molecular % ulvöspinel component (Fe_2TiO_4).

DISCUSSION

"Remagnetized" Hanna Formation occurs immediately above the Hanna II, Phases 2 and 3 UCG burn cavity and contains a single TCRM component. This component is characterized by the following magnetic properties:

- 1) NRM intensities greater than 0.5 A/m.
- 2) initial susceptibilities greater than 10^{-4} .
- 3) well-grouped directions whose inclinations are very similar to the present-day field magnetic inclination.
- 4) distributed, but generally high blocking temperatures and the simple removal of a magnetization up to maximum magnetite blocking temperatures.
- 5) relatively low coercivity spectra (as determined by alternating field demagnetization) in comparison to those of unaltered Hanna Formation units.
- 6) the absence of significant hematite (as determined by IRM acquisition curves).
- 7) Curie temperatures between 480 and 580°C, indicating a nearly pure titanomagnetite as the carrier of the magnetization.

Figure 26. Curie point determination curves (saturation magnetization vs. temperature), remagnetized Hanna Formation. Specimens from the 266' level of 2HP-174 and from the 262' level of 2HP-176.

The zone of remagnetization in drill cores 2HP-174 and 2HP-176 is approximately 10 m thick. The upper boundary of this zone is less than 1 m in thickness. The other Hanna post-burn cores penetrated the edge of the cavity and their magnetic properties either showed no or very slight stratigraphic variations with respect to proximity to the burn cavity. The magnetic properties of the Hanna Formation units beneath the burn cavity are apparently not affected by the UCG experiments.

Results of thermal demagnetization studies on unaltered Hanna Formation units suggest a mechanism to explain the origin of the zone of remagnetization. Figures 19 and 20 show that at temperatures greater than 300°C, the NRM intensities and initial susceptibilities show marked increases and continue to increase with further thermal treatments. Concomitant increases in susceptibility and NRM intensity dictate that magnetite is formed during thermal treatment. The intensities of the treated specimens, while higher than the initial, NRM intensities are still significantly lower than the NRM intensities of remagnetized material. This discrepancy can be explained by the facts that the unaltered specimens undergoing thermal treatment are heated and cooled in an essentially zero (less than 2 nTesla, or two gammas) magnetic field and that continued heating at higher temperatures would cause further intensity increases (Dunlop, 1972).

Few laboratory investigations have been carried out on the controlled formation of magnetite in clastic sedimentary rocks as a result of heating, and therefore, many conclusions reached here may be tentative. Stephenson (1967) and Dunlop (1972) studied the magnetic mineralogy of unheated and laboratory heated red sandstones. These workers found that considerable magnetite was produced during heating in air at temperatures below 675°C. On the basis of various rock magnetic investigations, they concluded that the source of the "secondary" magnetite was probably ferromagnesian silicates. Hematite was not formed during heating in air below 675°C and, furthermore, was not reduced to form the secondary magnetite. They estimated the activation energy of magnetite production in the sandstones using data on the susceptibility or magnetization intensity increases during heating. Were magnetite to be produced by conversion of a weakly magnetic or nonmagnetic mineral X, then Dunlop proposed that the reaction can be written as a first-order one, so the mass M of X at time t is described by:

$$dM/dt = -K_0 \exp(-Q/RT)M,$$

where K_0 is a constant, R is the universal gas constant, and Q is the molar activation energy of the process at temperature T . Assuming that the intensity of the remanence Δm_r at time t is proportional to the mass of magnetite produced, then

$$\Delta m_r(t) = \Delta m_r(\infty)[1 - \exp(-t/\tau)]$$

where:

$$\tau = (1/K_0)\exp(Q/RT).$$

Figure 27. Data for activation analysis of secondary magentite production in thermally "demagnetized" unaltered Hanna Formation units, assuming a first-order reaction. T is the heating (annealing) temperature.

Q may be determined by annealing for different times at a single temperature or, alternatively, by annealing for identical lengths of time at different temperatures, since for small values of t compared to

$$\Delta m_r(t) = \Delta m_r(\infty) t K \exp(-Q/RT).$$

The second method was used in this study, with the experimental data shown in Figure 27.

The $\log \Delta m_r$ vs. $1/T$ plots yield variable, and often negative, slopes with increasing temperature. This observation alone suggests that the process of magnetite formation may not be as simple as envisioned. Furthermore, Dunlop had greater success in this analysis by heating specimens at significantly higher temperatures. Three of the specimens treated (2HP-133-224, 2HP-133-270, and 2HP-133-290) do have consistent slopes over some temperature intervals, and yield activation energies of -26.3, -6.1, and -6.1 Kcal/mole, respectively. The activation energies have negative values because the increase in remanence intensity or susceptibility actually decreases with temperatures. This is opposed to the findings of Stephenson (1967) and Dunlop (1972). These experiments are being continued at higher temperatures in hopes of yielding more consistent, useful results.

Importantly, the thermal demagnetization experiments on unaltered Hanna Formation units do show that extreme (i.e. > 900°C) temperatures are not required to cause major changes in the magnetic mineralogy of the Hanna Formation units. It can be estimated with reasonable certainty that the top of the remagnetized zone must have been heated to temperatures above about 300°C. A (minimum) thermal gradient on the order of 700°C/10 m (1000-300°C) must have existed in the vicinity of drill holes 2HP-174 and 2HP-176 during UCG experiments.

The magnetic data strongly support the suggestion of Craig, et al. (1982), the UCG burning environment was reducing in nature, but unfortunately provide little exact information on oxygen fugacity conditions. Specific temperatures of heating are required before gas fugacity conditions can be estimated. If magnetite was formed under equilibrium conditions, the oxygen fugacity must be below the hematite/magnetite buffer curve at the appropriate temperature of formation. At a temperature of formation of 400°C, for example, the oxygen fugacity is 10-23. If hemoilmenite is formed simultaneously during UCG burning and thermal alteration, then an electron microprobe analysis of the compositions of coexisting titanomagnetites and hemoilmenites may yield information on the temperature-oxygen fugacity conditions during magnetite formation (Buddington and Lindsley, 1964; Lindsley, 1977; Lindsley, 1982) at a specific level above the burn cavity.

On a relative basis, the oxygen environment of UCG burning is relatively more reducing than the environment during natural burning of coal. Jones (1983) has shown with IRM acquisition tests and petrographic observations that most clinker of the Powder River Basin contains abundant (approximately 5 volume %, +/-) hematite formed during burning.

Goethite, probably formed during groundwater circulation attending burning, and magnetite are also present. The brick-red color of the baked rock strongly attests to an oxidizing environment.

The magnetic properties of the seven post-burn drill cores studied have important bearing on the geometry of the thermal aureole attending UCG experiments. A zone of remagnetization (and thus significant heating) is only present in drill holes 2HP-174 and 2HP-176, both located near the center of the burn cavity. All other holes are located closer to the edges of the burn cavity and do not exhibit zones of significant remagnetization. Thus, the highest thermal perturbations, well-exceeding 300°C, must have been "funnelled" toward the top and center of the burn cavity. The edges of the burn cavity were of course thermally affected, but temperatures probably did not exceed 300°C.

Two sources would thus contribute to a magnetic anomaly for the burn cavity created as a result of UCG testing. One would be a layer of largely intact, remagnetized Hanna Formation directly above the burn cavity and approximately 10 m thick. This layer would be uniformly magnetized (declination slightly east of north and inclination of +65-70°) with an NRM intensity of about 0.5 A/m. The lateral extent of the layer is presently unknown, but it is confined to within the boundaries of the burn cavity. The other source is the pyrometamorphosed rubble material in the burn cavity. Much of this material has high (> 10⁻⁴) susceptibilities, but NRM directions have probably been randomized as a result of burn cavity collapse. The contribution by this layer would therefore be the result of a straightforward (and large!) susceptibility contrast.

SUMMARY AND APPLICATIONS

Remanence and rock magnetic properties of overburden Hanna Formation at the Hanna II, Phase 2 and 3 UCG test site have been substantially modified as a result of a thermal perturbation during coal burning. Core holes 2HP-174 and 2HP-176 contain intervals approximately 10 m thick immediately above the burn cavity in which the NRM intensity, NRM dispersion, NRM inclination, initial susceptibility, and demagnetization properties all are anomalous in comparison to the "background" properties of fresh Hanna Formation.

The origin of the remagnetized zone is attributed to the production of 1-5 +/- volume % secondary magnetite from detrital ferromagnesian silicates (and, possibly, hematite). Thermal demagnetization experiments on fresh Hanna Formation material show that magnetite production can occur in air, at temperatures above about 300°C. Post-burn core holes located near the proximity of the burn cavity do not contain zones of anomalous magnetization properties. As well, Hanna Formation beneath the burn cavity is not remagnetized.

The magnetic data have significant application toward better understanding of UCG experiments and attending thermal anomalies. Thermal perturbations on surrounding Hanna Formation units must have been fun-

nelled vertically upward from the center of the burn cavity, not radially away from it. The thermal gradient above the burn cavity can be straightforwardly estimated (assuming that magnetite production is temperature-, not time-, dependent) to be approximately $70^{\circ}\text{C}/\text{m}$. Magnetization data are of considerable value in determining thermal environments; they may be more useful and more simple to interpret than data from other present techniques.

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