Paleomagnetic and $^{40}Ar/^{39}Ar$ Results from the Grant Intrusive Breccia and Comparison to the Permian Downeys Bluff Sill—Evidence for Permian Igneous Activity at Hicks Dome, Southern Illinois Basin

By Richard L. Reynolds, Martin B. Goldhaber, *and* Lawrence W. Snee

EVOLUTION OF SEDIMENTARY BASINS—ILLINOIS BASIN
Jennie L. Ridgley, *Project Coordinator*

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ABSTRACT

Igneous processes at Hicks dome, a structural upwarp at lat 37.5° N., long 88.4° W. in the southern part of the Illinois Basin, may have thermally affected regional basinal fluid flow and may have provided fluorine for the formation of the Illinois-Kentucky Fluorspar district. The timing of both igneous activity and mineralization is poorly known. For this reason, we have dated an intrusive breccia at Hicks dome, the Grant intrusion, using $^{40}Ar/^{39}Ar$ geochronometric and paleomagnetic methods. Concordant plateau dates, giving Permian ages, were obtained from amphibole (272.1±0.7 [1σ] Ma) and phlogopite (272.7±0.7 [1σ] Ma). After alternating-field (AF) demagnetization, specimens that contain titanomagnetite-bearing igneous rock fragments give a mean remanent direction of declination (D)=168.4°; inclination (I)=–8°; α_{95}=8.6°; number of specimens (N)=10; this direction yields a virtual geomagnetic pole (VGP) at lat 54.8° N., long 119.0° E., δp=4.4°, δm=8.7°, near the late Paleozoic part of the North American apparent pole wander path. A nearly identical magnetization was found for the nearby Downeys Bluff sill (previously dated at about 275±24 Ma by the Rb-Sr method), in southern Illinois. Both AF and thermal demagnetization isolated shallow, southeasterly remanent directions carried by magnetite in the sill and from pyrrhotite in the baked contact of the Upper Mississippian Downeys Bluff Limestone: D=158.6°; I=–11.8°; α_{95}=3.8°; N=15, yielding a VGP at lat 53.0° N., long 128.7° E., δp=2.0°, δm=3.9°. The paleomagnetic results, isotopic dates, and petrographic evidence thus favor the acquisition of thermal remanent magnetization by the Grant breccia and the Downeys Bluff sill during the Permian. The isotopic dates record rapid cooling from temperatures greater than 550°C to less than 300°C (the closure temperatures for diffusion of ^{40}Ar in amphibole and phlogopite, respectively) after emplacement during the Permian. The results further indicate that individual clasts of the Grant breccia were emplaced at temperatures greater than about 550°C, the magnetization-blocking temperature of the titanomagnetite in the breccia, and that it cooled very rapidly, within less than 1–2 m.y. After cooling, the breccia was not affected by thermal perturbations greater than about 300°C.

INTRODUCTION

Studies of igneous rocks in southern Illinois contribute to multidisciplinary investigations of the thermal activity, fluid-flow history, hydrocarbon generation, and mineralization in and around the Illinois Basin. In this study, we apply $^{40}Ar/^{39}Ar$ dating methods, along with paleomagnetic and rock magnetic techniques, to determine the age of emplacement and the cooling history of the Grant intrusive breccia at Hicks dome (figs. 1 and 2). Additional goals of this study are to estimate the emplacement temperature of the breccia and to interpret its post-emplacement thermal history. We also report paleomagnetic and rock magnetic results from a nearby intrusion—the Downeys Bluff sill (fig. 1), previously dated as Permian in age—for comparison to the results from the Grant breccia. The overall objective of the study is to provide information on intrusive activity that may then be used to test models linking thermal activity and mineralization in the southern Illinois Basin.

GEOLOGIC SETTING

TECTONIC SETTING OF IGNEOUS ROCKS AND FLUORSPAR DEPOSITS IN THE SOUTHERN PART OF THE ILLINOIS BASIN

The sampled intrusive bodies occur within the Illinois-Kentucky Fluorspar district in the southern part of the Illinois Basin (fig. 1) (Baxter and others, 1989; Bradbury and Baxter, 1992). The Fluorspar district is located at the

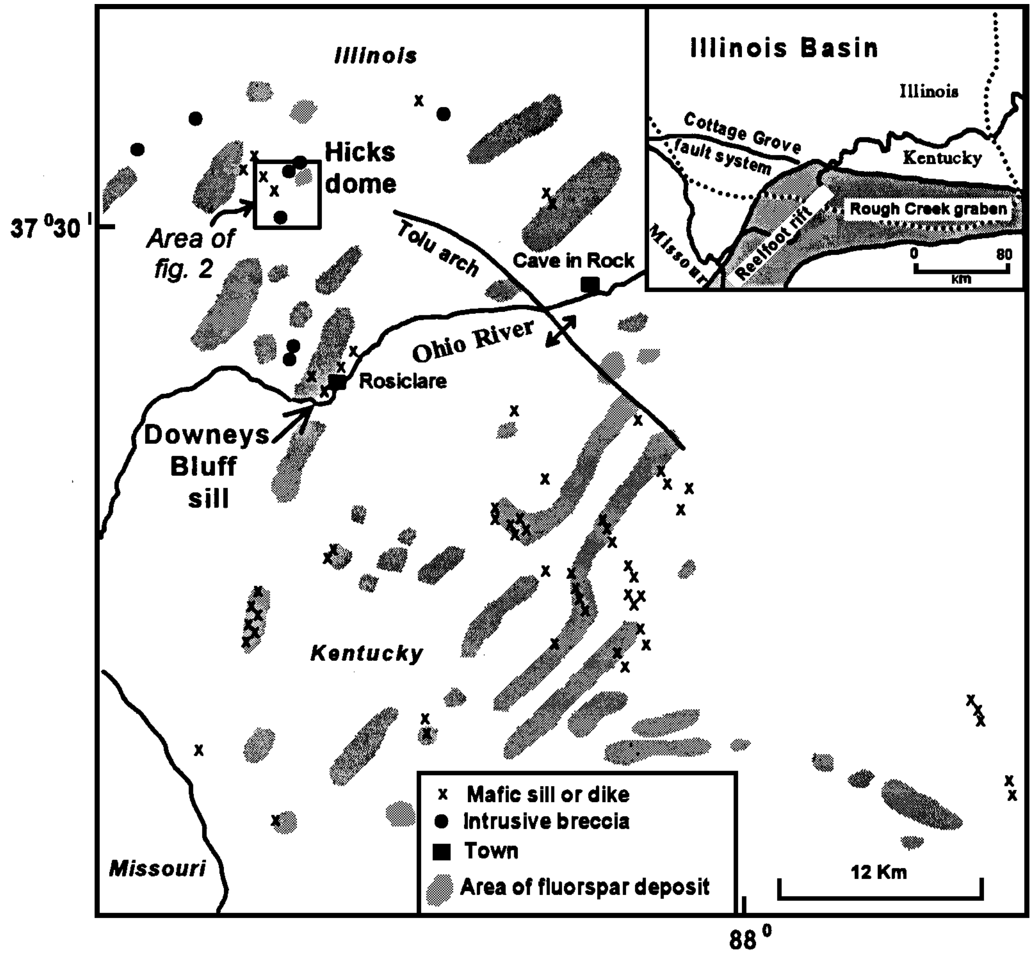

Figure 1. Map showing locations of Hicks dome and the Downeys Bluff sill, igneous rocks, and distribution of known fluorspar deposits. Modified from Baxter and others (1989).

intersection of the Reelfoot rift and the Rough Creek graben (fig. 1) (Nelson, 1991; Kolata and Nelson, 1991). The rift and graben, part of the New Madrid rift system that formed during late Precambrian–Cambrian extension (Bond and others, 1984), are filled with about 7 km of Paleozoic sedimentary rock in the vicinity of Hicks dome, a cryptovolcanic feature that lies in the northwest part of the Fluorspar district (Goldhaber, Potter, and Taylor, 1992; Goldhaber, Taylor, and others, 1992). During the Late Pennsylvanian and Early Permian plate collision that assembled Pangea, the interior of the North American plate was deformed to form the Tolu arch, a northwest-trending anticline, and a series of major north-northwest-trending faults. Many of these faults were intruded by mafic dikes (Zartman and others, 1967; Nelson and Lumm, 1984; Bradbury and Baxter, 1992; Kolata and Nelson, 1991). Fluorspar mineralization was localized in Mississippian strata and postdated the Pennsylvanian–Early Permian north-northwest-trending structures and intrusions. The mineralized faults of the Fluorspar district define a series of northeast-trending grabens that offset the axis of the Tolu arch and crosscut the mafic dikes. The time span represented by such offsets poorly constrains the period of mineralization between the Early Permian and the Late Cretaceous. The structural relief at Hicks dome—as much as 1,200 m that reveal Devonian and Lower Mississippian sedimentary rocks through a cover of Pennsylvanian beds—was related to the intrusion of alkalic igneous rocks at depth accompanied by explosive emplacement of gas-charged breccias at shallower levels (Bradbury and Baxter, 1992). The vertical displacement of the rocks and disruption of seismic reflectors underlying Hicks dome extend into the crystalline basement (Goldhaber, Potter, and Taylor, 1992). Hicks dome is itself underlain by an intensely fluorite mineralized explosion breccia hosted by Middle Ordovician rocks (Brown and others, 1954). As summarized below, however, the timing of uplift and intrusive activity at Hicks dome is also poorly known.

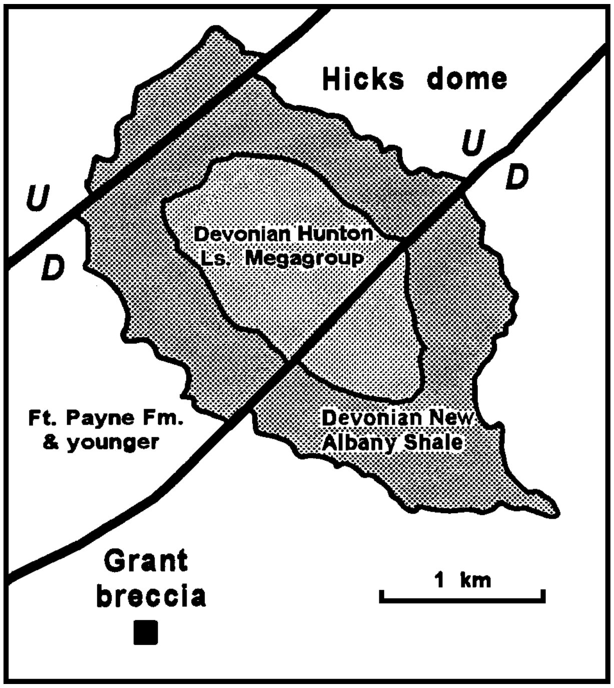

Figure 2. Simplified geologic map of the Hicks dome area, showing the location of the Grant breccia. Modified from Baxter and others (1989).

POSSIBLE ROLE OF THERMAL ENERGY AND MAGMATIC VOLATILES IN MINERALIZATION

The igneous activity in the southern Illinois Basin may have influenced fluid temperatures and fluid compositions in the southern Illinois Basin and the origins of Mississippi Valley-type (MVT) ore deposits at both the southern and northern margins of the basin. For example, Goldhaber, Potter, and Taylor (1992), Goldhaber and others (1994), Taylor and others (1992, 1995), and Plumlee and others (1995) propose genetic and temporal connections between thermal activity provided by intrusions and mineralization at Hicks dome and mineralization in the Illinois-Kentucky Fluorspar district. Moreover, Rowan and Goldhaber (1995) suggest that formation of the Upper Mississippi Valley district in southern Wisconsin may have involved the transport of fluorine and other ore constituents northward from the Hicks dome igneous center. The mineral deposits of the two districts may be related by a common, regional brine-flow regime. Evidence for such a relation comes from several studies (Goldhaber and others, 1994; Plumlee and others, 1995; Taylor and others, 1995), many of which illustrate the possible importance of heat and magmatic volatiles generated at Hicks dome. First, fluid-inclusion data show that Hicks dome was a thermal center and that fluid temperatures decreased away from the uplift. Second, fluorine concentrations in carbonate rocks above and below regional aquifers, such as the St. Peter Sandstone, show systematic decreases away from Hicks dome. Third, petrographic studies reveal that fluorite distribution and its associations with dolomite and K-feldspar are consistent with transport of hydrothermal brines northward, away from Hicks dome. Finally, lead isotopic data imply a common genesis for lead in deeply buried Cambrian-Ordovician carbonate rocks, in galena from overlying Mississippian carbonate rocks that host the Illinois-Kentucky fluorspar ores, in galena from Upper Mississippi Valley district MVT deposits, and in pyrite in non-mineralized beds that lie between the two districts (Goldhaber and others, 1995).

Another proposed source of thermal energy to drive fluid flow in the Illinois Basin involves the rapid convective release of radioactive heat caused by the fracturing of basement granite (Spirakis and Heyl, 1995). Such locally derived heat, and circulating basinal brines driven by this heat, might alternatively explain the Upper Mississippi Valley district MVT deposits without a connection to fluids from the Illinois-Kentucky Fluorspar district.

DISPARATE ISOTOPIC AGES FROM HICKS DOME AND UNCERTAIN RELATIONS TO MINERALIZATION

Tests and refinement of different models for MVT ore genesis and basinal fluid flow would benefit from a better understanding of the timing of igneous activity in the southern Illinois Basin. In fact, the temporal relations among the intrusion of dikes and sills in the southern Illinois Basin, the emplacement of breccias at Hicks dome (including the F-, Nb-, Be-, Y-, and REE-mineralized[1] breccias), and the widespread Fluorspar district mineralization are a matter of dispute (Bradbury and Baxter, 1992). Part of the problem centers on conflicting isotopic dates from rocks at Hicks dome that lead to uncertainty about the timing of emplacement of the mineralized breccias. K-Ar dating of xenocrystic mica (258±13 Ma) and amphibole (281±14 Ma) from the Grant breccia (Zartman and others, 1967; uncorrected for post-1977 decay constants) suggest explosive activity during the Permian. Other isotopic data suggest a younger age for brecciation. Heyl and Brock (1961) obtained a Pb-alpha age of between 90 to 100 Ma on brockite from Hicks dome that they took to imply influence from the reactivation of the New Madrid rift during the Cretaceous. An alternative interpretation was proposed by Ruiz and others (1988) on the basis of a comparison between strontium isotopes in biotite from Permian alkalic dikes and in nearby fluorite. Similar Sr isotopic compositions were attributed to a Late Triassic or Early Jurassic igneous event (at about 200 Ma) centered at Hicks dome that reset the Rb-Sr system in the dikes. Ruiz and others (1988) speculated that such thermal activity was the result of rift reactivation associated with the breakup of Pangea (see

[1]REE, rare earth element.

Bradbury and Baxter, 1992). An important consideration comes from petrographic evidence that alteration of some intrusions in the Illinois-Kentucky Fluorspar district was caused by later MVT mineralization (Oesterling, 1952; Snee and Hayes, 1992). Yet Chesley and others (1994) have obtained a 17-point ^{147}Sm/^{144}Nd isochron of 277±15.6 Ma from fluorite in the Fluorspar district. This date overlaps, within analytical uncertainty, K-Ar dates from igneous rocks in the southern Illinois Basin (Zartman and others, 1967). Thus, the time span between intrusion and mineralization is not well constrained. In another approach to the problem, paleomagnetic methods may be used to date both intrusions and ore minerals. For example, a paleomagnetic pole position obtained from fluorspar ore has been interpreted to indicate a Jurassic age of mineralization in the Illinois-Kentucky Fluorspar district (Symons, 1994). These results will be discussed in more detail below in the context of our paleomagnetic data.

ROCK UNITS STUDIED AND BASIS FOR PALEOMAGNETIC STUDIES

The carbonatitic Grant breccia was targeted for additional isotopic dating and for new paleomagnetic work because it is the least weathered outcrop of intrusive breccia in the Hicks dome area and because it contains fragments of igneous rock. Paleomagnetic tests for age, coherency of magnetization among clasts, and emplacement temperatures were conducted. For rocks of this age, paleomagnetic dating involves the measurement of a mean direction of remanence in a rock, the calculation of the position of the paleomagnetic pole from the mean direction, and the comparison of the pole to the apparent pole wander path (APWP) for cratonic North America (see Van der Voo, 1989). The pole positions from one or a few igneous units, as in this study, represent the

Table 1. ^{40}Ar/^{39}Ar data for mineral samples[1] from the Grant intrusive breccia, southern Illinois.

[Footnotes appear on facing page]

Temperature (°C)	Radiogenic ^{40}Ar(2)	K-derived ^{39}Ar(2)	$^{40}Ar_K/^{39}Ar_K$(3)	^{39}Ar/^{37}Ar(4)	Radiogenic yield (%)	Percent ^{39}Ar	Apparent age and error[5] (Ma)
PPib-Grant 1; AMPHIBOLE							
Total-gas date: 270.6±0.7 Ma; plateau date: 272.1±0.7 Ma (1,050°–1,150°C); J=0.010257±.25; wt = 189.8 mg							
500	0.1485	0.0156	9.51	0.55	13.6	0.2	168±3
600	0.3825	0.0283	13.51	0.11	43.6	0.4	234±3
700	1.2955	0.0872	14.86	0.09	57.7	1.4	255.9±1.0
750	1.2195	0.0784	15.56	0.1	85.9	1.2	267.1±1.0
800	2.4919	0.1592	15.66	3.2	92.7	2.5	268.6±0.8
850	1.7180	0.1108	15.51	4.3	96.3	1.7	266.4±1.2
900	2.0717	0.1336	15.50	3.0	96.9	2.1	266.2±0.9
950	4.0623	0.2597	15.64	0.76	97.8	4.1	268.5±0.7
1,000	31.750	2.0110	15.79	0.51	98.8	31.7	270.8±0.7
1,050[P]	31.210	1.9646	15.89	0.48	99.6	30.9	272.3±0.7
1,075[P]	10.968	0.6933	15.82	0.47	99.2	10.9	271.3±0.7
1,100[P]	6.3323	0.3975	15.93	0.40	99.4	6.3	273.0±0.7
1,150[P]	5.3005	0.3324	15.95	0.31	99.1	5.2	273.3±0.7
1,250	0.7156	0.0458	15.62	0.27	84.3	0.7	268±4
1,450	0.5294	0.0333	15.90	0.33	77.1	0.5	273±3
PPib-Grant 1; PHLOGOPITE							
Total-gas date: 272.3±0.8 Ma; plateau date: 272.7±0.7 Ma (700°–1,150°C); J = 0.010216±.25; wt = 45.2 mg							
500	0.0553	0.0073	7.58	4.9	21.3	0.1	134±15
600	0.3538	0.0251	14.12	0.78	88.8	0.5	243±3
650	0.8339	0.0529	15.77	1.8	67.1	1.1	269±2
700[P]	2.3073	0.1440	16.02	37	95.2	2.9	273.5±1.0
750[P]	4.2363	0.2654	15.96	265	98.1	5.4	272.5±0.7
800[P]	6.0702	0.3799	15.98	365	98.2	7.7	272.8±0.7
850[P]	7.0805	0.4430	15.99	404	97.6	9.0	273.0±0.7
900[P]	7.7166	0.4834	15.96	418	97.5	9.8	272.5±0.7
950[P]	7.0009	0.4397	15.92	380	97.9	8.9	271.9±0.7
1,000[P]	7.4618	0.4676	15.96	589	98.0	9.5	272.4±0.7
1,050[P]	11.875	0.7447	15.95	792	98.2	15.1	272.3±0.7
1,150[P]	23.476	1.4671	16.00	689	99.1	29.7	273.1±0.7
1,300	0.3227	0.0210	15.34	90	68.0	0.4	263±3

ancient magnetic pole position at a geologic instant when a thermoremanent magnetization is acquired upon cooling. Such pole positions are termed virtual geomagnetic poles, as distinct from paleomagnetic poles that are meant to represent geographic north after the short-term variations in magnetic field directions have been averaged out. When it is shown that magnetization is acquired during cooling of clasts in an igneous conglomerate or breccia, and that later magnetic overprints are lacking, the coherency of remanent directions provides clues to the cooling history (Hoblitt and Kellogg, 1979). If cooling takes place after emplacement of all the clasts, then directions of thermoremanent magnetization should be similar. At the other extreme, cooling of clasts, for example in the chimney of a diatreme, followed by emplacement will randomize directions. Paleomagnetic methods can also be used to recognize deposits in which, before emplacement, the clasts cooled within the higher range of temperatures over which remanent magnetization is acquired, but then came to rest at a lower but still elevated temperature for the remainder of their cooling. In such cases, thermal demagnetization at low temperatures would uncover coherent remanent directions and would reveal random directions at higher temperatures (still less than the maximum blocking temperatures of the included magnetic minerals). A similar condition might arise if rocks with randomized directions are subjected to low- to moderate-temperature thermal events to produce partial thermoviscous remanence. It is clear from these concepts that magnetic minerals and their origins must be identified to interpret paleomagnetic results.

The mineralogic and geochemical composition of the Grant breccia indicates an association with deep-seated alkalic igneous activity (Bradbury and Baxter, 1992). The breccia consists of a calcite-dolomite matrix with fragments

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[1] 1- to 3-mm size grains of brownish mica and amphibole were hand-picked from a sample of the Grant intrusive breccia. Based on microprobe analysis and petrographic characterization, the amphibole is richterite-riebeckite and the mica is phlogopite. Both samples were cleaned in 1.5-percent HCl, reagent-grade ethanol, acetone, and deionized water in an ultrasonic bath, air dried, wrapped in aluminum packages, and sealed in silica vials along with monitor minerals prior to irradiation. Samples were irradiated in the TRIGA reactor at the U.S. Geological Survey in Denver, Colo., for 40 hours at 1 megawatt.

[2] A Mass Analyzer Products 215 rare gas mass spectrometer with a Faraday cup was used to measure argon isotope abundances. Abundances of "Radiogenic ^{40}Ar" and "K-derived ^{39}Ar" are reported in volts. Conversion to moles can be made using 1.838×10^{-12} moles argon per volt of signal. Detection limit at the time of this experiment was 2×10^{-17} moles argon. Analytical data for "Radiogenic ^{40}Ar" and "K-derived ^{39}Ar" are calculated to 5 decimal places; "$^{40}Ar_R/^{39}Ar_K$" is calculated to 3 decimal places. "Radiogenic ^{40}Ar," "K-derived ^{39}Ar," and "$^{40}Ar_R/^{39}Ar_K$" are rounded to significant figures using analytical precisions. Apparent ages and associated errors were calculated from unrounded analytical data and then each was rounded using associated errors. All analyses were done in the Argon Laboratory, U.S. Geological Survey, Denver, Colo. Decay constants are those of Steiger and Jäger (1977), i.e., $\lambda_\varepsilon=0.581\times10^{-10}$/yr, $\lambda_\beta=4.962\times10^{-10}$/yr, and $\lambda=\lambda_\varepsilon+\lambda_\beta=5.543\times10^{-10}$/yr. The irradiation monitor, hornblende MMhb-1 with percent K=1.555, $^{40}Ar_R=1.624\times10^{-9}$ mole/g, and K-Ar age = 520.4 Ma (Samson and Alexander, 1987), was used to calculate J values for this experiment.

[3] "$^{40}Ar_R/^{39}Ar_K$" has been corrected for all interfering isotopes including atmospheric argon. Mass discrimination in our mass spectrometer was determined by measuring the ^{40}Ar/^{36}Ar ratio of atmospheric argon; our measured value is 298.9 during the period of this experiment; the accepted atmospheric ^{40}Ar/^{36}Ar ratio is 295.5. Abundances of interfering isotopes of argon from K and Ca were calculated from reactor production ratios determined by irradiating and analyzing pure CaF_2 and K_2SO_4 simultaneously with these samples. The measured production ratios for these samples are $(^{40}Ar/^{39}Ar)_K=1.181\times10^{-2}$, $(^{38}Ar/^{39}Ar)_K=1.302\times10^{-2}$, $(^{37}Ar/^{39}Ar)_K=1.74\times10^{-4}$, $(^{36}Ar/^{37}Ar)_{Ca}=2.61\times10^{-4}$, $(^{39}Ar/^{37}Ar)_{Ca}=8.25\times10^{-4}$, and $(^{38}Ar/^{37}Ar)_{Ca}=5.90\times10^{-5}$. Corrections were also made for additional interfering isotopes of argon produced from irradiation of chlorine using the method of Roddick (1983). The reproducibility of split gas fractions from each monitor (0.05–0.25 percent, 1 σ) was used to calculate imprecisions in J. J values for each sample were interpolated from adjacent monitors and have similar uncertainties to the monitors. Uncertainties in calculations for the date of individual steps in a spectrum were calculated using modified equations of Dalrymple and others (1981).

[4] To calculate apparent K/Ca ratios, divide the ^{39}Ar/^{37}Ar ratio value by 2.

[5] 1 σ error.

[P] Fraction included in plateau date.

and crystals of biotite and amphibole that are 1 cm or more across, clasts of various igneous and sedimentary rocks, and lesser amounts of apatite and pyroxene. Fragments of feldspathic rocks and grains of both phlogopite and amphibole are commonly surrounded by "lapilli" rims that are interpreted to represent crystallized melt. These clasts and grains thus existed within the magma at depth before emplacement of the breccia. Many original fragments and grains have been replaced by serpentine and carbonate, mainly dolomite. The relatively high contents of titanium (2.15 percent), Zn, and Sr are characteristic of rocks in alkalic provinces (Heinrich, 1966; Erickson and Blade, 1963).

The lamprophyric Downeys Bluff sill (Baxter and others, 1989) was selected for paleomagnetic comparison to the Grant breccia because (1) it likely contained thermoremanent magnetization; (2) it is located in nearly undeformed strata close to Hicks dome; and (3) its Permian isotopic date is close to the K-Ar date from the Grant breccia (Zartman and others, 1967). The Downeys Bluff sill yields an apparent age of about 275±24 Ma by the Rb-Sr method when recalculated from Zartman and others (1967) using post-1977 decay constants.

METHODS

For $^{40}Ar/^{39}Ar$ dating, mineral separates from a sample of the Grant breccia were obtained by a sequence of crushing, sieving, and hand picking. Mineral separates and neutron flux monitors were wrapped in aluminum foil, placed in quartz vials, and irradiated for 40 hours in the U.S. Geological Survey TRIGA reactor (table 1). The neutron flux was monitored using standards adjacent to each sample. The monitor used was hornblende MMHb-1, having an assigned K-Ar age of 520.4 Ma (Samson and Alexander, 1987; Alexander and others, 1978; Dalrymple and others, 1981). Measured argon isotopes of K_2SO_4 and CaF_2 included in the irradiated package were used to correct for interfering isotopes. The samples were heated in a double vacuum resistance furnace in a series of temperature steps for 20 min each to a maximum temperature of 1,450°C. At each step, the isotopes of ^{40}Ar, ^{39}Ar, ^{38}Ar, ^{37}Ar, and ^{36}Ar were measured using a mass spectrometer, and isotopic compositions were corrected for mass discrimination. The decay constants of Steiger and Jäger (1977) were used to calculate the apparent ages. The age plateaus were determined by inspection of contiguous gas fractions using the critical-value test of Dalrymple and Lanphere (1969).

Paleomagnetic measurements of specimens from oriented samples drilled from the outcrop were made using a cryogenic magnetometer, a 5-Hz spinner magnetometer, or a 90-Hz spinner magnetometer. After measurement of the natural remanent magnetization (NRM), each sample was demagnetized either in progressive alternating fields (AF)—typically in 10 steps from 5 mT to 80 mT peak induction—or by thermal techniques—typically in 8 steps from 100°C to 600°C. After we confirmed the presence of ferrimagnetic pyrrhotite in contact metamorphosed rock below the Downeys Bluff sill, two more samples were demagnetized with additional steps at 330°C and 360°C to better define the magnetization from pyrrhotite. Directions of remanent magnetization, listed in tables 2 and 3, were determined by least-squares line fitting of demagnetization decay paths (Zijderveld, 1967; Kirschvink, 1980). The identity of magnetic minerals was inferred from the magnetization lost in response to demagnetizing temperatures or alternating fields. Other, more direct methods for identifying magnetic minerals included thermomagnetic analysis and petrographic observation. Thermomagnetic analysis—the measurement of magnetization as a function of temperature—was used to identify magnetic minerals by measurement of their Curie temperatures. Magnetic iron oxide and iron sulfide minerals have diagnostic Curie temperatures and characteristic shapes of the thermomagnetic curve. Polished thin sections were examined in oil under reflected light at magnifications of as much as 1,000 ×. We examined six polished thin sections made from the end pieces of paleomagnetic samples. NRM directions and magnitudes along with magnetic susceptibility values are given in tables 2 and 3 because of their possible value for magnetic modeling of intrusions in the region. Magnetic susceptibility (MS) was measured using a frequency of about 600 Hz in an induction of 0.1 millitesla (mT).

RESULTS

GRANT INTRUSIVE BRECCIA

GEOCHRONOLOGY AND PALEOMAGNETISM

Concordant $^{40}Ar/^{39}Ar$ plateau dates for amphibole (272.1±0.7 [1σ] Ma) and phlogopite (272.7±0.7 [1σ] Ma) were obtained (fig. 3; table 1). Neither the amphibole nor the phlogopite age spectra show evidence for younger thermal disturbances above ≈550°C and ≈300°C (the amphibole and phlogopite argon closure temperatures, respectively). The concordance of the two dates indicates very rapid cooling from greater than about 550°C to less than 300°C.

Magnetic susceptibility varies greatly, from a low value of 6.9×10^{-4} to nearly 0.1 volume SI (table 2), reflecting the heterogeneous distribution of strongly magnetic fragments of igneous rock (see Bradbury and Baxter, 1992) that contain magnetic oxide minerals. NRM magnitude similarly varies by a factor of nearly 100. NRM directions scatter broadly with shallow to steep positive inclinations, suggesting variable degrees of overprinting in a normal polarity field (table 2). The downward component of magnetization is removed by both AF and thermal demagnetization in 10 of 15 specimens, isolating directions with south-southeast declination and nearly horizontal inclination (table 2; figs. 4*A*, 5). When uncovered by AF treatment, this direction is revealed over most of the demagnetization trajectory, although some specimens become unstable above the 60-mT step. With a few exceptions (fig. 4*B*), thermal demagnetization reveals the southerly, shallow direction in

Table 2. Summary of paleomagnetic results, Grant intrusive breccia, Hicks dome, southern Illinois.

[D_n, declination in degrees clockwise from true north; I_n, inclination in degrees, positive downward; M, magnitude (amperes/meter) of natural remanent magnetization; MS, magnetic susceptibility, in volume SI; Demag, demagnetization method (T, thermal; A, alternating field); Range, demagnetization range over which declination (D) and inclination (I) was calculated by principal component analysis (in degrees Celsius for thermal results, in milliTeslas for alternating-field results); ORG, origin of orthogonal demagnetization plot. $Range_P$, D_P, I_P ; demagnetization range, D, I of inferred late Paleozoic components. $Range_T$, D_T, I_T, demagnetization range, D, I of inferred remagnetization components. NRM, natural remanent magnetization]

Specimen (P0-7-)	D_n	I_n	M	MS	Demag	$Range_P$	D_P	I_P	$Range_T$	D_T	I_T
1B	26.9	72.8	3.35×10^{-2}	1.90×10^{-3}	A				NRM-30	34.1	73.8
2	277.2	71.0	1.55×10^{-1}	1.76×10^{-2}	T				500–600	139.0	–58.8
3A	197.7	11.4	9.58×10^{-2}	9.72×10^{-2}	T	400–600	164.2	–14.7			
						100–400	337.3	9.6			
3B	146.3	50.6	4.20×10^{-2}	4.42×10^{-3}	A	15–40; ORG	163.0	–4.8			
4A	0.7	53.4	1.53×10^{-1}	1.29×10^{-2}	T				100–600	315.4	32.9
4B	150.0	45.1	1.58×10^{-2}	1.09×10^{-3}	A	20–40	174.4	–2.5			
5A	58.4	74.1	1.07×10^{-2}	7.30×10^{-4}	T	400–550	165.8	–22.4	NRM-400	17.7	64.2
									550–660	152.5	–63.6
5B	48.3	28.0	5.80×10^{-1}	1.03×10^{-2}	A				5-ORG	70.2	67.2
6A	314.4	63.9	6.96×10^{-3}	6.91×10^{-4}	T				100–400	3.6	72.2
6B	335.4	66.0	9.71×10^{-3}	7.43×10^{-4}	T	500–600	156.3	–13.3			
7A	244.1	67.8	1.14×10^{-2}	1.15×10^{-3}	T	400–550; ORG	193.2	2.9	550–660	187.6	–72.5
8B	167.7	24.7	3.55×10^{-2}	1.33×10^{-3}	A	15–40	164.3	–10.7			
10A	191.6	15.7	8.28×10^{-2}	1.96×10^{-3}	T	400–600	173.8	–4.1			
10B	202.7	33.9	4.76×10^{-2}	1.70×10^{-3}	A	15–40	160.5	–1.3			
10C	292.9	10.8	2.52×10^{-2}	6.51×10^{-3}	T	400–600	165.6	4.0			
						100–300	333.0	11.0			

Table 3. Summary of paleomagnetic results, Downeys Bluff sill.

[Sp., specimen number; S, sill; B, baked sedimentary rock. Range, demagnetization range over which declination (D) and inclination (I) was calculated by principal component analysis (in degrees Celsius for thermal results, in milliTeslas for alternating-field results); ORG, origin of orthogonal demagnetization plot; T_{ub}, unblocking temperature. Other notations same as in table 2]

Sp. (P0-6-)	Rock type	D_n	I_n	M	MS	Demag	Range	D	I	Range high T_{ub}	D high T_{ub}	I high T_{ub}
1B	S	151.9	19.3	1.63×10^{-1}	1.13×10^{-2}	A	20–ORG	167.4	–16.6			
3A	S	95.6	59.5	8.40×10^{-1}	1.55×10^{-2}	T	400–ORG	146.6	16.8			
3B	S	84.5	57.1	8.17	2.01×10^{-2}	A	20–ORG	163.1	–1.1			
4A	S	98.2	35.5	6.99	1.12×10^{-1}	T	550–ORG	152.6	–9.9			
4B	S	100.8	34.1	5.41	1.09×10^{-1}	A	10–ORG	150.6	–15.0			
6A	S	111.9	32.6	2.97	8.76×10^{-2}	T	550–ORG	155.8	–7.9			
7A	S	100.7	32.8	5.57	5.71×10^{-2}	T	500–ORG	151.6	–4.7			
11A	S	81.0	–28.5	2.31	5.59×10^{-2}	T	550–ORG	149.7	–14.3			
13A	B	158.7	–12.2	3.72×10^{-2}	6.16×10^{-5}	T	200–400	157.7	–11.9	400–ORG	158.0	–14.3
14A	B	160.3	–12.4	3.34×10^{-2}	4.04×10^{-5}	T	100–360	161.5	–10.4	360–ORG	162.2	–15.2
15A	B	158.2	–13.6	5.45×10^{-2}	4.51×10^{-5}	T	200–400	158.5	–13.8	400–ORG	159.6	–14.7
16A	B	161.3	–12.9	1.07×10^{-1}	4.60×10^{-5}	T	200–400	160.0	–15.5	400–ORG	161.6	–15.7
16B	B	159.6	–14.7	5.62×10^{-2}	3.95×10^{-5}	A	20–ORG	159.3	–14.6			
17A	B	155.6	–21.3	6.10×10^{-2}	5.60×10^{-5}	T	200–400	156.1	–25.2	400–ORG	157.5	–18.4
19A	S	146.4	44.8	2.72×10^{-1}	3.12×10^{-2}	A	20–ORG	162.7	–10.3			
20B	S	106.9	45.2	2.37×10^{-1}	2.39×10^{-2}	T	550–ORG	154.8	–4.0			
21A	B	165.0	–13.3	4.92×10^{-2}	3.83×10^{-5}	A	20–ORG	164.8	–13.9			
22A	B	164.8	–11.0	8.85×10^{-2}	2.79×10^{-5}	T	200–360	164.8	–11.0	360–ORG	164.4	–12.4

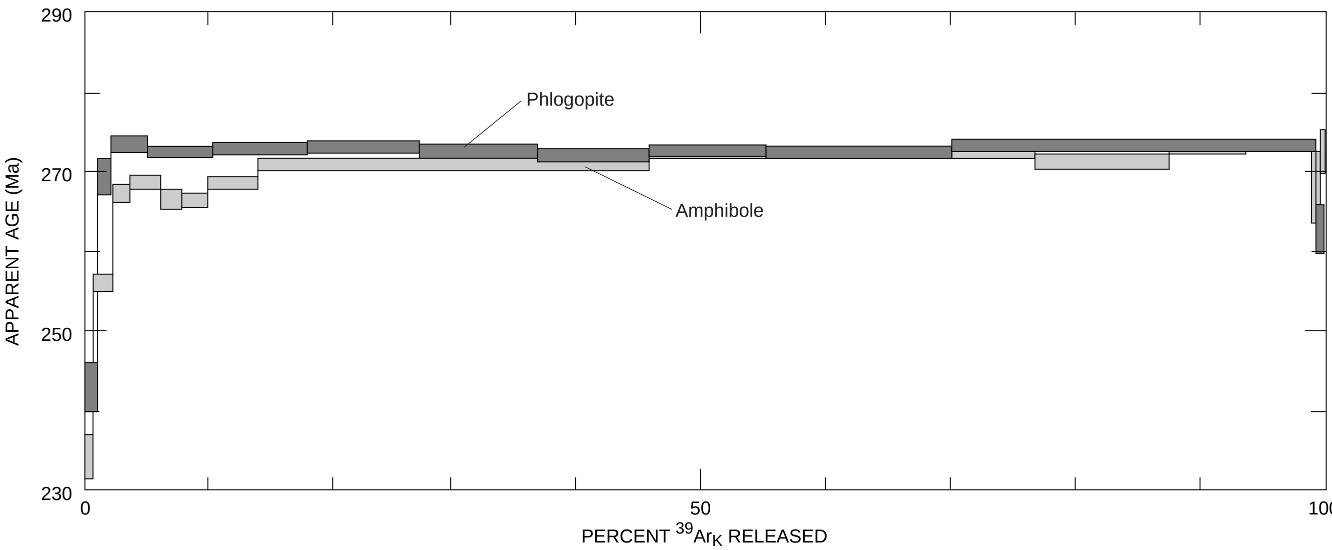

Figure 3. $^{40}Ar/^{39}Ar$ age spectrum for the Grant intrusive breccia. Plateau dates are 272.1±0.7 Ma for amphibole and 272.7±0.7 Ma for phlogopite.

more complicated demagnetization paths (fig. 4*D*) or in trajectories defined by only three heating steps (e.g., specimens 5A, 6B, 7A; table 2). Some specimens displayed erratic magnetizations after cooling from temperatures of 600°C probably because of spurious magnetizations acquired in small, ambient inductions by magnetite that formed from pyrite during heating. Curiously, two specimens (3A and 10C; fig. 4*D*; table 2) contained a magnetization, revealed over low unblocking temperatures (less than 400°C), nearly opposite to the southerly, shallow direction uncovered at higher unblocking temperatures.

The site-mean direction for the southeasterly magnetization, uncorrected for the attitude of the enclosing strata, is declination (D)=168.4°; inclination (I)=–8.0°; α_{95}=8.6˚; number of specimens (N)=10 (table 4; fig. 5). This direction yields a VGP at lat 54.8° N., long 119.0° E. (δp=4.4°, δm=8.7°). Specimens were given equal weight, including pairs from the same sample (samples P0-7-3 and -10) when one of the pair was treated by AF and the other by thermal demagnetization; thermally demagnetized specimen P0-7-10C was omitted from the calculation of the mean direction so that the mean does not include more than one specimen per sample for a given treatment. Correction for the tilt of the Fort Payne Formation (strike N. 54° W., dip 14° SW.) near the sampling locality yields a direction of D=166.0°; I=–17.2°; and a VGP at lat 58.6° N., long 119.0° E. (δp=4.6°, δm=8.9°).

In the other five specimens, steep inclinations prevailed through the demagnetization tests, probably the manifestation of remagnetization; the age of remagnetization is indeterminate and may encompass late Mesozoic to present-day magnetic fields. Cretaceous remagnetization of some specimens, particularly those with northwesterly or southeasterly declinations, cannot be ruled out. Moreover, three of the specimens having the southerly, shallow direction also contained distinct steep inclination components over different ranges of demagnetization treatment. Demagnetization isolates normal polarity directions (northerly, steep positive inclination not far from the present Earth-field direction) in three specimens and reversed polarity directions (southerly, steep negative inclination) in two specimens (fig. 5; table 2). One specimen (P0-7-5A) contains both components—a normal one from demagnetization to 400°C, and a reversed one between 550°C and 660°C. The isolation of the reversed direction over this temperature range, mostly above the 580°C Curie temperature of pure magnetite, indicates that hematite carries most of this magnetization. The reversed component may be related to chemical alteration during surficial weathering that formed hematite. The normal overprints isolated over low temperature ranges and low AF inductions are typical of viscous remanent components in magnetite.

MAGNETIC PETROLOGY

The demagnetization paths—the loss of magnetization with increasing temperature or AF induction—strongly suggests that magnetite is the main carrier of remanence, with minor contributions from hematite. In thermal demagnetization, most magnetization is removed by 550°C, just below the magnetite Curie temperature, and thus maximum blocking temperature, of 580°C. AF demagnetization to 80 mT removes nearly all remanence.

Magnetite is confirmed by petrographic observation and thermomagnetic results. The magnetite clearly contains or is associated with Ti, reflecting an igneous origin, and it is thus not a product of later diagenetic alteration. Many igneous rock fragments contain magnetite with ilmenite, either in composite grains or as intergrowths that resulted in the subdivision of magnetite by ilmenite lamellae (fig. 6). Magnetite is also commonly associated with TiO_2-rich alteration products, typical of high-temperature alteration during initial cooling. The magnetite has Curie temperatures of about 550°C (fig. 7), reflecting the presence of Ti in the magnetite in amounts that correspond to about 6 mol percent ulvospinel. Iron sulfide minerals (pyrite, marcasite, and chalcopyrite), some of which may have replaced magnetite, formed in the matrix and rock fragments after emplacement of the breccia.

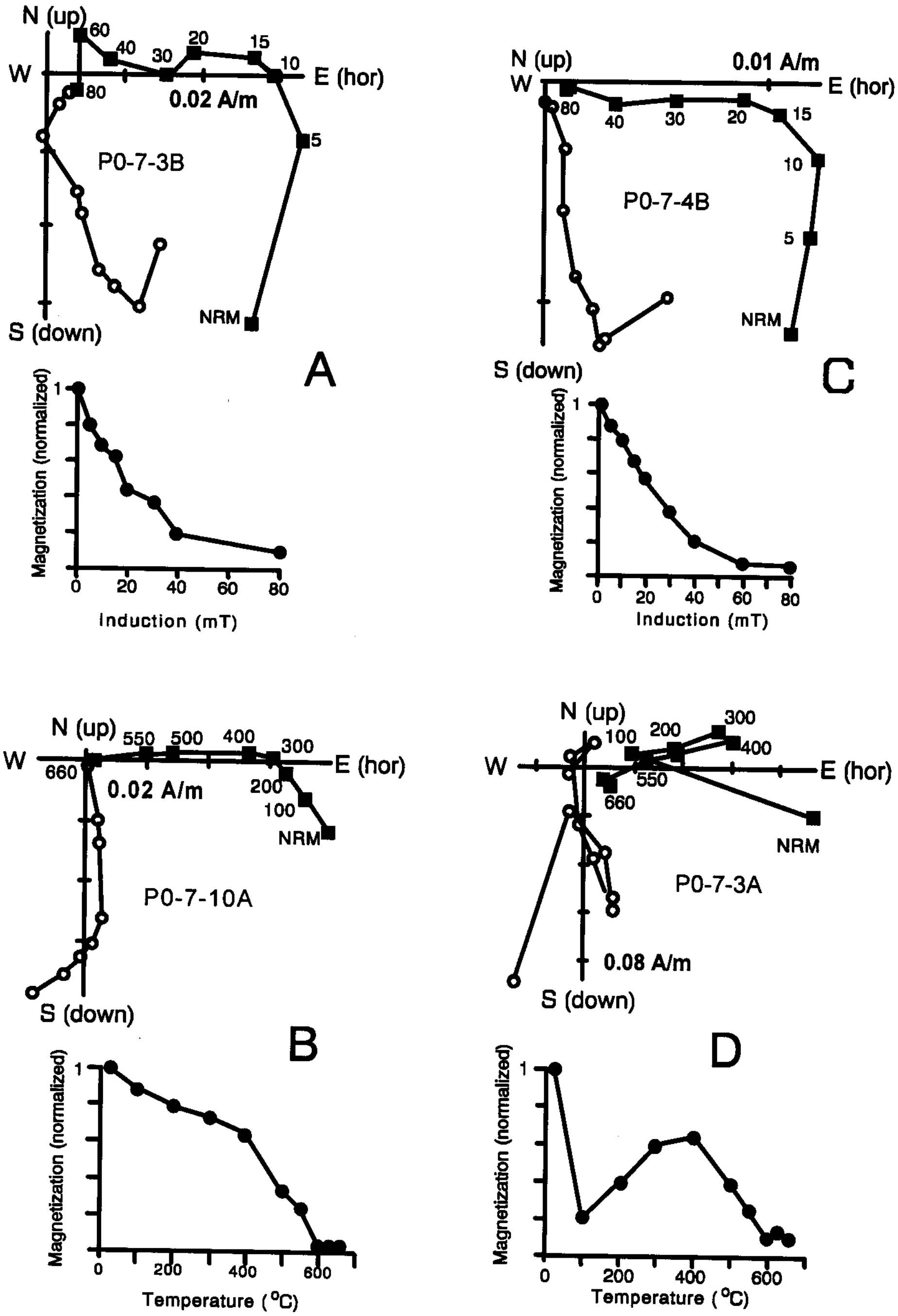

Figure 4. Demagnetization diagrams for specimens of the Grant breccia. The upper diagram in each set is an orthogonal demagnetization diagrams (Zijderveld, 1967) in which the closed symbols represent projections of the magnetic vector on the vertical plane, whereas the open symbols represent such projections on the horizontal plane. Remanent magnetizations are given in amperes/meter (A/m). Demagnetization levels are given in millitesla (mT) and degrees Celsius. The lower diagram in each set illustrates the decay of remanent magnetization, normalized to NRM, in response demagnetization induction or temperature.

DOWNEYS BLUFF SILL

PALEOMAGNETISM

Paleomagnetic samples from the site at the Downeys Bluff sill were taken from the intrusion and from the baked sedimentary rock of the Mississippian Downeys Bluff Limestone, within about 20 cm below the sill. Samples of the intrusion have high values of MS (0.02–0.1 volume SI) and NRM magnitude (0.2–8.2 A/m) (table 3). Samples of baked limestone have low MS values (about 4×10^{-5} volume SI) but moderately high values of NRM magnitude (0.03–0.1 A/m) approaching those of the sill (table 3). NRM directions from the sill plot in a diffuse band from the northeast to southeast, with shallow to moderate, mostly positive, inclination. In contrast, NRM directions from the baked limestone cluster tightly in the southeast with shallow negative inclination (table 3). At low inductions and temperatures, demagnetization of specimens from the sill removes northerly, downward components to isolate directions close to those of the NRM from the baked limestone (figs. 8*A*, 8*B*; table 3). Remanent directions of the baked limestone show minimal change in response to AF demagnetization, but most of the remanence is removed over the narrow temperature range between 300°C and 360°C. The small component of magnetization removed over higher unblocking temperatures has directions essentially identical to those removed between 300°C and 360°C (table 3). The site-mean direction, D=158.6°, I=–11.8° (α_{95}=3.8°, N=15) (table 3; fig. 5), that includes components from both the sill and baked limestone and that is uncorrected for the 2° or less dip of the beds, is statistically identical to the tilt-corrected direction of the Grant breccia. The direction from the sill plus baked limestone yields a VGP at lat 53.0° N., long 128.7° E.; (δp=2.0°, δm=3.9°). The magnetization direction from the baked limestone is close to the direction from another Mississippian limestone, the Salem Limestone at a site in Indiana, that was acquired through chemical alteration during Permian-Pennsylvanian time (fig. 5). These directions contrast with a magnetization direction calculated from a mostly Mississippian–Early Pennsylvanian pole position (fig. 5) (Van der Voo, 1990).

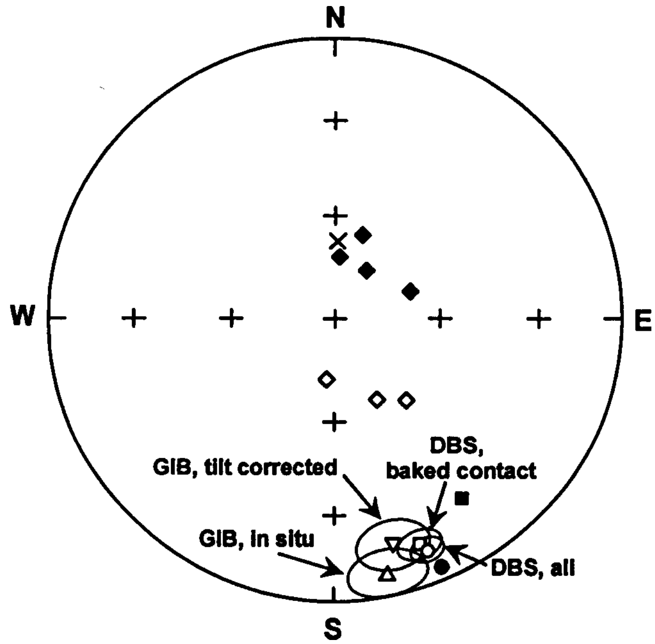

Figure 5. Equal-area plot of mean remanent directions from the Grant intrusion (GIB), the Downeys Bluff sill (DBS, all), and baked contact limestone (DBS, baked contact; the component carried by pyrrhotite). Solid symbols represent projections on the lower hemisphere. Open symbols represent projections on the upper hemisphere. Solid square, direction recalculated from early and middle Carboniferous paleomagnetic poles (Van der Voo, 1990) for geographic coordinates at Hicks dome. Solid circle, mean direction from the Mississippian Salem Limestone that carries a remagnetization direction acquired during the Permian-Pennsylvanian (from Van der Voo, 1989) recalculated for geographic coordinates at Hicks dome. Solid and open diamonds are inferred to represent respective normal and reversed polarity overprint components in specimens from the Grant intrusion. “X” represents present-day field direction at Hicks dome.

MAGNETIC PETROLOGY

The demagnetization behavior and petrologic results indicate that the sill and baked limestone have different magnetic minerals that, nevertheless, recorded the same geomagnetic field direction. In some specimens from the sill, demagnetization to 550°C eliminates all of the remanence, indicating titanomagnetite, but, in other specimens, remanence is not completely removed until the 630°C step (fig. 8*A*). These latter specimens do not show sharply defined maximum unblocking temperatures for magnetite or titanomagnetite, suggesting instead that thermally stable maghemite carries the remanence. However, a thermomagnetic curve for one such specimen (P0-6-11; figs. 8*A*, 9) defines a range of Curie temperatures between about 500°C and 540°C, indicative of titanomagnetite. Such inconsistency may reflect a heterogeneous distribution of magnetic oxides in the sill (the mass of the rock chip used for thermomagnetic analysis was about 10^{-4} that of the specimen). AF demagnetization of specimens from the sill show behavior consistent with the low coercivity of magnetite (fig. 8*C*). Petrographic evidence for Ti-bearing magnetite includes the common occurrence of titanium dioxide grains intergrown with magnetite (figs. 10*A*, 10*B*).

AF demagnetization of specimens from the baked limestone, in contrast, does not remove even half of the NRM magnitude by 60 mT, thus indicating a high coercivity magnetic mineral (fig. 8*D*). In thermal treatment, the loss of most remanence between 300°C and 360°C (fig. 8*C*) strongly suggested pyrrhotite as the dominant remanence carrier, an inference confirmed by petrographic examination. Insufficient amounts of pyrrhotite could be isolated to make a thermomagnetic analysis. Petrographic examination did not provide any clues to the origin (whether detrital or related to oxidation of sulfide minerals) of the small amount of iron oxide that carries a direction identical to that from pyrrhotite.

DISCUSSION AND CONCLUSIONS

The concordant $^{40}Ar/^{39}Ar$ plateau dates (272.1 and 272.7 Ma for amphibole and phlogopite, respectively) provide a straightforward interpretation that cooling of the Grant breccia through argon closure temperatures of about 550°C for amphibole and about 300°C for phlogopite occurred during the Permian. Because the amphibole and phlogopite cooling ages are identical within analytical error, cooling was essentially instantaneous; these apparent ages are likely identical to the age of emplacement. These results confirm the Permian age for the Grant intrusion. The $^{40}Ar/^{39}Ar$ results also indicate a lack of severe post-emplacement alteration at elevated temperatures, greater than about 300°C. Thus, a later, distinct igneous event associated with later fluorspar mineralization at Hicks dome is not indicated. Paleomagnetic results from thermal demagnetization indicate that the breccia was emplaced at high temperatures, at least 550°C.

Figure 6. Reflected-light photomicrograph of polished thin section of the Grant breccia. Phenocryst of magnetite (M, gray), partly replaced by hematite (H, white), showing evidence for the incipient development of ilmenite oxidation lamellae (IL). Field of view is 310 mm in the long dimension.

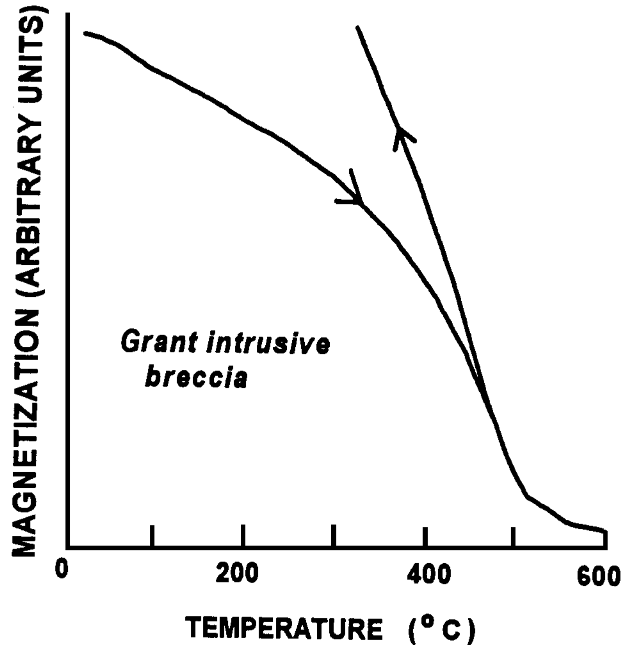

Figure 7. Thermomagnetic curve of a specimen of the Grant intrusion (sample P0-7-3) showing change in normalized magnetization as a function of heating and cooling. The decay of magnetization far below 580°C (the Curie temperature of pure magnetite) indicates the dominance of titanomagnetite in the specimen.

This conclusion is based on the observation that the characteristic southeasterly, shallow paleomagnetic direction was isolated in primary titanomagnetite at demagnetization temperatures to at least 550°C.

With regard to establishing the age of intrusion, the paleomagnetic results are not as definitive as the isotopic dates for several reasons. First, the VGP from any small intrusion represents only a spot recording of the ancient geomagnetic field, which at any moment (a few hundred to a few thousand years) may lie far from the average geomagnetic pole position that approximates the geographic pole throughout several thousand years to many millions of years. As seen in figure 11, the Grant breccia VGP lies close to the Early Triassic part of the APWP. For the reasons above, the lack of correspondence between the VGP's and the APWP is not unexpected and is within reasonable limits to be consistent with the Permian isotopic dates for both units. As an example, the present Earth field position lies nearly 20° of latitude from the geographic north pole (fig. 11).

The question about whether emplacement and cooling preceded or postdated tilting of Hicks dome, or took place during tilting, cannot be resolved from the paleomagnetic results because of the lack of other sites in rocks of equivalent age distributed in different fold limbs. After correcting the magnetization directions for the structural attitude of the Fort Payne Formation near the sampling locality, the VGP of the Grant intrusion moves to a position about midway between the Early Triassic and Middle Jurassic. This VGP position partly overlaps the two VGP's from the Downeys Bluff sill, one based on the pyrrhotite component and the other from all specimens (fig. 11). Whether or not the

Table 4. Paleomagnetic site-mean directions and virtual geomagnetic poles.

[DBS, Downeys Bluff sill; GIB, Grant intrusive breccia; Po comp (pyrrhotite component) based on thermal demagnetization of baked sedimentary rocks in steps to 360°C or 400°C; tilt correct, the resultant remanent directions and resulting pole position determined upon correction for the strike (N. 54° W.) and dip (14° S.) of strata that contain the breccia. N, number of specimens; D, mean declination, in degrees, clockwise from true north. I, mean inclination, in degrees, positive downward. α_{95}, semi-angle of the cone of 95 percent confidence in degrees. *k*, precision parameter (Fisher, 1953). R, resultant vector. Plat and Plong, latitude and longitude of the virtual geomagnetic pole (VGP). δp and δm, semi-minor and semi-major axes (in degrees), respectively, of the oval of 95 percent confidence surrounding the VGP]

Site	Selection	N	D	I	α_{95}	*k*	R	Plat (° N.)	Plong (° E.)	δp	δm
DBS	all data	15	158.6	–11.8	3.8	103.4	14.86	53.0	128.7	2.0	3.9
DBS	Po comp.	6	159.8	–14.6	5.2	167.8	5.97	54.8	128.1	2.7	5.3
GIB	in situ	9	168.4	–8.0	8.6	36.5	8.78	54.8	112.1	4.4	8.7
GIB	tilt correct		166.0	–17.2				58.6	119.0	4.6	8.9

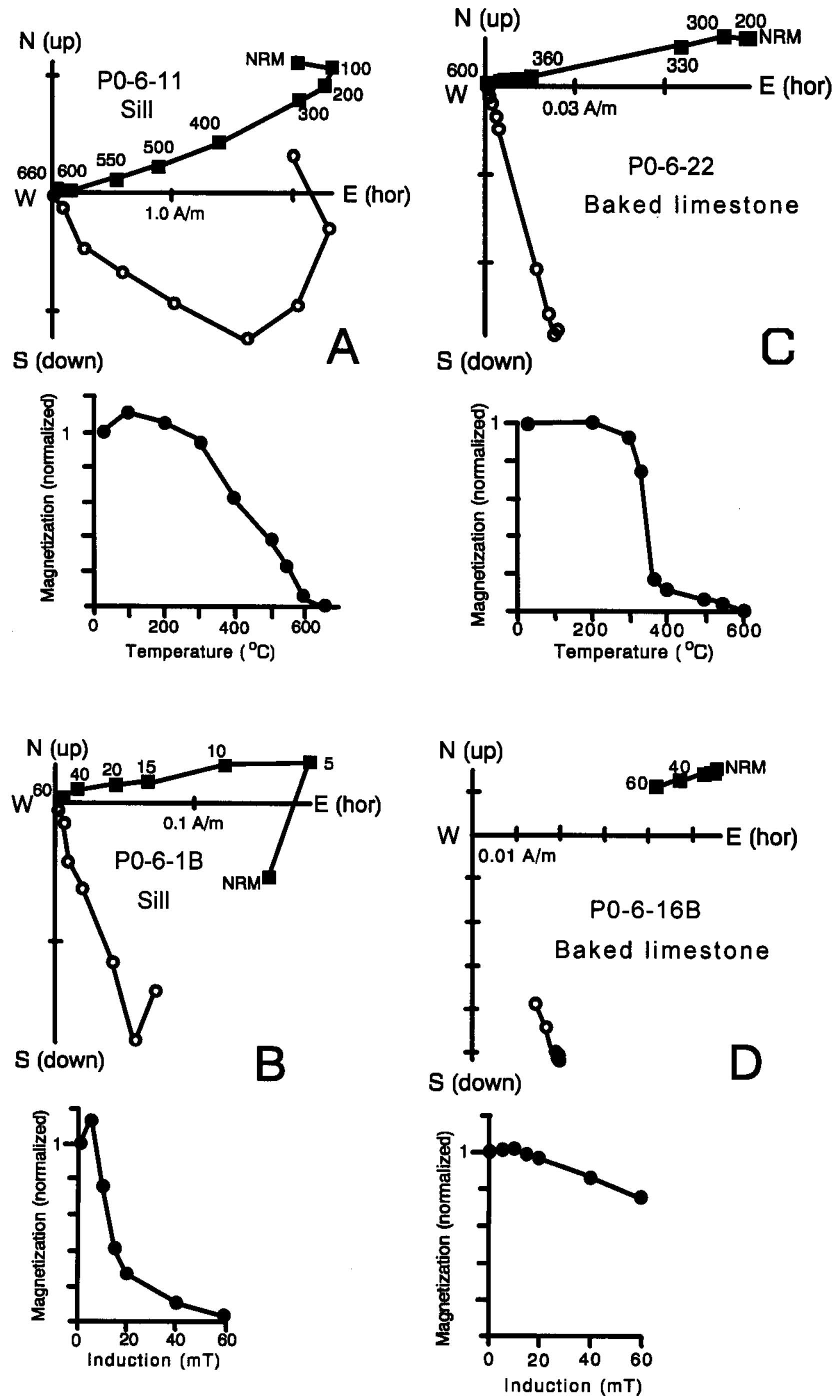

Figure 8. Demagnetization diagrams for specimens from the Downeys Bluff sill and baked limestone, as described for figure 4. Symbols as in figure 4.

VGP's are statistically equivalent is not at issue, inasmuch as several thousand to several million years may separate the cooling of the intrusions. That is, we cannot establish their temporal equivalence to the extent that would make such a comparison meaningful with respect to the timing of tilting at Hicks dome.

A major question addressed in this study is the timing of the igneous events in and near the study area relative to the timing of Fluorspar district mineralization. A number of lines of evidence are best reconciled with the interpretation that the fluorspar mineralization occurred during a geologically short time interval following the Permian igneous activity

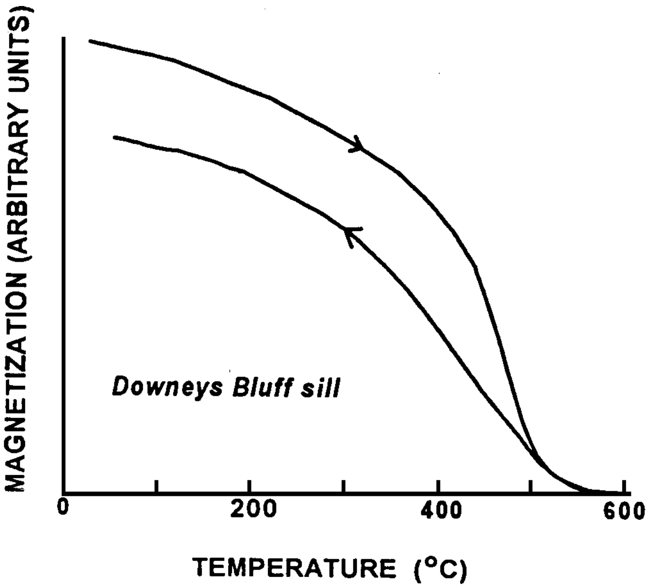

Figure 9. Thermomagnetic curve of a specimen from the Downeys Bluff sill (sample P0-6-11), indicating the presence of titanomagnetite.

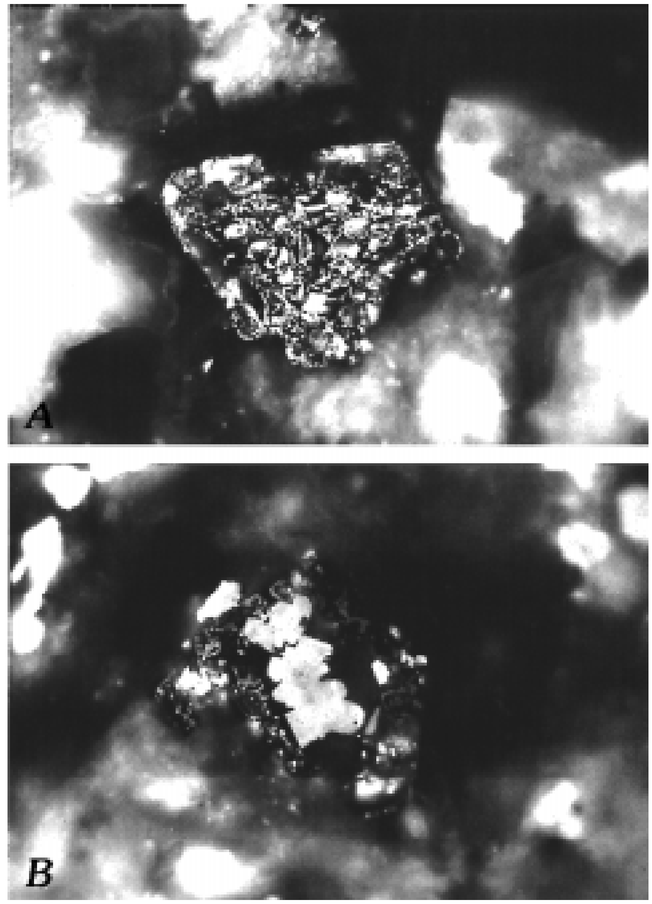

Figure 10. Reflected-light photomicrographs of polished thin sections, Downeys Bluff sill site. *A*, phenocryst of partly dissolved magnetite (gray), with concentration of TiO_2 near grain margins, from intrusion. *B*, Euhedral and subhedral clots of TiO_2 surrounded by relict magnetite in altered phenocrystic magnetite, from intrusion. Field of view is 160 µm in the long dimension in each photomicrograph.

responsible for both the intrusive breccias near Hicks dome and the other intrusive rocks of the area (fig. 1). The most persuasive evidence for this timing is the direct dating of fluorite using isotopes of Nd and Sm, which occur within the fluorite crystal lattice (Chesley and others, 1994, 1995). The studies by Chesley and others included samples that represent the range of fluorite paragenesis in the district. A well-defined 17-point isochron corresponding to an age of 277.0±15.6 Ma was determined. This age overlaps the $^{39}Ar/^{40}Ar$ ages from the Grant intrusive breccia reported here.

Additional lines of evidence for links between igneous activity and fluorspar mineralization are less direct. Fluid-inclusion filling temperatures associated with Fluorspar district mineralization have been interpreted to reflect a thermal zonation around Hicks dome (Taylor and others, 1992). Although this interpretation was questioned by Spry and Fuhrman (1993), a reevaluation of all available data (Taylor and others, 1995) confirms the existence of this zonation, suggesting that residual igneous heat affected fluorspar mineralization. Moreover, the possible involvement of magmatic volatiles in fluorspar mineralization is indicated from geochemical modeling (Plumlee and others, 1995) and the presence of magmatic volatiles in fluorite-hosted fluid inclusions from the district (Hofstra and others, 1995). Geochemical zonation around Hicks dome in mineral phases associated with Fluorspar district mineralization has also been recognized. High Sb contents characterize galena in the Illinois portion of the Fluorspar district near Hicks dome with systematically lower values with distance away from Hicks dome into Kentucky (Hall and Heyl, 1968). An expanded data set (Goldhaber and Mosier, unpub. data) further confirms this zonation. Likewise, a Pb isotope zonation around Hicks dome, reported first by Heyl and others (1966), has been confirmed by additional measurements (Goldhaber and Zartman, unpub. data). Zonation patterns of this type reflect an influence of Hicks dome on Fluorspar district mineralization.

Other attempts to date the Fluorspar district mineralization that yield ages other than Permian may be challenged on a variety of grounds. The 200-Ma age of Ruiz and others (1988) is a model age based on the questionable assumption that all Sr in fluorite was inherited from the biotite of igneous rocks. The 155-Ma paleomagnetic age of Symons (1994) may not represent a direct date on fluorite because the origin of the remanence carrier magnetite, whether coprecipitated with fluorite or formed later in microfractures, is unknown.

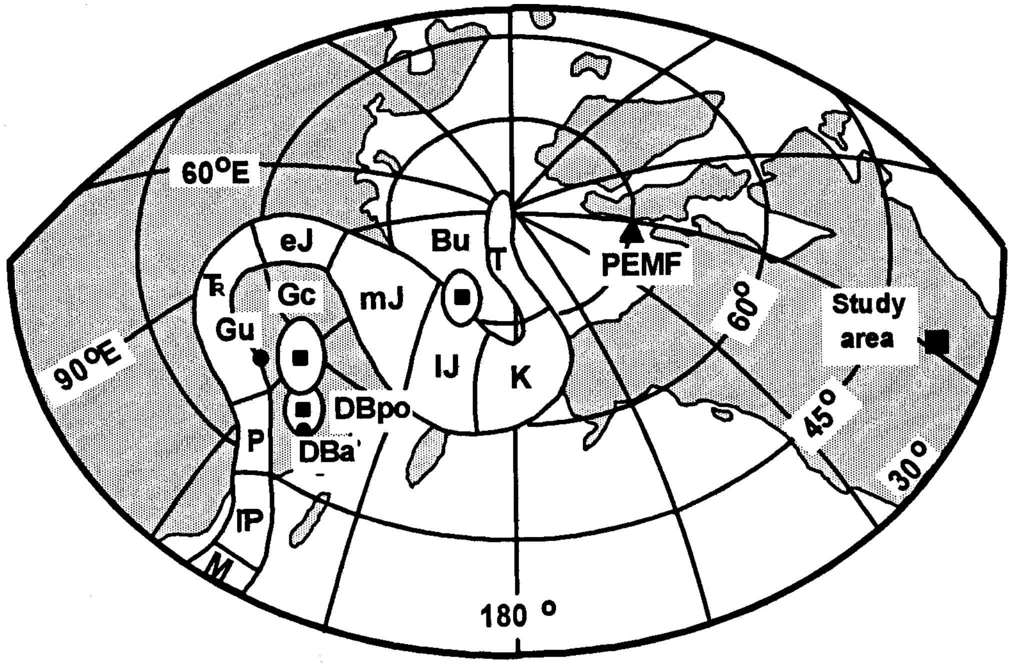

Figure 11. Apparent pole wander path for the North American craton from Symons (1994). Pole positions: Gu, Gc, Grant breccia—uncorrected and corrected, respectively—for structural attitude of nearby Paleozoic strata (see text); DBpo, Downeys Bluff sill location, pyrrhotite component from baked limestone; DBa, Downeys Bluff sill, all samples. Bu, pole from magnetite in fluorspar ore (Symons, 1994); PEMF, present Earth magnetic field. Ellipses of 95 percent confidence surround the Gc and DBpo poles. M, Mississippian; IP, Pennsylvanian; P, Permian; Tr, Triassic; eJ, Early Jurassic; mJ, Middle Jurassic; lJ, Late Jurassic; K, Cretaceous; T, Tertiary.

Another complication in paleomagnetic dating arises from uncertainty in the location of the APWP. Because of conflicting interpretations about the Middle and Late Jurassic APWP (reviewed by Van der Voo, 1992; Hagstrum, 1993; Courtillot and others, 1994; Symons, 1994), that part of the path was represented by Symons (1994) as a bulge, as shown in figure 11. The central issue is whether the path traces a low- or a high-latitude track between the Early Jurassic and Late Cretaceous. It is important to consider this uncertainty because the high-latitude paleomagnetic pole obtained by Symons (1994) from fluorite deposits (pole “Bu,” fig. 11) was attributed to magnetite presumed to have precipitated within fluorspar ore (Symons, 1994).

Interestingly, Brannon and others (1993) have recently used $^{238}U/^{206}Pb$ systematics to obtain an age of 156 Ma for late (post-mineralization) calcite in the Upper Mississippi Valley district at the north end of the Illinois Basin. This result contrasts with the Permian age of mineralization itself (Brannon and others, 1992). Brannon and others (1993) interpret the late calcite as having formed by meteoric water intrusion related to post-mineralization weathering events. The similarity between the calcite age and the one derived from paleomagnetic data from Fluorspar district mineralization raises the question as to whether the latter is related to post-mineralization incursion of meteoric water.

The results of this study (1) confirm a Permian age for the Grant intrusive breccia at Hicks dome, (2) indicate emplacement of the breccia at temperatures greater than 550°C, and (3) reveal the absence of later reheating above 300°C after rapid initial cooling. These results, complemented by additional information from the literature, closely link in time the mineralization in the Fluorspar district with igneous processes, including those identified from Hicks dome.

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