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Paleomagnetic dating of fracturing using breccia veins in Durness group carbonates, NW Scotland

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A R T I C L E I N F O

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A B S T R A C T

A paleomagnetic study of red fault-related breccia veins in the Cambro-Ordovician Durness Group in NW Scotland was conducted to determine the time of brecciation, the origin of the veins, and the nature and timing of associated fluid-related diagenetic alteration. The veins contain brecciated fragments of the host Durness Group and strike either east–west or north–south. Clasts of breccia cemented by calcite suggest multiple brecciation events. The host Durness Limestone is a gray dolomite and contains a Devonian chemical remanent magnetization (CRM) that resides in magnetite. The veins contain magnetizations that reside in hematite and are interpreted as CRMs. The breccias in north–south veins contain a Triassic CRM whereas the veins with east–west strikes contain a Jurassic CRM. Authigenic hematite is common in the breccias along growth planes in the calcite cements. The two CRMs within the veins are interpreted as dating two separate brecciation and fluid flow events that precipitated authigenic hematite. The brecciation and fluid flow events are interpreted to be related to extension in the Mesozoic which is consistent with the extensional history of the northern Atlantic margins.

1. Introduction

Clastic veins or breccias are becoming recognized in numerous geologic terranes (e.g., Wright et al., 2009; Wilson et al., 2010) and some contain sediment infills (e.g., Beacom et al., 1999). Most of these breccias are interpreted to be related to faulting (e.g., Woodcock et al., 2006) and they can also be sites for precipitation of hydrothermal minerals (e.g., Sibson, 1986). Determining the timing of movements on such faults is frequently problematic. Paleomagnetic analysis is one approach that can provide constraints on the timing of faulting events (e.g., Dulin et al., 2005).

Fault-related breccias occur in the Cambro-Ordovician Durness Group carbonates in northwest Scotland, adjacent to the Moine Thrust Zone (MTZ) (Wilson et al., 2010). These breccias cut through the carbonates of the Durness Group and display evidence that they were conduits for the migration of fluids that caused diagenetic alteration (e.g., hematite authigenesis, calcite cementation). Understanding the origin and timing of these breccias is important because it may provide clues to the timing of faulting and the structural history of the Durness Group rocks west of the MTZ. In addition, determining the nature and timing of the diagenetic alteration in the veins should provide information on fluid migration pathways and possible connections between the fluids and orogenic or other geological events.

The major objective of this paper is to date the brecciation by determining the timing of fluid-related diagenetic alteration in the fault-related breccias in the Cambro-Ordovician Durness Group near Durness, Scotland (Fig. 1). Another objective is to test if the faults and breccias were conduits for fluids as has been reported for the MTZ (Parnell et al., 2003; Blumstein et al., 2005) and other faults in Scotland (Elmore et al., 2002, 2006). Paleomagnetic data is used to date the migration events. Petrographic and geochemical studies are used to determine the nature and origin of alteration produced by the fluids.

2. Geologic history

The MTZ in the Highlands of Scotland extends from the Isle of Skye to the Durness area in northwest Scotland (Fig. 1). Cambro-Ordovician clastic and carbonate rocks in northwest Scotland unconformably overlie Archean Lewisian gneisses and Proterozoic Torridonian sandstones. The Cambrian Eriboll Group is at the base and consists primarily of quartz-cemented marine quartzarenites. These deposits are overlain by the Durness Group, a thick Lower Cambrian to Lower Ordovician carbonate sequence that was deposited on the shallow passive Laurentian continental margin of the Iapetus Ocean.

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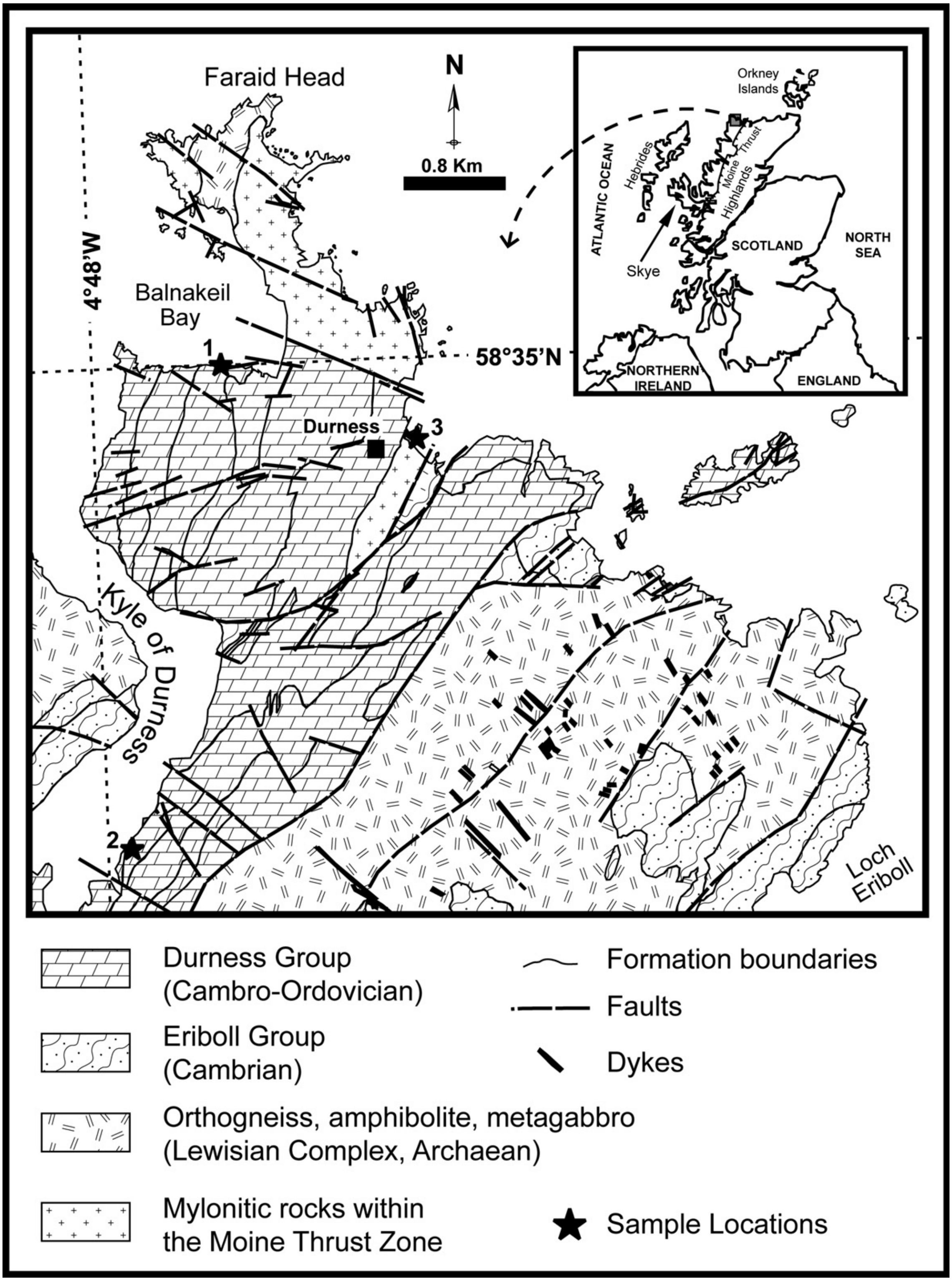


Fig. 1. Geologic map of study area in northwest Scotland showing the major geologic units and faults to the west of the Moine Thrust Zone. The Moine thrust is located to the east of the map area. Inset map shows the location of the study area in Scotland. Stars are sampling locations (1: Balnakeil; 2: A838 Road; 3: Durness beach). Modified from British Geological Survey (2002) map.

In the mid to late Ordovician an island arc collided with northern Scotland which deformed the Durness Group during this early Caledonian collision (Dalziel and Soper, 2001). During the Silurian and early Devonian Baltica collided with Avalonia and they subsequently collided with Laurentia (Torsvik and Rehnstrom, 2003) producing the MTZ where Proterozoic metasedimentary rocks of the Caledonian belt were carried over the foreland sequence of the Lewisian complex, Torridonian sandstones, and the Cambro-Ordovician shelf carbonates (Coward, 1988). The MTZ (Peach et al., 1907) consists of centimeter to kilometer scale thrusts and folds with the deformation occurring in the late Silurian-early Devonian (Elliott and Johnson, 1980). The rocks in the MTZ have been subjected to low-grade metamorphism (Johnson et al., 1985).

The MTZ is located to the east of Durness and Loch Eriboll. In the Durness area (Fig. 1), faults have down-thrown rocks of the overlying Moine Nappe to form the Durness and Faraid outliers (Holdsworth et al., 2006, 2007). In the Devonian, extensional faulting along with magmatic and volcanic activity occurred in Scotland (Butler and Coward, 1984; Serranne, 1992). Early Permian rifting in the North Atlantic involved siliciclastic sedimentation in extensional basins and widespread extrusive and intrusive magmatic activity (Francis, 1991; Hitchen et al., 1995). Normal faults developed in the hanging wall of Caledonian thrusts (Coward et al., 1989), suggesting the thrust zones were reactivated during the Permian extension (Hitchen et al., 1995). The normal fault-bounded basins were part of the initial stages of the breakup of Pangea and the opening of the Atlantic (Hitchen et al., 1995). Wilson et al. (2010) hypothesized that faulting occurred in the Mesozoic and describe examples of 'red breccias' associated with the faults in the Durness area. The major rift associated with opening of the Atlantic eventually developed west of Scotland (present orientation) in the Tertiary. In the Tertiary, a large igneous complex and associated dike swarm was intruded (55 Ma; Dagley et al., 1990) on the Isle of Skye.

Previous workers have attributed the regional SE dip (~10°) of the lower Paleozoic strata in NW Scotland to flexure because of thrust sheet loading (e.g., Soper and Barber, 1982) or to post-Caledonian tilting (Butler and Coward, 1984). Some studies point out that there is evidence for post-Mesozoic exhumation and tilting in NW Scotland that is probably related to Tertiary underplating associated with the proto-Iceland plume (e.g., Wilson et al., 2010).

Three localities were sampled in northwest Scotland (Fig. 1). Most samples of breccias (matrix and clasts) and host rock were collected in a fault zone with an east–west trend at Balnakeil, west of Durness (Figs. 1 and 2A, B). Here the host Durness Group consists of dark gray fractured crystalline dolomite (Fig. 2A). The breccias extend for over 100 m (Fig. 2A) and range from several cm up to ~25 cm in width (Fig. 2B). Some of the breccia clasts were large enough to be sampled. The breccias are red and contain clasts of the Durness Group carbonates that range from sand size up to ~20 cm (Fig. 2B). The contacts between the red breccias and the host dolomites are relatively sharp although red staining occurs in some thin fractures which extend away from the main fractures. Clasts composed of breccia are found in some breccias, suggesting multiple brecciation events.

Samples were also collected along the road (A838) south of Durness next to the Kyle of Durness (Figs. 1 and 2C, D). The host Durness is a gray dolomite that is not as fractured as at Balnakeil. The breccias here are not as defined as at Balnakeil but they have an orientation that is approximately north–south. The samples include clasts and matrix; individual clasts were too small to sample. Two sites were also collected in a dolomitized breccia from the Durness outlier (e.g., Holdsworth et al., 2006) along a fault in the intertidal zone on the beach in Durness (Fig. 1).

3. Methods

Twenty paleomagnetic sites (~8 cores per site) were sampled at the three localities (Fig. 1). Samples were collected from the host Durness Group around the veins for contact tests at Balnakeil and the Durness road location to determine if a remagnetization is localized in the veins. The cores were collected with a portable gasoline drill and oriented with an inclinometer and Brunton compass.

The natural remanent magnetization (NRM) of standard paleomagnetic samples (2.2 cm) was measured using a 2G-Enterprises cryogenic magnetometer in a magnetically shielded room. Most

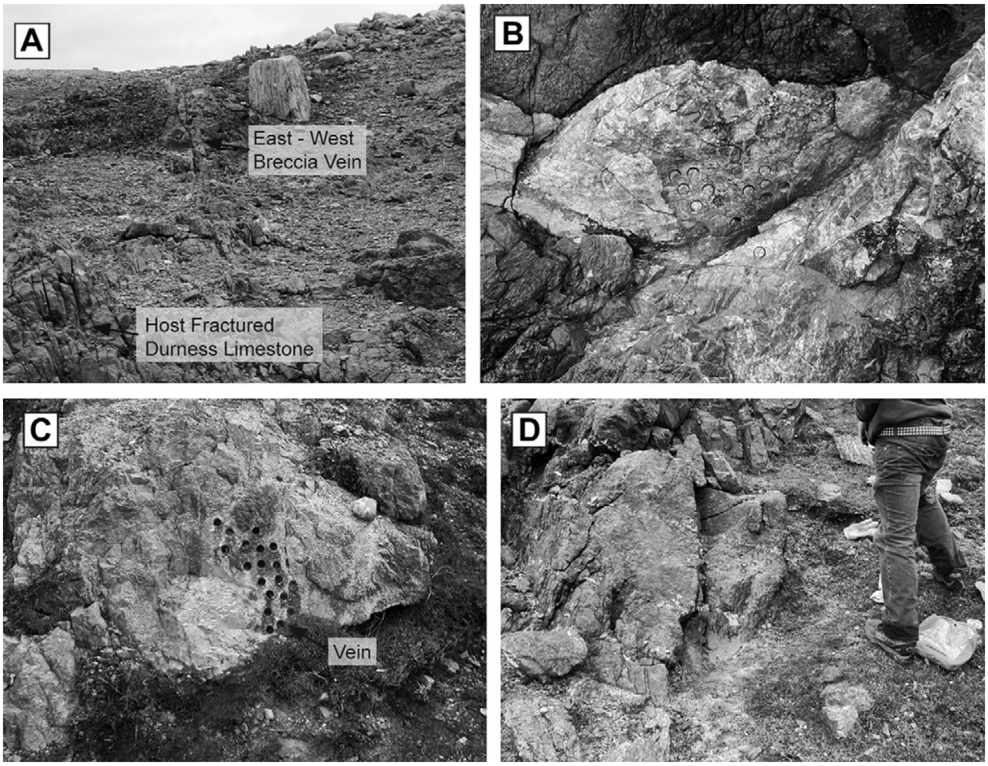


Fig. 2. Photographs of the breccias and associated rocks. A) A breccia vein in the center of the photograph at the Balnakeil location. The vein is ~20 cm thick. B) Close up of a breccia vein at Balnakeil. The core holes are one inch in diameter. C) A breccia vein along the Kyle of Durness south of Durness. The drill holes are in the vein. D) The host Durness Group from along the Kyle of Durness. Note white chert lenses which define the bedding.

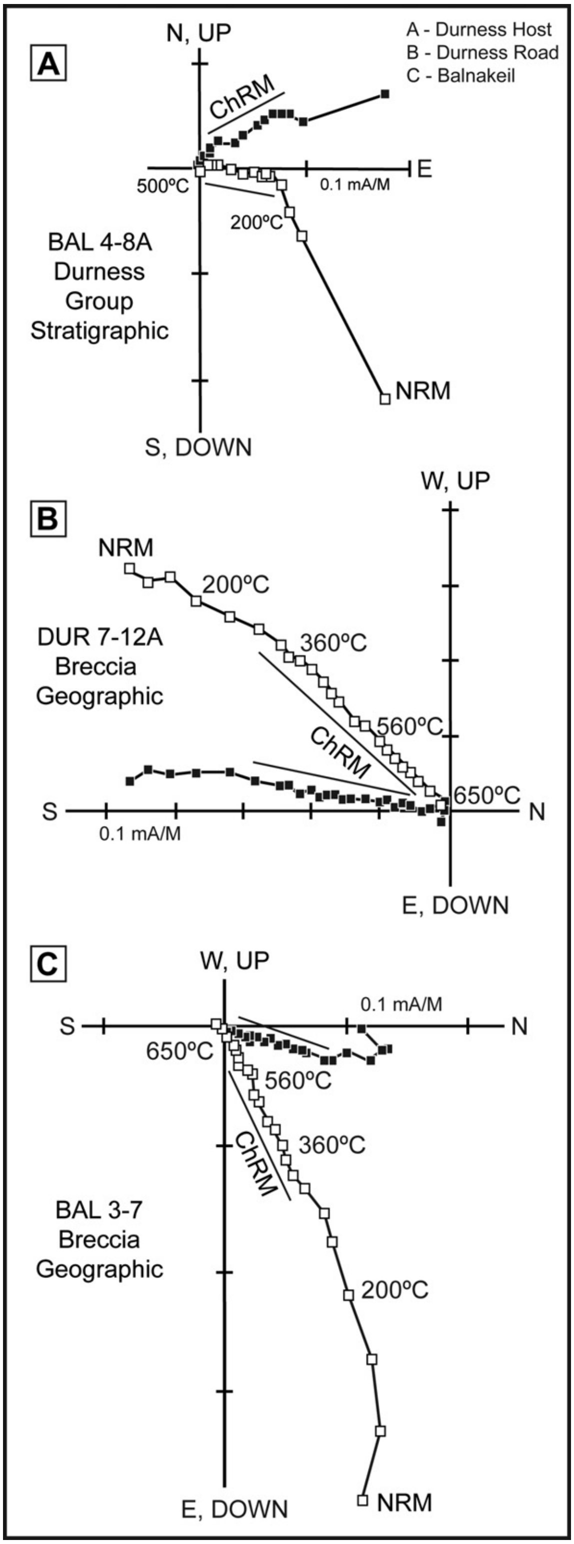


Fig. 3. Orthogonal projection diagrams (Zijderveld, 1967) of representative stepwise thermal demagnetizations of specimens. Open symbols represent vertical projections, solid symbols represent horizontal projections. The ChRMs are shown by lines next to the demagnetization steps on the diagrams. (A) Specimen of the host dolomite showing removal of ChRM1 during thermal demagnetization, (B) Specimen of the Durness dolomite from the Durness road location showing removal of ChRM2, (C) Specimen from a breccia at the Balnakeil location showing removal of ChRM3. Demagnetization steps were NRM, 100°, 200°, 250°, 275°, 20° steps from 300 to 600° and 25 °C from 600 to 700.

specimens were subjected to stepwise thermal demagnetization in an ASC Scientific Thermal Specimen Demagnetizer in 24 steps between the NRM and 680 °C. A few specimens were subjected to stepwise alternating field (AF) demagnetization between the NRM and 100 mT in a 2G automated degausser. The demagnetization data was plotted on Zijderveld (1967) diagrams and components were calculated using principal component analysis (Kirschvink, 1980). Fisher (1953) statistics were used to calculate the site means.

Coercivity spectrum analysis (Kruiver et al., 2001; Heslop et al., 2004) was performed on eight representative specimens to identify the magnetic mineralogy. After AF treatment to 100 mT, an isothermal remanent magnetization (IRM) was imparted to representative specimens in 25 steps using an ASC Scientific Impulse Magnetizer. The LAP-GAP-SAP modeling was performed on the IRM acquisition data using the software of Kruiver et al. (2001).

Petrographic analysis was conducted by examining 30 thin sections in transmitted and reflected light to identify magnetic mineralogy and diagenetic phases. Stable isotope analyses were performed on 15 whole rock dolomite samples from the host Durness Group dolomite and from the breccia using the procedure of Rosenbaum and Sheppard (1986). The standard error in our laboratory for replicate analyses of a pure carbonate is ±0.03‰ ($\delta^{13}C$) and ±0.2‰ ($\delta^{18}O$).

4. Results and interpretations

4.1. Paleomagnetism

Thermal demagnetization at low temperatures (<200 °C) removes a northerly and steep down component in most specimens that is interpreted as the Modern viscous remanent magnetization (VRM) (Fig. 3A). At higher temperatures, three different characteristic remanent magnetizations (ChRMs) were removed (Fig. 3).

4.1.1. Host Durness Group – ChRM1

At temperatures between 300 °C and 500 °C, the host Durness Group dolomites at the Durness road locality contain a ChRM1 with northeasterly declinations and shallow inclinations (Figs. 3A and 4; Table 1). Most sites (5) in the host Durness Limestone collected away from the veins at Balnakeil contain weak magnetizations that are dominated by the Modern VRM. The ChRM1 appears to be present in some of these sites based on a poorly defined magnetization with northeasterly declinations and shallow inclinations but the mean angular deviation (MAD) angles for the principal components were >15°. Statistics were not calculated from these sites. The host Durness Group beds sampled at the Durness road location have similar strike and dips so a tilt test is not possible. The mean geographic (post-tilt) direction (declination [D] = 37.2°, inclination [I] = −8.3°, k [grouping] = 29.5, α_{95} = 23.1; Table 1), although not well constrained, corresponds to a pole position (135.9°E, 20.6°N, dp = 11.7°, dm = 23.4° [axes of the 95% oval around the mean pole]) which is close to the Devonian part of the apparent polar wander path (APWP) (Fig. 5). If the direction is corrected for a 10° regional tilt that is hypothesized to have been acquired in the Tertiary, the pole is similar (136.2°E, 21.8°N) and is close to the Devonian-Carboniferous part of the APWP.

The coercivity spectrum analysis (Kruiver et al., 2001) suggests that samples from the host Durness Limestone commonly contain two components (Fig. 6A–C). The dominant (~60%) component is low coercivity (~50–60 mT) and probably resides in magnetite. This is consistent with the demagnetization data which indicates the ChRM1 is removed below 580 °C, the Curie temperature for magnetite. A higher coercivity component (~40%) that probably resides in hematite is also present but it is not interpreted to carry ChRM1.

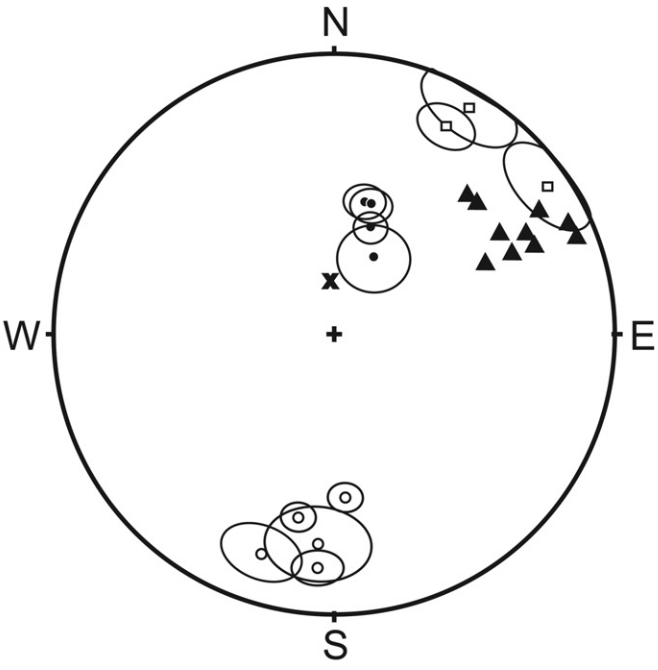


Fig. 4. Equal area projections of site means for ChRM1 (squares), ChRM2 (circles), and ChRM3 (filled circles) in geographic coordinates as well as specimen directions (triangles) from host dolomite sites at Balnakeil that have directions between ChRM1 and ChRM3. Open symbols represent negative inclinations and closed symbols represent positive inclinations. The circles around the site mean directions are the α_{95} values. The present field direction is shown by an 'x'.

4.1.2. Breccia – ChRM2

At temperatures between 200–300 °C and 650–680 °C, a ChRM2 with southerly declinations and moderate up (negative) inclinations is removed in breccia specimens from 5 sites at the Durness road locality. The AF treatment of breccia specimens did not remove the ChRM2. The specimens display linear decay up to 650–680 °C (Fig. 3B), suggesting that the ChRM resides in the hematite. One site from the Durness beach location (Dur12, Table 1) also contains a similar direction, although with a slightly steeper inclination (Table 1).

Table 1
Paleomagnetic data.

Site	Strike of veins	N/N_o	Dec_g (°)	Inc_g (°)	k	α_{95} (°)	Dec_s (°)	Inc_s (°)
Host (ChRM1)								
Dur2*		4/5	27.9	−14.9	156.5	7.4	28.1	6.5
Dur5		6/6	30.4	−4.5	33.9	11.7	30.0	1.9
Dur8		5/6	53.1	−4.9	34.3	13.3	50.4	−11.2
Mean – G		3/3	37.2	−8.3	29.5	23.1	–	–
Mean – S		3/3	36.5	2.7	26.9	24.2	–	–
Bal2#		8/8	47.0	22.7	45.6	8.3	53.9	16.6
Bal4#		6/7	63.4	19.2	118.7	6.2	67.6	8.4
Breccia								
Dur7	N–S	6/9	191.5	−34.0	266.7	4.1	206.0	−42.6
Dur12		8/8	176.6	−41.4	180.9	4.1	–	–
Dur4*	N–S	7/7	184.4	−17.5	94.8	6.2	190.9	−30.8
Dur6	N–S	6/6	199.0	−18.7	45.9	10.0	206.8	−27.5
Dur14	N–S	4/4	184.8	−25.3	49.5	13.2	194.4	−36.6
Dur (ChRM2) Mean		5/5	187.6	−27.6	41.6	12.0	195.5	−35.6
Bal1	E–W	8/8	15.6	49.6	100.9	5.5	40.2	51.4
Bal3	E–W	4/5	27.0	64.2	84.3	10.1	64.5	59.5
Bal5	E–W	3/3	18.2	56.3	701.5	4.7	48.8	56.1
BaL7	E–W	7/7	13.3	49.0	103.8	6.0	37.7	51.7
Bal (ChRM3) mean		4/4	18.1	54.9	110.6	8.8	46.9	55.1

N/N_o – Number of specimens with direction versus number of specimens demagnetized; Dec – Declination; Inc – Inclination; g – geographic direction; s – tilt corrected direction; k – Precision parameter; α_{95} – Cone of 95% confidence. #Not used in statistical analysis of mean. Strikes and dips (s/d) for host Durness sites are Dur2 – N44/20SE), Dur5 – N49/20SE, Dur8 –NN44E/20SE, BAL2 and BAL4 – N32E/20SE. The Dur breccia sites are in beds with s/d or N44E/20SE, the BAL breccias sites are in beds with an s/d of N32E/20SE. (*From Blumstein et al. (2005)).

Samples were collected from veins as well as from the host Durness Group away from the breccia veins for a contact test. Samples of the breccia contain ChRM2. Specimens from host Durness Group near the breccia generally contained weak magnetizations without a consistent decay pattern. The contact test at this locality is not conclusive.

The mean direction in geographic coordinates for the five breccia sites has southerly declinations and shallow inclinations ($D = 187.6°$, $I = -27.6°$, $k = 41.6$, $\alpha_{95} = 12.0°$; Table 1). The pole position (164.7°E, 45.7°N, dp = 7.2°, dm = 13.1°, $N = 5$) suggests that ChRM2 was acquired in the Triassic (Fig. 5). If the direction is corrected for a 10° regional tilt that is hypothesized to have been acquired in the Tertiary, the tilt-corrected pole (157.3°E, 48.6°N) is slightly younger but still Triassic.

Coercivity spectrum analysis suggest that the breccia samples are dominated by a high coercivity hematite component (~98%) and also contain a small magnetite component (<5%) (Fig. 6D–F). The small magnetite component probably resides in relatively unaltered clasts of the host Durness Group in the breccia.

4.1.3. Breccia – ChRM3

The breccia veins at Balnakeil contain ChRM3 (Fig. 2A) which have northeasterly declinations and steep down inclinations and is removed between 300 °C and 650 °C (Fig. 3C). The mean direction ($D = 18.1°$, $I = 54.9°$, $k = 110.6$, $\alpha_{95} = 8.8°$, geographic coordinates) is different from the Modern magnetic direction (5.1 W, 71.6 N) for the locality (Fig. 4). The pole position (140.0°E, 64.0°N, dp = 8.8°, dm = 12.5°, $N = 4$) suggests that ChRM3 was acquired in the Mesozoic, probably in the Jurassic (Fig. 5). If the direction is corrected for a 10° regional tilt that is hypothesized to have been acquired in the Tertiary, the tilt-corrected pole (116.8°E, 59.5°N) plots on the Jurassic part of the APWP.

The directions for ChRM2 and ChRM3 appear to be approximately antipodal and a reversal test (McFadden and McElhinny, 1990) was performed. The observed angle between the two directions (after rotation of one by 180°) is 28.35° whereas the critical angle where the two directions become significantly different at the 95% confidence level is 16.24°. Because the observed value is greater than the critical value, the reversal test fails. The two components are not antipodal and are interpreted to represent two distinct events.

Specimens from relatively large black to dark gray breccia clasts that were not noticeably red contain a magnetization that is weak and displays noisy decay after removal of the Modern VRM. A ChRM could not be identified in the clasts.

Samples were also collected from a breccia vein (Bal7) and from the host breccia away from the vein for a contact test. The vein contains a well defined ChRM3. The samples away from the vein contain weak and noisy magnetizations after removal of the Modern VRM. Two host sites from near the breccia veins (Bal2 and Bal4; Table 1), however, contain specimen directions between ChRM1 and ChRM3 (Fig. 4). These results suggest a vector addition between ChRM1 and CHRM3. Because of the possibility that the directions were contaminated, the means from these sites were not used in the calculation of the ChRM1 mean. These results suggest that ChRM3 is only locally present in the host rocks around the breccia veins.

As with ChRM2, coercivity spectrum analysis suggests that these breccia samples (3) are dominated by a high coercivity hematite component although a small magnetite component (<5%) is also present.

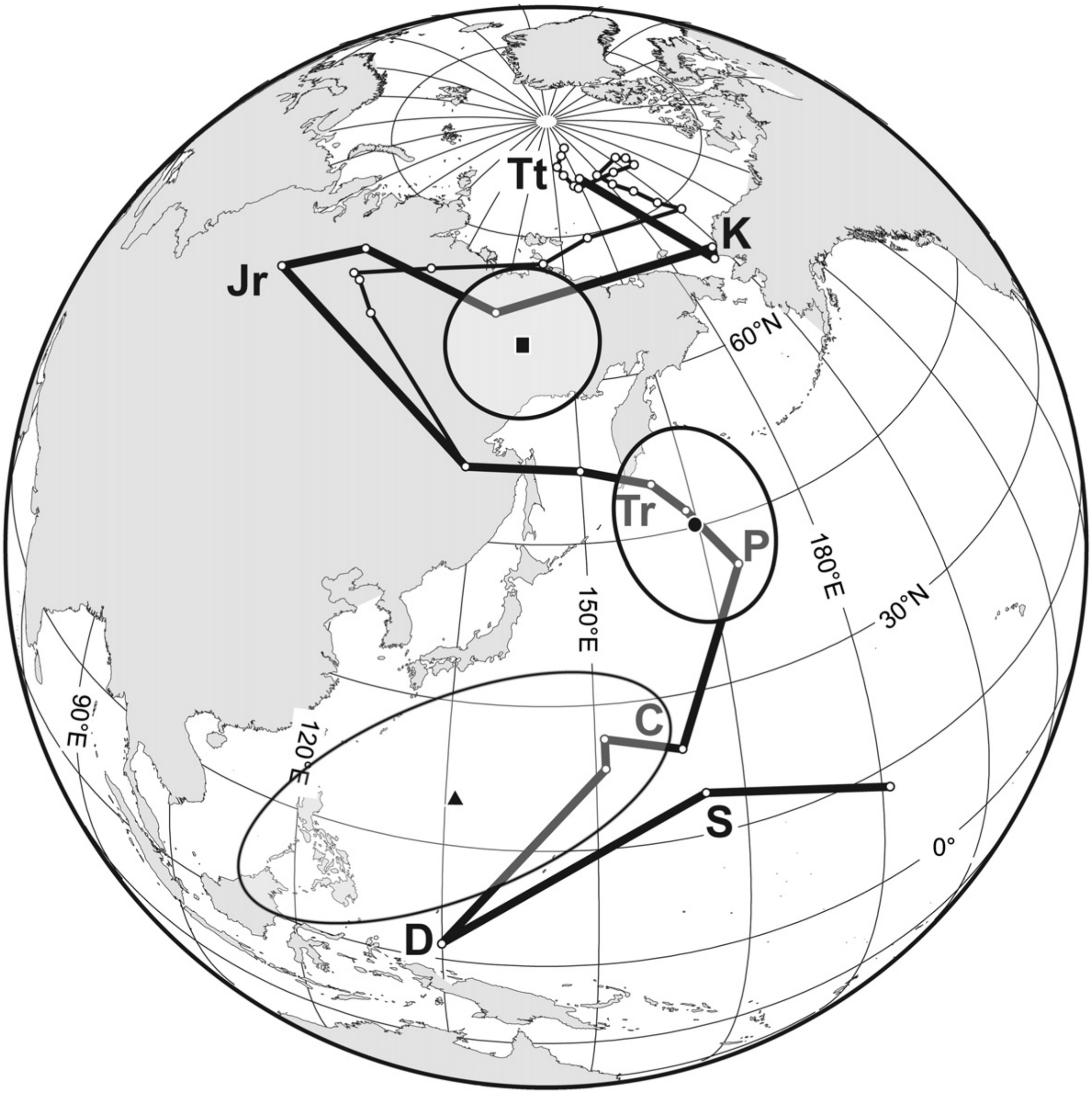


Fig. 5. Apparent polar wander paths from Van der Voo (1993) for the Phanerozoic (heavy line with the circles representing the median age poles) and Besse and Courtillot (2002) for the last 200 Ma (thinner line with circles representing the 10 Ma mean poles) with the poles and 95% error ellipses (dp and dm) for CRM1 (triangle), CRM2 (circle), and CRM3 (square).

4.2. Petrology and geochemistry

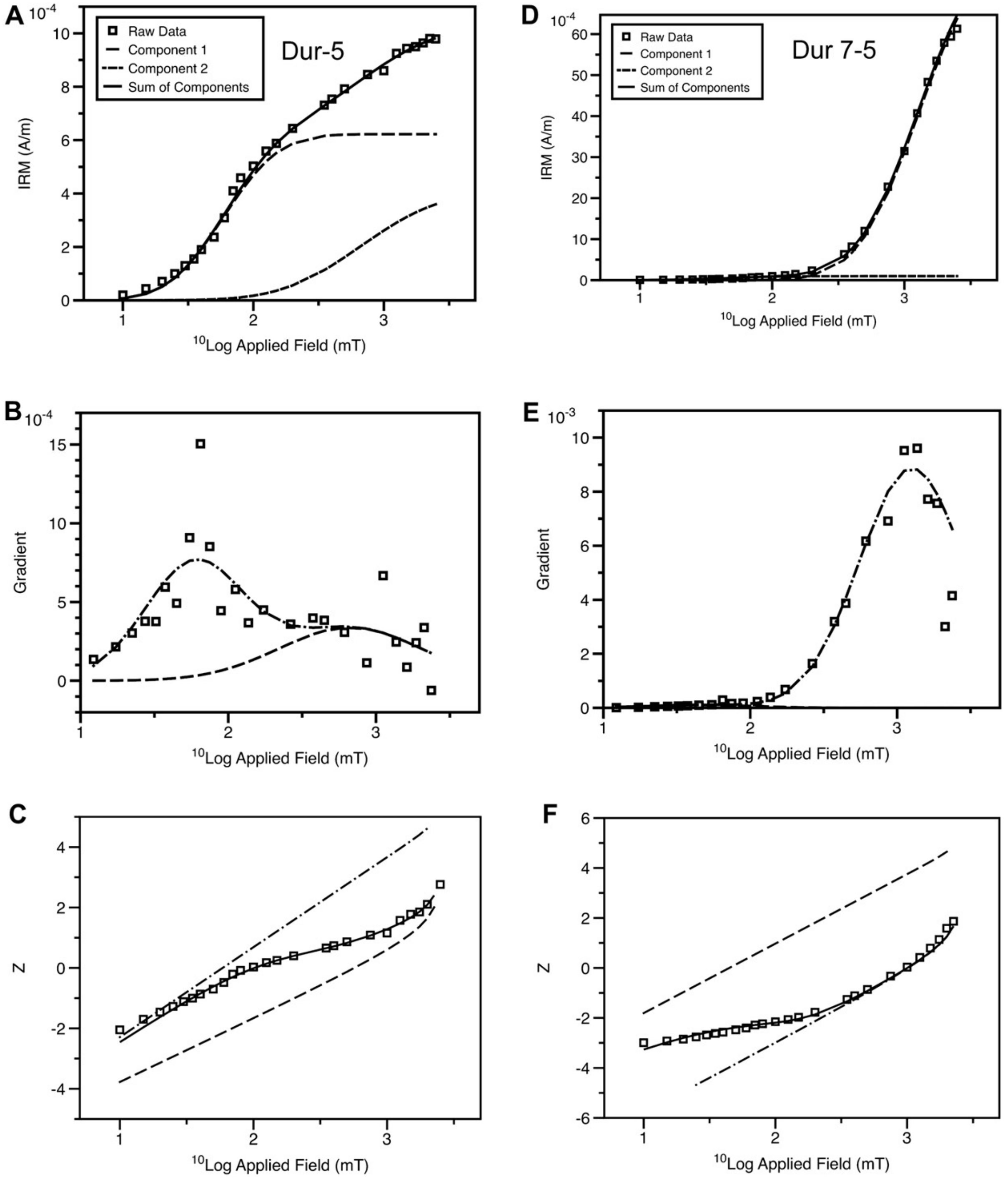
The host Durness Group dolomite consists of medium crystalline, subhedral cloudy crystals (Fig. 7A). Authigenic pyrite and hematite are present in some samples. Relict fossils are rare to absent.

The breccias are cemented by several generations of coarse calcite cement (Fig. 7B). There are also clasts that consist of breccia within the breccias (Fig. 7B), indicating at least two brecciation events. Hematite occurs along growth planes within the calcite cement (Fig. 7C, D) and rimming some of the breccia clasts.

The host Durness Group $\delta^{13}C$ values ranged from -1.5 to $-0.5‰$ and the $\delta^{18}O$ values ranged from approximately -12.0 to $-7.0‰$ (Fig. 8). The breccia cement $\delta^{13}C$ values ranged from -3.0 to $-0.5‰$ and the $\delta^{18}O$ values ranged from approximately -13.0 to $-7.0‰$. The isotopic compositions of the host rocks and breccias are similar, although some of the breccia calcite samples have more depleted $\delta^{13}C$ values. The stable carbon and oxygen isotope values fall within the range representative of Cambro-Ordovician marine carbonates (Viezer et al., 1999) and may reflect alteration by fluids with a low water to rock ratio (Lohmann, 1988; Sharp, 2007).

5. Discussion

Johnson et al. (1985) concluded that rocks below the Moine thrust reached temperatures of 300°–350 °C in the middle Silurian and those in the foreland reached a maximum burial temperature of 275° ± 50 °C during the late Silurian. The three magnetizations found associated with the breccias and host Durness Group are all younger and probably experienced lower temperatures. Fluid inclusions from several calcite phases in a breccia near Durness have homogenization temperatures between 60° and 175 °C with salinities between 4 and 18 wt.% NaCl equivalent (Blumstein et al., 2005). Petrographical analysis indicates that calcite phases which contain low/moderate homogenization temperatures bracket authigenic hematite.



Samples	Components	Contribution %	SIRM (A/m)	$B_{1/2}$ (mT)	DP (mT)
DUR 7-5	1	98.8	8.0	1258.9	0.36
	2	1.2	0.1	44.7	0.36
DUR - 5	1	39.5	0.4	668.2	0.48
	2	60.5	0.6	58.8	0.34

Fig. 6. Representative results from LAP-GAP-SAP modeling of a 25 step IRM acquisition (Kruiver et al., 2001) for samples from the host Durness dolomite (A–C, Dur5) and a breccia from the Durness roadside locality (D–F, Dur 7-5). The table shows the modeled components for both samples. The host dolomite is dominated by a lower coercivity component which is interpreted to be magnetite. The breccia is dominated by a high coercivity component that is interpreted to be hematite.

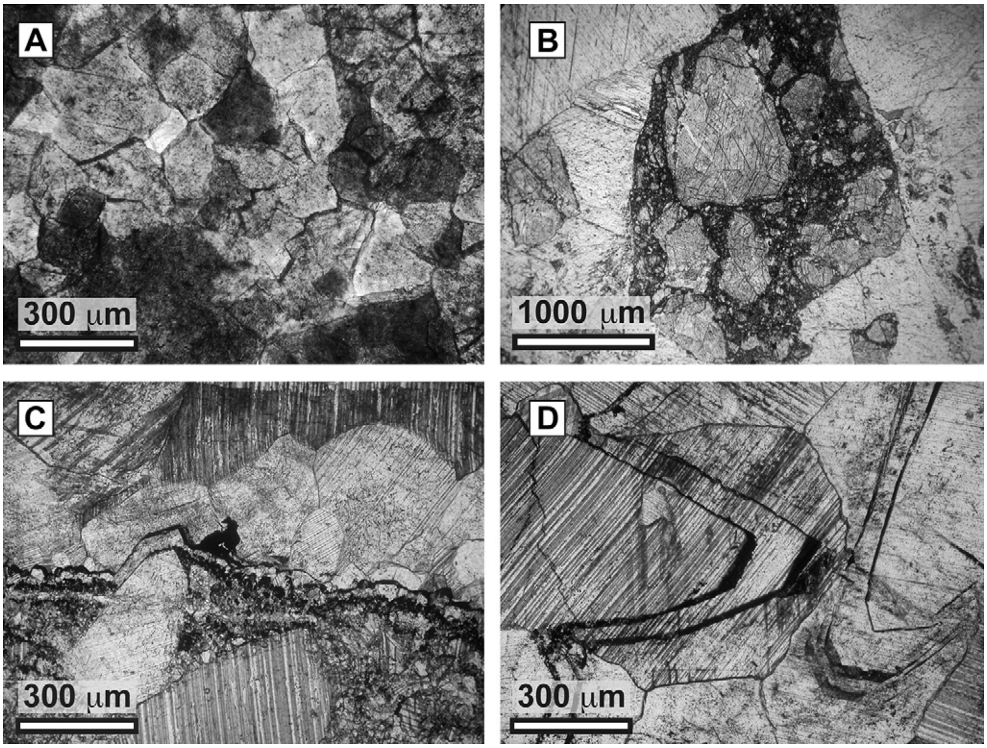


Fig. 7. Representative photomicrographs of rocks from the study area. A) Host Durness dolomite, TL, Sample DUR4, B) Breccia clast within a breccia indicating multiple brecciation events, TL, Sample DUR 4, C) Authigenic hematite along growth planes (black in photomicrograph) in calcite that cements the breccia clasts, Sample DUR4, D) Authigenic hematite in a breccia; TL, Sample DUR4.

5.1. *Origin of ChRM1*

The ChRM1 that resides in magnetite in the host Durness Group carbonates has a maximum unblocking temperatures of 500 °C. This maximum unblocking temperature is too high for the ChRM1 to be a thermal viscous remanent magnetization (TVRM) caused by burial heating based on the time–temperature relationships from Pullaiah et al. (1975), which are for single domain magnetite. Many rocks, however, contain multi-domain magnetite which can produce a high temperature tail during thermal demagnetization that can produce higher maximum unblocking temperatures than expected curves (e.g., Kent, 1985). The maximum unblocking temperatures, however, are not high enough to produce a TVRM based on mixtures of single and multi-domain magnetite grains (e.g., Kent, 1985; Dunlop et al., 1997), so ChRM1 is therefore interpreted as a chemical remanent magnetization (CRM).

The ChRM1 is similar to a Devonian post tilting CRM from a variety of lithologies along the MTZ (Blumstein et al., 2005) and to a Devonian remagnetization reported by Torsvik and Sturt (1988) that resides in magnetite and is found in Torridonian rocks near the MTZ about a hundred kilometers further south at Balmacara. The ChRM1 could be the result of diagenetic processes associated with hydrocarbons (e.g., Elmore and Crawford, 1990). Laurentian margin carbonates are hydrocarbon-bearing over a huge area in the

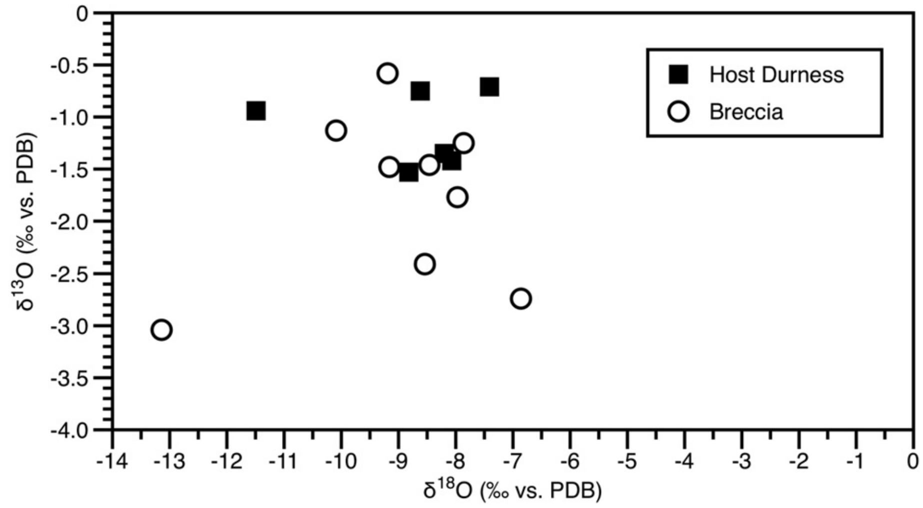


Fig. 8. Stable carbon (PDB) and oxygen (PDB) isotope values for representative samples from the breccias and host Durness Group.

North Atlantic region (e.g., Christiansen, 1989) and our own measurements on extracts from the Durness Group carbonates suggest that they have experienced hydrocarbon migration. Thus diagenesis related to an active petroleum system is a realistic explanation for the remagnetization event. Clay diagenesis is also a possible remagnetization mechanism (e.g., Katz et al., 1999).

5.2. Origin of ChRM2 and ChRM3

Using the temperatures from the fluid inclusions, and comparing these to the hematite curves of Pullaiah et al. (1975), indicates that the unblocking temperatures for ChRM2 and ChRM3 (650–680 °C) are too high for a TVRM in hematite and thus are interpreted as CRMs.

The CRMs are interpreted as forming from two fluid flow events that precipitated hematite, one in the Triassic and the second in the Jurassic. The fact that there were multiple brecciation events that were cemented by calcite containing authigenic hematite suggests that fluid flow and hematite precipitation were associated with brecciation. The fluids which caused acquisition of the Triassic CRM moved along north–south fractures whereas the fluids which caused the Jurassic CRM moved along east–west fractures and faults that probably cut the MTZ. The fluids were focused in the breccia veins and only locally remagnetized the dolomite away from the veins.

5.3. Comparison with previous work

The ChRM2 is similar to component 3 reported by Blumstein et al. (2005) from the Durness Group as well as from a number of different lithologies along the length of the MTZ. It resides primarily in hematite and a regional tilt test suggests it is post tilting. It was interpreted as Mesozoic in age. The ChRM2 is also similar to component 1 from Blumstein et al. (2005) which has southerly declinations and shallow inclinations. Tilt tests indicated it is post tilting and it is interpreted as Permian in age.

Laubach and Diaz-Tushman (2009) report that the Cambrian Eriboll Group Sandstones in NW Scotland west of the MTZ contain five sets of quartz-filled or lined fractures. Based on crosscutting relationships they determined the relative ages of the five sets. They interpreted that a north striking set and a west-northwest set formed prior to and during emplacement of the MTZ. The timing of the two youngest fracture sets (D and E), with west and north strikes, are interpreted by Laubach and Diaz-Tushman (2009) as Mesozoic or Tertiary in age. We suggest that their set D (west striking) could be related to the east–west breccia veins with the Jurassic CRM at Balnakeil and their set E (northerly striking) could be associated with the Triassic CRM at the Durness road locality. The timing for brecciation is also consistent with the hypothesis that some faulting occurred in NW Scotland in the Mesozoic (Wilson et al., 2010).

Many Precambrian and Paleozoic rocks in Scotland contain CRMs (e.g., Tarling, 1985; Torsvik and Sturt, 1988; Torsvik et al., 1989; Parnell et al., 2000; Elmore et al., 2002) that are interpreted to be late Paleozoic or Mesozoic in age. Recent studies suggest that some CRMs in Scotland are related to diagenetic alteration associated with fluid flow along fault zones. For example, Blumstein et al. (2005) reported that four CRMs (Devonian, Permian, Mesozoic, and Early Tertiary) occur in different lithologies along the MTZ from Skye to Durness, and can be related to specific geologic events such as hydrothermal fluids associated with Devonian and Tertiary igneous activity and regional crustal extension. Elmore et al. (2006) reports that fluid flow events that caused hematite precipitation occurred along different segments of the Great Glen Fault in the Permian and the Cretaceous. Elmore et al. (2002) reported that the Highland Boundary Fault was a conduit for fluids which caused hematite mineralization in the Permian.

Faults can act as barriers or conduits to flow at different times in their history (e.g., Woodcock et al., 2007). Faults and associated breccias such as those described in this paper were major conduits for fluids. They caused hematite mineralization, acquisition of CRMs, as well as other diagenetic features, and along with other faults (e.g., Blumstein et al., 2005), may have provided the paleoplumbing for diagenetic fluids in Scotland. The timing of faulting, brecciation, and fluid flow are consistent with the extensional history of the northern Atlantic margins (e.g., Hitchen et al., 1995).

This study illustrates how paleomagnetic analysis can be used to date faulting, associated brecciation, and fluid flow events. This dating approach should have applications to other fault-related breccias which are described from many tectonic settings (e.g., Wright et al., 2009).

6. Conclusions

The Durness Group carbonates and associated breccia veins contain three ChRMs. The host Durness Group dolomite contains ChRM1 that resides in magnetite and is interpreted to be a Devonian CRM. The breccia veins contain magnetizations that reside in hematite and are interpreted as CRMs. At one location where the veins are oriented north–south, the breccias contain a ChRM2 with southerly declinations and moderate up inclinations that is Triassic in age. At a second location where the veins strike east–west, the breccia contains a ChRM3 with north-northeast declinations and steep down inclinations that is Jurassic in age. Authigenic hematite in several forms is abundant in the breccias. The CRMs in the breccias are interpreted as reflecting two separate fluid flow events that precipitated authigenic hematite and date the brecciation. The brecciation and fluid flow events are interpreted to be related to extension in the Mesozoic which is consistent with the extensional history of the northern Atlantic margins.

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