RECONSTRUCTING FLUID EXPULSION AND MIGRATION NORTH OF THE VARISCAN OROGEN, NORTHERN ENGLAND

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ABSTRACT: Lower Carboniferous platform carbonates in northern England host lead–zinc–fluorite–barite deposits that have previously been classified as Mississippi Valley-type (MVT). The controls on the distribution of low-temperature, particularly MVT, minerals have long been debated, but the interplay of basin evolution and fluid movement is often neglected. Early Carboniferous sedimentation on the Derbyshire Platform took place within a back-arc extensional regime, north of the northward-migrating Variscan orogenic front, which increasingly influenced fluid movement on the platform throughout the Carboniferous. It is the interplay of fluid movement, cementation, and Variscan tectonism that is the focus of this paper, which aims to reconstruct fluid movement within a basin moving from an extensional to a compressional regime. In particular, it demonstrates the variability of fluid flux during post-rift subsidence and basin inversion and the corresponding influences of this upon mineral distribution.

During early burial of the Derbyshire Platform, pore-filling cements were precipitated from meteoric porewaters, driven downdip from the east under topographic drive. These cements occluded most interparticle porosity, and therefore permeability became fracture-controlled. The waning effects of extensional tectonism during post-rift subsidence permitted intermittent expulsion of small volumes of trace metal-charged, carbonate-saturated fluids from overpressured contemporaneous clastic basins adjacent to the Derbyshire Platform. Overall, however, waning tectonism meant that the volume of fluids released during this period remained minor. With the onset of the Variscan Orogeny, and resultant compressional tectonism and basin inversion, Caledonian basement fault systems were reactivated, channeling large volumes of trace metal-charged fluids from the basins onto the Derbyshire Platform, establishing an east–west component to fluid flow.

The reconstruction of fluid expulsion and migration within this tectonically active regime demonstrates variations in fluid source and migration pathways during basin evolution. Consequently, fluid movement is complex, with the platform receiving fluids from a variety of sources. This highlights the importance of understanding both the temporal and the spatial variations in cement chemistry when reconstructing flow. The results of this study have relevance to other mineralized carbonate platforms in extensional and compressional settings worldwide and especially to sedimentary basins that host MVT deposits and hydrocarbons, where it is crucial to understand the timing and mechanisms of diagenetic cementation and hydrocarbon emplacement.

INTRODUCTION

Mechanisms for fluid expulsion and migration within sedimentary basins have long been debated. Some carbonate platforms are extensively mineralized by fluorite, barite, galena, and sphalerite- so-called Mississippi Valley-type (MVT) deposits. The characteristics and origins of these ore deposits vary widely and remain uncertain. For example, hydrogeological flow models proposed for the stratabound MVT deposits of North America (e.g., Garven 1985; Garven and Raffensperger 1997; Garven et al. 1999) cannot always be directly applied to basins that were mineralized during ongoing tectonism. Although alternative mechanisms for the emplacement of fluids within these tectonic areas can be invoked, significant problems often remain in identifying a volumetrically significant source of fluid for mineralization.

Because of the association of pore-, fracture-, and fault-filling fluorite, barite, galena, and sphalerite mineralization and hydrocarbon deposits in the Lower Carboniferous limestone of the Derbyshire Platform, this mineralization is commonly referred to as Mississippi Valley-type (Quirk 1987; Coleman et al. 1989; Ixer and Vaughan 1993). The narrow stratigraphy and lateral extent, combined with an extensive database, make this mineralization an ideal candidate for the examination of fluid movement in an evolving tectonic regime. This study outlines how the integration of field, petrographical, and geochemical data from the study area can be used to comprehensively reconstruct the movement of fluids and emplacement of mineralization on the platform. The present paper builds upon previous discussions addressing the nature of burial diagenetic cementation on the platform (Hollis and Walkden 1996) and how paragenetic and geochemical trends among these cements can be used to constrain the timing of mineralization (Hollis 1998). In particular, the present study focuses on spatial variations in mineral and hydrocarbon distribution and cement geochemistry in order to evaluate how basin evolution and major Carboniferous tectonic events controlled fluid expulsion and migration pathways north of the Variscan Orogen. These results contribute not only to our understanding of mineral distribution in northern England, but also more generally to the reconstruction of fluid movement during post-rift subsidence and basin inversion.

SEDIMENTARY AND TECTONIC SETTING

Carboniferous sedimentation in northern England took place in a depositional setting that lay north of the Variscan Orogen (Fig. 1). Pulsed back-arc extension throughout the Dinantian was focused along NE–SW and NW–SE trending extensional faults (Fig. 1), often overprinting preexisting Caledonian trends (Fraser and Gawthorpe 1990). Extensional movement continued into the late Carboniferous (Collinson 1988; Guion and Fielding 1988) but was increasingly minor from the Namurian onwards. At that time post-rift thermal sag subsidence became increasingly important in the Pennine Basin (Leeder 1988). Onset of the Variscan Orogeny in the late Carboniferous–Permain established a compressional regime across northern England, reactivating NW–SE trending faults with a strike-slip component, ultimately leading to basin inversion (Leeder 1988; Fraser and Gawthorpe 1990).

Back-arc extension exerted a significant control on sedimentation, enabling extensive carbonate accumulation during periods of faulting. Accumulation of Dinantian limestone on the Derbyshire Platform, which developed on Lower Paleozoic basement, forms the westernmost part of the more-extensive Derbyshire–East Midlands carbonate platform (Fig. 1). The Derbyshire Platform persisted as a stable block during the Lower Carboniferous (Fraser and Gawthorpe 1990), while basins surrounding the platform subsided more rapidly. Consequently, these basins accumulated thick sequences of deep marine shales with thin, interbedded limestone and sandstone beds during the Dinantian and Namurian (Coleman et al. 1989; Kelling and Collinson 1992; Fig. 1). The locations and orientations of these basins are significant to this study. Until the mid-Namurian, sediment was supplied to the Edale and Gainsborough basins in the north by southward-
**FIG. 1.**—Generalized paleogeography of A) northern Europe, showing the regional Dinantian tectonic setting, and B) northern England in the Lower Carboniferous, showing the principal depositional and structural elements.

![Diagram](image)

**TABLE 1.**—Mean, minimum, and maximum values for $\delta^{13}C$, $\delta^{18}O$, and homogenization temperatures. $\delta^{18}O_{SMOW}$ values for precipitating fluids are calculated using mean $\delta^{18}O_{calcite}$ and mean $T_H$, using the fractionation factor of Friedman and O’Neil (1977).

<table>
<thead>
<tr>
<th>Zone</th>
<th>Calcite Type</th>
<th>Luminescence</th>
<th>$\delta^{13}C$ (%)</th>
<th>$\delta^{18}O$ (%)</th>
<th>Homogenization Temperature (°C)</th>
<th>$\delta^{18}O_{SMOW}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zone 1 calcite</td>
<td>Non-luminescent</td>
<td>-6.0 to -6.8</td>
<td>-3.0 to -1.7</td>
<td>57.3 (35.6 to 80.6)</td>
<td>2.3 (0.7 to 3.0)</td>
</tr>
<tr>
<td>2</td>
<td>Zone 2 calcite</td>
<td>Bright luminescence</td>
<td>-5.0 to -5.5</td>
<td>-0.6 to 3.2</td>
<td>-6.0</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Zone 3 calcite</td>
<td>Dull luminescence</td>
<td>-10.3 (-12.3 to -7.6)</td>
<td>2.3 (0.7 to 3.7)</td>
<td>106 (82.2 to 125)</td>
<td>6.0</td>
</tr>
<tr>
<td>4</td>
<td>Zone 4 calcite</td>
<td>Moderate luminescence</td>
<td>-6.0 (-5.8 to -6.3)</td>
<td>2.0 (0.3 to 3.3)</td>
<td>176 (148 to 200)</td>
<td>11.5</td>
</tr>
<tr>
<td>5</td>
<td>Zone 5 calcite</td>
<td>Bright luminescence</td>
<td>-7.5 (-6.5 to 2.8)</td>
<td>2.3 (0.7 to 3.9)</td>
<td>168 (117 to 207)</td>
<td>12.0</td>
</tr>
<tr>
<td>6</td>
<td>Zone 6 calcite</td>
<td>Dull luminescence</td>
<td>-7.5 (-6.5 to 2.8)</td>
<td>2.3 (0.7 to 3.9)</td>
<td>168 (117 to 207)</td>
<td>12.0</td>
</tr>
</tbody>
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Fig. 2.—Outline of study area, illustrating sample localities and platform positions.

prograding, turbidite-fronted fluviodeltaic systems. In contrast, deposition in the eastern Staffordshire Basin and the southern Widmerpool Basin was from fluviodeltaic systems that prograded northward from the Wales–Bra-
bant Massif (Trewin and Holdsworth 1973). Renewed delta progradation from the northeast effectively swamped the Pennine Basin from the mid-
Namurian into the Westphalian, and the Derbyshire Platform was progres-
sively buried by southward-prograding fluviodeltaic siliciclastics (Kelling and Collinson 1992).

METHODS

Samples were obtained from Asbian and Brigantian outcrops across the Derbyshire Platform (Fig. 2A and B; Hollis 1995). Each location is identi-
fied as being within one of five platform areas (Fig. 2): the northern, eastern, southern, or western margin or the platform center. The eastern margin is not adjacent to a contemporaneous clastic basin and simply de-
finesthe eastern limit of the limestone outcrop where it dips beneath the Upper Carboniferous succession. Geochemical analysis was performed within a paragenetic framework defined by cathodoluminescence (CL) and epifluorescence zonation of burial calcite cements contained both within interparticle pores and small (< 5 cm wide) fracture systems (Hollis and Walkden 1996). Individual cement zones were analyzed for Mg, Mn, Sr, and Fe by electron probe microanalysis, using a Camebax electron micro-
probe, and for the trace elements F, Zn, Ba, and Pb using a Cameca IMS 4f ion microprobe. A wollastinite standard and a range of internal standards were used for machine calibration. Errors for electron probe microanalysis were within three standard deviations (σ), whilst for the ion microprobe technique results were reproducible within a 90% confidence limit.

Analysis of fluid inclusions was conducted (prior to CL) on inclusions within calcite-cemented fractures that showed no evidence of stretching or leakage using a Linkham TH600 heating and cooling stage. All heating runs were repeated three times, and results were reproducible to within 3°C. Freezing runs were repeated twice, and all temperatures of final melting were reproducible within 0.5°C.

Stable-isotope (δ13C and δ18O) analysis was focused on fracture-fill cal-
cite from single-phase calcite-cemented fractures, which were microsam-
pled using a tungsten-tipped dental drill. Samples were run against an internal calcite standard, and all results were reproducible to ± 0.1‰ (2σ). Results were corrected according to standard procedures (Craig 1957) and are expressed in the standard ‰ notation relative to the PDB standard. The isotopic composition of diagenetic fluids were estimated using the oxygen fractionation factor (αcalcite-water) of Friedman and O’Neil (1977).

DIAGENETIC EVOLUTION

A complete diagenetic evolution, from synsedimentary to late burial ce-
mentation, is recorded on the Derbyshire Platform (Fig. 3). Marine cements have been described from the platform margins (Bingham 1992), and me-
eteric vadose and phreatic cements have been recognized across the central parts of the platform (Walkden and Williams 1991). On the basis of de-
tailed cathodoluminescence and geochemical data, four main phases of cal-
cite cementation (Zones 1–4) have been described from interparticle pore systems. They record the evolution of pore fluids from the meteoric phreatic (Zones 1–2) into the burial (Zones 3–4) diagenetic realms (Fig. 3; Berry 1984; Walkden and Williams 1991; Bingham 1992). Zone 3 calcite is the principal interparticle pore occluding phase on the Derbyshire Platform and
Fluid expulsion and migration in the Variscan orogen.

Distribution of Burial Calcite Cements

Understanding the spatial and temporal distribution of burial calcite cements on the Derbyshire Platform is key to the reconstruction of its fluid-flow history. The petrographical and geochemical properties of the burial cements in the study area have been outlined previously (Hollis and Walkden 1996; Hollis 1998). They are summarized briefly below, and in Figure 3, and are then discussed in terms of the geochemical variability they display across the Derbyshire Platform.

Paragenesis.—The earliest phase of burial calcite cementation is Zone 3A calcite, which occludes significant volumes of interparticle porosity. It has a dull luminescence and is not associated with any other minerals or hydrocarbon. It is succeeded by seven separate stages of burial calcite cements (Zones 3A–4D). These cements mainly occlude NE–SW and NW–SE trending fault and fracture systems and are identified on the basis of their cross-cutting relationships and crystallographic, CL and epifluorescence characteristics (Fig. 3; Hollis and Walkden 1996). Zones 3A to 4B calcites were precipitated along dilatant, extensional fractures. There are no ore minerals or hydrocarbon associated with Zone 3A calcite, whereas Zones 3B to 4B contain hydrocarbon inclusions and are associated with liquid hydrocarbon and solid bitumen deposits. Fluorite coexists with Zone 3B calcite, and successive calcite cement zones were co-precipitated with increasing volumes of galena, sphalerite, fluorite, and barite, although calcite remains the dominant mineral phase. Zone 4C calcite is typically intergrown with the complete mineral assemblage, most commonly healing faults and fractures that show oblique offset of wall-rock inclusions. Only rare fluorite is intergrown with the final, Zone 4D calcite cement, which is recognized in minor volumes along hairline fractures and within matrix macropores (the Zone 4 cement of Walkden and Williams 1991).

Fluid inclusion analysis reveals an overall increase in homogenization temperature (T_h) from Zone 3A to Zone 4C calcite (Table 1). Although stable-isotope variations are less systematic, calculation of the isotopic composition of pore fluids, using δ18O_{calcite} and T_h, indicates an increase in δ18O_{SMOW} in successive calcite cements (Table 1).

Spatial Trends in Mineral Distribution and Geochemistry.—Field and petrographical data indicate that calcite, fluorite, barite, and galena mineralization is concentrated within Brigantian strata, in particular on the northern, southern, and eastern platform margins, with only calcite cementation recorded on the western platform margin. Figure 4 displays the concentration of mineralizing elements, ratioed to calcium, in calcite cements on the Derbyshire Platform and shows that maximum concentrations of individual trace elements occurred at different times across the platform. The highest F/Ca (2.71 × 10^{-5}) and Zn/Ca (1.15 × 10^{-5}) ratios were measured in calcite from the platform center, where mean ratios of all measured trace elements reach peak values in Zone 4C cements. Similarly, F/Ca and Zn/Ca ratios in calcite cements from the southern platform margin all peak in Zone 4C calcite, and also exhibit the highest mean Ba/Ca (4.89 × 10^{-5}) and Pb/Ca (1.32 × 10^{-5}) ratios on the platform. On the northern platform margin, mean F/Ca and Zn/Ca ratios are at a maximum in Zone 3A (8.71 × 10^{-5} and 1.60 × 10^{-5} respectively), whilst mean ratios for Ba/Ca peak in Zone 3B (4.29 × 10^{-5}) and for Pb/Ca in Zone 4B (7.86 × 10^{-5}). On the eastern platform margin, mean Zn/Ca ratios are highest in Zone 4A (2.61 × 10^{-5}), Pb/Ca are at a maximum in Zone 4C (5.55 × 10^{-5}) and F/Ca and Ba/Ca peak within Zone 4D (3.62 × 10^{-5} and 2.39 × 10^{-6}, respectively).

Stable-isotope signatures (Fig. 5) vary between different platform localities, with the most depleted δ18O values measured in Zone 3B calcite on the western platform margin (δ18O = -3.0‰) and the most depleted δ18O occurring in Zone 3B calcite in the platform center (δ18O = -14.0‰). The most enriched δ13C value was recorded in Zone 3B calcite in the platform center (δ13C = 4.1‰) and the most enriched δ18O values were found in Zone 4A calcite from the southern platform margin (δ18O = -2.7‰).

The lowest homogenization temperatures in fluid inclusions (mean 93.1°C) were measured in the platform center, although analysis was pos-
Fig. 4.—Trace-metal concentrations for fracture-filling burial calcite cements, by platform position, displaying the mean, minimum, and maximum values for each phase. A) fluorine/calcite; B) zinc/calcite; C) barium/calcite; D) lead/calcite.

Precipitation of economic ore deposits requires a source and transport mechanism for large volumes of fluids, and to account for this, computer simulations for the emplacement of epigenetic, stratabound, MVT-deposits are well established. In particular, circulation of porewaters in response to topographic drive has been widely invoked to account for the formation of large, carbonate-hosted lead–zinc deposits in the Mississippi Valley region of North America (e.g., Garven 1985; Bethke 1986; Garven and Raffensperger 1997; Garven et al. 1999). Until recently, however, many of these models did not explicitly consider the role of faults and fractures in controlling fluid movement. Sibson (1993), Roberts and Nunn (1995), and Pedersen et al. (1997) discussed the influence of fault permeability on fluid migration for compactional and aquifer-derived fluids and porewaters released from overpressured compartments by seismic pumping. Correspondingly, the role of faults in controlling the circulation of meteoric-derived mineralizing fluids has been increasingly acknowledged (e.g., Oliver 1986; Gregg et al. 1993; Clendenin et al. 1994; Luenschloss et al. 1997; Somerville et al. 1997; Garven et al. 1999).

The Derbyshire Platform provides an opportunity to consider the relative importance of these models in a small basin and in an evolving tectonic regime. Although the timing of mineralization has never been conclusively established, there is strong evidence for calcite cementation, MVT mineralization, and hydrocarbon emplacement during Carboniferous burial (Hollis and Walkden 1996; Hollis 1998). During this period, the waning effects of Dinantian back-arc extension were giving way to post-rift thermal sag subsidence and ultimately to the onset of the compressional regime that characterized the Variscan Orogeny. Because these events had a strong influence on mineralization, detailed paragenetic and geochemical trends can be used to reconstruct patterns of fluid migration within a well-constrained basinal evolution.

Source of Fluids for Mineralization

Numerous models for mineralization on the Derbyshire Platform have been proposed, many focusing on mineral precipitation from trace metal-charged fluids that circulated within the burial diagenetic realm (e.g., Dunham 1983; Quirk 1987; Coleman et al. 1989; Ixer and Vaughan 1993). It has been established that the main phase of mineralization on the Derbyshire Platform was coincident with the onset of the Variscan Orogeny (Hollis 1998), and field observations indicate that mineralization on the Derbyshire Platform is concentrated in Brigantian limestones in the northern, southern, and eastern parts of the platform. However, different trace-element, stable-isotope, and fluid-inclusion compositions in cements from different parts of the platform suggest a complex pattern of fluid expulsion and migration, and examination of temporal and spatial variations in mineral and geochemical patterns reveals a more detailed pattern of fluid movement on the Derbyshire Platform than has previously been presented (Hollis and Walkden 1996). When the burial history of the Derbyshire Platform is considered as a whole, therefore, a fluid evolution can be modeled that...
Fig. 5.—$\delta^{18}$O and $\delta^{13}$C for fracture-filling burial calcite cements and whole rock samples from A) Eastern platform margin, B) Northern platform margin, C) Platform center, D) Southern platform margin, and E) Western platform margin.

reflects ongoing burial and tectonism and changes in fluid source. This integrated approach helps to reconstruct fluid movement across the platform from the earliest stages of burial, during the Namurian, into and beyond basin inversion during the late Westphalian.

**Westward-Driven Flow.**—Walkden and Williams (1991) described in detail the evolution of cements precipitated on the Derbyshire Platform in the near-surface to shallow-burial environments. They focused on Zone 3, which occludes much of the matrix macroporosity on the Derbyshire Platform, accounting for up to 35% of the total rock volume. The dull luminescence, low concentrations of trace elements, and exceptionally low $\delta^{18}$O calcite values ($-5.5$ to $-14.5\%$; Fig. 3) were used by Walkden and Williams (1991) to invoke precipitation from $^{18}$O-depleted (approximately $-6\%$ SMOW) meteoric porewaters. These fluids, they proposed, were sourced from the east, driven downdip along a carbonate aquifer system from the East Midlands Shelf by piezometric head (Fig. 7A).

The earliest phase of fracture-filling calcite mineralization on the Derbyshire Platform, Zone 3A, is a dull-luminescent cement with a low homogenization temperature, no co-precipitated minerals or hydrocarbon, and a relatively low concentration of trace elements (Fig. 3). These characteristics closely resemble the Zone 3 interparticle pore-filling cements of Walkden and Williams (1991) and Bingham (1992), which Zone 3A-cemented fractures crosscut. This relationship suggests that Zone 3A calcite is approximately contemporaneous with, or immediately postdates, Zone 3 pore-filling cements (Hollis 1995). Subsequent occlusion of remnant inter-
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**Fig. 6.** Homogenization temperatures ($T_h$) and temperatures of final melting ($T_m$) for fracture-filling burial calcite cements, by platform position, displaying the mean, minimum and maximum values for each phase sampled from A) Eastern platform margin, B) Northern platform margin, C) Platform center and D) Southern platform margin.

Particle macroporosity by Zone 3 calcite and continued circulation of meteoric porewaters combined to reduce interparticle volumes significantly. Consequently, evolution to fracture-controlled flow was inevitable. Furthermore, as continued erosion eliminated all topographic features to the east (Strank 1987; Kelling and Collinson 1992), there was a concomitant reduction in hydrostatic flow, such that an additional, tectonic mechanism for fluid migration was required to maintain fluid movement.

Although Zone 3A calcite has δ$^{13}$C values consistent with a marine fluid source ($+0.7$ to $+3.7\%$), the calculated δ$^{18}$O$_{\text{water}}$ (−3%ε SMOW) for this cement is lower than would be expected for marine porewaters (0%). This δ$^{18}$O$_{\text{water}}$ value is heavier, however, than the calculated composition (−6%ε SMOW) of Dinantian meteoric water, which precipitated Zone 3 calcite (Walkden and Williams 1991). Therefore, significant evolution of meteoric porewaters with continued burial or input of an 18O-enriched fluid source must have taken place. Zone 3A calcite is the earliest fracture-filling cement encountered on the Derbyshire Platform, and was precipitated at relatively low temperatures (< 80°C) and most likely at high fluid–rock ratios, and therefore it is unlikely that the isotopic composition of meteoric-derived fluids had evolved significantly. Therefore, an additional fluid source, which was less 18O-depleted than the east-derived meteoric fluids, is required.

Bingham (1992) noted a marked (greater than five-fold) increase in the concentration of Mg and Mn in pore-filling Zone 3 cements towards the depositional margins of the Derbyshire Platform and a change to more depleted δ$^{18}$O$_{\text{calcite}}$. These trends were interpreted as reflecting an input of hotter, more mineral-enriched, marine-derived pore fluids from the basins adjacent to the Derbyshire Platform. Given this scenario, the δ$^{18}$O$_{\text{SMOW}}$ value of −3%ε for Zone 3A calcite could have been generated by the mixing of easterly derived meteoric fluids with marine-derived formational porewaters from the basins surrounding the Derbyshire Platform (Fig. 7). Therefore, although a volumetrically significant source of fluids was available to the Derbyshire Platform from the East Midlands Shelf early in the burial history, continual cementation and burial soon limited the supply of these fluids, and hotter, more mineral-enriched, tectonically-derived fluids became volumetrically more significant.

Formational Fluids from the Edale, Staffordshire, and Widmerpool Basins. — Whereas emplacement of Zone 3A calcite is not associated with any other minerals, Zone 3B to 4C cements are increasingly intergrown with fluorite, barite, and galena, as well as hydrocarbon. Correspondingly, these cements display an increase in trace-element concentrations and homogenization temperature in successive cement phases (Fig. 3; Hollis and Walkden 1986). Occurrences of both burial calcite cements and other minerals along fault and fracture systems on the Derbyshire Platform suggest that faults provided conduits for mineralizing fluids. They must therefore have played an important role in fluid migration, whilst the presence of numerous crosscutting relationships, both within and between fractures, suggests prolonged evolution of stresses that generated intermittent fault movement (Hollis and Walkden 1996). Isotopic trends are complex, but δ$^{18}$O$_{\text{calcite}}$ of Zones 3B–4D calcite cements are typically more positive than Zone 3A calcite, with calculated δ$^{18}$O$_{\text{SMOW}}$ values displaying an enriched trend within successive cement phases (Table 1). These features are indicative of precipitation from increasingly evolved formational fluids, because a simple increase in temperature would be expected to result in a progressive depletion of δ$^{18}$O$_{\text{SMOW}}$ values. The Edale, Gainsborough, and Widmerpool basins, adjacent to the Derbyshire Platform, contain large volumes of trace metal-enriched siliciclastic sediments and have long been invoked as a potential source of fluids for mineralization (Fig. 7B; Quirk 1987; Coleman et al. 1989; Ixer and Vaughan 1993; Hollis 1995; Hollis and Walkden 1996). The observed geochemical trends in Zone 3A cements noted above are consistent with this interpretation. However, the availability of sufficient volumes of fluid, as well as mechanisms for their release from the basins onto the Derbyshire Platform, must be considered.

In order for sufficient volumes of fluid to be released to the Derbyshire
Platform from the basins during burial, fluids must either have been retained in the basins to depths of up to 3 km (on the basis of the burial history curves of Russell 1992) or replenished, perhaps by topographic drive. Recent studies of foreland basins north of the Variscan thrust belt in northern Europe have proposed that MVT mineralization took place from topographically driven meteoric fluids sourced from the Variscan Orogen (Muche et al. 1994; Muchez et al. 1995; Muchez and Sintubin 1997; Luenenschloss et al. 1997; Somerville et al. 1997; Garven et al. 1999). In the Irish Midlands, for example, the overthrust Old Red Sandstone is thought to have provided a suitable aquifer for MVT-mineralizing fluids derived from the Variscan foreland, with flow aided by fault and fracture networks (Somerville et al. 1997).

Such a model, however, is difficult to apply directly to mineralization on the Derbyshire Platform. In the Late Carboniferous, the Variscan front lay approximately 200 km south of the Derbyshire Platform (Fig. 1A; Leeder 1992). The Wales–Brabant massif, which bounded the southern margin of the Widmerpool Basin, still provided a significant barrier to northwards sediment migration from the Variscan mountains (Kelling and Collins 1992) and could also have obstructed northward migrating formation fluids. More importantly, low-permeability shales dominate Dinantian–Namurian sediments of the Edale, Staffordshire, and Widmerpool basins, and although thin sandstone and limestone beds were potential aquifers, both lithologies are laterally discontinuous and carbonate cemented. Furthermore, mid- to Late Carboniferous sedimentation in the Pennine Basin occurred dominantly within a low-relief coastal plain, crosscut by a network of fluviodeltaic systems. It is therefore doubtful that sufficient topographic variation existed between the basins and the platform to drive fluid expulsion. Clearly, a well-connected fault and fracture network could have permitted migration of mineral-enriched fluids northwards from the Variscan massif. However, the strong petrographical and geochemical evidence for a genetic link between diagenetic calcite cements on the Derbyshire Platform and surrounding contemporaneous basins (Hollis 1995; Hollis and Walkden 1996) suggests that it is unnecessary to invoke tectonically controlled flow over several hundred kilometers, because a more local source of fluids can be identified.

Formational porewaters could have been retained in the basins to the necessary late stages of burial if the basins were overpressured. Available data are inadequate to model overpressure development in the basins, but several factors indicate that abnormal pressures could have been generated. The very low permeability of the shales and the absence of any potential flow layers in the shale-dominated sequences of the Edale and Widmerpool basins imply an appropriate environment for overpressure development. Furthermore, rapid deposition of Dinantian–Namurian prodelta muds in the basins (Kelling and Collins 1992) aided preservation of organic matter for hydrocarbon generation and could have been conducive to overpressuring. Carbonate-cemented beds of limestone and sandstone could have provided effective top seals to overpressured compartments. Faults would act as good lateral seals during periods of tectonic quiescence but would have behaved as pathways for fluid migration during reactivation by expelling fluids onto the platform by seismic pumping. In this way, the interplay between fault movement and communication with overpressured compartments would have been crucial for fluid expulsion and emplacement onto the Derbyshire Platform from these northern and southern basins. In contrast, the western Staffordshire Basin contains greater volumes of carbonate and sand than either the Edale Basin or the Widmerpool Basin, and this may have inhibited development of overpressure by aiding compaction-induced fluid migration out of the basin during early burial.

Post-Dinantian sedimentation took place during post-rift thermal subsidence of the Pennine Basin and therefore in a relatively passive tectonic regime. Nevertheless, the waning phases of extensional tectonism were felt throughout the Namurian and Westphalian (Kelling and Collins 1992), with occasional fault movement potentially providing the drive for intermittent expulsion of mineralizing fluids onto the Derbyshire Platform. The infrequent and minor scale of this early fault movement, however, would have prevented large-scale fluid expulsion onto the platform (Hollis 1998). Furthermore, the relatively low permeability of the shales in the basin, and the often narrow width of fractures dissecting these shales, would have limited the duration of expulsion events, leading to rapid rescaling of ruptured overpressure compartments and a further buildup of hydrostatic pressure (e.g., Roberts and Nunn 1995). Only in the late Westphalian, when the onset of the Variscan Orogeny led to more vigorous compressional tectonism and basin inversion, would there have been substantial fluid expulsion from the basins. Reactivated fault systems would have provided wide conduits for these fluids, driving them from the basins to the platform by seismic pumping. It was during this phase of basin inversion that the large volume of minerals on the Derbyshire Platform was emplaced (Fig. 7C; Hollis 1998).

**Regional Variations in the Timing of Trace Element Expulsion**

Several regional trends in both mineral distribution and trace-element concentration in calcite can be identified (Figs. 4–6). On the southern platform margin, there is widespread intergrowth of calcite with fluorite, galena, and barite and peak F/Ca, Pb/Ca, and Ba/Ca ratios in Zone 4C calcite. In contrast, on the northern platform margin, maximum ionic ratios of all trace elements are measured in Zones 3A–4B calcite cements. Similarly, hydrocarbon coexists with Zone 4C calcite on the southern platform margin, whereas hydrocarbon inclusions on the northern platform margin are contained exclusively in Zones 3B–4B calcite.

Thermal maturation modeling by Russell (1992) suggested that normal geothermal gradients existed within the Widmerpool and Staffordshire basins, where sedimentation was from northward prograding fluviodeltaic systems. Such a gradient implies temperatures of 120°C in the basinal Namurian sediments at maximum burial. At this stage, a significant volume of trace elements would have been released to fluids by organic maturation and clay dehydration (Hollis and Walkden 1996). In accordance with this hypothesis, there is widespread intergrowth along fault and fracture systems on the southern margin of the platform of calcite with fluorite, barite, and galena, and F/Ca, Ba/Ca, Pb/Ca, and Z/Ca ratios peak in Zones 4C and 4D cements. These cements can be interpreted, therefore, to have been precipitated from fluids released from the Widmerpool Basin during maximum burial. Homogenization temperatures indicate a maximum temperature of 206°C in Zone 4C calcite in this location. This temperature clearly exceeds the maximum of 120°C invoked by burial-history modeling, but it could have been elevated by circulation through deep-seated Caledonian fault systems.

In contrast, northern-sourced Dinantian and Namurian shales in the Edale Basin contain elevated concentrations of U, K, and Th, and are therefore considered to be high heat-producing, through radioactive decay, and capable of maintaining an elevated geothermal gradient (Coleman et al. 1989). Burial-history modeling suggests that temperatures in basal Namurian shales in the Edale Basin were nearly 200°C at maximum burial (Coleman et al. 1989; Hollis 1998). This temperature relationship implies that mineralizing fluids could have been generated in the Edale Basin prior to maximum burial. Thus, greater volumes of mineralizing elements were available to fluids and would have been released from here earlier than in the Widmerpool or Staffordshire basins. This is borne out by the intergrowth of MVT minerals and calcite with elevated ionic concentrations in Zone 3A to Zone 4B cements on the northern platform margin, which is much earlier than in the south. Importantly, Bingham (1992) documented more depleted δ¹⁸O calcite in Zone 3 pore-filling cements on the northern platform margin than on the rest of the Derbyshire Platform. These isotope data suggest that even during the earliest phases of cementation, burial fluids released from the Edale Basin were hotter than those from the Widmerpool or the Staffordshire basins.
Direction of Fluid Flow

The simplest possible fluid migration pathway is the expulsion of fluids from the adjacent basins onto the margin of the Derbyshire Platform along bounding faults, with subsequent migration towards the platform center via fault and fracture networks. In this case, fluids would have more closely resembled their primitive, basinal compositions on the platform margin. It might be anticipated, therefore, that cements in these locations would show higher fluid temperatures, less-evolved isotopic signatures, and greater quantities of associated minerals and hydrocarbon than cements found at the platform center. Although Bingham (1992) recognized such trends during the earliest phases of burial calcite cementation, subsequent burial calcite cements on the Derbyshire Platform do not show such a simple geographical relationship. Wide-ranging isotopic compositions are found in cements from the platform center as well as from the platform margins, and there are no consistent variations in the palotemperatures of cements from the margins to the center of the platform, on the basis of fluid inclusion data. Similarly, both mineralization and hydrocarbon emplacement are abundant on the north, south, and east of the platform but decrease in volume to the west. If fluid expulsion had been directly onto the platform margins, a decrease in the volume of mineralization would be expected to the east, which is not in direct contact with a basin.

The Derbyshire Platform is connected to the Edale, Staffordshire, and Widmerpool basins by Caledonian basement faults (Fig. 1) and numerous, smaller Carboniferous extensional faults. All of these faults could have provided efficient migration pathways for fluids from the basins onto the platform at various stages of the burial history, and cementation of many faults and fractures by calcite, fluorite, barite, and galena supports this notion. The Caledonian basement faults are likely to have been key in controlling fluid migration onto and within the platform because they are the largest faults on the Derbyshire Platform and were continually reactivated during Carboniferous extension and compression. In particular, the Edale and Bakewell faults, on the northern margin of the platform, and the Cronkston–Bonsall fault, to the south, would have been the most important in controlling flow, because they extend across the platform and are in direct contact with the Edale and Widmerpool basins, respectively (Fig. 1). Fluids expelled from the Widmerpool Basin onto the East Midlands Shelf could also have migrated along the Cinderhill Fault (Fig. 1).

Most of these faults cut the eastern platform margin with an approximate southeast–northwest trend (Fig. 1). A pattern of fluid expulsion and migration from the basins onto the platform can be envisaged, whereby fluids were expelled from the basins to the east and driven westwards under a compressional drive induced by the onset of the Variscan Orogeny and concomitant reactivation of extensional lineaments (Fig. 7C). Such a model explains elevated fluid temperatures and ionic ratios and an abundance of mineralization along faults and in vein calcite cements on the eastern margin and in the platform center. The large volume of trace element-charged fluids available in the Widmerpool Basin at maximum burial, and the high degree of fault connectivity between it and the platform, suggest that this basin supplied large volumes of fluids to the platform during the main phase of mineralization. However, input of fluids from several basins of differing geothermal gradients following different fluid migration pathways was also significant and further highlights the complexity of the system. In addition, the potential for influx of cooler fluids during basin inversion explains further the widespread variation in fluid temperature and salinity measured in fluid inclusions. As the compressional drive for fluid migration waned or, more likely, the supply of basinal fluids was depleted, mineralization was terminated, and remnant fluids precipitated low volumes of Zone 4D calcite cements.

The low volumes of mineralization and hydrocarbons and the low trace element concentrations in calcite on the western platform margin are noteworthy and suggest that fluids carrying hydrocarbon and trace elements did not reach this area in large volumes. Mineralization across the Derbyshire Platform primarily affected the Brigantian limestone, which is the uppermost unit of the Dinantian succession. Fault systems terminate beneath Namurian shales which unconformably overlie the Dinantian succession and which are likely to have acted as a significant permeability barrier. On the western platform margin, Brigantian sediments were thin or absent prior to burial (Aitkenhead et al. 1985). Therefore, when mineralization took place, it should have been focused within the older, Asbian strata. As discussed, if overpressures were not developed in the Staffordshire Basin during burial, fluids may not have been retained in that basin until there was a suitable drive for expulsion of trace element charged-fluids. Furthermore, any fluids expelled from this basin need not have been driven onto the Derbyshire Platform but could have migrated to the north or west, in which case the source of mineralizing fluids on the western platform margin would have been limited to fluids derived from the east, driven westwards from the Widmerpool Basin along the Buxton and Cronkston–Bonsall Faults. In this case, fluids may simply not have vented on the western platform margin, or mineralization could have taken place much earlier along the flow path.

CONCLUSIONS AND IMPLICATIONS

1. Calcite cements that are intergrown with hydrocarbon, fluorite, barite, and galena along fractures indicate that burial diagenesis, mineralization, and hydrocarbon emplacement were coincident on the Derbyshire Platform and can be used to reconstruct fluid migration pathways.
2. During shallow burial, fluids were driven westward along an aquifer from the emergent East Midlands Platform. As interparticle porosity was progressively occluded and hydrostatic head was reduced, there was an evolution towards tectonically controlled fluid flow.
3. Basins surrounding the Derbyshire Platform provided a suitable source of trace elements, hydrocarbons, and fluids for mineralization. Differing geothermal gradients among the basins meant that trace elements were released to fluids at different times, resulting in temporal and spatial variations in calcite cement geochemistry across the Derbyshire Platform.
4. Large volumes of mineralizing fluids were retained in the Edale and Widmerpool basins by overpressuring, with periodic, minor expulsion during rupture of overpressure compartments controlled by the waning effects of extensional tectonism. It was not until the onset of the Variscan Orogeny and associated compressional tectonism in the late

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Fig. 7.—Conceptual fluid-flow history during burial-calcite cementation, mineralization, and hydrocarbon emplacement on the Derbyshire Platform. A) Early–mid Namurian. Meteoric-derived fluids are driven westwards along Dinantian limestone aquifers in the East Midlands Shelf. These contained no hydrocarbon or mineralizing elements, and largely resulted in occlusion of interparticle pores (Zone 3 calcite cementation). Minor volumes of formational fluids may have been expelled from clastic basins surrounding the platform. B) Mid Namurian–mid Westphalian. As interparticle pores in the aquifer were occluded and topographic relief was reduced in the east, the supply of meteoric-derived fluids was progressively removed. Periodic rupture of overpressured compartments and seismic pumping, during extensional fault movement, released small volumes of fluids from the surrounding basins onto the Derbyshire Platform. With ongoing organic maturation and clay dehydration, these fluids were increasingly charged with hydrocarbon and trace elements for mineralization. C) Mid Westphalian onwards. The onset of Variscan compression across northern England led to extensive fault reactivation and basin inversion. This provided a major drive for the expulsion and migration of mineral-charged fluids from the clastic basins, onto the Derbyshire Platform, resulting in the main phase of Pb–Zn–Ba mineralization on the platform.
Westphalian that there was a major drive for fluid expulsion and migration.

5. With the initiation of the compressional regime, fluids were driven onto the platform, primarily from the Widmerpool Basin. Migration was driven along Caledonian basement faults in an approximate southeast–northwest direction. The low volume of minerals other than calcite on the western margin of the Derbyshire Platform reflects selective precipitation of minerals on the eastern side of the platform and a low input of fluids to the platform from the Staffordshire Basin in the west.

6. Reconstruction of fluid expulsion and migration in a tectonically active regime demonstrates variations in fluid flux during post-rift subsidence and basin inversion. Consequently, the complexity of fluid movement on a platform that is receiving fluids from a variety of sources and the importance of understanding both the temporal and spatial variations in cement chemistry when reconstructing flow can be demonstrated.

The results of this study have relevance to other mineralized carbonate platforms in extensional and compressional settings worldwide. In particular, our findings are of relevance to sedimentary basins in extensional and compressional settings that host MVT deposits and also to hydrocarbon reservoirs, where it is crucial to understand the timing and mechanisms of diagenetic cementation and hydrocarbon emplacement.

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