Base Metal Sulfide Mineralization in Lower Carboniferous Strata, Northwest Ireland

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(Received April 16, 2009; accepted February 20, 2010)

Abstract — Zn-Pb sulfide mineralization at Abbeytown mine and Twigspark quarry comprise the only known carbonate-hosted base metal sulfide deposits in the Sligo syncline, northwest Ireland. Limestone sedimentation occurred uniformly throughout the region during the Early Carboniferous (Mississippian) as observed by field relationships and lithofacies; however, petrographic and stable isotope evidence indicate that host-rock dolomitization occurred under different conditions at localities to the west and east of the Ox Mountains inlier, suggesting significant uplift and geologic isolation of these areas prior to dolomitization. Localized fluid flow systems are thought to be responsible for sulfide mineralization and associated epigenetic carbonate cements. West of the Ox Mountains inlier at Abbeytown, evidence of three geochemically distinct fluids are observed: (1) a lower-temperature, lower-salinity fluid (70°–130°C, 4–9 wt.% equiv. NaCl); (2) a lower-temperature, higher-salinity fluid (70°–140°C, 15–24 wt.% equiv. NaCl); and (3) a higher-temperature, moderate-salinity fluid (165°–220°C, 8–14 wt.% equiv. NaCl). Similar fluid types were observed at the Twigspark deposit. The source of the higher-salinity fluid is likely seawater evaporated to near the point of halite precipitation. The higher-temperature fluid is thought to have been derived from deep circulation of basinal brines. It is speculated that mixing of the higher-salinity fluid with the high-temperature fluid was vital for ore formation at Abbeytown because fluid inclusions in sphalerite have homogenization temperatures and salinity values that fall along a mixing trajectory of these end member fluids. Also, areas where the high-salinity end member fluid is absent are barren of sulfides. Less complex fluid systems are indicated for sites east of the Ox Mountains inlier where no sulfide mineralization was observed. Data from base metal sulfide prospects in northwest Ireland indicate no connection with the regionally extensive flow system thought to be responsible for Zn-Pb deposits throughout the Irish Midlands. © 2010 Canadian Institute of Mining, Metallurgy and Petroleum. All rights reserved.

Key Words: Ireland, Abbeytown, Sulfide mineralization, Carbonate-hosted, Fluid inclusions.

Sommaire — Les minéralisations en sulfures de Zn-Pb de la mine Abbeytown et de la carrière Twigspark sont les seules gîtes de métaux usuels à encaissant carbonaté connus dans le synclinial de Sligo, au nord-ouest de l’Irlande. Ces carbonates se sont déposés d’une manière uniforme dans la région au Carbonifère inférieur (Mississippien) tel que l’indiquent les relations de terrain et les lithofaçies; les données pétrographiques et d’isotopes stables indiquent toutefois que la dolomitisation de l’encaissant s’est faite sous des conditions différentes aux localités situées à l’ouest ou à l’est de la boutonnière des Ox Mountains, ce qui suggère un soulèvement et une isolation géologique significative de ces secteurs avant la dolomitisation. L’action de systèmes de circulation locaux sont considérés être à l’origine de la minéralisation sulfureuse et des ciments carbonatés épigénétiques qui leur sont associés. À Abbeytown, à l’ouest de la boutonnière des Ox Mountains, on note les effets de trois fluides géochimiquement distincts: (1) un fluide à basse température peu salin (70°–130°C, 4–9% poids équivalent NaCl); (2) un fluide à basse température fortement salin (70°–140°C, 15–24% poids équivalent NaCl); and (3) un fluide formé à plus haute température et salinité modérée (165°–220°C, 8–14% poids équivalent NaCl). Des fluides similaires ont été observés au gîte Twigspark. La source prémise du fluide le plus salin est de l’eau de mer amenée par évaporation près du point de précipitation de la halite. Le fluide à plus haute température est probablement dérivé de la circulation profonde de saumures dérivées d’un bassin sédimentaire. Il est possible que le mélange du fluide à haute salinité avec celui à haute température ait joué un rôle central dans la genèse de la minéralisation d’Abbeytown parce que les températures d’homogénéisation et les valeurs de salinité des inclusions fluides dans la sphalérite se distribuent sur une ligne de mélange reliant ces deux pôles. De plus, les secteurs ou l’on ne trouve pas trace du terme le plus salin sont stériles en sulfures. Les sites sans minéralisation sulfureuse situés à l’est de la boutonnière des Ox Mountains présentent des systèmes fluides plus simples. Les données provenant des autres occurrences de sulfures de métaux usuels du nord-ouest de l’Irlande ne montrent pas de rattachement avec le système de circulation régional présumé être à l’origine des gîtes de Zn-Pb des Irish Midlands. © 2010 Canadian Institute of Mining, Metallurgy and Petroleum. All rights reserved.

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Introduction

The zinc-lead sulfide mineralization at Abbeytown Mine and Twigspark quarry comprises the only known carbonate-hosted, base metal sulfide deposits in northwestern Ireland (Fig. 1). This study examined epigenetic minerals at several localities within the Sligo syncline of northwestern Ireland to do the following:

1. Identify the source of mineralizing fluids at each locality, and determine whether they were regionally distributed basinal brines, locally convected epigenetic fluids, or some combination of both.
2. Characterize the fluid and diagenetic history at each locality.
3. Determine if, and to what extent, hydrologic connectivity existed between and among the localities during the mineralizing event.
4. Determine if there is any relationship between base metal sulfide mineralization in NW Ireland and that of the Irish Midlands.

Developing the fluid migration history in northwest Ireland will aid in understanding the genesis of Zn-Pb mineralization in the Abbeytown mine, and might have applications to other carbonate-hosted base metal sulfide deposits in similar geologic settings.

Recent studies conducted on Zn-Pb mineralization in the Rathdowney Trend in the Irish Midlands (Fig. 1) provided evidence for regionally persistent brines derived from seawater evaporated beyond the point of halite precipitation, which mixed on localized scales with other fluids, some of which likely circulated through basement rocks (Banks et al., 2002; Nagy et al., 2004; Wilkinson et al., 2005; Johnson et al., 2009). Several studies have shown that as many as three chemically distinct fluids were involved regionally in the mineralizing events (e.g., Gregg et al., 2001; Johnson et al., 2009). The relative tectonic isolation of mineralization in northwest Ireland from the mineralized regions in the Irish Midlands provides an ideal opportunity to investigate the fluid history and sulfide mineralizing events in this district relative to regional and/or localized fluid flow models that have been proposed for ore deposition elsewhere in Ireland.

Fig. 1. Map of the major tectonic provinces and sedimentary basins of Ireland. The region of study is indicated. Modified from Gregg et al. (2001).

Geological Setting

Structure and Basement Geology

The region of base metal sulfide mineralization in northwest Ireland is isolated structurally from carbonate-hosted mineralization of the Irish Midlands, and is related geographically to the Ox Mountains uplift (Fig. 2). Comprehensive petrographic examinations of the Proterozoic basement rocks underlying the region and of the Ox Mountains uplift are found in Molloy and Sanders (1983), Johnston (1995a, 1995b), MacDermot et al. (1996), and Thomas et al. (2004). The Ox Mountains are bounded by two regional-scale normal faults: on the southeast by the Dromahair Fault (DF) and on the northwest by the Ox Mountains-Pettigoe fault (OMPF) forming a horst structure with Carboniferous sedimentary rocks draped around this uplift (Fig. 3).

Hitzman (1986) proposed that the Ox Mountains were
not a paleogeographic feature at the onset of marine deposition during the Chadian, because of the absence of coarse siliciclastic sediments at the base of the sequence. However, pebbly channels within the Ballyshannon Limestone suggest that movement of faults might have begun in the late Chadian or early Arundian. Somerville et al. (2009) observed facies thickness variations in Glencar and Dartry Limestone strata, indicating that significant uplift had occurred prior to the early Asbian. The horst block likely was reactivated again at the end of the Carboniferous during the Variscan orogeny and during the Paleogene Alpine orogeny (Somerville et al., 2009).

A series of E- to NE-striking, high-angle reverse and normal faults transect the Sligo syncline to the west of the Ox Mountains, extending into Sligo Bay. Between these high-angle faults, Carboniferous strata are folded broadly, displaying a wide range of dip angles and directions. Movement along faults within the Sligo syncline commenced during the Early Carboniferous with significant variations in thickness in the Benbulben Shale, Glencar Limestone, and Dartry Limestone formations, possibly resulting from synsedimentary faulting (Hitzman, 1986; Somerville et al., 2009). Evidence for reactivation of basement faults during the Late Carboniferous has been identified in some areas of northwest Ireland (Price and Max, 1988; Mitchell, 1992).

Carboniferous Stratigraphy

Several earlier studies of the Sligo syncline region (Oswald, 1955; George et al., 1976; Philcox et al., 1992; MacDermot et al., 1996; Cözar et al., 2005, 2006; Somerville et al., 2009) focused on defining and correlating the Carboniferous strata that host sulfide mineral deposits in the Sligo area. The northwest was the last region of Ireland to be submerged by a northward-transgressing sea during the Late Devonian and Early Carboniferous. The basal Twispark Formation was defined by Philcox et al. (1992) from cores and quarries as a basal sandstone and sandy limestone (10–20 m thick), overlain by approximately 35 m of argilaceous micrites and capped by oolitic sandstones (Fig. 3). An age-equivalent unit of similar lithology is informally termed the Ballysodare Limestone with limited surface exposures near the Abbeytown mine (Hitzman, 1986).
Overlying the Twigspark Formation is the Chadian–Arundian Ballyshannon Limestone, which hosts Zn-Pb mineralization in the Abbeytown area. The Ballyshannon Limestone is marked at its base by the Lower Grit Unit, composed of a 1 to 2 m-thick pebbly calcarenite, and overlain by 60 m of fine calcarenites with interbedded shales (Fig. 3). The lower calcarenites and shales are overlain by dark, fine-grained crinoidal packstones with chert nodules and interbedded shales totaling ~200 m thickness (Philcox et al., 1992; MacDermot et al., 1996). Approximately 40 m above the base of the Ballyshannon Limestone is the 5 to 7 m-thick Index bed (Fig. 3), a calcareous cross-bedded sandstone to fine-grained conglomerate containing detrital quartz, feldspar, and mica cemented by carbonate and Zn-Pb-Fe sulfides in the mine area. The Index bed is an important marker in the Abbeytown area, but its lateral extent beyond the mine is unknown.

The Ballyshannon Limestone is overlain by the Bundoran Shale, Mullaghmore Sandstone, and Benbulben Shale formations, which in turn are succeeded by the Asbian Glencar Limestone (cyclic argillaceous limestone) and Dartry Limestone (carbonate mudmounds and cherty limestones; Fig. 3). During deposition of these latter two units, the region was a continuous carbonate shelf (Somerville et al., 2009). The Brigantian Meenymore Formation was deposited discomformably over the Dartry Limestone to the east and southeast of the Sligo syncline (east of the Ox Mountains inlier), marking the base of the Leitrim Group siliciclastic succession (Cózar et al., 2005, 2006). The Meenymore Formation consists of thin-bedded carbonates, laminated shales, fluvial sandstones, and two distinct evaporite deposits (West et al., 1968; Philcox et al., 1992). The presence of evaporite minerals and preserved mudcracks indicate periodic exposure in an intertidal/supratidal sabkha depositional setting.

**Mineralization**

Mining activity at Abbeytown occurred intermittently from the 1700s until 1961 with about 1.1 Mt of 5.3% combined zinc and lead recovered (Hitzman, 1986; Kelly, 2007). Sulfide mineralization at Abbeytown mine consists of sphalerite, galena, pyrite, and chalcopyrite (Hitzman, 1986; MacDermot et al., 1996). Below the Index bed, galena is the dominant ore mineral; within the bed, sphaler-
ite is dominant; and above the Index bed, pyrite is more abundant. Sulfide mineralization appears to be linked to the distribution of dolomitized host rock in the main orebody; however, some late-stage pyrite is present in calcite breccias. Sulfide minerals occur as open-space fillings in breccias and fractures as well as disseminated in meso- and microporosity, particularly in the Index bed. Hitzman (1986) recognized four stages of mineralization: (1) early epigenetic dolomitization of the host limestone followed by, (2) a main-stage sulfide event consisting of pyrite, sphalerite, galena, and infrequent chalcopyrite; (3) calcite-pyrite brecciation, which crosscuts earlier mineralization and includes minor pyrobitumen; and (4) late vug-filling calcite, pink saddle dolomite, quartz, and less frequently, euhedral chalcopyrite.

The Zn-Pb sulfide deposit at Abbeytown is bounded by the Ox Mountains-Pettigoe normal fault (OMPF) to the south, and the east-trending Ballysodare normal fault to the north (Fig. 2). Hitzman (1986) observed that the smaller western orebody is related closely to the presence of a minor high-angle reverse fault, the NNE-trending Abbeytown Fault, and the main orebody is related to an asymmetric syncline within the fault-bounded block (Fig. 4). The two orebodies are separated horizontally by approximately 150 m. Sulfide mineralization extends laterally away from the faults and is contained preferentially within and adjacent to the Index bed (Fig. 4), which is more porous than the surrounding limestone.

Twigspark quarry is located along the northern extension of the OMPF, 20 km northeast of Abbeytown (Fig. 2). Minor sulfide mineralization at Twigspark quarry consists of sphalerite, galena, pyrite, and chalcopyrite. MacDermot et al. (1996) suggested that mineralization occurs in NE-trending veins parallel to small faults in the area. Traces of pyrite and sphalerite were observed in this study at multiple stratigraphic intervals in cores from near Twigspark quarry. The lateral extent of the mineralized zone is unknown, although additional exploration in the area has been unsuccessful.

**Methods**

Sample localities were selected to include known sulfide mineralization in the region, and to allow for the development and examination of geographic and stratigraphic relationships. An emphasis was placed on collecting samples showing dolomitization, void-filling carbonate cements, and sulfide mineralization. West of the Ox Mountain inlier, 26 hand samples were collected from Abbeytown mine and quarry, 17 hand samples were selected from Trotter’s quarry and the nearby Twigspark quarry (TR/TW), and 11 samples were obtained from three diamond drill cores extending down through the Ballyshannon Limestone to the Proterozoic basement near Twigspark quarry (Fig. 2). East of the Ox Mountains inlier, five hand samples were obtained at O’Donnell’s Rock (Fig. 2) from the uppermost Glen car Limestone extending into the basal Dartry Limestone, and six hand samples were collected at Tate’s quarry from the Ballyshannon Limestone. Seventy-four thin sections were prepared from samples collected from the localities in northwestern Ireland (detailed descriptions are provided in Persellin, 2009).

Cathodoluminescence (CL) petrography of dolomite and calcite cements was conducted using a CITL CL8200 MK5-1 Optical Cathodoluminescence System mounted on an Olympus BX 41 microscope equipped with 4X and 10X long focal distance objective lenses, and a “Q Imaging”...

**Fig. 4.** *a.* Local map of Abbeytown mine area. The extent of old mine workings and modern quarry face are indicated. Modified from Hitzman (1986) and Kelly (2007). *b.* Generalized cross section of Abbeytown mine area. Location, orientation, and depth of penetration of faults are inferred from cores drilled in the mine area. Modified from Hitzman (1986).
Fluid inclusion microthermometric measurements were carried out using a Linkam THMSG 600 heating and cooling stage mounted on an Olympus BX41 microscope equipped with 40X and 100X long focal distance objective lenses. Temperatures of homogenization (Th) and last ice melting (Tm) have errors of ±1.0°C and ±0.3°C, respectively, based on analysis of synthetic fluid inclusions (Shelton and Orville, 1980). The inclusions analyzed in this study were aqueous, two-phase, primary, pseudo-secondary, and secondary inclusions, using the terminology of Roedder (1984). Salinities were calculated from Tm measurements using equations from Bodnar (1992).

Halogen contents of included fluids were determined using a crush-leach ion chromatography technique modified from Banks et al. (1991). The primary modification was that samples were rinsed 10 times in doubly deionized water and placed in a drying oven at 40°C to facilitate drying and to ensure that no fluid inclusions were decrepitated during drying. Samples for fluid inclusion leachate analysis were chosen from those previously studied using fluid inclusion microthermometry to select those that contained dominantly one generation of fluid. Detection limits are 0.005 ppm for Cl and 0.001 ppm for Br. Accuracy, as determined by analysis of standard control solutions, was within 1% of the known value. Fluid compositions were reconstructed using the method described by Banks et al. (2002), using estimated chloride concentrations determined from cooling experiments on fluid inclusions from our study.

Oxygen and carbon stable isotopic compositions of carbonates were determined using a Thermo-Finnigan Delta Plus gas-source mass spectrometer with a Kiel device. The δ¹³C and δ¹⁸O values (relative to the VPDB standard) have standard errors of less than ±0.05‰, based on replicate measurements of the NBS-19 calcite reference standard, and have been corrected for reaction with 103% phosphoric acid at 70°C (Rosenbaum and Sheppard, 1986).

**Results**

**Petrology**

**Abbeytown:** The host Ballyshannon Limestone at the Abbeytown mine is fossiliferous and composed of peloidal packstones and grainstones. Voids are filled by early diagenetic marine carbonate cements (Fig. 5).

Both field relationships and petrology indicate that replacement dolomitization occurred early (Fig. 5) and is limited generally to the main orebody within and adjacent to the Index bed. The western orebody is undolomitized to partially dolomitized near the Abbeytown fault. Replacement dolomite is commonly dark gray, coarsely crystalline (2–4 mm), and nonplanar, although some planar-s dolomite is present (Fig. 6a; using the dolomite textural classification of Sibley and Gregg, 1987). Replacement dolomite displays a consistent multizoned CL microstratigraphy throughout the Abbeytown area.

Epigenetic carbonate cementation occurs in breccias, fractures, joints, and vugs. Calcite cement is composed typically of large (>1 cm) blocky crystals. Dolomite cements occur in two forms: (1) large (cm-scale), white to pink to brown, saddle dolomite crystals; and (2) fine-grained, crystalline, gray, planar-e (sensu Sibley and Gregg, 1987), vug-filling dolomite cement. Dolomite cements at Abbeytown display a CL microstratigraphy consisting of three zones (Fig. 7a,b) followed less commonly by a fourth outer zone: CZ1 is a moderately luminescent, mottled core; CZ2 is a wide, moderately to non-luminescent zone; CZ3 is a brightly luminescent, typically thin band; and CZ4, where present, is a multibanded, luminescent zone.

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Fig. 5. Paragenetic sequence of events for: **a.** Abbeytown; **b.** Twigspark/Trotter’s quarry; **c.** O’Donnell’s Rock; and **d.** Tate’s quarry. Note multiple sulfide mineralization events at Abbeytown compared to a single mineralization event at Twigspark/Trotter’s quarry.
An early sulfide-mineralizing event, possibly correlative with the initial dolomitization, resulted in the formation of early sphalerite and pyrite (Fig. 5a). Early mineralization was limited to the Index bed (Fig. 6b) and underlying carbonates immediately adjacent to the Abbeytown fault. The main sulfide-mineralizing event (Fig. 5a) resulted in the emplacement of Zn-Pb sulfides adjacent to the Abbeytown fault in and below the Index bed.

Twigspark/Trotter’s Quarry: The Dartry Limestone, observed at the surface in Trotter’s quarry, was deposited as carbonate mud mounds infrequently draped by relatively thin (<1 m) shale beds and is composed primarily of micritic mud and crinoidal wackestones and packstones. Stromatolites cavities are present in undolomitized mud mound cores and are filled commonly with early diagenetic crypto-fibrous marine calcite cement followed by blocky calcite cement (Fig. 6c). Dolomitization of limestone is sparse at Trotter’s quarry and is more extensive in the stratigraphically lower Twigspark quarry and associated drill cores. The age of mineralized dolomitic limestone cropping out at Twigspark quarry is unknown, because only a small outcrop is visible at the surface with no observed contacts with other units. The nearby Twigspark drillhole was collared in Ballyshannon Limestone, so it is assumed that the quarry outcrop is also Ballyshannon.

Replacement dolomite at Twigspark/Trotter’s quarry is finely to coarsely crystalline (1–2 mm), planar-s and planar-e to nonplanar dolomite (Fig. 6d). Planar replacement dolomite crystals from the Twigspark cores exhibit a multizoned CL microstratigraphy similar to that observed at Abbeytown. Detrital grains are abundant in Twigspark samples, and are dominantly quartz with minor alkali feldspars and micas. The abundance of detrital material increases down section.

Epigenetic carbonate cements occupy most fractures and vugs at Twigspark/Trotter’s quarry. Large (8–10 mm), saddle dolomite formed in fractures, followed paragenetic-
Fig. 7.  

a. Partly cross-polarized light photomicrograph of open-space-filling epigenetic dolomite cement from the Abbeytown ore deposit.  
b. Cathodoluminescence photomicrograph of a, with distinctive three-zone CL stratigraphy labelled.  
c. Partly cross-polarized light photomicrograph of open-space-filling epigenetic dolomite cement from Twigspark quarry.  
d. Cathodoluminescence photomicrograph of c displaying two-zone CL stratigraphy typical of the Twigspark/Trotter’s quarry area.  
f. Cathodoluminescence photomicrograph of e, displaying two calcite zones (uniform and multibanded) and dull to non-CL dolomite cement.
ally by minor sulfide mineralization and blocky calcite cements (Fig. 5b). Pressure dissolution features are present in some samples. Uncemented fractures, dissolution of detrital grains (likely feldspar), and dissolution of saddle dolomite crystals account for significant porosity at Twigspark.

Epigenetic saddle dolomite cements from the Twigspark area display varying CL zonation patterns at different stratigraphic levels; however, the outer zones correlate throughout the section. Present at all levels is a distinct two-zone CL pattern consisting of a wide, nonluminescent inner zone and a typically thin, brightly luminescent outer rim (Fig. 7c,d). As many as three additional CL zones occur in the interior of dolomite cement crystals collected from Trotter’s quarry: (1) a slightly luminescent to nonluminescent core; (2) a wide, moderately luminescent, mottled zone; and (3) a thin, slightly darker zone. In all cases, the two-zone pattern observed in dolomite cement from Twigspark area exists overlying these interior zones (Fig. 7c,d).

East of the Ox Mountains Inlier: Host limestone at O’Donnell’s Rock is composed of fossiliferous grainstone with marine calcite cement. It commonly is dolomitized in the sampled area, but the lateral extent of dolomitization is unknown. Replacement dolomite is bimodal between medium crystalline (<1 mm) planar-s to nonplanar and very coarsely crystalline (2–3 mm) planar-e rhombs (Fig. 8a). Replacement dolomite crystals are moderately cathodoluminescent but display no zoning.

Epigenetic mineralization consists of vug- and fracture-filling calcite, dolomite, and quartz (Fig. 8a), with minor pyrite. Dolomite cement consists of 5–10 mm saddle crystals. Dolomite cement is dull to nonluminescent, and rarely displays faint zoning (Fig. 7e,f). Infrequently, dolomite crystals display a very thin, bright CL outer zone. Void-filling, cm-scale, blocky calcite cement crystals display an inner zone that is uniform to faintly banded bright CL, followed by a bright and dark multibanded CL zone (Fig. 7e,f). Quartz cement is polymorphic and non-CL, with individual grains up to 1 cm in size.

Limestone at Tate’s quarry is comprised of fossiliferous grainstone and packstone with marine calcite cement, containing scattered planar-e dolomite (<10 volume %), which has undergone minor dedolomitization (Fig. 8b). Replacement dolomite crystals at Tate’s quarry exhibit a simple two-zoned CL microstratigraphy. Epigenetic void-filling cements consist primarily of blocky calcite and less frequently fluorite (Fig. 8c). Epigenetic dolomite cement and sulfide mineralization are absent at this locality.

Fluid Inclusion Analysis

Fluid inclusions were analyzed in authigenic, open-space-filling minerals from all four study localities (Fig. 1). No fluid inclusions were observed in early marine calcites or replacement dolomites (Fig. 5). Individual homogenization temperatures (Th), Eutectic (first observed melting) temperatures (Te), last ice-melting temperatures (Tm), and calculated salinities for fluid inclusions measured in this study are tabulated in Persellin (2009). Ranges of values for Th, Te, Tm, and calculated values for wt.% NaCl equivalent are listed in Table 1. Pressure corrections were not applied to Th values, so they should be regarded as

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**Fig. 8.** Cross-polarized light photomicrographs showing: a. Nonplanar dolomite replacing Dartry limestone from O’Donnell’s Rock quarry, with open-space-filling dolomite and quartz cement. b. Lime packstone of the Ballyshannon limestone from Tate’s quarry, with scattered planar-p dolomite rhombs. c. Vug in limestone from Tate’s quarry filled by epigenetic fluorite and calcite cement.
minimum constraints on actual fluid temperatures. Based on previously published and their own work, Wilkinson and Earls (2000) estimated maximum pressure in the Irish ore fields during mineralization at approximately 230 bars, which indicates a pressure correction of only ~12°C. Figure 9 displays Th values plotted against wt.% NaCl equiv. for all individual fluid inclusions. Fluid inclusion assemblages were constructed from groups of measured inclusions in single fields of view (Goldstein and Reynolds, 1994). Values for inclusions that were judged to have been stretched, necked, leaked, or possibly mismeasured were disregarded. Fields of view that contained only one measurable inclusion also were disregarded. Figure 10 displays Th values plotted against wt.% NaCl equiv. for fluid inclusion assemblages.

Measured inclusions ranged from 2 to 12 µm in their longest dimension. Smaller inclusions were observed, but were not measured due to poor optical resolution. No daughter minerals were observed in any of the inclusions and, with exceptions noted below, all fluid inclusions contained ~5% vapor volume at 20°C.

Abbeytown: Dolomite-hosted fluid inclusions at Abbeytown ranged from 5 to 8 µm and were all judged to be primary or, in the case of one assemblage, pseudosecondary. Measured fluid inclusions in sphalerite range from 3 to 6 µm in size, and all were primary. Measured fluid inclusions in calcite range from 5 to 12 µm in size. Eutectic temperatures below -40°C (Table 1) indicate that the fluids likely are complex Na-Ca-Mg-Cl brines.

Calcite-hosted fluid inclusions are mainly primary with the exception of two pseudosecondary assemblages. Higher minimum Te values for calcite-hosted fluid inclusions (Table 1) suggest precipitation from simpler brines (more like NaCl-brines).

Dolomite- and calcite-hosted fluid inclusions from Abbeytown plot between three proposed fluid end members (Figs. 9a, 10a): a lower salinity (4–9 wt.% NaCl equiv.), lower temperature (70°–130°C) end member designated as fluid type 1 (Ft1); a higher salinity (15–24 wt.% NaCl

![Fig. 9. Homogenization temperature (Th) values vs. salinity (wt.% NaCl equiv.) for individual fluid inclusions from four localities in northwest Ireland: a. Abbeytown; b. Trotter’s quarry and Twigspark; c. O’Donnell’s Rock; and d. Tate’s quarry. Proposed end-member fluid-types Ft1, Ft2, and Ft3 are labelled.](https://pubs.geoscienceworld.org/cim/emg/article-pdf/177481/35.pdf)
Table 1. Ranges of Microthermometric Measurements for Fluid Inclusions from Northwest Ireland

<table>
<thead>
<tr>
<th>Location</th>
<th>Mineralogy</th>
<th>Inclusion Type</th>
<th>No.</th>
<th>Th (°C) Range</th>
<th>Te (°C) Range</th>
<th>Tm (°C) Range</th>
<th>Wt.% NaCl equiv. Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abbeytown Main orebody</td>
<td>Dolomite</td>
<td>Primary &amp; pseudosecondary</td>
<td>35</td>
<td>108 to 207</td>
<td>−45.2 to −21.9</td>
<td>−11.2 to −3.3</td>
<td>5.4 to 15.2</td>
</tr>
<tr>
<td></td>
<td>Sphalerite</td>
<td>Primary</td>
<td>27</td>
<td>109 to 168</td>
<td>−43.7 to −24.3</td>
<td>−12.6 to −7.0</td>
<td>10.5 to 15.5</td>
</tr>
<tr>
<td></td>
<td>Calcite</td>
<td>Primary</td>
<td>67</td>
<td>98 to 222</td>
<td>−30.6 to −22.4</td>
<td>−16.1 to −2.5</td>
<td>4.2 to 19.5</td>
</tr>
<tr>
<td>Abbeytown West orebody</td>
<td>Dolomite</td>
<td>Primary &amp; pseudosecondary</td>
<td>43</td>
<td>105 to 173</td>
<td>−43.0 to −20.2</td>
<td>−11.0 to −2.7</td>
<td>4.5 to 15.0</td>
</tr>
<tr>
<td></td>
<td>Calcite</td>
<td>Primary &amp; pseudosecondary</td>
<td>22</td>
<td>70 to 121</td>
<td>−36.5 to −24.0</td>
<td>−20.4 to −2.6</td>
<td>4.3 to 22.7</td>
</tr>
<tr>
<td>Trotter’s Quarry</td>
<td>Dolomite</td>
<td>Primary</td>
<td>25</td>
<td>95 to 198</td>
<td>−41.0 to −21.3</td>
<td>−9.3 to −3.5</td>
<td>5.7 to 13.1</td>
</tr>
<tr>
<td></td>
<td>Calcite</td>
<td>Primary &amp; pseudosecondary</td>
<td>19</td>
<td>84 to 188</td>
<td>−44.2 to −22.7</td>
<td>−10.2 to −0.8</td>
<td>1.4 to 14.5</td>
</tr>
<tr>
<td>Twigspark Quarry</td>
<td>Calcite</td>
<td>Primary</td>
<td>3</td>
<td>124 to 208</td>
<td>−42.8 to −35.1</td>
<td>−11.2 to −6.5</td>
<td>9.9 to 15.2</td>
</tr>
<tr>
<td>O’Donnell’s Rock</td>
<td>Dolomite</td>
<td>Primary</td>
<td>48</td>
<td>106 to 212</td>
<td>−49.2 to −23.1</td>
<td>−17.0 to −3.3</td>
<td>5.4 to 20.2</td>
</tr>
<tr>
<td></td>
<td>Calcite</td>
<td>Primary</td>
<td>29</td>
<td>74 to 198</td>
<td>−55.6 to −23.1</td>
<td>−16.4 to −4.3</td>
<td>6.9 to 19.8</td>
</tr>
<tr>
<td>Tate’s Quarry</td>
<td>Calcite</td>
<td>Primary</td>
<td>14</td>
<td>107 to 155</td>
<td>−48.6 to −30.8</td>
<td>−8.0 to −4.2</td>
<td>6.7 to 11.7</td>
</tr>
<tr>
<td></td>
<td>Fluorite</td>
<td>Primary</td>
<td>18</td>
<td>132 to 161</td>
<td>−29.2 to −21.4</td>
<td>−9.8 to −5.1</td>
<td>8.0 to 13.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Secondary</td>
<td>14</td>
<td>107 to 125</td>
<td>−30.0 to −19.6</td>
<td>−8.3 to −4.1</td>
<td>6.6 to 12.1</td>
</tr>
</tbody>
</table>

Base Metal Sulfide Mineralization in Lower Carboniferous Strata, Northwest Ireland • C.J. Persellin et al.

Twigspark/Trotter’s Quarry: Fluid inclusions in dolomite at Twigspark and Trotter’s quarry range in size from 4 to 8 µm, and were all judged to be primary. Calcite-hosted inclusions range from 2 to >10 µm and were judged to be primary with the exception of three assemblages that are regarded as pseudosecondary (Fig. 10b). The higher Th values (>175°C) measured for fluid inclusions in both dolomite and calcite (Fig. 9b) were judged to result from stretching or necking and are not included as fluid inclusion assemblages (Fig. 10b). As with Abbeytown, Te values of fluid inclusions from Twigspark and Trotter’s quarry (Table 1) indicate that fluids likely are complex Na-Ca-Mg-Cl brines.

Fluid inclusion assemblages (Fig. 10b) indicate that two of the three end member fluids encountered in Abbeytown fluid inclusions, Ft1 and Ft2, are present. It is not clear whether the moderate salinity, higher temperature fluid present at Abbeytown (Ft3) was present at Twigspark and Trotter’s quarry, because no fluid inclusion assemblages with this composition were documented, although several individual inclusions of this composition were observed (Fig. 9b). However, these might represent outliers resulting from later stretching.

O’Donnell’s Rock: All fluid inclusions measured in samples from O’Donnell’s Rock were judged to be primary. Fluid inclusions in dolomite at O’Donnell’s Rock range in size from 2 to 4 µm with vapor contents of ≤5 volume %. Calcite-hosted fluid inclusions from O’Donnell’s Rock range from 2 to 6 µm in size with similar vapor contents. Eutectic temperatures less than −40°C for dolomite- and calcite-hosted fluid inclusions indicate complex Na-Ca-Mg-Cl brines.

Fluid inclusions in authigenic quartz range from 4 to 10 µm in longest dimension, and vapor contents range up to 10 volume %. Eutectic temperatures measured for quartz-hosted fluid inclusions are distinctly higher than for those hosted in carbonate cements, suggesting precipitation by a less complex, NaCl-dominated brine.

Fluid inclusions at O’Donnell’s Rock are distributed between two end member fluids similar to Ft1 and Ft3 encountered at Abbeytown (Table 1, Figs. 9c, 10c). Dolomite- and quartz-hosted fluid inclusions range between both fluid types, whereas calcite-hosted inclusions have characteristics of Ft1 only.

Tate’s Quarry: Fluid inclusions in calcite from Tate’s quarry were judged to be primary and range from 4 to 6 µm, with vapor contents of ≤5 volume %.

Both primary and secondary fluid inclusions were observed in fluorite from Tate’s quarry (Table 1, Figs. 9d, 10d). The fluid inclusions range in size from 4 to 10 µm, with primary inclusions tending to be larger than secondary inclusions. Vapor contents of fluid inclusions in fluorite are ≤5 volume %.

Eutectic temperatures of calcite- and fluorite-hosted fluid inclusions all are greater than −36°C. Fluid inclusions from Tate’s quarry plot as two groups with moderate
other samples, which contain solely Ft1 or Ft2 inclusions, show no similar bromide enrichment. In any case, the data, taken as a whole, indicate evaporation of seawater past the point of gypsum saturation, but not to the point of halite precipitation.

The data from northwest Ireland are similar to those for ore-stage fluids in Zn-Pb sulfide deposits in the Irish Midlands (Banks et al., 2002), and to low-to-moderate salinity fluids found in dolomite cements in Lower Carboniferous strata in central and southern Ireland (fluid types 2 and 3 of Johnson et al., 2009). However, the data do not indicate the presence of saline fluids with high bromide concentrations, like those commonly found in regionally extensive dolomites of southern Ireland (fluid type 1 of Johnson et al., 2009) and in postore calcites of the Irish Midlands (Banks et al., 2002) (Fig. 11).

Stable Isotope Geochemistry

The $\delta^{13}C$ and $\delta^{18}O$ values (relative to VPDB) of samples analysed in this study are tabulated in Persellin (2009), and are summarized here.
Host limestones at Abbeytown mine and quarry have δ¹³C values of 1.3‰ to 4.3‰, and δ¹⁸O values of −9.0‰ to −6.6‰ (Fig. 12a). The δ¹³C and δ¹⁸O values of host dolomites are 2.1‰ to 4.1‰, and −9.9‰ to −8.2‰, respectively. Dolomite cements from the main orebody have δ¹³C and δ¹⁸O values of 3.4‰ to 3.6‰, and −7.4‰ to −5.4‰, respectively. Dolomite cements from the western orebody display lower δ¹³C and δ¹⁸O values of 2.1‰ to 3.0‰, and −10.9‰ to −8.6‰, respectively. Calcite cements have δ¹³C and δ¹⁸O values of 0.5 to 2.3‰, and −13.5‰ to −7.9‰, respectively.

Host limestones from Twigspark cores and Twigspark and Trotter’s quarries have δ¹³C values of 3.4‰ to 3.9‰, and δ¹⁸O values of −6.7‰ to −4.7‰ (Fig. 12b). Host dolomites have δ¹³C and δ¹⁸O values of 2.4 to 3.6‰, and −9.0‰ to −7.9‰, respectively. Dolomite cements display δ¹³C and δ¹⁸O values of 0.1‰ to 1.6‰, and −12.9‰ to −9.5‰, respectively, excluding one datum (δ¹³C = 3.4, δ¹⁸O = −4.4). Values obtained from calcite cements plot as two separate populations: those from Trotter’s quarry have δ¹³C and δ¹⁸O values of 3.0‰ to 3.2‰, and −9.2‰ to −7.1‰, respectively; whereas those from Twigspark cores have lower δ¹³C and δ¹⁸O values of 0.3‰ to 1.4‰, and −13.3‰ to −11.1‰, respectively.

A single sample of host limestone at O’Donnell’s Rock has a δ¹³C value of 2.5‰ and a δ¹⁸O value of −5.7‰ (Fig. 12c). Host dolomites have δ¹³C and δ¹⁸O values of 2.6‰ to 3.2‰, and −7.1‰ to −5.4‰, respectively. Dolomite cements display δ¹³C and δ¹⁸O values of 2.2‰ to 2.9‰, and −9.2‰ to −8.5‰, respectively. Calcite cements have δ¹³C values of 1.4‰ to 2.3‰ and δ¹⁸O values of −10.4‰ to −6.6‰, respectively.

Host limestone samples from Tate’s quarry have δ¹³C and δ¹⁸O values of 3.3‰ to 3.7‰, and −5.4‰ to −4.3‰, respectively (Fig. 12d). Two samples of calcite cement display identical δ¹³C values of 3.0‰ and δ¹⁸O values of −9.2‰ to −5.7‰.

**Discussion**

**Sedimentation and Early Diagenesis**

Field relationships and petrology, coupled with the relatively homogeneous δ¹³C and δ¹⁸O values measured in host limestones from the four study localities, suggest marine sedimentation conditions were similar across the region. This view is consistent with facies distribution mapping conducted by Cózar et al. (2005). The δ¹³C and δ¹⁸O values for limestones obtained from northwest Ireland are a good match for typical limestone deposited near equilibrium with Mississippian seawater, or affected by fresh water dia-

---

**Table 2. Chloride and Bromide Concentrations (log-ppm) of Inclusion Fluids from Northwest Ireland**

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Unit</th>
<th>Mineralogy</th>
<th>Fluid Type</th>
<th>Log ppm (Cl)</th>
<th>Log ppm (Br)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abbeytown West orebody</td>
<td>Ballyshannon Limestone</td>
<td>Dolomite Cement</td>
<td>1 &amp; 2</td>
<td>4.77</td>
<td>2.79</td>
</tr>
<tr>
<td>Abbeytown Main orebody</td>
<td>Ballyshannon Limestone</td>
<td>Dolomite Cement</td>
<td>1 &amp; 3</td>
<td>4.79</td>
<td>2.55</td>
</tr>
<tr>
<td>Abbeytown Main orebody</td>
<td>Ballyshannon Limestone</td>
<td>Sphalerite</td>
<td>2</td>
<td>4.94</td>
<td>2.23</td>
</tr>
<tr>
<td>Twigspark Quarry</td>
<td>Ballyshannon (?) Limestone</td>
<td>Calcite Cement</td>
<td>1 &amp; 3 (?)</td>
<td>4.87</td>
<td>2.17</td>
</tr>
<tr>
<td>Twigspark Core</td>
<td>Ballyshannon Limestone</td>
<td>Dolomite Cement</td>
<td>2</td>
<td>4.99</td>
<td>2.59</td>
</tr>
<tr>
<td>Twigspark Core</td>
<td>Twigspark Formation</td>
<td>Dolomite Cement</td>
<td>1 &amp; 2</td>
<td>4.75</td>
<td>2.74</td>
</tr>
<tr>
<td>O’Donnell’s Rock Quarry</td>
<td>Dartry Limestone</td>
<td>Calcite Cement</td>
<td>1</td>
<td>4.72</td>
<td>2.23</td>
</tr>
<tr>
<td>O’Donnell’s Rock Quarry</td>
<td>Dartry Limestone</td>
<td>Quartz Cement</td>
<td>1 (?) &amp; 3</td>
<td>4.88</td>
<td>2.60</td>
</tr>
<tr>
<td>Tate’s Quarry</td>
<td>Ballyshannon Formation</td>
<td>Calcite Cement</td>
<td>1 (?)</td>
<td>4.73</td>
<td>2.50</td>
</tr>
</tbody>
</table>

---

**Fig. 11.** Reconstructed chloride and bromide concentrations (log-ppm) of inclusion fluids from northwest Ireland. The seawater evaporation and dilution trend as well as the points at which gypsum (CaSO₄·2H₂O), halite (NaCl), and epsomite (MgSO₄·7H₂O) precipitate are shown. Also shown are ore fluids and postore fluids in calcite from the Irish Midlands (Banks et al., 2002), and fluids in regionally extensive dolomite cements from southern Ireland (Johnson et al., 2009).
genesis in the case of samples having slightly more negative \(\delta^{18}O\) values (Fig. 12; Popp et al., 1986).

Relatively homogeneous sedimentary deposition throughout the northwest Ireland region suggests that uplift of the Ox Mountains inlier occurred after sedimentation. In particular, stratigraphy and stable isotope geochemistry indicate that uplift of the inlier did not affect carbonate deposition. The influence of the Ox Mountains uplift on diagenetic processes is more evident in our geochemical data for dolomite. The host dolomite displays a tight cluster of \(\delta^{13}C\) and \(\delta^{18}O\) values for samples from Abbeytown and from Twigspark and Trotter’s quarries (Fig. 12a,b), which suggests that early dolomitization processes likely were similar in the two areas. Host dolomite from O’Donnell’s Rock has \(\delta^{18}O\) values more positive than those measured at Abbeytown or Twigspark and Trotter’s quarries, possibly indicating that sample localities east of the Ox Mountains Inlier (Fig. 2) were affected by dolomitizing fluids derived from a different source.

CL microstratigraphies of host dolomite can be traced within individual sample localities, but these do not correlate among the four areas within the northwest Ireland region. Differences in host dolomite CL microstratigraphies are greatest between eastern and western locations, suggesting that structural isolation caused by the Ox Mountains inlier might have already occurred prior to host-rock dolomitization.

Mineralizing Fluids

Mineralization in northwest Ireland is related closely to major structural features in the region. Abbeytown and Twigspark and Trotter’s quarries are close to the Ox Mountains-Pettigo fault (OMPf), a regional structural feature associated with uplift of the Ox Mountains (Fig. 2). Tate’s quarry and O’Donnell’s Rock are in the vicinity of the Dromahair fault, a companion fault to the OMPF that defines the southern and eastern edge of the uplift. Locally, the distribution of ore mineralization at Abbeytown appears to be related to structural features, including the Abbeytown fault (Fig. 4).

Fig. 12. Plots of \(\delta^{13}C\) vs. \(\delta^{18}O\) values (VPDB) for carbonate host rocks and calcite and dolomite cements from the sampled localities in northwest Ireland: a. Abbeytown; b. Trotter’s quarry and Twigspark; c. O’Donnell’s Rock; d. Tate’s quarry. The range of isotopic compositions for carbonates precipitated in equilibrium with Mississippian seawater is shaded.
Paragenetic sequences at the four sampled localities indicate a lack of regionally persistent epigenetic events (Fig. 5a–d). Sulfide mineralization at Abbeytown occurred in multiple phases: an early sphalerite and pyrite phase, followed by the main sphalerite and galena phase, punctuated by a relatively late pyrite phase (Fig. 5a). Two observed stages of dolomitization at Abbeytown are likely related to two separate sulfide mineralization events. At Twigspark and Trotter’s quarries, a single, paragenetically late sulfide event accounts for all Zn-Pb-Fe mineralization (Fig. 5b). However, multiple stages of dolomitization are also observed at this locality. The eastern localities, Tate’s quarry and O’Donnell’s Rock, contain no known sulfide mineralization. Instead, each locality has a unique paragenetic sequence with diverse mineralogy.

Importantly, in northwest Ireland, there is an absence of a regionally correlatable dolomite cement CL microstratigraphy such as that observed in the Irish Midlands (Gregg et al., 2001; Wright, 2001; Wright et al., 2001). Dolomite cement CL microstratigraphies at Twigspark and Trotter’s quarries correlate well between both quarries and stratigraphically in the associated cores, but do not correlate with the CL stratigraphies at Abbeytown (Fig. 7). This indicates that the fluids that precipitated the epigenetic cements at Twigspark and Trotter’s quarries are distinct from those at Abbeytown. The dolomite CL microstratigraphies at O’Donnell’s Rock are significantly different from those at Abbeytown and Twigspark and Trotter’s quarries (Fig. 7), and dolomite cements were not observed at Tate’s quarry. The presence of distinct CL stratigraphies in dolomite cements at each study locality indicates either geochemical evolution of regional mineralizing fluids (geographically or chronologically), or multiple, isolated fluid flow events.

In order to assess these possibilities, δ¹⁸O values of dolomite-depositing waters were calculated from the δ¹⁸O_dolomite values using temperatures estimated from fluid inclusion Th values of fluid inclusion assemblages in individual samples (Friedman and O’Neill, 1977). Although the Th values have not been corrected for pressure effects, the temperature correction is thought to be small (<1°C according to Wilkinson and Earls, 2000). This small temperature variation does not significantly affect the calculated results or conclusions drawn from them. This intent is to determine whether or not there are gross differences in the δ¹⁸O values of fluids that can be ascribed to differences in fluid source or fluid evolution (fluid/rock interaction) at the various localities.

Dolomite cements from Abbeytown’s main orebody, whose fluid inclusion assemblages have Th values of 131° to 188°C, yield calculated equilibrium δ¹⁸O_wat values of 5.7‰ to 11.9‰ (avg. 8.5‰, Table 3), whereas those from the western orebody, whose fluid inclusion assemblage Th values are 111° to 158°C, yield δ¹⁸O_wat values of 1.1‰ to 4.5‰ (avg. 2.9‰). These calculated values demonstrate that oxygen isotopic variations in dolomite cements of the Main and West orebodies are inconsistent with deposition from a single fluid at variable temperatures. They instead require the presence of multiple, isotopically distinct brines.

Fluid inclusion assemblages in Twigspark and O’Donnell’s Rock dolomite cements have Th values of 117° to 158°C, and 121° to 171°C, respectively, similar to those of the Abbeytown orebodies. These dolomite cements yield calculated equilibrium δ¹⁸O_wat values of −1.4‰ to 4.4‰ (avg. 1.7‰) and 3.1‰ to 7.1‰ (avg. 5.1‰) at Twigspark and O’Donnell’s Rock, respectively (Table 3).

If δ¹⁸O_dolomite values were simply the result of heating of a regional fluid, then dolomite cements from all localities should have yielded similar δ¹⁸O_wat values. The differences in calculated δ¹⁸O_wat values for various localities in northwest Ireland cannot be explained as a temperature variation of a single, regionally persistent fluid like that proposed by Hitzman (1986). There must instead be a geochemical difference in the fluids, either in their sources or in their history of interaction with rocks along their flow paths. For example, the differences in δ¹⁸O values from Abbeytown, Twigspark and Trotter’s quarries, and O’Donnell’s Rock could reflect variable amounts of meteoric water (lower δ¹⁸O) components in their mineralizing fluids. In any case, fluid inclusion evidence from calcite and dolomite cements at Abbeytown, Twigspark and Trotter’s quarries, and O’Donnell’s Rock suggest us to see that the observed variations in δ¹⁸O_wat values at each locality reflect multiple fluids, which might have mixed variably.

Evaluation of fluid inclusion data at each of the four study localities might shed light on the genesis of sulfide mineralization in northwest Ireland. Figures 9a and 10a display fluid inclusion data from calcite and dolomite cements and sphalerite from mineralization at Abbeytown. These data are interpreted to indicate the presence and mixing of three geochemically distinct end member fluid

<table>
<thead>
<tr>
<th>Location and Host Mineral</th>
<th>Th Range</th>
<th>δ¹⁸O_dolomite</th>
<th>δ¹⁸O_wat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dolomite Cement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abbeytown (Main)</td>
<td>131° to 188°C</td>
<td>−7.4‰ to −5.4‰</td>
<td>5.7‰ to 11.9‰ (avg. 8.4‰)</td>
</tr>
<tr>
<td>Abbeytown (West)</td>
<td>111° to 158°C</td>
<td>−10.2‰ to −8.6‰</td>
<td>1.1‰ to 4.5‰ (avg. 2.9‰)</td>
</tr>
<tr>
<td>Twigspark</td>
<td>117° to 158°C</td>
<td>−12.9‰ to −9.5‰</td>
<td>−1.4‰ to 4.4‰ (avg. 1.7‰)</td>
</tr>
<tr>
<td>O’Donnell’s Rock</td>
<td>121° to 171°C</td>
<td>−9.2‰ to −8.5‰</td>
<td>3.1‰ to 7.1‰ (avg. 5.1‰)</td>
</tr>
<tr>
<td><strong>Calcite (with Ft1 inclusions)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abbeytown (West)</td>
<td>101° C</td>
<td>−13.5‰</td>
<td>−0.5‰</td>
</tr>
<tr>
<td>Trotter’s Quarry</td>
<td>112° C</td>
<td>−9.2‰</td>
<td>5.1‰</td>
</tr>
<tr>
<td>O’Donnell’s Rock</td>
<td>111° C</td>
<td>−6.6‰</td>
<td>7.8‰</td>
</tr>
<tr>
<td>Tate’s Quarry</td>
<td>110° to 130°C</td>
<td>−9.2‰</td>
<td>5.1‰ to 7.2‰ (avg. 6.1‰)</td>
</tr>
</tbody>
</table>

Note:
types. Fluid type 1 (Ft1) is a lower-temperature (Th = 70°–150°C), lower-salinity (4–9 wt.% NaCl equiv.) fluid; fluid type 2 (Ft2) is a lower-temperature (Th = 70°–140°C), higher-salinity (15–24 wt.% NaCl equiv.) fluid; and fluid type 3 (Ft3) is a higher-temperature (Th = 165°–220°C), moderate-salinity (8–14 wt.% NaCl equiv.) fluid. It is not uncommon for more than one fluid type to be present in an individual calcite or dolomite cement crystal.

Paragenetically, all three fluid types were present throughout the mineralizing events (all three are present as primary inclusions in dolomite that is contemporaneous with sphalerite, as well as in later calcite). However, Ft1 and Ft3 appear to have been more dominant earlier in the paragenesis, whereas Ft2 was dominant later. Similar patterns have been documented in other carbonate-hosted base metal sulfide systems, in which the influence of multiple geochemically distinct brines varied both temporally and spatially during the complex history of dolomitization and ore deposition (e.g., Johnson et al., 2009; Shelton et al., 2009).

Complex three-fluid patterns were not observed in carbonate cements at either O’Donnell’s Rock or Tate’s quarry (Fig. 9c,d). A fluid with characteristics similar to Ft3 is present at O’Donnell’s Rock with Th values >200°C in authigenic quartz and, to a lesser extent, in dolomite cements, whereas an Ft2-like fluid is absent. Fluid inclusions in calcite cements might indicate the presence of a fluid similar to Ft1, although the range of data displays higher Th values and higher salinities (110°–140°C, 6–9 wt.% NaCl equiv.) at O’Donnell’s Rock than at either Abbeytown or Twigspark and Trotter’s quarries.

At Tate’s quarry, both calcite- and fluorite-hosted fluid inclusions have similar Th and Tm values (Fig. 9d). Inclusions in calcite at Tate’s quarry appear to be similar to those in calcite from O’Donnell’s Rock; however, it cannot be determined from fluid inclusion data alone whether or not the fluid at Tate’s quarry is equivalent to Ft1 at O’Donnell’s Rock, a cooled Ft3-like fluid from O’Donnell’s Rock, or a third, unrelated fluid. Calcite cement δ18O values from O’Donnell’s Rock and Tate’s quarry are similar, suggesting the same fluid might have affected the two geographically proximate localities.

**Origin and Timing of Mineralizing Fluids**

Fluid inclusion and geochemical studies conducted in the Irish Midlands on Waulsortian Limestone-hosted Zn-Pb deposits indicate the presence of multiple geochemically distinct fluids in that region. Banks et al. (2002) used halogen geochemistry of fluid inclusions to illustrate that the mixing of two end-member fluids, at least one of which was evaporated seawater, was responsible for sulfide mineralization at the Tynagh and Silvermines deposits (Fig. 1). Wilkinson and Earls (2000), Wilkinson (2003), Wright et al. (2004), Wilkinson et al. (2005), and Johnson et al. (2009) all provide similar fluid inclusion and halogen geochemical evidence suggesting the presence of as many as three seawater-derived fluids during epigenetic dolomitization and mineralization in the Irish Midlands.

A similar multiple-fluid situation existed in northwest Ireland. A higher-salinity fluid, Ft2, is present only at Abbeytown and Twigspark and Trotter’s quarries. Salinities calculated from fluid inclusion Tm values (Figs. 9 and 10) and halogen data (Fig. 11) indicate that this fluid is an evaporated seawater brine, similar but not identical to high-salinity fluid found in the Irish Midlands (Johnson et al., 2009). Ft2 in northwest Ireland was evaporated near to or just beyond the point of gypsum precipitation, whereas that in the Irish Midlands was evaporated past the point of halite precipitation. The presence of thick gypsum beds in the late-Asbian/Britanian Meenymore Formation (Fig. 3) suggests evaporitic conditions were present within the Sligo Basin after the deposition of the host limestones (Philcox et al., 1992; Cózar et al., 2005, 2006).

The temperature difference between fluid types Ft1 and Ft3 in northwest Ireland (Figs. 9 and 10) might represent either a cooling trend or differences in the depths of penetration along faults of two different fluids, with the higher Th values for Ft3 indicating deeper circulation and possible basement interaction. At Trotter’s quarry, the cooler fluid, Ft1, was found in the Dartry Limestone, but was not observed in underlying strata of the Twigspark and Ballyshannon Limestone formations sampled from the Twigspark cores.

Fluid inclusions in sphalerite from Abbeytown form a comparatively tight cluster on a trajectory between fluid types Ft2 and Ft3 (Fig. 10a). The distribution of these data indicates that the presence and interaction of evaporated seawater (Ft2) and a higher-temperature fluid (Ft3) accompanied ore deposition. We speculate that at Abbeytown, the higher-temperature, moderate-salinity fluid penetrated downward along faults through basement rocks where it leached metals, before moving upward and mixing with a sulfide-bearing brine, in a system similar to the thermohaline convection model proposed by Russell (1978, 1986; Fig. 13).

If our conjecture is correct, that fluid type Ft3 was a deeply penetrating fluid capable of mobilizing metals from basement source rocks, then its presence would be a necessary requirement for ore formation. This fluid type is poorly represented in fluid inclusions measured in epigenetic cements at Twigspark and Trotter’s quarries, where sulfide mineralization is less abundant.

Lower-temperature, lower-salinity Ft1 brines were found throughout the study area. This need not imply a mutual regional flow system, because moderate evaporation of seawater that could lead to Ft1 salinities is a common phenomenon, which could have occurred simultaneously at different localities. The δ18O value of calcite cements that host Ft1 fluids (Table 3) allows us to speculate on the origin of these brines. Ft1 brine in the Abbeytown mine’s western orebody was found in calcite cement whose δ18O value is ~13.5‰. The calculated δ18Owater value for this calcite is ~−0.5‰ (Table 3), which is incompatible with simple evaporation of seawater. This value is consistent with low δ18Owater values calculated for dolomite cements of the western orebody, which might reflect a common link to the fault-related mineralizing system in this portion of the mine (Fig. 3). Ft1 brine might therefore represent cooler,
less-saline fluid in shallower portions of the system, a possibility suggested by Johnson et al. (2009) for similar fluids in the Irish Midlands.

Ft1 fluids in other localities might not be related to ore processes at all. Following evaporation, these brines could have developed similar chemistries through reaction with carbonate host rocks. Calcite cements that contain Ft1 inclusions from Trotter’s and Tate’s quarries and O’Donnell’s Rock yield similar calculated δ18O values of 5.1‰ to 7.8‰, which approach those for waters in isotopic equilibrium with host limestones at 110°C.

Whatever their origin, Ft1 brines are not ore fluids and do not appear to be integral to the ore-forming event.

There is no indication of the relative timing of mineralization at Abbeytown compared to that at Twigs park and Trotter’s quarries or the other localities studied, because no regionally consistent mineral paragenesis was observed. Hitzman (1986) suggested an Asbian or later timing for mineralization at Abbeytown. Dolomite CL microstratigraphies at Twigs park and Trotter’s quarries can be correlated throughout the stratigraphic section, suggesting that dolomitization associated with mineralization at Twigs park and Trotter’s quarries occurred after deposition of the Dartry Limestone. This indicates late Asbian as the earliest possible timing for the initiation of mineralization at Twigs park and Trotter’s quarries. At these localities, base-metal sulfide mineralization is shown to have taken place after the initial onset of movement of faults associated with uplift of the Ox Mountains inlier. The relative timing of mineralization compared with later reactivation of basement faults in the Late Carboniferous is undetermined.

**Comparison to the Irish Midlands**

Base metal sulfide mineralization in northwest Ireland represents a distinct mineralizing system, isolated geologically from that of the Zn-Pb district in the Rathdowney trend and the Irish Midlands (Fig. 1). Halogen data from northwest Ireland do not reflect an important presence of saline fluids with high bromide concentrations, like those commonly found in regionally extensive dolomites of southern Ireland (fluid type 1 of Johnson et al., 2009) and in postore calcites of the Irish Midlands (Banks et al., 2002; Fig. 11). The absence of this fluid component in northwest Ireland provides further evidence of the isolated nature of the flow system in the Sligo Basin and its lack of connection with a regionally extensive flow system thought to be associated with dolomitization and Zn-Pb deposition in the Irish Midlands. Furthermore, the absence of a meteoric water component as well as the relative isolation, petrographically and geochemically, of the studied mineralized areas argues against the application of regionally extensive topographically driven fluid flow models to this area.

The absence of a thick basal Devonian or Lower Carboniferous siliciclastic formation in the Sligo syncline of northwest Ireland likely also had an impact on the fluid flow system of the area. The Devonian Old Red Sandstone in the Irish Midlands might have served as a conduit for regional fluid flow, perhaps also acting as a source of metals for mineralization (Hitzman and Beatty, 1996; Hitzman et al., 1998; Wright et al., 2003; Johnson et al., 2009). There is an absence of an underlying siliciclastic formation, similar to the Old Red Sandstone, in northwest Ireland. No such regional fluid flow system is indicated by our study of the Sligo syncline.

**Conclusions**

Field relationships, petrography, and isotope geochemistry indicate that marine conditions were relatively uniform in northwest Ireland during deposition of the host Ballyshannon and Dartry limestones, and suggest the existence of a single carbonate platform during the Upper Viséan.

Each of the four study areas has a different postdepositional fluid history as indicated by petrology, fluid inclusions, and stable isotope data. Fluid inclusion data from Abbeytown and Twigs park/Trotter’s quarry indicate the presence of three geochemically distinct fluid types. The presence of two of these fluids, a lower-temperature, higher-salinity fluid and a higher-temperature, moderate-salinity fluid is associated with sulfide mineralization at Abbeytown and minor mineralization at Twigs park, and it is suggested that mixing of these two fluids might have led to ore deposition. At O’Donnell’s Rock and Tate’s quarry, no sulfide mineralization was present and one or both of these fluids was missing at each locality.

The largest paragenetic differences in mineralization are between localities to the west and to the east of the Ox Mountains inlier. This indicates that late stage base metal sulfide mineralization formed after significant uplift of the Inlier had occurred. Initial movement of faults associated
with the uplift has been dated to be Arundian to Asbian. This provides the earliest possible timing of mineralization in northwest Ireland.

Data from base metal sulfide occurrences in northwest Ireland indicate no connection with a regionally extensive flow system that has been proposed for Zn-Pb deposits in the Irish Midlands.

Acknowledgments

Acknowledgment is made to the Society of Economic Geologists (Hugh E. McKinstry Student Research Award) for partial funding of this project and to Devon Energy Corporation for providing a graduate fellowship to the senior author that enabled him to undertake this research. We wish to thank the respective staff members at Abbeytown, Trotter’s, and Tate’s quarries, County Sligo, for access to the working quarries and, in the case of Trotter’s quarry, access to the nearby Twigspark quarry and associated cores. Thanks are extended to J. Kelly (JBA Ltd., Dublin) for providing access to the underground workings of the Abbeytown mine, to J. Beasley (University of Missouri) for help in the field and assistance in fluid inclusion analysis, and to T. Culligan (University College Dublin) for his help in sample preparation. Thanks are due to J. Puckette (Oklahoma State University) who commented on an early version of this manuscript. We thank reviewers S.E. Kesler and D.J. Kontak, and editor J.P. Richards for helping us to substantially improve this paper.

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