



<b>Title</b>	3-D Modeling of the Lisheen and Silvermines Deposits, County Tipperary, Ireland: Insights into Structural Controls on the Formation of Irish Zn-Pb Deposits
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<b>Publication date</b>	2019-02-01
<b>Publication information</b>	Kyne, Roisin, Koen Torremans, John Güven, Robert Doyle, and John J. Walsh. "3-D Modeling of the Lisheen and Silvermines Deposits, County Tipperary, Ireland: Insights into Structural Controls on the Formation of Irish Zn-Pb Deposits." Society of Economic Geologists, February 1, 2019. <a href="https://doi.org/10.5382/econgeo.2019.4621">https://doi.org/10.5382/econgeo.2019.4621</a> .
<b>Publisher</b>	Society of Economic Geologists
<b>Item record/more information</b>	<a href="http://hdl.handle.net/10197/10857">http://hdl.handle.net/10197/10857</a>
<b>Publisher's statement</b>	Gold Open Access: this paper is published under the terms of the CC-BY license
<b>Publisher's version (DOI)</b>	<a href="https://doi.org/10.5382/econgeo.2019.4621">10.5382/econgeo.2019.4621</a>

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# 3-D Modeling of the Lisheen and Silvermines Deposits, County Tipperary, Ireland: Insights into Structural Controls on the Formation of Irish Zn-Pb Deposits

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## Abstract

Faults are important structures in the formation of many mineral deposits, often acting as conduits for ore-forming fluids and sometimes providing, or generating, the bounding structures to associated mineralizing sites. Using 3-D analysis and modeling of the Lisheen and Silvermines deposits within the Irish ore field, we investigate the geometry of normal fault systems and their implications on the origin and nature of associated deposits. These Irish-type deposits are carbonate hosted and developed within the hanging walls of normal faults arising from an Early Carboniferous episode of north-south rifting, with relatively limited amounts of later deformation. Structural analysis of high-quality mine datasets indicates that fault segmentation is ubiquitous with left-stepping segments arising from north-south stretching developed above generally ENE-NE-trending fault arrays, which are subparallel to older Caledonian penetrative fabrics and structure within underlying Silurian and Ordovician rocks. Fault segments occur on different scales and have a profound impact on structural evolution, with larger scale segments and intervening relay ramps defining distinct orebodies within deposits and smaller scale segments and relays potentially providing paths for upfault fluid flow. The difference in behavior is attributed to the integrity of associated relay ramps where intact ramps represent orebody-bounding structures, and smaller breached ramps provide enhanced associated hydraulic properties and act as vertical conduits. Hanging-wall deformation along the rheological boundary between host-rock limestones and underlying shales has an important control on the localization of earlier dolomitization and/or brecciation and later mineralization adjacent to this contact, and on the migration pathways for basinal brines and mineralizing fluids.

## Introduction

Structures and tectonics play a vital role in the formation of economic deposits particularly when host lithologies either exhibit low primary porosity and/or permeability or are bounded by impermeable units which impede fluid flow. By acting as pathways and conduits for flow, structures help focus ore-forming fluids into areas where they can precipitate mineralization.

The significance of faults on the formation of Irish-type Zn-Pb deposits, hosted within the Zn-Pb ore field of the Irish Midlands in one of the major base metal provinces in the world, has long been recognized by many workers, researchers, and industry alike (Fig. 1; Andrew, 1986; Hitzman and Large, 1986; Hitzman et al., 1992; Johnston et al., 1996; Carboni et al., 2003; Fuscuardi et al., 2004). Our study develops on this previous work by providing better constraints on the 3-D geometries and kinematics of fault systems within Irish-type Zn-Pb deposits and their specific controls on mineralization. We use state-of-the-art 3-D modeling techniques and/or packages to investigate the structure of two Irish Zn-Pb deposits, Lisheen and Silvermines, in order to identify key structural controls on their geometry and location as well as flow-related issues ranging from fluid migration through to the mineralization of orebodies.

Since the discovery of the Irish ore field in the early 1960s there have been many studies on the origin and formation of its mineral deposits. These studies have established that Lisheen and Silvermines, along with other Irish-type deposits

including Tynagh, Galmoy, Kilbricken, and the Rapla prospect, are hosted within the hanging walls of normal faults that developed during the Lower Carboniferous (Wilkinson and Hitzman, 2014). Previous work completed during mine appraisal, for both research and production purposes, has shown that these normal faults are not simple, singular structures but are instead complex arrays composed of linked or anastomosing and/or unlinked fault strands (Andrew, 1986; Hitzman et al., 1992; Hitzman, 1999; Johnston 1999; Carboni et al., 2003; Fuscuardi et al., 2004). This complexity, whereas not necessarily having implications for some processes, certainly has a great effect on fault-related fluid flow. Over the last few decades, these studies have shown that the complexity of segmented fault arrays exercise major controls on deposit formation and, in particular, on individual orebodies that appear to be spatially associated with individual fault segments (e.g., Hitzman, 1999; Johnston et al., 1996; Fuscuardi et al., 2004).

Within the Irish context the most widely accepted explanation for this type of fault complexity is that underlying pre-Carboniferous basement structures, which are generally ENE-oriented, control the formation of the main faults. Later oblique extension (closer to N-S) on the controlling basement faults caused vertical fault propagation and/or nucleation, which then led to segmentation within the Carboniferous, often forming left-stepping fault arrays (Johnston et al., 1996; Worthington and Walsh, 2011; Bonson et al., 2012). In this study we establish the 3-D geometry and kinematics of fault systems associated with Irish mineral deposits and reconcile their structural evolution with existing models for segmented normal fault arrays.

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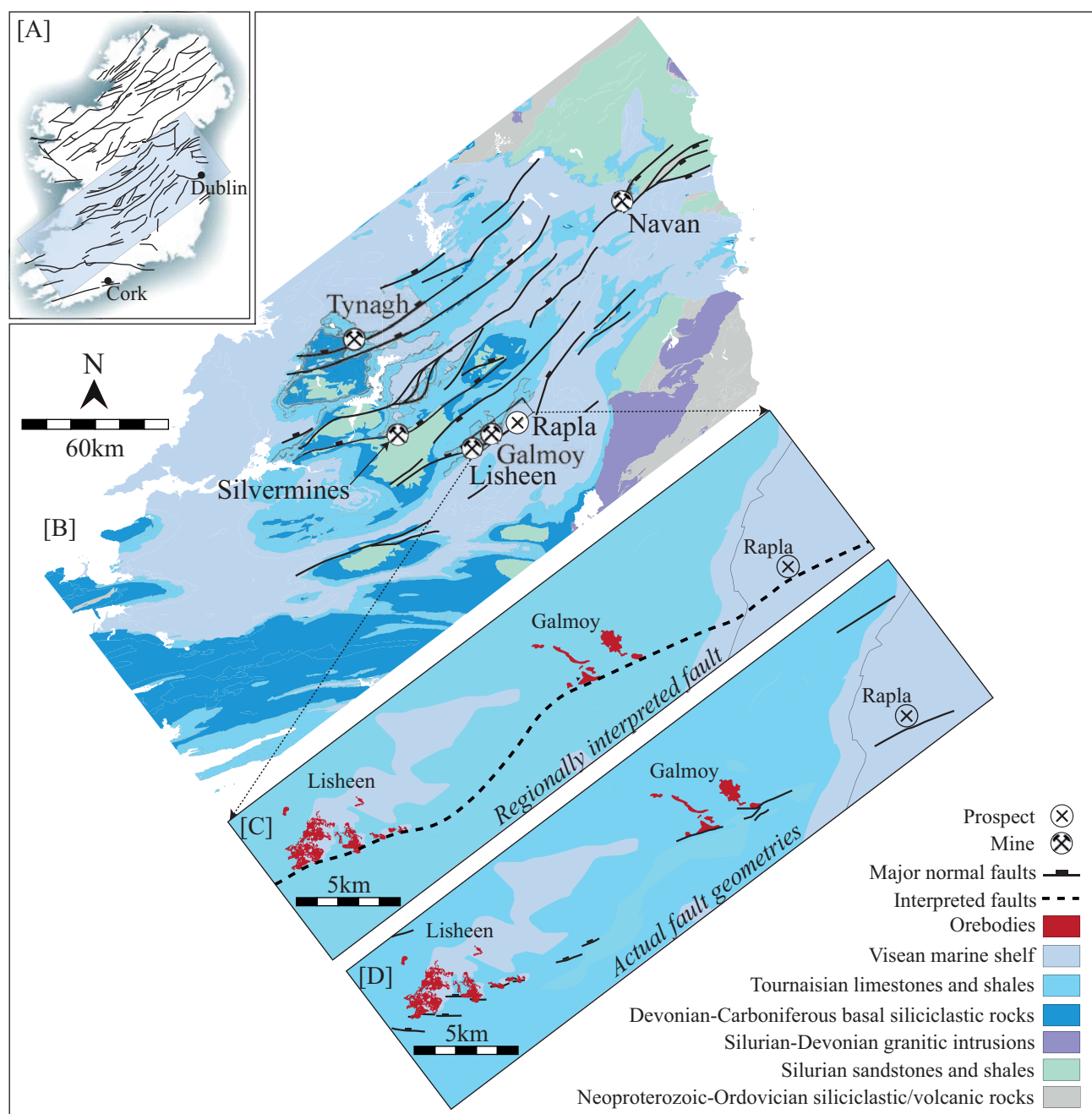


Fig. 1. A. Map of Ireland showing major structural trends and (B) bedrock geologic map showing the locations of the various Zn-Pb deposits within the Irish ore field. The map and faults in the inset map of Ireland are modified from the 1:500,000 map of the Geological Survey of Ireland (2014). The main faults and lithologic sequences are shown. C. Enlargement of regional map of the Rathdowney trend and the area adjacent to the Lisheen, Galmoy, and Rapla deposits. Here, the main regional structural trend suggests the presence of one continuous fault. D. Fault map for the Rathdowney trend defined from higher resolution exploration and mining data, which highlights the presence of an array of left-stepping fault segments rather than one continuous fault.

A fault array is defined as containing two or more fault segments, which have developed in conjunction with each other and, therefore, show complementary displacement changes such that their aggregate displacements appear to constitute a single, kinematically coherent system (Walsh and Watterson, 1989, 1990, 1991; Peacock and Sanderson, 1991; Dawers and Anders, 1995; Walsh et al., 2003). The kinematic evolution of

such fault systems is generally attributed to the formation of soft-linked segments (i.e., those linked by intervening, intact relay ramps, which accommodate displacement transfer) at the early stage of faulting which, with increased displacements, gradually evolve into hard-linked segments arising from the breaching of intervening ramps (Fig. 2; Peacock and Sanderson, 1991; Childs et al., 1995, 2009; Soliva and

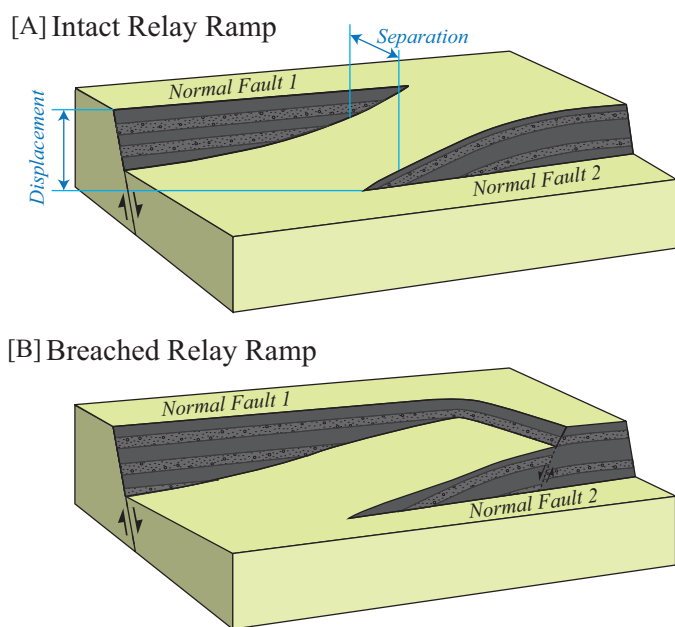


Fig. 2. Relay ramp evolution with respect to breaching. A. Intact relay ramp with no breaching. B. Breached relay ramp showing a hanging-wall breach.

Benedicto, 2004; Long and Imber, 2011; Fossen and Rotevatn, 2016). Hard-linkage of individual fault segments arises from the increased rotation and strain of intervening ramps leading to the formation of breaching faults, sometimes with considerable damage and brecciating adjacent to, and within, the intervening ramp (Bonsen et al., 2007; Childs et al., 2009; Rotevatn and Basteson, 2012; Fossen and Rotevatn, 2016).

In this study, we investigate, in more detail than previously possible, the 3-D geometries and kinematics associated with the principal structural controls on the formation of Zn-Pb deposits in the southern part of the Irish ore field. In particular, we focus on the geometries of normal faults, the importance of fault segmentation and how these relate to mineralization within two Irish-type deposits, Lisheen and Silvermines. We show how an understanding of the structural architecture as it relates to the formation of Lisheen and Silvermines has been used to successfully inform exploration for similar ore deposits within the region (i.e., the Rapla prospect). Recent advancements in 3-D modeling software have allowed us to generate much improved 3-D models from current and legacy mine datasets, including fault and horizon surfaces as well as mineralization volumes. Using these 3-D models coupled with fault analysis, this study better defines and quantifies the nature of fault segmentation, relay ramp geometries and ramp breaching in relationship to mineralization and formation of the Lisheen and Silvermines Zn-Pb deposits.

### Regional Geologic Setting

The geology of the Irish Zn-Pb deposits has been studied by various workers over the past 50 years of mining and exploration activity, producing a number of comprehensive reviews (Philcox, 1984; Taylor, 1984; Andrew, 1986, 1993; Hitzman and Large, 1986; Phillips and Sevastopulo, 1986; Shearley et al., 1995; Hitzman and Beaty, 1996; Sevastopulo and

Wyse-Jackson, 2001; Hitzman et al., 2002; Wilkinson et al., 2005a; Wilkinson, 2013). Here, we present a summary of the geologic setting of the Irish ore field as a backdrop to our 3-D modeling and analysis of the Lisheen and Silvermines deposits.

### Structural evolution of the Irish ore field

The formation of the Irish Carboniferous basins, host to the Irish ore field, was prefaced by the closure of the Iapetus ocean and the collision of the Laurentian and later Eastern Avalonian continents during the Ordovician-Early Devonian Caledonian orogeny (Chew and Stillman, 2009; Woodcock, 2012; Wilkinson and Hitzman, 2014). The resulting Iapetus suture is generally considered to extend in an approximately east-northeast direction roughly from the Shannon estuary through the Irish Midlands, alongside the Silvermines and Navan deposits, and out into the Irish Sea (e.g., McConnell et al., 2015); in detail the suture is approximately east-west oriented in the west and east, and northeast trending in the Central Midlands. This continental suture dips shallowly to the north and is believed to be coincident with a subduction zone where the intervening Iapetus ocean was consumed (Phillips et al., 1981). Deformation associated with the Caledonian orogeny includes generally ENE- to NE-trending fabrics, folds, and major terrane-bounding strike-slip faults, structures which are most clearly developed within Ordovician and Silurian metasedimentary basement rocks deposited within and immediately adjacent to the Iapetus ocean (Chew and Stillman, 2009; Davies et al., 2012).

During the Late Devonian to Early Carboniferous, a series of interconnected extensional basins developed in response to north-south to north-northwest-south-southeast episodic extension located in the back-arc of the N-dipping Variscan subduction zone (Leeder and McMahon, 1988; Gawthorpe et al., 1989; Philcox et al., 1992; Johnston et al., 1996; Fraser and Gawthorpe, 2003; Davies et al., 2012). Associated with this extension was the development of E-W- to NE-SW-trending normal faults, including those at Lisheen and Silvermines (Figs. 3, 4), the localization and evolution of which is believed to have been controlled by the geometries of reactivated Caledonian basement structures (Coller, 1984; Brown and Williams, 1985; Phillips and Sevastopulo, 1986; Johnston et al., 1996; Johnston, 1999; O'Reilly et al., 1999; Worthington and Walsh, 2011; Davies et al., 2012).

The Irish Carboniferous basins were subsequently deformed by the Late Carboniferous Variscan orogeny, during which north-south compression and a significant component of dextral transpression led to basin inversion (Coller, 1984). This inversion produced open folding and reverse faulting in the Central Midlands with intensified deformation close to the reactivated normal fault (Johnston et al., 1996; Carboni et al., 2003). The location of the Lisheen deposit, for example, is within an inversion-related open fold, known as the Littleton syncline, which complicated the earlier extensional faulting recognized within the deposit (Fusciardi et al., 2004). Likewise, the Silvermines deposit lies on the southern limb of the Kilmastulla syncline, another inversion-related open fold, whose easterly trend rotates to become northeasterly to the west of the deposit in line with an earlier Caledonian structure (Andrew, 1986). Other expressions of Variscan inversion

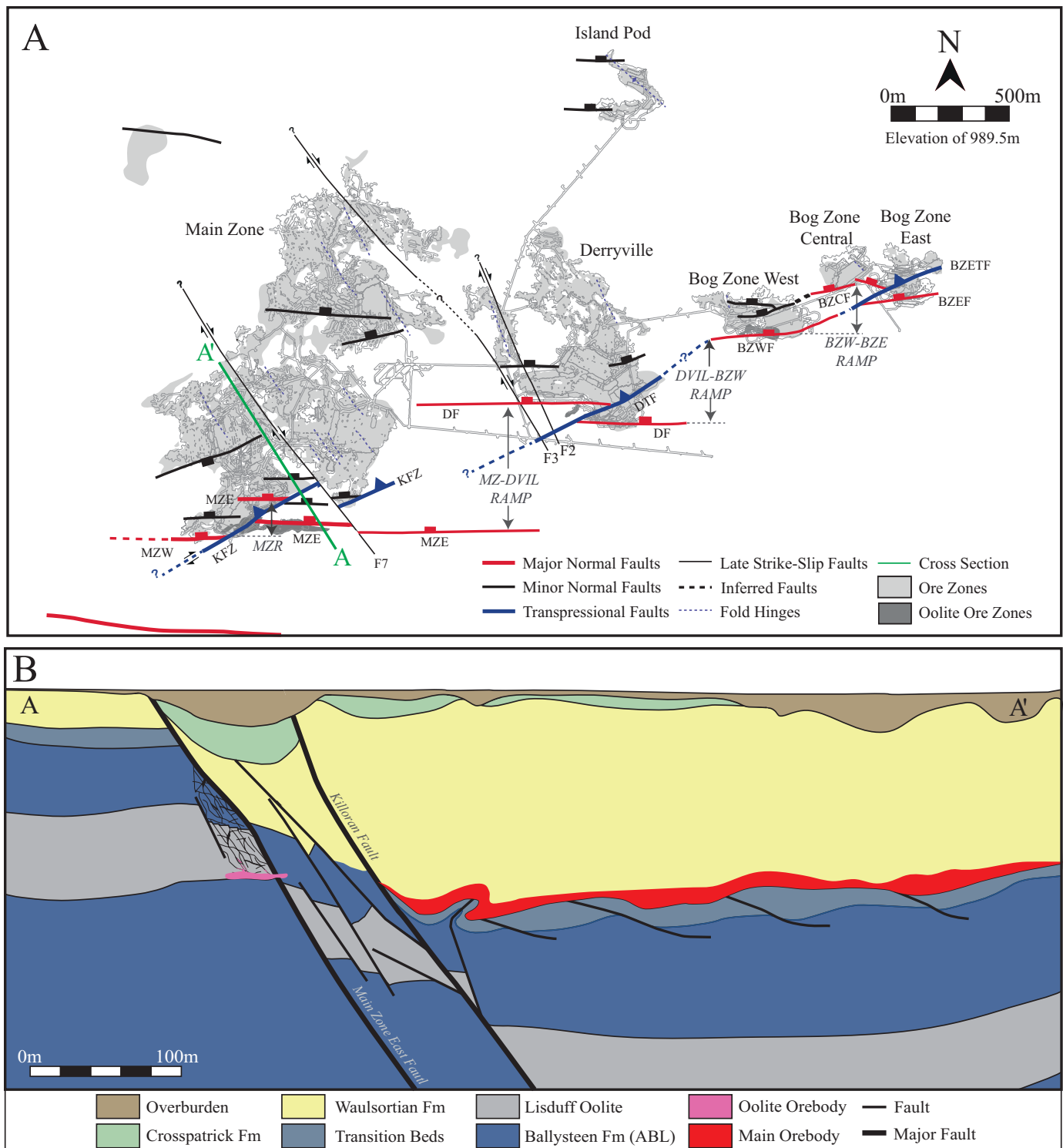


Fig. 3. Map and cross section of the Lisheen Zn-Pb deposit, Tipperary, Ireland. A. Map showing the left-stepping segmented fault array that controls the location and geometry of the various orebodies within the deposit. The red faults represent the original normal faults, which were later complicated by ENE-trending Variscan dextral strike-slip transpressive faults (blue) and finally by NW-trending Cenozoic dextral strike-slip faults (black). Abbreviations for each fault segment and relay ramp are as follows: Main zone west (MZW), Killoran fault zone (KFZ), Main zone east (MZE), Main zone ramp (MZR), Derryville fault (DF), Derryville transpressive fault (DTF), Main zone-Derryville ramp (MZ-DVIL), Bog zone west fault (BZWF), Bog zone central fault (BZCF), Bog zone east fault (BZEF), Bog zone west-Bog zone east ramp (BZW-BZE), Bog zone east transpressive fault (BZETF). B. NW-oriented cross section of the Lisheen deposit, showing the main faults and lithologic sequences. See (A) for location (green line).

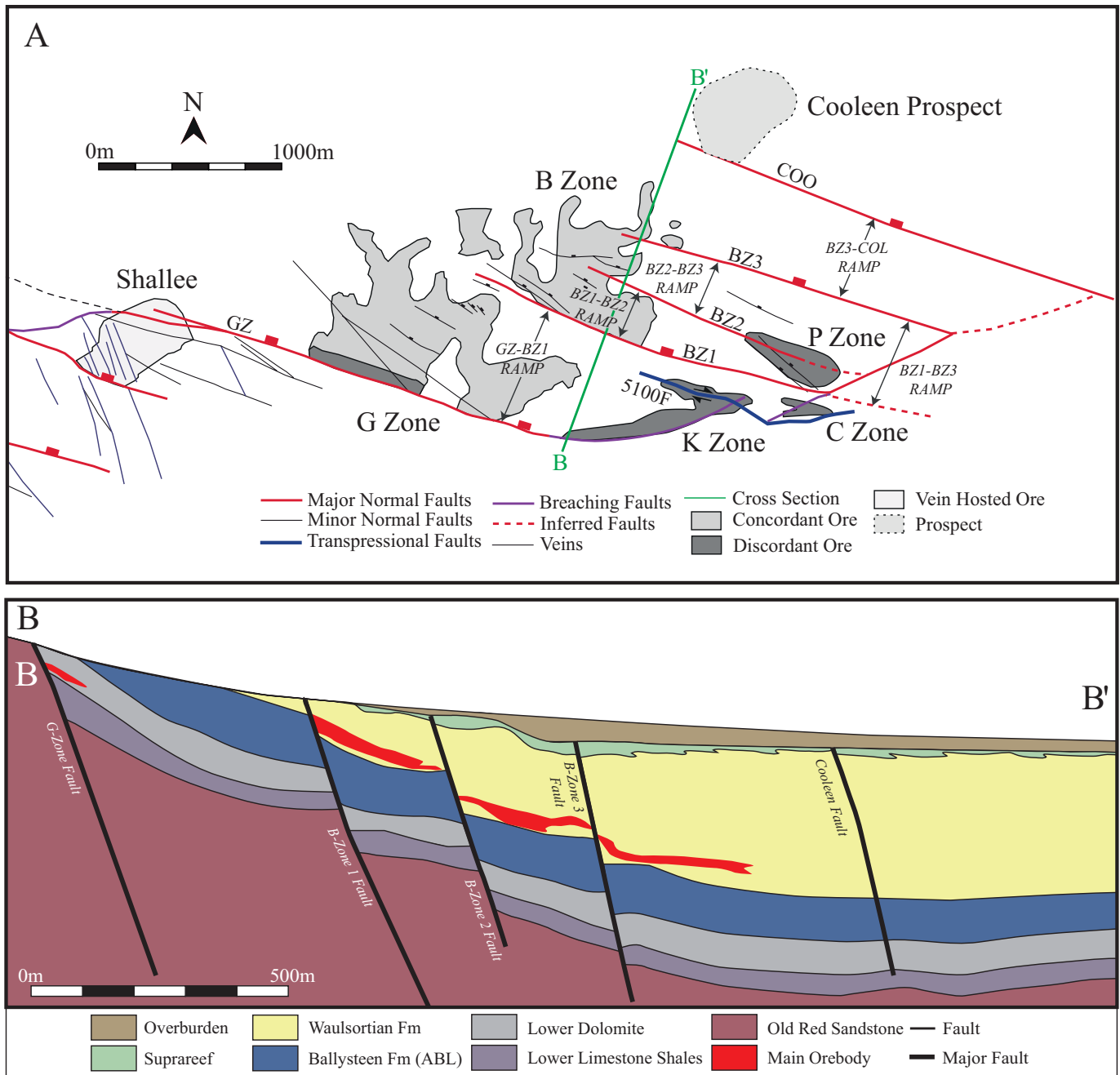


Fig. 4. Map and cross section of the Silvermines Zn-Pb deposit, Tipperary, Ireland. A. Map showing the left-stepping segmented fault array that controls the location and geometry of the various orebodies within the deposit. The red faults represent the original normal faults which were later complicated by E-W-trending Variscan dextral strike-slip transpressive faults (blue). Four NW breached relay ramps can be identified: (1) between the G zone (GZ) and B zone 1 (BZ1) faults, (2) between the BZ1 and B zone 2 (BZ2) faults, (3) between the BZ2 and B zone 3 (BZ3) faults, and (4) between the BZ3 and Coolleen (COO) faults. B. NW-oriented cross section of the Silvermines deposit, showing the main faults and lithologic sequences. See (A) for location (green line).

include the formation of ENE-trending dextral oblique-slip transpressional faults, the nature of which will be discussed later in the context of the Lisheen 3-D model.

The final phase of deformation involves the formation of N-NW-trending dextral strike-slip faults, which offset all pre-existing structures. At Lisheen and Silvermines, these faults have a displacement of up to 50 m, but usually less than 10 m,

and act as major conduits for present-day groundwater flow at the scale of individual deposits (Carboni et al., 2003; Fusciardi et al., 2004). These and other NNW-trending dextral strike-slip faults have been attributed to north-south Alpine-Pyrenean compression during the Paleocene and Oligocene (Carboni et al., 2003; Fusciardi et al., 2004; Cooper et al., 2012; Anderson et al., 2016, 2018).

*Stratigraphy of the Irish ore field*

The Irish ore field is hosted in a Lower Carboniferous marine carbonate sequence, deposited during a northward-migrating transgression, which occurred intermittently from the Late Devonian through to the Upper Carboniferous (Philcox, 1984). This carbonate sequence sits conformably above fluviatile terrigenous clastic of the Devonian-Carboniferous Old

Red Sandstone Formation (Rhoden, 1958; Phillips and Seavastopulo, 1986). The Old Red Sandstone Formation lies uncomfortably atop lower Palaeozoic Caledonian basement rocks, usually represented by Silurian metasedimentary sequences of graywackes, siltstones, shales, and volcanic rocks that were deformed during the Caledonian orogeny and metamorphosed to prehnite-pumpellyite grade (Fig. 5; Archer, 1981; Philcox, 1984).

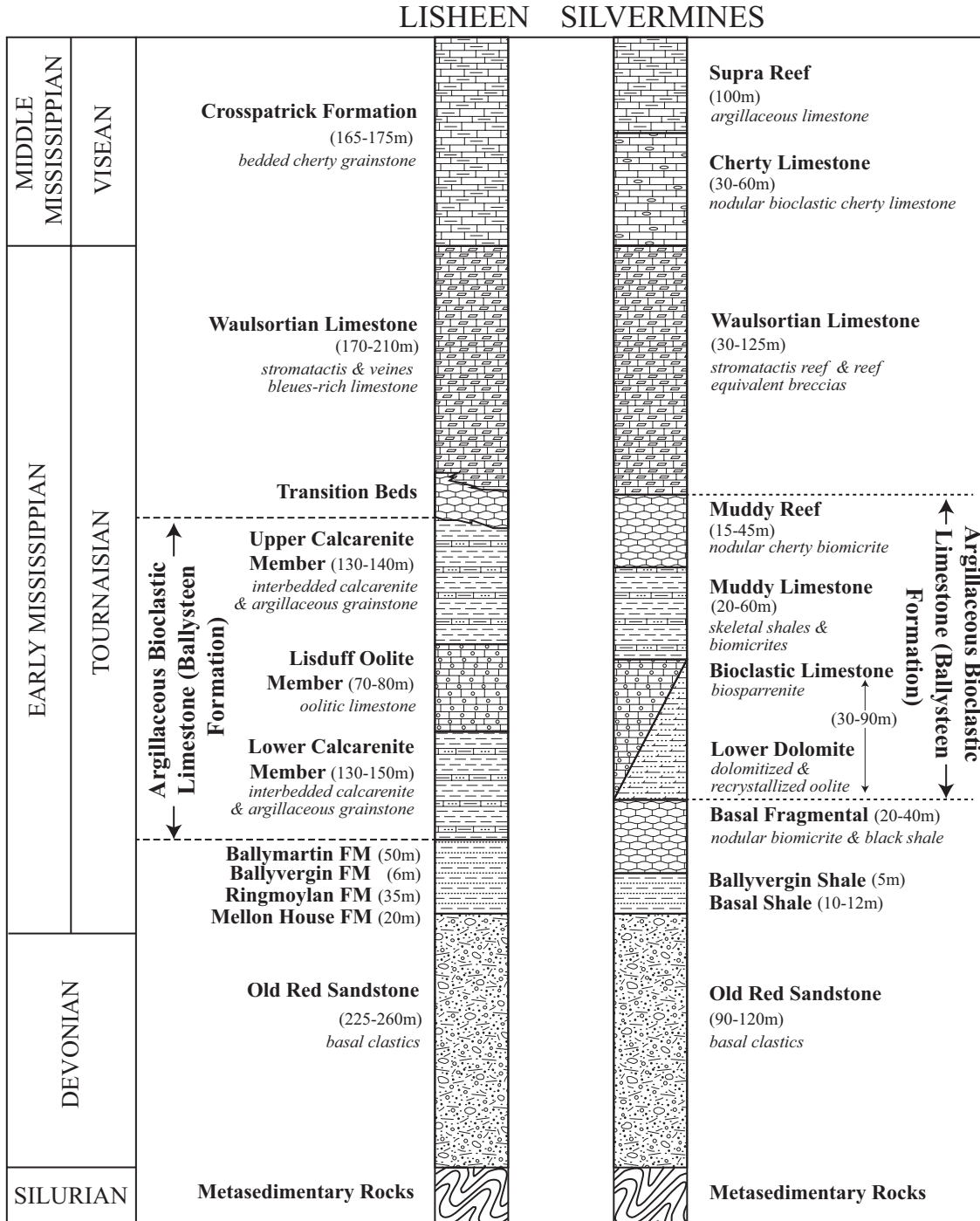


Fig. 5. Stratigraphic column for both the Lisheen and Silvermines deposits. Approximate timing of the formation of the various units is shown as uncertainty within the timescale of the Carboniferous prevents direct correlation between radiometric dates and stratigraphic ages (Lipphol and Hess, 1985; Leeder and McMahon, 1988; Hitzman et al., 2002).

The Lower Carboniferous sequence within both the Lisheen and Silvermines deposits begins with a series of mixed clastic sediments (shales and siltstones) and carbonates. These are referred to as the Mellon House Formation, Ringmoylean Shale Formation, Ballyvergin Shale Formation, and the Ballymartin Formation at Lisheen, the Basal Shale Formation, Ballyvergin Shale Formation, and the Basal Fragmental Formation at Silvermines (Fig. 5). Within both deposits the Ballyvergin Shale Formation (at Lisheen) and the Basal Fragmental Formation (at Silvermines) are overlain by an argillaceous bioclastic limestone (ABL) known as the Ballysteen Formation. At Lisheen, the ABL unit is 330 to 380 m thick and has been subdivided into three distinctive members. The first member is a 130- to 150-m-thick calcarenite unit known as the Lower Calcarenite Member, which is overlain by the second member, a 70- to 80-m oolitic limestone referred to as the Lisduff Oolite Member (Fig. 5). The uppermost member of the Ballysteen Formation is a 130- to 140-m-thick calcarenite unit known as the Upper Argillaceous Bioclastic Limestone Member. At Silvermines, the Ballysteen Formation is 85 to 235 m and has been subdivided into five members (Andrew, 1986). The lowermost member is a 10- to 40-m-thick unit of thick-bedded calcarenites and shales known as the Basal Fragmental Member. This unit is overlain by a 0- to 35-m-thick oolitic limestone referred to as the Lower Dolomite Member, which forms laterally coeval with a 30- to 35-m-thick fossiliferous limestone known as the Bioclastic Limestone Member. Above these members is the Muddy Limestone Member, a 20- to 60-m-thick skeletal planar bedded shaley unit, which in turn is overlain by the Muddy reef, a 15- to 45-m-thick nodular micrite unit (Fig. 5). Immediately above the Ballysteen Formation within both deposits sits the Waulsortian Limestone Formation (Fig. 5). Mineralization within most deposits, including Lisheen and Silvermines, is best developed toward the base of this relatively thick sequence of reef limestones (Figs. 3, 4). At Lisheen, the Waulsortian Formation is a 170- to 210-m-thick unit of stromatactis- and veins bleues-rich biomicritic limestone, whereas at Silvermines this formation is only 30 to 125 m thick and is composed of stromatactis biomicrites and reef-flanking crinoidal biosparroids and reef breccias. Finally, above the Waulsortian Formation at Lisheen sits the Crosspatrick Formation, a bedded cherty grainstone unit that is 156 to 175 m thick. Overlying the Waulsortian Formation at Silvermines is a similar cherty sequence known as the Cherty Limestone, a 30- to 60-m-thick nodular siliciclastic calcarenite and the Supra reef unit, a 100-m-thick argillaceous dark cherty limestone (Fig. 5).

### Mineralization

Mineralization within the Irish Zn-Pb deposits is usually located in the hanging walls of normal faults, toward the base of the Waulsortian reef limestone or in the Lower Dolomite unit (Figs. 3, 4). Within the Irish ore field, mineralization is thought to be a product of a two-fluid mixing system in which hot upwelling hydrothermal fluids mix with cold, dense basal brines, resulting in orebody generation. This conclusion stems from textural, fluid inclusion, and Sr-Fe-Zn isotope studies (Samson and Russell, 1987; Banks and Russell, 1992; Eyre, 1998; Fallick et al., 2001; Blakeman et al., 2002; Wilkinson et al., 2005b; Barrie et al., 2009; Gagnevin et al., 2012, 2014; Doran et al., 2017) as well

as S isotope studies, which suggest the presence of a heavier S hydrothermal fluid as well as a lighter bacteriogenic, basinal brine (Wilkinson et al., 2005; Doran et al., in prep).

Mineralization at Lisheen is composed primarily of sphalerite, galena, and pyrite with minor amounts of Cu-, Ni- and Ba-bearing minerals (Hitzman et al., 1992; Fusciardi et al., 2004). Orebodies are stratiform and mainly hosted in the Waulsortian reef limestone within 20 m of the Waulsortian-ABL contact (Fig. 3B) and are often spatially associated with earlier, generally stratiform, dolomitization, and related brecciation. Minor amounts of mineralization are also found within the Lisduff Oolite unit when adjacent to the Waulsortian reef limestone. Mineralization occurs in the following six distinct areas of the deposit: (1) Main zone, (2) Derryville zone, (3) Bog zone west, (4) Bog zone central, (5) Bog zone east, and (6) Island Pod zone (Fig. 3A). Each orebody consists of a number of massive and semimassive sulfide lenses separated and surrounded by vein and/or disseminated sulfides. While early stages of mineralization (i.e., Fe) at Lisheen may have occurred during active normal faulting, the main phase of Zn-Pb mineralization has been attributed to postnormal, pre-Variscan faulting and is thought to be of epigenetic origin (Hitzman et al., 2002; Fusciardi et al., 2004).

Mineralization within the Silvermines deposits comprises sphalerite, galena, barite, and pyrite with minor amounts of Cu- and Ag-bearing minerals. Orebodies are primarily hosted within either the Lower Dolomite unit or near the base of the Waulsortian Limestone Formation (Fig. 4B). Minor amounts of mineralization are also found within the Basal Clastic (Old Red Sandstone Formation) unit and basement rocks (Andrew, 1986). There are six discrete orebodies within Silvermines; (1) G zone, (2) B zone, (3) K zone, (4) P zone, (5) C zone, and (6) Shallee ore zone (Fig. 4A). Mineralization occurs either within the fault zones of normal faults (i.e., the lower G zone mineralization) or as stratiform bodies within the host lithologies. The ore itself occurs either as massive sulfide mineralization or as disseminated or vein-style mineralization (Andrew, 1986). While the early stages of mineralization, consisting primarily of Fe and Ba with minor amounts of Zn and Pb, show textural and isotopic characteristics interpreted to support a sedimentary exhalation origin (Larter et al., 1981; Boyce et al., 1983, 2003; Andrew, 1986), the main stage of Zn-Pb mineralization postdates deposition and early diagenesis of carbonate rocks and is therefore epigenetic in nature.

### Methods

The 3-D modeling software packages and techniques were used to quantitatively analyze the geometry and structure of fault arrays and stratigraphic horizons, and, in particular, their spatial links to mineralization, within the Lisheen and Silvermines deposits. The combination of methods we have employed provides an excellent means of defining the geometric and kinematic links between faulting, structure, and mineralization. The data sets which underpin our 3-D modeling are sourced from differing ages of mining and exploration operations.

For Lisheen, data archives were available digitally and much of it already captured in 3-D, including an initial Vulcan 3-D model and block model, digitized diamond drill logs (roughly 30-m spacing), drill core photos, digitized assays,

detailed face sheets, and underground maps. This data was then combined in order to extrapolate 3-D surfaces (Fig. 6). Figure 6A-C shows an example of the distribution of both drill hole intercepts of the top of the ABL unit as well as the detailed face sheets (showing both lithologic intercepts and geometries as well as structural measurements) used to construct an accurate 3-D surface of the Lisheen mine. For Silvermines, 3-D data were mainly derived from paper archives,

including paper drill logs, limited assays (mainly Pb and Zn with sparse Ag and Cu), interpreted mine plans and sections, as well as surface maps from the literature. We used a combination of Midland Valley's Move, ESRI's ArcGIS, and QGIS to digitize and evaluate both data sets prior to being uploaded into the various 3-D modeling packages. Figure 6D-F shows an example of the distribution of drill hole intercepts for the top of the C5 unit that was combined with paper cross

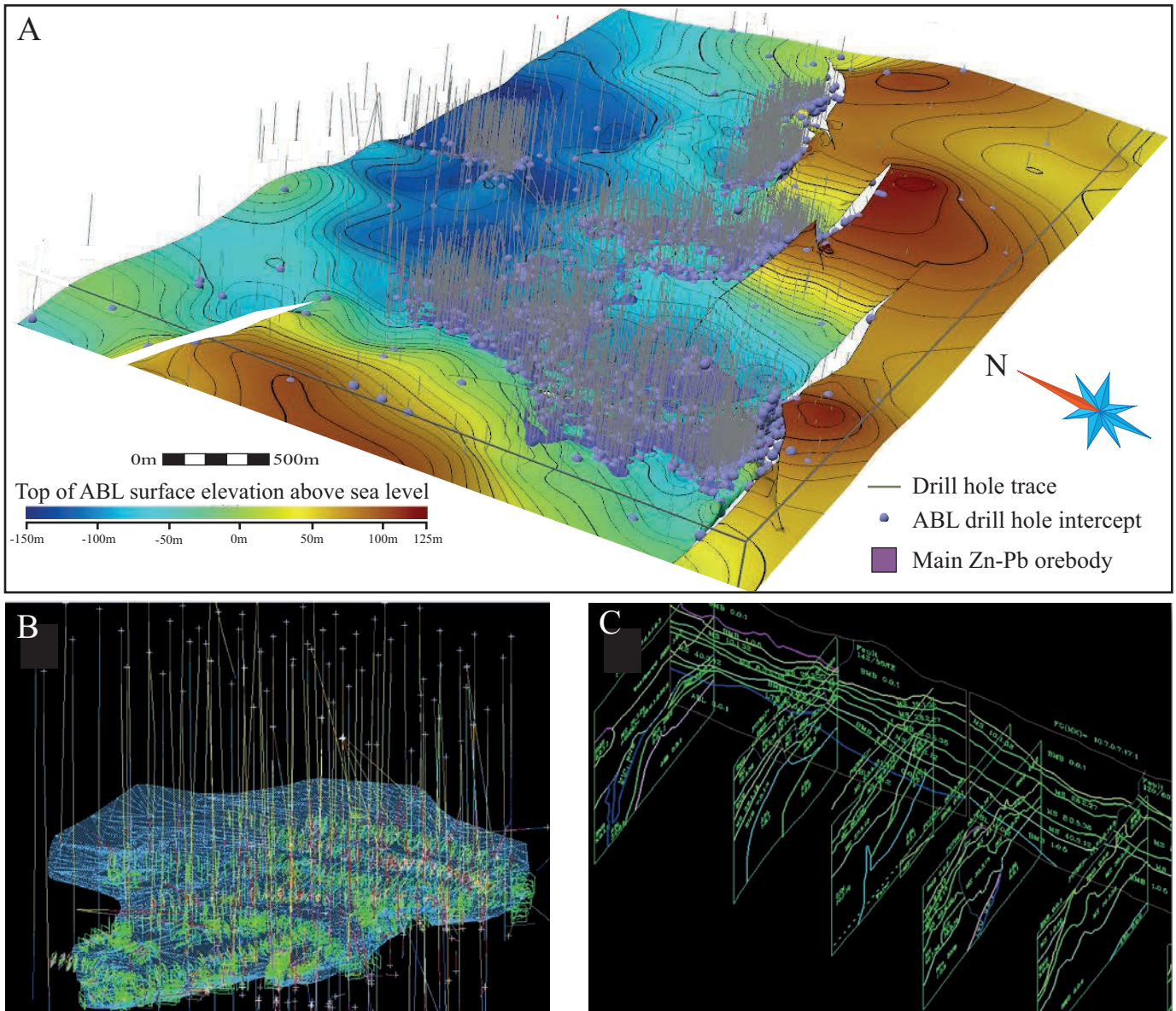


Fig. 6. Examples of the various datasets used to construct 3-D surfaces for both the Lisheen and Silvermines deposits. A. 3-D perspective of the top of the argillaceous bioclastic limestone (ABL) unit at Lisheen, highlighting the diamond drill hole ABL intercepts (purple spheres along gray drill hole traces) used as input data to constrain the ABL surface. B. 3-D perspective of the top of the ABL unit (blue mesh surface) in the vicinity of the Derryville orebody at Lisheen. This perspective highlights the drill holes (vertical and angled traces colored by lithology) used in conjunction with detailed face sheets (outlined in bright green) to constrain the ABL surface in 3-D. C. Close-up example of the detailed face sheets mapped within the Lisheen deposit. Face sheets were mapped after each blast when expanding the tunnels within the deposit. D. 3-D perspective of the top of the C5 unit at Silvermines, highlighting the diamond drill hole C5 intercepts (purple spheres along gray drill hole traces) used as input data to constrain the C5 surface. E. Example of the cross section and corresponding drill holes (colored by lithology) used to constrain 3-D surfaces (yellow, blue, and gray) for Silvermines. F. An example of an underground plan map from the Silvermines deposit, showing the structural and geologic data also used to constrain 3-D surfaces of the various geologic units within Silvermines.

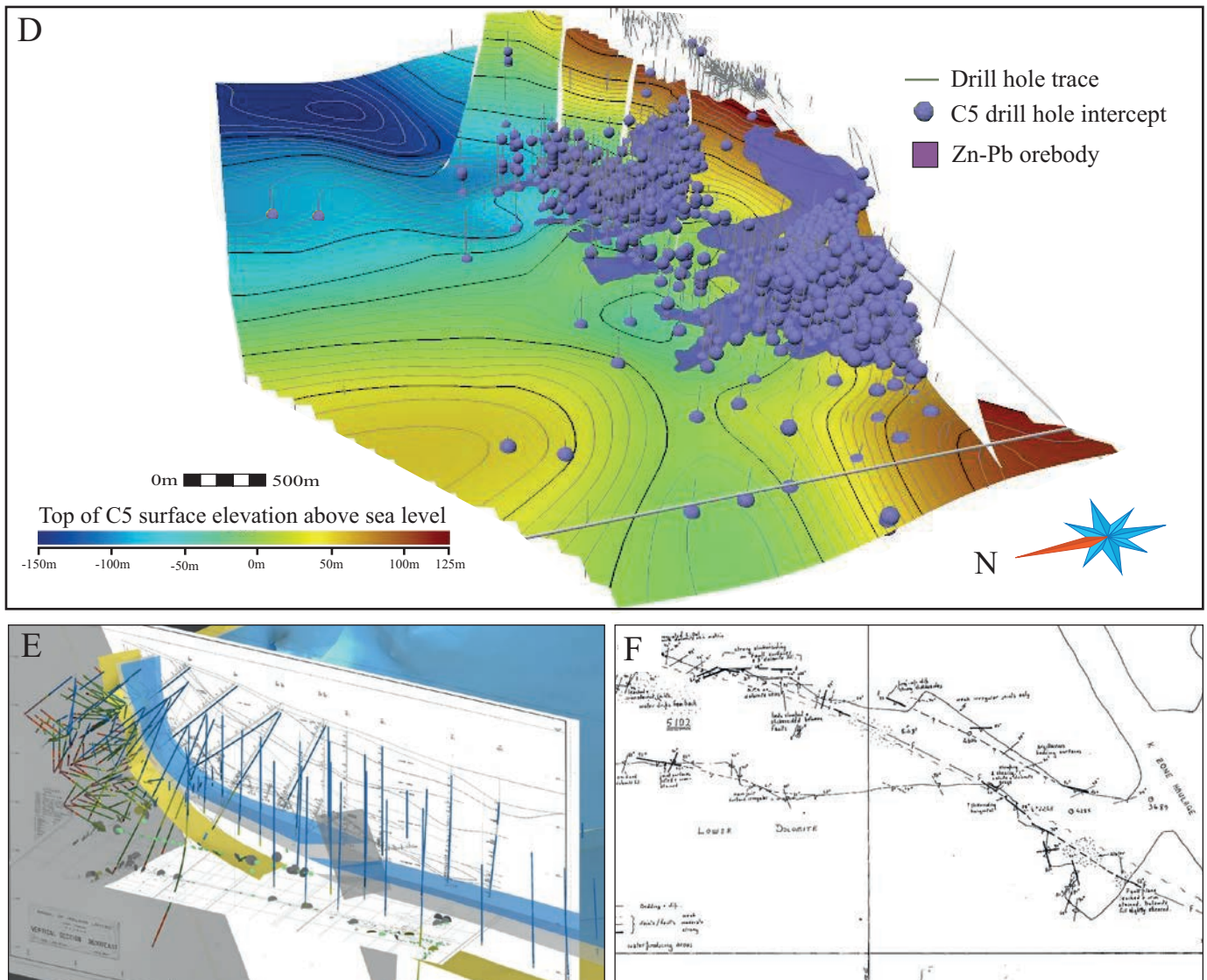


Fig. 6. (Cont.)

sections and detailed plan maps to extrapolate a 3-D surface for Silvermines.

We use Maptek's Vulcan modeling software to manually digitize surfaces, fault lines, and volumes in areas of densely spaced data (i.e., within the individual orebodies), which has permitted the detailed delineation of various parts of the fault systems and stratigraphic horizons within the two deposits. Once created, these interpreted surfaces, fault lines, and volumes were used as input data for Paradigm's SKUA-GoCAD modeling software, coupled with Mira Geoscience's Mining Suite plugins to extrapolate between areas of dense data to create complete fault arrays and horizon surfaces.

To best constrain the normal fault systems within both deposits, and to produce the most accurate fault displacements and geometries, data points contained within individual fault zones were reduced to a single fault surface (i.e., fault plane). Individual fault zones which are composed of fault rock and slip surface bounded, variably deformed host-rock lenses, generally occur in decameter (up to ca. 30 m)

down to centimeter scales. At this scale, structures cannot be explicitly and fully mapped within 3-D models. In some cases, individual horizon points from drill hole intersections close to fault planes, which are known to be produced by localized inversion on normal faults, were ignored to produce surfaces that are akin to the initial normal fault geometries and pre-inversion displacements. The completed surfaces and volumes created using SKUA-GoCAD allowed for the production of cross sections, plan and elevation maps, and Allan diagrams all of which help to refine our interpretation of the structure of both deposits. Allan diagrams, which involve the mapping of horizon intersections against fault surfaces, are a particularly useful means of integrating fault and horizon data. Final 3-D models were then visualized using Seequent's Leapfrog3-D.

### Deposit-Scale Structures

Our analysis and 3-D modeling of the Lisheen and Silvermines deposits have identified a range of structures that can be attributed to a selection of deformation phases from Lower

Carboniferous normal faulting through to Upper Carboniferous inversion and finally Cenozoic compression. In this section we briefly describe the structure of each mineral deposit, highlighting some of the main structural features, their timing and geometrical consequences, and their relationship to ore-body configurations within each deposit.

### *Lisheen deposit*

The basic structural architecture of the Lisheen deposit is an array of four E-trending left-stepping normal fault segments, which downthrow to the north by between 160 and 220 m. These E-trending fault segments are the S-bounding structures of four individual orebodies, which decrease in scale toward the east, referred to as the Main zone, Derryville zone, Bog zone west, and Bog zone east (Figs. 3, 6). Two secondary orebodies also exist, Bog zone central (to be discussed in more detail below) and the Island Pod zone, unusual insofar as it is distal from the main E-trending normal faults and other orebodies but nevertheless spatially related to two smaller E-trending normal faults also with downthrows to the north. Similar E-trending minor normal faults, with downthrows of up to 15 m to the north, are contained within the hanging wall of the Lisheen fault system (Fig. 3A). The main bounding fault surfaces generally dip at ca 60° N, though variations in dip do occur and are related to complex fault zone structures, which is often an intrinsic characteristic of fault zones, but, in this case, also arises from later inversion. Displacement along the entire system is conserved by displacement transfer from one fault segment to another, a feature that is reflected in the broadly common hanging- and footwall elevations away from the well-defined relay ramps (Fig. 7). This preservation is best highlighted in the Allen diagrams and displacement profiles for the base of the Waulsortian reef in Figure 8. Captured in these diagrams is the rapid transfer and complementary nature of displacements both between bounding segmented faults and along the system as a whole; a feature which reflects the geometric coherence of the faults (Walsh and Watterson, 1991). Illustrated in the displacement profiles is the gradual decrease in the displacement across the entire system toward the east and the appearance of a deficit in combined displacements (i.e., between the Main zone and Derryville orebodies) attributed to both hanging-wall bed rotation and the effects of inversion associated with later transpressional faults. Perspective views of the 3-D model and the structural contour map of the base of the Waulsortian reef highlight the geometry of relay ramps which dip shallowly, 15° to 21° WNW, having dip directions of 280° to 290° (Fig. 7). Of the four main relay ramps that can be observed at deposit scale (Fig. 7), the two

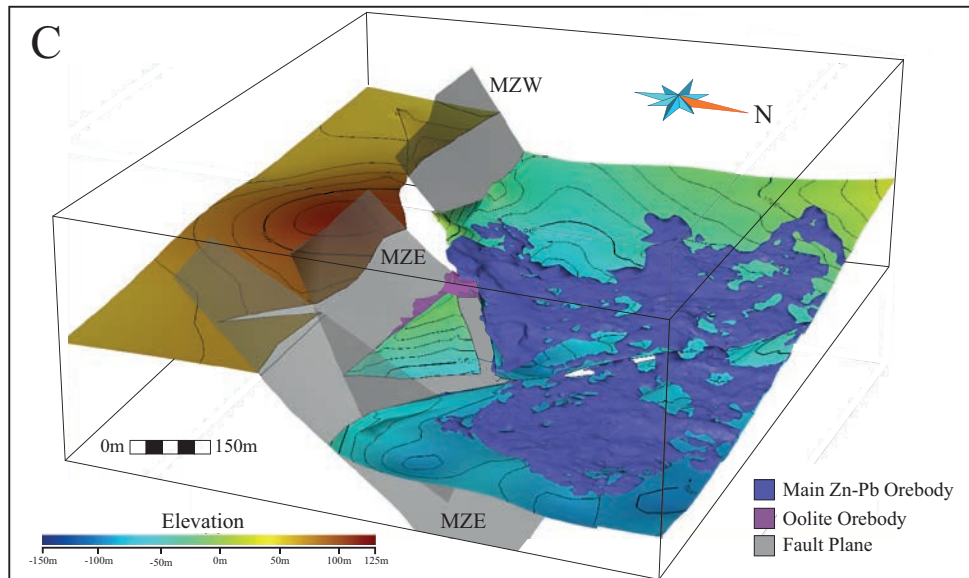
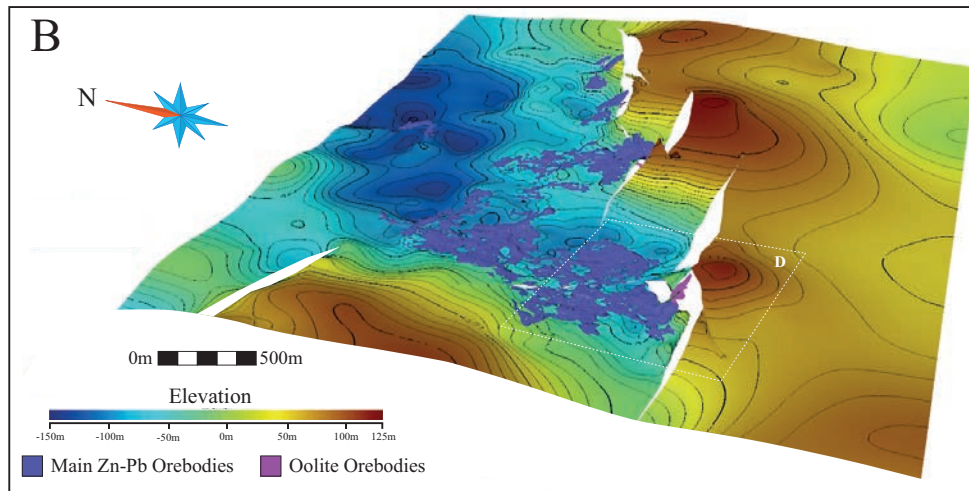
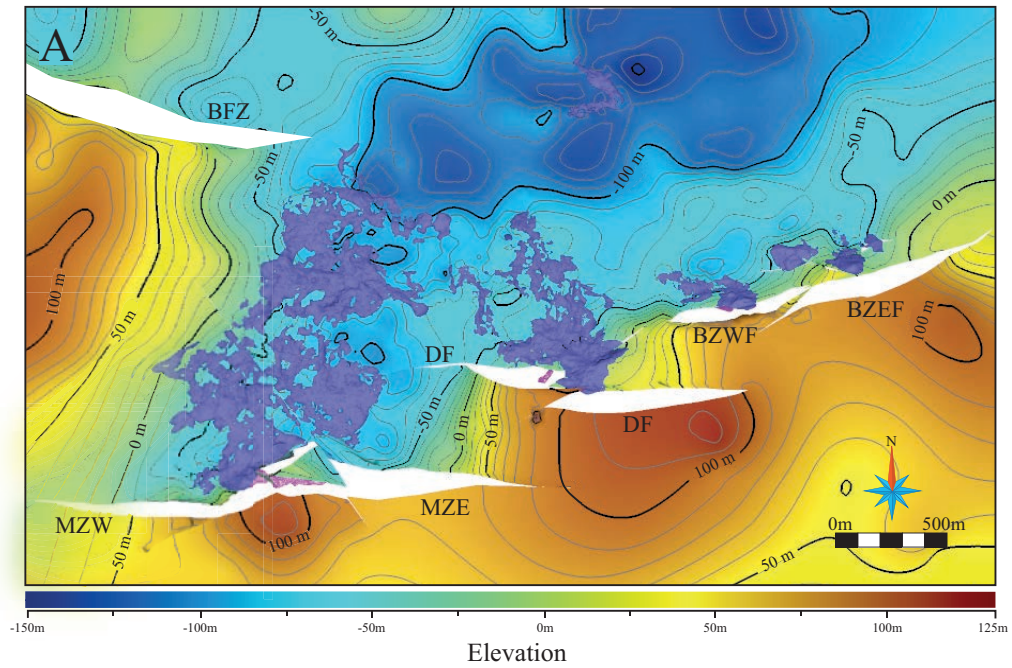
larger relay ramps between the Main zone and the Derryville and Derryville and Bog zone west have fault segment separations of 550 and 475 m, respectively, accommodate 220-m displacement, and are intact, whereas the two smaller scale relay ramps within the Main zone and between the Bog zone west and Bog zone east, have fault separations of 150 and 220 m, respectively, accommodate 220- and 160-m displacement, and are breached. At even smaller scales than can be defined within our 3-D models and Allen diagrams, fault zone complexities have been identified in underground mapping and from drill hole data, which consist of decameter (<1,00 m) thick fault-bounded lenses containing deformed and rotated host-rocks sequences through to fault rock (Fig. 3B).

A series of structures postdating the main phase of mineralization are attributed to the later, end Carboniferous, Variscan orogeny, a deformation phase regionally characterized by north-south compression, and a component of dextral transpression. Offsets, crosscutting relationships, and repetition of units observed through 3-D modeling, underground mapping, and field observations have allowed for the identification of these dextral, transpressional, oblique-slip faults, which offset the preexisting normal fault array geometries (Figs. 3A, 7). Figure 3A shows the location of these transpressional oblique-slip faults (blue) within the Main zone, Derryville, and Bog zone east orebodies. Inversion is also concentrated in the immediate hanging wall of the faults with localized folding and thrusting, particularly adjacent to preexisting minor normal faults, and often characterized by overfolds and detachment-type folds (Fig. 3B). Deformation and folding of the originally stratiform orebodies is common and is sometimes associated with the remobilization and deposition of minerals, in particular sphalerite, in veins or in the saddles of inversion-related folds.

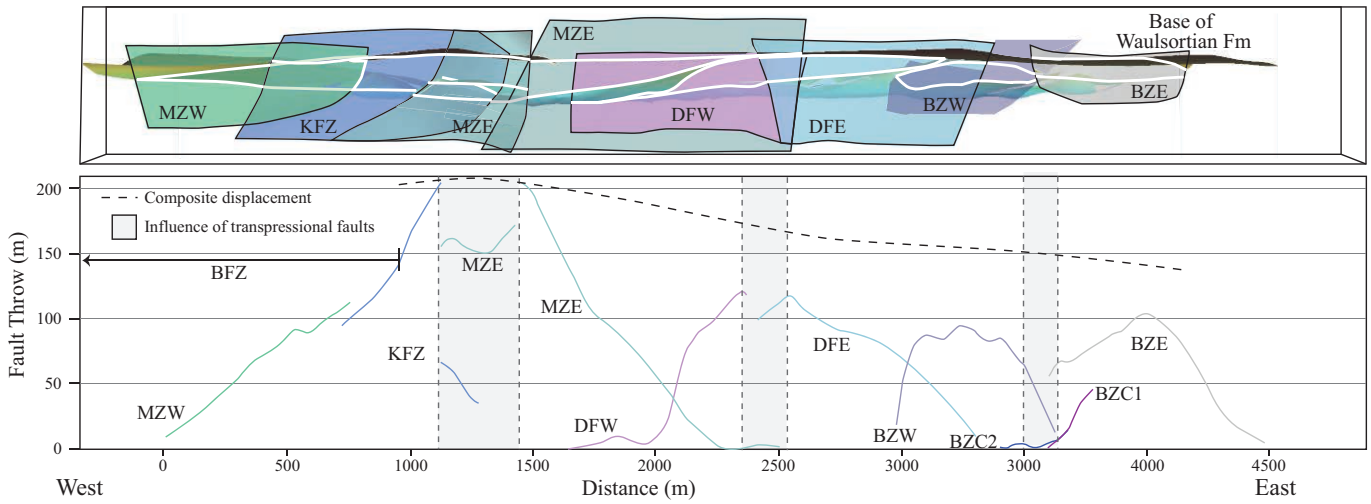
A NW-trending set of folds and/or low displacement faults occurs most notably in the southwestern portions of the Main zone orebody and the northern limb of the Island Pod (Fig. 3A). While it is difficult to define exactly when these structures formed, their association with Zn-rich trends suggests they were formed either with main-stage Zn-Pb mineralization or during the remobilization accompanying Variscan deformation.

The final deformation phase is characterized by NNW-trending strike-slip faults (i.e., F<sub>2</sub>, F<sub>3</sub>, and F<sub>7</sub>), with up to 50-m dextral displacement, which offset all earlier structures (Figs. 3A, 7). These faults are often karstified, particularly at depths of 200 m or less, but where preserved they are usually vuggy, strongly fractured, and sometimes with vein infilling (typically with pink dolomite). Their vuggy and karstified nature is

Fig. 7. Various perspectives of the 3-D model of Lisheen, showing the top of the argillaceous bioclastic limestone (ABL) surface contoured by elevation relative to sea level. Orebodies are shown in purple for the main hanging-wall ore and pink for the oolitic ore. The argillaceous bioclastic limestone surface is torn by the main normal faults (represented by the white areas of the map) using both their locations and displacements. The model highlights the presence of four major relay ramps and their associated fault segments within the deposit. It also shows the location of orebodies at the base of relay ramps with their southeastern edges parallel to the strike of the adjacent ramps (e.g., Derryville and Main zone orebodies). A. Plan view. Abbreviations for each fault segment and relay ramp are as follows: Barnalisheen fault zone (BFZ), Main zone fault west (MZW), Main zone fault east (MZE), Derryville fault (DF), Bog zone west fault (BZWF), Bog zone east fault (BZEF). B. East-northeast view of the top of argillaceous bioclastic limestone layer highlighting the relay ramps present within the deposit. 3-D model shows the distinct geometries of the relay ramps, which is best exemplified by the ramp located between the Main zone and Derryville. C. Cross-sectional, oblique, southwest view of the Main zone orebody, showing the juxtaposition of the oolite ore (in pink) against the main ore (in purple) due to displacement of the Main zone relay ramp.



[A] Allan Diagram and Fault Displacement Profile for Lisheen



[B] Allan Diagram and Fault Displacement Profile for Silvermines

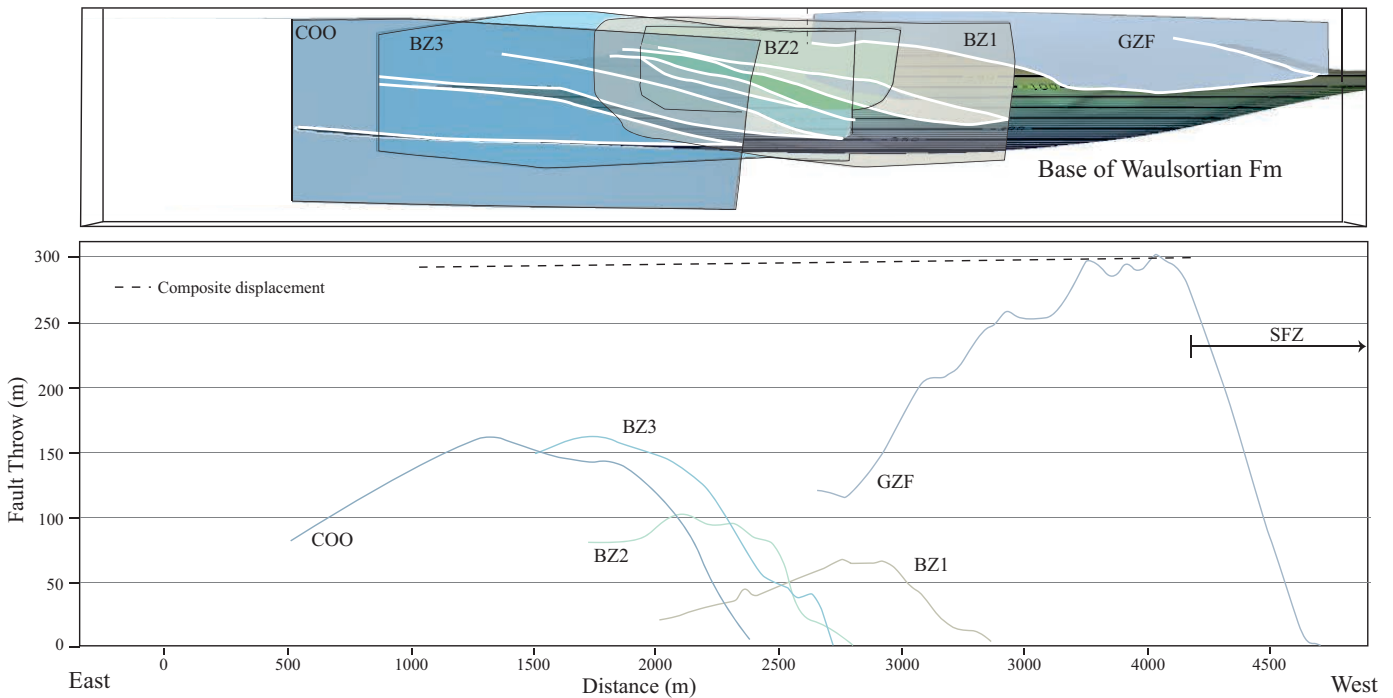


Fig. 8. Allan diagrams and fault displacement profiles for the array of faults bounding the Lisheen and Silvermines deposits. An Allan diagram is a strike-parallel vertical projection plane which highlights each of the bounding faults (in different colors and labeled) together with the intersection lines of the base of the Waulsortian Formation horizon against the fault (white lines), often referred to as hanging-wall and footwall cutoffs. Each of the bounding faults extends up to the present-day surface and downward beyond the depths of the mapped geometries shown. Displacement profiles along the bounding fault show the changes in vertical displacement, or fault throw, for each of the segments. Segments outside of each deposit are not mapped, but we expect displacement to be conserved extending toward the east and west. A. Displacement across the Lisheen deposit decreases eastward from 220 to 167 m. On the west side of the deposit displacements are at least partly transferred onto the Barnalisheen fault, whereas those in the east are transferred onto other unmapped segments extending toward Galmoy. B. Displacement across the Silvermines deposit is preserved from west to east. Abbreviations can be found for (A) in Figure 3 and for (B) in Figure 4.

consistent with their role as the main groundwater-controlling structures within Lisheen and other deposits (e.g., Galmoy).

Whereas the multiple phases of deformation which have affected Lisheen have not, at deposit scale, completely

masked the original segmented nature of the fault system, there are places where the associated structure becomes very complicated and requires reconstruction. An example of this occurs within the southern end of the Main zone orebody

where a palinspastic reconstruction has identified the presence of a small-scale, preexisting relay ramp. Figure 9 shows the three-stage reconstruction of faulting, through time, from present-day fault geometry through to the original relay ramp configuration. Figure 9A shows the complexity of the present-day fault network and in particular highlights the offsetting of the Main zone fault, initially by a NE-trending, strike-slip fault locally referred to as the Killoran fault, and then later by the crosscutting, NW-trending F<sub>7</sub> strike-slip fault. Figure 9B shows the configuration of the Main zone orebody, and its associated faults, prior to the late northwest faulting. Finally, Figure 9C shows the initial orientation of the various faults within the Main zone orebody prior to Variscan dextral strike-slip faulting, revealing the presence of a smaller, breached relay ramp (i.e., MZR, Fig. 9C). This initial breaching fault highlighted in Figure 9C is later reactivated during Variscan dextral transpression to form the Killoran fault identified in Figure 9B. The palinspastic reconstruction reveals that the geometry of the southernmost portion of the Main zone orebody parallels the shape of the initial Main zone relay ramp terminating against the Killoran breaching fault (Fig. 9C). A similar geometry is also observed along the easternmost portion of both the Main zone and the Derryville orebodies where the geometry of the orebody parallels the base of the Main zone-Derryville relay ramp (Fig. 7A). This reconstruction in Figures 7 and 13, and the Allan diagram in Figure 8A, show that the displacement is sufficiently large to juxtapose the Lisduff Oolite Member of the ABL in the footwall (dark gray, Fig. 9C) with the Waulsortian Limestone in the hanging wall (light gray, Fig. 8C). The same situation occurs in the Derryville fault and Bog zone West fault (Figs. 3, 7). This juxtaposition is important as it brings the structurally deformed

and stratigraphically lower Lisduff Oolite, which acts as a conduit for both lateral and vertical flow, into contact with the main host rock for mineralization, the Waulsortian reef limestone (see below for a more detailed discussion).

### Silvermines deposit

The basic structure of the Silvermines deposit (often referred to as the Silvermines fault system) is an array of six principal N-dipping fault segments, each of which is WNW-trending (Fig. 10). These fault segments are associated with five main orebodies, three of which are within the hanging wall (the B and G zones, and Cooleen prospect) and two others (K and C zones), which are spatially related to where these segments link to one another. Taken together the segments define an approximately ENE-trending normal fault array that is rotated approximately 15° anticlockwise from the Lisheen array. Smaller scale normal faults, with displacements of 1 to 10 m, trend subparallel to the larger normal fault segments and also generally downthrown toward the north (Fig. 10). Whereas the main fault surfaces generally dip between 60° to 80° NE, the faults are composed of lenses of fault rock and variably deformed host rock ca. 30-m scale or less, similar to the Lisheen system (Fig. 4B). The principal difference at Silvermines is that displacements are larger (>200 m) and the main fault segments are linked by relays which are breached mainly by footwall breaches; the one exception being the Shallee vein-hosted ore zone which is associated with a hanging-wall breach (Fig. 4A). These breaching faults have small displacements (<40 m) compared to that of the main fault segments. A further difference at Silvermines is that the fault system is located on the southern limb of a locally more significant regional fold, the Kilmastulla syncline, a situation which

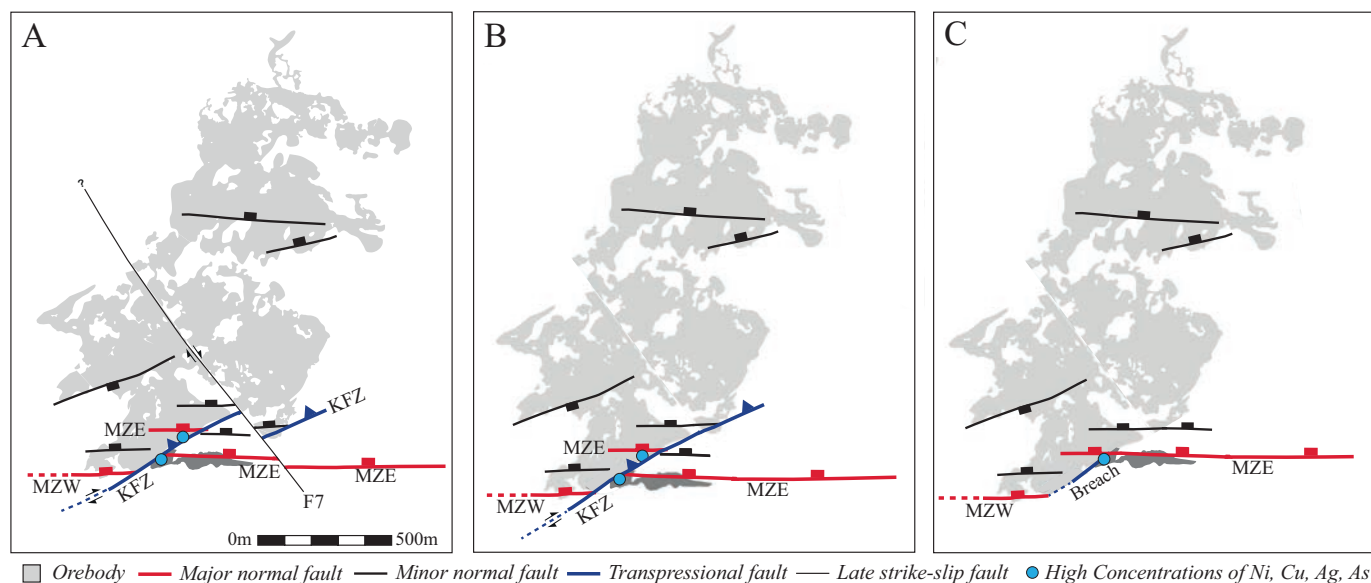
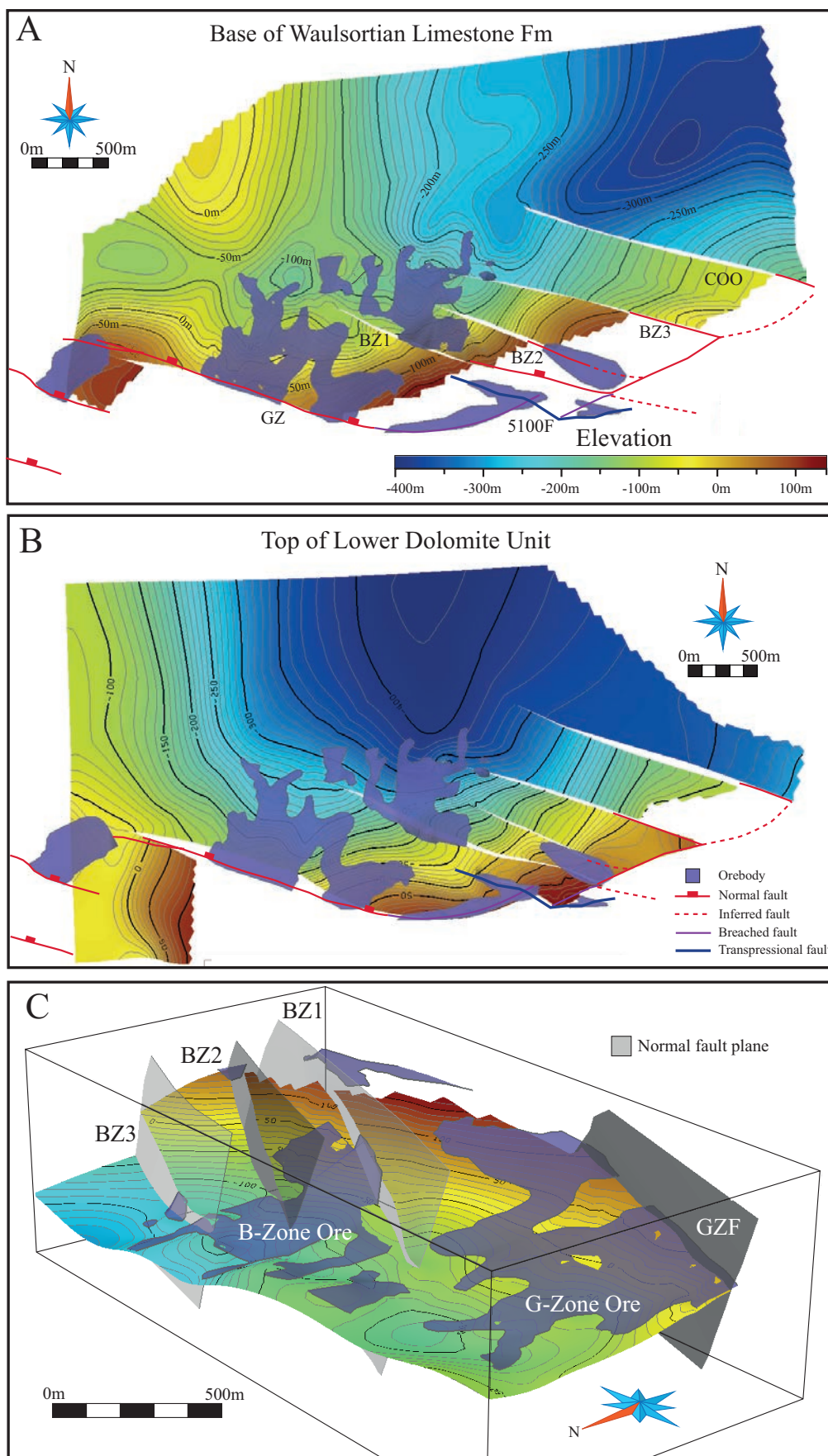


Fig. 9. Palinspastic reconstruction of the Main zone orebody in Lisheen. Three major stages of faulting are shown to have complicated the original Main zone relay ramp geometry. A. Shows the present-day fault system observed within the deposit and the segmented nature of the Main zone fault (MZ). B. Reconstruction of the Main zone orebody, and associated fault geometries, prior to the NW-trending Cenozoic dextral strike-slip fault (F<sub>7</sub>). The area within both the Oolitic and Main zone orebodies with highest Ni, Cu, Ar values (light blue dot) are separated by the Killoran fault into two distinct areas. C. Reconstruction of the initial Main zone geometry orientation by restoration of displacements along the ENE-trending Variscan dextral strike-slip fault, showing the presence of a small relay ramp (the MZR) that is fully breached, which is responsible for the single localization of ore along the Main zone fault.



complicates the interpreted geometries of preexisting relays and is compounded by a deeper level of erosion, which makes definition of the footwall structure very difficult.

The 3-D analysis of the Silvermines segmented fault array shows that the major relay ramps are breached (GZ-BZ1, BZ1-BZ3, and BZ3-COO; Figs. 4A, 8, 10). The easternmost portion of the fault array is also interpreted to be breached but is ill defined due to lack of data. In general, relay ramps at Silvermines dip shallowly (between 18°–24°) to the northwest (dip direction of 303°–337°), but accounting for the later Variscan folding associated with the regional Kilmastulla syncline, original ramp dips are estimated to have been 7° to 13°. No significant change in total displacement east to west along the Silvermines fault system can be resolved from the available data. The preservation of displacements across Silvermines is highlighted by the Allan diagram and displacement profiles for the base of the Waulsortian reef, which demonstrate the rapid transfer, and complementary nature, of displacements between fault segments and the geometric coherence of the fault array (Fig. 8). The 3-D model of Silvermines demonstrates that, similar to Lisheen, the main portions of both the G and B zone orebody portions (i.e., areas of best grade and highest tonnages as identified from reports and assays) occur within the Waulsortian reef limestone at the base of the GZ-BZ1 and BZ1-BZ3 relay ramps, respectively (Fig. 10C). Unlike Lisheen, however, mineralization in these two Silvermines orebodies continue half-way up the relay ramps. Furthermore, the K and C zone orebodies, hosted within the Lower Dolomite unit, are located along the GZ1-BZ1 and BZ1-BZ3 ramp breaching structures and do not continue down their respective ramps.

Folding of assumed Variscan age has been observed underground at Silvermines in the immediate hanging walls of the normal faults (Andrew, 1986), particularly adjacent to the K and C zones breaching fault, linking the CZ and BZ1 faults and BZ1 and BZ3 faults, respectively (Figs. 8B, 10). These structures cannot, however, be explicitly modeled in 3-D, given the scale and quality of the available archive data. Dextral transpressive oblique-slip faults have also been identified within the Silvermines deposit and are sometimes expressed as mappable structures at deposit scale. The 5100 fault, located in the eastern portion of the G to B zones relay ramp, is the best example of this type of accommodation structure (Fig. 8B). The dextral offset of the K zone breaching fault by the 5100 fault highlights how an original minor normal fault can be reactivated during compression as an oblique-slip fault structure that can locally complicate orebody geometries. Finally, the NNW-oriented dextral strike-slip faults, which

are common in Lisheen, are not identifiable from the available 3-D dataset for Silvermines; a Silvermines feature, which could reflect a proposed regional decrease in the intensity of these faults toward the west (Moore and Walsh, 2013). Sub-vertical NNW- and N-trending veins, with barite, carbonate, and galena infillings, have been observed within the Shallee ore zone (Rhoden, 1958; Everett et al., 1999).

#### *Summary of normal fault structure from the Lisheen and Silvermines deposits*

The normal fault structures within the Lisheen and Silvermines deposits have the following many shared features, suggesting that a common generic model may be applicable.

1. Both deposits are controlled by bounding faults, which downthrow and dip toward the north and which have mineralization almost exclusively contained within their respective hanging walls.
2. Vertical displacements across the bounding faults are of hundred-meter scale, with Lisheen and Silvermines accommodating up to 200- to 400-m displacement, respectively.
3. Both fault systems are segmented comprising individual segments, which are either physically hard-linked (i.e., by breached faults) or soft-linked by relay ramps that transfer displacement between segments.
4. Left-stepping segmentation of east-west fault segments provides arrays which are approximately east-northeast trending.
5. The resolvable separation between mappable fault segments ranges from 1,500 m (in the case of the Barnalisheen-Maine zone relay) down to ca 500 m, for the main orebody bounding segments, and below ca. 100 m for smaller scale complexities.
6. Where higher resolution data constraints are locally available, they demonstrate that smaller scale fault zone complexities occur, taking the form of variably deformed fault surface-bounded lenses with thicknesses 30 m or less and with internal deformation accommodated by rotated bedding or fault rock generation.
7. There is a very clear spatial association between the hanging walls of individual fault segments and separate orebodies within each deposit.
8. Mineralization is usually localized toward the base of the Waulsortian reef limestone, often replacing earlier dolomites and breccias (Figs. 3B, 4B).
9. Small-scale fully breached relays are a primary focus for upfault flow and act as feeders for orebodies. A secondary focus for orebody generation, and upfault flow, are the faults associated with the breaching of relays (Figs. 4B, 10).

Fig. 10. Various perspectives of the 3-D model of Silvermines, showing the base of the Waulsortian limestones and the base of the Lower Dolomite unit. Orebodies are shown in purple and the surfaces torn by the main normal faults (represented by the white areas within the model), using both their locations and displacements. The model highlights the presence of five major relay ramps and their associated bounding segmented faults. A. Plan view of the 3-D model of the Silvermines deposit, showing the base of the Waulsortian Limestone Formation surface contoured with elevations relative to sea level. The contoured base of Waulsortian Limestone Formation surface ends in the southeast where it intersects the present-day topographic surface. Abbreviations for each fault segment and relay ramp are as follows: G zone fault (GZ), 5100 fault (5100F), B zone fault 1 (BZ1), B zone fault 2 (BZ2), B zone fault 3 (BZ3), Cooleen fault (COO). B. Plan view of the 3-D model, showing the base of the Lower Dolomite unit surface contoured with elevations relative to sea level. C. Southeast view of the base of the Waulsortian reef limestone formation surface, contoured by elevation relative to sea level. This view of the 3-D Silvermines model shows the location of the G and B zones orebodies in relationship to the geometry of the segmented normal fault array and its accompanying relay ramp geometries.

All of these characteristics are addressed in the following discussion section, which starts with a consideration of why and how fault segmentation is developed, followed by a quantitative assessment of what controls the integrity and breaching of relays, a critical determinant on orebody geometry. We then turn our consideration to the impact of faulting and segmentation on fluid flow and mineralization, and its implications for mineral exploration.

## Discussion

### *Origins of fault segmentation and importance of inheritance*

It is well documented that normal faults are typically segmented in map view as well as in cross-section (Peacock and Sanderson, 1991; Childs et al., 1995, 2009, 2017; Fossen and Rotevatn, 2016; Freitag et al., 2017). Within the Irish ore field segmented normal fault arrays can be identified both at deposit scale and on the larger, regional scale (Figs. 1C, 3A, 4A). Segmentation occurs on a range of scales with regional-scale segmented fault arrays often comprising smaller scale segmented fault arrays relaying displacement from one array to another across relay ramps. The Rathdowney Trend fault system illustrates segmentation on different scales (Fig. 1B) where two NW-trending, left-stepping regional fault segments are in turn comprised of the orebody defining fault segments observed within the Lisheen and Galmoy deposits, and also appear to be developed at Rapla farther to the east. A similar regional-scale relay, with a separation of ca. 1,500 m, appears to transfer displacement from the Lisheen fault system to Barnalisheen in the northwest (Fig. 7A). On the deposit scale, the displacements across the Lisheen fault system decrease from 220 m in the west to 160 m in the east (Fig. 8), suggesting that displacement is being relayed to the Galmoy deposit fault system across a large-scale “monocline” or relay ramp which is of similar scale (ca. 1,500-m separation) to that of the Barnalisheen-Lisheen ramp. Overall, displacements across the three deposits gradually decline from 220 m in the western side of Lisheen, to 130 m at Galmoy, and 130 m at Rapla, a change which is more consistent with the lower displacement gradients typical of individual faults or arrays, than the very rapid displacement changes (see below) accommodated by strong displacement transfer between segments at well-defined relay ramps.

Since the Rathdowney trend is parallel to that of the underlying NE-ESE-trending Caledonian structures, as observed from structural analysis of adjacent Silurian basement inliers and analysis of ground gravity (Sanderson et al., 1980; Johnston et al., 1996; O'Reilly et al., 1999), whereas the deposit-scale Carboniferous normal fault segments are closer to east-west trending, this configuration is indicative of basement control and oblique reactivation (Fig. 11). Previous work on Carboniferous basins in the UK and in the north of Ireland have shown that basal structures parallel earlier Caledonian fabrics, suggesting a fundamental control (Bott, 1987; Fraser and Gawthorpe, 1990, 2003; Woodcock and Strachan, 2000; Worthington and Walsh, 2011; Davies et al., 2012). Worthington and Walsh (2011) pointed out the wrapping of both Caledonian structure and later Carboniferous normal fault systems around the Midland craton and into the North Sea (where NW-trending normal faults dominate),

strongly suggesting basement inheritance. They also showed that both the trends and the localization of later normal faults is strongly controlled by preexisting Caledonian structure and that the largest normal faults localize closer to the most significant Caledonian terrane boundaries, in particular. However, the polarity and dips of later Carboniferous normal faults are clearly not defined by preexisting structures, a characteristic explained by two reasons. First, the preexisting Caledonian structures range from near-vertical strike-slip terrane boundaries through shallow-inclined structures (<ca 200 m) such as the Iapetus suture. There is no suggestion that the later Carboniferous tectonic faults are anything other than conventionally dipping (>ca 600 m) normal faults. Second, the polarity of later normal fault systems changes along their length, even along zones that are adjacent to major terrane boundaries, a characteristic which is not consistent with the discrete reactivation of individual preexisting basement structures, but is instead a reflection of the general localizing effect of preexisting basement heterogeneities.

Given the importance of preexisting structure in the general orientations of later normal faults, the key to producing left-stepping segmented arrays is the notion that rifting within the Carboniferous was generally north-south trending and therefore oblique to the main fault trends (Fig. 11; Johnston et al., 1996; Worthington and Walsh, 2011; Bonson et al., 2012). There are a variety of types of structural studies demonstrating that the oblique reactivation along preexisting trends or structures generates segmented arrays. For example, analysis of 3-D seismic datasets shows that oblique reactivation of preexisting structures generates upward bifurcating (i.e., splaying) normal fault surfaces that segment and twist, or form fault segments that are soft-linked in 3-D, as they propagate upward through overlying cover sequences (Walsh et al., 2003; Worthington and Walsh 2011; Giba et al., 2012). Sandbox and numerical modeling also highlight the importance of oblique displacement in the generation of arrays of fault segments (Acocella et al., 1999; Le Calvez and Vendeville, 2002; Gartrell et al., 2005; Hus et al., 2005; Konstantinovskaya et al., 2007; Schöpfer et al., 2007, 2016). However, these studies have also shown that segmentation does not require oblique displacement, but can instead simply arise from the propagation of faults through heterogeneous mechanical stratigraphies at lower confining pressures. These requirements for segmentation are met by faulting within the Irish Zn-Pb ore field, which is marked by oblique displacement on faults contained within extremely heterogeneous sequences at deformation depths of less than ca. 500 m.

The above observations support the application of a segmentation model in which different scales of relay develop within a fault system, which is geometrically coherent, related on a regional scale, and transfer displacements of ca. 200 to 400 m over strike distances of at least 10 km. This persistence is promoted by localization along basement structures where segmented fault arrays arise from the upward propagation of a fault which bifurcates at different stratigraphic levels in response to both changes in the stress regime and/or rheological differences within the faulted sequence (Fig. 11; Bonson et al., 2012). In Silvermines, the GZ-BZ1 segments have significant separations (>ca. 500 m) at the top of the Old Red Sandstone, as do the faults bounding the BZ1-BZ2 and BZ2-BZ3

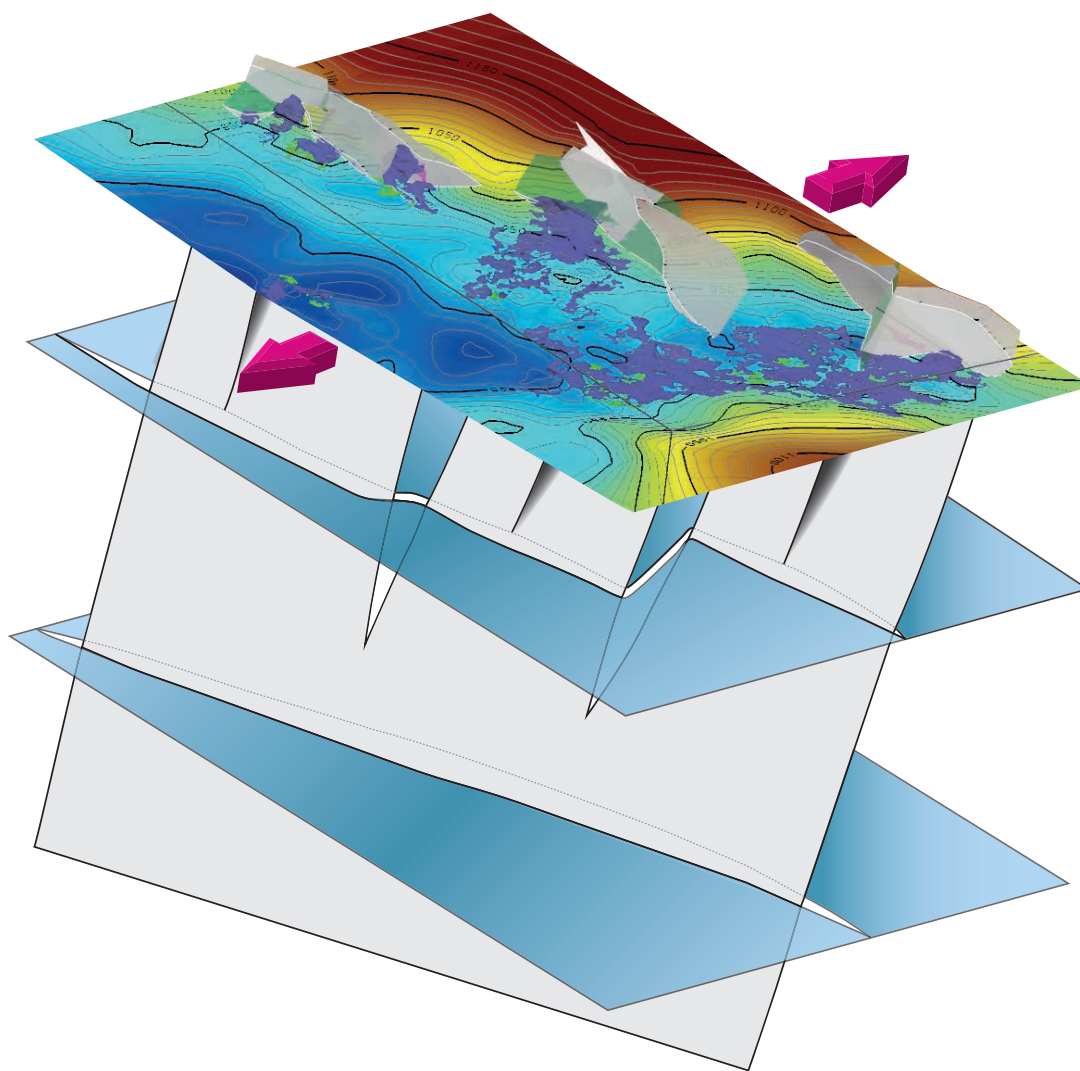


Fig. 11. 3-D model of the top of the argillaceous bioclastic limestone (ABL) horizon within the Lisheen deposit, showing a schematic projection of the bounding fault surfaces with depth. The model for fault segmentation is one in which the orientations of Carboniferous normal faults are inherited from ENE-trending preexisting basement fabrics/structures. Subsequent faulting Carboniferous cover sequence bifurcates and twists to provide fault segments which are east-west trending at higher stratigraphic levels and perpendicular to the N-S Carboniferous extension.

ramps (up to ca. 200-m separation). Bifurcation therefore must happen deep within the Old Red Sandstone Formation, and almost certainly below the Old Red Sandstone Formation-Silurian boundary, perhaps even extending into the underlying Ordovician. For the MZ-DVIL and DVIL-BZW ramps at Lisheen, extrapolation of bounding fault segments downward suggests that bifurcation is either close to the base of the Old Red Sandstone Formation or within the underlying basement. By contrast, the Main zone relay at Lisheen, after palinspastic reconstruction, has a separation of 200 m, and visual extrapolation would suggest bifurcation toward the base of the Carboniferous. Cross sections of Lisheen suggest that even smaller scale relays or complexities, with separations of <50 m, can bifurcate from the Lisduff Oolite, one of the more distinctive mechanical units of the sequence underlying the Waulsortian reef. Taking the available quantitative constraints, it therefore appears that if segments arise from bifurcation of a single fault surface, then larger scale relays

(with separations of >500 m) must bifurcate from deeper levels within the Caledonian basement, with smaller scale relays (separations of <200 m) involving bifurcation within the Carboniferous cover sequence (Fig. 11). In line with recent work (Walsh et al., 2002; Giba et al., 2012; Schöpfer et al., 2016), we consider that the localization of all of these segments is relatively rapid, and that their further evolution is dominated by displacement accumulation, relay breaching and fault rock generation, as outlined in the next section.

#### *Quantitative model for relay evolution within the Lisheen and Silvermines deposits*

The fundamental structural framework identified within both deposits is left-stepping segmented fault arrays with associated relay ramp geometries (Figs. 7, 10). Fault displacement profiles plotted for the normal fault segments within both Lisheen and Silvermines show that displacements along the various segmented normal faults decrease rapidly away from

point of maximum displacement (Fig. 8). This is best exemplified within the Lisheen Derryville orebody where 100 m of displacement on the Derryville normal faults dies out laterally within 500 m (Figs. 3A, 7–8). In Silvermines, displacements of 300 to 400 m on the various segmented faults are lost laterally within 800 m (Figs. 4A, 8, 10). Such high-displacement gradients are typical of relay ramps associated with fault segmentation and provide an efficient means of generating complex fault structures and patterns. In an effort to provide quantitative constraints on the evolution of fault segmentation and breaching for the Lisheen and Silvermines deposits, we have measured the displacement versus thickness or separation for the four fault geometric components used in defining the fault zone model of Childs et al. (2009): intact relay, breached relay, fault zone, and fault rock. The separation of a relay zone is the distance, measured normal to the fault, between a pair of relay ramp-bounding faults. A relay is classified as “breached” if one, or both, of the relay bounding faults has propagated to intersect the other. Fault zone thickness is defined as the distance between related synthetic slip surfaces (the same dip direction and sense of offset) that can be demonstrated in outcrop to be kinematically related. Fault zones typically comprise lenses of variably deformed host rock

created by anastomosing networks of throughgoing synthetic slip surfaces and associated fault rock. Fault-rock thickness refers to a variety of fault-rock types, including fault gouge, breccia, and cataclasite. Our Lisheen and Silvermines data (Fig. 12) show that relays with smaller displacement to separation ratios are intact relays (e.g., Main zone-Derryville relay ramp at Lisheen), those with larger displacement to separation ratios are more likely to be breached (e.g., GZ-BZ1 relay at Silvermines and the Main zone ramp relay at Lisheen), and fault zones and fault rock have progressively higher displacement to thickness ratios. This relationship is consistent with the fault zone model of Childs et al. (2009) which, on the basis of a global dataset of natural fault data, reconciled the progressive evolution of intact and breached relays into fault zones, lenses, and ultimately fault rock, with an increase in displacement and associated across-fault shear strain equivalent to the displacement to thickness or separation ratio (Childs et al., 2009).

The broad equivalence between our Irish ore field fault data and other global datasets provides support for the conceptual framework underpinning the fault zone model of Childs et al. (2009). The question is whether the same model provides a basis for predicting the structure of fault zones. Because the global dataset includes data from many fault systems, which

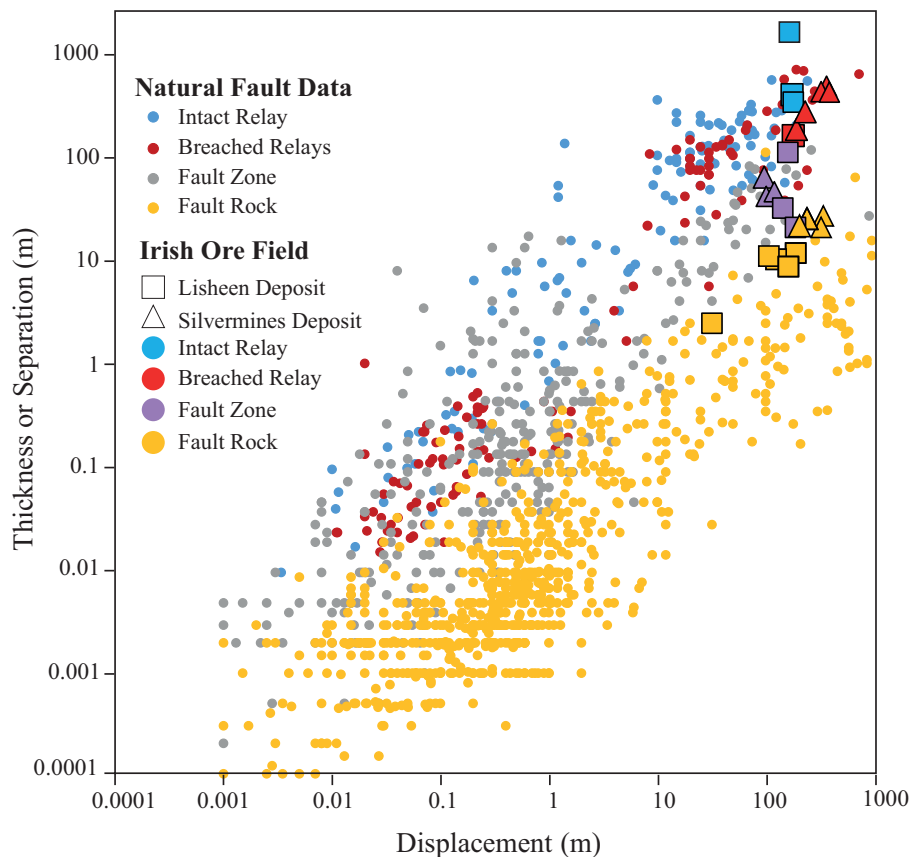


Fig. 12. Quantitative data for different fault zone components on a thickness or separation vs. displacement plot for a global database updated from Childs et al. (2009), and including Lisheen and Silvermines data. Separation represents the fault perpendicular distance between segments of intact relays, breached relays or lenses, and thickness refers to fault rock. Different fault zone components provide distinctive, albeit overlapping, distributions with an increased displacement to thickness (or separation) ratio, and therefore shear strain, from intact relays through breached relays and into fault zones and ultimately fault rock. The Irish ore field data appear to be consistent with global datasets, circumstances which could provide a quantitative basis for predicting fault zone structure and content. See text for details.

are contained within different host-rock sequences and were formed under variable deformation conditions, the associated data show a significant degree of scatter and overlap between different fault zone components and structures, even if the data distribution is generally systematic. This variability diminishes the predictive potential of the global dataset, from a practical perspective, and makes a strong case for the use of quantitative fault parameters between comparable fault systems or, ideally, for the construction of more local or regional datasets. The Lisheen and Silvermines data are, however, more internally consistent than the global dataset. Because they are derived from areas with similar layer-cake limestone stratigraphy and deformation conditions (e.g., burial depths or amount of extension), they provide a better ground for potential prediction of the integrity or content of fault zone components. For example, they provide a rationale for the intact nature of the larger scale relays with 450- to 550-m separations at Lisheen compared to the breached relays with similar separations at Silvermines, which are characterized by fault displacements that are nearly twice as high (i.e., 400 rather than 200 m). They suggest that relays with separations of less than 50 m on faults with a displacement of 100 m or greater will be fully breached. This potential predictive capability will further benefit from ongoing work collating quantitative fault zone data from several other deposits in the Irish Midlands. This emerging quantitative framework provides support for the conceptual fault zone model of Childs et al. (2009) and could have major implications for fluid flow and mineralization.

#### *Effect of segmented fault arrays on the geometry of orebodies*

The 3-D modeling of the Lisheen and Silvermines deposits shows that there is a very strong link between individual fault segments, relay ramps, and the location of associated orebodies. At Lisheen, each major fault segment contains hanging-wall orebodies located at the base of the Waulsortian reef (Fig. 3). A similar observation can be made for the Silvermines deposit where the geometries of the G and B zone orebodies are controlled by their respective relay ramp architecture, and the highest concentration of mineralization occurs at the base of the ramps (Fig. 4). These orebodies are spatially associated with, and replace, stratiform hydrothermal carbonate breccias (Hitzman et al., 2002; Fusciardi et al., 2004; Wilkinson et al., 2005a). Both sulfide mineralization and hydrothermal carbonate breccias are thickest within the hanging walls of the bounding normal faults, often thinning away from the fault plane.

The locations of both mineralization and carbonate breccias are not simply at the point of maximum displacement of the individual fault segments, but are strongly controlled by hanging-wall geometries and relay zones. For example, the eastern side of the Main zone orebody at Lisheen is bounded by, and parallels, the base of the Main zone-Derryville relay ramp (Figs. 3, 7). The Derryville orebody shows a similar relationship on its southeastern edge, which again appears to be bounded by, and parallel to, the base of the Derryville-B zone west relay ramp (Figs. 3, 7). These relationships suggest that fluid migration, and subsequent mineralization, was restricted to the base of large-scale relay ramps in the bathymetric lows of individual fault segments and close to the Waulsortian-ABL contact. In this model, dense, cool, seawater-derived brines pond at the Waulsortian (permeable)-ABL (impermeable)

contact and mix with hot, buoyant, hydrothermal metal-bearing fluids to produce mineralization (cf. Banks and Russell, 1992; Eyre, 1998; Blakeman et al., 2002; Wilkinson et al., 2005a, b, 2014; Wilkinson and Hitzman, 2014). Because colder brines are relatively dense, unlike buoyant hydrocarbons, they do not rise or migrate up the relay ramps, thus restricting mineralization to the lower most portions of the Waulsortian reef limestone host rock. The permeability contrast between the argillaceous bioclastic limestone-Waulsortian, in combination with the bathymetry created by the normal faults and relay ramp geometries, also controls fluid movements at time of mineralization. Consequently, the observed “ponding” effect of the orebody in the bathymetric lows is attributed to migration of fluids into the structurally lower hanging walls of faults and fluid mixing between hydrothermal ore-forming fluids and seawater-derived brines.

In addition, there is a concentration of deformation and dilatancy within the hanging walls of normal faults in the form of brecciation, bed-parallel slip and low-angle faulting, particularly adjacent to important rheological boundaries such as the Waulsortian-ABL contact (Muir-Wood and King, 1993; Zhang and Sanderson, 1996; Walsh et al., 2018). At Lisheen, abundant evidence for low-angle faults and bedding-parallel slip at the Waulsortian-ABL contact are observed (Fusciardi et al., 2004; Bonson et al., 2012). This deformation created enhanced structural permeability and increased reactive surface area, especially in more brittle units such as the Waulsortian Limestones, Lisduff Oolite, Lower Dolomite, and Old Red Sandstone. Chemical dissolution-precipitation processes associated with fluid mixing at these sites, buffered by clean carbonate host rocks, augmented the earlier structurally enhanced permeability and created significant additional secondary permeability during precipitation of hydrothermal carbonates and sulfides.

Whereas it is true that the majority of mineralization in the Silvermines deposit occurs at the base of the GZ-BZ1 ramp in the G zone and the BZ1-BZ3 ramp in the B zone, smaller quantities of ore are observed as far as half-way up the ramps. At Lisheen small faults are found at the base of the MZ-DVIL ramp and are associated with typical feeder signatures (Torremans et al., 2018). This difference is attributed to the increased deformation experienced by the two breached relay ramps, which has produced greater structural complexity and a subsequent increase in permeability, allowing these ramps to act as partial conduits for upwelling fluids and the formation of nonstratiform orebodies (see below).

#### *Scale of relay ramps and fluid flow*

The impact of relays on fluid-flow changes with the scale of the structure. For the Lisheen and Silvermines deposits the upward flow of hot, metal-rich, hydrothermal fluids will be buoyancy driven but with sulfide deposition controlled by the migration of colder and highly saline brines with bacteriogenic signatures into the hanging-wall depressions of bounding faults acting as strong, bathymetrically controlled traps. The interaction of buoyant and nonbuoyant fluids within these trap sites produces orebodies within the hanging walls of individual fault segments leaving the relay ramps barren (Figs. 7, 10). At a large scale, individual segments are the locus for strong mineralization because they provide the essential

hanging-wall structure which traps dense brines, a scenario which is the opposite of fault-bounded hydrocarbon reservoirs which are typically footwall traps entirely controlled by buoyant fluid migration (Manzocchi et al., 2010).

At Lisheen and Silvermines, breached relays are interpreted to have enhanced permeability due to an increase in fracture density and structural complexity as a result of high shear strain across the ramp (Fig. 12) in line with the fault zone model of Childs et al. (2009). Smaller scale fault-related complexities, generating lenticular bodies of deformed and brecciated fault rock, will also be marked by enhanced permeability relative to undeformed host rock (Fig. 13). Increased

structural complexity and permeability allows the breached ramps to act as potential conduits for upfault fluid flow and may, therefore, act as ingress points (feeders) for hydrothermal ore-bearing fluids to enter host lithologies (Fig. 13C). For example, palinspastic reconstruction of the Main zone orebody at Lisheen identified the presence of a small-scale, fully breached relay ramp (MZ relay ramp), which is interpreted to have acted as a focal point for upwelling hydrothermal ore-bearing fluids to enter the Waulsortian reef host rock and mix with cold, dense, high-salinity brines to precipitate mineralization (Fig. 9). This suggestion is supported by the higher concentrations of Cu, Ag, Ni, and As directly adjacent

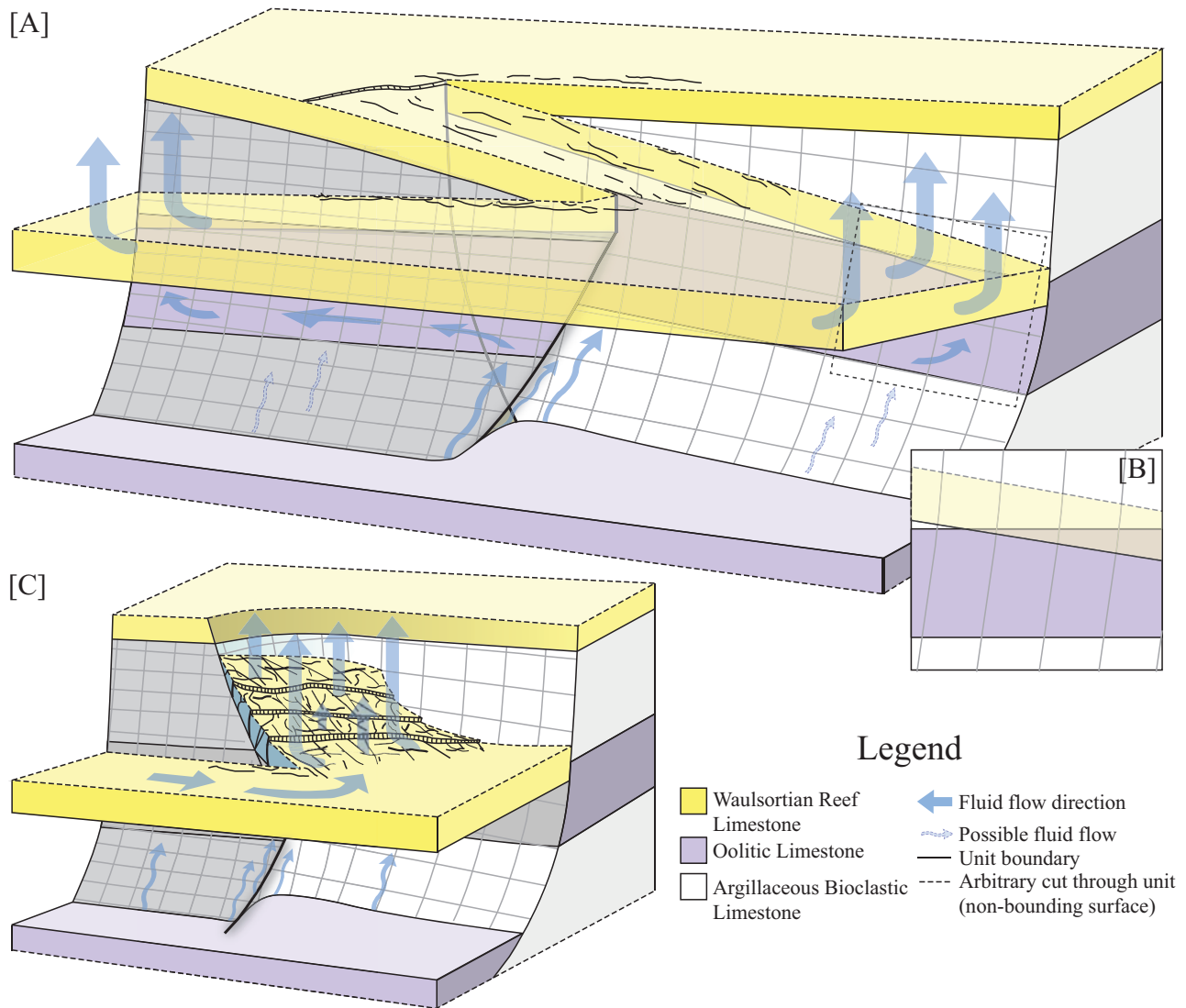


Fig. 13. Schematic drawing of relay ramp systems typically found within the Irish-type Zn-Pb deposits. A. Large-medium-scale relay ramp which is about to breach at the stratigraphic level of the Waulsortian reef. Here, upwelling hydrothermal fluids will be focused away from the ramp itself into the hanging walls of the bounding segmented normal faults. B. A close up of (A) showing the juxtaposition of the Waulsortian reef limestone and the oolitic limestone at vertical displacements equivalent to the stratigraphic thickness of the intervening upper argillaceous bioclastic limestone (ABL) unit (ca. 150 m). The associated footwall oolites are particularly transmissive and soluble and upwelling fluids, either travelling vertically up the fault surface or laterally through the oolitic limestone, are able to spill out into Waulsortian host rock. Footwall oolite mineralization always occurs where there is juxtaposition with Waulsortian orebodies, a scenario which reflects the postfaulting timing of the main phase of Zn-Pb mineralization. C. Small-scale fully breached relay ramp, at the same displacement, with associated highly fractured and broken ramp providing a pathway for upwelling fluids.

to this breached relay, with all four orebodies showing similar feeder-related metal distributions associated with small-scale complexities along individual segments (see Torremans et al., 2018). At Silvermines, areas of high concentrations of Ag and copper-bearing minerals are localized in structurally complex fault lenses, which occur within the GZ and BZ1 fault zones, as identified both in historic underground maps and by our 3-D modeling (cf. Andrew, 1986; Torremans et al., 2018). We also interpret these fault lenses as earlier small-scale relay ramps that have experienced the full displacement on the GZ and BZ1 faults, with the associated structural complexity and deformation masking the early relay ramp architecture.

Observations from both Lisheen and Silvermines also show that where relay ramps start to be breached, hydrothermal fluid flow can be localized along individual breaching faults (i.e. BZW-BZE in Lisheen and the K zone in Silvermines; Fig. 13). In the case of the BZW-BZE relay ramp at Lisheen, fluids were focused into both the bounding fault segments (BZWF and BZEF), forming the Bog zone west and Bog zone east orebodies and along the breaching fault forming the Bog zone central orebody (Fig. 3A). Similarly at Silvermines, upwelling hydrothermal fluids migrated both into the bounding fault segments (i.e., the GZ and BZ1 faults), forming the G and B zone orebodies and also into the hanging-wall breach fault structure forming the K zone orebody (Fig. 4A). This scenario is also applied to the ramp between the BZ1-BZ3 faults for which the breaching fault is mineralized to form the P zone orebody and may also be applicable to breaching fault linking the BZ3-COO faults.

Another potential control on the position of feeder points along bounding fault segments could be the across-fault juxtaposition of units with high permeability. At Lisheen, for example, the displacement on the bounding segmented normal faults sometimes juxtaposes the two best flow units within the Carboniferous sequence, the Lisduff Oolite, which is brecciated and fractured adjacent to fault planes, and the Waulsortian reef limestone (Figs. 6, 13A-B). When this occurs mineralization is present within the juxtaposed units, a feature which suggests two things. First, the continuity of mineralization from footwall oolites to hanging-wall limestones suggests that Zn-Pb mineralization largely postdates fault movement, timing which reinforces the epigenetic nature of the deposit (Sevastopolo and Redmond, 1999). Second, flow continuity could actually involve the upward migration of mineralizing fluids along the fault, which then first enter into brecciated and fractured footwall oolites before leaking into hanging-wall reef, a scenario which has rarely, if ever, been suggested for Irish deposits. Resolving this issue is not straightforward and will be the subject of future work. Whatever the contribution of upward and lateral migration within stratigraphic flow units, the spatial association between orebodies and complexities along the main faults shows that the upfault flow is the preeminent pathway utilized by fluids.

### Implications for Exploration and Mining

Definition and understanding of the structural architecture of fault systems from the regional down to deposit scale is a fundamental requirement in the exploration of Irish-type deposits. Structural analysis gives context to both geophysical and geochemical data and can provide a complementary, and

sometimes independent, means of vectoring toward higher grade mineralization. A better appreciation of the control of Caledonian basement structures on the position, geometry, and orientation of overlying Carboniferous structure can help geologists make more informed decisions about where to target future exploration regionally. We have seen, for example, that Carboniferous normal faults are localized along the northeast trends of basement structures as arrays of fault segments, which are attributed to the upward fault propagation, with associated segmentation and rotation, arising from approximately north-south stretching. On a larger scale, individual faults, which may not be physically linked in 3-D, can show strong degrees of interaction with the development of intervening ramps (i.e., between Main zone and Barnalisheen faults). These features demonstrate the ability of faults or fault segments within the Irish ore field to die out quickly and for displacements to be transferred from one fault to another. Given the crucial role that faults play in the formation of Irish-type deposits, it is clear that an improved understanding of the principles underpinning the geometry and coherence of fault systems, including associated displacement changes and host-rock deformation, will allow geologists to better predict fault system geometry and target the next orebody from limited data.

Definition of the geometry and linkage of segmented normal faults within the Irish ore field is crucial in making informed decisions regarding the targeting of faults and the locating of associated feeder points and orebodies. Within the Rathdowney trend, for example, displacements range on the order of 200 m along both the Lisheen and Galmoy fault systems, a scenario which suggests that displacement is being relayed from Lisheen to Galmoy along a left-stepping array, and will continue laterally in the absence of a major segment boundary. This understanding and our quantitative definition of associated fault linkage underpins a selection of potential exploration decisions which could assist in the targeting of potential prospects. For example, definition of the nature of the fault system connecting Lisheen and Galmoy is informed by prior knowledge. Earlier regional-scale fault maps derived from the Geological Survey of Ireland suggested the presence of a continuous fault defining a local relatively large-scale NNE-NE-trending bend. However, by comparison with existing quantitative data (Fig. 10), the separation between the Galmoy and Lisheen fault systems is very large (ca. 1.5 km) relative to fault displacement (ca. 200 m), which suggests the presence of an array of fault segments bounded by intact relays, rather than a continuous linked structure. In these circumstances, identifying that intervening drill holes are situated within a shallowly dipping continuous monocline would support the presence of an intact relay ramp rather than a single continuous fault. The recorded bed dips will also relate to the scale of intervening relay ramps, in terms of their length and separation, a scenario which will better inform the structural vectoring of potential prospects and associated mineralization. A successful use of this type of structural vectoring was employed by Vedanta Resources during exploration in 2013. Using their knowledge of the architecture of the Lisheen and Galmoy fault systems, including the left-stepping nature of fault segments and the scale of displacements relayed between individual orebodies, exploration geologists stepped farther to the northeast looking for the next

prospect (Fig. 1). The first drilled hole to the east of the initial Rapla discovery hit an intervening relay ramp, allowing geologists to vector farther to the northeast and successfully locate additional orebodies within Rapla.

Structural vectoring can enable geologists to identify areas of potentially better grades within individual deposits. Geologists can vector toward better mineralization, using the emerging knowledge that, within the Irish ore field, feeder points and orebodies are located along the bounding fault segments of intact relay ramps and not necessarily at a particular point of maximum displacement. Feeder points themselves are most likely localized in association with the breaching and deformation of preexisting fault zone complexities, such as smaller scale breached relay ramps and fault-bounded lenses, an issue which is dealt with in more detail in another paper (Torremans et al., 2018). Understanding the relationship of the evolution and geometry of faults, from soft-linked discrete segments, to hard-linked segments connected by breached faults, down to fault zones and ultimately fault rock, can help geologists locate areas of enhanced permeability and fluid flow. Fluids are focused both laterally and vertically into the bounding fault segments of intact relays, by predominantly upward flow associated with vertically disposed zones of increased structural complexity, and permeability, a scenario which is the equivalent of the long established principle that ore deposits are often localized on fault-related structural complexities (Newhouse, 1942).

### Conclusion

Segmented fault arrays developed within Lisheen and Silvermines play a critical role in deposit formation by controlling the location, geometry, and nature of fluid flow on a broad range of scales. Segmentation occurs generally as left-stepping arrays which are attributed to upward propagation of individual ENE-striking fault arrays arising from north-south extension of underlying Silurian and Ordovician rocks containing preexisting Caledonian penetrative fabrics and structures. Different scales of segmentation are developed within individual deposits, a feature which is in line with existing models suggesting the segmentation arises from the bifurcation of fault surfaces at depths controlled by the mechanical stratigraphy, and marked rheological changes of the faulted sequence (e.g., Walsh et al., 2003; Childs et al., 2009; Schöpfer et al., 2016). The scale of segmentation has a direct impact on the nature of linking structures, such as relay ramps and breaching faults. Larger scale relay ramps have segment separations which are significantly greater than the displacement transferred across the intervening ramps and thus remain intact. Larger to medium-scale relay ramps, with increased displacements relative to fault separations, will experience higher stresses leading to breaching of the intervening relay. By contrast, smaller scale relay ramps, which have drastically higher fault displacement to separation ratios, will be fully breached with high strains in associated ramps and may even lead to double breaching-forming fault lenses.

Relay ramp geometries produced by the various scales of segmented fault arrays, in turn, have a bearing on fluid-flow localization and orebody geometries. In the case of Lisheen and Silvermines, large-scale, fully intact relay ramps with considerable fault separations and relatively smaller displacements,

separate individual orebodies. The geometry of these intact relay ramps force fluids both vertically and laterally into the hanging walls of the bounding fault segments. Smaller scale, fully breached relay ramps along these bounding fault segments are, by contrast, strongly deformed and highly fractured zones that act as conduits and ingress points (feeders) for upfault fluid flow. Fluid migration in relay ramps, which experience increased strain and begin to breach, is focused into both the bounding fault segments and the intervening breaching structures (i.e., the BZW-BZE relay ramp in Lisheen). Ultimately it is the geometry and degree of breaching of the various relay ramps that plays a crucial role in the creation of porosity and produce conduits for upwelling fluid flow.

Our study of high-quality datasets from the Irish Zn-Pb ore field has highlighted generic aspects of the origin and structural evolution of Irish-type deposits. Whereas the fundamental importance of segmentation and the development of complexities along fault surfaces have long been recognized as key characteristics of the Irish-type Zn-Pb deposits, our study provides improved understanding of, and quantitative constraints on, fault segmentation. This new understanding will ideally lead to better methods for the discovery of deposits in Ireland and elsewhere, providing a much improved context for associated geochemical vectoring and ore-grade distribution studies.

### Acknowledgments

The authors would like to thank Colin Andrew, John Ashton, Claire Chaimberlain, John Conneally, Aileen Doran, Emily Fejes, Steve Hollis, Sean Johnson, Anraoi Milner, Conor Moynihan, Michael Philcox, Alex Russell, Ray Scanlon, Oakley Turner, and Koen Verbruggen for their observations and insights into the structural controls of the Irish ore field. The authors would also like to thank Vedanta Resources and Geological Survey of Ireland for providing data. Thanks is also given to ESRI, Maptex, Paradigm, Mira Geoscience, Seequent, and Midland Valley for generously granting academic licenses of their software. Finally, the authors would also like to thank David Sanderson and fellow reviewers for their insightful and pertinent reviews which have helped make this manuscript more robust. This publication has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant 13/RC/2092 and is cofunded under the European Regional Development Fund. Part of the work of Koen Torremans was carried out as part of Marie Skłodowska-Curie grant agreement 745945, funded from the European Union's Horizon 2020 research and innovation program.

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