The control of basin evolution on patterns of sedimentation and diagenesis: an example from the Mississippian Great Orme, North Wales

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Abstract: The Mississippian North Wales Platform is located on the margins of the East Irish Sea Basin and has been little studied over the last 30 years. The exposed Visean limestones provide new insights into the deposition, porosity evolution, distribution of dolomitization, and Pb–Zn and Cu mineralization on the North Wales carbonate platform. This is of relevance to the characterization of fault-related dolomite hydrocarbon reservoirs and age-equivalent Mississippi Valley-type mineral deposits. In particular, the study demonstrates the intimate relationship between sedimentation, basin-scale tectonism and post-depositional fluid flux. Depositional cyclicity is marked, with metre-scale upward-shallowing cycles in which pervasive marine and meteoric calcite cements occlude matrix porosity and syndepositional fractures. Consequently, subsequent burial diagenetic replacive dolomitization is matrix selective and cements are primarily restricted to fractures. Seven phases of dolomite are defined based on texture and cathodoluminescence petrography, with phases D1–D3 as the most volumetrically significant. Dolomite phases D0–D2 are matrix replacive, cross-cutting stratigraphy and locally finger ing along beds for several metres. Dolomite phases D3–D7 are hosted by faults and fractures and also line vugs. Evidence of telogenesis is recorded where burial diagenetic products are post-dated by calcite cements precipitated from meteoric fluids. Dolomitization probably occurred during the Mississippian and continued into the Pennsylvanian. Pb–Zn mineralization is also interpreted to have occurred during the Pennsylvanian, associated with Variscan tectonism. Overall, the North Wales Platform displays a more complex paragenesis than age-equivalent platforms in the Pennine Basin, owing to multiple phases of burial and exhumation. The study demonstrates the importance of linking burial history to detailed field and petrographical data to understand and predict the spatial and temporal controls on diagenetic processes and products within syn- and post-rift sequences.

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Understanding and predicting porosity evolution and diagenetic fluid flow pathways on carbonate platforms has long been a challenge. Although numerous case studies exist, many focus on one aspect of the diagenetic history, resulting in a limited understanding of the tectonostratigraphic controls on the timing and distribution of single diagenetic events. To gain a full understanding of porosity evolution, multiscalar, interdisciplinary datasets are required. In particular, outcrop studies, supported by detailed petrographical analysis and geochemistry, allow 2D and pseudo-3D visualization of faults, fractures, facies and diagenetic products such that the interplay between basin evolution, fluid flow and diagenetic processes can be determined. Such an approach can then constrain the relationship between these large-scale elements and porosity evolution.

The Mississippian of the Pennine Basin has long provided a framework for platform- and basin-scale diagenetic studies (e.g. Walkden & Williams 1991; Fraser & Gawthorpe 2003; Hollis & Walkden 2012, and references therein). Gutteridge (1987, 1991), Walkden & Williams (1991), Hollis (1998) and Hollis & Walkden (2002) have published a comprehensive and well-constrained paragenesis for the Derbyshire Platform, with some comparative work on the southern margin of the Askrigg Platform (Hollis & Walkden 2012) and the Lake District (Hurbury & Adams 1989). Complementary studies focusing on the mineralization of northern England and Wales were carried out by Patrck & Russell (1989) and Ixer & Vaughan (1993). Similarly, Wilkinson (2003, 2010), Shelton et al. (2011) and Hendry et al. (2014) have detailed the paragenesis of age-equivalent successions on the Isle of Man and in southern Ireland (Johnson et al. 2009).

The diagenetic history and structural evolution of the Mississippian succession on the North Wales Platform has not been fully described. Previous studies have focused upon sedimentological (George et al. 1976; Warren et al. 1984; Davies et al. 2004) and paleontological description (Neaverson 1930, 1935, 1937; Somerville & Strank, 1984a,b; Bancroft et al. 1986; Somerville et al. 1989; Davies et al. 2004) as well as models for copper–iron and lead–zinc–barium mineralization (Pattrick & Russell 1988; Lewis 1994, 1996; Ixer & Stanley 1996; Davies et al. 2004). This study builds upon the above work and presents an updated sedimentological, palaeo-environmental and diagenetic interpretation of the outcropping Asbian and lower Brigantian (Upper Dinantian; Mississippian) strata.

This study provides an overview of four key outcrops representing the exposed Asbian and Brigantian strata of the North Wales Platform (Figs 1–3). The outcrops span an area of c. 45 km², full details of which can be found in British Geological Survey sheets 95, 107, 108 and 121 and corresponding memoirs (Smyth 1925; Warren et al. 1984; Davies et al. 2004). Although field and petrographic data were gathered from across the North Wales Platform, the most robust sample set is from the Great Orme, Llandudno, and thus is the main focus of this paper. The Great Orme is a headland situated on the NW coast of Wales, adjacent to the town of Llandudno (Fig. 3). It is 4 km long by 0.8 km wide and provides excellent exposure of up to 200 m thickness of Asbian and
Brigantian limestone that is locally dolomitized. The succession exposed on the Great Orme is considered a proxy for diagenetic events that developed from the early marine–meteoric realm into the burial realm and during subsequent uplift and burial events. The primary objective of the project was to relate the timing and distribution of diagenetic products to the depositional and post-depositional, tectonic evolution of the North Wales Platform. Through development of such a framework, it is possible to determine the likely origin of fluids, and their migration pathways during platform burial and exhumation. By comparison with other age-equivalent platforms in northern England it is then possible to show how differences in basin evolution have influenced not just the
diagenetic overprint but also the occurrence of economically important mineral deposits.

**Geological setting**

**Tectonostratigraphic framework**

The North Wales Platform was one of a series of carbonate platforms that developed in the Mississippian on stable footwall highs that formed during back-arc extension, north of the Variscan Orogen (Davies et al. 2004; Figs 1 and 2). During this period the UK was situated in an equatorial position, giving rise to tropical seas and optimum conditions for carbonate platform growth. The North Wales Platform, flanked by the East Irish Sea Basin to the north and St Georges Land to the south, records the evolution of a ramp to rimmed shelf geometry from the Asbian to the Brigantian (Walkden 1987; Somerville et al. 1989; Adams et al. 1990). The land-attached platform developed a steep, north- to NE-facing margin, broadly in line with the present-day coastline, which most probably comprised coral–algal build-ups in the Late Dinantian (Bancroft et al. 1986; Fig. 4). Close proximity to exposed land resulted in sporadic incursions of siliciclastic sediments throughout the Mississippian. Not much is known of the North Wales Platform to East Irish Sea Basin transition because of poor present-day exposure; however, carbonate sediment is thought to have been supplied to the hanging-wall basin as calciturbidites and debris flows (Davies et al. 2004, and references therein). In addition, mud-dominated mounds have been recorded on the platform slope and within the basin (Bancroft et al. 1986; Davies et al. 2004).

Depositional environments within the Dinantian succession mainly comprise open marine or sheltered subtidal environments with high-frequency, shallowing-upward cycles overlain by exposure surfaces (Neaverson 1935, 1937; Al-Fadel 1983; Somerville & Strank 1984a,b; Warren et al. 1984; Bancroft et al. 1986; Somerville et al. 1989; Davies et al. 2004). Similar time-equivalent cycles are observed on the Derbyshire and Askrigg Platforms (Walkden 1987; Arthureton et al. 1988; Vanstone 1998). Carbonate sedimentation ceased during the Late Brigantian and gave way to clastic sedimentation, predominantly sourced from the Wales–Brabant Massif. Subsequently, within the hanging-wall basin, the black organic-rich Holeywell Shales were deposited (Early Namurian, Pendleian to Yeadonian in age; Davies et al. 2004). During the Late Namurian to Early Westphalian a secondary source of siliciclastic material was supplied in the form of turbidite-fronted fluvo-deltaic systems prograding southwards and westwards from the Pennine High to the NE of the East Irish Sea Basin (Gawthorpe et al. 1988; Kelling & Collinson 1992; Davies et al. 2004; Halleworth & Chisholm 2007). These deposits are known locally on the North Wales Platform as the Gwespyr Sandstones (Yeadonian to Langsettian in age) (Williams & Eaton 1993; Jerrett & Sampson 2007).

Sedimentation on the North Wales Platform was controlled by inherited Caledonian lineaments, which were the focus for subsequent structural deformation (Fig. 2). In particular, NE–SW, NW–SE and east–west faults were reactivated with a strike-slip component during the Variscan and Alpine Orogenies (Late Carboniferous and Cenozoic respectively) (Smyth 1925; Al-Fadel 1983; Williams & Eaton 1993). The strong fault control on sedimentation resulted in contrasting sediment thicknesses, with Asbian successions reaching up to 800 m in close proximity to large fault systems (Al-Fadel 1983; Leeder & Gawthorpe 1987; Williams & Eaton 1993).

Studies from the eastern flank of the Clwydian Range (Al-Fadel 1983) and adjacent highs (Derbyshire Platform and Askrigg Platform; Fraser et al. 1990) suggest that burial of the Dinantian succession was to a depth of up to 2.5 km close to subsiding faults. Hendry et al. (2014) discussed burial history in the Manx region, citing 800 ± 300 m of post-Carboniferous exhumation on the Isle of Man and eastern margin of the East Irish Sea Basin, based upon data published by Green et al. (2012). However, the northern margin of the North Wales Platform remained a relative topographic high throughout the Carboniferous (Williams & Eaton 1993) and burial depths for the uppermost Dinantian succession did not reach more than 1–1.5 km (Al-Fadel 1983). Surrounding basins (East Irish Sea and Cheshire) experienced burial depths of c. 1–1.5 km in the Carboniferous and maximum burial depths of c. 4 km (top Namurian) during the Cretaceous (Hardman et al. 1993; Floodpage et al. 2001).

**Sedimentation and lithostratigraphy**

The Asbian to Brigantian succession on the North Wales Platform comprises the Clwyd Group (Waters & Davies 2006; Fig. 5), also locally known as the Dyserth Limestone, and the Gronant Groups.
Cyclicity is defined by the stacking of 5–10 m thick cycles, initially recognized by Somerville (1977) and Gray (1981). Within the Asbian, cyclicity is characterized by shoaling-upward sedimentation, comprising thick-bedded pale grey or well-bedded dark grey skeletal wacke–packstones, algal laminites and interbedded mudstones grading upwards into skeletal, oolitic packstone–grainstones and stromatolitic build-ups (Figs 6 and 7). Cycle tops are defined by irregular erosive surfaces, protosoils and palaeosols, and subaerially deposited volcanic debris (Al-Fadel 1983; Walkden & Davies 1983; Davies et al. 2004). Similar surfaces have been comprehensively described in other areas by Walkden & Williams (1991), Wright (1992) and Vanstone (1998), and in general accounts by Davies et al. (2004). In contrast, Brigantian successions display thinner, well-bedded argillaceous limestones and interbedded mudstones, capped by exposure surfaces (Somerville 1977, 1979; Gray 1981). Similar sedimentation patterns are evident on the Derbyshire and Askrigg Platforms (Power & Somerville 1975; Ramsbottom 1984). On the Great Orme, the succession is divided into six lithostratigraphic units, the Pier Dolomite Formation, Tollhouse Mudstone Formation, Great Orme Formation, Craig Roffit Sandstone Member, Bishops Quarry Limestone Formation and Summit Limestone Formation (Figs 4 and 5; Warren et al. 1984, and references therein).

Mineralization and hydrocarbon emplacement

Mineralization on the North Wales Platform is predominantly fracture-hosted, within limestone and dolomite lithologies.
Fractures range in width from sub-millimetre to metre scale. The principal gangue mineral is calcite. Other minerals include economic assemblages of galena, sphalerite, fluorite and barite, which are mainly restricted to fractures, secondary dissolution porosity and proximal to reopened stylolites. The mineral assemblage decreases in volume away from the NE and eastern platform margin, with only minor amounts recorded to the NW, on the Great Orme (Lewis 1996).

Copper–iron minerals (principally chalcopyrite) are restricted to the northern platform margin (Great Orme, Meliden and Prestatyn). The mineralization occurs mainly within north–south-trending joints and is coeval with the latest stages of calcite cementation. Lewis
(1996) and references therein have suggested that copper mineralization is spatially and temporally related to dolomitization. Iron mineralization occurs as hematite and rarely limonite. The ores have been worked from veins and north–south-trending faults within the Foel and Llanarmon Limestone Formations (Davies et al. 2004).

Minor volumes of hydrocarbon (bitumen) have been observed on the North Wales Platform on the Great Orme and around Halkyn, in this study and documented in the literature (e.g. Parnell 1983, 1992; Parnell & Swainbank 1990), although no hydrocarbon inclusions were observed within minerals during this study.

**Techniques**

**Observational and analytical methods**

Key sections within the Asbian and Brigantian succession of the North Wales Platform were investigated by integrating routine field observations with detailed petrographic analysis of thin sections. Sedimentological logs were recorded from natural outcrop and disused quarries. Over 350 m of logged section were recorded from 14 sites including eight sites located on the Great Orme (Figs 3 and 4). Each locality was sampled systematically to cover the available stratigraphy and range of lithofacies. Where possible, samples were recovered using a 1.5 inch diameter motorized corer to minimize the effects of surficial weathering. A total of 160 polished thin sections were prepared from resin-impregnated subsamples and half of each section was stained with a combination of alizarin red S and potassium ferricyanide following procedures described by Dickson (1965). All sections were examined using optical transmitted light and cathodoluminescence (CL) microscopy. CL observations were made using a CITL CCL 8200 Mk3 ‘cold’ cathode device coupled with a Progress C10 Laser Optik digital photographic system. Operating conditions for CL were set to 10 kV and 300 µA at a pressure of c. 0.2 torr and maintained by microcomputer control.

Selected samples of ‘bulk’ limestone, bioclasts (brachiopods) and discrete cement phases for carbon (13C/12C) and oxygen (18O/16O) analysis were recovered using a tungsten-tipped dental burr. Samples of calcite and dolomite were reacted with phosphoric acid at 25°C (c. 16 h) and 50°C (c. 48 h) respectively following procedures described by McCrea (1950). Product CO2 was recovered cryogenically and mass ratios were measured using a dual-inlet VG SIRA 10 mass spectrometer. Oxygen isotope ratios were corrected for 17O (Craig 1957) effects and adjusted for temperature-dependent isotopic fractionations associated with the carbonate–phosphoric acid reaction using fractionation factors (α) of 1.01025 for calcite (Friedman & O’Neill 1977) and 1.01066 for dolomite (Rosenbaum & Sheppard 1986). All isotopic ratios are reported as delta values with respect to the VPDB carbon and oxygen isotope scales. Measurement precision (1σ) for both calcite and dolomite is better than ±0.1‰, based on replicate analysis of in-house quality control materials.

**Results**

**Facies distribution and palaeoenvironments**

**Pier Dolomite Formation (Asbian)**  

The Pier Dolomite Formation comprises limestone that has been partially to completely dolomitized and is organized into 10–50 cm thick beds of skeletal (crinoidal) packstones with alternating mudstone layers of 0.3–0.5 cm thickness and infrequent mudstone beds of up to 40 cm thick. Beds are bounded by dissolution-enhanced planes and erosional contacts below mudstone units. There is evidence of weakly preserved unidirectional cross-bedding and in situ coral growth, but otherwise biogenic and sedimentary structures have largely been obscured by bioturbation.

Constituent allochems of high initial magnesium composition are well preserved and include abundant crinoid and coral debris of up to 3 cm in diameter resulting in distinctive rudstone–floatstone beds. Interparticle micrite and smaller, less abundant allochems are no longer visible owing to complete dolomitization. The majority of the beds contain the same skeletal assemblage but grain size can vary (<1 mm to 3 cm). The initial porosity of the dolomitized limestone is unknown because of the extent of replacement, whereas current porosity is entirely secondary, estimated at <10% and comprising fractures, vugs and intercrystalline porosity.

Coarsening-upward and cleaning-upward trends have been recognized in single units (from mudstone to wackestone to pack–grainstone) within the Pier Dolomite Formation, and suggest deposition under conditions of increasing depositional energy. In situ Syringopora ramulosa corals are ubiquitous, implying high levels of light penetration (Flügel 2004). The generally high abundance of poorly sorted, large, angular skeletal allochems indicates limited transportation whereas the clean texture suggests sustained periods of high depositional energy, consistent with development of a high-energy platform margin. It is therefore suggested that the environment of deposition is a platform shoal. Comparative deposits have been recorded by Bancroft et al. (1986) to the east of the Gloddaeth Syncline.

**Tollhouse Mudstone Formation (Asbian)**

The Tollhouse Mudstone Formation overlies the Pier Dolomite Formation on the Great Orme, although the contact is not visible. The unit ranges in thickness from 1 to 4 m and thins to the NW. The contact with the overlying Great Orme Limestone Fm is gradational. The Tollhouse Mudstone Formation comprises reworked and intact (un-micritized) crinoid bioclasts, fragments of echinoderm, Dasyycladaceae (green algae) and productid brachiopods (Fig. 8). The constituent facies are skeletal wacke–packstone with allochem size that ranges from sub-millimetre to 2 mm. Much of the sediment is dissected by solution seams and stylolites, resulting in a nodular appearance on a sub-centimetre scale. There is no visible macroporosity, and any remaining porosity (estimated as <5% from blue-dyed resin-impregnated thin section) is matrix mesoporosity.

The volume of lime mud, and resultant wackestone–packstone textures, and relative increase in abundance of reworked carbonate grains compared with the underlying Pier Dolomite Formation suggest that deposition occurred in a moderate- to low-energy environment through gentle winnowing. The diverse, normal marine fauna, including an abundance of echinoderm fragments and green algae, is suggestive of a protected subtidal environment on the platform top. This is supported by the presence of sharp-walled burrows indicating soft but stable sediment. In addition, there are no indicators of deposition and/or flow on a high-angle slope. Similar facies have been described for the subtidal sediments in the Llangollen area (Gray 1981). The Tollhouse Mudstone Formation (Fig. 5) has been correlated with the Dulas Limestone Fm and Porcellaneous Mudstone in Abergwesyn outcrops to the east of the Great Orme by Warren et al. (1984), although these correlations remain uncertain (Bancroft et al. 1986).

**Great Orme Limestone Formation (Asbian)**

The Great Orme Limestone Formation is the thickest formation on the headland (175 m thick) comprising 20–100 cm thick beds. Bedding surfaces are generally planar and are enhanced by chemical compaction. Single beds typically comprise algal-laminated skeletal wackestones at the base of beds, coarsening into skeletal wackestones to crinoidal packstones and oolitic skeletal grainstones (Fig. 7). Skeletal allochems are dominated by crinoid and echinoid fragments (Fig. 8). Bed tops intermittently exhibit isolated corals and stromatolitic build-ups (20–30 cm thick). Erosion surfaces and the development of rubble,
red-stained palaeosols and/or karst are evident at the top of these coarsening- and cleaning-upward units (Fig. 7). The limestone contains <1% porosity, hosted within fractures.

The repetitive stacking pattern is interpreted as a series of transgressive–regressive cycles, from a basal, low-energy, shallow water intertidal setting (algal laminites) into high-energy subtidal shoal (oolitic skeletal packstone–grainstones). The deposits were capped by stromatolites that grew in very shallow water before exposure (Fig. 7). Control on this cyclicity has been attributed to sea-level fluctuation and possible syndepositional faulting (Gray 1981; Warren et al. 1984). Cycles at the base of the Great Orme Limestone Formation are bounded at the top and base by algal facies typical of very shallow intertidal–peritidal environments whereas the top of the formation displays cycles that lack evidence of algal laminae. However, red palaeosols become more frequent and more developed towards the top of the formation. These observations are consistent with the overall regressive nature of the Asbian succession (Warren et al. 1984).

Craig Rofft Sandstone Member (Asbian)

The Craig Rofft Sandstone Member is situated towards the summit of the Great Orme. It is 1–1.5 m thick and weathers a distinctive pink colour. The unit grades upwards from grainstone to carbonate-cemented sandstone and back to limestone again. Limestones above and below the sandstone are composed of skeletal and ooidal grains. The quartz grains are well sorted, well rounded and fine to medium grained (Fig. 8). Sedimentary and biogenic structures such as small-scale northeasterly dipping cross-beds, rootlets and/or burrows are observed. The Craig Rofft sandstone is well cemented with less than 2% porosity, hosted in fractures, and less than 1% porosity in solution-enhanced vuggy porosity at the margins of dolomite crystals.

The NE-directed palaeoflow direction indicated by cross-bed sets would suggest that this sand incursion was most probably derived from St Georges Land to the south. The medium- to fine-grained, well-sorted and well-rounded grains indicate texturally mature sediment and a relatively long transport distance. The pink coloration is most
Great Orme

Fig. 9. Summary of the cycles observed on the North Wales Platform that show overall upward-shallowing, regressive trends. Example from the Great Orme (i.e. platform margin), Summit Limestone Formation. Height of the outcrop c. 2 m.

probably the result of the presence of iron oxides. The evidence for biological activity suggests stable conditions in a shallow or marginal marine system. This is supported by the shallow high-energy limestone facies above and below with frequent development of palaeosols and minor karst surfaces.

Bishops Quarry Limestone Formation (Brigantian)
The Bishops Quarry Limestone Formation comprises dark grey, bioclastic wackestones and packstones with interbedded fissile mudstone. The well-bedded unit has bed thicknesses that range from 2 to 50 cm. Component allochems include a variety of reworked crinoid, echinoid, coral and brachiopod fragments (Fig. 8). Towards the top of the formation, brachiopod (gigantoproductid) shells become more abundant and reach 20 cm in size. The contacts between beds are sharp with evidence of compaction (flattened bioclasts and undulose surfaces). Small coral build-ups are evident at the top of beds and burrows are seen in thin section. No visible porosity is observed although minor matrix mesoporosity is suggested by green coloration in blue-dyed resin-impregnated thin sections.

The fine grain size and muddy texture of the Bishops Quarry Limestone Fm suggests that it was deposited within a relatively low-energy environment, allowing fine-grained sediment to accumulate, under conditions stable enough for brachiopod and other fauna and flora to thrive. The presence of in situ corals at the base of the formation indicates relatively shallow and clear water conditions whereas in situ brachiopod assemblages higher in the formation suggest either slightly deeper water or that light conditions had degraded (Flügel 2004). The interbedded mudstones are composed of carbonate material.

Summit Limestone Formation (Brigantian)
The Summit Limestone Formation is located at the top of the Great Orme, with a disconformable contact with the underlying Bishops Quarry Limestone Formation. The limestone is pale grey in appearance and rubbly. Beds are 20–40 cm thick with undulose bedding planes (Fig. 9). The Summit Limestone Formation is primarily composed of skeletal wackestone-packstone. Chert nodules are also visible, parallel to bedding and along fractures. Component grains include sub-millimetre-sized foraminifera and undifferentiated skeletal fragments. No visible porosity is observed although minor matrix mesoporosity is suggested by the green coloration of blue-dyed resin-impregnated thin sections.

The Summit Limestone Formation is characteristic of a low-energy, subtidal environment with prevailing fine-grained sedimentation, limited winnowing and a lack of bioturbation. The Summit Limestone Formation lacks thin-bedded cyclicity that could indicate supratidal or peritidal deposition, and reworked productid brachiopod fauna and skeletal allochems observed within the unit point towards normal marine conditions (Fig. 8). It is therefore likely that sedimentation was in subtidal, shallow water conditions under the increasing influence of siliciclastic sediments that eventually terminated carbonate platform growth in the Namurian.

Petrography, mineralogy and paragenesis

Micrite envelopes and crusts
Micrite envelopes and partial micritization of grains are the earliest diagenetic features observed. They are prevalent across the North Wales Platform and form on skeletal and non-skeletal allochems. Micritization of allochems is preferentially developed on foraminifera and shell fragments, and varies in extent from minor envelopes (10 µm thick) to complete replacement and loss of internal texture. Under CL, micrite is dull brown luminescent to non-luminescent and occasionally dull orange luminescent.

Grain-fringing cements (M1)
The first cements to coat skeletal and non-skeletal allochems have fibrous, isopachous textures (Fig. 10a). They form crystals that are up to 500 µm in length, are relatively inclusion rich and non-luminescent to dull orange luminescent. These cements are best developed on the platform margin within grainstone shoals, and become less common further onto the platform.

Syntactical cements SC1–SC3 and pore-filling C4
Syntactical calcite cements SC1–SC3 and pore-filling C4 are volumetrically the most important pore-filling cement phases on the North Wales Platform. They are best developed in grainstone facies and occlude most primary and dissolution-enhanced porosity. SC1–SC3 are limpid, non-ferroan, syntactical cements that most commonly grow on crinoid and echinoid fragments that lack micrite envelopes (Fig. 10b–d). The overgrowths range in thickness from 50 to 1000 µm. Under CL the SC1 cements are non-luminescent with bright yellow subzones (5–10 µm thick) followed by dull to very dull brown luminescent SC2–SC3 cement, with concentric subzones up to 30 µm thick. Limpid, blocky crystals of C4 range in size from 50 to 500 µm and are very dull brown to non-luminescent under CL (Table 1). The cement zones are equivalent to zones 1–4 of Al-Fadel (1983). Stable isotope and geochemical analyses were not acquired for these cement phases.

Matrix-replacive dolomite D0–D2
Matrix-replacive dolomite is evident only on the northern margin of the North Wales Platform, and is best exposed on the Great Orme headland. Three phases of non-ferroan dolomite occur as partially to fully fabric-destructive, turbid, subhedral to euhedral interlocking mosaics, preferentially nucleating upon crinoid and coral fragments (Fig. 10c–f). Crystals range in size from 50 to 1000 µm and display homogeneous red luminescence under CL (Table 1; Fig. 11b). The three phases were identified primarily on the basis of their petrographic characteristics. D0 preferentially replaces crinoid fragments mimetically. D1 is toffee brown, coarsely crystalline and contains some ghost textures of the replaced limestone, whereas D2 comprises smaller euhedral crystals with a higher concentration of inclusions and is primarily fabric destructive. Bed-parallel stylolites cross-cut phases D0–D2. The relationship between the D0–D2 dolomite phases and the SC1–C4 calcite cements is unclear.

Blocky fracture and secondary porosity fill C5–C8
On the northern and eastern margin of the North Wales Platform, C5–C8 calcite cements were observed within matrix pore systems
and fractures, with a dominant north–south and NE–SW orientation. Phases C5–C8 are ferroan and occur as limpid fracture fill cements with blocky and drusy textures. Crystal sizes range from 20 to 200 µm. The cements are differentiated on the basis of their crystal morphology, cathodoluminescence (Table 1) and their cross-cutting relationships. The bright orange luminescent C5 cement is intergrown with fluorite, galena and chalcopyrite.

Calcite cements C9–C11
Cement C9c cements post-date dissolution, as revealed by the etched margins of host porosity. C9b–C11 calcite cements are ferroan, predominantly blocky and form interlocking mosaics. They are confined to fault zones and nearby fractures, stylolites and secondary dissolution porosity, and are locally replacive of the host limestone. Crystal sizes range from 10 to 200 µm. The cements are differentiated on the basis of their crystal habit and cathodoluminescence, which varies from dull orange (C9) to dull to bright subzoned luminescence (C10) and non-luminescence (C11; Table 1).

Vein dolomite D3–D7
Five phases of non-ferroan dolomite occlude fractures (D3–D7). Phases D3–D4 display subhedral to euhedral rhombic dolomite textures, with curved crystal faces and an increase in iron-oxide inclusions toward the crystals margins (Figs 8a, 11e, f and 12a, c). D3 exhibits a homogeneous dull pink to red luminescence under CL, whereas D4 and D5 are red luminescent (Table 1). These phases are mainly restricted to fractures, cross-cut stylolites and replace D0–D2 dolomite (Fig. 11). Phases D4 and D5 display some zonation and etched crystal margins; D5 is differentiated by its intergrowth with chalcopyrite. Phases D6 and D7 are turbid crystals with undulose extinction and restricted to fractures, and display dark red (D6) to bright pink (D7) CL and etched margins (Table 1; Fig. 11e and f).

Vug and micro-fracture fill C12–C15
Phases C12–C14 have been recorded primarily from the northern margin of the North Wales Platform. These non-ferroan calcite cements are limpid, blocky to rhombic with etched margins and occur within extensional fractures and vugs. Crystals range in size from 100 to 700 µm. Under CL, C12 cements are non-luminescent with bright CL subzones. C13 cements are bright luminescent and C14 cements are dull luminescent with infrequent bright yellow to pinkish subzones that are 5–30 µm thick with variable frequency. C13 cements are frequently intergrown with chalcopyrite along east–west-trending extensional fractures that overprint C12 and north–south-trending fractures (Fig. 11a).

C15 non-ferroan calcite has been recorded only from veins within the Pier Dolomite and Tollhouse Mudstone Fm on the Great Orme. It occurs within north–south-striking fractures that host earlier dolomite cement and that exhibit evidence of reactivation through crack-seal vein textures. The calcite appears rhombic and turbid in transmitted light, similar to D2, but with a homogeneous bright yellow luminescence. Crystal sizes range from 200 to 500 µm.

Secondary vug and fracture fill, C16–C19
Phases C16–C19 non-ferroan calcite cements occur within secondary, dissolution-enhanced vugs within all formations on the Great Orme. Crystals are blocky and limpid and range in size from 20 to 100 µm. They can be differentiated under CL by a dull luminescence.
| Cement | Morphology | CL | Extinction | Inclusion density | Inclusion type | Mineralization | Distribution |
|--------|------------|----|------------|------------------|----------------|----------------|--------------|
| SC1    | Syntaxial  | Non-luminescent with few bright orange bands | Unit | Limpid | Rare fluid | Extensive veins; interparticle porosity |
| SC2    | Syntaxial  | Dull brown | Unit | Limpid | None | Interparticle porosity |
| SC3    | Syntaxial  | Very dull brown with subzones | Unit | Limpid | None | Interparticle porosity |
| C4     | Blocky     | Dull brown to non-luminescent | Unit | Limpid | Rare fluid | Interparticle porosity; extensional veins |
| C5     | Blocky     | Dull orange–brown | Unit | Limpid | – | Extensional veins |
| C6     | Blocky–massive | Non-luminescent | Unit | Limpid | – | Extensional veins |
| C7     | Blocky–massive–dogtooth | Zoned bright to dull orange–brown | Unit | Limpid | – | Extensional veins; opened stylolite |
| C8     | Blocky     | Non-luminescent to orange–brown | Unit | Limpid, micro-inclusions | Undifferentiated | Extensional veins, intra- and inter-particle |
| C9     | Blocky     | Dull orange zonation | Unit | Limpid–turbid | Undifferentiated | Extensional veins, intra- and inter-particle |
| C10    | Euhedral   | Dull orange, bright orange outer zone | Unit | Limpid | – | Replacement |
| C11    | Blocky–massive | Non-luminescent | Unit | Limpid | – | Extensional veins |
| C12    | Blocky     | Non-luminescent to bright; high-frequency zonation | Sweeping | Limpid–turbid | Undifferentiated | Extensional veins |
| C13    | Blocky–massive | Bright orange–yellow | Unit | Turbid | Undifferentiated | Chalcopyrite | Extensional veins |
| C14    | Blocky–massive | Dull orange–yellow, etched | Unit | Limpid–turbid | Undifferentiated | Chalcopyrite? | Secondary vug and fracture |
| C15    | Blocky–massive | Bright orange–yellow, etched | Unit | Limpid–turbid | Undifferentiated | Chalcopyrite? | Secondary vug and fracture |
| C16–C17 | Blocky–massive | Medium dull orange | Unit | Limpid–turbid | Undifferentiated | Chalcopyrite? | Secondary vug and fracture |
| C18    | Blocky–massive | Bright orange high-frequency zonation | Unit | Limpid–turbid | Undifferentiated | Secondary vug and fracture |
| C19    | Blocky–massive | Bright orange high-frequency zonation | Unit | Limpid–turbid | Undifferentiated | Secondary vug and fracture |
| D0     | Mimetic    | Medium pink or red | Unit | Turbid | Rare fluid | – | Echinoid clasts |
| D1     | Planar-s   | Medium pink or red | Unit | Turbid | Fluid | – | Bioclastic wacke–packstones |
| D2     | Planar-e   | Medium pink or red | Unit, undulose | Turbid | Fe oxides | Fe oxides | D1 overprint, adjacent to extensional veins |
| D3     | Planar-e, baroque | Medium pink or red | Undulose | Limpid | Fe oxides; fluid | Gaetana, sphalerite, minor barite | Extensional veins |
| D4     | Planar-e, baroque | Red | Undulose | Limpid–turbid | Fe oxides; fluid | – | Extensional veins |
| D5     | Planar-s, xenotopic | Red | Unit and undulose | Limpid–turbid | – | Chalcopyrite | Extensional veins and passive fill |
| D6     | Planar-s, baroque | Dark red–brown | Undulose | Turbid | Fe oxides; fluid, solid | Fe oxides | Mixed mode veins around normal and strike-slip faults |
| D7     | Planar-s, xenotopic, diffuse | Bright pink | Undulose | Turbid | Fe oxides; fluid, solid | Fe oxides | Mixed mode veins around normal and strike-slip faults |

For definition of dolomite morphology [planar-e, planar-s and xenotopic] please refer to Sibley & Gregg (1987).
(C16 and C17), bright, highly subzoned luminescence (C18) and non-luminescence with bright subzones (C19; Table 1). These phases have petrographic characteristics similar to those of the syntaxial SC1 and SC2 cements but cross-cut early diagenetic and burial phases (e.g. D1–D2, Fig. 12).

**Laminated fracture fill**

Infrequent open fractures observed on the northern margin of the platform contain alternating laminated layers and fringing calcite cements, with small spherical calcite nodules (MC, Fig. 11g and h). The fractures are 0.05–0.5 cm thick and cross-cut all previous diagenetic phases. It is not uncommon for these fractures to display secondary porosity, formed by dissolution, as evidenced by irregular boundaries and etched truncation of the cement. Further stable isotope and geochemical analyses were not acquired for these cement phases owing to the very small volume of material available.

**Geochemistry**

Carbon and oxygen stable isotope data are plotted in Figure 13. It was not always physically possible to isolate phases because of the very small volumes of material. The samples are labelled based on whether they represent a whole-rock limestone sample, a mixture or an isolated phase. For comparison, values for whole-rock limestone samples and brachiopods are also plotted. The limited number of
analysed dolomite samples covers a relatively narrow range in δ¹⁸O (−5.5 to −7.5‰) and δ¹³C (−0.5 to 3.0‰). The isotope values for δ¹⁸O of the different dolomites display a large overlap. The highest values for δ¹³C are in D3 and the lowest are in D6–D7. Isotopic analysis of combined D1–D2 reveals δ¹⁸O = −5.5 to −7.5‰ and δ¹³C = 0.8–2.3‰ (Fig. 13). No stable isotope analyses were acquired for D0 because of the small volume of material available. D3 dolomite has δ¹⁸O = −6.9‰ and δ¹³C = 3.0‰. Phases D6–D7 have δ¹⁸O = −5.6 to −6.1‰ and δ¹³C = −0.5 to 1.2‰ (Fig. 13).

Calcite cement samples from veins and vugs that cross-cut the dolomite display a wide range of isotopic values. Isotope values for δ¹⁸O range from −12.7 to −4.4‰ and for δ¹³C range from −7.3 to 2.2‰. The isotope values for δ¹⁸O of the different calcites display less of an overlap than the dolomite samples. The highest values for δ¹⁸O are in C10 and the lowest are in C15. The highest values for δ¹³C are in C5–C7 and the lowest are in C13–C16. Stable isotope analysis of C5–C7 measured δ¹⁸O calcite of −8.3 from to −6.6‰ and δ¹³C = 0.2–2.2‰ (Fig. 13). Combined analysis of C13–C16 calcite measured δ¹⁸O = −4.4 to −5.2‰ and δ¹³C = −7.3 to −2.9‰. C15 stable isotope values range from δ¹³C = −2.3 to −1.7‰ and δ¹⁸O = −12.7 to 12.4‰ (Fig. 13).

Discussion and interpretation

Deposition on the Great Orme

Sedimentological observations outlined in this study supplement published data for the Great Orme headland and the wider North Wales carbonate platform (e.g. Warren et al. 1984; Bancroft et al. 1986). Four depositional environments are defined: restricted lagoon, shallow subtidal, deep subtidal and platform margin (Fig. 14), indicating a range of shallow-marine shoaling and subtidal facies that are characteristic of platform top and margin environments. No large reefal build-ups have been recorded within the outcropping succession on the Great Orme although the nearby Little Orme and Nant-y-Gamar host coral and bryozoan build-ups (e.g. Warren et al. 1984; Bancroft et al. 1986). This suggests that the platform margin was characterized by discontinuous patch reefs, knolls and shoals. These interfingered with subtidal mud and wackestone facies and laterally equivalent, higher energy coarsely-grained, cleaner facies (e.g. the Pier Dolomite Fm and Tollhouse Mudstone Mb). The shoals and patch reefs may have baffled wave activity and allowed finer grained sediment with normal marine assemblages to accumulate across the platform top, as seen within the Great Orme Limestone Fm.

Towards the end of the Asbian, small pulses of siliclastic sediment were deposited (Warren et al. 1984) in the most distal platform area. On the Great Orme, this incursion of siliclastic sediment is represented by the Craig Rofft Sandstone Member, probably sourced from the Wales–Brabant Massif to the south. Siliciclastic deposits have also been observed on Anglesey to the west of the Great Orme, an area considered more proximal to the palaeo-coastline (Walkden & Davies 1983). The increase in siliciclastic deposition is likely to have coincided with the earliest stages of Variscan uplift and an associated fall in relative sea level (Gawthorpe et al. 1988; Kelling & Collinson 1992; Davies et al. 2004; Hallsworth & Chisholm 2007).

Carbonate sedimentation was re-established in the Brigantian. On the Great Orme, cyclical wackestones to packstones of the Bishops Quarry Limestone Fm were deposited, along with the chert-rich mudstones–packstones of the Summit Limestone Fm. The stacking pattern and faunal assemblages of the Bishops Quarry Limestone Fm are comparable with those observed in Llangollen (e.g. Gray 1981) and record the demise of shallow-marine fauna. The Summit Limestone Fm has previously been interpreted as representing basinal deposition. However, considering the absence of evidence for platform slope structure and/or any other evidence for a major eustatic rise in sea level elsewhere on the platform it is not unreasonable to consider the formation representative of a subtidal, platform top environment that experienced increased water column turbidity owing to the influx of siliciclastic deposits.

Early diagenesis

Early diagenesis embraces all diagenetic events that take place before significant burial (<300 m burial, prior to the onset of stylolitization) predominantly within the marine and meteoric realms. Marine diagenesis on the North Wales Platform is characterized by isopachous grain-fringing cements (M1) and micritization. M1 cements locally precipitated in cleaner facies on the higher energy platform margin. Preservation of these delicate cement morphologies was most probably a result of early, rapid
precipitation of the subsequent pore-occluding blocky calcite prior to compaction. This is consistent with the pre-compactional timing and lack of pendant morphologies, which would have implied precipitation under vadose conditions. Where these cements have a dull luminescence they have most probably undergone subsequent mineralogical stabilization under reducing conditions. In the more protected platform top setting, marine cementation is much less pervasive, consistent with lower depositional energy.

In outcrop there is clear evidence of extensive meteoric diagenesis through the development of multiple, stacked, calcitites, karst and palaeosol at the top of upward-shallowing units, indicating several periods of subaerial exposure. Similar observations have been documented from high-frequency cyclic deposits on adjacent platforms (South Wales: Raven 1983; Searl 1988b; Wright 1992; Derbyshire: Walkden & Williams 1991; Horbury & Adams 1989; Alston–Ask Gregg: Gawthorpe 1986; Tucker 2003). Extensive cementation in the meteoric realm across the North Wales Platform is evidenced by abundant syntaxial overgrowths of non-ferroan calcite, preferentially seeded on crinoid and echinoid fragments, and interparticle pore-filling cement characterized by cement phases SC1–SC3. The occlusion of primary and secondary porosity, the lack of vadose cement textures and/or dissolution prior to cementation suggest that the pores were completely water saturated, typical of a meteoric phreatic environment. SC1–SC3 and C4 cements post-date marine cements (M1) and are cross-cut by stylolites and solution seams, suggesting that they pre-date compaction. The high-frequency sub-zonation, syntaxial nature and large crystal size of the cement means that they resemble cements on age-equivalent carbonate platforms in the Pennine Basin and South Wales that have been interpreted to have precipitated in the meteoric phreatic realm (Al-Fadel 1983; Walkden & Berry 1984; Searl 1988 a,b, 1989; Horbury & Adams 1989). In particular, the non-luminescence of SC1 cements is consistent with limited Mn or incorporation of CL quenchers such as Fe, whereas bright luminescent subzones could reflect incorporation of Mn into the calcite crystal lattice. Elsewhere in the Pennine Basin, this high-frequency CL zonation is interpreted to reflect frequent changes in the redox conditions (see Walkden & Berry 1984; Horbury & Adams 1989). The similarity in cement patterns at different stratigraphic levels may result from water table fluctuations. The presence of multiple palaeokarstic surfaces across the North Wales Platform suggests that meteoric conditions were frequently established during sealevel lowstands and recharged by aquifer systems sourced from St Georges Land to the south. The periods of emergence range between a few thousand and a few tens of thousand years (Walkden & Walkden 1990; Walkden & Williams 1991; Wright 1992).

The dull luminescence of subsequent SC2–SC3 calcite implies limited Mn and/or incorporation of Fe into the crystal lattices. Similar CL characteristics have been observed from cements precipitated from suboxic conditions (e.g. Walkden & Berry 1984). The presence of C4 in extensional fractures suggests that fractures provided a more favourable fluid flow pathway and may also indicate a lack of porosity or permeability within the host-rock limestone at the time of precipitation. The petrographic characteristics of C4 cements are similar to those documented on the Derbyshire Platform (compare Zone 3 of Walkden & Williams 1991, and Zone Z3P of Hollis & Walkden 2012), potentially resulting from evolved meteoric porewaters driven downdip within a palaeo-aquifer. Further geochemical analyses would be required to further constrain cements phases SC1–SC3 and C4.

Dolomite cement phases D0–D2 were described only from the northern platform margin of the platform, on the Great Orme, preferentially replacing allochems that were initially composed of high-Mg calcite, such as crinoid oisscles and echinoid fragments. These skeletal allochems were the dominant constituents of coarse-grained skeletal pack- or grainstone beds within the Pier Dolomite Formation. Crinoid and echinoid fragments are single crystals and are therefore common nucleation sites for calcite (Walkden & Berry 1984; Fligel 2004), and in this case also for dolomitization. Mimetic replacement was favoured by high reactive surface areas within the crinoid oisscles and echinoderm fragments and the presence of remnant magnesium within microdolomite inclusions. This suggests that the abundance of allochems composed of high-magnesium calcite, the circulation of Mg-enriched fluids along high-permeability beds and/or favourable thermophysico-chemical conditions initiated dolomitization. Given that this earliest phase of dolomitization predates stylolitization, and therefore significant burial, and is located in the vicinity of platform margin faults, dolomitization could have been initiated by geothermal convection of seawater (see Frazer 2014, for the age-equivalent southern margin of the Derbyshire Platform). It is important to emphasize the strongly stratabound geometry of D0–D2 dolomite, which is confined to the Lower Ashian Pier Dolomite Formation, and which terminates beneath the Tollhouse Mudstone Formation. This suggests that the Tollhouse Mudstone Formation acted as a low-
would imply precipitation from seawater of 0‰ and limited depletion of temperatures above 60°C. The combined shallow burial depths of two samples from D6 limestone. Oxygen isotopic values are consistent at around formational brines and/or buffering by interaction with the host signatures (Fig. 13). This suggests a marine origin for the Platform at this time. Samples of C5 that a flux of metal-rich fluids was circulating on the North Wales C5 is intergrown with fluorite, galena and chalcopyrite, indicating (Popp analyses of pristine brachiopod shells and marine calcite cements values for Late Dinantian seawater (Fig. 13; Al-Fadel 1983). Assuming a geothermal gradient of 30°C km⁻¹, the temperatures would have been at least 50°C and probably higher, as this basin formed during rifting. Consequently, fluids migrating via faults and fractures were most probably hydrothermally heated. Precipitation of cements C5–C9 and D3–D7 is therefore interpreted to have occurred at or close to maximum burial of the North Wales Platform. The intergrowth of C5–C9 calcite cements with mineralization across the North Wales Platform is also indicative of the fluid source. Detailed studies of burial carbonate cements that are intergrown with sulphides and sulphates on carbonate platforms within the Pennine Basin have invoked a flux of hot, metal-enriched brines from Dinantian and Namurian sediments within juxtaposed hanging-wall basins during the Variscan Orogeny (Gawthorpe 1986; Coleman et al. 1989; Ixer & Vaughan 1993; Hollis & Walkden 2002; Hollis & Walkden 2012). Data restrictions mean that it is not possible to sample age-equivalent basinal sediments from the East Irish Sea Basin, but by analogy the same process is proposed for the North Wales Platform. Rapid deposition of Late Dinantian and Namurian basinal sediments within the East Irish Sea Basin and, to a lesser extent, the proto-Cheshire Basin (Smith 1999) and sediment loading could have generated overpressures, retained basin fluids and limited fluid flux during burial. This process of disequilibrium compaction and subsequent rupture and mass fluid flux has recently been modelled for the Edale and Widmerpool Basins adjacent to the Derbyshire Platform (Frazer et al. 2014). Localized dolomite cementation on the northern margin of the North Wales Platform (Great Orme, Little Orme and Prestatyn) may indicate preferential activation of some faults and/or access to a

| Key | Crinoids | Mudstone |
|----|---------|---------|
| C5 | Coquinas | Coral |

Fig. 14. Summary of palaeoenvironments and environmental evolution for the outcropping Ashian and Brigantian strata based on field and petrographical observation from the Great Orme; EISB, East Irish Sea Basin. The bold black boxes represent the positions of key locations within the North Wales palaeogeography and relate to the corresponding idealized upward-shallowing cycles at these locations.
Fig. 15. Summary paragenesis for the Great Orme and the North Wales Platform plotted against (a) the burial curve for the East Irish Sea Basin (Hardman et al. 1993; Newman 1999; Floodpage et al. 2001) and (b) North Wales Platform (burial curve modified from Al-Fadel 1983). Major tectonic events are indicated by pale grey from the Late Carboniferous, Jurassic and Late Cretaceous onwards.
determined by Parnell & Swainbank (1990) and for base metal (1993).

Triassic Pb timing for the Pb northern England. An alternative explanation would be a Mesozoic chemistry compared with platforms within the Pennine Basin of North Wales Platform reflects exposure to a different fluid there would have been less potential for trace element and metal–maturation and clay diagenesis (e.g. Hollis & Walkden 1996, 2012), release to fluids is likely to have been strongly influenced by organic

Mikkelsen & Flood page 1997) compared with depths of >3 km for disequilibrium between pore fluids and the carbonate cements. also supported by the subsequent etching, which suggests further

interpreted as having precipitated from meteoric porewater based on geological convection of seawater (Frazer 2014). The latter would be supported by the overlapping geochemical data and potential recrystallization of earlier dolomite resulting in speckled and homogeneously red-luminescent dolomite. Conversely, the occurrence of ghost structures, coarse dolomite crystals observed in plane-polarized light petrography and slightly depleted $^{18}$O suggests limited overprinting of multiple dolomite phases by modified seawater.

A mid- to late Carboniferous timing is favoured for the dolomitization. The post-rift, sag phase during the Carboniferous could have provided favourable extensional, structural orientations for fluid flow and crustal thinning with elevated heat flow. Late Carboniferous onset of Variscan compression had the potential to further ‘squeeze’ diagenetic fluids from the East Irish Sea Basin. However, a Mesozoic timing cannot be ruled out (see further discussion below). The relatively lower volume of Mississippi Valley-type mineralization on the North Wales Platform compared with the Pennine Basin and Isle of Man is noteworthy. Both the East Irish Sea Basin and the Cheshire Basin were buried to depths of only c. 1 km (top Namurian) in the Carboniferous (Hardman et al. 1993; Mikkelsen & Floodpage 1997) compared with depths of >3 km for basins within the Pennine Basin (Hollis 1998). Because metal release to fluids is likely to have been strongly influenced by organic maturation and clay diagenesis (e.g. Hollis & Walkden 1996, 2012), there would have been less potential for trace element and metal-enriched fluid flux towards the North Wales Platform compared with the carbonate platforms of northern England. It is therefore possible that the lower volume of Pb–Zn mineralization on the North Wales Platform reflects exposure to a different fluid chemistry compared with platforms within the Pennine Basin of northern England. An alternative explanation would be a Mesozoic timing for the Pb–Zn and copper mineralization as suggested by the Triassic Pb–Pb age for bitumen at Ty Gwyn copper deposit determined by Parnell & Swanbank (1990) and for base metal mineralization in Parys Mountain, North Wales of Fletcher et al. (1993).

**Post-Variscan burial history**

Uplift, exposure and erosion related to the onset of the Variscan Orogeny took place during the Late Carboniferous, before the North Wales Platform was then rapidly reburied in the Mesozoic, reaching a maximum burial depth of around 1 km in the Jurassic (Fig. 15). It is unclear whether C10 and C11 cements precipitated within the burial realm or during uplift and exposure. The thin section staining indicates ferroan calcite; however, this is in contrast to the light measured $^{13}$C value that potentially indicates a meteoric origin. Paragenetically, the late vein fill calcite cement (C12) is observed cross-cutting D6–D7 and C8–C11, and has been tentatively interpreted as having precipitated from meteoric porewater based on its CL characteristics (Table 1). A meteoric porewater origin is also supported by the subsequent etching, which suggests further disequilibrium between pore fluids and the carbonate cements.

**Mesozoic burial**

Regional tectonic extension prevailed across northern England and Wales from the Permo-Triassic until the Late Jurassic and ceased during the Cretaceous (Turner 1997; Fig. 14). The top Dinantian sediments of the North Wales Platform reached a maximum burial of around 1 km during the Jurassic (Al-Fadel 1983; Fig. 15). The episode of extension reactivated faults in and around the East Irish Sea Basin with an east–west orientation (Needham & Morgan 1997; Quirk & Kimbell 1997), providing the opportunity for fault- or fracture-controlled fluid migration across the North Wales Platform. The recognition of chalcopyrite, intergrown with bright to dull luminescent C13 and C14, suggests precipitation under suboxic conditions in a burial environment, and the identification of these cements in east–west-trending fractures and vugs adjacent to the fractures suggests that they are Mesozoic in age. The origin of the copper-rich fluids is still poorly constrained, but possible sources include Permo-Triassic basal fluid phases, or downward migrating marine, meteoric and/or formation fluids derived from the overlying successions or from the Lower Palaeozoic (volcanic and metasediments) basement to the south. Fluid derived from Permo-Triassic sediments is considered to be the most probable source, as Variscan compression and related basin dewatering would have depleted the Late Carboniferous basin sediment of fluids. This is consistent with the proposed fluid source for other copper deposits in northern England, at Alderley Edge in Cheshire and Ecton in Derbyshire, where mineralization is hosted by major faults and adjacent permeable horizons within the Carboniferous and Triassic host-rock (Holmes et al. 1983). Fluid circulation and mineralization during the Mesozoic has been proposed by Hendry et al. (2014) for the Isle of Man and north East Irish Sea Basin, whereby the extensional tectonic regime provided favourable structural orientations for fluid flow. Rifting was probably accompanied by elevated heat flow, and thick evaporitic strata deposited in the Visean and/or the Permo-Triassic supplied hypersaline brines that also transported magnesium (e.g. Solway, Peel and East Irish Sea Basins; Ward 1997; Chadwick et al. 2001). Hendry et al. (2014) further postulated a Mesozoic timing for fault-related dolomitization on the Isle of Man.

Bright luminescence C15 calcite implies incorporation of Mn into the crystal lattice and/or low concentrations of Fe, indicative of reducing conditions. The $^{13}$C data suggest a source of isotopically light carbon such as organic material or meteoric fluids, which could also provide a source of isotopically light $^{18}$O. Combined with the suggested shallow burial depths it is likely that the cements are meteoric in origin and the presence of meteoric porewaters could have resulted in dedolomitization.

**Cenozoic uplift and exposure**

Calcite phases C16–C19 are non-luminescent with bright yellow–pink concentric subzones. They are present as blocky and rhombic crystals that occur within secondary dissolution-enhanced vugs that cross-cut all other phases and specifically post-date copper mineralization. Petrographically, the C16–C19 cements resemble SC1–SC2 cements, particularly with respect to their CL. From the CL characteristics, their distribution and their position in the paragenetic sequence, C16–C19 are interpreted to be meteoric cements that formed during Cenozoic uplift and exposure of the North Wales Platform. Compression was marked by the onset of Alpine compression. Crustal shortening and related inversion of Cenozoic and Neogene basins occurred primarily within the south and east of the UK and southern Europe. Deformation (uplift and exhumation) has also been documented around the Irish Sea Basin. However, the cause of this movement is still debatable and has previously been suggested to have arisen in response to Palaeogene igneous activity (Turner 1997).

**Regional context**

The North Wales Platform was established to the west of the Pennine Basin, where age-equivalent, isolated carbonate platforms developed during back-arc extension in the Mississippian (Fraser & Gawthorpe 2003). Fluctuations in relative sea level, in response to glacio-eustacy and footwall uplift, resulted in comparable depositional environments and early diagenetic products on the North Wales, Derbyshire, Askrigg and South Lakeland Platforms; in
particular, early cements present as fibrous turbid or limpid calcite precipitating around allochems (Hollis & Walkden 2012), followed by primary and dissolution-enhanced, pore-occluding and cementing overgrowths of calcite (SC1–SC3 in North Wales (Solomon 1989; this study). Equivalent cement phases include Z1–Z3 in Derbyshire (Walkden & Williams 1991) and AZ1–AZ3 on the Askigrigg Platform (Hollis & Walkden 2012). These cements are widely interpreted to have precipitated within meteoric phreatic lenses during sea-level lowstands.

Despite similarities in the depositional environments and early diagenetic features, the platforms have significant differences in their burial diagenetic sequences. The North Wales and Derbyshire Platforms host fault- or fracture-related dolomite. In comparison, dolomite on the Askirgg Platform does not form a discrete fault- or fracture-related body, potentially because of the early release of magnesium-enriched brines from the juxtaposed Craven Basin (Gawthorpe 1986; Hollis & Walkden 2012). Fault-related dolomite bodies observed on the Isle of Man by Hendry et al. (2014) are more similar in geometry to those in North Wales. The Isle of Man dolomite bodies display lateral fingering into the host-rock limestone, multiple overlapping generations of dolomite and evidence of fluid-related breccia. The Derbyshire and Askirgg Platforms host economic volumes of galena, barite and fluorite, whereas volumes of these minerals on the North Wales Platform are minor. Hollis & Walkden (1996, 2002) described a fracture paragenesis dominated by calcite cementation on the Derbyshire Platform, but one that is indicative of a single burial event during the Late Carboniferous (Hollis 1998). In contrast, the North Wales Platform hosts a complex paragenetic history with 19 calcite and seven dolomite diagenetic phases (Fig. 15).

Paragenetic complexity on the North Wales Platform appears to increase towards the platform margin and close to deep-seated lineaments, where fracturing and faulting at a local scale is more pronounced. The East Irish Sea Basin, north of the North Wales Platform, is invoked as a possible source of metals and mineralizing fluids. The East Irish Sea Basin experienced two burial episodes: during the Late Carboniferous (burial depth of c. 1 km, latest Namurian) and reaching a maximum burial of c. 4 km in the Late Cretaceous–Early Cenozoic (Hardman et al. 1993; Floodpage et al. 2001; Fig. 15). Geothermal gradients of 30°C km⁻¹ have been proposed by Al-Fadel (1983) and Hardman et al. (1993), implying that the Namurian succession reached temperatures between only 30°C and 120°C during the Late Carboniferous. These temperatures would mean that hydrocarbon maturation and clay diagenesis, both of which could have released trace metals, could have occurred only immediately prior to the onset of the Variscan Orogeny (Hardman et al. 1993).

During Variscan compression, mineral-enriched fluids were supplied to the Derbyshire Platform from the Namurian succession in the Edale, Widmerpool and Staffordshire Basins (Coleman et al. 1989; Hollis & Walkden 2002). On the North Wales Platform, the shallower burial and lower temperatures within the East Irish Sea Basin resulted in only minor Pb-Zn mineralization and limited hydrocarbon emplacement. Reburial in the Mesozoic has been invoked as the mechanism for more widespread hydrocarbon generation and migration, in the Late Cretaceous (Hardman et al. 1993), at which time fluid flux from overlying Permo-Triassic siliciclastic sediments could have provided a charge of iron- and copper-rich fluids onto the North Wales Platform (Holmes et al. 1983). These differences in burial history and therefore timing of trace element release probably contribute to the lower volumes of Variscan Mississippi Valley-type mineralization on the North Wales Platform and greater abundance of copper minerals and hematite.

Conclusions

Focusing on outcropping Mississippian strata of the Great Orme, this study documents the sedimentology and diagenetic events for the North Wales carbonate platform. Field study, petrographical and geochemical analyses have allowed the following conclusions to be reached.

1. Sedimentation in the late Visean (Ashian–Brigantian) on the North Wales Platform took place on a steeply dipping carbonate platform rimmed by microbial build-ups and grainstone shoals. On the platform top, metre-scale upward-shallowing successions of winnowed, skeletal packstone and grainstone are capped by palaeosols and palaeokarst, providing evidence for the high-frequency fluctuations in relative sea level.

2. Early diagenesis is recorded by thin, grain-fringing marine cements and well-developed, pore-occluding cements precipitated within the meteoric phreatic realm. These cements are found to occlude all primary porosity and some secondary porosity. Early cementation has predominantly been preserved within the grainstone units located at the centre and towards the top of shoaling-upward cycles. The cementation took place within regressive units during high-frequency relative sea-level fall and exposure of the platform top. Late diagenetic cements are predominantly confined to the faults and fractures. Secondary porosity development can be observed in close proximity to the throughgoing fractures and along bedding planes. The secondary porosity is partially occluded by diagenetically late meteoric calcite that post-dates the main stage of burial and burial cement phases, thus indicating a telogenetic environment.

3. Matrix-replacive and vein dolomite phases (D0–D7) are recorded on the platform margin. The dolomitization most probably represents two main fluid flow events: a shallow burial event that partially replaced the host limestone, and a later, fault- or fracture-controlled phase of dolomitization.

4. In total, 19 calcite cement phases have been defined by petrographic and CL analysis, documenting the progressive burial and exhumation of the Ashian and Brigantian succession on the Great Orme. Following marine and meteoric cementation, burial fluids were fluxed onto the platform via fault and fracture networks. These fluids were most probably sourced from the adjacent East Irish Sea Basin, by dewatering during the Variscan Orogeny, and were co-precipitated with minor volumes of galena and sphalerite. Subsequent copper mineralization occurred during the Late Palaeozoic potentially related to Early Cenozoic Alpine uplift.

5. When compared with other Mississippian platforms within the adjacent Pennine Basin, the North Wales Platform displays a more complex paragenesis, which relates to shallower burial depths in the Late Carboniferous and a complex post-Variscan burial history.

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