Solution-collapse breccias of the Minkinfjellet and Wordiekammen Formations, Central Spitsbergen, Svalbard: a large gypsum palaeokarst system

ARILD ELIASSON and MICHAEL R. TALBOT
Department of Earth Sciences, University of Bergen, Allégaten 41, N-5007 Bergen, Norway
(E-mail: areli@statoil.com)

ABSTRACT
Large volumes of carbonate breccia occur in the late syn-rift and early post-rift deposits of the Billefjorden Trough, Central Spitsbergen. Breccias are developed throughout the Moscovian Minkinfjellet Formation and in basal parts of the Kazimovian Wordiekammen Formation. Breccias can be divided into two categories: (i) thick, cross-cutting breccia-bodies up to 200 m thick that are associated with breccia pipes and large V-structures, and (ii) horizontal stratabound breccia beds interbedded with undeformed carbonate and siliciclastic rocks. The thick breccias occur in the central part of the basin, whereas the stratabound breccia beds have a much wider areal extent towards the basin margins. The breccias were formed by gravitational collapse into cavities formed by dissolution of gypsum and anhydrite beds in the Minkinfjellet Formation. Several dissolution fronts have been discovered, demonstrating the genetic relationship between dissolution of gypsum and brecciation. Textures and structures typical of collapse breccias such as inverse grading, a sharp flat base, breccia pipes (collapse dolines) and V-structures (cave roof collapse) are also observed. The breccias are cemented by calcite cements of pre-compaction, shallow burial origin. Primary fluid inclusions in the calcite are dominantly single phase containing fresh water (final melting points are ca 0 °C), suggesting that breccia diagenesis occurred in meteoric waters. Cathodoluminescence (CL) zoning of the cements shows a consistent pattern of three cement stages, but the abundance of each stage varies stratigraphically and laterally. δ18O values of breccia cements are more negative relative to marine limestones and meteoric cements developed in unbrecciated Minkinfjellet limestones. There is a clear relationship between δ18O values and the abundance of the different cement generations detected by CL. Paragenetically, later cements have lower δ18O values recording increased temperatures during their precipitation. Carbon isotope values of the cements are primarily rock-buffered although a weak trend towards more negative values with increasing burial depth is observed. The timing of gypsum dissolution and brecciation was most likely related to major intervals of exposure of the carbonate platform during Gzhelian and/or Asselian/Sakmarian times. These intervals of exposure occurred shortly after deposition of the brecciated units and before deep burial of the sediments.

Keywords Breccia, evaporites, karst, limestones, Spitsbergen, stable isotopes.

1Present address: Statoil ASA, N-4035 Stavanger, Norway.
INTRODUCTION

Collapse breccias formed as a result of karst processes in evaporitic successions are a common phenomenon in many sedimentary basins all over the world (Friedman, 1997). The mode of formation of these systems varies, and several brecciation models have been presented from different basins (e.g. Stanton, 1966; Blount & Moore, 1969; Smith, 1972; Park & Jones, 1985; Simpson, 1988; Swennen et al., 1990; Warren et al., 1990; Karakitsios & Pomoni-Papaioannou, 1998). When describing fossil breccia systems (palaeokarst systems), several problems must be addressed. Some of the key problems are: the age of the karst system and its collapse, the burial depth during dissolution and brecciation, and the type of fluids causing the dissolution and subsequent collapse of the overlying rocks. In this paper, an attempt is made to address these important issues by studying a well-exposed Mid-Carboniferous evaporitic karst system in central Spitsbergen, Svalbard.

Thick and widespread carbonate breccias occur within the Mid-Carboniferous succession of the Billefjorden Trough in central Spitsbergen. Breccias are developed in the Moscovian Minkinfjellet Formation and the basal part of the Kazimovian Wordiekammen Formation (Fig. 1). These breccias exhibit considerable lateral extent over an area of more than 250 km² (Fig. 2). To the south, the rocks plunge into the sub-surface making their southern limit difficult to define. Their maximum thickness is measured to more than 200 m in the central part of the basin, but the dominant occurrence is as individual beds of 0.5–15 m thick breccia that are interbedded with undeformed limestones and siliciclastics. The origin of these breccias has been debated in the literature. Although various mechanisms of brecciation have been suggested (McWhae, 1953; Cutbill & Challinor, 1965; Dallmann, 1993; Lenoy, 1995), no detailed studies have been carried out concerning the distribution and mode of breccia formation. The aim of this study is to describe, in detail, the breccia field relations and their diagenetic and stable-isotope characteristics, and to suggest a model for breccia formation. This particular karst system has been chosen because it is a direct analogue to Palaeozoic karst systems occurring in the subsurface of the Barents Sea. The latter may have an important influence on oil and gas distribution in this region. Better understanding of evaporite karst systems in general, and the Mid-Carboniferous system in Spitsbergen in particular, is thus important for hydrocarbon exploration in the region.

GEOLOGICAL SETTING

During the Early to Late Carboniferous, active rifting formed the narrow, NNW–SSE trending Billefjorden Trough, which was restricted to the west by the Nordfjorden Block and to the east by the Ny-Friesland platform (Fig. 3). The basin is a half-graben bounded to the west by a major fault zone – the Billefjorden Fault zone. This half-graben is thought to be the result of oblique-slip movement along the Billefjorden Fault zone that commenced in the Bashkirian and terminated in Kazimovian time (Steel & Worsley, 1984). The Billefjorden Trough is one of a series of NNW–SSE trending rift basins that formed in Spitsbergen during the Carboniferous (Gjelberg & Steel, 1981; Gjelberg, 1987; Johannessen & Steel, 1992). During the Moscovian, active rifting ceased and the basin filled with sediment. In the Early Kazimovian, regional subsidence caused drowning of the structural highs and a wider basin developed.

The early syn-rift deposits of the Billefjorden Trough (Ebbadalen Formation) consist of a series of clastic sandstone and conglomerate wedges (Odellfjellet Member) that were shed from the Nordfjorden High. These sandstones and conglomerates laterally interfinger with a basin-centre, evaporite-dominated succession (Tricolorfjellet
Member) (Johannessen & Steel, 1992). The eastern limit is a successive onlap onto the Ny-Friesland Platform (Fig. 3). Maximum thickness of the Ebbadalen Formation is 500 m. Conformably overlying the Ebbadalen Formation is an up to 300 m thick carbonate-dominated succession with subordinate evaporites and clastics of Moscovian age (Minkinfjellet Forma-
tion). This succession represents the uppermost syn-rift sediments in the Billefjorden Trough (Pickard et al., 1996) and is interpreted as transgressive in character. It represents the onset of Late Carboniferous subsidence and drowning of the structural highs. During the Moscovian, the Nordfjorden block remained sub-aerially exposed, limiting deposition of the Minkinfjellet Formation to the west. The eastern limit is defined as differential onlap onto the New Friesland Platform, extending further east than the Ebbadalen Formation sediments (McCann & Dallmann, 1996).

The Upper Carboniferous and Lower Permian deposits (up to 350 m thick) of the Wordiekammen Formation accumulated as transgressive to regressive, post-rift sediments in a much broader basin covering much of central Spitsbergen (Steel & Worsley, 1984; Pickard et al., 1996; Samuelsberg & Pickard, 1999). The sediments were predominantly carbonates that were deposited on a platform in open to restricted, shallow subtidal marine and intertidal to supratidal environments (Sundsbø, 1982; Dallmann et al., 1999; Samuelsberg & Pickard, 1999).

The lower part of the Cadellfjellet member (Fig. 1) in the area around Billefjorden consists of thick, massive dark mudstones termed the Black Crag Beds. These beds are restricted to the central part of the Billefjorden Trough. They thicken from the south to the north with thicknesses ranging from 20 to 60 m (Pickard et al., 1996; Samuelsberg & Pickard, 1999).

In this paper, particular attention is given to intervals in which gypsum dissolution has resulted in brecciation of carbonate rocks. These intervals include the top of the Tricolorfjellet member, the whole of the Minkinfjellet Formation and the Cadellfjellet Member of the Wordiekammen Formation.

METHODS

Logging and sampling of the Minkinfjellet Formation were carried out during July and August 1999 and July and August 2000. Petrographic study of thin sections was carried out using plane-polarized transmitted light and cathodoluminescence (CL) with a Technosyn cathodoluminescence microscope. Fluid-inclusion analysis was carried out at the Norsk Hydro Research Centre, Bergen, using a Fluid Inc. Heating/Freezing Stage mounted on a Leitz Orthoplan Microscope. Samples for carbon and oxygen stable isotopes were drilled from polished slabs with a 0.6 mm
jeweller’s drill. Stable isotopic analyses were performed using conventional methods on a Finnegan Mat 251 mass spectrometer at the GMS Laboratory, Department of Earth Sciences, University of Bergen. Results are expressed as per mil (‰) deviation from the Pee-Dee Belemnite (PDB) standard unless otherwise noted.

RESULTS

Based on field occurrence, breccias have been divided into two main groups. The first group comprises thick bodies of completely brecciated rocks. These massive breccias can be more than 200 m thick and are the dominant type in the central part of the basin (Figs 2 and 3). Here, the middle and upper parts of the Minkinfjellet and the lower part of the Wordiekammen Formation crop out as continuously brecciated sections (Fig. 4). The breccias have been given an informal name, the Fortet member (Dallmann et al., 1999). This stratigraphic interval, however, includes only the breccias within the Minkinfjellet Formation, even though brecciation continues into the overlying Black Crag Beds at the type section at Fortet. The other breccia type occurs as discrete breccia beds interbedded with unbrecciated rocks of the Minkinfjellet Formation. These beds range in thickness from 30 cm to tens of metres (Fig. 4).

Breccia features

Textures and structures

Breccias show a wide range of clast sizes and clast composition and in general have a chaotic appearance. Clast size varies from a few millimetres to more than tens of metres, but the most common are typically between 1 and 10 cm. Limestone fragments are most common, but clasts of chert, shale and sandstone also occur. The limestone clasts are typical of the limestone facies that occur in the unbrecciated parts of this stratigraphic interval; these include wackestones, grainstones, mudstones and neomorphic crystalline limestones (Eliassen & Talbot, 2003a). Dolomite clasts are rare. Breccias can be classified into all categories proposed by Morrow (1982), and range from chaotic unsorted polymict rubble breccia to nearly undeformed crackle breccias with subtle rotation and fracturing of the host rock. Both monomictic and polymictic breccias exist, but a monomict composition is more common (Fig. 5A,B). Clasts are mostly angular, but sub-angular and sub-rounded clasts are common. Rounded clasts are most common in polymict chaotic breccias (Fig. 5A). Evidence of re-brecciation is observed and large clasts composed of an earlier breccia generation are common.

Sections comprised of thick brecciated units that cut through most of the Minkinfjellet Formation show subtle bedding or zonation of different types of breccias. These zones are not laterally consistent. This bedding is caused by variations in clast size and lithology. The degree of brecciation (mixing) is also quite variable both vertically and laterally giving the breccias a distinct zonation. The breccias are matrix poor, clast supported and have a high interclastic porosity. Throughout the whole breccia package there is a general coarsening upward trend. The largest breccia clasts (up to 30 m) are found within the Black Crag Beds. Breccias within the unit directly overlying the Minkinfjellet Breccias are a part of the continuous thick breccia column in the central basin area. The transition between the two formations is, however, easy to define because of the sharp facies change within the clasts.

The base of the thick breccia bodies is well exposed at the Fortet section (Fig. 2). Here, the base is sharp and flat, and is located within the middle Minkinfjellet Formation directly above a dark micritic limestone. The breccia directly above the contact is a relatively fine-grained (clasts 1–5 cm) unit with clasts of lithology similar to the underlying limestone. A continuous section of breccia more than 100 m thick occurs above this sharp base. Further to the north in the central basin, at Lovehovden and Gizahfjellet, the base of the brecciated body is more complex. At these localities, the lower part of the Minkinfjellet Formation contains stratabound breccia beds underlying the main breccia body. These beds are similar to the stratabound breccias discussed below.

Breccia pipes and V-structures

In the central basin the upper limit of the brecciated section lies within the Black Crag Beds. This limit is vertically irregular and laterally inconsistent. The Black Crag breccias are commonly confined to breccia pipes typically 20–200 m high, circular in plan view and funnel-shaped in vertical plane (Fig. 5C,D). They resemble typical doline or sinkhole breccias, with sharp lateral boundaries against unbrecciated, flat-lying strata. Clast composition in the breccia pipes, is
of the same facies as surrounding undeformed material, implying in situ brecciation and little transport. Another important feature seen at the top of the brecciated interval is large V-structures (Fig. 5E,F). These are broken and tilted carbonate beds commonly showing an internal crackle or

---

Fig. 4. Selected parts of logged profiles showing typical occurrence of interstratal breccias at Luxorfjellet and Tricolorfjellet. The Fortet profile shows a part of the thick cross-cutting breccia body in the central part of the Minkinfjellet Basin (see Fig. 2 for locations).
mosaic breccia. The size of V-structures is several tens of metres in vertical direction and more than 100 m in lateral extent. At some locations, close spacing between breccia pipe, rotated blocks, and V-structures yields a more continuous brecciated Black Crag section.

Interstratal breccias

Outside the central area of thick breccia columns, breccias within the Minkinfjellet Formation are thinner but have a large lateral extent (Figs 2 and 4). These breccias differ texturally and structurally from the thick, basin-centre breccias. They

Fig. 5. (A) Minkinfjellet Formation polymict matrix-rich breccia with slightly rounded clasts. (B) Monomict cement-rich angular breccia from the Minkinfjellet Formation. (C) Example of a breccia pipe (arrow) developed in the lower Wordiekammen Formation at Fortet. In plan view the breccia pipe has a circular shape. (D) Breccia pipe from Gizahfjellet cross-cutting most of the Cadellfjellet Member. The top of the original pipe is stratigraphically higher than the top of the breccia preserved within it, which implies that the collapse occurred after deposition of the Black Crag Beds. (E) Large scale V-structure (arrow) at the base Wordiekammen Formation. (F) Picture of Mount Wordiekammen showing transition from the brecciated and deformed basal part of the Wordiekammen Formation into undeformed strata to the east.

© 2005 International Association of Sedimentologists, Sedimentology, 52, 775–794
are bounded above and below by undeformed Minkinfjellet Formation deposits, and the breccia beds range in thickness from 30 cm to tens of metres. In general, the degree of exposure of these breccia beds is poor and exact thicknesses are often difficult to obtain because the base and top are covered by scree. Texturally, interstratal breccias differ from the thick cross-cutting breccias. Clast sizes are generally smaller, typically from sub-centimetre size to metre size and are predominantly monomict, consisting of various kinds of limestone. They show neither internal bedding nor zonation, but inverse grading is common. Clast size typically increases towards the top. The lower boundary (where visible) is sharp, flat and well defined (Fig. 6A). The upper boundary is irregular and transitional, showing a gradual change into unbrecciated carbonates. The transition zone commonly consists of disrupted bedding, crackle breccias and small scale V-structures (metre size) (Fig. 6B).

**Relationship between breccia types**

The cross-cutting and stratabound breccias have a transitional relationship. The volume of breccia lessens further away from the central basin area. Stratigraphic intervals of brecciation also thin towards the basin margins, where breccia beds are restricted to the upper part of the Minkinfjellet Formation. In the north-eastern basin area, this relation is not consistent. At Luxorfjellet in Ragnadalen and at Hultberget in Ebbadalen (Fig. 2) brecciated beds occur within the lower part of Minkinfjellet Formation and in some places even the base Minkinfjellet Formation is brecciated (Fig. 6C).

**BRECCIATION MECHANISM**

The origin of these breccias is a subject of controversy. McWhae (1953) and Lonøy (1995) suggested they are solution-collapse breccias caused by dissolution of underlying gypsum and anhydrite. Dallmann (1993) proposed a seismic origin, whereas Pickard et al. (1996) interpreted the Black Crag breccias as sedimentary deposits, but considered the Minkinfjellet breccias at Campbellryggen as solution-collapse breccias. Cutbill & Challinor (1965) also suggested that the breccias had a tectonic origin caused by sub-surface sliding associated with Late Jurassic faulting. Despite the debate on the origin of the breccias, no detailed study of the units have previously been carried out.

The study presented here supports a solution-collapse origin for these breccias. Interstratal karstification of gypsum and anhydrite beds within the Minkinfjellet Formation, and also within the upper part of Ebbadalen Formation, are considered responsible for all breccia development in this stratigraphic interval.
Fig. 7. Photograph from Fortet showing location of logged profiles. Gypsum beds separating units A (sandstone), B (limestone) and C (breccia body) to the east were in the western section removed by dissolution. The exact locations of the gypsum dissolution surfaces are shown (arrows) (see Fig. 8 for log correlations and Fig. 2 for location).
Gypsum dissolution fronts
Direct evidence of gypsum dissolution is seen in outcrop at a few locations. This is shown by lateral transition of flat-lying gypsum beds into carbonate breccia with clast lithologies comparable with undeformed limestones and dolomites above the gypsum beds (Figs 6C, 7 and 8). The breccias formed by collapse into the void space.
were produced by the removal of gypsum beds. At the Fortet locality, three dissolution fronts are observed in three gypsum beds ranging from 5 to 8 m in thickness and separated from one another by carbonate and sandstone beds. These fronts step upwards through succession in an easterly direction. Towards the west, the basal breccia lies at a progressively lower stratigraphic level. The log correlation from the Fortet profiles shows the disappearance of gypsum beds and downcutting of the base of breccia over a short distance (Figs 7 and 8). Further south, at Campbellryggen, a similar and thicker dissolution front can be seen. A 50 m thick, evaporite-dominated section in the middle part of the Minkinfjellet Formation abruptly disappears in a north-eastward direction. No evaporites are found north of this contact, but the lateral stratigraphic equivalent is a brecciated succession. The dissolution contact at this location is not directly exposed. The sudden lateral disappearance of the thick evaporite succession at this locality resembles the effect of faulting. However, no displacement of underlying units is observed. The gypsum dissolution fronts at Fortet and Campbellryggen all occur within gypsum beds in the middle part of the Minkinfjellet Formation.

Further north in the basin, dissolution fronts are observed in the uppermost Ebbadalen Formation evaporites (Fig. 6C) causing a collapse of the base of the Minkinfjellet Formation. These ‘deep’ breccias are not laterally traceable over long distances and are interpreted to be the result of local evaporite dissolution.

The general gypsum/breccia association
As remarked by McWhae (1953) and others, gypsum beds are important constituents of the Minkinfjellet Formation. Several authors have observed a thickening and increasing abundance of evaporite beds towards the central part of the Minkinfjellet basin (Lønøy, 1995; Pickard et al., 1996; Samuelsberg & Pickard, 1999; Eliassen & Talbot, 2003a). These beds pinch out towards the eastern and western margins of the basin. These pinch outs can be seen especially well in the southern Minkinfjellet basin – south of the central cross-cutting breccia area.

It is reasonable to presume that the area of thick brecciated units in the central Minkinfjellet basin was caused by dissolution of the thicker and more abundant gypsum beds originally deposited in this area. In the brecciated sections, little in situ gypsum remains in the middle and upper part of Minkinfjellet Formation. However, boulders of gypsum up to tens of metres in diameter are incorporated in the breccias at Fortet and Lovohvden. These boulders are interpreted as being remnants of primary gypsum beds. Thinner brecciated beds within the Minkinfjellet Formation are also interpreted as being the direct result of dissolution of evaporite beds. Dissolution of these marginal beds created individual beds of collapse breccias. The existence of gypsum beds, albeit few, preserved between individual breccia beds (Fig. 4), indicates that gypsum was indeed deposited in these settings.

The extent of brecciation seems to be directly related to the amount of gypsum deposited in the basin. Thus a larger volume of gypsum deposited in the central part presumably led to thicker solution-collapse breccias in this region. Dissolution of thinner and more isolated gypsum beds towards the basin margins produced thinner, stratabound collapse breccias.

Textural evidence of solution collapse
The textural composition of the breccia beds is typical of solution collapse caused by dissolution of evaporite beds. The sharp flat base, inverse grading and irregular undulating top of each individual bed is a good indication of a collapsed cave (Middleton, 1961; Park & Jones, 1985; Simpson, 1988). Dissolution of a gypsum bed will produce a cave with a flat floor following the boundary between the gypsum and underlying carbonate bed (Simpson, 1988). The subsequent roof collapse of this cave normally produces an inverse-graded breccia in which the most mixing, abrading and crushing of rock will occur during the initial collapse. The basal cave fill thus consists of a fine-grained, chaotic breccia with a large matrix content. When the cave starts to fill up and there is less space for clast mixing, less dramatic brecciation occurs close to the former cave roof. Smaller V-structures, crackle breccias and less matrix are typical, close to the upper boundary. The top of a breccia unit does not appear to be constrained by a bed-boundary, but rather by the available space created by the underlying cave. The thickness of the brecciated units is thus controlled by the amount of evaporite dissolution. The crude zoning or stratigraphy seen in thick breccias is a common feature of solution-collapse breccias (Middleton, 1961; Smith, 1972). Zonation is controlled by the primary facies changes in the original succession. Competence differences in the primary beds control the fracture pattern of the collapse breccia (Smith, 1972). With increasing degree of
brecciation (mixing) the ‘bedding’ is destroyed and results in a chaotic polymict breccia.

Dissolution of a single evaporite bed produces a single breccia bed. Sequential dissolution of closely spaced evaporite beds results in superposition of the breccia beds, and thus any re-brecciation will form a more chaotic sediment that can be of significant thickness. Amalgamation and re-brecciation are the principal controls on the difference between the thick brecciated units in the central basin and the thinner, breccia beds towards the margins. There is no genetic difference between small-scale bed breakage and V-structures seen at the top of single breccia beds, and the large-scale karst topography developed at the upper limit of breccias in the central area. Although these structures are several orders of magnitude larger, they formed by the same process.

Breccia cements

Breccia cements are completely dominated by equant calcite spar with a typical drusy fabric (Fig. 9A). Crystal sizes may reach 500 μm towards the centre of the pores. Intergranular porosity is abundant in many breccias where spar fill is incomplete. These pores are in some cases completely or partially filled with crystal silt or detrital silt (Fig. 9B).

Many clasts show truncated vein-filling cements developed prior to the main brecciation event (Fig. 9C). These cements formed in the original sediment, and were later brecciated. Re-brecciation is commonly seen (large clasts composed of breccia), which implies that more than one phase of cementation and lithification occurred. The vein-filling cements may thus have been precipitated during an early brecciation.
episode (this cement generation will be referred to as generation zero).

The abundance of sparry cement varies. Some breccias contain little well-developed sparry cement but rather a micritic or microsparitic matrix. However, in most breccias, sparry calcite is dominant. A few breccias contain silica cements, composed of amorphous quartz, partially filling porosity between clasts. Interclastic gypsum is also observed, but is relatively rare.

**CL zonation of cements**

Cathodoluminescence study of breccia cements was carried out on breccia samples from a range of stratigraphic and geographic occurrences of Minkinfjellet Formation breccias (Fig. 2). A distinct pattern of luminescence zoning, representing different cement generations is observed. Each zone represents calcite that precipitated from porewaters of different chemical composition (Meyers, 1991; Machel, 2000). Three generations have been detected in the main breccia cement, referred to as ‘generations A, B and C’ (Fig. 9D). The vein-filling cement seen within some clasts (generation zero) is an even earlier generation than those described here. Generation zero cements are non-luminescent.

The initial generation of the main breccia cements (A) is non-luminescent or very dark dull luminescent, containing occasional thin, dull to bright luminescence bands. This cement generation appears in all breccias and is volumetrically dominant. The second generation (B), is bright luminescent containing thin dull or non-luminescent bands. This cement generation is less common overall, but may be dominant in some breccias. The third generation (C) has a homogenous dull orange CL. This cement is volumetrically small and occurs as the last void fill in large pores.

All three cement generations co-exist only rarely. Generation A is the dominant cement within drusy mosaic spars, but commonly a thin rim of generation B is present (Fig. 9D). Veins filled with generation B cement in some samples cross-cut generation A cements. Cracking (or brecciation) of generation A-cemented breccias must, in these cases, have occurred between cementation episodes. Generation C cements do not show a similar relationship.

The distribution of the three different cement generations is to some extent geographically controlled. Southern breccias (south of Adolfbukta) are completely dominated by generation A cements. Generation B, if present at all, is only developed as a thin rim in the innermost pore fills. North of Adolfbukta, generation A is still volumetrically dominant in many breccias, but generation B is always present and in some samples volumetrically dominant. A thin inner rim of generation A is, however, always present. Generation C is also restricted to this area, and does not appear in the southern basin. In addition, the breccias of the thick cross-cutting breccia-bodies in the central basin area tend to contain more generation B and C cements than the peripheral stratabound breccias.

**Fluid inclusions in breccia cements**

Populations of primary fluid inclusions are well developed in the breccia calcite cements. The inclusions are generally small (10–25 μm) and all-liquid, one-phase inclusions dominate. Inclusions containing a gas bubble are exceptions although they may occur within primary inclusion populations. Homogenization temperatures \(T_h\) of inclusions containing a gas phase vary between 110 and 152 °C. No consistent pattern was observed and none of the \(T_h\) measurements gave similar results indicative of post-trapping stretching or leaking of fluid inclusions. Final melting point \(T_m\) temperatures were within the range 0-0 to +0-1 °C. Repeated measurements from the same inclusion gave the same result. Fluid inclusions in calcite cements, representing all generations observed under CL yield the same \(T_m\) values. Freezing points during cooling of the inclusions are low, averaging −58 °C.

**Cementation model**

With the exception of the generation zero cement (no measurements have been performed on this cement), fluid-inclusion data reveal that all the carbonate cements precipitated from fresh water. This indicates that the cementation of breccias occurred in meteoric waters. The fact that the inclusions are dominantly liquid, one-phase implies that the cements precipitated at temperatures below 50 °C (Goldstein, 1986).

The petrographic observations are also consistent with a near-surface meteoric origin for the breccia cements. Drusy and equant calcite spar commonly develops in vadose and phreatic meteoric environments, although this texture in not necessarily diagnostic of this environment (Tucker & Wright, 1990; Tucker, 1991). Porefilling crystal silt and detrital silt that infiltrated after cementation confirm a setting in proximity
to vadose environments (Tucker & Wright, 1990).

Under CL, meteoric cements are typically non-luminescent with minor bright zones, reflecting the generally oxidizing nature of shallow meteoric waters (Mussmann et al., 1988; Tucker, 1991; Smith & Dorobek, 1993). After initial burial, reducing conditions develop that result in luminescent calcites (Niemann & Read, 1988; Tucker, 1991). The observed cathodozonation in the breccia cements are consistent with this model. Generation zero and generation A cements are indistinguishable by CL, probably because both cements precipitated in oxic meteoric conditions. With increasing burial, reducing conditions led to incorporation of Mn$^{2+}$ and/or Fe$^{2+}$ into calcite cements, and bright luminescent calcite precipitated (Smith & Dorobek, 1993). The ‘dull’ luminescent stage C cement is interpreted to have precipitated after deep burial of the breccias probably long after precipitation of stage A and B cements. A change in the elemental composition of the porewater most likely occurred, thus explaining the difference in luminescence.

**Stable isotopes of breccia cements**

Oxygen and carbon stable isotope analysis was carried out on 75 samples of breccia cements. The data set represents breccias from throughout the basin, both stratigraphically and geographically. $\delta^{18}O$ values range from $-1.7$ to $-15.0\permil$ and $\delta^{13}C$ values range from $+5.5$ to $-7.0\permil$ (Fig. 10). Ninety per cent of breccia cements, however, have $\delta^{18}O$ values lower than $-10.0\permil$. Similarly, the lowest $\delta^{13}C$ value ($-7.0\permil$) is exceptionally low compared with all other $\delta^{13}C$ values. Oxygen and carbon isotopic values show slight positive covariance (Fig. 10). Four samples have a marked deviation towards positive values. These samples were taken from breccias containing very little cement and may thus be contaminated by the host rock. The carbon and oxygen values of these samples probably reflect the isotopic composition of the limestone clasts. The $\delta^{18}O$ and $\delta^{13}C$ values for these samples are directly comparable with those of unbreciated limestones of the Minkinfjellet Formation (Eliassen & Talbot, 2003b). These measurements are defined as Group X (Fig. 10).

![Fig. 10. Cross-plot of oxygen and carbon stable isotopes of breccia cements and recent calcite precipitates. Breccia cements have been grouped based on isotopic composition. Group 1 represents the isotopic composition of generation A breccia cement. Group 2 represents the isotopic composition of breccia cements that are a mix of generation A with generations B and C. The higher the percentage of B and C present, the lower the oxygen isotopic composition. Group 3 represents generation zero cement. See text for description of the cement generations. Group X represents host-rock-contaminated samples and reflects the isotopic composition of the breccia clasts. Recent calcite precipitates show less depleted oxygen isotopic compositions and more positive carbon isotopic composition than the breccia cements. The positive carbon values are probably due to the total lack of vegetation in the mountains of Svalbard.](image-url)
Most sampled breccia cements plot within a narrow range of $\delta^{18}O$ values. Sixty-six per cent of the $\delta^{18}O$ values lie between $-10.5$ and $-12.5\%_o$ (mean value $= -11.5 \pm 1\%$). The $\delta^{13}C$ values within this group range from +2.5 to $-7.0\%_o$. This is defined as Group 1 (Fig. 10). Group 2 is defined by oxygen isotope values more negative than those of Group 1, with $\delta^{18}O$ values from $-12.6$ to $-15.0\%_o$ and $\delta^{13}C$ values ranging from +2.4 to $-1.4\%_o$ (Fig. 10). Group 3 cements form a separate cluster with a mean $\delta^{18}O$ value of $-8.7\%_o$ and $\delta^{13}C$ values ranging from +3.4 to +1.3\%o. Their less negative oxygen isotopic values clearly separate these cement samples from the main group (Fig. 10).

Three samples have $\delta^{18}O$ values slightly less negative than the main group (Group 1) and thus fall outside the range of one standard deviation (Fig. 10). However, although they range from $-10.0$ to $-10.3\%_o$, these samples are nevertheless regarded as belonging to Group 1. They contain the non-luminescent cement typical of generation A. Most likely some clast-material has been incorporated during sampling for isotope analysis.

**Relationships between cement generation and stable isotopes**

There is a direct relationship between the abundance of different cement generations and their stable isotope composition. As described above, most breccias are cemented by generation A cement. Generation A cement coincides with Group 1 of stable isotope values. Samples showing oxygen values more negative than those of Group 1 have a greater proportion of generation B or C cements. The higher the percentage of generation B and C cements, the more negative the $\delta^{18}O$ values. Group 2 oxygen isotope values thus represent mixtures of the isotopic composition of all three cement generations.

It is difficult to explain the origin of Group 3 cements in terms of their CL zoning. These samples contain a non-luminescent cement not distinguishable from generation A cement. The most reasonable explanation would be that this group represents generation zero cement and that their composition represents the fluids associated with the earliest brecciation and lithification phase. However, unequivocal evidence for this does not exist.

**Interpretation of the stable isotopes**

Overall, the breccia cements are significantly $^{18}O$-depleted, and become more so with increased cementation. Progressive isotopic depletion is a typical feature of cement precipitation during burial. Oxygen isotope fractionation in carbonates is controlled by temperature and fluid composition (Hays & Grossman, 1991). Inferring that all cement generations were precipitated in meteoric water (results from studies of fluid inclusions), the generations B and C have an isotopically lighter composition reflecting higher precipitation temperatures than generation A. Generation A cement most likely formed from a fluid with a $\delta^{18}O$ composition close to $-11\%_o$, deduced from the mean value of Group 1, which is dominated by generation A cement. The oxygen isotopic composition of pure generations B and C is more difficult to constrain because homogeneous samples of these do not exist.

Stable isotope studies have been performed on cements in unbrecciated limestones of the Minkinfjellet Formation (Elissen & Talbot, 2003b). They identified a ‘meteoric calcite-line’ (MCL, Lohmann, 1988) in cements occurring proximal to minor karst and other exposure surfaces. The mean $\delta^{18}O$ value for this MCL is $-7.4\%_o$, which is typical for meteoric calcites that precipitated in a coastal environment at lower latitudes (Allan & Matthews, 1982; Given & Lohmann, 1986; Lohmann, 1988; Muchez et al., 1998). The Billefjorden Trough was situated at ca 30°N during deposition (Steel & Worsley, 1984). Comparing this value with the $\delta^{18}O$ values of breccia cements, indicates that only generation zero (average $\delta^{18}O$ of $-8.6\%_o$) can be inferred to have formed from similar diagenetic fluids. The other generations of breccia cement (A, B and C) are isotopically more negative compared to these inferred for Upper Carboniferous meteoric values. The relationship between A and B and C cements is, as described above, most likely thermal due to increasing burial depth. The origin of the significantly more negative $\delta^{18}O$ values of generation A cement than generation zero (which is interpreted as a meteoric cement, precipitated in oxic conditions) is, however, problematic. Three alternative explanations are considered for the observed isotopic composition of generation A relative to other meteoric cements.

Generation A, B and C could have precipitated after a $3\%_o$ shift in the isotopic composition of local rain-water. A $3\%_o$ shift in isotopic composition of precipitation requires major meteorological changes (shift to inland or high altitude climatic conditions) or a major drift towards higher latitudes prior to brecciation and cemen-
tation (Hays & Grossman, 1991; Fricke & O’Neil, 1999). This explanation is, however, not considered to be likely (see Discussion).

The second possibility is that generation A cement precipitated at higher temperatures than generation zero and the meteoric cements in the unbrecciated Minkinfjellet Formation. The δ18O value of generation A cement is 4‰ lower than Minkinfjellet cements and 3‰ lower than generation zero cement. The two cements are thought to have precipitated at, or close to, surface temperatures. If a precipitation temperature of 20°C is assumed for generation zero cement, then local meteoric water had a δ18O composition of ca −8‰ (SMOW). The 3‰ negative shift in δ18O between these near-surface cements and generation A cement implies the latter precipitated at ca 35°C (using the equation of Hays & Grossman, 1991), assuming that the cements were precipitated from waters of similar isotopic composition. If the basin had a geothermal gradient of 30°C/1000 m, this precipitation temperature implies a burial depth close to 500 m during precipitation of generation A cement. The Minkinfjellet Formation was, however, deposited in an active rift basin (the Billefjorden Trough) and higher geothermal gradients can thus be expected during the Late Carboniferous. Considering this, a burial depth of <500 m is possible during precipitation of generation A cement. Assuming continued flushing by meteoric water (as implied by the fluid-inclusion data), generation B and C cements have δ18O compositions that require precipitation at burial depths of up to 1000 m.

The third possibility is that precipitation of the main breccia cements (A, B and C) occurred in the deep burial realm. Calcite cements precipitated at depth in a basin are generally 18O depleted (Walls et al., 1979; Meyers & Lohmann, 1985; Choquette & James, 1986). The measured δ18O values of the breccia cements are within the range of such cements. Hydrothermal waters migrating upward along joints and faults could thus have been responsible for the low isotopic composition of the cements. Fluid inclusions and petrographic data do not, however, support this model. Warm formational waters typically range from brackish to highly saline, reducing conditions dominate, and primary fluid inclusions generally contain both gas and liquid phases. Cement CL is characteristically dull and may or may not show compositional zonation (Choquette & James, 1986). Only generation C cement is a possible candidate for a typical burial diagenetic environment but few fluid-inclusion data are available for this cement.

Carbon isotope values of the cements provide some insight into the nature of the diagenetic fluids from which breccia cements precipitated. The δ13C values of the cements show a weak trend towards lower δ13C values with increasing burial, a trend that is typical for many calcite cement populations (Choquette & James, 1986). Measured δ13C values of the breccia cements are mainly positive (higher than 0‰; Fig. 10). Thus isotopically depleted carbon, derived from soil organic matter or terrestrial vegetation, was not likely to have been a major contributor to the breccia cements given the 13C-depleted signatures of cements precipitated at or close to vegetated exposure surfaces (Allan & Matthews, 1982; Beier, 1987; Saller & Moore, 1991). The breccia cements rather have carbon isotopic values that are rock-buffered with values comparable with whole-rock samples of Minkinfjellet Formation marine limestones (Eliassen & Talbot, 2003b). One sample has a significantly lower δ13C value (−7.0‰) that suggests the possible influence of isotopically depleted soil CO2.

DISCUSSION

The petrographic and geochemical data presented here have many implications concerning the overall understanding of the formation of the breccias in the Minkinfjellet Formation. One of the most important and challenging questions concerns the age of the karst system and the timing of brecciation. Three hypotheses can be postulated: (i) the karst system developed in a shallow burial realm through contact with meteoric water shortly after deposition of the Minkinfjellet and Wordiekammen Formations, thus dating the breccias to Late Carboniferous/Early Permian. (ii) The gypsum karst and breccias developed since the Miocene, following uplift and exposure of the Svalbard archipelago (Kellogg, 1975). (iii) The karst system has a deep-burial origin and formed in the sub-surface between the Late Permian and Tertiary.

The deep burial alternative seems unlikely based upon present interpretations of the petrographic and geochemical data. Deep burial gypsum dissolution with subsequent brecciation has, however, been described elsewhere (Dravis & Muir, 1993). Pre-brecciation stylolites within breccia clasts and compaction because of heavy overburden prior to cementation are characteristics of such breccias. Clasts containing stylolites are present at one location in the Minkinfjellet...
Formation breccias (at Tricolorfjellet), but the well-cemented breccias show few signs of pre-cementation compaction and the clasts typically ‘float’ in calcite spar (Eliassen, 2002). Minkinfjellet Formation breccias containing little sparry cement show some evidence of compaction (Eliassen, 2002), which could imply a shallow burial origin. More likely, the observed cracking, reorientation of clasts, compaction and minor gypsum dissolution occurred during subsequent deep burial of the Minkinfjellet and Wordiekammen Formations.

A recent (post-Miocene) origin for the breccias is, however, a possible alternative. Since the Miocene, Svalbard has been situated at high latitudes. The marked $^{18}O$-depletion in the breccia cements (the $3\%$ negative shift between generation zero and generation A) could therefore be explained by the large latitudinal and climatological shift of Svalbard since the Late Carboniferous. The mean annual $^{18}O$ composition of present-day precipitation in Spitsbergen is $-9.3\%$ (SMOW, $-10.4\%$ winter and $-8.3\%$ summer, measured at Isfjord radio; Fricke & O’Neil, 1999). The $^{18}O$ value for calcite precipitated from this water would be $-5.3\%$ (using the equation of Kim & O’Neil, 1997), assuming a temperature of $0^\circ C$ (mean annual temperature is $<0^\circ C$). The $^{18}O$ values of the two modern calcites analysed in this study are $-5.7\%$ and $-6.8\%$ (Fig. 10), which are in good agreement with the anticipated value. The significantly lower $^{18}O$ values of the breccia cements relative to the modern calcites do not suggest a post-Miocene origin of the breccias.

The oxygen isotopic composition of the ice that has accumulated from AD 1100 to 1970 on the Lomonosov glacier (Fig. 2) situated to the east of Billefjorden, but within the drainage area of the Minkinfjellet and Wordiekammen Formations, has a mean $^{18}O$ value of $-14.0\%$ (SMOW) (Kotlyakov et al., 1980), which is lower than the present-day precipitation at Isfjord. The theoretical $^{18}O$ value of calcite precipitated in equilibrium with this glacial meltwater would be $-10.0\%$. The ice shows a weak trend towards lower values with increasing age, and many samples have values lower than $-14\%$, with a minimum of $-16\%$ (SMOW). These more $^{18}O$-depleted meteoric waters could potentially be the source of the more negative $^{18}O$ values of generations A–C breccia cements.

One important observation contradicts this interpretation. The breccia cements become progressively isotopically lighter throughout precip-

Gypsum beds of the Minkinfjellet and underlying Ebbadalen Formation are widely exposed in the Billefjorden area, where they are subject to active dissolution and karstification. Salvigsen et al. (1983) report well-developed, recent collapse dolines and gypsum caves in the Mathiesondalen, which are a result of karstification of gypsum within the Ebbadalen Formation. Some gypsum dissolution and brecciation has therefore occurred in this area during the Quaternary, but it occurred on a modest scale and there is no evidence for karstification of the extent and intensity required to explain massive brecciation.

Considering these arguments, a Late Carboniferous to Early Permian origin is considered the most likely time of development of the breccias and associated karst system. The gypsum dissolution was interstratal and by the time brecciation occurred, the surrounding rocks were lithified and cemented (Eliassen, 2002). Furthermore, the collapse breccias developed after dolomitization and formation of chert nodules in the host rocks (Eliassen, 2002). These facts imply that brecciation must have occurred some time after deposition of the Minkinfjellet and Wordiekammen Formations, and that it took place in the subsurface after some degree of burial. The subsequent cementation of the breccias must have occurred at similar or slightly greater depths. Thus burial depths of up to 500 m during brecciation and cementation are not unlikely. The $3\%$ difference in the $^{18}O$ values of the inferred near-surface meteoric cements and the main breccia cements (generation A) reflects this genetic relationship. At a depth of 500 m in this active rift basin considerable thermal heating of porewater must have occurred, thus explaining the low $^{18}O$ values of the breccia cements. In addition, there was clearly a considerable time gap between deposition of the Minkinfjellet Formation and

© 2005 International Association of Sedimentologists, Sedimentology, 52, 775–794
cementation of the collapse breccias. A change in the stable isotopic composition of meteoric waters due to climatic or latitudinal changes is therefore possible (Smith & Dorobek, 1993). Thus the lower δ18O values of the breccia cements are probably a result of the combined effects of heating during shallow burial and a change in the isotopic composition of local rain-water with time. Considering this, and that the thermal gradient in the Billefjorden Trough may have been higher than 30 °C/1000 m, the δ18O values of generation A cement are consistent with a meteoric origin for the pore fluids. Gypsum karst, both modern and ancient, usually develops via interstratal dissolution in the shallow sub-surface, and is typically associated with breccia pipes (Ford & Williams, 1991). Commonly, such breccia pipes are several hundred metres deep, but pipes as deep as 1200 m have been recorded (Ford & Williams, 1991). The deepest breccia pipe observed within Minkinfjellet and Wordiekammen Formations is nearly 200 m (Fig. 5D). These morphological features imply that brecciation (most breccias are not confined to breccia pipes, but as horizontal beds or thick brecciated bodies) and cementation occurred after at least 200 m of burial, consequently some thermal heating of porewaters must have occurred prior to cementation.

Diagenesis in the current Late Carboniferous/Early Permian model of breccia formation occurred at depth but from waters of meteoric origin. At this time vertical permeability in the basin was probably enhanced by faults (Eliassen, 2002). As evaporite dissolution proceeded, a karst system developed with large conduits capable of high water flux. The collapse breccias themselves also had a much higher permeability than the lithified carbonates. Thus the combination of faults, karst-aquifers and highly permeable breccias at depth in the basin would have permitted a high flux of oxidized meteoric water deeper into the sub-surface than would have been possible in a ‘tight’ unkarstified succession.

A significant fall in relative sea-level leading to exposure of the broad Late Carboniferous to Early Permian carbonate platform must have occurred to enable the development of such a large karst system in these marine and marginal-marine deposits. Surfaces with evidence of exposure have been identified within the Wordiekammen Formation (Pickard et al., 1996; Samuelsberg & Pickard, 1999). As the thickest deepest pipes in the system extend down through the Black Crag beds (Fig. 5D), these Gzhelian and Asselian/Sakmarian exposure surfaces are the best candidates for the timing of karstification of Minkinfjellet Formation evaporites. A Late Carboniferous/Early Permian timing for the development of the karst system correlates with the major phase of Palaeozoic glaciation in the southern hemisphere (Isbell et al., 2003). The eustatic changes caused by this major glaciation may have been an important controlling factor of the development of the karst system.

In the area of most intense brecciation (central part of the basin) the thickness of the Cadellfjellet Member exceeds 250 m (Dallmann et al., 1999) and the Minkinfjellet Formation is generally >200 m thick (up to 300 m). Given that the base of the Minkinfjellet Formation is brecciated at some locations in the northern basin, the karst system must have been more than 500 m deep if its formation was related to the Gzhelian exposure. If Asselian/Sakmarian exposure were responsible for the brecciation, the system would have to have been even deeper. These considerations further strengthen the suggestion that the Minkinfjellet Formation breccias formed at moderate burial depth.

CONCLUSIONS

The carbonate breccias of the Minkinfjellet and Wordiekammen Formations were formed by gravitational collapse following dissolution of gypsum and anhydrite beds within the Minkinfjellet and Ebbadalen Formations.

The most extensive brecciation occurred in the central part of the basin, where brecciated units up to 200 m thick formed. Towards the basin margins breccias occur as individual beds interbedded with undeformed beds of limestone and dolomite.

- The central breccia bodies and interstratal breccia beds are connected, forming a large palaeokarst system.
- The Minkinfjellet Formation breccias are cemented by equant, calcite spars exhibiting drusy, mosaic fabric. Crystal or detrital silt is locally developed in large pores typical of meteoric diagenetic cements. At least two episodes of brecciation and cementation are recorded in the breccias, but several episodes of re-brecciation are likely to have occurred.
- Primary fluid inclusions in the breccia cements are dominantly single phase (liquid) implying low precipitation temperature. The final melting point (T_m) of the fluid inclusions are 0 °C to +0.1 °C indicating that the cements precipitated in fresh water.

© 2005 International Association of Sedimentologists, Sedimentology, 52, 775–794
• Stable oxygen isotopes of the breccia cements are depleted with respect to $^{18}\text{O}$, and range from $-8$ to $-15\%_\text{o}$. The oxygen isotopic compositions covary with the cement generations recognized in CL. The $\delta^{13}\text{C}$ values of breccia cements reflect the composition of the original marine limestones which have been brecciated.

• Penetration of meteoric waters into the deep sub-surface was probably aided by a large fault system (the Billefjorden Fault Zone) adjacent to the main evaporite depocentre.

• The timing of the main phase of dissolution and brecciation is considered to be Late Carboniferous to Early Permian, and was probably related to laterally extensive exposure surfaces observed within the middle and upper part of the Wordiekeamnen Formation.

ACKNOWLEDGEMENTS

We gratefully acknowledge funding for fieldwork, and for a Ph.D. stipend for A.E. from Norsk Hydro ASA. We especially thank Arve Lønøy and Tommy Samuelson at Norsk Hydro for invaluable help and comments, both in the field and during the analytical part of our study. Thanks also to Mina Aase for all her help during the 2000 field season and to Eirik Aasersø, Anne-Sofie van Cauwenberge and Mette Haugan Eliassen for their field assistance and to Eirik Aaserød, Anne-Sofie van Cauwenberge Aase for all her help during the 2000 field season. We especially thank Arve Lønøy and Tommy Samuelson at Norsk Hydro for invaluable help and comments, both in the field and during the analytical part of our study. Thanks also to Mina Aase for all her help during the 2000 field season and to Eirik Aasersø, Anne-Sofie van Cauwenberge and Mette Haugan Eliassen for their field assistance during the 1999 and 2000 field seasons. We also thank Johannes M. Rykkje at Norsk Hydro Research Centre for his help with fluid inclusion analyses, and Mateu Esteban for valuable comments during the 1998 reconnaissance of the study area.

REFERENCES


Manuscript received 30 April 2004; revision accepted 3 January 2005.

© 2005 International Association of Sedimentologists, Sedimentology, 52, 775–794