Timing of Diagenesis and Deformation of Carboniferous Gypsum & Anhydrites in Spitsbergen

A Thesis Presented To The

DEPARTMENT OF GEOLOGY - GEOGRAPHY
UNIVERSITY OF NEBASKA -OMAHA

In Partial Fulfillment Of The
Requirements For The Degree

BACHELOR OF SCIENCE

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SUMMER 2008
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Abstract

Gypsum and anhydrite of the Middle Carboniferous Ebbadalen and Minkinfjellet Formations were deposited in an asymmetric rift basin, the Billefjorden Trough of central Spitsbergen. The Billefjorden Fault Zone, the western boundary of the basin, has previously been documented but the role of evaporites in the deformation history has received little attention. A complicated, polyphase deformation history has characterized the Billefjorden Fault Zone since at least the Caledonian. Since the deposition of the Mid-Carboniferous evaporites, they have played an integral role in accommodating and recording deformation in the current study area, as well as in the development of the basin.

Textures relating to the deposition, deformation, prograde and retrograde diagenesis of the evaporites have been analyzed to understand their evolution. Kinematic indicators, extracted from structural fabrics were also explored to understand the movement history along the Billefjorden Fault Zone. Kinematic results indicate dominant dip-slip motion with a minor strike-slip component that varies along strike as a function of position relative to the relay zone between two major faults.

Incomplete, post-consolidation diagenesis of gypsum is seen as pseudomorphic anhydrite replacing the deformed gypsum fabrics. Variations in pore fluid salinities, pore fluid pressures and hydrodynamics of the basin is thought to be a major factor in local prograde and retrograde diagenetic variations, therefore earlier gypsum textures are preserved. A model for the evolution of Mid-Carboniferous evaporites in the Billefjorden Fault Zone is proposed based on analyses of kinematic indicators and diagenetic textures. The results also help constrain the timing and kinematics of reactivation along the BFZ. Timing of these events is consistent with Carboniferous rifting and is constrained by late diagenetic pseudomorphic anhydrite overprinting deformed gypsum fabrics.

Introduction

A variety of undeformed and deformed evaporite deposits are exposed within the Billefjorden Fault Zone of central Spitsbergen. Samples from these exposures were collected and analyzed to understand their importance in the structural history of the Billefjorden Fault Zone. Questions addressed in this paper are as follows:

Are any primary/depositional feature preserved in the gypsums?
When did diagenesis occur and what features are associated with it?
When did deformation occur and what features are associated with it?
What was the role of gypsum/anhydrite during deformation events?
What movement history is recorded by evaporites within the Billefjorden Fault Zone?
What textures have been preserved and why?
Figure 1 – Overview map of Svalbard with red box indicating study area on Spitsbergen (Norwegian Polar Institute 1:3,000,000 geologic map).

**Geologic Setting**

The Billefjorden Fault Zone is a well-known lineament that runs north-south across the island Spitsbergen, within the archipelago of Svalbard. This section will provide an overview of deformation and sedimentation in the Billefjorden Fault Zone with emphasis on Carboniferous events. The basic tectonic history of this fault complex has been thoroughly documented, but some disputes still exist. This 2-4 km wide deformation zone is believed to be an inherited zone of weakness that originated in the Caledonian Orogeny (McCann & Dallmann, 1996). Rapid facies changes and segmentation of the fault system has developed a complex stratigraphy. The oldest exposed rocks are dominantly Proterozoic schists, gneisses and amphibolites with minor
amounts of quartzites and marbles. These have been deformed as a result of ductile Caledonian deformation and earlier events.

Sediments unconformably overlying the basement rocks to the west of the fault zone are Devonian in age. Other unconformable contacts do exist. The Andree Land Group spans the whole Devonian period. The Balliolbreen Fault forms the eastern margin of the Andree Land Group, so the only exposures of the Devonian sediments are found to the west of the fault (figure 2). These sandstones, conglomerates and siltstones are faulted and folded from the reactivation of basement faults and shear zones. The clastic sediments tend to coarsen to the southeast. The thickness is estimated to be 4 km thick. The base of the Devonian section is exposed west of the study area (Harland et al, 1974).

To the east of the Billefjorden Fault Zone, the Early Carboniferous Billefjorden Group unconformably lies above the Devonian sediments, and to the west it locally unconformably overlies Devonian strata. The Early Carboniferous period was characterized by subsidence, terrestrial sedimentation and minor faulting. The study area (figure 1) went through a period of denudation followed by the sedimentation of the lower most Billefjorden Group the Horbye breen Formation. This succession includes relatively thin basal conglomerate horizons. Small syn-sedimentary fault movements have been suggested from the presence of conglomerate horizons that are intercalated with coal seams and shales (McCann and Dallmann, 1996). Lithologies of this group consist of fluvial and near-shore sandstones, yet the amount of conglomerates and coal quickly diminishes in the upper Billefjorden Group. The Hultberget Member Formation marks the base of the Gipsdalen Group with red sandstones and shales, but is only exposed within the Billefjorden Trough (Eliasson, 2003b). The reactivation of the Odellfjellet and Balliolbreen faults is marked by rifting the first red beds (McCann and Dallmann, 1996).

Conformably above the Billefjorden Group is the Middle Carboniferous Gipsdalen Group, which is of a focus of this paper. The Middle Carboniferous was a more active period for the study area. During this time a half-graben, the Billefjorden Trough developed during a marine transgression leading to subsidence filling the basin with approximately 500 m of Ebbadalen sediments and the 350 m of Minkinfjellet sediments (Eliassen and Talbot, 2005; Stemmerik et al, 1999; McCann and Dallmann, 1996). The half-graben development has been attributed to oblique slip along the Billefjorden Fault Zone. McCann and Dallmann, 1996 suggest sinistral transtension during the Early and Middle Carboniferous periods.

The Ebbadalen Formation is contained within the Billefjorden Trough and marked by westward thickening clastics, carbonates and evaporates. Adjacent to faults are fault scarp deposits that intercalate with the other lithologies as a result of occasional normal movements. At this time, the basin narrowed and deepened to the north causing the axis to be slightly oblique to the basin bounding Balliolbreen Fault (McCann and Dallmann, 1996). The Minkinfjellet Formation is characterized by clastic carbonates and minor amounts of evaporates that extend much further east in the Billefjorden Trough. McCann and Dallmann (1996) note a lack of fault scarp deposits within the Minkinfjellet Formation, but during this study conglomeritic beds were observed near the base of the Wordiekammen Formation to the north of Pyramiden.

Total estimated offset during the Carboniferous is estimated to be more than 1300 m as a maximum value, but the more accepted value is approximately 1000 m of total offset (McCann and Dallmann, 1996).

The Late Carboniferous to Early Permian post-rift Wordiekammen Formation was deposited across a broader area than both the Ebbadalen and Minkinfjellet Formations. The Wordiekammen Formation is dominantly platform carbonates identified by the distinct basal
Black Crag Bed in addition to large breccias (Eliasson and Talbot, 2005). The open carbonate shelf continued to migrate to the east depositing the Gipshken Formation, dolomite and evaporites. Some authors have proposed that during this transgression evaporites of the Minkinfiellet were dissolved and produced intraformational brecciation and collapse structures (Eliasson and Talbot, 2005; McCann and Dallmann, 1996). Late Permian sedimentation persisted with the Tempelfjorden Group’s Kapp Starostin Formation, thought to indicate continued platform subsidence and ceased Permian tectonics (McCann and Dallmann, 1996).

The Tertiary history presented by McCann and Dallmann (1996) suggests reverse reactivation along the Ebbadalen, Balliobreen and Lovehovden Faults related to the Tertiary tectonics. A large synclinal feature dipping into Petuniabukta was reported to be the result of relaxation of compressive forces, faulting down to the east along the Odellfjellet and Pyramiden Faults. The syncline axis is said to be oriented NNW-SSE oblique to the fault zone’s strike of ENE-WSW. McCann and Dallman reconcile the oblique extension by postulating a releasing bend from later dextral displacement across Billefjorden Fault Zone. Evidence from the current study is not consistent with the proposal for substantial Tertiary reactivation along the Billefjorden fault zone, as discussed below. In this study, kinematic indicators and textural relationships in gypsiums and anhydrites were used to constrain the directions, mechanics and timing of deformation associated with the Billefjorden Fault Zone.

Figure 2- Geologic map from Geological map of Svalbard 1:100,000 sheet C7G Dicksonfjorden (Dallman, et al; 1994).

Stratigraphy of Carboniferous and Permian units in the study area
| **Tempelfjorden group**  
| Late Permian | Kapp Starostin Formation | Silicified carbonate rocks and cherts |
| Gipshuken Formation | limestones, dolomites, dolomite breccias, anhydrite and gypsum |
| Wordiekammen Formation | limestones, dolomites |
| **Gipsdalen Group**  
| Mid-Carboniferous-Early Permian | Minkinfjellet Formation | sandstones, dolomites, limestones, dolomite breccias, **anhydrite and gypsums** |
| Ebbadalen Formation | limestones, sandstones, conglomerates, **anhydrite and gypsum** |
| Hultberget Formation | red sandstones and shales |
| **Billefjorden Group**  
| Early Carboniferous | Mumien Formation  
| Horbyebreen Formation | sandstones, shales, conglomerates and coal |

Figure 3- Stratigraphy of sedimentary rocks found in the Billefjorden Trough (Eliasson and Talbot, 2005; McCann and Dallmann, 1996)

Previous work documented the deformation and diagenesis of gypsum and anhydrite rocks in Spitsbergen (Eliassen, 2003a; Eliassen, 2003b; Holliday, 1967; Holliday, 1968; Harland, et. al, 1988; Lauritzen, 1976). Focus has been placed in on deposits of the Permian Gipshuken Formation, and to a lesser extent, on the Middle Carboniferous Ebbadalen and Minkinfjellet Formations. This paper is primarily concerned with the Middle Carboniferous evaporites found in Billefjorden Fault Zone. The current study area lies north and east of where prior work was concentrated. Holliday has documented anhydrite rocks that he regarded to be from primary growth and early diagenesis. He proposes a diagenetic sequence where primary gypsum grows within the host sediment followed by gypsum being dehydrated to secondary anhydrite, and lastly primary anhydrite growth within the host sediment and within the secondary anhydrite (Holliday, 1967). Harland et. al, 1988 also identified that, during a limited mining operation,
nanhydrite was encountered in the subsurface. In contrast to Holliday’s sequence, this study recognizes post-consolidation deformational features in the Middle Carboniferous sediments. Evaporites of Spitsbergen have also been reviewed in regard to solution breccia features (Schreiber and Helman, 2005; Eliasson and Talbot, 2005). This investigation proposes a timeline for the formation, diagenesis and deformation of the Middle Carboniferous calcium sulfate deposits in Spitsbergen, as it relates to Billefjorden Fault Zone activity. First some background on the behavior of anhydrite and gypsum will be presented before discussing the textures and evolution of evaporites pertaining to this investigation.

**Origin of Gypsum and Anhydrite**

This section focuses on marine derived calcium sulfate evaporites; gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}_{(s)}$), anhydrite ($\text{CaSO}_4_{(s)}$), the intermediate phase bassanite also known as hemihydrate ($\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}_{(s)}$), and the processes that convert one to another. Bassanite has been reported to temporarily exist in very hot, arid environments where water evaporates from surficial gypsums during the day, and at night the atmospheric moisture rehydrates the surface back to gypsum. The primary reaction of concern is $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}_{(s)} \leftrightarrow \text{CaSO}_4_{(s)} + 2\text{H}_2\text{O}_{(l)}$ (Hardie, 1967). Mechanisms of the reaction can be solid-state, dehydration or dissolution-reprecipitation (Holliday, 1967). Gypsum can be precipitated in nearly all realms of the marine environment. In the marginal marine region (fig. 4), gypsum is subjected to diagenesis at both near surface and deeper burial conditions. The dynamic environment contributes to multiple phases of textural and mineralogical changes that can be difficult to unravel (Hardie, 1967).

![Figure 4- Marginal marine depositional environments (Warren 1989).](image-url)

The gypsum-anhydrite system is complex. Brine composition, temperature and climatic conditions should be considered in detail when trying to interpret the genesis of a calcium sulfate deposit. Overlapping temperature-salinity conditions, along with ambiguous alteration features further complicate the interpretation process (Hardie et al., 1983). In addition, these alteration processes can occur multiple times. Depending on the burial depth, location within the basin and tectonic activity, gypsum may transform to anhydrite, transform back to gypsum and the process
can continue if conditions permit.

Three dominant factors that control evaporite formation and dissolution are ionic ratios, temperature and relative humidity. As water is evaporated the remaining brine becomes more concentrated in ions with respect to gypsum. Throughout the evaporation the ions continue to become more concentrated and increase the density and surface tension of the brine. Higher density brines can percolate down into underlying sediments, as well as remain in surface reservoirs (Murray, 1964). Within dense brines sunlight is refracted back into the water and increases the internal temperature (Schreiber et al., 2000). The presence of halophilic bacteria can also raise the internal temperature of the brine, thus perpetuating evaporation. Organisms like microbes are important in the dissolution of gypsum because they consume sulfate ions. As sulfate is taken out of the brine gypsum’s solubility increases and more sulfate ions enter into solution as an attempt for equilibrium. However, the presence of a common ion like Ca\(^{2+}\) in the brine can decrease the solubility of gypsum; such is the case when calcite is dissolving simultaneously.

The most common experimental sequence of precipitates derived from seawater is calcium carbonate first, then gypsum, halite and finally potassium and magnesium salts. As the sequence progresses the brine becomes increasingly concentrated (Warren, 1989). Figure 5 illustrates the range of temperatures and salinities where calcium sulfate minerals are stable. Ancient seawater from shallow seas did not have a constant composition like modern seawater. Variations in ancient seawater composition could be from the absence or fluctuations in seafloor spreading. The mid-ocean ridge works like a gigantic filter for the oceans and helps maintain a fairly constant composition. Rapid spreading rates cause seawater to be enriched in Ca\(^{2+}\) (Spencer, 2000). Seawater enriched with Ca\(^{2+}\) is indicated by widespread, ancient evaporite units that required persistent elevated salinities (Warren, 1989).

As stated above, climatic conditions like humidity and pressure affect gypsum’s solubility too. Arid to semi-arid environments favor evaporite precipitation (Schreiber, 1988). Generally, gypsum precipitation is favored in locations of lower air pressures, lower temperatures and lower salinities relative to other salts (Warren, 1989).
Early work on calcium sulfates focused much attention to which mineral, gypsum or anhydrite was precipitated first. Recent publications by Schreiber, 2000; Shearman, 1983; Warren, 1989; Hardie, 1967; Murray, 1964 agree that gypsum is precipitated first within both the gypsum and anhydrite stability fields (fig. 5). These thoughts contrast with many early publications by MacDonald, Posnjak and Van’t Hoff. Posnjak (1938) summarized all prior work and attempted to determine the realm of gypsum stability by dissolution. He concluded that in pure water above 42ºC, anhydrite is more stable and will be precipitated. Increasing the salt concentration lowered the transition temperature for gypsum to become stable anhydrite, but at temperatures around 60-80ºC metastable gypsum was precipitated.

Later work by Hardie is viewed to be reliable because the results were achieved from reversible reactions carried out in the lab instead of reactions that approach equilibrium.
conditions from only one direction. In addition to that, there are remaining uncertainties in the thermo-chemical data that were utilized in earlier efforts. Hardie, 1967 confirmed that within the temperature and salinity conditions for anhydrite to be stable, metastable gypsum was actually being precipitated.

Conely & Bundy provided additional support for gypsum being the dominant calcium sulfate mineral precipitated at the surface. They found that the transition from gypsum anhydrite + water was very slow or non-existent below 42°C, but certain salts can catalyze the hydration process. Speeding up this reaction would favor the transition from gypsum to anhydrite. Therefore, even if anhydrite was precipitated in seawater it would quickly convert to gypsum because effective activators like K and Na are present.

These experiments treated the transition from gypsum to anhydrite at atmospheric pressure to be a function of temperature and activity of H₂O only. Hardie suggests that gypsum is always the primary precipitate of calcium sulfate based on new, higher equilibrium temperatures derived experimentally and from observed recent evaporite deposits. Richter, 1961 also states that primary precipitation of anhydrite from seawater is inhibited because of the abundant activating cations in the seawater. Warren, 1989 argues against primary anhydrite precipitation in modern evaporites because the observed elevated humidity is detrimental for the preservation of anhydrite.

Even though Hardie’s model provides a simple resolution for recent evaporite deposits, it doesn’t account for ancient environments where gypsiums are found outside of equilibrium conditions or where anhydrite is present at the surface (Klimchouk, 1996).

**Depositional Environment**

One depositional setting of the marginal marine environment is the coastal sabkha, or salt flat. Evaporite deposits in the Billefjorden Trough have been attributed to a marginal marine depositional environment. Early work described the environment as something between the continental red beds and the marine carbonates, but later work has narrowed the environment to be a sabkha (Harland, 1988; Holliday, 1967 &1968). From work in the eastern portion of the current study area, the Minkinfjellet evaporites were characterized to be from a peritidal to shallow subtidal environment with fluctuating depositional energy, salinity and oxygen levels. This area could have been sub-aerially exposed periodically too (Lonoy, 1995). A coastal sabkha is a subaerially exposed mud flat that is intermittently covered with shallow water. Formation of marine evaporites, such as gypsum, is attributed to periods of exposure. The name ‘sabkha’ is Arabic and derived from the first noted locality in the Persian Gulf.

Three common facies that comprise typical marginal marine setting are the subtidal, intertidal and supratidal sabkhas. These are characterized by marine sediments and marine derived groundwater. Evaporites of the Minkifjellet Formation are believed to have formed in both the supratidal setting as well as in subaqueous settings such as lagoons or salinas. This interpretation was based on a dolomitization analysis of the underlying carbonates (Eliasson & Talbot, 2003). Calcium sulfate minerals form displacively and replacively in these realms. In the capillary zone above the saline groundwater brine is drawn up-ward, evaporates and intrastratal gypsum forms (Warren, 1989). These crystallize as individual crystals, isolated nodules or clusters of nodules. Displacive growth causes a demand for space, and the nodules of gypsum will coalesce to form layers. With continued growth the layers become contorted and can lift the surface of the sabkha above the vandose zone to create an erosional surface (Murray,
Understanding the deposition of calcium sulfate and its textures is difficult to do without mentioning the possibility of concurrent diagenesis. Most sabkha deposits are represented by nodular, chicken wire, microbial laminae and stromatolite forms of sulfates (Kasprzyk, 2005). The next section will introduce the three common diagenetic environments that are widely agreed upon for the transition of gypsum to anhydrite. Syn-depositional (A), early (B) and late diagenetic (C) processes can pervasively or randomly affect a gypsum deposit. Variation on the extent of diagenesis depends on the type of the deposit, nodular or laminar. Components of the gypsum-anhydrite diagenetic process are dehydration, cementation and compaction. Later exhumation can cause mineral and textural changes by rehydration and re-crystallization. Differentiating the timing of diagenesis can be difficult because deposits may have been affected in all environments (Kasprzyk, 2005). This paper will follow the distinction of early diagenesis...
from late diagenesis made by Lowenstein, 1990 despite the equivocal distinction between primary and secondary features of calcium sulfate rocks. Syn-depositional (A) and early diagenesis (B) occur from similar processes that reflect the current depositional environment. The difference between the two diagenetic localities is based on minor textural characteristics resulting from variable degrees of cementation and compaction. Late diagenesis reflects the subsurface environment and is characterized by very different processes and textures than the shallow environment (Lowenstein, 1990).

**Syn-depositional and Early Diagenesis (A-B)**

Solution-precipitation is process that is characteristic of syn-depositional or early diagenesis. Hardie and other (1967) authors mention metastable gypsum or gypsum deposits that fall outside of the equilibrium range. Solution-precipitation process dissolves the metastable gypsum and subsequently precipitates anhydrite. Driving mechanisms for shallow alteration are the dolomitization of surrounding carbonates and dissolution of surrounding aragonites (Klimchouk, 1996).

The diagenetic process of solution-precipitation starts within gypsum crystals by dissolving cave-like hollows where anhydrite crystals loosely accumulate. The anhydrite crystals will grow and form rough pseudomorphs of the gypsum crystal. As anhydrite crystals continue to form, the nodule expands and forms a new nodular mass that does not resemble the gypsum precursor (Shearman, 1983).

Contradictions exist regarding the chicken-wire texture (figure 7) and whether it is a diagenetic or primary feature. According to Hussain, chicken-wires are generated by the primary displacive growth of gypsum and from the diagenesis of gypsum to anhydrite. The process of nodule formation can be perpetuated through syn-depositional and early diagenetic growth to create larger and/or coalescing nodules of both gypsum and anhydrite. Gypsum nodules can precipitate on layers already rich in gypsum (Hussain, 1989). In primary nodular growth the wire material is typically carbonate, or whatever lithology the gypsum displaces. Yet Schreiber notes transition from gypsum to anhydrite by solution-reprecipitation is often characterized by chicken-wire textures. As anhydrite crystallizes the dissolved carbonate mud and other original impurities are pushed out and form a film around the anhydrite nodules (Schreiber, 1988). Later Schreiber notes that the coalesced nodules and enterolithic beds can be either gypsum or anhydrite (Schreiber et. al, 2000). Holliday, 1967 says that diagenetic chicken-wire can preserve both lines of carbonate or lines of darker gypsum or anhydrite. The dark gypsum and anhydrite is thought to be from replacement of the carbonate.

Shearman, 1983 also attributes extensive nodular growth to syn-depositional diagenesis because of the availability of Ca and SO₄ ions in the nearby brines. This process has been described as self-perpetuating growth. If there is intergranular movement of anhydrite crystals before consolidation, new nuclei can be generated from the crystal collisions. Expansive nodule growth is attributed to new crystals nucleating inside older nodules, as well as nodules forming in the spaces from dissolved gypsum. Coalesced nodules and contorted layers, called enterolithic veins, are common structures because of the ease of intergranular deformation due to grain shapes and the moisture of nodules in the near surface environment (Shearman, 1983).

As stated above, Murray recognized that gypsum forms displacively with in soft sediments and nodules can coalesce, but he also states that nodular anhydrite is characteristic of sulfate rich waters evaporated out of subaerially exposed soft sediment (Murray, 1964).
Figure 7-Nodular growth of calcium sulfate in Spitsbergen.  A&B) Typical primary chicken-wire texture with both weathered and fresh surfaces.  C) Coalescing growth of nodules to form larger nodules.  D) Coalescing growth of nodules to form beds of calcium sulfate.

Petrography is especially helpful to interpret the timing of diagenesis and deformation of calcium sulfate deposits. In thin section, diagenetic anhydrite generated syn-depositionally forms a loose conglomeration of small, high bi-refringent platelets (Shearman, 1983; Holliday, 1967). The arrangement of the grains can be variable, but bent, broken, intersecting and aligned grains are common. Crystal deformation results from early compaction and expansive growth before lithification. There is a strong tendency for crystals to align subparallel to the margin of the nodule. Textures of intersecting crystals have also been called felted, interwoven laths in an irregular and unoriented fashion, and fascicular, crystals that resemble a bundle (Kasprzyk, 1998). Single crystals with rounded euhedral terminations is also a trait of syn-depositional dissolution (Hardie, 1983).

There is a gradual change between syn-depositional and early diagenetic features so it is difficult to place a boundary between the environments. The degree of gypsum compaction and cementation at the time of anhydrite formation is the most distinguishable characteristic. Early diagenetic processes occur after the gypsum has been precipitated, but before it has been substantially buried. The implications of anhydrite pseudomorphs after gypsum are disputed among a few authors. According to Shearman, 1983, pseudomorphs suggest early diagenesis, yet Hardie, 1983 regards pseudomorphous replacement to be an ambiguous feature. Kasprzyk, 1998 suggests that poor preservation of pseudomorphs indicates very early diagenesis.

Pseudomorphs cannot discern early from late diagenesis without additional evidence, but information about deformation can still be inferred without knowing the timing of replacement (Hardie, 1983). Irregularly distributed anhydrite masses within gypsum are also common. Compared to textures of syn-depositional diagenesis, textures of early diagenesis will have fewer signs of mechanical breakage because the onset of cementation provides strength to the framework grains (Kasprzyk, 2005; Shearman, 1983).

Replacement of gypsum occurs preferentially along cleavage planes, crystal boundaries and relict growth surfaces. The extent of replacement also depends on the deposit’s location within the basin and the tectonic history. Late diagenesis occurs as a response to increasing temperature and pressures during burial, as opposed to earlier diagenesis responding to conditions of the depositional environment (Schreiber, et al, 2000).

Late Diagenesis (C)

Interpretation of late diagenesis to anhydrite is difficult because the change is unobservable and the change lacks any definitive textures. Shearman has speculated a sequence of events for burial diagenesis: Initially, the stable framework of gypsum deteriorates and destroys any sign of primary bedding. (Shearman, 1983). Then a crystal mush of anhydrite and water forms as water is driven from gypsum grains. With progressive compaction, the crystals would pack tighter and possibly break. The compaction slows as the pore pressure increases. There is also a possibility of the anhydrite crystal mush fluidizing and redistributing all the anhydrite crystals and impurities (Shearman, 1983). According to Kasprzyk, at the depths required for late diagenesis, the deposit would have no effective permeability. The high overburden pressures can cause the sulfate sediments to fluidize. Intense folding and hydroplastic deformation could destroy any previous lithologic features (Kasprzyk, 1998).

Suggested features attributed to late diagenesis are very different crystal fabrics than
fabrics associated with earlier diagenesis. Polygonal mosaic texture results from annealing recrystallization as grains try to minimize energy by optimizing their size and shape. Modest burial can generate this texture, but the distribution may be patchy (Hardie, 1983). Anhydrite crystals have been described as more elongate laths that have a tendency to split along their length and fan in one direction. These arms formed from splitting crystals are typically broken where split occurs rather than continuous. Textures of crystals pressed against and/or into one another, similar to pressure dissolution, are suggestive of late diagenesis (Shearman, 1983).

**Transition**

The burial of gypsum and the late transition to anhydrite is accompanied by a 38% volume loss (Kasprzyk, 2005; Shearman, 1983). Values for volume changes vary throughout the literature, but other reports have remarked that the transition from anhydrite to gypsum is at least a 50% volume increase (Schreiber and Helman, 2005). The delayed compaction suggested by Sheaman would cause a delayed volume reduction. Ancient beds of anhydrite are estimated to represent approximately 1/3 of the original gypsum depositional thickness. Volume reduction still occurs even if diagenesis is syn-depositional through re-packing of loose anhydrite crystals within the nodules. Anhydrite from the subsurface has been recognized to have no pore space (Shearman, 1983). Continued compaction and dissolution of evaporites in a basin perpetuates and increases subsidence even long after tectonic activity has ceased (roundtable abstract).

Figure 5 shows generalized temperatures and depths for gypsum dehydration. Transition temperatures and depths typically start at, but are not limited to, 60°C and 1900 feet below ground surface. With depth, the temperature increases because of the geothermal gradient is commonly recorded as shallow as 200 meters depth, but the transition depth has also and the pressure increases because of overlying deposits (Warren, 1989). Variations in transition depth do exist. In the Badenian Basin, primary gypsum transforming to anhydrite been recorded at 400-500 meters depth (Kasprzyk, 1998). The transition also depends on salinity of pore fluids and the deposits location within the basin. The center of the basin typically has the highest salinity pore fluids and has the most overburden, where as the basin margins have more dilute pore fluids and aren’t buried as deep (Kasprzyk, 1998). As gypsum is buried, water is driven off and the volume is reduced by about 38%. The porosity is decreased from the tighter packing of crystals too. Depending on surrounding lithologies the expelled water may be able to escape, may increase pore pressures resulting in slowed compaction and dehydration in addition to possibly fluidizing the bed (Shearman, 1983). Burial alteration usually destroys most primary textures depending on the extent of replacement and recrystallization. The same step-wise path is taken in reverse to rehydrate anhydrite to gypsum upon exhumation by saturation from surface waters, high humidity or from storm events (Hardie, 1967).

**Deformation**

It is obvious that determining the diagenetic evolution of gypsum and anhydrite is very complex, and textures of different diagenetic episodes are difficult to discern. Deformational textures also contribute to the difficult interpretation by overprinting primary and/or secondary textures. Deformational textures have also been misinterpreted as sedimentary structures. Viscous flow, foliation development and recrystallization of evaporites occur at much lower temperatures than other rocks. Factors that determine the deformation of sulfates are mainly temperature and presence of water, and to a lesser extent average crystal size and the amount of surplus water within the rock (Schreiber and Helman, 2005). The salinity of the pore fluid can effect time-dependent deformation since processes like intergranular pressure solution may control the behavior of flow and compaction in evaporites (de Meer and Spiers, 1999). This
factor is important to evaporite deposits that contain high salts like halite and sylvite, but may not be as pertinent to this investigation because only gypsum and anhydrite have been documented in the study area.

From experimental data, recrystallization of fine-grained anhydrite starts around 120°C and, under typical geologic strain rates of $10^{-14}$/second, flow occurs at 150-180°C. Anhydrite has been observed in the field to start deformation and recrystallization at nearly 80°C (Schreiber and Helman, 2005). Deformation features seen at the outcrop scale are isoclinals folds, intrafolial folds, deformed nodules, boudins, porphyroblasts and augen-like clasts (Helman and Schreiber, 1983). In the Eureka Sound fold and thrust belt, deformation has caused nodular anhydrite to coalesce and resemble layering (Schwerdtner, et al. 1988). Textures characteristic of evaporite deformation are similar to ductile deformation textures of other lithologies. Deformation twins, slip lines, slip bands, undulose extinction, bent cleavage and foliation are all indicative of intragranular deformation (Hardie, 1983). Textures of aligned, prismatic anhydrite crystals that are nearly equant in size and lack signs of mechanical breakage are interpreted to be from recrystallization. Equant polygonal grains, associated with recovery recrystallization, are common as well as foliation and mylonitic fabrics (cite). Structural features of the gypsum and anhydrite layers are affected by the variable amount of brittle components they contain (Lugli, 2001).

Gypsum and anhydrite are incompetent compared to the more rigid lithologies they are usually associated with. The more competent rocks associated with sabkha deposits usually show signs of brittle, cataclastic flow, whereas the associated evaporites flow viscously around the fragments. Fragments vary in size and often show signs of sliding and rotation. Schreiber and Helman describe a site from Tuscany where there is comminution of brittle rocks within the evaporites.

The thickness of the associated bed in proportion to the thickness of the evaporite bed is a factor in the amount of deformation displayed. Thin beds of carbonate are commonly more deformed than thick beds, but can sometimes more competent beds look completely undeformed while between the evaporite layers are deformed (Schreiber and Helman, 2005). Lugli documented dolostones of the Burano Formation as disrupted beds with boudins. Pulverization of thin dolostone layers created clasts on the same scale as single crystal components (Lugli, 2001). Fine-grained fragments can accumulate along shear planes giving the appearance of a sedimentary deposit. Another interesting note on the fragment size is that a uniform fragment size has been recorded for evaporites that deformed at temperatures above 180°C (Schreiber and Helman, 2005).

**Methodology**

Field work for this study was conducted during the summer of 2007. Primary research focuses on the 31 samples that were collected to reflect the wide variety of textures seen in outcrops. Most of samples were in-place and marked with orientation notations of strike and dip, as well as a north arrow. Samples with textures most representative of those seen in the field were chosen for thin section preparation. 27 thin sections were made by Spectrum Petrographics and examined with conventional optical methods. Other orientation data such as bedding, fold axes, foliations and elongation lineations were collected using the right-hand rule. Data was entered into an existing ArcGIS database of the Billefjorden Trough and surrounding areas, which was used to complete a query for locations with measurements of bedding & foliation pairs and bedding & fold axis pairs adjacent to the Billefjorden Fault Zone. These results were
extracted and used for further analysis in StereoWin, a stereographic projection program (Allmendinger, 2006). Assuming simple shear contributed to the formation of asymmetric folds and bedding-oblique fabrics; orientations of intra-bedding fold axes and bedding-foliation intersections in the shear plane were plotted on the stereographic projections as kinematic indicators. Reorientation was considered and is addressed in the results. All the shear indicators (elongation lineations, pairs of bedding/foliation and pairs of bedding/fold axes) were plotted as vectors on the ArcGIS map for further analysis of the spatial distribution of local transport directions.

**Results**

Gypsum and anhydrite occur in thick sections of the Middle Carboniferous Ebbadalen and Minkinfjellet Formations within the Billefjorden Fault Zone. Exposures display a range of textures such as laminated beds, isolated nodules within carbonate material, thick sequences of chicken-wire textures, and variably thick sequences of foliated and lineated material. Primary gypsum textures, diagenetic anhydrite, rehydrated secondary gypsum and deformational textures were all observed either in the field or in thin section. The focus here is on the deformation and late diagenetic textures.

**Primary Growth Features**

Primary growth of gypsum is hard to distinguish at the outcrop scale for various reasons: gypsum and anhydrite are difficult to separate and gypsum is often physically and/or chemically altered shortly after deposition. Features that are thought to be characteristic of primary growth, but which may have undergone alteration only visible at the micro-scale, are both chicken-wire and isolated nodular growth, enterolithic folds and bedding (figures 7, 8).
Figure 8- Features developed during the deposition of gypsum in the marginal marine environment. A) Finely laminated bedding of gypsum/anhydrite rocks. Darker bands are likely carbonate material or organics. Preservation of such primary laminations provides some constraints on the degree of subsequent diagenesis and deformation. B) Band of nodular gypsum/anhydrite that tapers towards the top, the direction the fluids evaporated during deposition. C) Contorted fold (enterolithic) of coalesced gypsum/anhydrite nodule formation.

**Solution Related Features**

Features thought to be associated with pressure solution are nodules or accumulations of nodules that have sharp basal contacts and/or sharp top truncations against carbonate material. Nodules also appear flattened and oblate from compaction (figure 9).

Figure 9- View facing east of a shoreline outcrop on the east side of the fjord. Layers of oblate gypsum/anhydrite nodules bound by sharp truncation surfaces, interpreted as pressure solution surfaces. Red lines indicate the approximate position of two truncation surfaces. Also note that the carbonate material is draped above and below some of the nodules.

**Deformation**

Deformation textures observed at the outcrop scale includes a range of fabrics that grade from slightly deformed, oblate nodules to mylonitic fabrics where foliation is oblique to the
enclosing, undeformed carbonate beds (figure 10A). The boundaries of some deformed nodules appear to flatten out and connect as the nodules are sheared. Coalesced boundaries appear transposed parallel to bedding, superficially resembling the laminae of host rock (figure 10F). Due to its incompetent character, gypsum readily preserves folds and foliations from multiple deformation events. Assymetrical porphyroclasts of selenite occur in more deformed exposures (figure 10E). The foliation wraps around the porphyroclasts and with distance from the selenite the tail thins and become concordant with the foliation.

Thin beds of carbonate within the deformed evaporites also show signs of deformation. The competency difference between evaporites and carbonates resulted in brittle fragmentation of carbonate material while the surrounding evaporites viscously flowed around the clasts or beds. In some samples, there is a trail of ground carbonate that has been torn from a larger clast. The grain size of the carbonate trail appears to decrease with increasing distance from the larger clast (figure 13E).
Figure 10- Outcrop photos of deformational features of the gypsum and anhydrite rocks of the Billefjorden Fault Zone. A) View to the north where gypsum beds are highly deformed with fold vergence down to the east from layer parallel displacement. Foliation is oblique to interbedded dolomite (blue lines). Axial planar cleavage is also developing at the hinges of the asymmetrical folds (red dashed lines). B) View to the south of mylonitic-like fabric of gypsum/anhydrite layer viscously deforming down to the east. Bedding strikes approximately north. C) View west of cross section of a possible up-right fold limb of a sheath fold. On the outer edges of the photo are oblate evaporite nodules within carbonate. In the center of the photo is a highly deformed evaporite bed with foliation ($S_1$) and crenuation cleavage ($S_2$) developed. Just above the gun case is fold with opposite vergence from the smaller crenulations to the right. D) Close-up view of polyphase deformation. Evaporite shear fabric, foliation (blue) and cleavage (red), being crenulated. Yellow arrows indicate relative sense of motion. E) Augen-like clast of selenite within deformed gypsum/anhydrite fabric. F) Boudinage of more competent lithology within gypsum/anhydrite rock. The arrow towards the bottom of the sample points along the transposed nodule boundaries that could eventually resemble bedding. G) View north of outcrop with oblique foliation that is consistently shallower than bedding. H) View facing southeast of the north slopes of Pyramiden. Here a branch continuation of the Odellfjellet Fault cuts through layers of the Carboniferous Billefjorden Group and some of the Ebbadalen Formation where it bends and flattens out to become parallel to bedding. Dashed lines are just below traceable layers that bend into the steep portion of the fault zone. I) View to the northwest of east slope of Svenhogda. This slope is hundreds of meters to east (basinward) of the slope in 10H.
Alternating layers of carbonate and evaporates are dipping down to the east. There is a large normal fault buried in the scree between the Ebbadalen Formation (east) and the Billefjorden Group (west). Also, the dashed orange line in the background indicates a large offset on the Billefjorden Fault Zone where Carboniferous sediments are adjacent to basement rocks.

**Kinematic Indicators**

Gypsum and anhydrite rocks that underwent deformation display shear zone textures provide kinematic indicators of the movement history of the Billefjorden Fault Zone. Large folds, minor crenulations, foliated and lineated fabrics were used for structural analysis. The majority of kinematic indicators found in show dominant normal dip-slip motion with a minor dextral component (figure 11). The lower map illustrates an area with local variations in bedding orientation and kinematic indicators.
Figure 11- Maps of Billefjorden Fault Zone with kinematic indicators of fault related transport directions including; elongation lineations (red), bedding/foliation intersections (purple) and intrafolial fold axes/bedding intersections (blue) (Nanfito & Maher, 2008). Top map is of the entire length of the fault zone where structural fabrics were measured. The yellow box indicates the area the lower map is from.

Previous work has indicated that the gypsum and anhydrite horizons are an important factor in the high angle normal faulting that developed the architecture of the rift basin. The beds act as detachment zones for layer parallel slip, fault flats and participate in complex tri-shear zones. Dip slip motion is dominant, but a basin parallel strike-slip component does exist and varies along strike. Initial kinematic results from the southern end of the BFZ appear complex because of the complex history and the presence of both compressional and extensional features (Nanfito & Maher, 2008). Evidence of reverse reactivation is seen in few up-dip folds that fold the earlier rift related foliation (figure 10C, D).
Soft sediment deformation within sulfate deposits occurs as a result of nodules coalescing, displacing uncemented host sediment, and often forming very convolute structures. The environment must have a sustained supply of sulfate as well as consistent evaporation. Crystals of either gypsum or anhydrite are lubricated by near surface brines and are easily able to deform intergranularly (Schreiber & El Tabakh, 2000; Shearman, 1983). Distinction between soft sediment deformation and later deformation in samples from the Billefjorden Fault Zone is based on the behavior of the host carbonate material and the fabric of the sulfates. In soft sediment deformation, carbonate fabrics are more penetrative, ductile behavior, and evaporites deform inter-granularly (figure 12)(Shearman, 1983). Deformed carbonate material exhibits more brittle behavior from post-consolidation flow, whereas the calcium sulfates are dominated by either re-crystallization or intra-granular deformation.

Samples from the Billefjorden Fault Zone with soft sediment deformation show deformed nodules with gypsum-anhydrite laths that tend to align parallel to the plane of flattening and/or shearing, aligned to form folds sometimes aligned sub-parallel to the margin of the nodule. The oriented laths also outline small folds at thin section scale (figure 12A). In folds, the laths are stacked to form a curve in aggregate instead of the individual grains actually bending. Whole nodules comprised of many crystals often have an elongate, irregular appearance.
Figure 12- Thin section photos of interpreted soft sediment deformation textures. A) Deformed, oblate nodules of anhydrite and gypsum with crossed nichols and gypsum plate in. Nodule boundaries within red circles appear to be cognate. B) At the base of the carbonate seam there is local inter-granular deformation developing a fold. This thin section is from an enterolithic style fold in plain light. C) Deformed carbonate material that in-filled a desiccation crack or shallow vein. Surrounding material is predominantly anhydrite. Photo without gypsum plate. D) Deformed carbonate layers creating asymmetric folds and convolute bedding in plain light.

Fault Related Ductile Deformation

In thin section, observed deformation fabrics of gypsum and anhydrite are analogous to metamorphic textures, even though the adjacent carbonates are unmetamorphosed. Primary bedding within the highly deformed gypsum and anhydrite rocks is absent, instead penetrative crystalline fabrics exist. Evidence of primary bedding was preserved by carbonate layers. Fabrics of elongate oriented grains define foliations and crenulations, and polygonal grain boundaries with 120° junctions were all found in samples from the Billefjorden Fault Zone. Other signs of intra-granular deformation were the development of periphery sub-grains and extensive undulose extinction. Micro-boudinage, fragmentation and rotation of the carbonate grains were also seen in thin section. Another indicator of deformation was the development of selenite porphyroblasts. The selenite porphyroblasts typically had sutured grain boundaries within them and sub-grain development on their periphery. Figure 13 shows images of thin
sections that are most representative of ductile fault related deformation.
Figure 13- Fault related deformational textures and features in gypsum-anhydrite rocks.  
A) Crenulated gypsum fabric with brecciated carbonate grains adjacent to the larger ‘source’ clast.  
B) Sheared gypsum fabric around porphyroblasts with sub-grains. Foliated fabric is flowing 
around the clasts and there is evidence of pressure shadow development adjacent to the clast on 
the right border.  
C) Polygonal fabric of gypsum. Fairly equigranular grains with 120° junctures 
and both flat and concavo-convex grain boundaries. Undulose extinction is also present.  
D) Shear fabric around a porphyroclast with brecciated carbonate grains along the preferred grain 
orientation. Porphyroclast has a serrated grain boundary within it, and sub-grains developing on 
the periphery. It may be rotated.  
E) Fragmented carbonate material parallel to the preferred 
orientation of the gypsum shear fabric. Note the finer grained size of adjacent gypsum grains.  
F) Gypsum shear fabric developing around a carbonate grain. Portions of carbonate material were 
torn away from the larger grain (within red oval).  
G) Internally deformed gypsum grains exhibiting undulose extinction, most visible at top of photo. Fabric is also being replaced by 
higher birefringence anhydrite as well as cloudy secondary gypsum.  
H) Anhydrite pseudomorphic after gypsum with a preferred grain orientation. Note that the anhydrite crystals 
are unstrained and subhedral and are therefore postdepositional. From strain face near the 
Lovehovden Fault without gypsum plate.  
I) Anhydrite partially pseudomorphically replacing gypsum in a fold. More distinct grains are anhydrite and cloudy grains are secondary gypsum.  
Fine grained carbonate material is also being folded. From strain face near the Lovehovden 
Fault and with gypsum plate in.
Prograde Diagenesis

Features of prograde diagenesis were also observed in thin section samples from the Billefjorden Fault Zone. Prograde diagenesis occurs when anhydrite replaces gypsum due to burial. In thin section, anhydrite has a higher birefringence so it is easily discerned from gypsum, but this distinction was not recognized in the field. The relative timing of anhydrite forming after gypsum is based on observed anhydrite grains cutting across gypsum grain and fabric boundaries. Most anhydrite pseudomorphed both the grain shape and orientation of the original gypsum grain (figure 14), but some grains have a clear overprinting relationship.

The pseudomorphing character of anhydrite also preserved earlier deformational fabrics of gypsum. In areas where the original gypsum had a preferred grain boundary orientation, the later anhydrite grains developed with the same orientation. The degree of anhydrite replacement is locally variable so some samples are complete anhydrite, while others retain much of the precursor gypsum.

In addition to variable degrees of replacement, there was variation in the shapes and fabrics of anhydrite grains. Samples with more deformed precursor gypsum the anhydrites tended to develop lath shaped anhydrite grains. Other anhydrite grains had raggedy grain boundaries and a few anhydrite grains were very square shaped and cut across other anhydrite grain boundaries (Fig. 14d). The lath shaped grains tended to be decussate, felted and sometimes radiating. Some of the packages of felted anhydrite grains were sub-parallel to either carbonate material or a band of gypsum. Samples with decussate and radiating anhydrite laths had multiple nucleation sites for these packages. Most samples showed a combination of at least two of these fabrics.
Figure 14- Thin section images, without gypsum plate, of anhydrite replacing gypsum. A) Anhydrite grains pseudomorphing a folded gypsum fabric. B) Felted anhydrite laths replaced aligned gypsum grains. Note some anhydrite grains sub-perpendicular to the gypsum fabric in center left portion. C) Anhydrite laths psuedomorphically replacing deformed gypsum fabric. Laths are sub-parallel to folded carbonate material. D) Large euhedral anhydrite crystal overprints gypsum fabric and possibly other anhydrite grains. E) Crenulated gypsum fabric pseudomorphically replaced by anhydrite. F) Deformed gypsum laths (undulose extinction and subgrains and lower birefringence) replaced by smaller anhydrite laths. G) Sample that is dominantly anhydrite with a chaotic arrangement, or decussate texture. No carbonate material is present, but there does seem to be an earlier fabric partially preserved oriented diagonally across the photo.

Textures associated with Retrograde Diagenesis

In addition to gypsum being deformed and diagenetically altered to anhydrite, it can be rehydrated back to gypsum. Rehydration is observed as gypsum rounding anhydrite grain boundaries preferentially along cleavage planes (figure 15C). Secondary gypsum is also texturally different than primary gypsum (Schreiber and El Tabakh, 2000). Similar to prograde diagenesis, evidence for retrograde diagenesis in the study samples also varies locally. Samples with a complex history often show signs of deformation with both prograde and retrograde diagenesis overprints. Anhydrite’s pseudomorphic behavior is distinctly different from most of the secondary gypsum fabrics. Secondary gypsum forms as a result of anhydrite being rehydrated. Rehydration is incomplete and concentrated along cleavage, certain shear planes and adjacent to carbonate fragments (figure 15 B,D-F). Deformation is still obvious in these sections due to the fact that rehydration was not pervasive.

There are distinct textures associated with rehydration. In these areas the secondary gypsum has indistinct grain boundaries and a cloudy appearance. There are areas of the secondary gypsum that have the same lattice orientations, but any boundary between these areas is unclear (figure 15D). Grains that are being rehydrated have semi-parallel linear areas that partition the original grain. In other areas the rehydration areas form bands that are bound by anhydrite laths oriented sub-parallel to the band. Thin sections with a deformational fabric have rehydration concentrated in bands adjacent to deformed carbonate material, but parallel rehydrated bands also develop when there is no carbonate present. These bands look like they mimic the deformational foliation. Most thin sections characterized by polygenetic textures have rehydration occurring along all three features: cleavage, shear zones and adjacent to carbonate (Figure 15).
Figure 15- Thin sections with signs of rehydration. Anhydrite has high birefringence, gypsum has low birefringence and carbonate is often fine-grained and semi-opaque. A) Both decussate and aligned anhydrite laths with rehydrated secondary gypsum concentrated along carbonate material. Crossed Nichols with gypsum plate in. B) Sub-parallel bands of cloudy, ameboidal secondary gypsum with some rounded anhydrite grains inside the bands. Crossed Nichols with gypsum plate in. C) Rounded anhydrite fragments being cut by rehydration. Now isolated fragments are optically continuous, and represent an originally intact larger anhydrite grain. Gypsum plate in. D) Cloudy, ameboidal secondary gypsum concentrated around carbonate material with anhydrite laths on the perimeter. Notice below the carbonate band the indistinct boundaries between areas of secondary gypsum with different lattice orientations. Crossed nichols without gypsum plate. E) View of same area as D to show the relationship of the carbonate with the indistinct gypsum and more defined anhydrite laths. In plain light. F) Rehydrated gypsum concentrated along a possible shear zone. Shear fabric in anhydrite laths is more developed along the lower contact. Sample from the Lovehovden Fault without gypsum plate in.

Discussion

Are primary early diagenetic textures preserved?

Primary and early diagenetic features of marginal-marine gypsum are highly variable because of rapid facies changes in the depositional environment. In the Billefjorden Fault Zone, features such as bedding and nodular growth are interpreted to represent the depositional environment based on analogous features found in modern sabkha environments, but these features may have undergone diagenesis that is only visible at the micro-scale. In thin-sections diagenetic textures are preserved, but most have been destroyed by deeper diagenesis and deformation. Syn-depositional diagenesis is said to occur prior to cementation and create loose aggregates of the anhydrite laths (intersecting & aligned) and as a result of compaction these are seen to be mechanically broken (Shearman, 1983; Hussain, 1989). There are thin-sections with loose aggregates, but no mechanical breakage (figure 14G).

Laminated gypsum-anhydrites have been correlated with both the base of a sabkha cycle, sub-tidal zone, and top of the sabkha, the supra-tidal zone or tidal flats. Sub-aqueous deposition in the sub-tidal zone creates layers that may represent annual cycles (Schreiber and El Tabakh, 2000; Hardie, 1970). Deposition on top of the tidal flat is thought to be a result of storm deposits. Analysis of grading and the composition of the interbedded material can distinguish the type of deposit (Hardie, 1970). Light colored layers are originally gypsum and the darker layers are carbonate or organic material. Micritic interbeds support the presence of algal binding (Hussain, 1989; Hardie, 1970). In-depth analysis of the depositional environment within the sabkha cycle was not reviewed for laminated gypsum-anhydrite samples in this study.

Other forms of bedding occur when nodules begin to coalesce and sometimes form contorted beds. Coalesced beds are typical of the capillary zone as long as sulfate rich waters are available in order for precipitation to continue. Depending on the availability of sulfate enriched waters and the rate of evaporation, nodules can be isolated, enlarged, form mosaics of nodules or coalesce to form layers. Textures evident in figures 7 and 8C are interpreted as mosaics of nodules that have coalesced to form layers. The structures can be composed of either gypsum or anhydrite depending on if and when diagenesis affects the deposit (Schreiber and El Tabakh,
Syn-sedimentary diagenesis probably had only a minor role because crystal deformation from early compaction was not observed, but signs of early diagenesis seemed to correlate with samples of soft-sediment deformation (figure 12). Evidence of diagenesis beginning early was seen in samples with characteristic felted and fascicular anhydrite laths (figure 14G) (Kasprzyk, 1998, 2005). These grains appear to have a chaotic arrangement, yet lack evidence of mechanical breakage from early compaction, thus some cementation was complete before burial diagenesis started (Kasprzyk, 1998, 2005; Shearman, 1983). Early diagenesis may have occurred with only a small volume change allotting more space for an irregular arrangement of anhydrite laths to develop.

Shearman (1983) reported a tendency of syn-depositionally altered anhydrite crystals to align sub-parallel to the margin of the nodule in modern sabkha environments. Anhydrite laths sub-parallel to nodule margins and bedding have also been reported in syn-depositionally altered deposits, but these crystals all show effects of breakage from compaction (Kasprzyk, 1998). Other instances of aligned anhydrite laths occur within soft sediment deformation (Schreiber and Helman, 2005). In thin sections from the Billefjorden Fault Zone there are aligned anhydrite laths that pseudomorph a deformed gypsum fabric without crystal breakage (figure 14A-C, E). If the alignment was a result of early diagenesis, we would expect most laths to be broken and aligned only at the margins of the nodule and/or bed. In samples with evidence of soft sediment deformation from the Billefjorden Fault Zone, the laths are aligned along nodule margins, beds and folds, but have little indication of mechanical breakage (figure 12A-B). The samples may be a result of early diagenesis followed by soft sediment deformation and compaction. One possibility is that lithification occurred quickly after soft sediment deformation. The inter-granularly deformed anhydrite laths were protected from early compaction by the lithified host sediment, but signs such as pressure solution would indicate later compaction too. This possibility may be consistent with samples with soft sediment deformation from the Billefjorden Fault Zone that have more isolated nodules and/or more carbonate compared to evaporite (figure 12). Another possibility for producing aligned crystals without deformation would be if loosely packed anhydrite laths reorient themselves during compaction, but this process would be fairly inefficient. Instead, parallel lath orientation maybe the result of stress controlled growth where the seeds of a certain orientation relative to the stress field grow faster than others. The high pressure pore fluids may work as a lubricant during the process to prevent mechanical breakage. Two ideas on why the reorientation of anhydrite laths is not pervasive are because of (1) the escape of pore-fluids or (2) because once a certain pore-pressure threshold is reached reorientation is inhibited. The second possibility may be addressed in future work.

**Timing & Conditions of Prograde Alteration**

Prograde diagenesis, or anhydritization, has been observed to affect many samples in this study to a variable degree. Resultant anhydrite grain size is one feature that varies throughout samples that have undergone prograde diagenesis. For example, in thin sections at the same magnification 14C is finer grained and contains more anhydrite compared to coarser grained 14F with less anhydrite. One idea is that prograde diagenesis affects fine grained areas more pervasively than coarse grained areas because water is able to escape more efficiently when there are more grain boundaries to travel along. In the Billefjorden Fault Zone there are anhydrite textures that suggest dehydration from both early and late diagenesis. In most cases, dehydration post-dates deformation of the precursor gypsum. Thus resultant grain size of gypsum from
deformation could control intergranular porosity and possibly the extent of dehydration. Since most dehydration is incomplete, samples show the relative timing of deformation and dehydration as anhydrite pseudomorphs overprinting deformed gypsum fabric (figure 14A-C, E). As mentioned earlier, there are contradictions in the literature about what pseudomorphic replacement independently indicates about the timing of diagenesis (Hardie, 1983; Shearman, 1983). Despite disagreements about when diagenesis took place, pseudomorphic replacement clearly cross-cuts the deformational fabric of precursor gypsum in the Billefjorden Fault Zone.

Late burial diagenesis occurs because of factors like increasing temperature, lithostatic pressure, fluid pressure and the activity of pore-fluid waters. There is some agreement between authors that around depths of 400-450m dehydration begins, but the lower limit of the transition zone varies from 500m-1.4km (Kasprzyk, 1998; Warren, 1989). An experimental study found that overlying sediments and tectonic stability also affect the depth of transition. When gypsum is overlain by poor conductors in a rift setting, the transition starts around 400 m, but when gypsum is overlain by good conductors in a more stable environment the transition occurs at about 4 km. Poor conductors are gypsum and shales while good conductors are halite and dolomites (Jowett, et al, 1993). The Billefjorden Fault Zone presents a complex situation of stability and conductivity variations. Dominant rift activity occurred throughout the deposition of the Ebbadalen and Minkinfjellet Formations, but following this the region was fairly stable undergoing platform subsidence and sedimentation from the Early Permian until the Cretaceous (McCann & Dallmann, 1996). Gypsum layers were deposited with interbedded limestones that have since undergone diagenesis to become good conducting dolomites. Therefore it is reasonable to assume that the onset of gypsum diagenesis occurred deeper than predicted depths because the Billefjorden Fault Zone was tectonically stable by the time Ebbadalen and Minkinfjellet deposition ended, in addition, some dolomite (good conductor) may have been present during the subsidence period.

The Carboniferous Ebbadalen and Minkinfjellet Formations have been involved with two major reactivation periods in the Billefjorden Fault Zone. The first was concurrent Carboniferous rifting and basin infill. The second event was Tertiary compression. McCann & Dallmann (1996) reported that relaxation of Tertiary compressive stresses during minor normal reactivation produced a large syncline oblique to the axis of the Billefjorden Trough. Estimated subsidence during Ebbadalen deposition is 300-500m and at most 350m of subsidence during the Minkinfjellet deposition (McCann & Dallmann, 1996).

Support presented below demonstrates that deformation of evaporites is consistent with Carboniferous rifting prior to platform subsidence and late diagenesis. If the Ebbadalen and Minkinfjellet Formations accumulated the maximum estimated value, 850m, then the base of the Ebbadalen Formation would still be within the predicted transition zone reported by Warren, 1989. McCann & Dallmann also report an additional 750m of platform subsidence occurring during Late Carboniferous-Early Permian. Post-rift sedimentation during the Permian and Triassic added roughly another 2km of burial (McCann & Dallmann, 1996). With the reported transition depths, we would not expect to see deformation fabrics in gypsum after being buried 3.5km, but instead only deformed anhydrite fabrics. The lowest basal limit of the gypsum-anhydrite zone is estimated at 1.4km (Warren, 1989). This assumption is based on maximum subsidence estimates from McCann and Dallman, as well as a general pressure-temperature geothermal gradient from Warren’s diagenetic model (McCann and Dallmann, 1996; Warren, 1989).

Hardie, 1967 indicates that dehydration of gypsum to anhydrite is a function of
temperature and the activity of water only. The transition temperature between gypsum-anhydrite is lowered with increasing salinity, lower activity of pore water (Hardie, 1967). As the activity of pore water increases, the transition from gypsum to anhydrite is delayed (Jowett, et al., 1993). If we assume the maximum burial depth of 3.5km in the Billefjorden Trough, then factors such as low salinities, high activity pore-waters, low pressure-temperature gradient, tectonic stability and/or overlying sediments that are good conductors would enable gypsum textures to be preserved below 3.5km. In addition to these factors, the pore fluid pressure also plays a significant role. If the pore-water cannot escape during compaction, the overburden pressure is felt by both the solid and liquid phases. Transition depth from gypsum to anhydrite is lowered in that case, whereas if the pore water can escape all the overburden pressure is felt by the solid phase, thus transition to anhydrite occurs at a more shallow depth (Jowett, et al., 1993).

In the Billefjorden Fault Zone there are Carboniferous gypsum textures preserved that have been deeply buried, potentially 3.5 km. Thus, the factors stated above that lower the transition depth of gypsum have played a dominant role in late diagenesis of the Ebbadalen and Minkinfjellet Formations. Observations of features consistent with early and late diagenesis in the Billefjorden Fault Zone indicate that gypsum dehydration was locally variable and in some places occurred from more than just loading effects.

**Condition & Mechanics of Fault related Deformation**

Gypsum and anhydrite are relatively soft, weak and easily deformed. Their layers become even weaker when gypsum is compacted, because as pore-pressures near the amount of overburden pressure, the effective normal stress is reduced and the layer is very prone to deformation (Heard, 1966). Fault related simple shear dominated the deformation of the Middle Carboniferous evaporites and the interbedded carbonate in the samples studied. Deformational features at the outcrop scale, like elongation lineations and foliations (figure 10), are well developed throughout the deformation zones in the Billefjorden Fault Zone. When analyzing kinematic data from gypsum and anhydrite rocks of the Billefjorden Fault Zone, deformation is consistent with dominant dip-slip motion recorded in the Carboniferous times. Kinematic data from the Ebbadalen and Minkinfjellet evaporites differs from the evaporites of the Permian Gipshuken Formation. Harland; et al, 1988 found that deformation in the Gipshuken Formation was consistent with the Tertiary Fold and Thrust Belt (figure 16).
Deformed fabrics in outcrop were consistently oblique to and less shallow than the adjacent carbonate bedding (figure 10A-B). The fabric is not consistent with orientations that would be axial planar to the Petuniabukta syncline, and thus do not represent a folding related flattening fabric. Small-scale asymmetric folds, normal microfaults of more competent layers and deformed gypsum samples are clearly spatially associated with tri-shear zones of normal faulting. In thin section, grains of gypsum have been elongated, re-crystallized and have undulose extinction.

As the grains of gypsum were sheared, dislocations developed in the lattice producing undulose extinction. In some samples, a polygonal mosaic texture developed as a result of recovery re-crystallization, where the crystals tried to obtain their lowest energy possible by optimizing their shape (Hardie, 1983). In most of the samples of this study, it does not appear that conditions allowed complete recovery re-crystallization. Instead, many grains boundaries retained their preferred orientation and have developed a mylonitic-like fabric.

Larger clasts of selenite have also been deformed. Instead of having smooth boundaries
with the surrounding fabric flowing around them, the selenite clasts also have sub-grains developing at their periphery (figure 13B,D). Porphyroblasts with irregular boundaries were also recognized by Holliday, 1967. Holliday proposed that evaporite porphyroblasts south of the current study area were the earliest form of secondary gypsum (Holliday, 1967). He described the selenite porphyroblasts to have irregular boundaries and abundant relict anhydrite inclusions. Relict anhydrite inclusions were not evident in porphyroblasts of the current study, but irregular boundaries were recognized and appear consistent with the development of sub-grains. They have a clear ‘augen’ shape and tails of recrystallized material that are coarser than the matrix.

Holliday also reported there was only local post consolidation flow of the Lower Permian evaporites, but in hand samples, outcrop photos and thin section photos from this study there is clear evidence of brittle disruption of carbonate material indicating that consolidation preceded the deformation in Ebbadalen and Minkinfjellet Fm. evaporites (figure 13)(Holliday, 1968). One possibility for features similar to those produced by post-consolidation flow is diagenesis, instead of tectonic strain. During compaction water is driven out of gypsum crystals, the beds near the overburden pressure and fluidize, but in the Billefjorden Fault Zone there are patterns and orientations clearly associated with fault related deformation, thus diagenesis cannot explain all of the deformed fabrics (Helman and Schreiber, 1983). Folds with a consistent asymmetry are just one example. Competency differences during deformation led to carbonate interbeds to deform rigidly with gypsum flowing between clasts. Portions of carbonate clasts were ground down with continued shearing, and often created a tail of material that decreased in grain size away from the larger carbonate clast (figure 13A).

Localized deformation, 20m wide zones, in the Ebbadalen and Gipshuken Formations of the Billefjorden Trough were noted by Harland, but were attributed to nearby faults. He adds that lower evaporite units in the Billefjorden Trough were protected from Tertiary Fold and Thrust Belt deformation by Nordfjorden Block, but that eastward displacement is seen within the stratigraphically higher Gipshuken Formation (Harland, 1988). This interpretation supports deformation textures seen in this study as being a result of Carboniferous rifting, protected from Tertiary strain.

As mentioned earlier, evidence of dominant dip-slip motion across the Billefjorden Fault Zone, consistent with Carboniferous rifting, is seen in deformation textures that pre-date burial diagenesis. This timing is better constrained on the east side of the fjord along the Lovehovden Fault, where no reports of Tertiary normal motion have been suggested, indicating that normal slip related features are Carboniferous in age, as does work documenting stratigraphic differences across the fault. Samples from figure 13H-I were taken from a strain face near the Lovehovden Fault on the east side of the fjord (figure 2). Extension and brecciation of the carbonate material occurred with normal fault movement (Maher, pers. comm.), Tertiary reactivation was reported to have reverse motion across the Lovehovden Fault by McCann and Dallmann (1996), but more recent work indicates the kinematics dominantly are that of a normal fault. In any case, no post-Carboniferous normal reactivation has been reported along this fault (McCann & Dallmann, 1996). Textures from these samples are more clearly associated with Carboniferous rifting.

A minor strike-slip component may exist along the western basin bounding faults, but this varies along strike, and may reflect local strain related to relay/transfer zones. Observed local sheath folds and late folding events play a role in some of the anomalous kinematic indicators. Sheath folds have been observed in the Gipshuken Formation at Skansbukta and were attributed to shearing towards the ENE (Harland, et al., 1988). Simple normal fault tri-
shear zones do not explain the observed shortening features such as intrafolial folds (with a predominant down-dip, normal slip vergence). Such features can be explained through fault-flats where shear was concentrated in gypsum rich portions.

**Why hasn’t a retrograde history dominated?**

The Billefjorden Fault Zone is the western boundary of a half-graben that created the Billefjorden Trough. Samples used in this study were collected in areas along the western basin margin of the trough and along the shallower, eastern, subordinate fault margin (the Lovehovden lineament) of the trough. A factor that influences the timing of rehydration is the deposit’s location within the basin. Deposits at the basin margin are shallowly buried and during exhumation are thought to come in contact with surface waters before the deposits located in the deepest part of the (Kasprzyk, 2005 & 1998). The Ebbadalen and Minkinfjellet Formations fill in a half-graben, therefore the eastern margin would be more shallowly buried and exposed first, where as the western margin is deepest and against the fault complex. The amount of secondary gypsum in sample shows no simple correlation to the basinal location. Without more samples and geographic coverage within the Billefjorden Trough, we cannot directly correlate the degree of diagenesis to the paleogeography of the sample’s site.

The incomplete rehydration of gypsum-anhydrite rocks presented in figure 15 was also documented by Holliday, 1967. This observation has been speculated to be from the region’s history of deep permafrost and perennially frozen ground, in addition to the present day low air temperatures that inhibit changes at the outcrop (discussion following Holliday, 1967). This explanation seems most viable if minimal uplift occurred prior to Pleistocene glaciations. The broad lack of secondary gypsum and localized lack of diagenetic anhydrite in Spitsbergen may suggest considerable effects of permeability and porosity on the prograde and retrograde diagenesis. Lugli, 2001 notes that the rehydration of gypsum is regulated by availability of coexisting water and porosity. As the volume increases at the rims of crystals from gypsum rehydration, the rock porosity is sealed and further hydration cannot continue. According to Kasprzyk, 1998, at deep burial depths there is no effective permeability because of the extreme expulsion of the water. Minimal evidence for early diagenesis supports alteration of gypsum occurring at depth (figure 14). This in addition to solution related features (figure 9) supports that the evaporites of the Billefjorden Fault Zone were substantially buried. Eliasson and Talbot also recognized features within breccias of the Minkinfjellet Formation that are consistent with deep burial (Eliasson and Talbot, 2005).

Reduced permeability is likely a key factor in the preservation of anhydrite through exhumation and the semi-arid, low temperature environment is also a factor at the surface. What minor rehydration did occur is concentrated along permeable areas like cleavage planes, shear surfaces and/or near fragmented carbonate. Holliday, 1967 also recognized rehydration along carbonates. The observed bands of secondary gypsum may represent cleavage planes or because of the sub-parallel orientation of the adjacent un-replaced grains, these bands may represent shear surfaces (figure 15D-F). Their amoeboïd textures suggest defects within the crystal lattice possibly attributed to rapid hydration and/or closely spaced growth centers. Holliday’s account from Spitsbergen and Lugli’s study from the Burano Formation of the Northern Apennines both suggest that the rapid hydration occurred at or very close to the surface (Holliday, 1967; Lugli, 2001). These surfaces acted like conduits to disperse low-salinity groundwaters to the anhydrite rocks. Re-hydration concentrated along the boundaries of evaporite beds was also observed in the Carpathian Foredeep Basin of Southern Poland (Kasprzyk, 1998 & 2005).
Eliassen reports the flushing of dilute waters based on isotopic studies of the surrounding carbonate material (Eliassen & Talbot, 2003), and in association with carbonate breccia formation. Rainfall and storm events at the surface, in addition to flushing events in the subsurface may account for the cloudy, amoeboidal texture seen within secondary gypsum which is attributed to rapid rehydration (Lugli, 2001). Abrupt change in sea level could also be associated with changes in the degree of rehydration and/or lack of dehydration. Holliday noted frequent changes in sea level during the Middle Carboniferous through Lower Permian times (Holliday, 1967).

Figure 13A-F shows the deformational micro-fabrics of gypsum rocks without anhydrite present. Two possibilities come to mind for the deformed deposits occurring without anhydrite. One may be the result of deformation and no subsequent diagenetic alteration at that location, and the other may reflect a separate later deformation event where pervasive gypsum rehydration destroyed anhydrite prior to later deformation.

The first possibility for deformation fabrics occurring in gypsum rocks is attributed to deeper diagenesis never occurring. The rehydration process is thought to occur during exhumation/uplift from tectonic activity, when the deposits come in contact with meteoric waters at the surface or in contact with low-salinity groundwater in the subsurface. No volume increase is usually observed with rehydration, because in the near surface environment evaporites are often dissolved or fractures and joints provided pathways for low-salinity groundwater to reach the subsurface (Kasprzyk, 1998 & 2005). As stated earlier, the rehydration is controlled by the availability of water and the porosity (Lugli, 2001).

In this study many samples preserve variable degrees of prograde anhydrite; such samples without anhydrite may be all secondary gypsum mineralogy. The possibility of pervasively rehydrated gypsium makes it difficult to constrain the timing of deformation because rehydration has also been reported as deep as 3500 ft in the Permian San Andres Formation of Texas (Murray, 1964). Based on factors that also play a role in prograde diagenesis, we have strong evidence for gypsum being stable below expected depths; therefore it is possible that rehydration could be occurring far below near surface conditions.

Model for diagenetic/deformation history of the sulfates

Examination of gypsum and anhydrite rocks in outcrop and thin section has shed light on the timing of deformation and diagenesis in the Billefjorden Fault Zone. Through textural analysis, an evolution of the calcium sulfate deposits is proposed. Gypsum and anhydrite growth in each sample has been affected by at least one of the following phases: primary growth, synsedimentary or early diagenesis, late diagenesis, deformation and rehydration. The number of processes and pervasiveness of each process varies for each sample, but the relative timing of each process is clear.

Recent studies cite a diagenetic cycle for calcium sulfate deposits that was initially proposed by Murray, 1964 (Lugli, 1999). This cycle is as follows: primary gypsum growth, followed by burial diagenesis to anhydrite and finally rehydration to gypsum upon exhumation. This model doesn’t explain the features and textures seen in the calcium sulfate rocks of the Billefjorden Fault Zone. Dominant discrepancies include: 1) an omission of a role for deformation, 2) most samples are not completely rehydrated, if at all, and 3) diagenesis doesn’t appear pervasive. Samples exist that are unaltered to incompletely diagenetically altered, with signs of both shallow and deep diagenesis. Holliday proposed this diagenetic sequence for the
evaporites of Spitsbergen: “1) growth of euhedral gypsum crystals within previous sediment; 2) dehydration of gypsum to secondary granular anhydrite which therefore forms pseudomorphs after gypsum; 3) extensive growth of primary anhydrite laths within the host sediment to form new anhydrite nodules, and also within the secondary anhydrite destroying, in the main, the monoclinic shape indicative of primary gypsum (Holliday, 1968).

Contrasting observations from the current study have led to the development of a new sequence of events for the Ebbadalen and Minkinfjellet Formation gypsum and anhydrite rocks of the Billefjorden rift basin. Textural analysis has given us a relative timing for when diagenesis and deformation occurred in various parts of the basin.

Deposition of primary Ebbadalen and Minkinfjellet Formations took place during the Middle Carboniferous through Early Permian times. Gypsum deposition was dominated by displacive growth within sediments and to a lesser extent shallow subaqueous deposition probably in small pools and lagoons that were fed by seawater. Some deposits underwent soft-sediment deformation, likely from their own displacive growth. Depending on local conditions early diagenesis, including some cementation may have occurred. Deformation consistent with Carboniferous rifting affected many deposits on both sides of the fjord. Slip planes parallel to bedding developed through ductile flow of evaporites and brecciation of associated carbonate material. These zones were weakened and were likely preferred slip planes for periods of reactivation. As sedimentation and platform subsidence continued into the early Mesozoic, gypsum was compacted and to a variable degree dehydrated (McCann & Dallmann, 1996). Variable salinities, pore-fluid pressures and depth related pressures and temperatures may be the dominant factors in the localization of anhydrite production. Anhydrite crystals pseudomorphically partially replaced gypsum fabrics.

Some Tertiary reverse reactivation was observed in outcrops on the western margin of the Billefjorden Trough as folding of an earlier developed foliation (figure 10C-D), and reverse offsets along the Balliolbreen Fault (McCann and Dallmann, 1996). Effects of reverse reactivation are not as common or as distributed as deformation associated with normal motion. Later exhumation and surface exposure from the HALIP uplift, or the Tertiary Fold and Thrust Belt activity, and/or glacial retreat caused minor rehydration of some anhydrite deposits, that was hydrodynamically controlled. Rehydration has not been pervasive and is controlled by the porosity along fractures, cleavage planes and shear zones, as well as the availability of water. Figure 17 summarizes the evolution of evaporites in this study area.
In contrast to Holliday's recognition of primary anhydrite growth, this study has no evidence for primary anhydrite such as anhydrite laths projecting into the host carbonate sediment or isolated single anhydrite laths (Holliday, 1968). Host carbonate material has been disrupted by gypsum's displacive growth and deformation, and because of incomplete dehydration and the pseudomorphic character of anhydrite, we can characterize the majority of anhydrite of this study to be due to secondary diagenesis at substantial depth. Surrounding carbonate material is also observed to be draped around larger nodules, which according to Murray, 1964 is evidence that anhydrite did not replace carbonate material (figure 9). Few isolated primary gypsum grains have been observed, but Hardie, 1983 describes euhedral or nodular growth within sediment to be an ambiguous feature among calcium sulfate deposits.

Last to form in the study area was secondary gypsum, as a result of rehydration, was observed to be cloudy and amoeboidal. The grain boundaries are very indistinct from the amount of dislocations still present within the crystals. Other documentation of this texture has related it to local deformation or defects from a volume increase during rapid re-hydration (Lugli, 2001).
Next Steps

Micro-textural studies are stressed to be the most useful for determining if textures in samples are primary, syn-depositional or late alteration. More in-depth analyses such as fluid inclusion analysis, $^{87}$Sr/$^{86}$Sr ratios and $^{32}$S/$^{34}$S ratios can be conducted for a more detailed interpretation of depositional and alteration environments. This interpretation will help narrow down which factors dominated in the preservation of gypsum at depth and preservation of anhydrite at the surface. These types of analyses can provide very narrow temperature ranges which can be used to deduce an approximate depth of the environment. $^{32}$S/$^{34}$S analysis can be uniquely helpful to calcium sulfate deposits because sulfur content in seawater has been fairly consistent through geologic time and sulfur isotopes do not fractionate upon the precipitation of gypsum and anhydrite. Therefore, $^{32}$S/$^{34}$S analysis on calcium sulfate deposits provides insight to the brine they precipitated from (Schreiber, 2000).

Conclusions

* The following textural and kinematic evidence is consistent with the majority of gypsum deformation being associated with Carboniferous rifting
  - replacement anhydrite pseudomorphing deformational textures of gypsum, suggesting deformation during the prograde path.
  - kinematic indicators show dominant dip-slip motion with a minor oblique components that varies along strike
  - deformed evaporite fabrics are in an orientation consistent with Carboniferous rifting directions.
  - deformation textures from the Lovehovden structure are clearly extensional, Carboniferous and are very similar to those associated with the Billefjorden fault zone.

* Secondary gypsum from rehydrated anhydrite by meteoric waters on exhumation was not pervasive and is only seen in patches.

* Anhydrite growth clearly overprints deformed gypsum fabrics. The lack of mechanical breakage among anhydrite grains is consistent with diagenesis occurring after cementation, but before deformation (figure 17).

* The amount of anhydrite and secondary gypsum likely varies because of changes in pore-fluid activity and pressure, the conductivity of overlying beds and pore-fluid salinities from the reported flushing of meteoric waters and quick facies changes (Eliasson et al, 2003 & 2005). The hydrodynamics of the basin appear to be a dominant factor in local diagenesis.

* Significant amounts of accommodation space could have been created in the Billefjorden Trough by the initial compaction of gypsum, by the delayed compaction of gypsum after porosity has been decreased and by pressure solution.
Acknowledgements

I want to thank Dr. Harmon Maher, Jr. for the opportunity to work on this project and for his patience and suggestions throughout the writing/revision process. I would also like to thank Dr. Robert Shuster for all of his revision suggestions, the whole UNO Department of Geography and Geology for the use of all the lab equipment involved in this project and my family for their support.
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