Regional geometry, petrographic variation, and origins of Upper Ordovician dolomites in Hadeland, Norway

COLIN J. R. BRAITHWAITE & RACHEL A. HEATH

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Dolomites are widespread in the Upper Ordovician Kalvsjøen and Klinkenberg Formations in Hadeland, Norway. Their distribution reflects generation by the repeated passage of fluids passing from a shallow shelf in the east towards a deeper basin in the west. The Kalvsjøen Formation consists of thin-bedded limestone turbidites and shales deposited on a relatively deep slope. As sea level fell, these were incised to form a series of shallow channels that were subsequently filled by chaotic debris-flow deposits. The upper parts of this assemblage were ultimately emergent. The Klinkenberg Formation marks a new transgression and is a mixed carbonate-siliciclastic assemblage deposited on a storm-reworked shallow shelf or slope. Dolomite occurs throughout this interval. In the Kalvsjøen Formation it is generally dispersed, but is most common in eastern areas. Idiotopic and xenotopic textures show five distinct cathodoluminescent zonal sequences and three non-luminescent forms. By contrast, the Klinkenberg Formation also includes a significant laterally extensive dolostone unit. This is thickest in the east, although thickness has been reduced there by erosion. Three distinct dolomite morphologies and five cathodoluminescent zone types are identified. The greatest concentrations of dolomite, the brightest zones, and the greatest variety of zones, are found in eastern regions, suggesting that the bulk of the waters responsible for dolomitization came from that direction, driven down into the basin by shelf drainage as sea level fell. The diversity of zones illustrates the chemically heterogeneous and temporally variable nature of this flow. In parts of the succession, dolomite is associated with dissolution seams and results from flow of reactate solutions along these seams. Such flow was sometimes confined within the seam but was more often pervasive. Evidence of dilation suggests that some seams were also paths for the upwards migration of overpressured fluids, a process which may have been driven by sea level change or by compaction.

C. J. R. Braithwaite, Department of Geology and Applied Geology, Glasgow University, Glasgow G12 8QQ, Scotland, UK; Rachel A. Heath, 4 Lammerton Terrace, Dundee DD4 7BW, Scotland, UK.

Introduction

Models used to explain dolomitization range from those driven by surficial processes such as evaporative pumping, seepage reflux, self drainage, or mixing zone processes, to burial effects brought about by compaction, geothermal circulation or rising hydrothermal fluids (Braithwaite 1991). No petrographic or textural patterns are exclusive to any of these, although stable isotopes may provide clues to the origins of the waters responsible. The identification of origin therefore rests on the definition of a regional geometry that encompasses the shape of the dolomite, its relationship to the facies containing it and the place these occupy in the configuration of the depositional system, and also on recognizing the distribution of the products of diagenetic events within the dolomitized body.

Dolomitization was earlier regarded as a singular event taking place in a geologically short time and it was assumed that, once started, it tended to proceed until the rock was completely dolomitized. The circumstantial evidence for this is summarized in the data presented by Sperber et al. (1984) which showed that dolostones are typically 97% stoichiometric dolomite, whereas dolomitic limestones commonly contain calcian dolomites which rarely form more than 20% of the rock. However, many dolostones are the result of multiple nucleation and replacement events (Qing & Mountjoy 1989; Machel & Anderson 1989). The dolomites of Hadeland illustrate such an iterative origin and show how geometry and regional petrographic variation can be used to determine the source, distribution and character of dolomitizing fluids.

Regional geology and depositional history

Hadeland lies in the Oslo Graben, about 50 km north of Oslo, and forms one of the geographical districts of the graben defined by Størmer (1953, Fig. 1). The Upper Ordovician of Hadeland consists of a limestone-shale succession, the Kalvsjøen Formation (Heath & Owen 1991), overlain by the dominantly arenaceous Skøyen Group, which extends into the Silurian (Owen 1978). The Skøyen Group is divided into a lower calcarenaceous and siliciclastic unit, the Klinkenberg Formation, while the upper siliciclastic assemblage, the Sælabonn Formation, represents the base of the Silurian (Heath & Owen 1991, see Fig. 2 here). Dolomite is found throughout the Ordovician part of this sequence, but is predominantly associated with carbonates.

During the late Ordovician, Hadeland occupied part of a carbonate slope. Deeper water, with sediments domi-

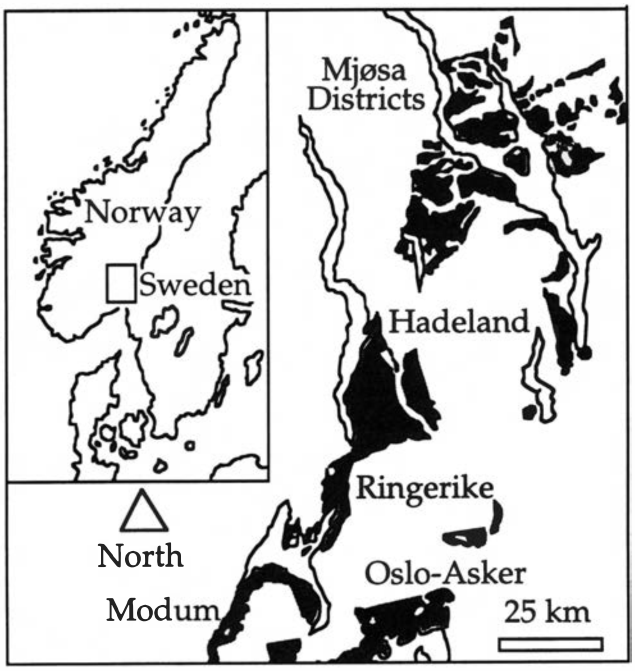

Fig. 1. Map of the Oslo region showing the location of Hadeland. Areas in black represent outcrops of Ordovician rocks (modified from Størmer 1953.

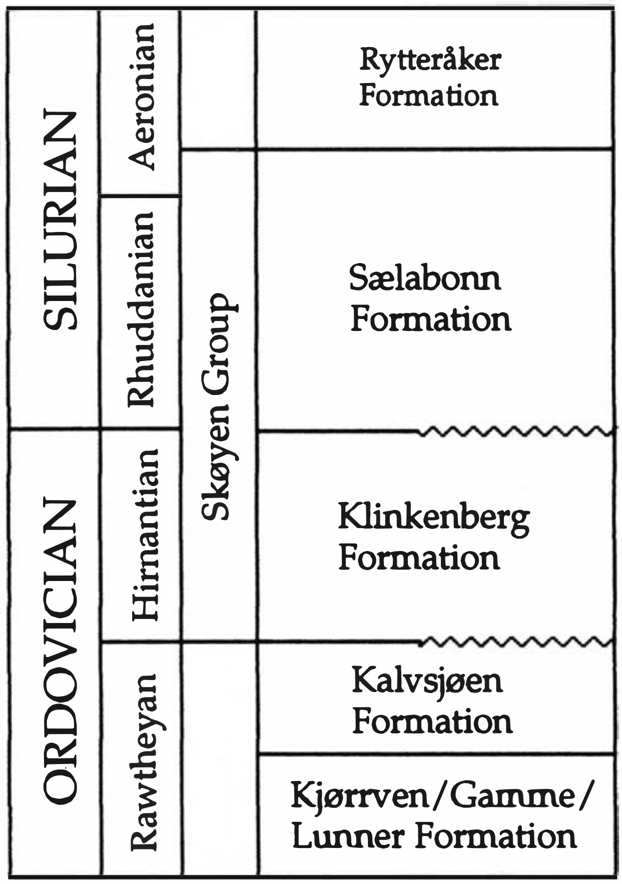

Fig. 2. Stratigraphy of the Ordovician–Silurian interval in Hadeland, based on Heath & Owen (1991).

nated by muds and silts (now shales), lay to the west, while to the east, a shallow shelf extended outside existing outcrops (Heath 1989; Braithwaite et al. 1995). This terrain has been lost as a result of faulting and erosion along the margins of the present Oslo graben but its character can be inferred from the sedimentary rocks that remain.

The Kalvsjøen Formation consists predominantly of thin interbedded stylonodular limestones and shales. The limestones are poorly sorted with coarser grains including fragments of algae (locally common) gastropods, crinoids, bryozoa and nautiloids set in a matrix of carbonate mudstone with 5–40% silt-size quartz grains. The laterally extensive beds are commonly graded and are regarded as turbidites (which may have been storm-generated) with the shaley interlayers, enhanced by pressure dissolution, representing the hemipelagic background deposition (Braithwaite & Heath 1992).

At several localities, the top of the Kalvsjøen Formation has been incised by channels cutting into the nodular limestones (Braithwaite & Heath 1992). These channels are filled with chaotic breccias consisting of disoriented blocks, up to 50 cm in diameter, of previously lithified limestones, set in a mudstone-wackestone matrix. Blocks are of contrasting lithologies and contain a diverse biota, including colonial corals and algae. Cements within the blocks record differing diagenetic histories which also reflect differing provenance. These features are not represented in the nodular limestones and the source of the blocks is believed to have been a shallow shelf which lay 5–10 km to the east (Braithwaite & Heath 1992). The blocks and matrix are crudely interbedded with further wackestones and grainstones. The debris-flows may have originated in response to falling sea level and, as sea level continued to fall, they were themselves exposed, together with the associated limestones. Prolonged exposure locally resulted in the development of karst cavities (Braithwaite & Heath 1992).

A relative rise in sea level subsequently flooded the area, leading to the deposition of crinoidal sands in the cavities which had formed within the debris-flow deposits. It also initiated deposition of the Klinkenberg Formation. This shallow-water, mixed carbonate-siliciclastic association, included putative aeolian material derived from the adjacent land mass. The sediment was delivered to Hadeland through distinct pathways in the shelf and is thus distributed as a series of lobes (Braithwaite et al. 1995). Sea level fluctuated throughout deposition, but a relatively large fall resulted in local emergence at the end of Klinkenberg time. In the Mjøsa district, about 30 km NE of Hadeland, emergence began much earlier (Heath 1989; Braithwaite et al. 1995).

Deposition of the Sælabonn Formation, the upper part of the Skøyen Group, marks a rise in sea level. Siliciclastic sands were again introduced from the east via limiting channels in the remnant margin and were deposited rapidly, spreading as discrete lobes (Heath 1989; Braithwaite et al. 1995).

Dolomite occurs throughout the Ordovician part of this succession. Although it is more common in areas dominated by carbonates, its character and distribution vary in relation to facies and to presumed groundwater movements during sea-level change.

The distribution of dolomite

The Kalvsjøen Formation

Dolomite forms only 1–30% of the Kalvsjøen Formation and is irregularly distributed. It is most common in eastern areas of Hadeland but only scattered rhombs are present in limestones below the debris-flow channels. Within the channel-breccias, dolomite forms a partial replacement of the fine-grained calcite of the matrix and of some algal bioclasts, but is most commonly associated with dissolution seams. It occurs as idiomorphic crystals of up to 0.2 mm in diameter and as xenotopic patches, either confined within or extending peripherally from seams. The controls on crystal shape have been discussed by Sibley & Gregg (1987) whose terminology is adopted here.

Isolated crystals are euhedral, while intergrowths typically have planar-E boundaries (Sibley & Gregg 1987) although groups may enclose interstitial clay. There are several distinct dolomite types, each with characteristic cathodoluminescence (C.L.) zones or composites of zones. In central areas of Hadeland there are at least three sequences. In one sequence the cores of crystals were corroded before deposition of the rim, while the other two show differing zone sets without any clear identity of zones. Very few rhombs are seen in western areas and those present are typically dully or non-luminescent.

The various types of dolomite may constitute entire rhombs with an apparently uniform composition or may form part of concentrically zoned sequences. However, these sequences vary in completeness and there are local omissions. This makes it difficult to determine age relationships but comparison of zonal sequences, representing cognate sets of chemical events from different geographical areas within the Kalvsjøen Formation allows a paragenetic sequence stratigraphy to be identified (Braithwaite 1993) (see Fig. 7A for a summary).

Type 1. The oldest rhombs, 50–100 μm in diameter, are uniformly non-luminescent or dull. They form both isolated crystals and the cores of crystals overgrown by younger zones. Typically, they occur in clay-rich lithologies of the limestones but form only 5% of dolomite within the Kalvsjøen Formation, principally in areas to the west of the debris-flow complex.

Type 2. Rare limpid rhombs up to 100 μm maximum diameter occur in micrite-dominated rocks throughout Hadeland, but principally in the west. These comprise between three and six sharply defined brightly luminescent concentric zones separated by dull zones. Significantly, they lack overgrowths of any other zones.

Type 3. Euhedral (idiotopic) rhombs up to 80 μm maximum diameter locally replace micrite interstitial to bioclasts and quartz-silt grains. Crystals are commonly concentrically zoned dull red and dull brown. In parts of the area, rhombs of this type have been partially neomorphosed to give a ruby-red luminescence to the cores. In one example, rhombs have been calcitized leaving only remnants of zones.

Type 4. Bright and blotchy composite zones are patchily distributed overlying dull red and brown Type 3 zones. They are generally neomorphosed, giving bright orange patches within the medium orange to pale brown background, and neomorphism may extend to other zones, masking earlier zone boundaries. Dull Type 3 and bright Type 4 zones may form repeated sequences, principally in central and eastern regions of Hadeland (Fig. 3A).

Type 5. Abundant rhombs up to 100 μm maximum diameter and with a brick red or bright red luminescence form 30% of some rocks within and beneath the debris-flow complex in eastern areas of Hadeland. Nucleation was again fabric-selective and was principally in micrite, leaving included bioclasts unaffected. Crystals vary from idiotopic to xenotopic with the latter type associated with clays which may reflect compaction rather than impeded growth. Some Type 3 and Type 4 rhombs have outer zones with similar bright red luminescence.

Type 6. The youngest dolomites seen in the Kalvsjøen Formation are either non-luminescent or dully luminescent. Three varieties have been recognized.

(a) Saddle dolomite (Radke & Mathis 1980) occurs in rare nodules within grainstones and replacing pseudospar, sparry cement, and some bioclasts in cavity-filling grainstones (Fig. 3B). It also forms vein-fillings within the debris-flow complex. Crystals are 0.1–1 mm maximum diameter, significantly larger than other dolomite crystals, with planar-S or planar-E boundaries (Sibley & Gregg 1987). Saddle dolomites are commonly brownish, inclusion-rich, and characteristically show curved cleavage planes and sweeping extinction. They are here typically non-luminescent.

(b) Dark or dully-luminescent dolomite with linear extinction occurs in patches distributed throughout the nodular limestones and the debris-flow channels of the Kalvsjøen Formation. Crystals of up to 40 μm in diameter locally constitute up to 10% of the rock. They may form either isolated subhedral rhombs with corroded boundaries, or interlocking groups with xenotopic or planar-S boundaries (Sibley & Gregg 1987). In some areas adjacent to the debris-flows, dully-luminescent dolomite selectively replaces micrite, particularly where siliciclastic grains are present.

(c) Some dully luminescent dolomites, otherwise similar to Type 6b have distinctive bright red luminescent cores (Fig. 3C). Crystals of this kind are found in grainstones deposited in cavities within the debris-flow channels and also in cross-bedded grainstones in the overlying Klinkenberg Formation.

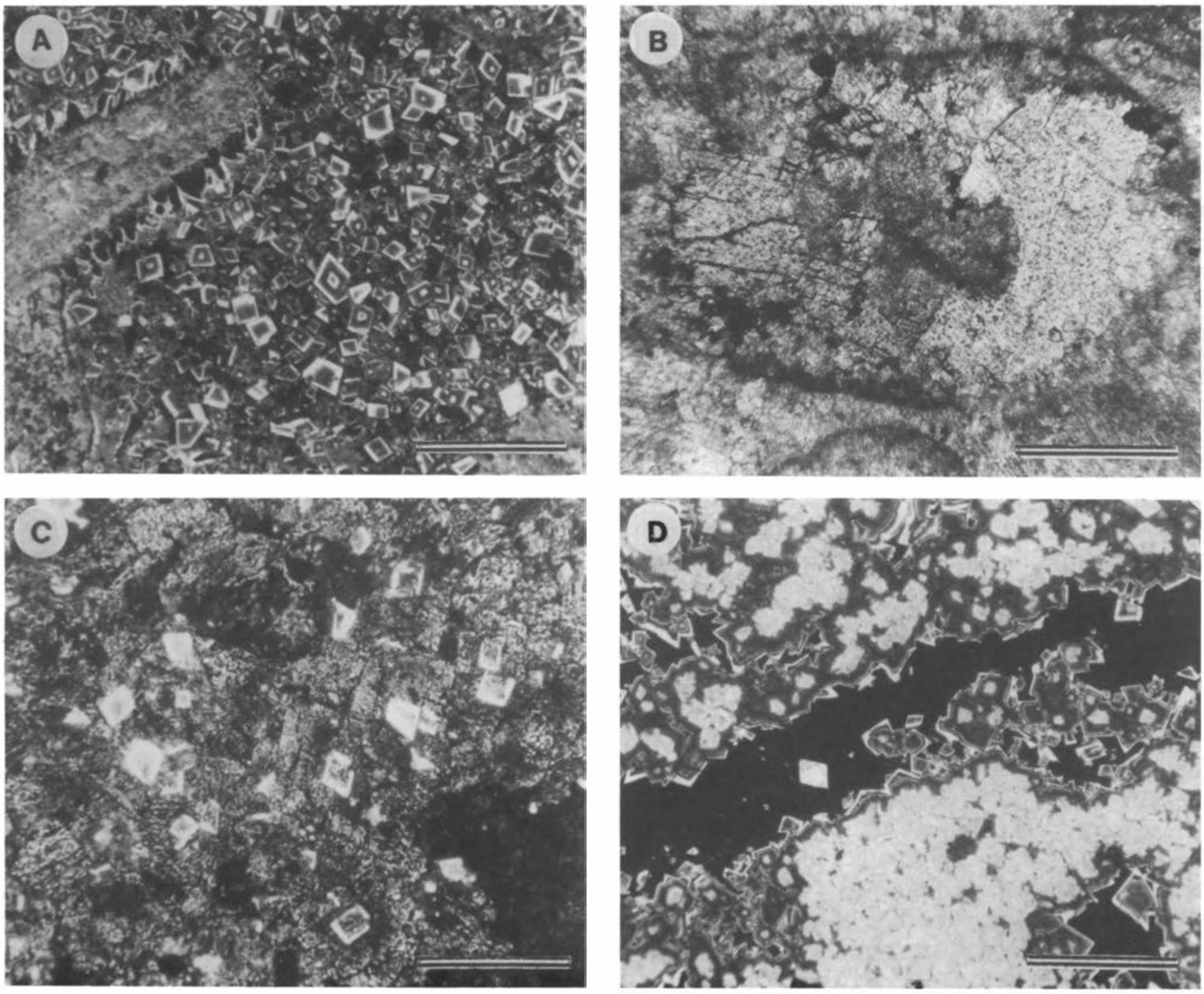

Fig. 3. (A) Multiple bright zones in idiotopic dolomite within debris-flow channels. Kalvsjøen Formation, eastern Hadeland. CL. Bar 0.2 mm. (B) Non-luminescent saddle dolomite replacing calcite bioclast. Kalvsjøen Formation beneath debris-flow channels, eastern Hadeland. OL. Bar 0.4 mm. (C) Hypidiotopic dolomite with small bright cores and very thick non-luminescent rims. Kalvsjøen Formation, eastern Hadeland. CL/OL (CL with low level of ordinary light to illuminate non-luminescent areas). Bar 0.2 mm. (D) Three generations of dolomite, replacing matrix and forming pore-lining and pore-fill. Klinkenberg Formation, northeastern Hadeland. CL. Bar 0.2 mm.

A variety of dolomite crystals are associated with 'pressure-dissolution' seams. Crystals may be confined within a seam or spread as a corona around it. However, towards the top of the Kalvsjøen Formation some seams with associated dolomite contain columnar crystals of ferroan calcite which show a parallel alignment at some angle to seam margins. A few seams of this kind contain two sets of aligned crystals.

The Klinkenberg Formation

The Klinkenberg Formation (the lower part of the Skøyen Group) is a shallowing-up sequence of mixed carbonate and siliciclastic sandstones. Within these, near the base of the formation, dolomite forms a laterally extensive dolostone unit up to 16 m thick but including dolomitic sandstones 1–4 m thick. The dolostone is fine-grained, massive, unbedded and lacks macrofossils. In eastern Hadeland burrows are common within the dolomitic interval, whereas in the west the rocks are commonly laminated with few burrows. In most areas the boundaries with overlying lithologies are gradational. However, to the east, erosional truncation of early lithified surfaces is seen within the succession and the top of the dolostone forms an irregular eroded surface at Gamme. It is not known how much dolostone has been removed, but erosion seems to have been substantial, perhaps in the order of tens of metres.

The eroded surface of the dolostone unit is overlain to the east by cross-bedded calcarenites and to the west by siliciclastic sandstones. Generally, bioclastic grainstones, which afforded permeabilities more favourable for dolomitization, are thicker in central areas where patchy dolomitization extends vertically over about 8 m, while at Kalvsjø only 6 m of dolostone is preserved.

Dolomites from the Klinkenberg Formation are typically polymodal, with crystal sizes of 20–60 μm. Former bioclasts are represented by unimodal patches in which crystals can be up to a millimetre in diameter, some preserving traces of the original bioclast structure. However, cathodoluminescence reveals that even these supposedly homogeneous areas represent more than one nucleation event. Groups of dolomite crystals containing only supposed early zones are found next to patches dominated by crystals made up of later zones with few early cores (Fig. 3D).

There are three crystal morphologies:

(1) *Planar-E* dolomites, crystals are idiotopic (euhedral). They are present in three situations: (a) in partially replaced limestones, commonly grainstones, where they grow unimpeded, replacing both bioclasts and cement and growing between existing crystal boundaries (Fig. 4A); (b) in some dolomitic rocks containing clays or quartz grains (Fig. 4B) where these separated dolomite crystals during growth and prevented interference; and (c) in wholly dolomitic rocks characterized by idiotopic crystals with cloudy non-ferroan cores and limpid ferroan rims.

(2) *Planar-S* dolomite crystals are xenotopic but with planar compromise boundaries. Such crystals are common in Hadeland where there has been growth to mutual contact. They are associated particularly with coarser grains and, presumably, with situations where nuclei were more widely spaced. However, groups of planar-S crystals may grade into idiotopic or non-planar crystals within a few microns. Evidently, the primary controls on boundary shape only have local validity and this is important in view of the relationship between shape, temperature, and crystal growth discussed by Sibley & Gregg (1987)

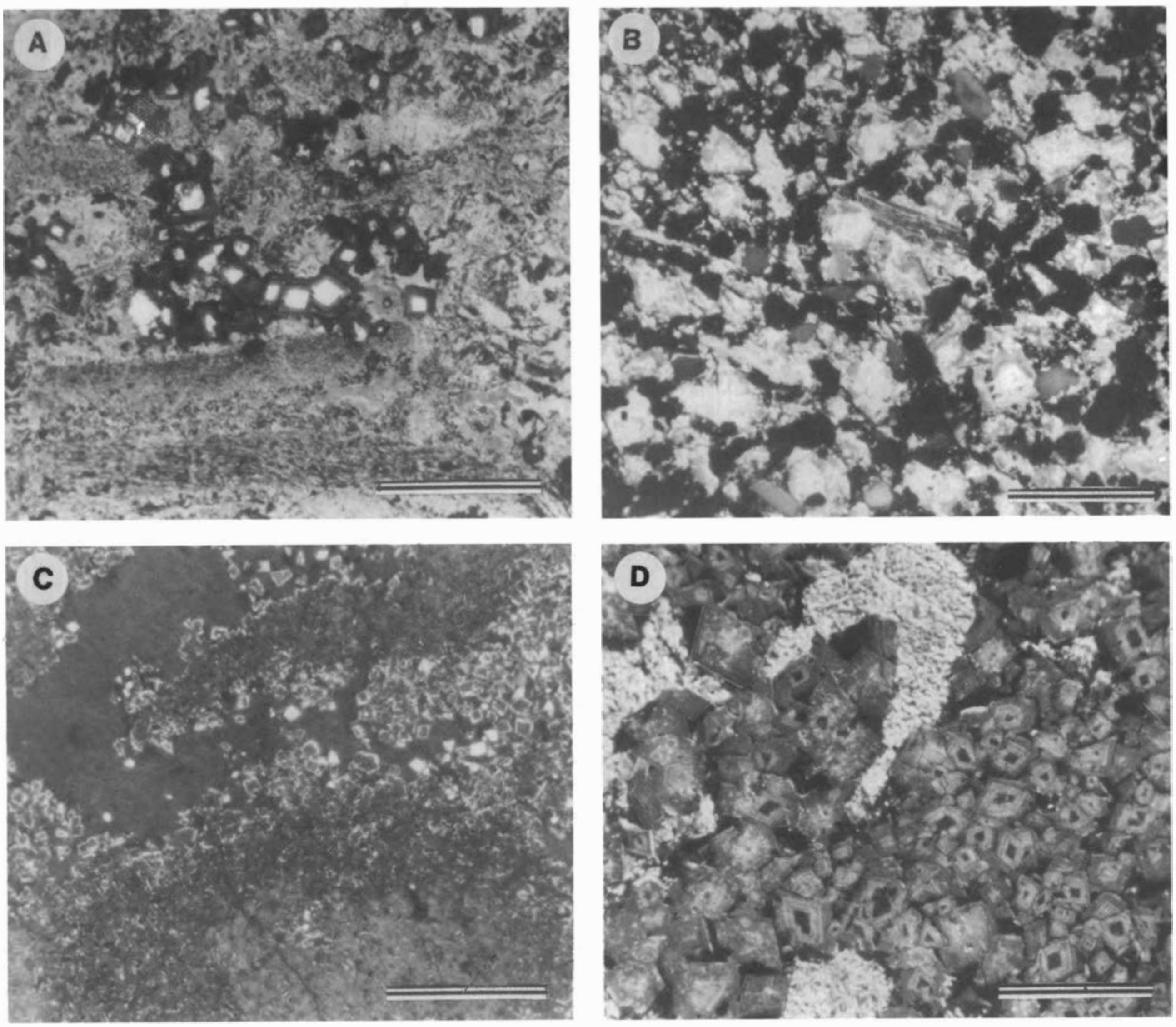

Fig. 4. (A) Idiotopic dolomite rhombs with bright cores and multiple dull rims. Upper Klinkenberg Formation, central Hadeland. CL. Bar 0.4 mm. (B) Dolomite crystals showing corrosion and subsequent emplacement of bright calcite cement. Calcarenaceous sandstone in Klinkenberg Formation, eastern Hadeland. CL. Bar 0.2 mm. (C) Homogeneous dolomite with dull cores and thin bright rims overlain by non-luminescent dolomite. Klinkenberg Formation, northeast Hadeland. CL/OL. Bar 0.4 mm. (D) Idiotopic dolomite with dull cores and multiple moderately luminescent outer zones replacing calcite. Note residual bioclasts. Klinkenberg Formation, northeastern Hadeland. CL. Bar 0.2 mm.

and Braithwaite (1991). Extensive dolomite cements develop planar compromise boundaries.

(3) *Non-planar* dolomites consist of closely packed xenotopic crystals with irregular consertal compromise boundaries. In Hadeland these are common in fine-grained lithologies, along some stylolitic boundaries and where dolomite forms crystal silt. In the last two, however, shape is not necessarily controlled by crystal growth.

In NE outcrops of the Klinkenberg Formation (e.g. Gamme) dolostones are cut by an irregular, possibly karstic, erosion surface. Sinuous cracks extend downwards from this. Those near the surface (up to 1 m depth) contain aeolian millet-seed sands. At deeper levels open fractures have been filled with saddle dolomite. Silt-size quartz grains occur within this. At greater depth (1–2 m below the erosion surface) patches of dolomite occur at intervals along cracks. These consist of fragments of crystals, of a range of sizes, which are commonly brightly luminescent and rest in a non-luminescent cement, contrasting with the dull zones of the host dolomite. Finally, some fractures have closed and have a stylolithic 'fitted' appearance (cf. Buxton & Sibley 1981) implying compaction. Braithwaite (1986, 1989) noted similar stylolitic surfaces in Devonian Limestones from Montana (see discussion).

Idiotopic dolomite crystals with cloudy centres and clear rims are common in Hadeland. The cores of these crystals are typically brightly luminescent and may be zoned, while the rims are commonly ferroan and non-luminescent. In some examples cloudiness is caused by calcite inclusions incorporated into the lattice during early growth. Such inclusions may extend across several crystals, preserving relics of an original fabric.

The cathodoluminescence of the Klinkenberg dolomites varies both areally and stratigraphically. In western areas, crystals are generally dull and show only a simple sequence of dull red and dark zones. In contrast, those in eastern areas have a complex and locally varied concentric zoning with the following paragenetic sequence, summarized in Fig. 7B.

Type 1. Dull or dark cores (Fig. 4C).
Type 2. Composite, thin, bright orange and pale orange, usually patchy, zones (Fig. 4D).
Type 3. Dull red and dull brown zones.
Type 4. Multiple brightly luminescent zones (Fig. 5A).
Type 5. Non-luminescent zones (Fig. 5B).

Individual zones may be missing from a sequence and composites of Type 1, 2 or 3 zones may be repeated within or between localities.

In eastern area dolomites at low levels of the Klinkenberg Formation include several dark and bright concentric zones, but these are commonly neomorphosed and in places calcitized (Fig. 5C). Higher in the unit, zones become more numerous and are generally brighter, but show no neomorphism and no calcitization. In central Hadeland fewer zones are present. Here, at the base of the sequence, zones representing stages early in the paragenesis are generally thin, and are overlain by later dull and dark zones. At stratigraphically higher levels these are overlain in turn by multiple bright zones. By contrast with eastern areas, neomorphism and calcitization are common, masking or obliterating zones. Partially dolomitized grainstones at the top of the Klinkenberg Formation include large, idiotopic, inclusion-rich crystals with a uniform bright red luminescence.

When some apparently uniform dolostones are observed under C.L., they become differentiated into dense areas which resemble discrete blocks and linear (or probably planar) channels which are more porous. Blocks are of millimetre to centimetre dimensions (Fig. 5D). In some samples their margins are sharply defined, while in others there is a gradual passage from dense block to apparently porous channel. Crystals within blocks are generally xenotopic or hypidiotopic while those in channels include more which are idiotopic. Luminescent zone sequences are commonly also different, with crystals in channel areas showing later zones not present in those in blocks. Similar block-like textures are seen in both central and western Hadeland but are less common.

In the Klinkenberg Formation the total volume of carbonates and the proportion of dolomite present in them generally decrease from east to west. In many western areas dolomite crystals are predominantly dull or non-luminescent. There may still be a range of brighter cores and sub-zones, but these are less varied than in eastern localities. A few samples contain crystals in which zonal sequences were apparently brecciated or disrupted during growth. In some samples from central areas there is evidence of corrosion and dissolution. Pores formed by the dissolution of bioclasts and late fracture fills include coarse dully-luminescent saddle crystals (Fig. 6A).

Discussion and conclusions

General characteristics of Hadeland dolomites

The size of crysals formed in a crystallizing phase reflects both the number and growth rate of nuclei. Growth is determined by the thermodynamic properties of the phases involved and by ambient conditions (Maaløe 1985). It depends on a continued supply of saturated fluid and may be limited by the growth rate and time available (Spry 1974), or by changes in pore-water chemistry. Activation energies for growth are generally lower than those required for nucleation (Spry 1974), particularly for dolomite where there are important kinetic barriers to nucleation (Braithwaite 1991). Thus, where other growth conditions are met, and no new nuclei formed, the result should be a uniform coarsely crystalline rock.

Hadeland dolomites typically display polymodal fabrics. These are attributable to three principal factors

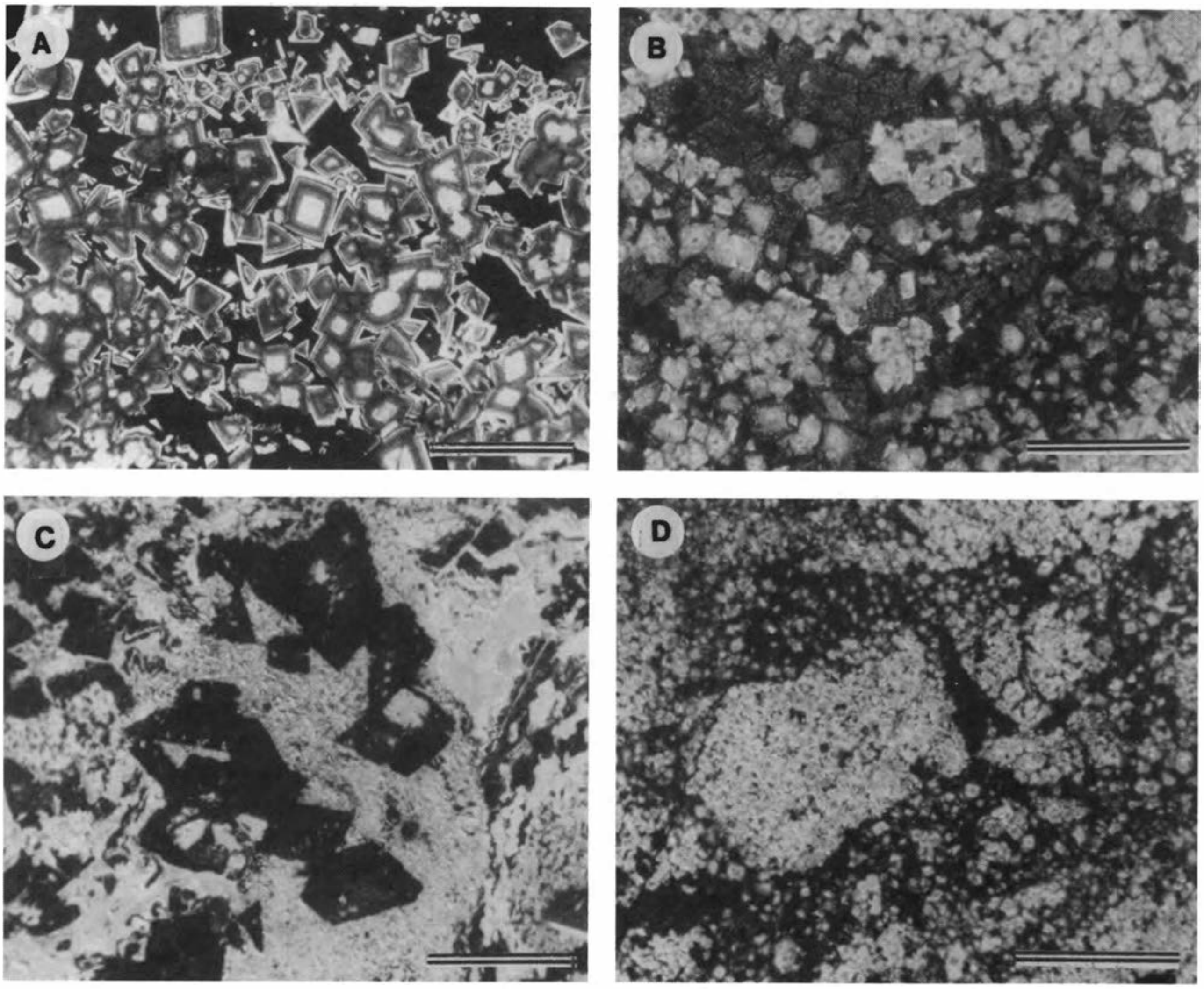

Fig. 5. (A) Multiple bright zones in early formed idiotopic dolomite overlain by later non-luminescent dolomite. Klinkenberg Formation, western Hadeland. CL. Bar 0.2 mm. (B) Dolomite showing medium to bright cores overlain by thick non-luminescent rims. Klinkenberg Formation, northeastern Hadeland. CL/OL. Bar 0.4 mm. (C) Corrosion of dolomite (non-luminescent) and emplacement of bright calcite cement. Klinkenberg Formation, central Hadeland. CL. Bar 0.2 mm. (D) Cryptic brecciation in dolomites; note contrasting zonation within and between blocks. Klinkenberg Formation, Central Hadeland, CL. Bar 0.4 mm.

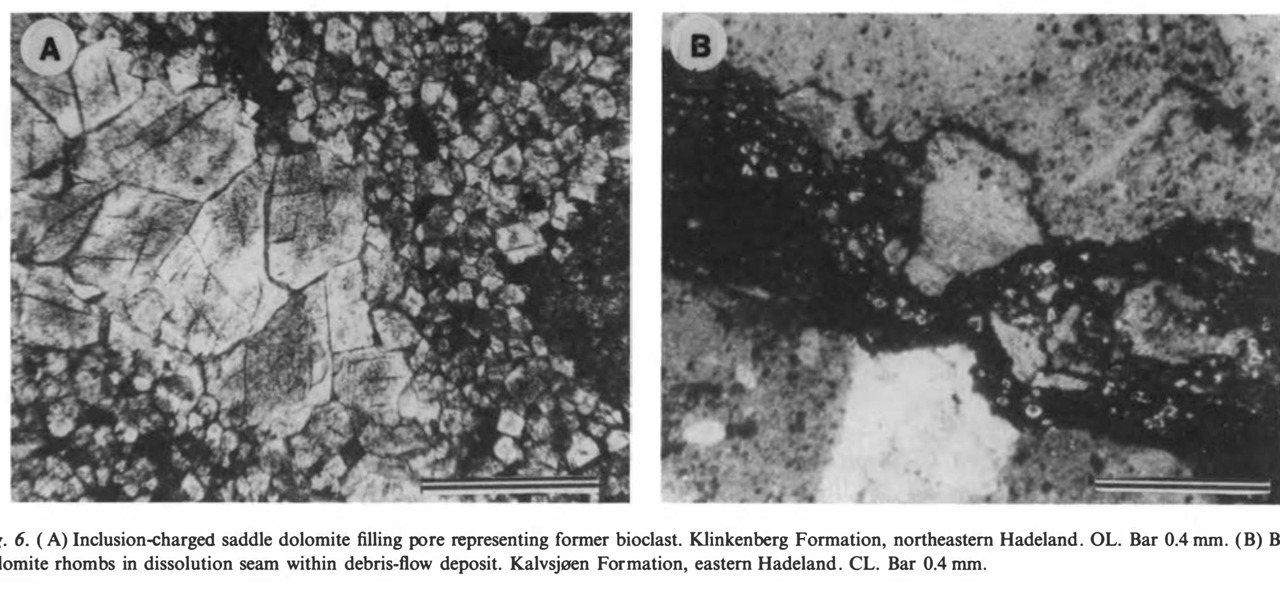

Fig. 6. (A) Inclusion-charged saddle dolomite filling pore representing former bioclast. Klinkenberg Formation, northeastern Hadeland. OL. Bar 0.4 mm. (B) Bright dolomite rhombs in dissolution seam within debris-flow deposit. Kalvsjøen Formation, eastern Hadeland. CL. Bar 0.4 mm.

(Gregg & Sibley 1984): they may reflect the heterogeneous distribution of nucleation sites, local variations in growth rates, or discrete phases of nucleation. Nucleation sites may follow variations in the primary fabric. Sibley and Bartlett (pers. comm. Sibley 1988) have shown by experiment that carbonate mud is preferentially replaced by fine-grained dolomite as a result of the higher boundary free-energy and larger surface area available for reactions. The effects of growth rate variations are seen where growth ceases locally because of crowding of nuclei, but continues elsewhere forming larger idiotopic crystals. Several dolomitizing events have occurred in Hadeland with nucleation and growth rates varying between them.

Much of the dolomite in Hadeland consists of crystals with cloudy centres and clear rims. Murray (1964), Sibley (1980, 1982), and others, have attributed cloudy areas of crystals to the trapping of calcite inclusions within the dolomite lattice during growth and have offered several explanations. The most appropriate is based on growth kinetics. Rapidly formed dolomite is commonly calcian and non-stoichiometric (Sperber et al. 1984; Althoff 1977; Randazzo & Cook 1987) and, because of the speed of growth, crystals incorporate foreign bodies which happen to rest against them. By contrast, crystals which grow slowly are well-ordered (Althoff 1977), exclude foreign particles, and are therefore limpid.

Saddle (baroque) dolomites with a sweeping, undulose, extinction have been associated with several environments; with deep burial (Lee & Friedman 1987), and elevated temperatures (60–150°C, Radke & Mathis 1980), with sulphide mineralization (Beales 1971; Radke & Mathis 1980), with hydrocarbon reservoirs (Radke & Mathis 1980) and with dilute waters. The saddle dolomites of Hadeland apparently formed at shallow depths. Their slightly ferroan character may indicate deposition in a reducing environment.

The colour and intensity of cathodoluminescence zones of carbonates have been treated as indicators of Eh conditions and the time of formation, dull luminescence reflecting relative anoxia, and bright luminescence oxidation (Barnaby & Rimstidt 1989). However, although this assumption produces predictable regional interpretations (e.g., Dorobek 1987; Grover & Read 1983) evidence for the precise correlation of luminescence with oxidation states is no longer clear (Heydari & Moore 1993). Machel & Burton (1991) have identified 26 factors influencing cathodoluminescence intensity, while Savard et al. (1995) have shown, contrary to earlier views, that there is no absolute correlation between intensity of luminescence and either Mn or Fe contents. There remains, however, a general correspondence between bright zones and shallow diagenetic environments and dull zones and deeper burial (cf. Meyers 1991).

Hadeland dolomites are often associated with dissolution seams. Wanless (1979) pointed out that dolomite in such seams usually cannot be explained simply as a residue of precursor limestones. Dolomite growth is favoured by the higher temperature and pressure conditions of burial. Wanless (1979) differentiated 'precursor dolomite', i.e. that present before seams were formed, and that formed during and post-dissolution. He suggested that crystals concentrated as a residue are of similar size and character, which would include luminescence zones, to those in adjacent limestones untouched by dissolution. By contrast, crystals formed during or after dissolution may be morphologically distinct and show luminescence zones absent elsewhere. Wanless believed that post-dissolution and post-compaction dolomites should display more intergrowths. In practice, these characteristics have to be viewed with additional evidence of both compaction and pressure-dissolution, especially where dolomite has grown at different stages of volume reduction.

In Hadeland the zoning of dolomite crystals associated with dissolution seams indicates that they have grown episodically. They are not insoluble residues. There are three alternative explanations: (1) dolomite may have formed under favourable stress conditions; (2) growth may have occurred in an overpressured environment where channel walls were kept open, allowing crystallization and fluid flow; and (3) dolomite precipitation may have occurred following the tensional reopening of seams and the consequent passage of dolomitizing fluids.

The evidence for more open stylolites will be discussed below. The later reopening of seams is demonstrated where columnar ferroan calcite crystals have grown parallel to a direction of opening rather than normal to seam margins. Such growth, described by Grigor'ev (1965), requires that the rate of opening and dilation of fractures should be equal to or less than the slowest growth rate of the crystals. Under these conditions crystals grow parallel to each other, and in the direction of opening, irrespective of orientation. Dilational fractures are present in Hadeland, and some show two separate phases of opening, but they are not specifically associated with dolomite.

The Kalvsjøen Formation

Most dolomites in the Kalvsjøen Formation are idiotopic. Concentric luminescent zones reflect chemical changes in dolomitizing fluids concurrent with crystal growth. The sharp boundaries show that compositional changes responsible for zones were relatively abrupt and that the successive fluids passing through the rocks were chemically distinct. Nucleation was favoured by the high surface free-energy of fine-grained areas, while bioclasts were more resistant. The wide variations in zonal sequences imply either spatially differentiated and completely independent nucleations, without any overlap in the period of growth, or local diversity in pore-water chemistry. Lithologies containing siliciclastic grains seem to have favoured nucleation and both these and dissolution seams apparently acted as pathways for fluid movement.

There is no simple distribution of dolomite phases within the formation. Little dolomite is found in the lower part of the succession. In eastern areas, only scattered idiotopic rhombs formed below the debris-flow conglomerates. These are generally dully luminescent but may comprise two or three zones, and outer rims may be bright. In SE areas bright microrhombs reflect either a chemically differentiated environment or a completely separate nucleation event. These are summaried in Fig. 7A.

Type 1 crystals form less than 5% of Kalvsjøen Formation dolomite, although rhombs are locally abundant. Crystals are generally non-luminescent or dull and are rarely overgrown by younger zones. Type 2 crystals, also locally distributed, appear only as isolated rhombs, apparently formed under conditions in which fluid-flow and chemical change were more prolonged. Changes in porewaters resulted in the repetition of bright zones that vary in number and thickness. Nucleation was evidently more difficult because no further new grains were formed and there are no overgrowths of older zones. Type 3 dolomites reflect a single event, implied by the regular and uniform dull luminescence, but the size of rhombs varies, indicating that the substrate was polymodal (cf. Sibley & Gregg 1987). Type 4 zones are composite, reflecting a distinct phase in growth rather than a new nucleation. In some areas conditions seem to have returned to those favouring Type 3, but elsewhere later changes brought about neomorphism. Types 3 and 4 both show a return to duller luminescence that may imply a transition from relatively shallow, perhaps oxidizing, conditions, to a more deeply buried environment with greater chemical uniformity. Both types show neomorphism and calcitization, reflecting the penetration of Mg-poor waters.

Brightly luminescent Type 5 crystals imply shallow burial. They are abundant within and immediately beneath debris-flow deposits that were diagenetically distinct from surrounding rocks (Braithwaite & Heath 1992) and facilitated flow of the dolomitizing fluids. Some Type 5 dolomite formed zones overlying Type 2 rhombs adjacent to the debris-flow complex, pervasively replacing limestones along dissolution seams. Type 6 dolomites reflect the final growth stage of replacive crystals and also the final cements in residual pores. Crystals are commonly ferroan and non-luminescent but may be idiotopic or corroded, shapes varying within and between samples.

Dolomite within the debris-flow complex is commonly associated with dissolution seams (Fig. 6B). Its general absence outside seams indicates that it formed in response to the channelled movement of fluids along the seam. However, crystals are locally found as a pervasive zone outside seams, replacing calcite and isolating resistant grains such as echinoderm fragments, and forming a texture similar to the 'reactate supported texture' of Logan & Semeniuk (1976) and 'zones of pervasive flow' of Buxton & Sibley (1981). This argues for a dispersed flow of dolomitizing fluids along seams but not exclusively confined within them. Put simply, pervasive replacement reflects pervasive flow. Seam-related pervasive dolomitization is analogous to the stylolite-associated cementation described by Dunnington (1967), and Harms & Choquette (1965).

Small amounts of dolomitic sediment, crystal silt, which includes some detrital quartz grains, have accumulated along some styolites. These, and consertal fitted fabrics, are evidence of fluid transport along more open conduits (cf. Braithwaite 1989). They may indicate collapse of such permeable passageways following the removal of support as sea level fell.

The Klinkenberg Formation

Dolomite is relatively common in the Klinkenberg Formation in which some carbonate units are almost entirely dolomite. The total volume of dolomite in the formation decreases from west to east, implying that the source of the fluid lay in the west. However, the changes in thickness are the result of erosion of the principal dolomite unit and the compositional stratigraphy of crystals argues against such an interpretation. As in the Kalvsjøen Formation, textures range from idiotopic to hypidiotopic and crystals show multiple concentric zones, although sequences differ locally. This variety may be time-dependent, reflecting different nucleation events, or synchronous growth may have taken place in pore-fluids that were spatially differentiated, local variations in chemistry producing the different growth sequences summarized in Fig. 7B. In eastern areas crystals show complex concentric zones with dull or dark cores, overlain by thin bright zones, dull red or brown zones, and multiple bright zones, which become more numerous upward in the succession. Crystals in the lower part of the succession are usually calcitized, whereas those at higher levels are unaffected. Most late cements are baroque and dully or non-luminescent. In central areas, there are fewer zones and calcitization and neomorphism are more common, while in the west crystals are generally dully luminescent with simple zonal sequences.

Locally, Klinkenberg Formation dolomites show a crypto-brecciation, only visible in cathodoluminescence. Breccia clasts are unlikely to have become differentiated within a homogeneous mass. The apparent jig-saw fit of blocks suggests that they reflect *in situ* fracturing. If this took place before dolomitization, we might expect little textural differentiation of blocks and channels, and a time-dependent sequence of zonal variation common to both, resulting from inherent differences in permeability. If brecciation occurred after dolomitization, then there should be greater differentiation of blocks and truncation of contained crystals and fabrics at block margins. Although luminescence sequences vary, they appear to show that dolomitization of blocks proceeded to completion, while that in conduits (fractures) was limited to the

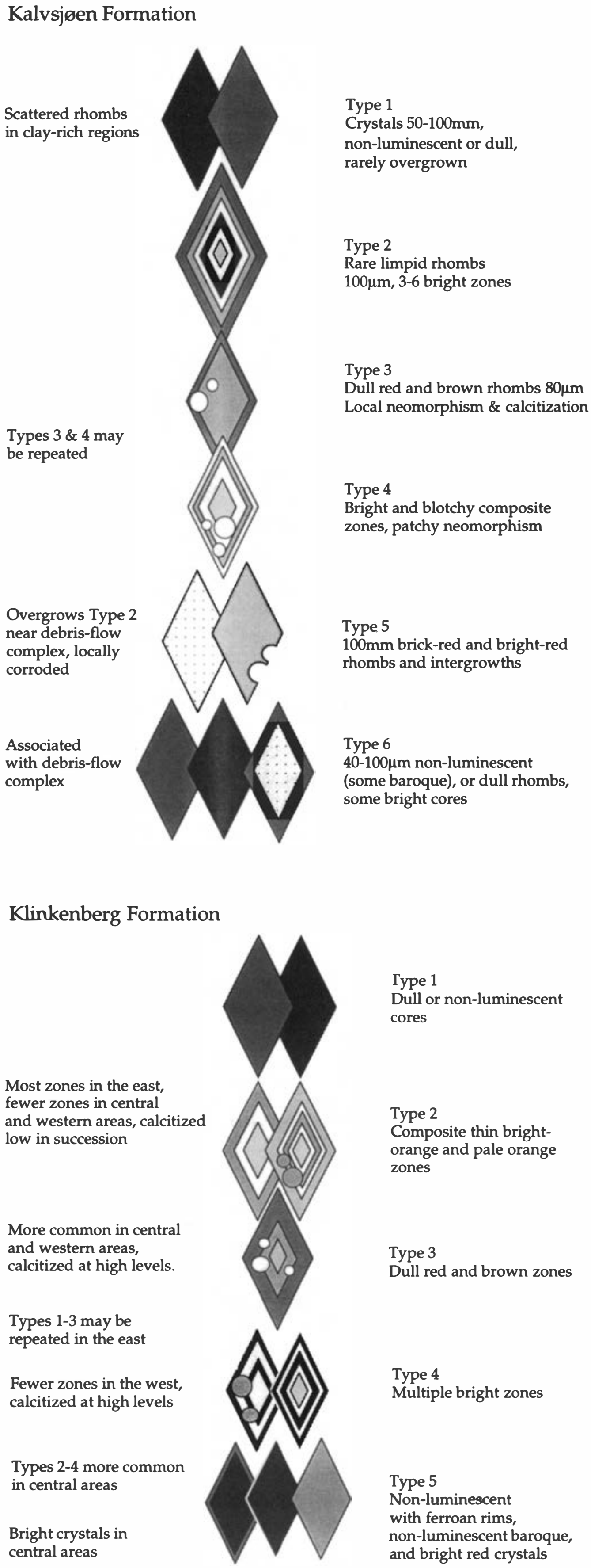

Fig. 7. Summary paragenesis of Hadeland dolomites. Note that these are schematic and are not accurate representations. (*Top*) Kalvsjøen Formation, (*bottom*) Klinkenberg Formation.

growth of relatively sparse, commonly idiotopic, crystals. Growth of these latter crystals continued after all porosity in the blocks was occluded. This seems paradoxical if flow was more effective in the conduits. If flow renewed supplies of any reactants, why did these pathways remain porous and permeable while areas without these advantages were rapidly occluded? The logical answer is that brecciation occurred during or after dolomitization and that these conduits were simply not available when growth commenced.

The erosion surface truncating the thick dolomite unit indicates that this dolomite was either synsedimentary or epigenetic and was exposed at the surface by erosion. The quartz silts below the surface were evidently introduced and trapped within growing cements. Their presence indicates that cements grew relatively near to the surface. The dolomitic crystal silts in the cracks beneath also formed at shallow depths, and the cracks evidently formed pathways for fluids capable of transporting internal sediments excluded from the bulk of the rock. However, the erosion surface may already have been buried as the cement crystals are brightly luminescent.

Fluids and fluid movement

There is no clear evidence of when dolomitization of the Kalvsjøen Formation took place. The debris-flow breccias are truncated by a subaerial erosion surface and the grainstones deposited during the subsequent sea-level rise also show subaerial influence. Widespread emergence occurred north and east of Hadeland during deposition of the Klinkenberg Formaton (see Heath & Owen 1991; Braithwaite et al. 1995) and sea-level changes continued during deposition of the Silurian. Because the zonation seen in dolomite crystals reflects sequential changes in pore-water chemistry, there is some justification for attempting to link the two sets of events.

A broad shallow shelf lay east of Hadeland at the end of the Ordovician (Braithwaite & Heath 1992; Braithwaite et al. 1995). This was eroded to provide the blocks for the debris-flows at the top of the Kalvsjøen Formation. Sea level fluctuated following emplacement of these deposits, and these movements probably repeatedly pumped mixing-zone waters down-dip towards the basin. There is no evidence of evaporites on the shelf and no evidence either of fluids having moved updip on a large scale. For this reason we rule out derivation either from compactional waters or by geothermally driven circulation within the margin of the platform (Kohout circulation). The models of groundwater hydrology beneath carbonate platforms provided by Kaufman (1994) suggests that glacio-eustatic sea-level fluctuations alone are capable of driving large volumes of seawater through platform margins.

At the end of Kalvsjøen Formation time, fluids draining from the shelf passed through the permeable paths provided by the debris-flow breccias, with little penetration of the thin-bedded limestones and shales forming the envelope rocks. We can attribute this to two factors. First, the muddy carbonates would have had relatively low permeability. Second, sedimentological and diagenetic evidence (Braithwaite & Heath 1992) indicates that these rocks were lithified before erosion of the channels in which the debris flows rest. Blocks within the debris-flows are relatively impervious and contain little dolomite, while dolomite in the matrix is dispersed along stylolites and dissolution seams, and also in linear or planar zones lacking obvious dissolution surfaces and implying a more pervasive flow (compare Buxton & Sibley 1981).

The concentration of dolomitization in eastern Hadeland in both the Kalvsjøen and Klinkenberg Formlations only partly reflects the primary distribution of limestones, predominantly indicating the direction of derivation of the bulk of dolomitizing fluids. Brightly luminescent zones are more common and more numerous in eastern areas and in stratigraphically higher positions. They probably reflect emplacement in relatively shallow environments close to the sources of fluids. Evidently, the fluids were not chemically homogeneous. In western, supposedly deeper, locations there are fewer such fluctuatons. Conditions allowed more Fe^{2+} to be incorporated into the dolomite lattice, resulting in the growth of dull or non-luminescent zones (Pierson 1981). Neomorphism probably reflects the passage of waters undersaturated with respect to dolomite. Early-formed calcian and inclusion-rich dolomite was dissolved and replaced by calcite (cf. Thériault & Hutcheon 1987). Dissolution may also have been responsible for opening conduits within the limestones which later collapsed and promoted brecciation. Sequences do not have a uniform paragenesis and this implies that fluids moved intermittently and that successive penetrations did not necessarily occupy precisely the same volumes. These effects spread outwards from the basin margin and thus parallel the lateral penetration of surface waters described by Hitchon & Friedman (1969). Widespread dissolution by surface-derived waters has been described by Hanshaw & Back (1980).

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