

Disseminated ‘jigsaw piece’ dolomite in Upper Jurassic shelf sandstones, Central North Sea: an example of cement growth during bioturbation?

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ABSTRACT

Unusual textural and chemical characteristics of disseminated dolomite in Upper Jurassic shelf sediments of the North Sea have provided the basis for a proposed new interpretation of early diagenetic dolomite authigenesis in highly bioturbated marine sandstones. The dolomite is present throughout the Franklin Sandstone Formation of the Franklin and Elgin Fields as discrete, non-ferroan, generally unzoned, subhedral to highly anhedral ‘jigsaw piece’ crystals. These are of a similar size to the detrital silicate grains and typically account for ≈5% of the rock volume. The dolomite crystals are never seen to form polycrystalline aggregates or concretions, or ever to envelop the adjacent silicate grains. They are uniformly dispersed throughout the sandstones, irrespective of detrital grain size or clay content. Dolomite authigenesis predated all the other significant diagenetic events visible in thin section. The dolomite is overgrown by late diagenetic ankerite, and bulk samples display stable isotope compositions that lie on a mixing trend between these components. Extrapolation of this trend suggests that the dolomite has near-marine $\delta^{18}\text{O}$ values and low, positive $\delta^{13}\text{C}$ values. The unusual textural and chemical characteristics of this dolomite can all be reconciled if it formed in the near-surface zone of active bioturbation. Sea water provided a plentiful reservoir of Mg and a pore fluid of regionally consistent $\delta^{18}\text{O}$. Labile bioclastic debris (e.g. aragonite, Mg-calcite) supplied isotopically positive carbon to the pore fluids during shallow-burial dissolution. Such dissolution took place in response to the ambient ‘calcite sea’ conditions, but may have been catalysed by organic matter oxidation reactions. Bioturbation not only ensured that the dissolving carbonate was dispersed throughout the sandstones, but also prohibited coalescence of the dolomite crystals and consequent cementation of the grain framework. Continued exchange of Mg^{2+} and Ca^{2+} with the sea-water reservoir maintained a sufficient Mg/Ca ratio for dolomite (rather than calcite) to form. Irregular crystal shapes resulted from dissolution, of both the dolomite and the enclosed fine calcitic shell debris, before ankerite precipitation during deep-burial diagenesis.

Keywords Bioturbation, calcite seas, dolomite, isotopes, Jurassic, North Sea.

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INTRODUCTION

Extensive work on calcite cementation in marine sandstones in recent years has greatly improved our understanding of the origins, lateral distribution and precipitation controls for such cements (e.g. Bjørkum & Walderhaug, 1990; Wilkinson, 1991; Taylor *et al.*, 1995; Hendry *et al.*, 1996). Dolomite can also form cements in marine sandstones, but it is much less common than calcite, and controls on its precipitation are less well understood. Early diagenetic dolomites are rare, except in very organic-rich siltstones and mudstones where Ca^{2+} and Mg^{2+} were supplied from sea water by diffusion and/or bio-irrigation, and bicarbonate was produced from organic matter by bacterial sulphate reduction or methanogenesis (e.g. Burns *et al.*, 1988; Compton, 1988; Middelburg *et al.*, 1990). Minor, ferroan, burial dolomite cement may also be present adjacent to faults that link Mesozoic reservoirs to Permian evaporite sequences, for example in the outer Moray Firth. In such cases, hot and saline brines were transported up faults during rifting and halokinesis, and these precipitated dolomites upon mixing with more dilute pore fluids from dewatering of mudrocks surrounding the reservoirs (Burley *et al.*, 1989; Burley, 1993).

Dolomite cements are quite common in arid-region continental sandstones, especially those closely associated with evaporite deposits (e.g. Morad *et al.*, 1990; Spötl & Wright, 1992). In the North Sea, burial dolomite cements are abundant in the Permian Rotliegend and Leman sandstones of the Southern Gas Basin. Their origin is usually ascribed to mixing of evaporite-derived brines with *in situ* depositional fluids during burial (e.g. Sullivan *et al.*, 1990; Purvis, 1992; Turner *et al.*, 1993).

This paper describes pervasive early diagenetic dolomite in Upper Jurassic shelf sandstones that host important hydrocarbon reserves in the South Central Graben of the UK North Sea. The distribution and chemistry of the dolomite indicate that it is a near-surface marine precipitate, but it is atypical of dolomites described previously from marine sandstones. We propose a new interpretation that is consistent with accepted dolomitization models, and that associates the particular characteristics of this dolomite with the highly bioturbated nature of the host sandstones.

SEDIMENTOLOGY AND DIAGENESIS

Dolomite was investigated during an extensive diagenetic study of the Franklin and Elgin gas condensate fields. These are situated in blocks 29/5b, 22/30b and 22/30c of the deep South Central Graben, about 240 km east of Aberdeen (Fig. 1). The reservoir unit is the 300-m-thick Oxfordian Franklin Sandstone Formation (Lasocki *et al.*, 1999), which is broadly equivalent to the Fulmar Formation in less deeply buried parts of the South Central Graben (Price *et al.*, 1993; Howell *et al.*, 1996). It consists of an aggradational succession of very fine-grained marine sandstones, silty sandstones and siltstones, with subordinate mudstones. The majority of sandstones are highly bioturbated (Howell *et al.*, 1996), leading to a heterogeneous distribution of clay matrix (e.g. in burrow linings). Minor horizontal and medium-scale cross-stratification is rarely preserved, and primary sedimentary structures have frequently been obliterated. The ichnofabric is dominated by *Teichichnus*, *Ophiomorpha*, *Anconichnus* and *Planolites*, and relatively slow net sedimentation rates permitted complete bioturbation of the sandstone (Taylor & Gawthorpe, 1993; Gowland, 1996; Martin & Pollard, 1996). Together with the uniformly fine grain size (2.2–4.1 Φ), this suggests deposition in the lower shoreface to offshore transition zone of a well-oxygenated open marine shelf with episodic, rather than sustained, storm influence (Gowland, 1996; Howell *et al.*, 1996; Lasocki *et al.*, 1999). Regional facies distributions were strongly influenced by changing basin topography resulting from synsedimentary tectonism and halokinesis.

Sandstones were sampled from two Franklin Field cores and three Elgin Field cores, at present-day burial depths of 5000–6000 m. The cored wells are between 1.3 and 3.6 km apart, forming a NW–SE transect of about 9 km. The sandstones are variably argillaceous subarkoses and sublitharenites, possibly with some lithic or arkosic wackes (neoformed detrital and authigenic clays being difficult to discriminate). Preserved bioclastic material is limited to sporadic lags of etched and silicified, thick-shelled oysters, but moulds and internal casts of bivalves can sometimes be identified within argillaceous sandstones or late diagenetic ankerite concretions. Dolomite and minor framboidal pyrites are the earliest diagenetic phases in the sandstones. They were followed by microquartz and K-feldspar overgrowth cementation. Late diagenesis featured

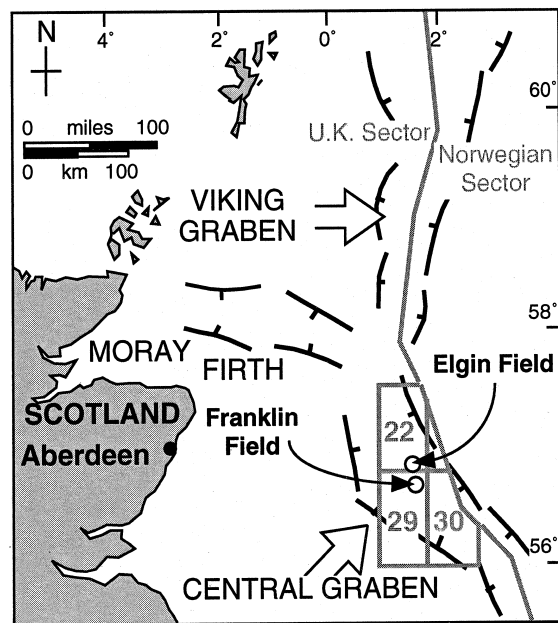


Fig. 1. Map of the South Central Graben showing the location of the Franklin and Elgin Fields.

ankerite and quartz overgrowth cementation, illite authigenesis, dissolution and albitization of K-feldspar and, finally, pyrobitumen deposition (Wilkinson *et al.*, 1997; Lasocki *et al.*, 1999). Ankerite commonly formed concretions as well as syntaxial rim cements overgrowing dolomite. Its deep burial origin is discussed by Hendry *et al.* (2000).

METHODS

Reservoir sandstones were initially examined in more than 240 blue dye-impregnated thin sections cut from Soxhlet-extracted core plugs and hand specimens. These were stained for carbonate and feldspar identification, and 60 were point counted (400 points per section). The bulk mineralogy of some samples was determined by X-ray diffraction (XRD). Selected thin sections were subsequently polished for cathodoluminescence (CL) and photoluminescence (PL) petrography. CL was carried out in a CITL Technosyn 8200 Mk II cold cathode instrument, and PL was carried out using a Nikon EF-D mercury fluorescence unit with filter blocks giving incident blue ($\lambda \approx 560$ nm) and ultraviolet ($\lambda \approx 360$ nm) light. These polished sections were then carbon coated for backscatter scanning electron microscopy (BSEM), using two instruments: an ISI ABT-55 at Aberdeen University and a Leica

Stereoscan 360 at Glasgow University. Both were equipped with LINK systems energy-dispersive X-ray analysers for compositional analysis. Operating conditions were 20 kV and 60 s count time, and data were corrected using the ZAF4 FLS program. Several fluid inclusion wafers were also prepared and examined, but dolomites contained few inclusions large enough to be examined.

Offcuts from selected point-counted core samples were manually disaggregated with a mortar and pestle for carbonate stable isotope analysis at the Scottish Universities' Research and Reactor Centre (SURRC, East Kilbride, UK) and in the laboratories of Elf Aquitaine Production (EAP, Pau, France). All the samples contained minor to abundant late diagenetic ankerite in addition to dolomite, and the two were impossible to separate physically. For the purposes of characterizing the dolomite isotopically, samples were selected in order to avoid concretions where the isotopic signal would be overwhelmingly dominated by ankerite. 'Bulk' analyses (samples completely reacted in anhydrous phosphoric acid at 100 °C) were combined with a 'progressive leach' procedure, whereby the disaggregated sample was reacted with phosphoric acid for 3 h at 25 °C, then for ≥ 8 h at 100 °C, the CO₂ being fully extracted and analysed after each stage. Results show that this procedure was unable to separate the two carbonate phases completely. Consequently, all the isotope analyses consist of a mixture of dolomite and ankerite in varying proportions, with artificial enhancement of the dolomite:ankerite ratio in some samples. Extracted CO₂ was purified and analysed according to standard procedures, and samples were run on cross-calibrated VG SIRA10 mass spectrometers. Analytical reproducibility in both laboratories was better than 0.1‰ for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. The results are reported in conventional ‰ notation with respect to the PDB standard and are listed in Table 1.

RESULTS

Dolomite petrography

Dolomite usually accounts for no more than 5% of the sandstone by volume, occasionally reaching about 10%. Its textural attributes are consistent throughout the Franklin and Elgin reservoirs. Dolomite crystals are 20–200 μm in size, similar to or smaller than the associated sand grains. The

Table 1. Isotopic data for carbonate in Franklin Formation samples.

Sample	$\delta^{13}\text{C}$ (‰ PDB)	$\delta^{18}\text{O}$ (‰ PDB)
Franklin Field		
FR1	-3.0	-7.6*
FR2.1A	-3.1	-10.3*
FR2.1B	-3.9	-10.6*
FR2.2A	-3.0	-10.0*
FR2.2B	-3.1	-8.8*
FR2.3A	-1.8	-7.9*
FR2.3B	-1.2	-3.4*
FR2.4A	-3.2	-10.6*
FR2.4B	-2.9	-8.2*
FR3.1A	-1.6	-6.7*
FR3.1B	-0.7	-5.0*
FR3.2A	-1.7	-6.8*
FR3.2B	-0.9	-5.3*
FR4.1A	-1.5	-8.1*
FR4.1B	-3.2	-8.6*
FR4.2	-2.0	-8.2
FR5	-2.5	-9.5
FR6	-4.8	-11.5
FR7	0.1	-3.1
FR8	-3.6	-9.4
FR15A	-4.3	-8.3*
FR15B	-4.1	-12.8*
Elgin Field		
ELA1	-3	-10.5
ELA2	-1.5	-6.9
ELA4	-3.7	-12.2
ELA6	-2.32	-8.6
ELA8	-2.4	-9.2
ELB1	-2.8	-8.1
ELB2	-1.8	-5.8
ELB4	-2.4	-8.1
ELB5	-2.8	-8.5
ELC1	-4.1	-9.9
ELC2	-5.5	-11.5
ELC3	-3.0	-11.1
ELC34	-3.6	-9.6
ELC35	-2.7	-7.6
ELC36	-1.5	-5.5

* Samples were analysed by the progressive leach technique (A = first extraction, B = second extraction), with the remainder as bulk digestions.

crystals are equant, but range from (rare) planar-rhombohedral to (frequent) highly anhedral 'jigsaw piece' shapes (Fig. 2A and B). Despite this textural variability, they are remarkably consistent in CL. The overwhelming majority of crystals are uniformly bright orange-red (Fig. 2B and C), with less than 5% (estimated) displaying orange, yellow and green-yellow colours and/or showing subtle concentric zonation. These atypical crystals are randomly dispersed among the more common variety; there is no consistent cement

stratigraphy. None of the dolomites are photoluminescent. Data from EDXA confirm that the dolomites are non-ferroan (Fig. 3B) and slightly calcic compared with stoichiometric dolomite. All the dolomite crystals are overgrown by syntaxial, non-luminescent ankerite, either as thin rims or as pore-filling cements (Fig. 2A–C). Dolomite–ankerite boundaries are invariably sharp in both CL and BSEM, but some compositional variation is present within the ankerite (Fig. 3; Hendry *et al.*, 2000).

One of the most striking features about dolomite in the Franklin sandstones is that it is only developed as discrete, single crystals. Concretions or polycrystalline aggregates (even on a sub-millimetre scale) are never seen (e.g. Fig. 2B and C). Furthermore, although dolomites sometimes contain silt-grade material (quartz silt and, rarely, framboidal pyrite), they never envelop the surrounding sandstone grain framework. In this respect, they differ markedly from later diagenetic ankerite; dolomite crystals are only ever in point contact with adjacent quartz sand grains, whereas ankerite both encloses and peripherally replaces such grains (Fig. 2A, D and 3A). Point counting and CL petrography indicate that the dolomite is uniformly distributed through the sandstones, with no quantifiable relationship with sediment texture, detrital composition (including clay content) or ankerite content (Fig. 4).

Another peculiar feature of the dolomite is the nature of the anhedral, 'jigsaw piece' crystals. These contain polygonal or curved 'notches', 10–20 μm in diameter, which are always filled with syntaxial ankerite (Fig. 2B and C). Some of the notches appear to be entirely surrounded by dolomite, but this may be a cut effect. The full range of crystal shapes from well-formed rhombohedra to these "jigsaw piece" examples may be present within an individual microscopic field of view.

Isotopic results

Carbonate isotopic compositions determined by bulk and progressive leach procedures plot on a well-defined positive covariant trend, with $\delta^{18}\text{O}$ ranging between -3.1 and -12.8‰ PDB and $\delta^{13}\text{C}$ between 0.1 and -5.5‰ PDB (Fig. 5). Data from each of the sampled wells overlap, but the more ^{18}O -enriched values generally correspond to the second extractions from the progressive leach analyses. This arises from the fact that dolomite is always overgrown by ankerite. The first dissolution therefore selectively sampled the ankerite rims of the manually crushed samples.

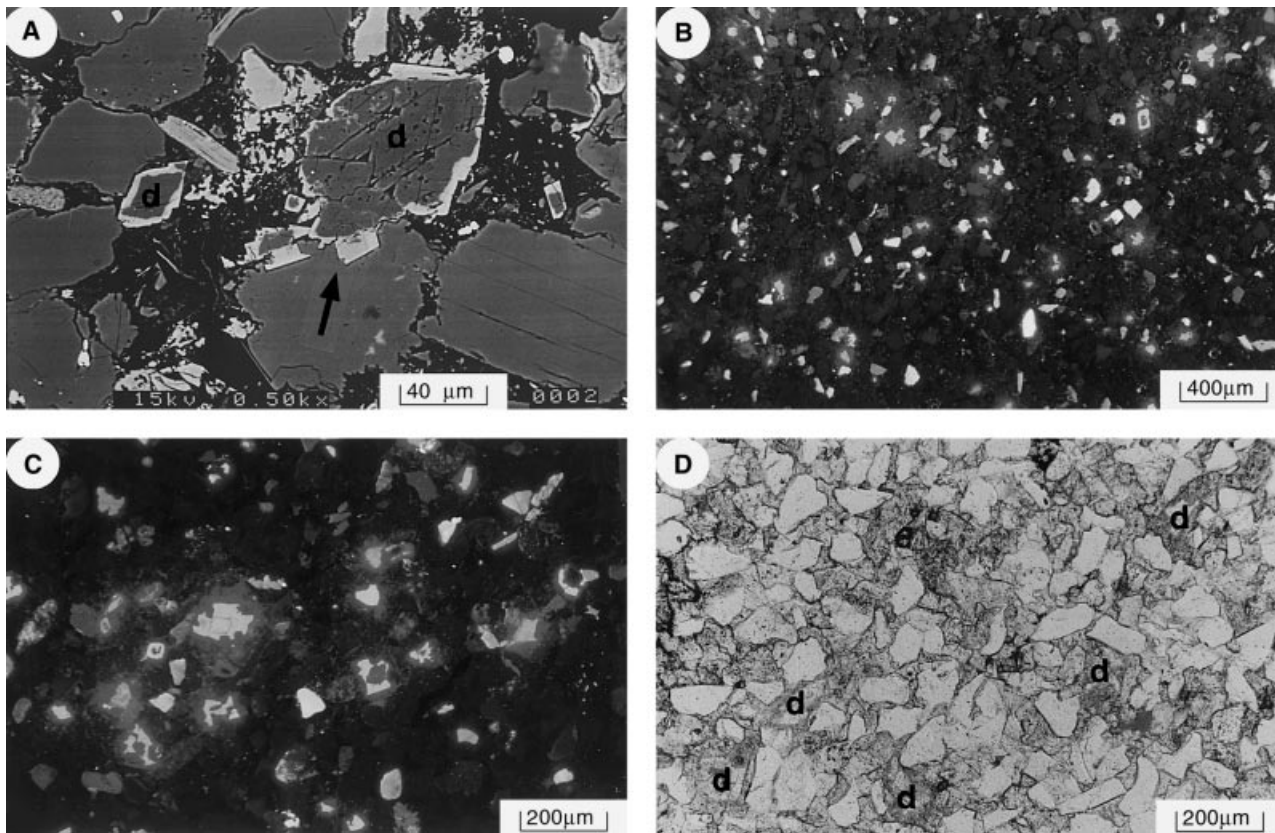


Fig. 2. Dolomite petrographic fabrics in the Franklin sandstones. (A) BSEM photomicrograph showing typical, anhedral dolomite crystals (d) with ankerite rims (pale grey); note that ankerite replaces the surrounding detrital grains (arrow), but dolomite does not. (B) CL image from typical Franklin Formation sandstone showing the disseminated moderate-bright luminescent and anhedral dolomite crystals. Very bright luminescent grains are feldspars. The 'fuzzy' luminescent rims around the bright dolomite (and feldspar) crystals are photographic artifacts and not zones. (C) CL image of brightly luminescent dolomite in non-luminescent ankerite concretion; note the variability of crystal shapes from subhedral rhombs to highly anhedral 'jigsaw pieces', and a similar dolomite distribution to that in porous sandstones (B). As in (B), the luminescent haloes around the bright dolomite crystals are a photographic artifact. (D) Superimposed CL and transmitted light photomicrograph showing dolomite crystals (d) in point contact with surrounding siliciclastic grains. Subsequent ankerite occludes intergranular pore space.

A straight-line $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$ trend can result in two ways:

- 1 From physical mixing between two end-members, each of limited compositional range.
- 2 By continuous evolution of pore-water $\delta^{13}\text{C}$ during precipitation at increasing temperatures.

The second explanation has been widely used for explaining such trends in petrographically and compositionally zoned dolomites (e.g. Burns & Baker, 1987; Klein *et al.*, 1999). However, in the case of Elgin–Franklin, the small crystal sizes prohibit rigorous testing of the interpretation using standard analytical procedures (ion microprobe data might have helped but were unavailable). It is conceptually difficult to propose a straightforward mechanism for progressively decreasing the pore fluid $\delta^{18}\text{O}$ and the $\delta^{13}\text{C}$

its dissolved CO_2 in constant relationship during very shallow burial. Temperature directly controls the fractionation of O isotopes between the pore fluid and diagenetic cements, but indirectly influences the stages of organic matter breakdown that release CO_2 to the pore fluid. During shallow burial, the composition of this CO_2 can fluctuate widely (Irwin *et al.*, 1977) and, even during deeper burial, there is no direct evidence that the decarboxylation of organic matter proceeds at a constant rate with increasing temperature (e.g. Lundegard & Kharaka, 1994).

Circumstantial evidence favours the first of the interpretations for the Elgin–Franklin isotopic data. First, a lack of CL zonation in dolomite and tightly defined major element compositions of dolomite and ankerite are consistent with isotopic uniformity (Fig. 3B). Secondly, although

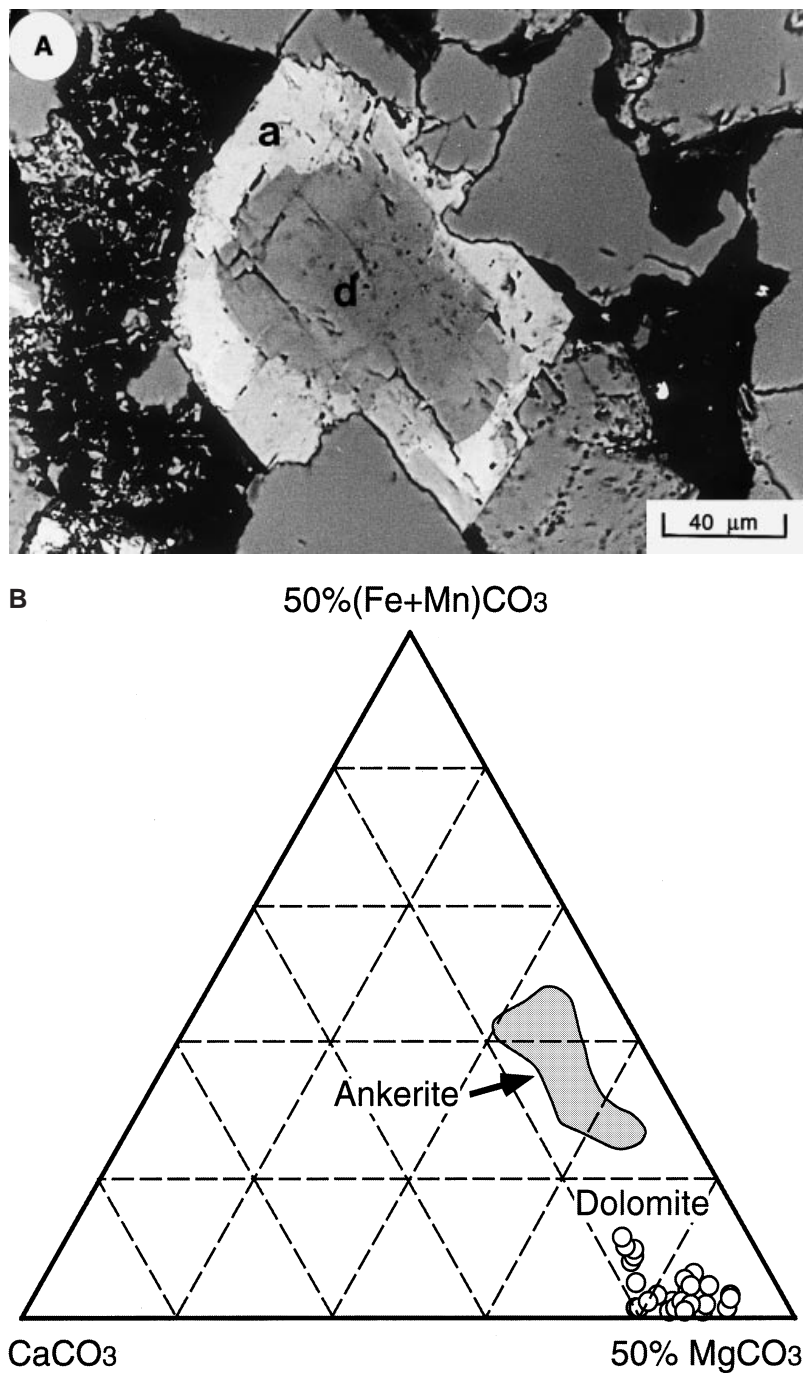


Fig. 3. (A) BSEM photomicrograph of a typical anhedral dolomite (d) crystal syntaxially overgrown by ankerite (a). Note the irregular zonation of ankerite but sharp dolomite–ankerite boundary. (B) Chemical composition of dolomite determined by EDXA. Range of ankerite values from Hendry *et al.* (2000) shown for comparison.

ankerite syntaxially overgrows dolomite throughout the Franklin sandstones, there is a paragenetic break between dolomite and ankerite that represents more than 3000 m of burial (Hendry *et al.*, 2000). During this interval, there is both minor dissolution of the dolomite as well as the onset of quartz overgrowth cementation. The fact that ankerite syntaxially overgrows dolomite merely reflects a substrate control on ankerite

precipitation and its relative volumetric dominance (see Fig. 4D). Thirdly, while it was not possible to demonstrate a strong correlation between point-counted dolomite:(dolomite + ankerite) ratio and isotopic composition (owing to large errors inherent in point counting low-abundance phases), visual examination suggests that the isotopically lightest analyses are dominated by ankerite. This is further supported by

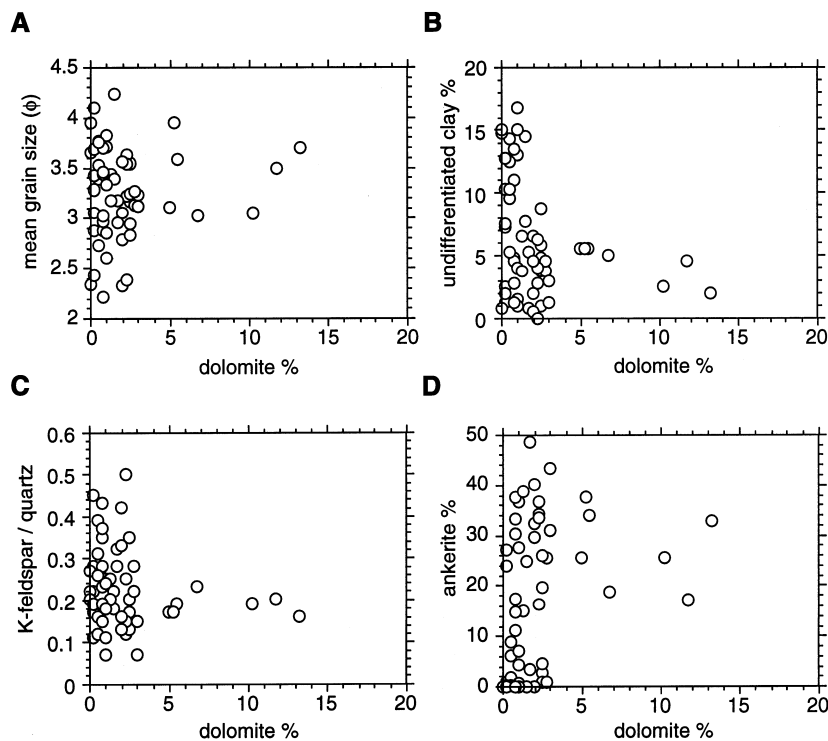


Fig. 4. Point-counted dolomite vs. (A) detrital grain size, (B) clay content, (C) K-feldspar:quartz ratio and (D) ankerite content.

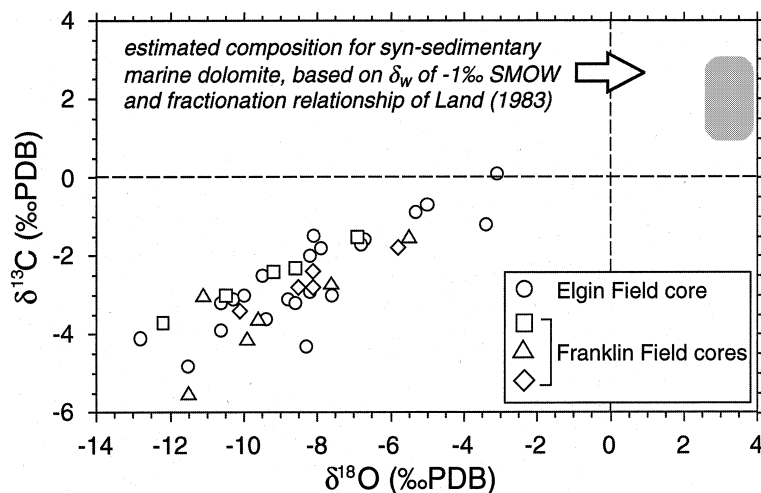


Fig. 5. Cross-plot of carbon and oxygen isotope data from carbonate in Franklin Formation sandstones (other than ankerite concretions). See text for discussion of dolomite end-member value.

the fact that ankerite-cemented concretions in the formation all have bulk $\delta^{18}\text{O}$ values $\leq 10\text{‰}$ PDB (Hendry *et al.*, 2000).

While accepting that isotopic zonation of the dolomite cannot be disproved, we conclude that the linear isotopic trend in Fig. 5 is a product of physical mixing, and that the dolomite is likely to have a very limited range in isotopic composition. Given that all samples contain some isotopically light ankerite, the dolomite end-member should then have an average $\delta^{18}\text{O}$ value that is more

positive than -3.1‰ PDB and a $\delta^{13}\text{C}$ value that is more positive than 0.1‰ PDB.

DISCUSSION

A realistic interpretation of dolomite petrogenesis in the Franklin sandstones must account for: (1) its pervasive distribution; (2) its chemical and petrographic homogeneity for some 9 km distance across both the Franklin and the Elgin

fields; (3) its variable and frequently very irregular crystal shapes; (4) its positive $\delta^{13}\text{C}$ composition and limited O and C isotopic range; and (4) the ubiquity of disseminated individual crystals that do not enclose the detrital sand grains, rather than poikilotopic, polycrystalline or concretionary cements.

Environment of precipitation

Several factors argue for dolomite being an early diagenetic precipitate, formed close to the sediment–water interface. First, sea water offers the most abundant and geographically widespread source of Mg^{2+} , and there is no evidence for dissolution of Mg-rich phases in the sandstones before dolomite authigenesis. Secondly, sea water also provides a reservoir of geographically constant $\delta^{18}\text{O}$ composition. In contrast, dolomite cements formed as a consequence of subsurface fluid flow would be expected to show a range in chemical/isotopic composition and abundance with respect to the flow vector. This would be most pronounced if Mg-rich fluids were sourced from underlying strata (such as Permian evaporites) via fault conduits (e.g. Burley, 1993), or from dewatering mudrocks surrounding the reservoir (e.g. Gawthorpe, 1987; Macaulay *et al.*, 1993). Likewise, dolomite formed in coastal aquifers tends to show complex zonation, reflecting the dynamic chemistry of mixing zones (e.g. Taberner & Santisteban, 1987; Morad *et al.*, 1992). In any case, the Franklin sandstones are predominantly outer-shelf deposits deposited several kilometres from the palaeoshoreline (e.g. Lasocki *et al.*, 1999). Thirdly, the non-ferroan nature of the dolomite suggests that it formed either in oxic conditions before the bacterial reduction of ferric iron, or during shallow-burial bacterial sulphate reduction when any Fe^{2+} was incorporated into highly insoluble Fe-sulphides (Raiswell, 1982). Otherwise, Fe^{2+} would readily have exchanged for Mg^{2+} in the dolomite lattice.

Using the fractionation relationship of Land (1983), it is possible to estimate the $\delta^{18}\text{O}$ value of dolomite precipitated from unmodified Jurassic sea water. A palaeotemperature range of 15–20 °C is assumed for the outer shelf, in comparison with the Callovian age Oxford Clay Formation (Anderson *et al.*, 1994). Given a non-glacial sea-water value of -1‰ SMOW, near-surface dolomite cement should have a $\delta^{18}\text{O}$ composition of about +2.7 to +3.9‰ PDB. Assuming that the isotopically lightest values on Fig. 5 are overwhelmingly dominated by ankerite, the heaviest bulk analysis of -3.1‰ PDB would correspond to

a dolomite:ankerite ratio of about 50:50. This compares favourably with visual estimation from stained thin sections.

The fact that dolomite never envelops the adjacent detrital sand grains, but is in point contact with them, raises a question as to whether it is detrital. This point is very difficult to prove conclusively. The local development of euhedral dolomite rhombs in addition to the ‘jigsaw piece’ crystals favours an authigenic origin, as does the lack of any geographic or stratigraphic trends in its abundance. However, the principal argument against a detrital origin for the dolomite is the lack of a potential source. It seems unlikely that a suitable parent rock can have remained undetected in this area of the North Sea, which is one of the most intensively explored regions in the world. The Fulmar Formation (including the Franklin sandstones) was mostly derived from Triassic sources, but with much intrabasinal reworking (Gowland, 1996). Triassic Skagerrak Formation and mid-Jurassic Pentland Formation sandstones in the Central Graben may contain local dolomite, but are predominantly of continental origin (Steel & Ryseth, 1990; Gowland, 1996). They are not considered to be a suitable source for detrital dolomite with the fine grain size and near-marine isotopic composition inferred for Franklin sandstones. Despite the effects of upper Jurassic faulting and halokinesis, regional studies (from seismic data) do not suggest that Permian Zechstein (carbonate) facies were exposed to erosion during the Upper Jurassic (Price *et al.*, 1993). In addition, previous studies of the Fulmar Formation sandstones have noted frequent early diagenetic dolomite, but no abundant detrital dolomites (Johnson *et al.*, 1986; Saigal *et al.*, 1992; Clelland *et al.*, 1993).

Carbonate supply and controls on precipitation

Positive $\delta^{13}\text{C}$ values for the dolomite, extrapolated from Fig. 5, strongly suggest that the carbon was supplied from a marine bioclastic source. The alternative, CO_2 produced via bacterial oxidation of organic matter, would tend to produce carbonate with a characteristic large negative $\delta^{13}\text{C}$ (about -15 to -25‰ PDB; Curtis, 1987). Direct precipitation from dissolved carbonate in the sea water is also unlikely in the outer-shelf setting, in which there was an absence of vigorous and prolonged current activity analogous to that responsible for hardground formation (James & Choquette, 1990).

Dolomite precipitation from modern sea water is inhibited relative to CaCO_3 by low CO_3^{2-} activities and by the activation energy to dehydrate the Mg^{2+} ion (Machel & Mountjoy, 1986). Sandstones generally do not contain enough labile organic matter for sufficiently intense microbial activity to overcome kinetic barriers for dolomite precipitation. Dolomite is therefore much less common than calcite as near-surface cement in marine sandstones. In contrast, it is relatively common as dispersed cements and concretions in organic-rich mudrocks and siltstones, particularly where slow sedimentation rates and intense bacterial activity maximize carbonate alkalinity in the sulphate reduction to anaerobic methane oxidation zones (e.g. Burns *et al.*, 1988; Middelburg *et al.*, 1990). Furthermore, results from DSDP studies of organic-rich continental margin sediments confirm that dolomitization is enhanced by the presence of detrital carbonate, which provides both CO_3^{2-} and Ca^{2+} ions (Compton, 1988).

Assuming that dolomite in the Franklin sandstones grew at the expense of bioclastic carbonate, it is necessary to account for the cause of this transformation. Biogenic aragonite and Mg-calcite are metastable in sea water, and their dissolution is known to be triggered by pH decline during open-system bacterial sulphate reduction, bacterial sulphide oxidation and aerobic bacterial oxidation of organic matter (Berner & Westrich, 1985; Morse *et al.*, 1985; Walter & Burton, 1990; Boudreau, 1991; Canfield & Raiswell, 1991). Such processes also introduce ^{13}C -depleted CO_2 into the pore fluids, for which there appears to be little evidence in the Franklin dolomite. However, the Oxfordian represents the acme of the late Mesozoic 'calcite seas' episode, when elevated oceanic $p\text{CO}_2$ levels and decreased $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratios would have decreased the carbonate saturation level of contemporary sea water compared with the present day (Wilkinson *et al.*, 1985; Palmer *et al.*, 1988). It is therefore possible that very little organic matter oxidation was required to initiate aragonite and Mg-calcite dissolution in the uppermost sediment column (cf. Hendry, 1993; Hendry *et al.*, 1995).

Once aragonite and Mg-calcite started to dissolve, a more stable carbonate would have been able to precipitate in a geologically rapid, mineral-controlled transformation (Morse & Mackenzie, 1990). Under these circumstances, it is reasonable to assume that the dissolved carbon reservoir would have been dominated by the bioclastic source, with minimal contribution from organic

matter (particularly if there was some *in situ* replacement of the shell material).

Origin of irregular crystal habits

Dolomite precipitated at low temperatures tends to crystallize by layer-growth mechanisms and usually adopts rhombohedral, planar crystal fabrics (Sibley & Gregg, 1987). Anhedral, scalloped and rounded carbonate cement crystals have been ascribed to dissolution (e.g. Taylor, 1990; Morad *et al.*, 1992; Kupecz & Land, 1994) and, by analogy, some dissolution of Franklin dolomite crystals is interpreted to have taken place before ankerite precipitation. However, the extreme 'jigsaw piece' crystal shapes (Fig. 2B and C) are not typical of simple corrosion textures. There is no evidence that the dolomite crystals formed part of a formerly extensive cement mosaic, and framework grain surfaces examined by scanning electron microscopy (SEM) show none of the characteristic textures of dolomite dissolution (Burley & Kantorowicz, 1986; Maliva & Siever, 1990).

An alternative explanation is that dolomite crystals partially enclosed silt-grade, calcitic bioclastic debris that remained intact until replacement by ankerite to 'repair' the crystal outlines during deeper burial (Fig. 6). Molluscs would have been the dominant bioclasts in an Upper Jurassic shelf setting, so calcitic shell fragments would inevitably have accompanied the less stable aragonite and Mg-calcite detritus in the sediment. This calcite subsequently acted as the principal carbonate source for the ankerite (Hendry *et al.*, 2000). The presence of silt-grade bioclastic material throughout the sandstone would simply have arisen from the decay of the organic matrix in the shells, followed by disaggregation and dispersal during bioturbation (cf. Alexandresson, 1979).

Significance of bioturbation

Franklin Formation sandstones are very heavily bioturbated and contain an unusual example of disseminated early diagenetic dolomite that has been described above. It is reasonable to examine the possibility of a causal link between these features: can bioturbation account for the cement textures, mineralogy and composition? Figure 7 illustrates schematically how bioturbation may have been a major control on the nature and distribution of early cementation.

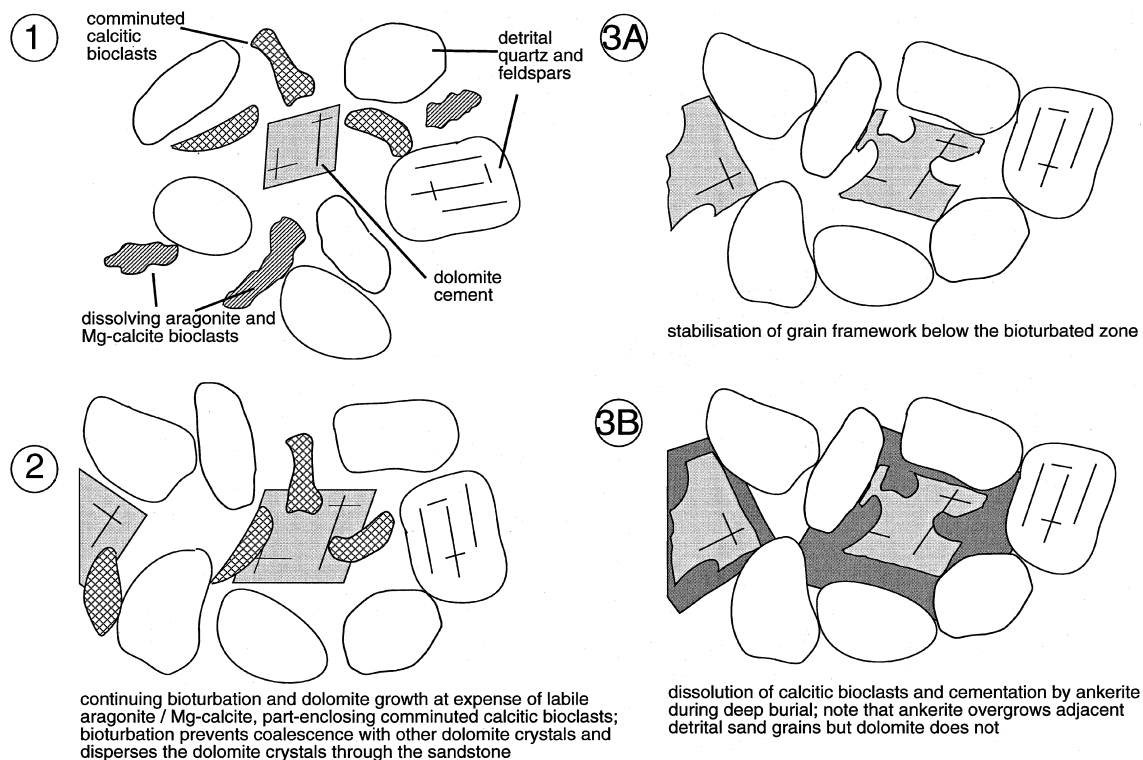


Fig. 6. Cartoon depicting the probable origin of highly irregular dolomite crystal morphologies and the point-contact relationship of dolomite with detrital sand grains.

Bioturbation is an important symsedimentary process. It redistributes the grain framework, disaggregates and disperses bioclastic material through the uppermost sediment column, irrigates the sediment by enhancing the exchange of oxygen and solutes with the overlying sea water, and introduces CO_2 and organic matter through the metabolic activities and post-mortem decay of burrowing organisms (e.g. Aller, 1982; Berner & Westrich, 1985). All these processes have the potential to affect early diagenesis profoundly (Fig. 7). For example, many limestones contain dolomite or silica-cemented burrows. However, the influence of bioturbation on sandstone diagenesis has rarely been considered.

As discussed above, bioturbation may have triggered the dissolution of labile bioclastic carbonate. The preservation potential of carbonate shells in modern, organic-rich siliciclastic sediments is minimized at high bioturbation rates, particularly when shell density is relatively low (Aller, 1982). Pore fluid within the zone of bioturbation is typically heterogeneous, with both lateral and vertical gradients in oxygenation. Despite this, the Franklin dolomite is remarkably unzoned, suggesting that it formed either in fully oxygenated conditions or in anoxic microenvi-

ronments where sulphate reduction was prevalent. C isotope data support the former, except in rare cases in which the dolomite contains framboidal pyrite.

Bioturbation offers an explanation for the development of dolomite rather than calcite as the near-surface precipitate in the Franklin sandstones. Global mass balance calculations (Wilkinson & Algeo, 1989) suggest that Upper Jurassic ocean water had an $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratio of about 1. Although much less than the present-day value (≈ 5), this was sufficient for dolomite formation. Dolomitization of calcite can be expressed by Eq. 1:



The equilibrium constant for this reaction is 0.67, so aqueous $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratios of >0.67 favour the dolomitization process (Hsü, 1967). Wilkinson & Algeo (1989) also argued that elevated $p\text{CO}_2$ levels of the calcite seas would have destabilized aragonite and Mg-calcite relative to both calcite and dolomite, the latter remaining the more thermodynamically stable phase. As Franklin pore fluids were undersaturated with respect to aragonite and Mg-calcite (but not calcite), these minerals could be replaced by dolomite provided that the $\text{Mg}^{2+}/$

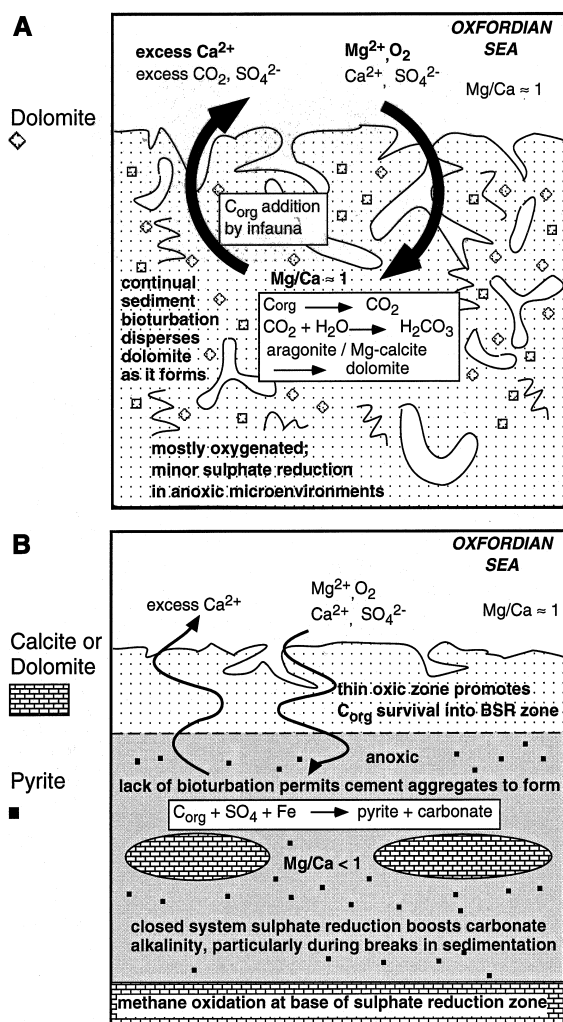


Fig. 7. Cartoon summarizing the inferred biological and chemical processes operative during shallow-burial precipitation of Franklin Formation dolomite, and a comparison with the more common situation of early diagenetic concretionary carbonate cementation in marine sandstones.

Ca^{2+} ratio was maintained close to unity. This required both a plentiful supply of Mg^{2+} from sea water and constant removal of excess Ca^{2+} released by the reaction. Intense bioturbation is a considerably more efficient agent for vertical transport of pore fluid constituents than diffusion (Goldhaber *et al.*, 1977); in its absence, the increasing Ca^{2+} pore fluid concentrations would have led to calcite cementation of the Franklin sandstones. Prolonged and intense bioturbation was therefore vital for dolomite precipitation.

Textural features of the Franklin dolomite also suggest that bioturbation of the host sediment influenced the cementation process. The disseminated and pervasive nature of the dolomite is likely to reflect a similar distribution of precursor

labile bioclastic debris, resulting from thorough mixing of the uppermost sediment layers. Moreover, continued bioturbation during cement growth could readily have prohibited both the amalgamation of adjacent crystals to form cement aggregates and the envelopment of detrital sand grains by the dolomite. The fact that dolomite crystals could so easily be misinterpreted as detrital grains argues strongly for their formation while the sediment was still being reworked by the burrowing fauna and/or intermittent storm events.

The Franklin dolomite is unlikely to be unique. Mazzullo *et al.* (1995) described subtidally precipitated, ^{13}C -enriched dolomite in highly bioturbated Holocene sediments off Belize. In contrast, early diagenetic dolomite in less bioturbated marine sandstones is typically present as concretions, patchy cements or at least aggregates of rhombohedral cements (e.g. Boles & Ramseyer, 1987; Lawrence, 1991; Taylor *et al.*, 1995). These have 'organic' $\delta^{13}\text{C}$ signatures and probably formed below the biologically reworked surface layers when breaks in sedimentation prolonged the residence time of individual beds in the anaerobic sulphate reduction and methanogenic zones.

Regional perspective

Dolomite is a common cement in the Fulmar Formation throughout the Central Graben region of the North Sea. Dolomite in the Fulmar Field itself consists principally of isolated sparry rhombs with ferroan rims and near-marine isotopic compositions (Johnson *et al.*, 1986; Saigal *et al.*, 1992; Clelland *et al.*, 1993). By analogy with the Franklin sandstone, it is suggested that a relatively slow net sedimentation rate and intense bioturbation across the Fulmar shelf permitted dolomite to form at shallower depths than in other marine sandstone reservoirs. However, non-ferroan dolomite aggregates and concretions are also present in the Fulmar Field, and amounts of dolomite (mean values from 4.5 to 18 vol.%) are much greater than in the Franklin sandstones. The reason for this discrepancy is uncertain, but probably relates to subtle differences in the depositional environment, primary bioclast content and amount of bioturbation, favouring dolomite precipitation at slightly greater depths where the sediment was less frequently disturbed. Johnson *et al.* (1986) noted that disseminated dolomite typifies the finest grained and most bioturbated offshore sandstones (similar to Franklin sandstone facies), and

concretions occurred in coarser, more porous upper shoreface strata.

In contrast, bioturbated Upper Jurassic shoreface sandstones of the Ula Formation (Ula Field, East Central Graben) contain early diagenetic calcite cement (Nedkvitne *et al.*, 1993). As discussed above, this may be a consequence of insufficient bioturbation to maintain sufficiently high Mg^{2+}/Ca^{2+} ratios for dolomite to form, particularly given that the calcite forms tightly cemented beds associated with bioclasts. Hendry *et al.* (1996) interpreted marine carbonate cements in the Lower Cretaceous Scapa Field of the outer Moray Firth as having formed by stabilization of aragonite bioclasts shortly after deposition below the ambient aragonite saturation depth. The host sediments were less bioturbated than the Fulmar Formation, such that low-Mg calcite was the favoured precipitate, and initially dispersed crystals were able to coalesce into concretions.

CONCLUSIONS

Very fine-grained, highly bioturbated, shelf sandstones of the Upper Jurassic Franklin Formation contain disseminated, authigenic non-ferroan dolomite crystals. The dolomite is syntaxially overgrown by variable amounts of late diagenetic ankerite, but extrapolation of a bulk isotopic mixing trend suggests that dolomite has a relatively uniform isotopic composition. The dolomite is atypical of marine carbonate cements in sandstones in terms of its pervasive distribution, lack of cement mosaics or concretions, chemical homogeneity and essentially 'marine' rather than 'organic' $\delta^{13}C$ signature. It also possesses highly variable and irregular crystal shapes, reflecting the envelopment of silt-grade calcitic bioclastic detritus that was replaced by ankerite during later diagenesis. These features can all be explained in terms of precipitation from ambient marine pore fluids within the zone of bioturbation.

Sea water was the only realistic source of Mg^{2+} for widespread early diagenetic dolomite formation, and a marine origin for the dolomite accounts for the limited range of isotopic composition far better than any models involving subsurface fluid flow or fluid mixing. Carbonate was derived from aragonite or Mg-calcite bioclasts that were disseminated through the sandstones by the burrowing fauna. These bioclasts were relatively unstable in Oxfordian 'calcite seas' water, and dissolved in response to transient and/or localized pH decrease

during microbial oxidation of organic matter. Less soluble calcitic bioclasts remained intact, and silt-grade fragments were locally incorporated into growing dolomite crystals.

Severe bioturbation was critically important in replenishing Mg^{2+} and removing excess Ca^{2+} from the shallow pore fluids, such that dolomite could continue to form at the expense of aragonite and Mg-calcite. Given the non-ferroan dolomite chemistry, it is likely that bioturbation kept the sediment well aerated. The lack of intergrown dolomite crystals, cement mosaics or envelopment of adjacent detrital sand grains can also be attributed to burrowing activity, which prevented physical stabilization of the uppermost sediment column during dolomite precipitation.

We propose that our observations demonstrate that the process feedback between bioturbation and diagenesis, long recognized from mudrocks and limestones, is equally applicable to some sandstones. It should be particularly important during 'calcite seas' times when early diagenetic carbonate stabilization reactions are enhanced, and many more examples are probably awaiting documentation.

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