Depositional environment and apparent age of the Fauske carbonate conglomerate, North Norwegian Caledonides

VICTOR A. MELEZHIK, TOM HELDAL, DAVID ROBERTS, IGOR M. GOROKHOV & ANTHONY E. FALLICK

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The Fauske conglomerate represents a rather rare case of a monomict carbonate conglomerate in the Late Neoproterozoic to Silurian, lithostratigraphic successions of the Norwegian Caledonides. Lithological varieties of this conglomerate unit from the Løvgavlen quarry have a highly decorative quality and are well known in both domestic and international markets under trading names such as 'Norwegian Rose', 'Jaune Rose', 'Norwegian Green', 'Antique Foncé' and 'Hermelin'. The Fauske conglomerate is a 60 m-thick unit which rests on either dark grey ('blue') calcite marbles or white dolomite marbles. The latter are jointed and fragmented, and also appear as sedimentary collapse-breccia and debris where they are in direct contact with the conglomerate. Although the Fauske conglomerate has been involved in two main pulses of Caledonian tectonic deformation, which produced an early, syn-metamorphic flattening of the clasts and a later folding or rotation of clasts into a spaced cleavage, the overall sedimentary features are still remarkably well preserved.

The Fauske conglomerate unit consists of 25 beds (5 cm to 3 metres thick) comprising landslide, carbonate debris and carbonate breccia–conglomero-breccias–greywacke lithofacies. Blocks, fragments, cobbles, pebbles and smaller clasts are mainly of white dolostone and pink, beige, white and 'blue' calcite marbles. The matrix has a granoblastic texture and similar range in lithology with variable amounts of quartz, fuchsite, sericite, muscovite and chlorite. Within the unit, an upward fining of the clasts is followed by the gradual development of calcareous greywacke layers which show both cross bedding and channelling. The depositional model involves: (*i*) a locally developed, tectonically unstable carbonate shelf-margin , (*ii*) a temporary lowering of sea level, (*iii*) formation of a high-relief, shore-to-basin fault scarp followed by (*iv*) the development of a channel, with (*v*) subsequent, long-distance transport of clasts of pink carbonates from the continent-basin margin, which were (*vi*) redeposited together with a carbonate debris (white dolomite and 'blue' calcite marbles) on the tectonically fragmenting edge of a carbonate shelf. Both matrix and pebbles show a similar range in isotopic values: -1.9 to +0.6‰ (vs. PDB) for $\delta^{13}C_{carb}$ and 0.70896 to 0.70946 for $^{87}Sr/^{86}Sr$. The least altered $^{87}Sr/^{86}Sr$ (0.70896) isotopic value plotted on the calibration curve is consistent with a seawater composition corresponding to ages of 470-475, 505-510 and 520, whereas the least altered $\delta^{13}C_{carb}$ (-0.6‰) value matches only 520 Ma.

Victor A. Melezhik, Tom Heldal & David Roberts, Geological Survey of Norway, N-7491 Trondheim, Norway; Igor M. Gorokhov, Institute of Precambrian Geology and Geochronology, nab. Makarova 2, 199034 St. Petersburg, Russia; Anthony E. Fallick, Scottish Universities Environmental Research Centre, G75 0QF East Kilbride, Glasgow, Scotland.

Introduction

Polymict carbonate-silicate conglomerates are abundant rocks in the Late Neoproterozoic to Silurian, lithostratigraphic successions of the Norwegian Caledonides, including those known in the Fauske area (Fig. 1). The conglomerates occur either as clast- or matrix-supported varieties (Fig. 2a, b). Many of them have clasts of schist, quartzite, vein quartz and white dolostone, and some may contain large cobbles of volcanites (Fig. 2c) or rare fragments of pink marbles (Fig. 2d). Monomict carbonate conglomerates, however, represent a rather rare case. In one unit of carbonate conglomerate exposed near Fauske, in Nordland, northern Norway – the *Fauske conglomerate* – predominantly carbonate material composes both the clasts and the matrix. This particular conglomerate has been exploited as a dimensional stone since 1870 from the Løvgavlen quarry, and each of the main lithological varieties is well known under commercial names (Heldal 1996) such as 'Norwegian Rose' (pink and white), 'Jaune Rose' (pale pink and white), 'Norwegian Green' (white with green patches), 'Antique Foncé' (grey with white veins) and 'Hermelin' (white with grey veins). As these different types of conglomerate have an economic significance, there is a practical reason for carrying out research on their depositional environment and age. Results of such a study should help to provide better theoretical grounds for future exploration of this and similar deposits.

Geological setting

The Fauske conglomerate constitutes a c. 60 m-thick lensoid unit (Fig. 1) within a formation known from earlier literature as the *Fauske limestone* (Vogt 1927, Strand 1972) or the *Fauske marbles* (Rutland & Nicholson 1965). These carbonates, both banded calcite marbles and dolomite marbles, were considered to form part of the middle unit (the *Fauske*

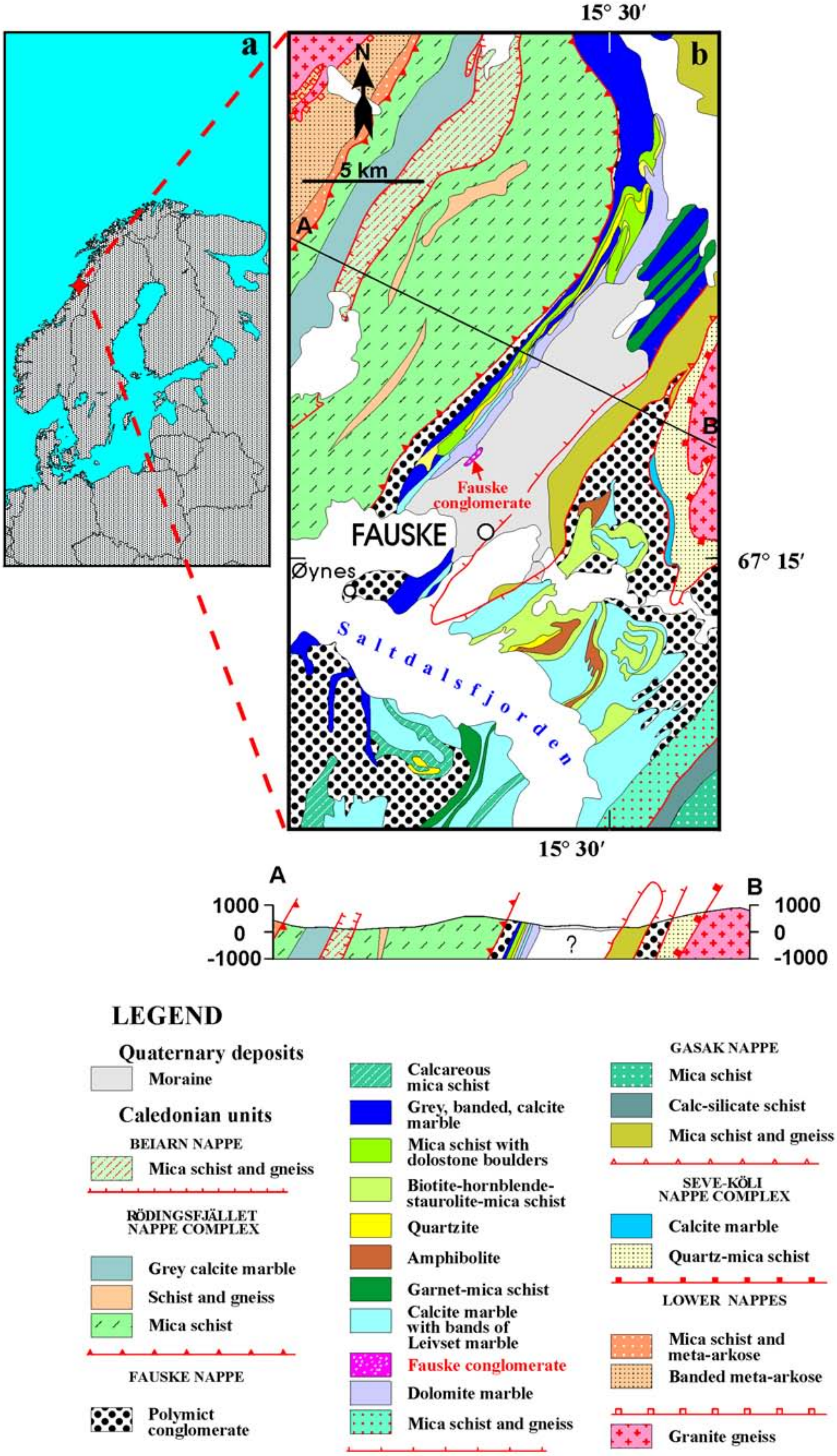

Fig. 1. Location map (a) and simplified geological map (b) of the Fauske area, modified after Gustavson (1996).

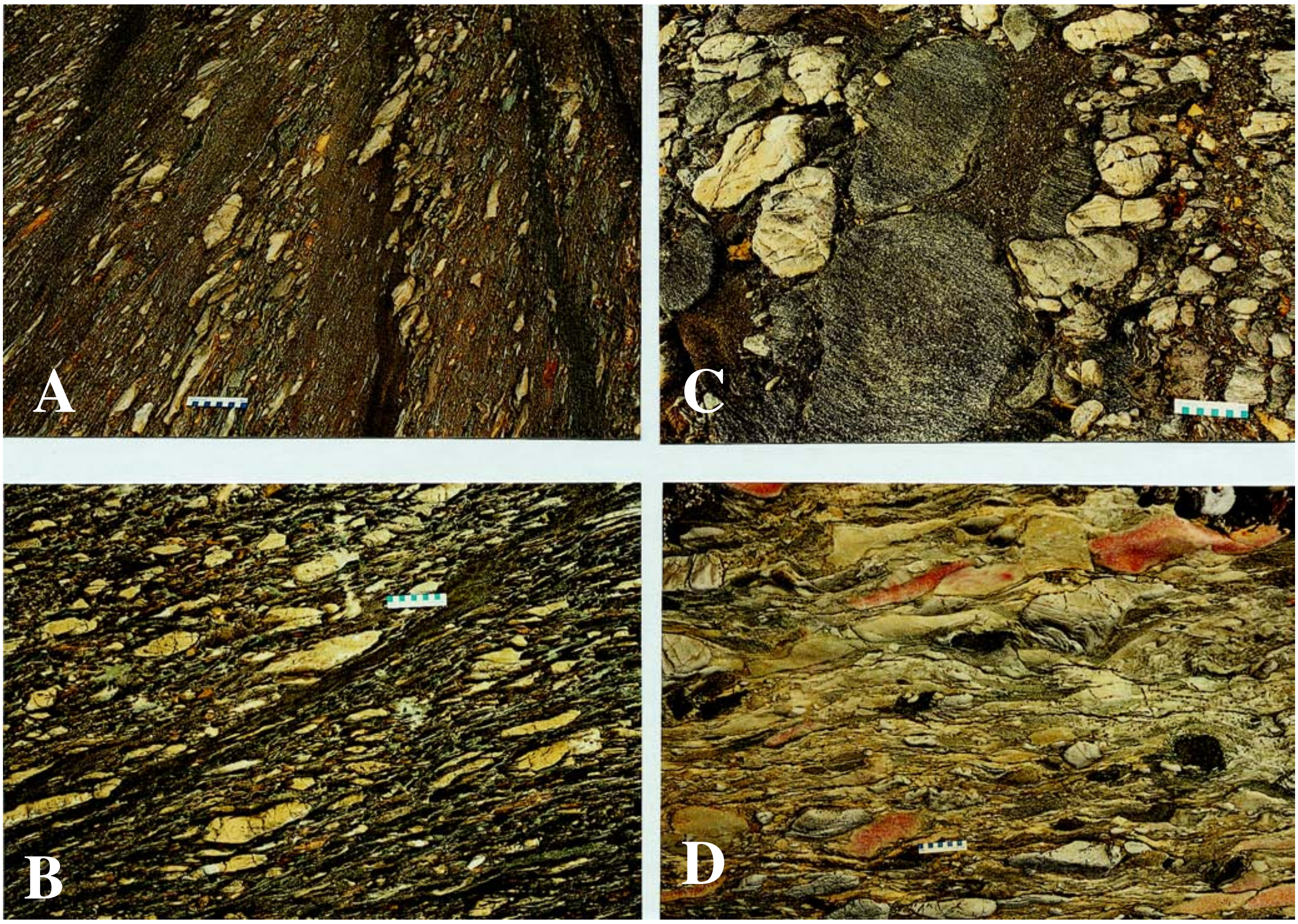

Fig. 2. Photographs of natural exposures showing typical polymict conglomerates of the Rognan Group: (a) Matrix-supported conglomerate interbedded with gritty and silty greywacke; unsorted and unevenly distributed clasts are represented by arkosic and quartzitic sandstones (*pale grey*) and dolostones (*pale brown*). In this and the next photo, the clasts are flattened and elongated within a schistosity at a low angle to the bedding. (b) Clast-supported conglomerate; clasts are quartzitic sandstones (*pale grey*) and dolostones (pale brown) in greywacke matrix. (c) Clast-supported conglomerate; unsorted clasts are quartzitic sandstones (*pale grey*), intermediate volcanites (*dark grey*) and dolostones (*pale brown*) in a greywacke matrix. (d) Clast-supported conglomerate; clasts are quartzitic sandstones (*pale grey*), amphibolites (black) and pink calcite marbles in an arkosic sandstone matrix. The photographs were taken along the shore of Saltdalsfjorden, east of Øynes (Fig. 2). Scale bars = 10 cm.

Marble Group of Nicholson & Rutland (1969)) of three main structural elements in the metamorphic allochthon of the Nordland Caledonides. The two main carbonate formations were later placed together under the name *Rognan Group* (Kollung & Gustavson 1995). Nicholson (1974, p. 184) introduced the term *Fauske Nappe* for the medium-grade, marble-rich successions lying structurally above the high-grade Gasak Nappe and below rocks of the Rödingsfjället Nappe Complex (including the Beiarn Nappe). The designation Fauske Nappe[1] has been retained in most recent map compilations (Gustavson et al. 1995, 1999, Kollung & Gustavson 1995, Gustavson 1996).

In a compilation of tectonostratigraphic units in the Scandinavian Caledonides carried out in the early 1980s (Gee et al. 1985, Roberts & Gee 1985), the Fauske Nappe was incorporated in the Uppermost Allochthon. Later mapping showed, however, that the Fauske carbonates were more likely correlatable with rocks of similar metamorphic grade in, e.g., the Hattfjelldal and Jofjället Nappes farther south, i.e., the highest tectonic units in the Upper Köli Nappes, part of the Upper Allochthon. Subsequent map compilations have favoured this affiliation (e.g. Gustavson 1996, Roberts et al. 1998).

As no fossils have been found in the carbonate formations of the Rognan Group, the actual ages of the units are unknown. Earlier workers, e.g. Vogt (1927), considered that the Fauske limestones could be followed southwards and then eastwards along the margin of the Nasafjellet tectonic window into the Pieske limestone of Sweden, which Kulling (1972, p. 263) considered to be of Middle Ordovician age. Nicholson & Rutland (1969) did not believe in this correlation, and it has not been verified by later mapping. In another, longer distance correlation, Strand (1972) suggested that the Fauske carbonate and its structurally overlying Øynes conglomerate may be equivalent to the Evenes limestone and Evenskjær conglomerate, respectively, of the Ofoten district

1. Although use of the same geographical name for different geological units is generally not acceptable (Norwegian Committee on Stratigraphy; Nystuen 1989), we retain the name Fauske here pending a future decision on revision of nomenclature.

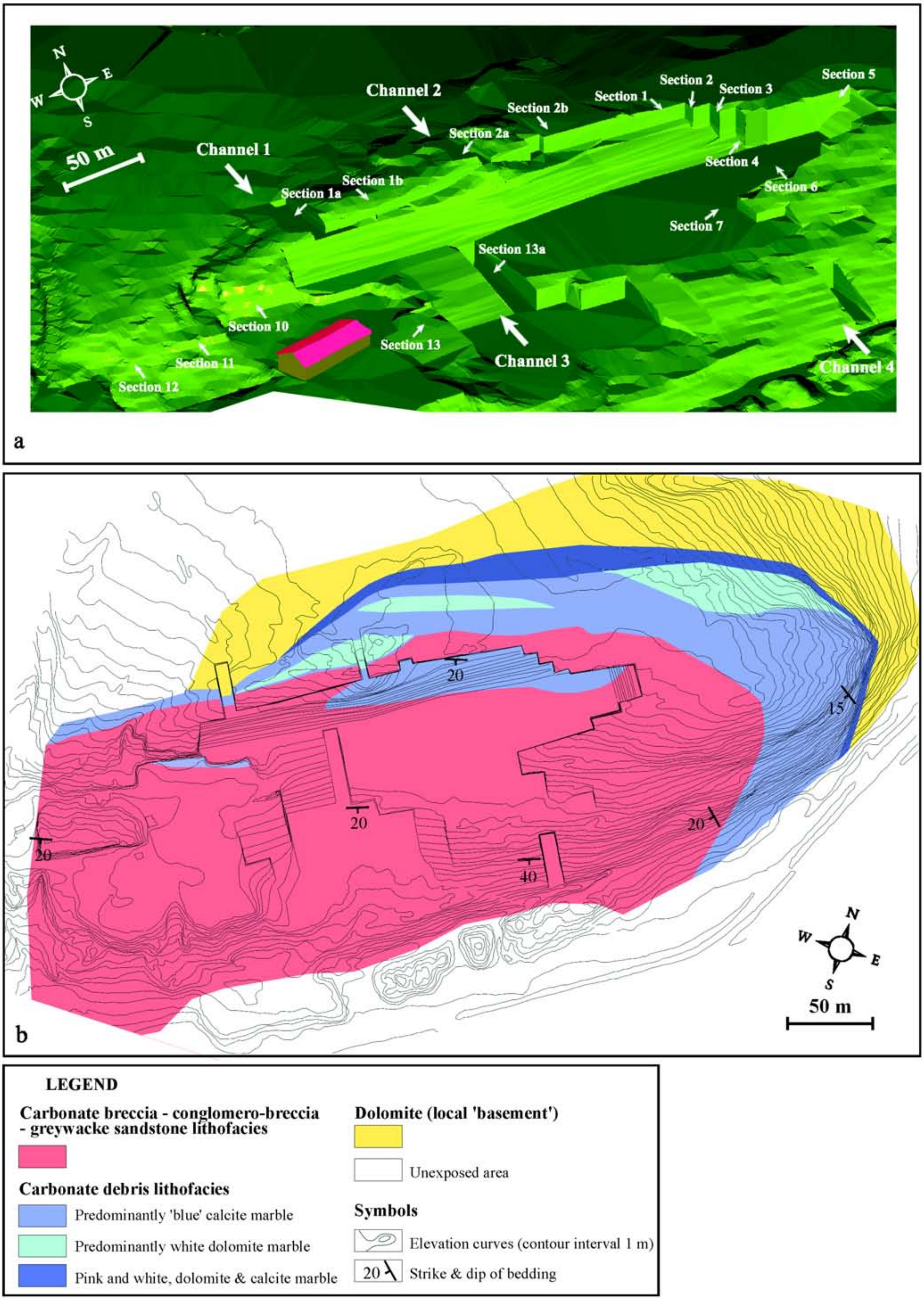

Fig. 3. (a) Three-dimensional model showing location of the studied sections and channels. (b) Simplified geological map of the Løvgavlen quarry.

of southern Troms. The possible equivalence of the Fauske and Evenes carbonates was also suggested by Nicholson & Rutland (1969).

In this paper, our use of the name Fauske conglomerate (FC) or Fauske carbonate conglomerate is strictly informal. The lithofacial and bed-to-bed variations are such that we will also occasionally use the plural form, Fauske conglomerates (FCs), when referring collectively to this intraformational diversity.

Local geology and tectonic deformation

The Rognan Group carbonate rocks are comparatively poorly exposed in the wide valley immediately north of Fauske. In the Løvgavlen quarry, only the lower contact of the Fauske conglomerate is exposed, against subjacent dolomite marble (Fig. 3). Judging from the quarry exposures and nearby outcrops, the lateral extension of the FC lens is at least 500 m, but its true dimensions are unknown.

In general, the FC dips at low to moderate angles to the southeast, which contrasts with the steep to intermediate northwesterly dips of most rocks within the Fauske Nappe in this particular district (Gustavson 1996). In the quarry, the lower parts of the FC tend to dip at 20-30° to the SSE whereas the highest exposed beds dip at 35-45° to the SE. The clasts in the conglomerates show clear signs of tectonic deformation, yet there are interesting differences depending on the clast lithology. White dolomite clasts appear to have been largely mechanically rotated into a prominent, tightly spaced cleavage dipping at low angles to the NW, whereas pink, calcite marble clasts are in many cases tightly folded (Fig. 4a) with the spaced cleavage functioning as the axial plane to these mesoscopic folds. Pebble elongation lineations plunge at very low angles to the southwest.

In addition to this quite penetrative spaced cleavage, it is clear that the more ductile calcite marble clasts show the

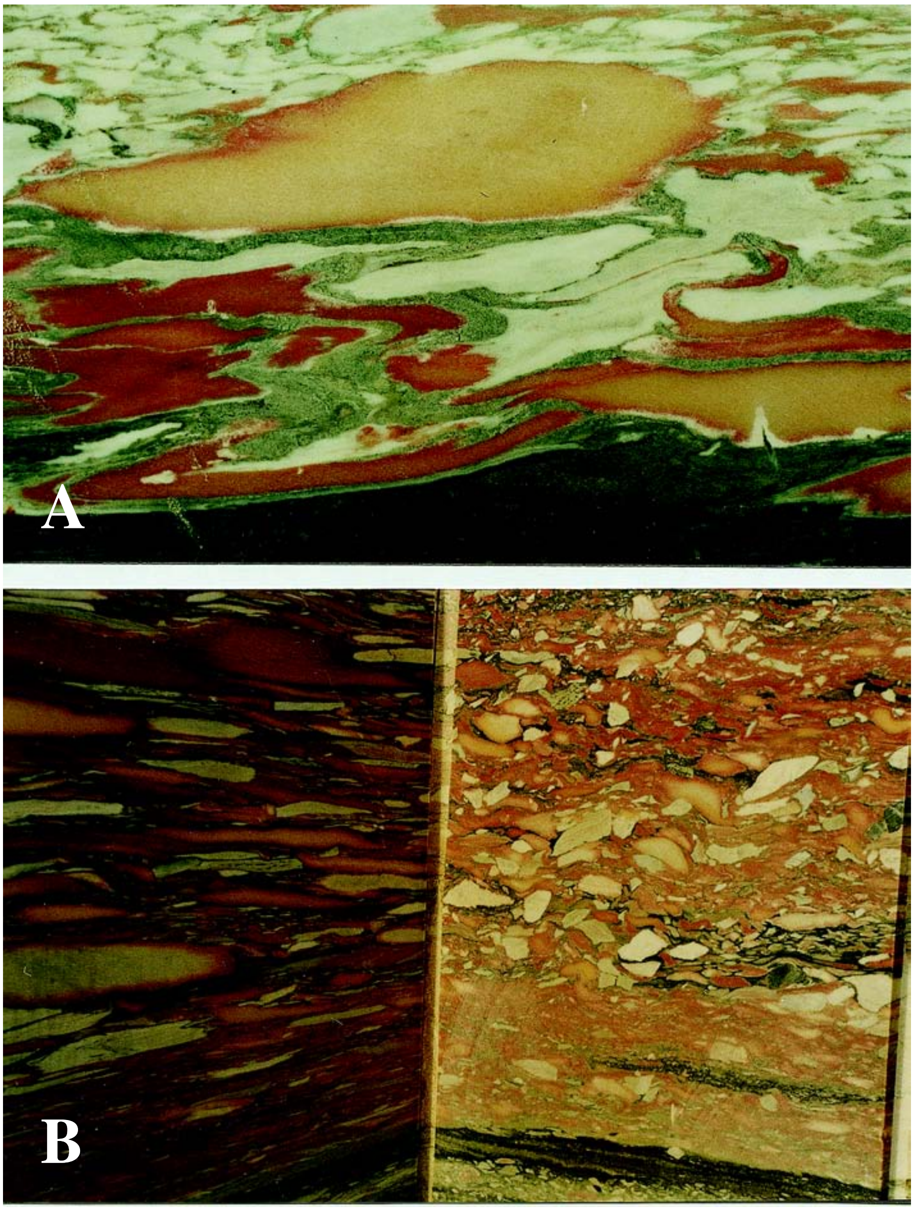

Fig. 4. Photographs of sawn surfaces in the Løvgavlen quarry (Section 5, Fig. 3. Plate 5) showing the typical style of tectonic deformation in the Fauske conglomerate. (a) Tightly folded clasts of beige- to red-coloured, calcite marble. Width of the photograph is 0.5 m. (b) An inner corner of two walls of the quarry demonstrating X:Z ratios of ca.10:1 in calcite marble clasts compared with only ca. 6:1 in dolomite clasts (*left wall*). In the right wall, normal to the clast elongation trend, many of the white dolomite clasts appear to have been largely mechanically rotated into the second phase cleavage (*top right to bottom left*) whereas clasts of pink, calcite marble are in many cases folded. Height of walls = 2.5 m.

effect of an earlier deformation which has had only a minimum effect on the much more competent dolomite clast material. In one bed, X:Z ratios of 13:1 in calcite marble clasts compare with only 6.5:1 in dolomite clasts (Fig. 4b). More importantly, the flattened calcite marble clasts dip at just a slightly greater angle to that of bedding; and the plane of flattening parallels the principal metamorphic fabric in the rock. This syn-metamorphic flattening deformation is thus presumed to represent the earliest Caledonian deformation in the Rognan Group. The age of this earlier deformation is not known. While one might infer it to be Scandian, i.e. Late Silurian to Early Devonian, a possible Ordovician age cannot be dismissed at the present time. No pre-pebble metamorphic fabrics could be detected in the pebbles and cobbles. The prominent spaced cleavage with folded marble clasts is considered to belong to a second main deformation phase. In addition to these structures, excellent examples of NW-directed, meso-scale, ramp-and-flat thrusting can be seen in the Løvgavlen quarry; and these thrusts and the earlier fabrics pre-date the spaced cleavage. The thrusts are also cut by a few NW-dipping mafic dykes and subparallel, thin quartz veins. The structural and dyke-intrusive history of the FCs is thus a fascinating topic in itself, but will not be considered further in this contribution.

The Løvgavlen quarry

In the Løvgavlen quarry, 25 beds with thicknesses of 5 cm to 3 metres have been recorded in the Fauske carbonate conglomerate unit. The FC is characterised by rapid facies changes, both vertically and laterally. Four man-made channels with near-vertical smooth walls cut through the conglomerates provide excellent sections through the lithostratigraphy and lithofacies. These are here numbered from 1 to 4. In addition, there are long, near-vertical quarry faces cut approximately at right-angles to these channels.

Vertical lithofacies change

The vertical facies change described below relates to one of the profiles stretching from Channel 1 towards Channel 3 (Fig. 3). These two channels (Plates 1 and 2[1*]), and partly Channel 2 (Plate 3) have been used as the basis for the description.

Local basement

The 'basement' or local substrate to the FC unit in Channel 1 is composed of white dolomite marbles (Plate 1). These rather massive rocks become jointed close to the contact with the conglomerates (Fig. 5a). In places, the dolomite marble has been broken into blocks. Some of the blocks (up to 6 x 4 m in size) immediately beneath the carbonate conglomerate-breccia sequence have been prized apart or are completely detached as a result of gravitational instability on a steep slope, and the open spaces between the blocks are

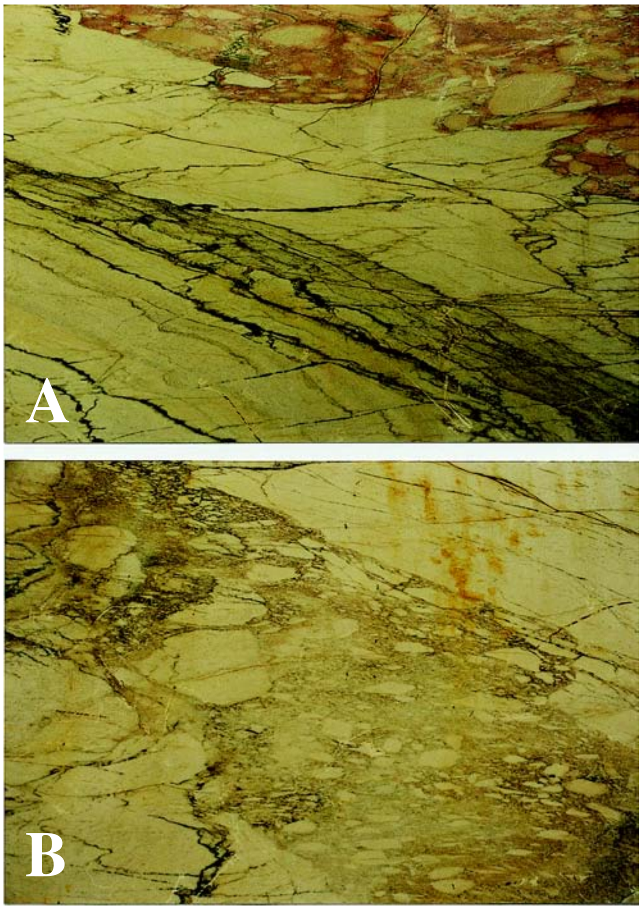

Fig. 5. The substrate to the Fauske conglomerate. (a) Banded, white to pale grey, dolomite marble with an irregular upper surface overlain by pink conglomerates. Note that the irregular palaeorelief beneath the conglomerate is strongly affected by the tectonic deformation, i.e., folding with a spaced cleavage forming the axial planes to mesoscopic folds. (b) An 'open' space between two large blocks of white dolomite marble filled with fragments of the same dolomite marble. The dolomite marble forms the substrate to the Fauske conglomerates. The photograph is taken 6 m below the contact with the conglomerates. Width of photographs = 2.5 m. Photographs taken from Channel 1, east face.

filled with angular fragments of the same dolomite (Fig. 5b). Foreign clasts have not been observed here. The detached blocks of the basement dolostones may be assigned to a landslide facies. Fragmentation of the substrate was apparently caused by instability along the edge of a carbonate shelf, with the blocks moving under the force of gravity. Jointing, fragmentation, detachment and initial movements occurred when the dolostones were lithified but still remained uncovered by other sediments/rocks as indicated by the lack of foreign clasts among fragments filling joints, cavities and open spaces.

Carbonate debris lithofacies

The first input of carbonate clasts overlying the landslide facies appears in the form of carbonate debris which constitutes Beds 2 to 5 (Plate 1). Each bed in the carbonate debris lithofacies is characterised by rather sharp boundaries due to differences in the matrix and in the sizes of clasts. The thicknesses of all these beds are highly variable. The carbonate

1. The following abbreviations are used in Plates 1-5: PCM - pink calcite marble, WDM - white dolomite marble, GDM - grey dolomite marble, BCM - 'blue' calcite marble.

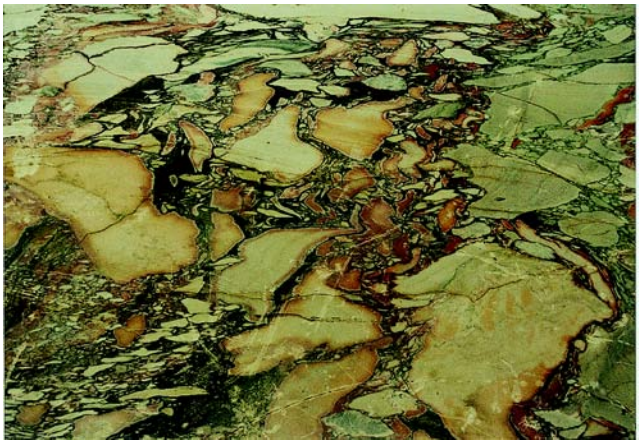

Fig. 6. Chaotically deposited, unsorted blocks and angular fragments of pink and pale pink calcite marbles and white dolomite marbles in a dark calcareous schist matrix. Bed 5, carbonate debris, mass-flow facies. Width of photograph = 2.5 m. Photograph taken from Channel 1, west face.

debris facies at the base of the FC is only locally developed and it is rapidly replaced by carbonate breccias and conglomerates.

The beds of carbonate debris are composed of angular, unsorted blocks and fragments of carbonate rocks. The clasts are represented by white dolostones, white and pink calcite marbles and single blocks of white-rimmed, dark calcite marbles ('blue' marbles). The clasts range in size from less than 1 cm to 3 m. Although the majority of the white dolostone and 'blue' calcite marbles appear as angular fragments, some of the pink marbles are rounded. In general, the carbonate debris is composed of large chaotically organised fragments (Fig. 6). However, a few channels filled with medium-size, moderately sorted clasts have also been recognised in Channel 1 (Plate 1). The majority of the 'blue' marble clasts and blocks are bleached around their margins and along joints (Fig. 7a). The bleaching was apparently caused by oxidation with subsequent removal of organic material. This might have happened in a subaerial environment when the 'blue' carbonates were exposed to atmospheric oxygen. Alternatively, the loss of organic material could have occurred during fresh-water diagenesis in a phreatic zone where the rocks might have been subjected to alteration by oxygen-containing fluids. A detailed isotopic study is required before we may choose between these alternatives.

Beds 3, 4 and 5 compose the bulk of the carbonate debris lithofacies in Channel 1. At the same time Bed 2, consisting of large blocks of white dolomite marble and white-rimmed 'blue' marble, occurs in Channel 1 in a very abbreviated form. In contrast, the same Bed 2 appears in Channel 2 (80 m east of Channel 1, Fig. 3) as the major unit in the carbonate debris lithofacies (Plate 3). There, it is composed of large blocks (≤5 x 1 m in size) of strongly jointed, white-rimmed, 'blue' marbles (Fig. 7b) and white and pale grey dolostones in a 'blue' calcite matrix. Beds 3 and 4 are not present in Channel 2 (Plate 3). Bed 5 mechanically 'intruded' into Bed 2 from its surface and deformed it. Based on this relationship, and given the condition that Beds 3-5 and 2 are almost mutually exclusive, it is suggested that the attenuation of Bed 2 in

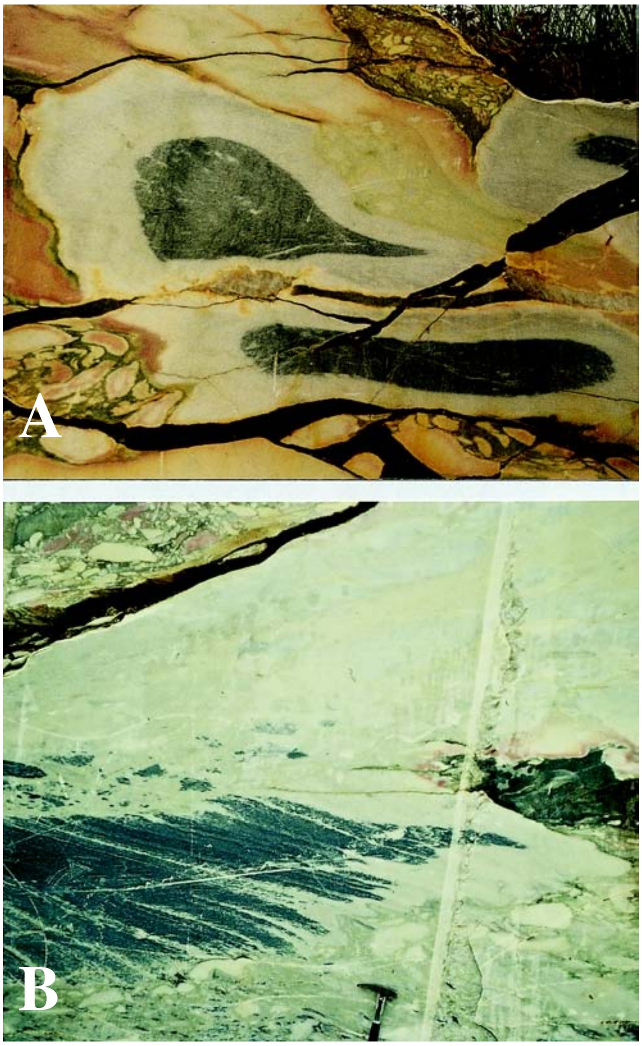

Fig. 7. Photographs illustrating different styles of bleaching of 'blue' calcite marble in Bed 2. (a) Large rounded blocks of 'blue' calcite marble bleached around their margins. Width of photograph = 2.5 m. (b) Large angular block of 'blue' calcite marble bleached around its margins and along lamination surfaces. Hammer head = 15 cm. Both photographs taken from Channel 2, east face.

Channel 1 might be due to an effect of erosion. An extensive erosion of previously deposited beds by newly transported debris flows might have caused very irregular contact surfaces, as such features are seen in the carbonate debris lithofacies in Channels 1 and 2. Additional effects might also have been caused by syn-depositional deformation.

The overall sedimentological features of this rock assemblage indicate transport in and deposition from a mass flow, in which ill-sorted masses of sediment moved down-slope due to a loss of internal strength of the sediment mass. At least two major pulses of mass flow have been recognised in the carbonate debris lithofacies. The first is represented by Bed 2. The second phase resulted in partial erosion of Bed 2 and deposition of Beds 3-5. Clast material was transported from different sources. White dolostone and 'blue' calcite marbles are derived from a local source which has been identified immediately beneath the carbonate debris. Clasts of pink marbles, on the other hand, are comparatively long

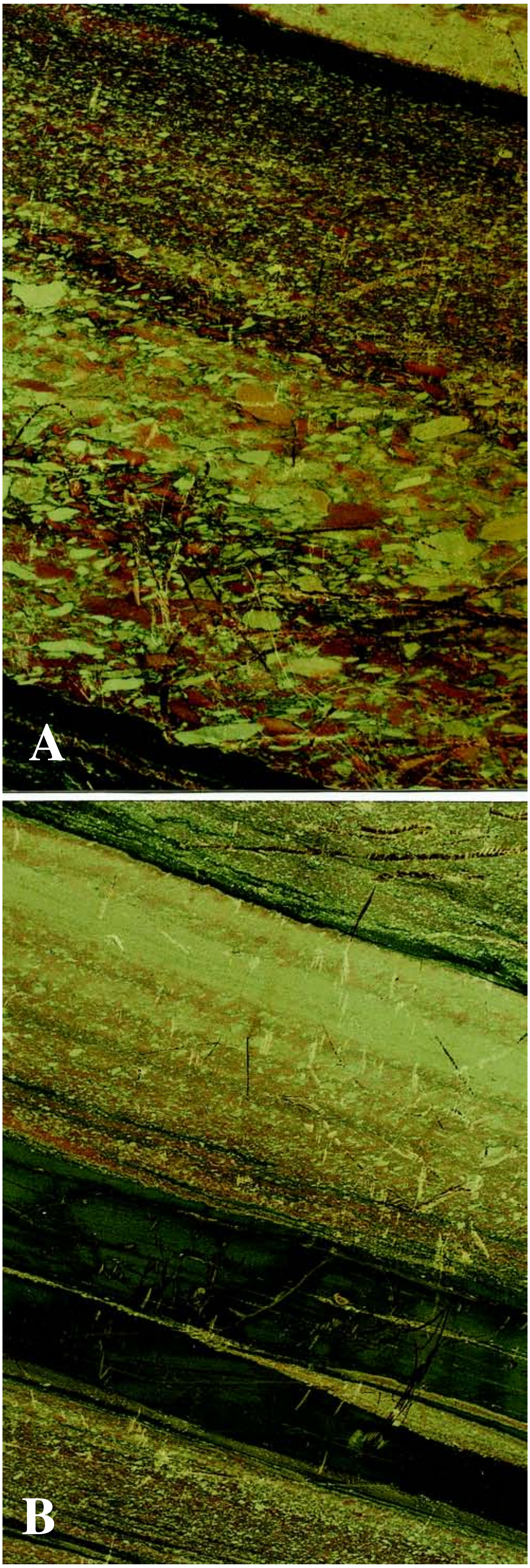

Fig. 8. Upward fining of clasts within individual beds. (a) Bed 14 exhibits four distinctive units which correspond to the A, B, C and D units of a typical Bouma sequence. The bed starts with a thick unit of conglomero-breccia overlain progressively by a fine-pebble conglomerate with parallel lamination, a thin unit of current-bedded gritstones, and at the top by a silty greywacke with plane-parallel lamination. Height of photograph = 1.2 m. (b) Lower part of Bed 18 (above the dark grey greywacke layer) exhibiting graded bedding accompanied by the development of an internal planar lamination. Height of photograph = 2.5 m. Both photographs taken from Channel 3, east face.

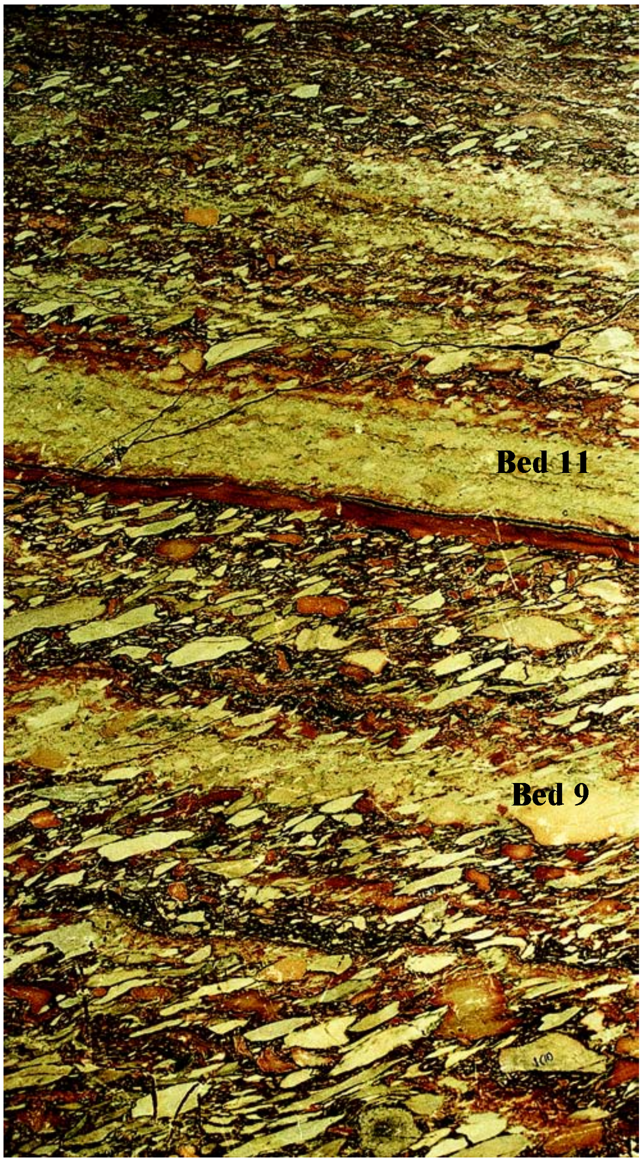

Fig. 9. Originally horizontally bedded carbonate breccia showing a gradual upward decrease in fragment size accompanied by the gradual development of an internal planar lamination; Beds 8-12. Note that Beds 9 and 11 are distinguished in the conglomerate sequence by their paler colours caused by a dominance of white dolostone fragments in a pale grey calcarenite matrix. The clasts are here (re)orientated within the D2 (S2) schistosity. Fault-related, proximal, submarine channel facies. Height of photograph = 2.5 m. Photographs taken from Channel 1, east face.

Fig. 10. Upward fining of the clasts within Beds 4-12 accompanied by the gradual development of an internal planar lamination. Height of photograph = 8.5 m. Photographs taken from Channel 1, west face.

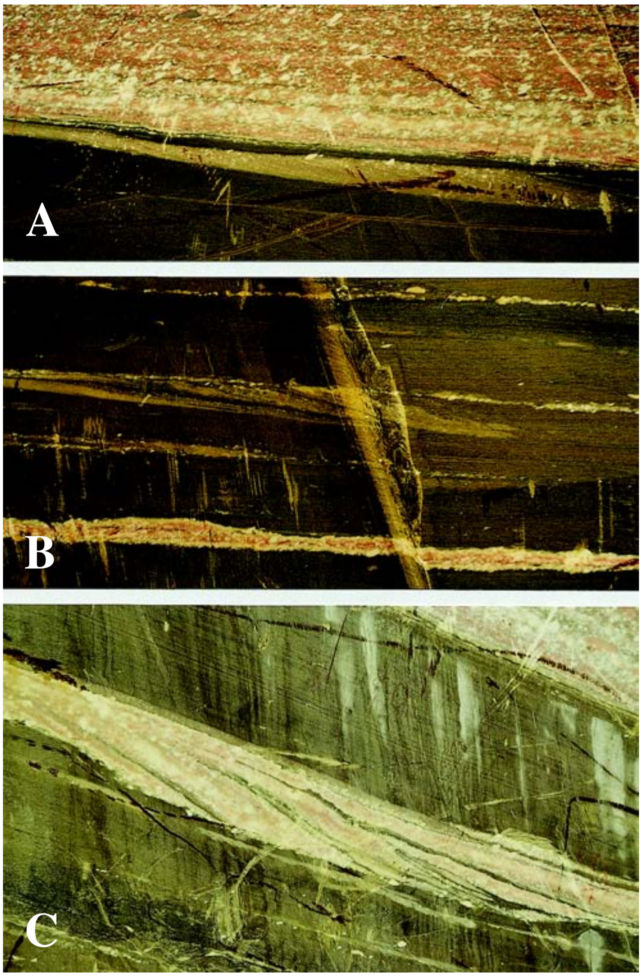

Fig. 11. Combination of planar and cross-lamination in Bed 17. (a) Cross-lamination in the channel filled with coarser greywacke sandstone (*pale brown*) appearing in the uppermost part of Bed 17; note that the channel thickness gradually increases down dip, and the cross-laminated sandstone is then abruptly replaced by silty greywacke (*to the right*) which exhibits no visible lamination. Height of photograph = 0.6 m. (b) Cross-laminated sandstone channel developed in the middle part of Bed 17. Height of photograph = 0.75 m. (c) Erosional channel in laminated dark grey greywacke of Bed 17. The former is composed of current-bedded, pink, carbonate gritstones and fine-pebble conglomerate; note that the cross-bedding is emphasised by a rhythmic repetition of cross-bedded calcarenite-greywacke couplets. Fault-related, distal, submarine channel facies. Height of photograph = 0.7 m. All photographs taken from Channel 3, east face.

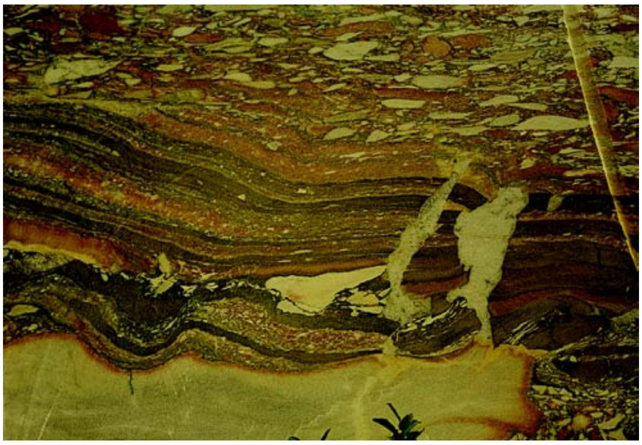

Fig. 12. The 0.5 m-thick Bed 7 (*middle part of photograph*) showing a lateral Bouma sequence; the bed begins as a bedded, fine-pebble, carbonate conglomerate which is gradually replaced down-dip by carbonate gritstones, carbonate gritstones interbedded with laminated greywacke, and then by plane-laminated greywacke and siltstone with a massive appearance. Height of photograph = 1.7 m. Photograph taken from Channel 2, east face.

transported, as indicated primarily by their more rounded shapes and the absence of any definite source rock in the vicinity of Fauske (see discussion of geochemical data).

Carbonate breccia—conglomero-breccia—greywacke lithofacies

The carbonate debris lithofacies is overlain with a sharp, straight contact by fragment-supported carbonate breccias represented by Bed 6. High-angle cross-bedding has been observed in Bed 6 as indicated by the imbricated distribution of predominantly white dolostone fragments (Plate 1). In the upper part of Channel 1, Bed 6 has a thickness of 2 m which increases to 4 m down-dip within a distance of 12 metres. The breccias are composed of fragments of the same rocks as described in the debris lithofacies. The fragments, however,

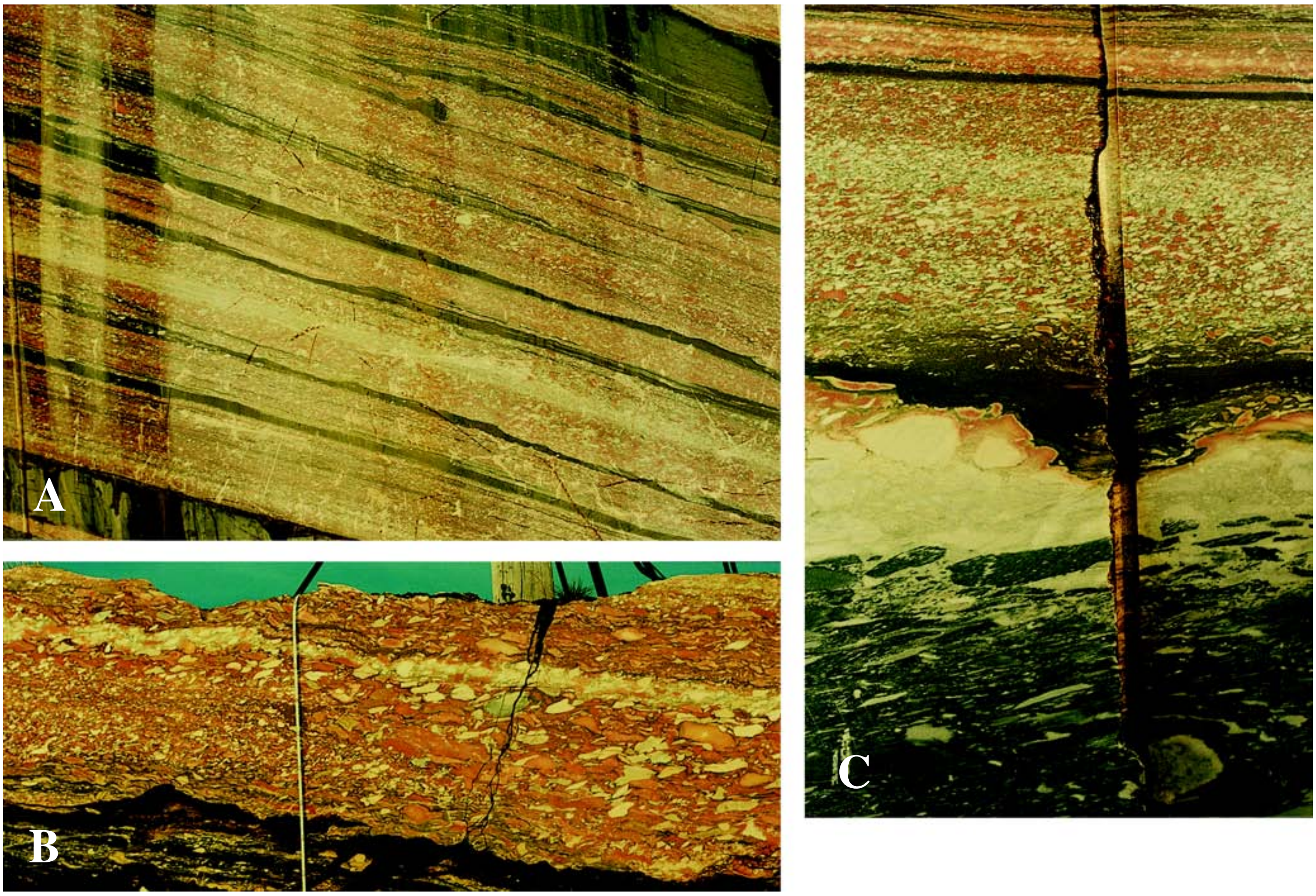

Fig. 13. Photographs illustrating different scales of channelling. (a) White, pale grey and pink, small-pebble conglomerates interbedded with dark grey greywackes, the latter becoming an essential component of the upper part of the Fauske conglomerate unit; note that carbonate gritstones and greywackes usually form couplets, and that channelling and low-amplitude, long-wavelength current ripples are very characteristic features of the conglomero-breccia—greywacke lithofacies. Bed 18, fault-related, distal, submarine channel facies. Width of photograph = 5 m. Photograph taken from Channel 3, east face. (b) Channel (*right of measuring tape*) developed in small-pebble conglomerate beds and infilled with coarser material. Width of photograph = 2 m. Photograph taken from Section 7, Fig. 3, Plate 5. (c) Large-pebble conglomerates of Bed 2f eroded and channelled, with a subsequent infill of the channel consisting of finely dispersed material (*black and dark grey silty greywacke*) of Beds 8-10. Height of photograph = 2.7 m. Photograph taken from Section 2, Fig. 3, Plate 4.

are generally much smaller and 'blue' marbles have never been observed among the clasts. Although the clasts are poorly sorted and angular, many of the pink marbles are represented by well rounded pebbles. Clast size ranges from 0.5-12 cm in the lower part of Bed 6 to 0.2-7 cm in its upper part. Upward fining is evident from systematic measurements. However, this is almost a cryptic gradation as it is difficult to detect visually. The breccias are capped by a 1-20 cm-thick Bed 7 consisting of laminated, silty greywacke. This is composed of muscovite, biotite, quartz, plagioclase and calcite.

The breccia-greywacke couplet is overlain by a series of conglomero-breccia beds (8 to 12 in Channel 1, Plate 1; 12 to 15 in Channel 3, Plate 2) containing medium- to small-size fragments. The conglomero-breccias are interbedded with thin beds and layers of white and pink calcarenite. The conglomero-breccia beds (12, 14 and 15) are capped by beds of silty greywacke (Plate 2). The thicknesses of individual conglomero-breccia beds range from 0.3 m to more than 2.5 m (e.g., Bed 12) whereas calcarenite lenses are usually less than 0.2 m in thickness. The thicknesses of Beds 12, 14 and 15 are almost uniform down dip, from 1.5 to 2.5 m. In general, the bed thicknesses in the conglomero-breccia sequence become rather constant down dip as compared to the lower debris lithofacies. However, the greywacke beds still exhibit highly variable thicknesses.

Conglomero-breccias are both matrix- and clast-supported. Fragments, cobbles, pebbles and smaller clasts are mainly of white dolostone and pink, beige and white calcite marbles. The majority of the clasts are angular or poorly rounded. However, clasts of pink calcite marble as well as a few of the white dolomite marble are represented by well-rounded pebbles. Although clasts are poorly sorted, graded bedding has been observed in several beds (Fig. 8a, b). Two laterally continuous beds (9 and 11) are readily distinguished in the conglomerate sequence by their paler colours caused by a dominance of white dolostone fragments in a pale grey calcarenite matrix (Fig. 9). In other cases, the matrix is composed of calcareous schist. Although the matrix shows a similar range in lithology, fuchsite, sericite, muscovite, quartz and chlorite may be present in variable proportions in addition to fine carbonate clasts, a feature which gives the different beds their slightly variable coloration.

A series of changes in terms of rock structure and lithology can be detected in moving upwards in the stratigraphy within the conglomero-breccia sequence exposed in Channel 1. An upward fining of the clasts is clearly visible within both a sequence of beds (Beds 8-12, Fig. 9, Fig. 10) and individual beds (e.g., Bed 14, Fig. 8a). This is accompanied by the gradual development of an internal planar lamination in the conglomero-breccia.

The structure of the silty greywacke, which overlies the conglomero-breccia beds, changes upwards in the stratigraphy. The lower silty greywacke, Bed 7, has an indistinct planar lamination whereas the uppermost and the thickest Bed 17 is characterised by a combination of planar and cross-lamination (Fig. 11a). Cross-lamination appears in channels filled with coarser greywacke. These 1 to 15 cm-thick channels are less than 1.5 m in length and have low-angle erosional contacts with the silty greywacke. In the cross-sections, the rear parts of the channels are only 1-2 cm in thickness and are composed of massive pale grey sandstone, but the channel thickness gradually increases down dip. The thickness increase is followed by the development of visible cross-lamination due to a heterogeneity in lithology resulting from an alternation of sand- and silt-rich laminae (Fig. 11a). Further down dip, cross-laminated sandstone is abruptly, though conformably replaced by silty greywacke which exhibits no visible lamination. This channel-greywacke then becomes indistinguishable from the main greywacke body, both consisting of muscovite, biotite, quartz, plagioclase and calcite (Fig. 11a). Cross-laminated sandstone channels have been observed mainly in the uppermost parts of silty greywacke beds though in a few cases they have been detected in the lower and middle parts (Fig. 11b).

The appearance of cross-laminated sandstone channels in the silty greywacke of Bed 17 is accompanied by the development of numerous 0.5-10 cm-thick layers of white and pink, cross-bedded carbonate gritstones and fine-pebble conglomerate lenses. These layers and lenses are irregularly spaced in the silty greywackes as well as in the subjacent conglomero-breccias. In places, the cross-bedding is emphasised by a rhythmic repetition of cross-bedded conglomerate-calcarenite and calcarenite-greywacke couplets (Fig. 11c).

The upper parts of the carbonate breccia—conglomero-breccia—greywacke lithofacies exhibit a sequence of sedimentary structures which are typical of those observed in turbidity current deposits. Bed 14, for example, exhibits four distinctive units (Fig. 8a). The bed starts with a thick unit of massive or graded conglomero-breccia which is overlain progressively by a fine-pebble conglomerate with parallel lamination, a thin unit of current-bedded gritstones, and is capped by a silty greywacke with plane-parallel lamination. These four units appear to correspond to the A, B, C and D units of a typical Bouma sequence. While Bed 17 demonstrates a vertical Bouma sequence, Bed 7 in Channel 2 appears to show a lateral Bouma sequence (Fig. 12). The 0.5 m-thick Bed 7 begins as a bedded, fine-pebble, carbonate conglomerate and this is gradually replaced down-dip over a distance of 8 m by carbonate gritstones, carbonate gritstones interbedded with laminated greywacke, and then by plane-laminated greywacke and siltstone with a massive appearance (Fig. 12, Plate 3).

Overall, the sedimentological features of the breccia—conglomero-breccia—greywacke lithofacies are comparable to those found in sequences deposited from debris flow followed by turbidity currents. Available data demonstrate that many of the conglomero-breccia beds and all the conglomero-breccia—silty greywacke couplets were deposited from a single debris flow–turbidity current pulse. The general upward fining of the clasts indicates either that the clasts were transported from a greater distance as compared with the clasts from the carbonate debris lithofacies or that there was a rise in sea level. We suggest that the first option was the more likely as it is consistent with the observed increased degree of roundness of the transported clasts.

Conglomero-breccia—greywacke lithofacies

This lithofacies lies with a rather subdued erosional contact on top of the channelled and cross-laminated greywackes of Bed 17. The lithofacies is composed of pale pink carbonate gritstones irregularly interbedded with dark grey greywackes and subordinate white calcarenites. Carbonate gritstones and greywackes usually form couplets (Fig. 13a), which start with a 0.2-1.5 m-thick gritstone layer and end with a 0.1-0.5 m-thick greywacke layer. The contact between these two lithologies is commonly gradational within a distance of 1-2 cm. Both gritstones and greywackes exhibit planar and low-angle cross-lamination. Planar and cross-lamination is expressed by the development of laminae with either coarse or finer clasts as well as by the appearance of thin greywacke laminae in the gritty framework. Each carbonate gritstone-greywacke couplet exposes an erosional relationship with the underlying one. Clasts of rounded pink calcite marble and semi-rounded white dolomite marble are poorly sorted. They exhibit no gradation in size within layers. Small-scale channels and pockets of fine-pebble conglomerate in the gritty framework are common phenomena of this lithofacies. Some beds at the base of the conglomero-breccia—greywacke lithofacies exhibit graded bedding resembling that in Bouma sequences.

Sedimentological features of the conglomero-breccia—greywacke sandstone lithofacies indicate that both the clastic material and the finer sediments were transported in and deposited from low-energy currents on a gently inclined slope.

Lateral thickness, clast size and lithological variations

All the 25 beds recorded in the Løvgavlen quarry show a certain degree of lateral variation in lithology, clast size and thickness. Bed thickness has been affected by tectonic strain producing a general thinning of the sequence. However, signs of differential tectonic thinning of different lithologies, such as pinch-and-swell and boudinage, have only been detected in a few, thin (2 to 10 cm thick), silty greywacke layers. Most other beds seem to have been similarly affected by

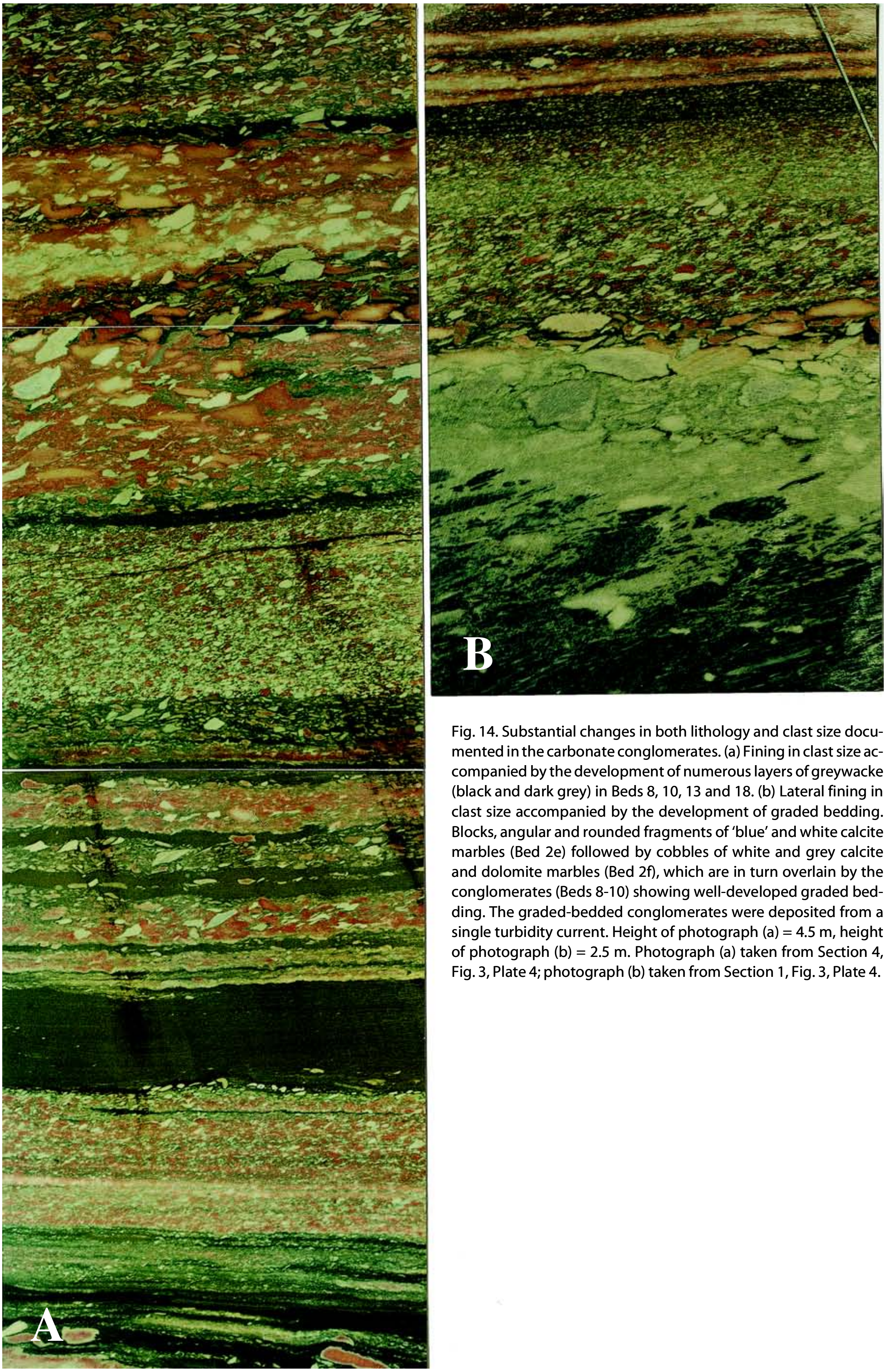

Fig. 14. Substantial changes in both lithology and clast size documented in the carbonate conglomerates. (a) Fining in clast size accompanied by the development of numerous layers of greywacke (black and dark grey) in Beds 8, 10, 13 and 18. (b) Lateral fining in clast size accompanied by the development of graded bedding. Blocks, angular and rounded fragments of 'blue' and white calcite marbles (Bed 2e) followed by cobbles of white and grey calcite and dolomite marbles (Bed 2f), which are in turn overlain by the conglomerates (Beds 8-10) showing well-developed graded bedding. The graded-bedded conglomerates were deposited from a single turbidity current. Height of photograph (a) = 4.5 m, height of photograph (b) = 2.5 m. Photograph (a) taken from Section 4, Fig. 3, Plate 4; photograph (b) taken from Section 1, Fig. 3, Plate 4.

an overall tectonic thinning. This is also clearly indicated by very well preserved sedimentary features such as sedimentary layering, graded bedding, cross-lamination, erosional channels, etc. The measured thickness variations should therefore largely remain comparable with the original values.

Pronounced thickness variations of primary origin may be observed in any one bed over distances of 10 to 100 m. The most remarkable change in thickness, with the complete disappearance of beds in three directions within a distance of less than 100 m, is characteristic of Beds 3-6. This can be demonstrated by comparing the cross-sections recorded in Channels 1 and 2 (Plates 1 and 3). Beds 3 and 4 are observed in Channel 1, but they do not reappear in Channel 2, over a distance of only 90 m. On the contrary, Bed 2 is a prominent unit in Channel 2 but reappears in Channel 1 in a considerably attenuated form.

Less dramatic though substantial thickness changes with associated wedging-out either in two or three directions have been documented in Beds 5-7, 9, 11-13, 16 and 25. This is demonstrated in the longitudinal lithological sections (e.g., Plates 4 and 5). Fine-clast conglomerate of Bed 16 and large-clast conglomerate of Bed 25 form medium-scale erosional channels. Bed 25 has a thickness of 7 m whereas the lateral extension of the channel is less than 50 m. Channelling on different scales is a common feature of many beds and layers. In the most common cases, channels which developed in small-pebble conglomerate beds were infilled with coarser material (Fig. 13b). Large-pebble conglomerates have also been observed to be eroded and channelled, with a subsequent infill of the channel consisting of finely dispersed material (silty greywacke) (Fig. 13c). This implies the existence of high-energy water currents developed on a steep submarine slope. Gradually progressing down-slope erosion of greywacke and fine-pebble conglomerate beds marked by channelling and low-amplitude, long-wave current ripples are very characteristic features of the conglomero-breccia—greywacke lithofacies (Fig. 13a).

A considerable lateral variation in clast size is commonly observed in those beds which demonstrate well-pronounced thickness variations. A positive correlation between bed thickness and clast size is a common rule for Beds 6, 12 and 14. These three beds exhibit great lateral variation in clast size and thicknesses whereas their lithological compositions remain unchanged. In Bed 6, clast size ranges from 10 x 30 cm (Section 10, Plate 4) to 2 x 5 cm (Channel 2, Plate 3) within a distance of 100 m.

Substantial changes in both lithology and clast size have been documented in the carbonate conglomerates of Beds 8, 10, 13 and 18. In these cases the fining in clast size is accompanied by the development of numerous layers of greywacke (Fig 14a). As a result, in some cases carbonate conglomerates are completely replaced by greywacke (Bed 13, Section 2, Plate 3; Bed 18, Channel 3, Plate 2). Lateral fining in clast size has also been observed to be accompanied by the development of graded bedding (Fig. 14b).

Variations in lithology and clast size hamper correlation between sections separated by unexposed ground. Some beds, however, may serve as a marker. Two white-pebble conglomerate beds (9 and 11), which are only 0.1-0.5 m thick, are distinguishable in the conglomerate sequence by their comparatively pale colour pattern. Although these beds are thin they are easy to detect and can be traced both along strike and down dip (e.g., Plate 4). The pale coloration is expressed by a dominance of white dolostone fragments in a pale grey calcarenite matrix.

The examples described above serve to demonstrate that the high degree of variability in lithology, clast size and thickness is a general characteristic of the FCs. This implies unstable depositional environments. The thickness variations have apparently been caused by a number of factors, including erosional effects and channelling, an irregular palaeorelief of the depositional surface and a lateral restriction of turbidity currents. Tectonic factors have also played their part in modifying bed thickness and, as noted earlier, in causing flattening of the calcite marble clasts in particular.

Clast composition

Lithologically, the FCs consist of blocks, fragments, cobbles, pebbles and smaller clasts mainly of white dolostone and pink, beige, white and dark grey ('blue') calcite marbles (Fig. 16a). Clasts of quartzites and vein quartz are subordinate. A quantitative estimate of clast composition shows that the clasts of 'blue' calcite marbles are exclusively assigned to Bed 2 (Figs. 15, 16b) and they have never been observed in any other bed. Clasts of quartzites and vein quartz are also preferentially concentrated in Bed 2. On the other hand, clasts of pink calcite marble have never been recorded in Bed 2. The fragments of white and grey dolostone, and white calcite marbles are distributed throughout the entire sequence and neither the vertical nor the lateral distribution shows any visible regularity (Fig. 15). The main mineral in the matrix is calcite, with minor quartz and muscovite. The matrix is characterised by a granoblastic texture and retains no primary sedimentary features. Measured clast-matrix ratios range between 0.3 and 4.6 with an average value at 1.5 (n=30). This indicates the presence of both clast-supported and matrix-supported conglomerates where the former are predominant. However, the data obtained must be treated with care as some clast-matrix boundaries exhibit a diffuse, unclear appearance due to recrystallisation. Although the matrix has a similar range in lithology, fuchsite, sericite, muscovite and chlorite may be present in variable proportions as minor components in addition to fine carbonate clasts.

Chemically, all the carbonate clasts can be divided into two groups, namely dolomite and calcite marbles (Table 1). Dolomite marbles from the local 'basement' and in the clasts are identical in terms of major and trace element abundances. On various diagrams they are clustered together (Fig. 17), clearly indicating that the clasts derived from the underlying dolomite marble unit. The Mg/Ca ratio for the underlying dolostones ranges from 0.58 to 0.64 which is close to stoichiometric dolomite (0.62) whereas the average Mg/Ca ratio for all the clasts is 0.53. This apparently points to a process of dedolomitisation during the course of transportation and redeposition.

The overall bulk chemical composition of other carbon-

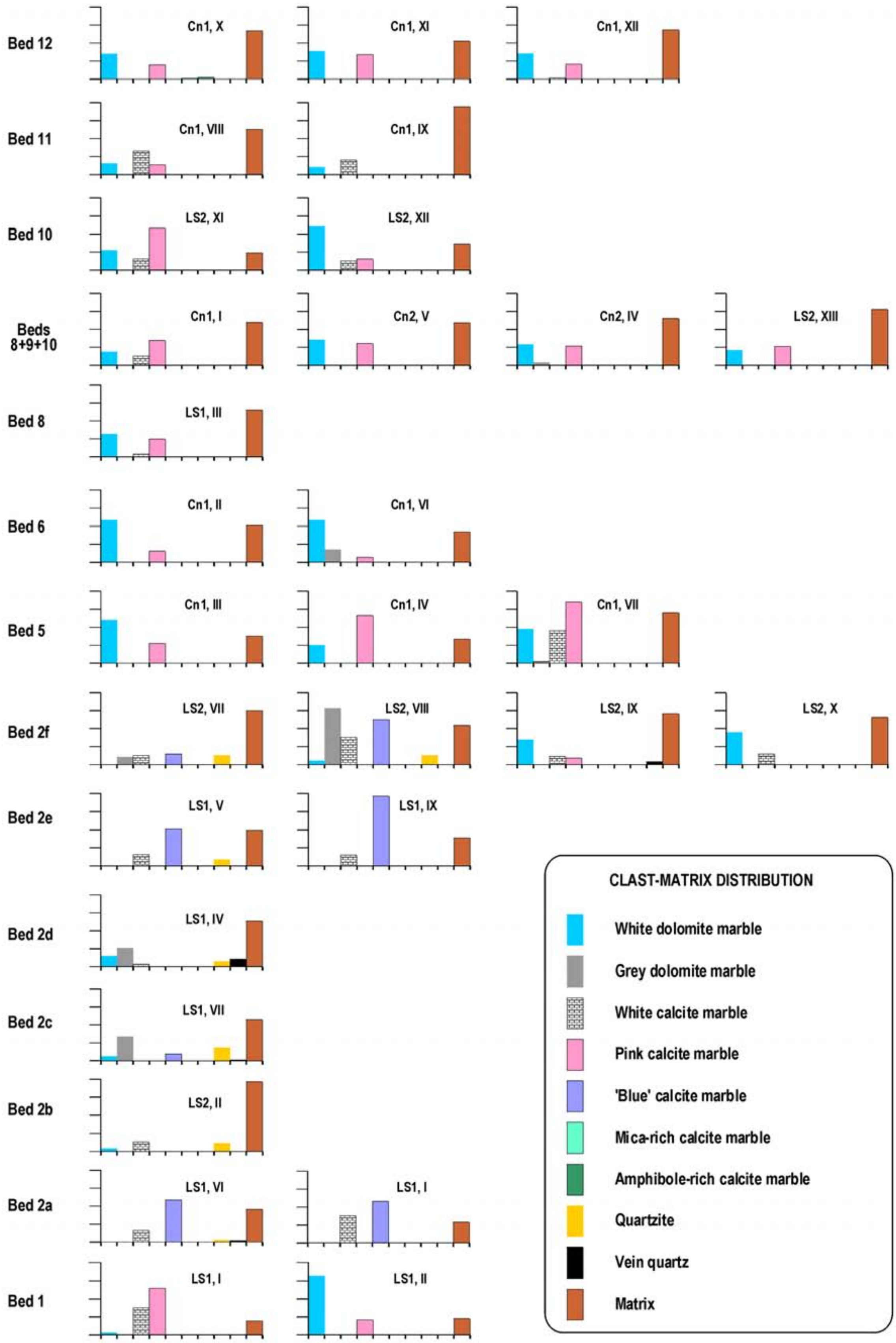

Fig. 15. Composition of clasts and matrices measured from different beds.
The following abbreviations are used in the figure: Ch1 - Channel 1, Ch2 - Channel 2, LS1 - Longitudinal Section 1, LS2 - Longitudinal Section 2. Roman numerals indicate the section number which was used to count pebble composition; these sections are marked on Plates 1 and 2. Detailed logs of LS1 and LS2 are not presented in the article but they may be obtained from the first author on request.

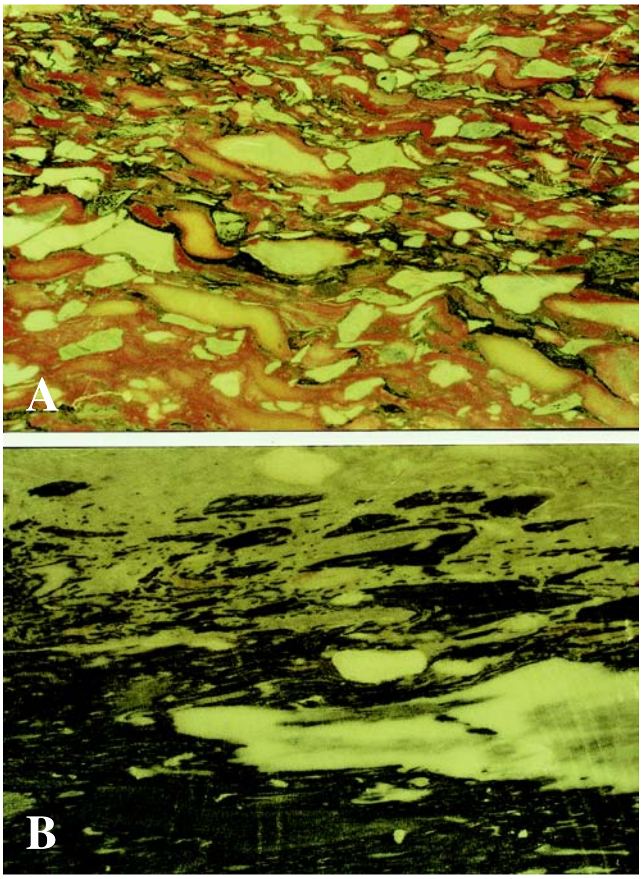

Fig. 16. Photographs illustrating the variable clast composition of the FCs. (a) Carbonate breccia composed of angular fragments and sub-rounded pebbles of pink, calcite marble, white, calcite marble with pink rims, and white dolomite marble in a dark calcarenite matrix. The initial flattening and elongation of clasts is a Caledonian D1 fabric. Clast reorientation and/or folding relates to D2 deformation. Bed 10. Channel 1, east face. (b) Clasts of 'blue' calcite marbles. These are exclusively assigned to Bed 2. Width of photographs = 0.8 m.

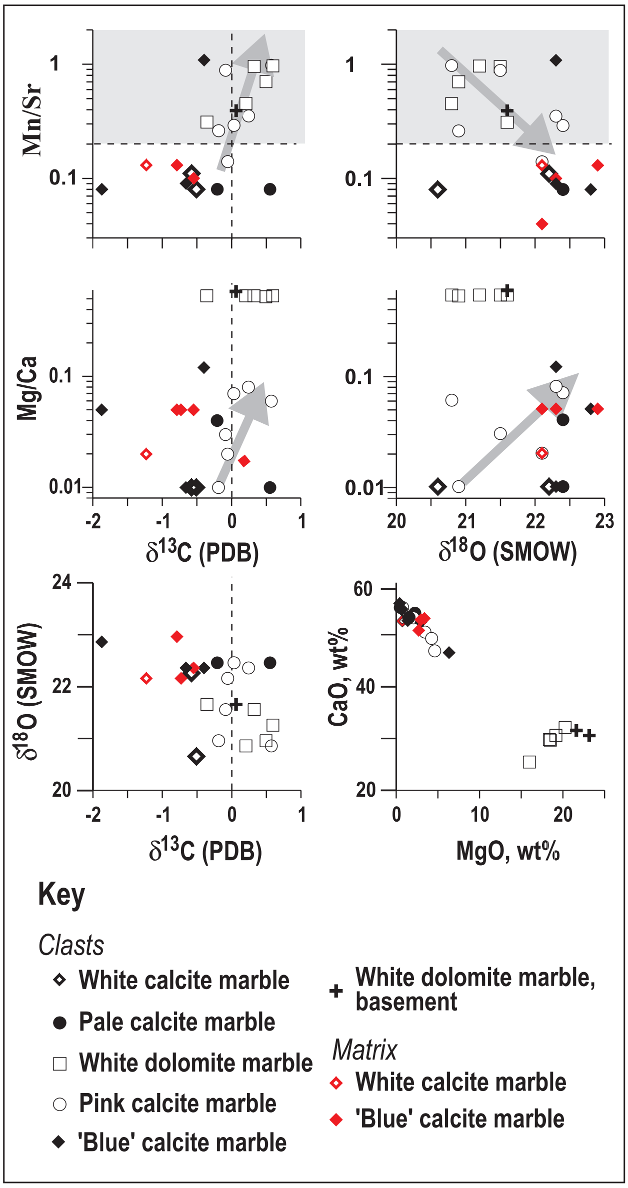

Fig. 17. Cross-plots showing the composition of different clast lithologies and matrix. Samples in the shaded areas are considered to have been subjected to alteration, i.e., with a Mn/Sr ratio > 0.2. Arrows indicate alteration trend caused by dolomitisation.

ate clasts approximates to that of a sandy calcite marble. The main siliciclastic component is quartz though variable amounts of muscovite may also be present. On a CaO-MgO diagram all the calcite marbles plot along a dolomite-calcite mixture line (Fig. 17) indicating varying degree of dolomitisation. The various calcite marble lithologies are not distinguished by major and trace element geochemistry. Even though this is the case, the clast provenance has to be different for the 'blue', white and pink calcite marbles. Whereas the source for the 'blue' marbles has been identified, the provenance of the white, and in particular, of the pink calcite marbles remains enigmatic.

Isotope geochemistry and indirect age constraints

Methods

Oxygen and carbon isotope analyses were carried out at the Scottish Universities Environmental Research Centre using the phosphoric acid method of McCrea (1950) as modified by Rosenbaum & Sheppard (1986) for operation at 100 °C. Carbon and oxygen isotope ratios in carbonate constituents of the whole-rock samples were measured on a VG SIRA 10 mass spectrometer. Calibration to international reference material was through NBS 19 and precision (1σ) for both isotope ratios is better than ±0.2‰. Oxygen isotope data were corrected using the fractionation factor 1.00913 recommended by Rosenbaum & Sheppard (1986) for dolomites. The $\delta^{13}C$ data are reported in per mil (‰) relative to V-PDB and the $\delta^{18}O$ data in ‰ relative to V-SMOW.

Rb-Sr analyses were carried out at the Institute of Precambrian Geology and Geochronology of the Russian Academy of Sciences (St. Petersburg) as specified in detail in Gorokhov et al. (1995). Prior to Rb-Sr isotope analysis, all the samples were treated by 1N NH_4OAc to remove loosely bound chemical elements from the silicate components of the rock. The

Table 1. Carbon, oxygen isotope and elemental composition of marbles from the Fauske conglomerates.

Sample No.	Lithology	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	S	C_{tot}	Sr	Mg/Ca	Mn/Sr	$\delta^{13}C$, ‰	$\delta^{18}O$, ‰
		wt %												ppm				
Uppermost conglomerate, Bed 25																		
An1	White dolostone, pebble	9.50	0.68	0.78	0.037	18.37	29.79	-	0.213	0.015	0.05	-	12.00	166	0.52	0.70	0.5	20.9
An2	White dolostone, pebble	7.11	0.39	0.49	0.019	19.16	30.62	-	0.120	0.021	0.06	-	12.30	171	0.53	0.95	0.3	21.5
An3	White dolostone, pebble	9.93	0.56	0.57	0.026	18.50	29.66	-	0.177	0.010	0.04	-	11.90	172	0.53	0.45	0.2	20.8
An4	White dolostone with pink stripes, pebble	22.75	1.00	1.05	0.035	15.99	25.48	-	0.289	0.018	0.03	-	10.00	144	0.53	0.96	0.6	21.2
An5	Pink calcite marble, 5 cm-thick layer	5.81	0.56	0.33	0.031	4.26	49.23	-	0.184	0.013	0.07	-	11.90	342	0.07	0.29	0.03	22.4
An6	Pink, banded calcite marble, cobble	6.94	0.76	0.51	0.048	4.64	46.82	0.16	0.258	0.015	0.06	-	11.60	328	0.08	0.35	0.2	22.3
An7	Pale calcite marble, pebble	1.50	0.15	0.14	0.009	0.50	55.13	-	0.011	0.005	0.09	-	12.30	478	0.01	0.08	0.6	22.4
An8	Pale calcite marble, pebble with pink rim	0.97	-	0.11	0.004	2.26	54.10	-	0.011	0.005	0.08	-	12.30	479	0.04	0.08	-0.2	22.4
An9	Pink calcite marble, 6 cm-thick layer	3.02	0.26	0.27	0.022	1.56	53.25	-	0.091	0.007	0.08	-	12.20	380	0.02	0.14	-0.06	22.1
An15a	Greywacke	52.02	11.10	5.47	0.81	4.99	11.80	0.15	1.88	0.06	0.22	-	2.70	216			n.d.	n.d.
An16a	Greywacke	44.75	10.39	5.56	0.82	4.54	15.90	-	1.42	0.07	0.24	-	3.70	298			n.d.	n.d.
Mass-flow lithofacies, Beds 3-5																		
An11	White, coarse-grained, calcite marble, large cobble	0.52	-	0.02	-	0.43	55.92	-	-	0.004	0.08	-	12.40	391	0.01	0.08	-0.5	-20.6
An12	Light, medium-grained calcite marble, matrix for An11	4.83	0.27	0.12	0.023	1.41	52.63	-	0.046	0.006	0.08	-	12.00	363	0.02	0.13	-1.2	22.1
EX13	Pink calcite marble, 7 cm-thick layer	2.44	0.56	0.30	0.043	3.47	50.44	-	0.095	0.022	0.10	-	12.94	175	0.06	0.97	0.6	20.8
EX16	White calcite marble, thin outer rim of cobble of blue calcite marble	0.64	0.06	0.03	0.007	0.65	54.93	-	0.013	0.006	0.11	-	13.07	426	0.01	0.11	-0.6	22.2
EX17	White dolostone, pebble	1.74	0.04	0.13	-	20.26	32.09	-	0.008	0.007	0.06	-	13.95	172	0.53	0.31	-0.4	21.6
EX18c	Pink calcite marble, core of pebble	0.34	0.12	0.09	0.008	0.79	55.14	0.24	0.015	0.010	0.11	-	13.18	295	0.01	0.26	-0.2	20.9
EX18r	Pink calcite marble, rim of pebble	1.12	0.44	0.21	0.032	2.08	53.16	0.19	0.108	0.026	0.10	-	13.04	227	0.03	0.88	-0.1	21.5
'Blue' marbles, Bed 2																		
An13	'Blue' calcite marble, cobble	1.69	0.18	0.15	0.021	2.98	52.33	-	0.044	0.005	0.06	-	12.40	467	0.05	0.08	-1.9	22.8
An14	Pale calcite marble, pebble	6.19	1.09	0.79	0.117	6.36	46.48	-	0.277	0.028	0.07	-	11.80	200	0.12	1.08	-0.4	22.3
An15	'Blue' calcite marble, matrix with small fragments	1.97	0.28	0.15	0.024	2.99	52.80	-	0.068	0.008	0.08	-	12.30	483	0.05	0.13	-0.8	22.9
An16	Grey calcite marble, matrix	1.01	0.06	0.05	0.009	3.40	53.06	-	0.030	0.002	0.07	-	12.40	374	0.05	0.04	-0.7	22.1
EX12	'Blue' calcite marble, matrix from 1 m-thick layer	5.38	0.25	0.14	0.020	2.72	50.75	0.11	0.057	0.005	0.09	-	12.60	376	0.05	0.10	-0.6	22.3
EX15	'Blue' calcite marble, cobble	0.80	0.05	0.02	0.005	0.67	54.74	-	0.008	0.005	0.10	-	13.09	422	0.01	0.09	-0.7	22.3
Local 'basement' for conglomerates																		
EX14	White dolomite marble	0.17	0.09	0.14	-	23.15	30.55	-	0.022	0.006	0.06	-	14.26	88	0.64	0.53	n.d.	n.d.
An10	White dolomite marble	1.30	0.80	0.31	0.049	21.61	31.52	-	0.116	0.006	0.06	-	13.10	119	0.58	0.39	0.06	21.6

'Dashes' - below detection limits: 0.1% for Al_2O_3, and Na_2O; 0.02% for S; 0.003% for K_2O; 0.004% for TiO_2. 'n.d.' - not determined.

Rb and Sr concentrations were determined by isotope dilution. The Rb isotopic composition was measured on a MI 1320 mass spectrometer. Strontium isotope analyses were carried out in static mode on a Finnigan MAT-261 mass spectrometer. All $^{87}Sr/^{86}Sr$ ratios were normalised to a $^{86}Sr/^{88}Sr$ of 0.1194. During the course of the study the value obtained for the $^{87}Sr/^{86}Sr$ ratio of the NBS SRM-987 standard averaged 0.710238±0.000012 ($1\sigma_{mean}$, n=2).

The major and trace elements were analysed by X-ray fluorescence spectrometry at NGU using a Philips PW 1480 X-ray spectrometer. The accuracy (1σ) is typically around 2% of the oxide present (SiO_2, Al_2O_3, MgO, CaO), even at the level of 0.05 wt%, and the precision is almost invariably better than the accuracy.

Data

Twenty-four samples representing carbonate clasts, matrix and the immediate local 'basement' rocks (white dolomite marble) were collected from the quarry. The complete sample collection was analysed for major and trace elements, twenty-three for oxygen and carbon isotopes, and nine samples for strontium isotope composition (Tables 1 and 2).

The O and C isotope measurements are summarised in Figs. 17 and 18. The spread of oxygen and carbon isotope values in the data set is about 20.6-22.9.0‰ and -1.9 to +0.6‰, respectively. A $\delta^{13}C$-$\delta^{18}O$ cross-plot reveals no statistically significant covariation between oxygen and carbon isotopes (Fig. 17). However, all dolomite samples with one exception exhibit positive $\delta^{13}C$ values, the pink calcite marbles all plot around zero, whereas the 'blue' and white calcite marbles have slightly negative values (Fig. 17). The 'blue' marbles are characterised by the highest $\delta^{18}O$ values, while other lithologies have variable values. The pink marbles exhibit covariation between $\delta^{13}C$ and Mn/Sr (r=0.53), $\delta^{18}O$ and Mg/Ca (r=0.45), $\delta^{13}C$ and Mg/Ca (r=0.56), and a negative correlation between $\delta^{18}O$ and Mn/Sr (r=-0.56) (Fig. 17). No covariations are observed for other lithologies. No reliable difference in elemental concentration and isotopic ratios has been detected between the clasts and their matrix (Fig. 17).

The initial $^{87}Sr/^{86}Sr$ ratios in carbonate constituents range between 0.70896 and 0.70946, with the least radiogenic value measured from the 'blue' marble clast (Fig. 18). The 'blue' calcite matrix and the clasts of the same rock are seen to overlap on the $^{87}Sr/^{86}Sr$ diagram (Fig. 18).

Evaluation of diagenesis and metamorphism and clast provenance

Dolomite is generally considered as essentially a diagenetic mineral. However, there is growing evidence that precipitation of dolomite in the Precambrian was either coeval with calcite, or that dolomitisation was an early diagenetic phenomenon caused by waters isotopically comparable to that of seawater (e.g. Veizer & Hoefs 1976; Veizer et al. 1992a, b). However, in this study, for reasons of precaution, we exclude dolomite samples from exercises applied to the reconstruction of the primary composition of seawater.

Several geochemical screening methods for providing evidence of diagenetic and metamorphic alteration have been devised. Hudson (1977) found that oxygen isotopes may be a sensitive indicator of diagenetic alteration. Diagenesis and metamorphism commonly cause a decrease in $\delta^{18}O$ values and the alteration effect can be revealed by a $\delta^{13}C$ and $\delta^{18}O$ cross-plot. Oxygen isotopes are commonly much more easily affected by exchangeable oxygen derived from either meteoric water or interstitial fluids at elevated temperatures (e.g., Fairchild et al. 1990) whereas $\delta^{13}C$ may be buffered by pre-existing carbonate. In general, depletion in both oxygen and carbon isotope values may be considerable during late diagenesis as well as in the course of low-grade metamorphism accompanied by deformation (Guerrera et al. 1997). In the studied case no significant covariation has been observed between oxygen and carbon isotopes. However, the covariations between $\delta^{18}O$ and Mg/Ca, and $\delta^{13}C$ and Mg/Ca observed in the pink marbles can be attributed to the dolomitisation. Thus, we suggest that slightly elevated $\delta^{13}C$ and $\delta^{18}O$ values in some pink marbles were caused by diagenetic dolomitising fluids. The least altered sample is characterised by $\delta^{13}C$ and $\delta^{18}O$ values of –0.2‰ and 20.9‰, respectively.

The Mn/Sr ratio may serve as a tool to discriminate between the altered and the least altered samples. Fluids generated during the course of diagenesis and metamorphism commonly introduce manganese and radiogenic strontium, and decrease the Sr content in carbonate rocks (Brand & Veizer 1980, Derry et al. 1992, Kaufman & Knoll 1995). Samples having a Mn/Sr ratio above 0.2 should be treated as severely altered and must not be used for reconstruction of seawater composition (e.g., Kusnetzov et al. 1997). These samples would normally have lost Sr and their Rb-Sr isotope systems were disturbed. Based on the Mn/Sr ratios the majority of the pink marbles and, apparently, all dolomite marbles (Figs. 17 and 18) should be excluded from further discussion.

Based on the limitation criterion, which includes Mn and Sr geochemistry, a $\delta^{13}C$ vs. $\delta^{18}O$ cross-plot and Mg/Ca ratios, we suggest that the best preserved Sr and oxygen isotope values for the carbonates studied are 0.70897 and 22.9‰, respectively (Fig. 18b, Tables 1 and 2). Both values have been measured from 'blue' marble clasts. As far as the carbon isotope composition is concerned it is not clear which of the values reflect a primary signal. The least altered $\delta^{13}C_{carb}$ value for the 'blue' marbles is -0.5‰ (Fig. 18a). However, as even non-discriminated $\delta^{13}C_{carb}$ values for all the clasts and matrices of calcite marbles are closely clustered between -1.9 and +0.6‰, we may assume that the source rocks were isotopically homogeneous and apparently represent carbonates of the same age precipitated from a normal seawater.

Implication for depositional age

In general, dating of non-fossiliferous carbonates provides many problems regardless of their actual age. In order to obtain an apparent depositional age for the FC, the measured $\delta^{13}C_{carb}$ and Sr isotopic data have been used along with $\delta^{13}C_{carb}$ and $^{87}Sr/^{86}Sr$ calibration curves. We exclude the dolostone samples from our consideration as isotopic values measured for dolostones may not reflect the isotopic compo-

Table 2. Strontium isotope and elemental composition of marbles from the Fauske conglomerates.

Sample No.	Lithology	Insoluble residue	Rb	Sr*	Mg/Ca	Mn/Sr	$^{87}Sr/^{86}Sr$ measured	$^{87}Sr/^{86}Sr$ initial**	Minerals in insoluble residue
		wt%	ppm	ppm					
Uppermost conglomerate, Bed 25									
An7	Pale calcite marble, pebble	1.7	0.031	481	0.01	0.08	0.70941	0.70941	Qu
An8	Pale calcite marble, pebble with pink rim	1.5	0.080	484	0.04	0.08	0.70947	0.70946	n.d.
Mass-flow lithofacies, Beds 3-5									
An11	White, coarse-grained, calcite marble, large cobble	1.1	0.031	401	0.01	0.08	0.70916	0.70916	n.d.
EX13	Pink calcite marble, 7 cm-thick layer	1.8	0.124	171	0.06	0.97	0.70944	0.70943	Qu, Ms, Chl
EX17	White dolomite marble, pebble	1.8	0.032	168	0.53	0.31	0.70921	0.70921	Qu
'Blue' marbles, Bed 2									
An13	'Blue' calcite marble, cobble	2.0	0.085	475	0.05	0.08	0.70922	0.70922	Qu, Ms
An16	Grey calcite marble, matrix	2.6	0.050	379	0.05	0.04	0.70930	0.70929	Qu, Ms
EX12	'Blue' calcite marble, matrix from 1 m-thick layer	5.5	0.323	433	0.05	0.10	0.70910	0.70908	Qu, Ms
EX15	'Blue' calcite marble, cobble	0.6	0.104	408	0.01	0.09	0.70897	0.70896	n.d.

* Acid-soluble Sr analysed by standard isotope dilution and solid-source mass spectrometry.

** The initial $^{87}Sr/^{86}Sr$ ratios are calculated under the assumption that the age of these rocks is equal to 520 Ma. 'n.d.' - not determined.

Abbreviations used: Ms – muscovite, Qu – quartz, Chl – chlorite.

sition of coeval seawater. If we treat all the carbonate clasts as if they have derived from carbonate rocks of a similar age, then the best-preserved $^{87}Sr/^{86}Sr$ value of 0.70896, which has been obtained for the clasts of 'blue' marbles, is consistent with apparent depositional ages of 470-475, 505-510 and 520 Ma (Fig. 19). However, the least altered $\delta^{13}C_{carb}$ value of -0.6‰ matches only 520 Ma. Strictly speaking, the reconstructed ages should relate to the formation of the carbonate rocks before they were incorporated into conglomerate clasts. However, available data suggest that the conglomerates are intraformational, and therefore their time of deposition should be close to the age of carbonates from which they formed. If this was the case, then the obtained age of 520 Ma, Early Cambrian, indicates the lower limit for the apparent depositional age of the Fauske conglomerate.

Another assumption which can been made is that the carbonates incorporated into the clasts were of different ages. Then, the least altered $\delta^{13}C_{carb}$ and $^{87}Sr/^{86}Sr$ values have to be selected separately for different lithological groups of carbonates represented by the studied clasts. In this case, the least altered $\delta^{13}C_{carb}$ value of -0.5‰ together with the $^{87}Sr/^{86}Sr$ of 0.70916 obtained for the clasts of white calcite marbles would give an apparent age which is indistinguishable from that of the 'blue' marbles. The pink and pale pink carbonates cannot be used for these exercises as even the least altered Sr isotope values measured from them (0.70944 and 0.70941, respectively) are highly radiogenic, and on the diagram they plot above the $^{87}Sr/^{86}Sr$ reference curve within any appropriate time interval (Fig. 19).

Depositional model

Wilson (1975) defined three types of carbonate platform margin corresponding to (1) energetically quiet, (2) moderate and (3) rough seas. All three types of environment usually produce talus on a foreslope to the carbonate platform margin. However, type 3 margins are characterised in particular by the development of widespread giant talus blocks, debris flows and turbidites on foreslopes and in deep-shelf settings (Wilson 1975, Leeder 1982). Although the sedimentological

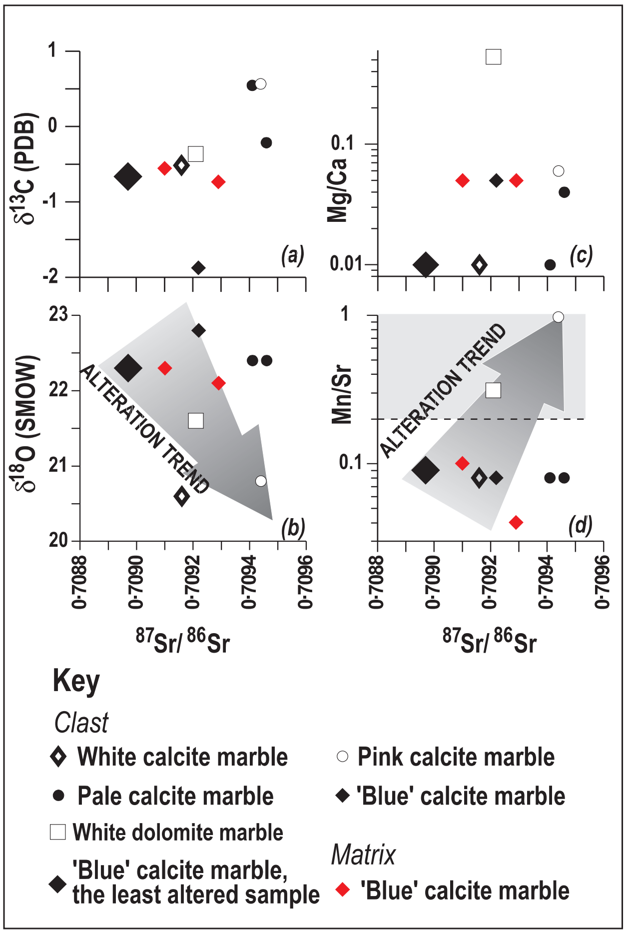

Fig. 18. Cross-plots showing $^{87}Sr/^{86}Sr$ ratios in different clast lithologies and matrix. Samples in the shaded area are considered to have been subjected to alteration, i.e., with a Mn/Sr ratio > 0.2. Arrows indicate alteration trend.

features of the FCs are superficially consistent with a type 3 margin, the geological data do not match this type of environment as the Fauske conglomerate is only locally developed. Such a local development requires that a local factor should be involved in the formation of the conglomerates, breccias and debris. Moreover, the presence of foreign clasts, i.e. fragments of the pink calcite marbles, requires a system that could have transported such material to the carbonate platform/shelf margin. Based on this, we suggest that the depositional model should involve (Fig. 20): (*i*) a locally developed, tectonically unstable, carbonate shelf margin, (*ii*) a temporary lowering of sea level, (*iii*) formation of a high-relief, shore-to-basin fault scarp, followed by (*iv*) the development of a channel with (*v*) subsequent, long-distance transport of clasts of pink carbonates from the continent-basin margin, which were (*vi*) redeposited together with a carbonate debris (white dolomite and 'blue' calcite marbles) on the tectonically fragmenting edge of a shallowing carbonate shelf.

A high-relief fault scarp apparently played an important role both in exposing previously deposited carbonates (white dolomite and 'blue' calcite carbonate rocks) and in the development of a channel. The latter is considered as an essential feature for transportation of the relatively far-travelled (from the shoreline?) clasts of pink carbonates.

Depositional model and its application for exploitation and exploration

The depositional model has several implications. First of all, the data obtained may be used to quantify the commercial quality of the marbles in the quarry. This applies especially for the pink and white conglomero-breccias, which are clearly

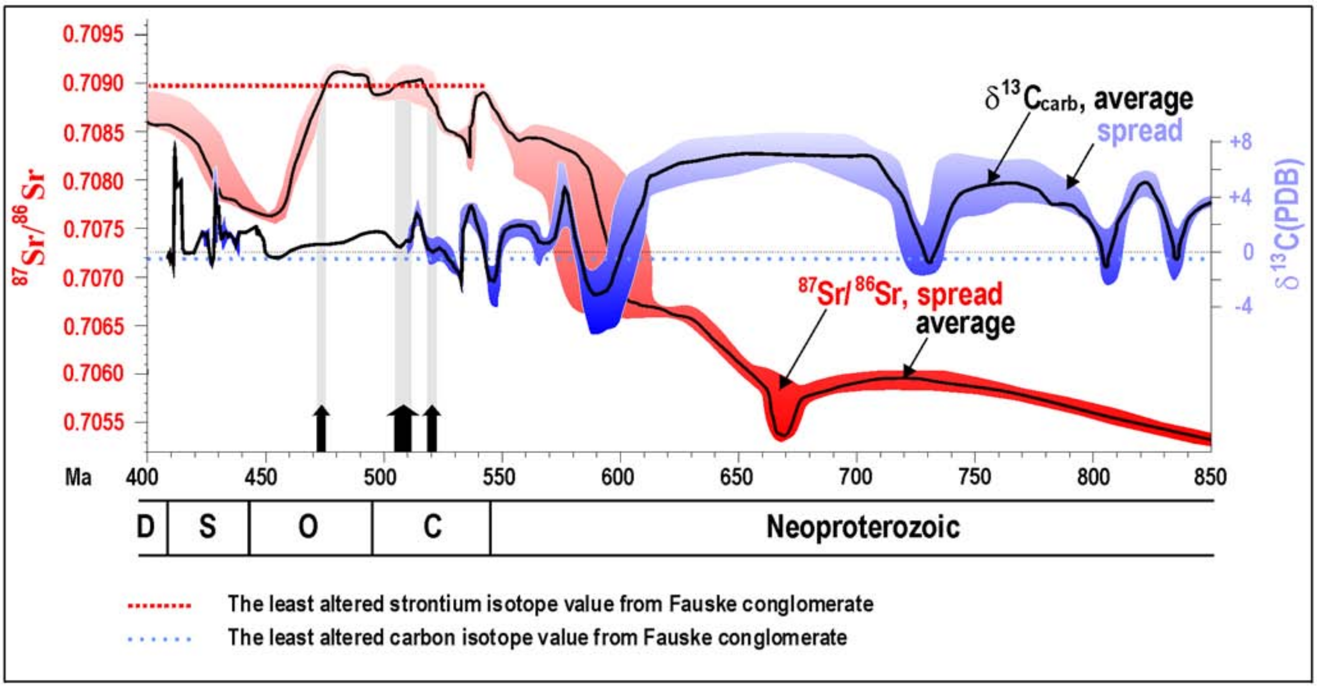

Fig. 19. Apparent depositional age of the Fauske conglomerates (*indicated by black arrow*). The Sr- and C-isotope calibration curves are based on data from Veizer et al. (1983), Asmeron et al. (1991), Derry et al. (1992, 1993), Gorokhov et al. (1995), Kaufman & Knoll (1995) and Azmy et al. (1998).

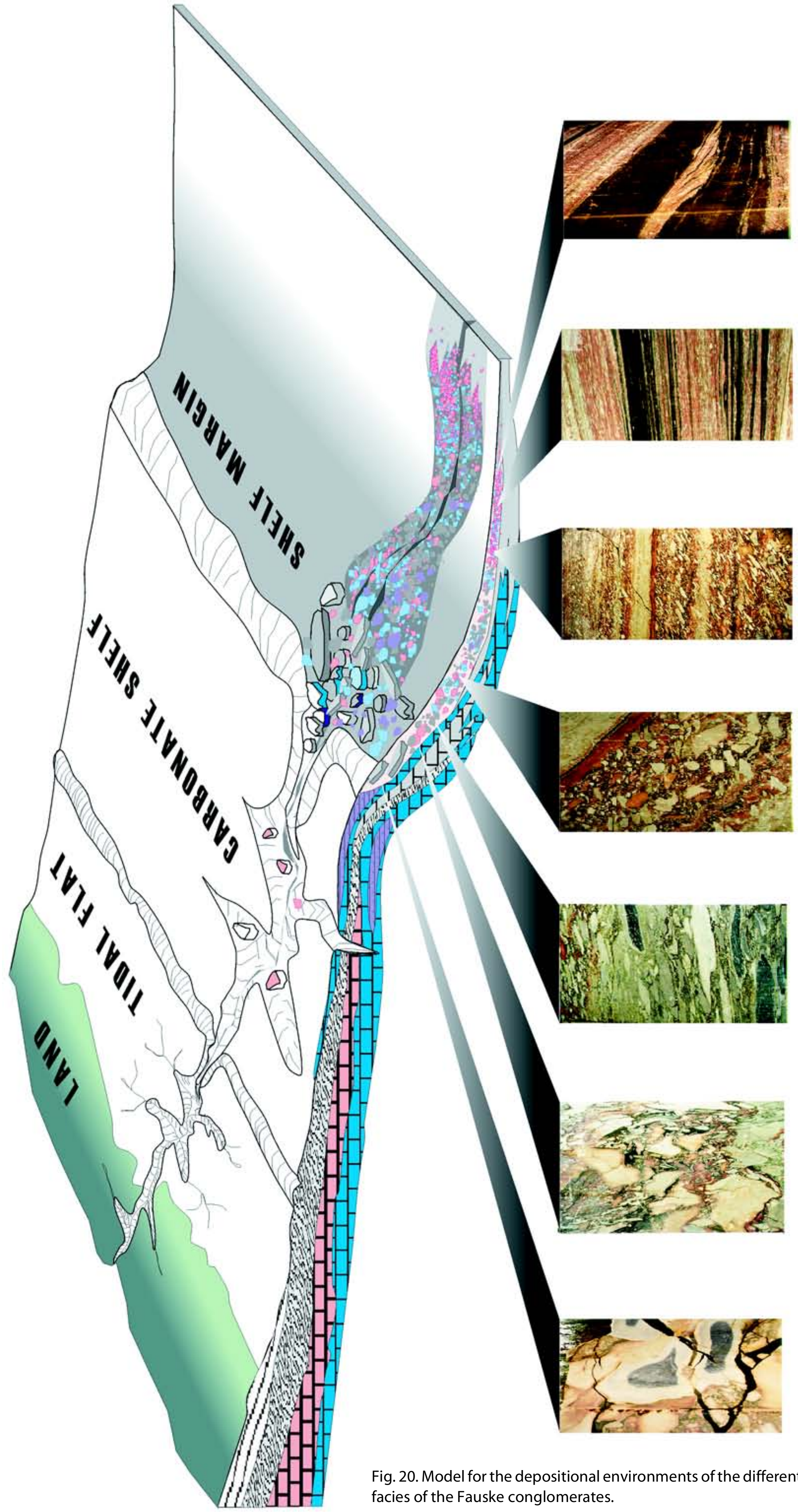

Fig. 20. Model for the depositional environments of the different facies of the Fauske conglomerates.

the most attractive commercial types and the basis for the commercial value of the deposit. To be of any value at all, the conglomero-breccia beds should have at least a 0.5 m thickness of uniform marble. As shown above, there are significant lateral thickness variations of the individual beds and, in actual fact, all exploitable beds are shown to thin out laterally within the quarry area. Consequently, the commercial part of the deposit occurs as a limited number of lenticular beds onlapping each other, and separated by non-commercial beds. The vast majority of trading blocks have in the past, and will in the future, come from the lower, thick, conglomero-breccia beds of the second lithofacies, mainly Beds 8-11, 12, 14 and 15. For the future, Bed 25 may represent an additional potential resource, although the size of the clasts are generally larger than in the currently exploited beds.

In addition to the thickness variations, the marble production is sensitive to the variations of quality within the beds. The pricing of marble depends totally on customer tastes, and in the case of the Fauske quarry these tastes have developed towards the conglomerate sub-facies with small, sorted pebbles as the prime quality material. These types are essentially found in distal (thin) parts of the beds and in the upper part of upward-fining beds. The pink conglomero-breccias with large, sorted pebbles are considered to be somewhat less attractive in the market than the small-pebble conglomerate, but still of considerable interest. Coarse, poorly sorted breccia (such as Bed 25) is, at the present time, not of any commercial value, but it might be used in the future as a separate sorting. The pricing of blocks is also dependent on the composition of the matrix. A pure carbonate matrix is preferable, whilst the value drops significantly and proportionally with an increase in volume of dark silicate minerals. In general, the commercial value of the FCs is strongly linked to even minor variations in lithofacies and depositional environment. Therefore, the depositional model will clearly contribute to our further understanding of such variations, and thus help in the estimation of the future reserves within the deposit.

Another application of the model is that of a prospecting philosophy for deposits of similar quality. Two major components, namely pink and white marbles, make the FCs commercially attractive. These two components derive from two different sources. The white dolomite marbles are from a very local source, whereas the pink marbles were transported from an unknown distant source. Moreover, for a commercially attractive rock, the amount of other foreign clasts must be very limited. This combination of factors highlights several strict limitations on depositional environments: (1) a Fauske-type conglomerate may only form on the relatively steep slope of a carbonate shelf; (2) a direct contact with white dolomite is essential; (3) a high-relief fault scarp is considered to play an important role both in exposing and fragmenting white dolomite and in the development of a channel; (4) the channel is an essential feature for transportation of far-travelled clasts of pink carbonates. Thus, we suggest that a search for new deposits should be areally limited to the development of relatively thick units of white dolomite marbles of Early Cambrian age; and a special attention should be paid to the upper contacts of dolomite units with irregular surfaces indicating syndepositional faulting and fragmentation.

Conclusions

The Fauske conglomerate represents a rather rare case of a monomict carbonate conglomerate in the Late Neoproterozoic to Silurian, lithostratigraphic successions of the Norwegian Caledonides. Lithological varieties of this conglomerate unit from the Løvgavlen quarry have a highly decorative quality and are well known in both domestic and international markets under trading names such as 'Norwegian Rose', 'Jaune Rose', 'Norwegian Green', 'Antique Foncé' and 'Hermelin'.

The Fauske conglomerate rests on dark grey ('blue') calcite marbles and white dolomite marbles. The latter are jointed and fragmented, and also appear as sedimentary collapse-breccia and debris where they are in direct contact with the conglomerate. Although the Fauske conglomerate has been involved in two main pulses of Caledonian tectonic deformation, the overall sedimentary features are still remarkably well preserved.

The Fauske conglomerate is a 60 m-thick unit consisting of 25 beds which are from 3 to 5 metres thick. The unit is composed of landslide, carbonate debris and carbonate breccia–conglomero-breccias –greywacke lithofacies. An upward fining of the clasts is followed by the gradual development of calcareous greywacke layers which show both cross bedding and channelling. Blocks, fragments, cobbles, pebbles and smaller clasts are mainly of white dolostone and pink, beige, white and 'blue' calcite marbles. The matrix has a similar range in lithology with variable amounts of quartz, fuchsite, sericite, muscovite and chlorite.

Both matrix and pebbles show a similar range in isotopic values: -1.9 to +0.6‰ (vs. V-PDB) for $\delta^{13}C_{carb}$ and 0.70896 to 0.70946 for $^{87}Sr/^{86}Sr$. The least altered $^{87}Sr/^{86}Sr$ (0.70897) isotopic value plotted on the calibration curve is consistent with apparent depositional ages of 470-475, 505-510 and 520 Ma 520 Ma, whereas the least altered $\delta^{13}C_{carb}$ (-0.6‰) value matches only 520 Ma.

The conglomerates were deposited on a tectonically unstable carbonate shelf margin. Clast of white dolomite and 'blue' calcite marbles were locally derived. Clasts of pink carbonates were transported from the continent – basin margin to the shelf margin through the channel formed by a high-relief, shore-to-basin fault scarp. Both local and foreign clasts were locally redeposited together with a carbonate debris (white dolomite and 'blue' calcite marbles) on the tectonically fragmenting edge of a carbonate shelf.

The depositional model may by used to quantify the commercial quality of the marbles in the quarry. A search for new Fauske-type deposits should be areally limited to the development of relatively thick units of white dolomite marbles of Early Cambrian age with an upper contact marked by irregular surfaces indicating syndepositional faulting and fragmentation.

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