Study of a Palaeogene intrabasaltic sedimentary unit in southern East Greenland: from 3-D photogeology to micropetrography

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Establishment of robust reservoir models and estimates of subsurface hydrocarbon volumes in relatively unknown subsurface settings can be improved by using data from field analogues. The discovery of the Rosebank oilfield in the Faroe–Shetland Basin showed that intrabasaltic sandstones can form important hydrocarbon reservoirs in volcanic basins (Helland-Hansen 2009). The Sødalen region in southern East Greenland (Fig. 1) forms an excellent field analogue to the Rosebank oilfield where contemporaneous Palaeogene sediments interbedded with lava units can be studied and sampled (Larsen *et al.* 1999). In this area many of the exposures are located along steep, inaccessible cliffs with excellent exposures that are ideal for 3-D photogeological studies based on digital high-resolution photographs taken from a helicopter.

The analogue study reported on here has integrated results from a wide range of spatial scales. On a large scale (kilometre to metre), 3-D photogeology was used to study the extent, geometry and interfingering of volcanic and intrabasaltic sedimentary units. Photogeology was also used to map faults, dykes and sills, which may lead to compartmentalisation (division) of reservoirs. On an intermediate scale (metre to millimetre), sections are logged in the field, sedimentary and volcanic facies are mapped and depositional environments are interpreted. Three-dimensional photogeology is also applied on an intermediate scale to map lateral variations of sedimentary units between logged sections. On a small scale (millimetre to micrometre), mineral-chemical, petrographical and zircon age determinations provide information on sediment source, provenance area and diagenetic influences on reservoir properties.

The analogue study has resulted in a large database, which can form an important source of estimates of reservoir size, geometry and connectivity, and of vertical and lateral variations in the sandstone content of reservoirs. Ultimately this may improve estimates of the actual volumes and recoverable volumes of hydrocarbons in intrabasaltic subsurface sediments.

The 3-D photogeological method

The 3-D photogeological method used in this study was developed at the Geological Survey of Denmark and Greenland (GEUS) and builds on earlier work by Dueholm *et al.* (1993) and Dueholm & Olsen (1993). The method allows the acquisition of geological data from vertical and oblique aerial photographs, with a three-dimensional overview of the outcrops. The oblique photographs (1:15 000–1:17 000 scale) are triangulated with coloured, vertical, aerial photographs (1:27 000 scale) using a 3-D stereo-plotter coupled with stereo-mirror technology. The mapping of geological features includes determination of strata thickness, strike direction and dip values working on a 3-D high resolution vision of the cliffs. The resolution of volcanic and sedimentary beds and geological features is *c.* 10 cm. All the mapped features are stored in a GIS database and 3-D polylines can be exported

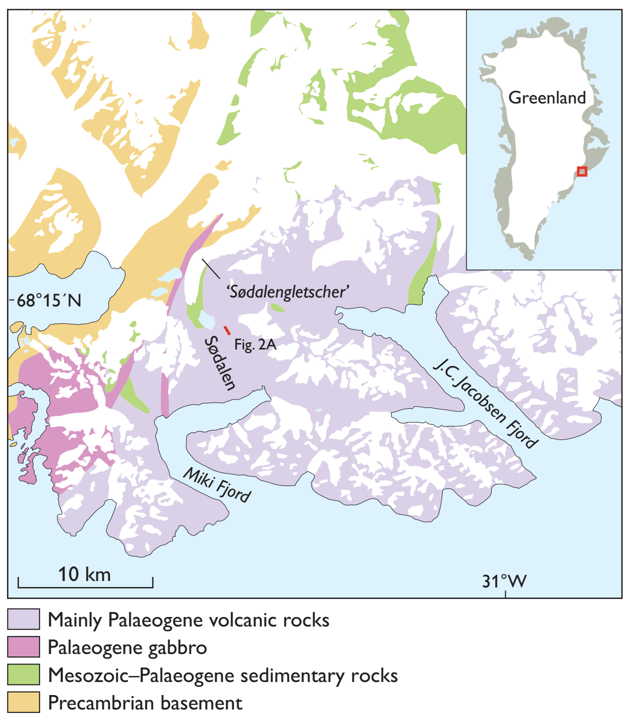
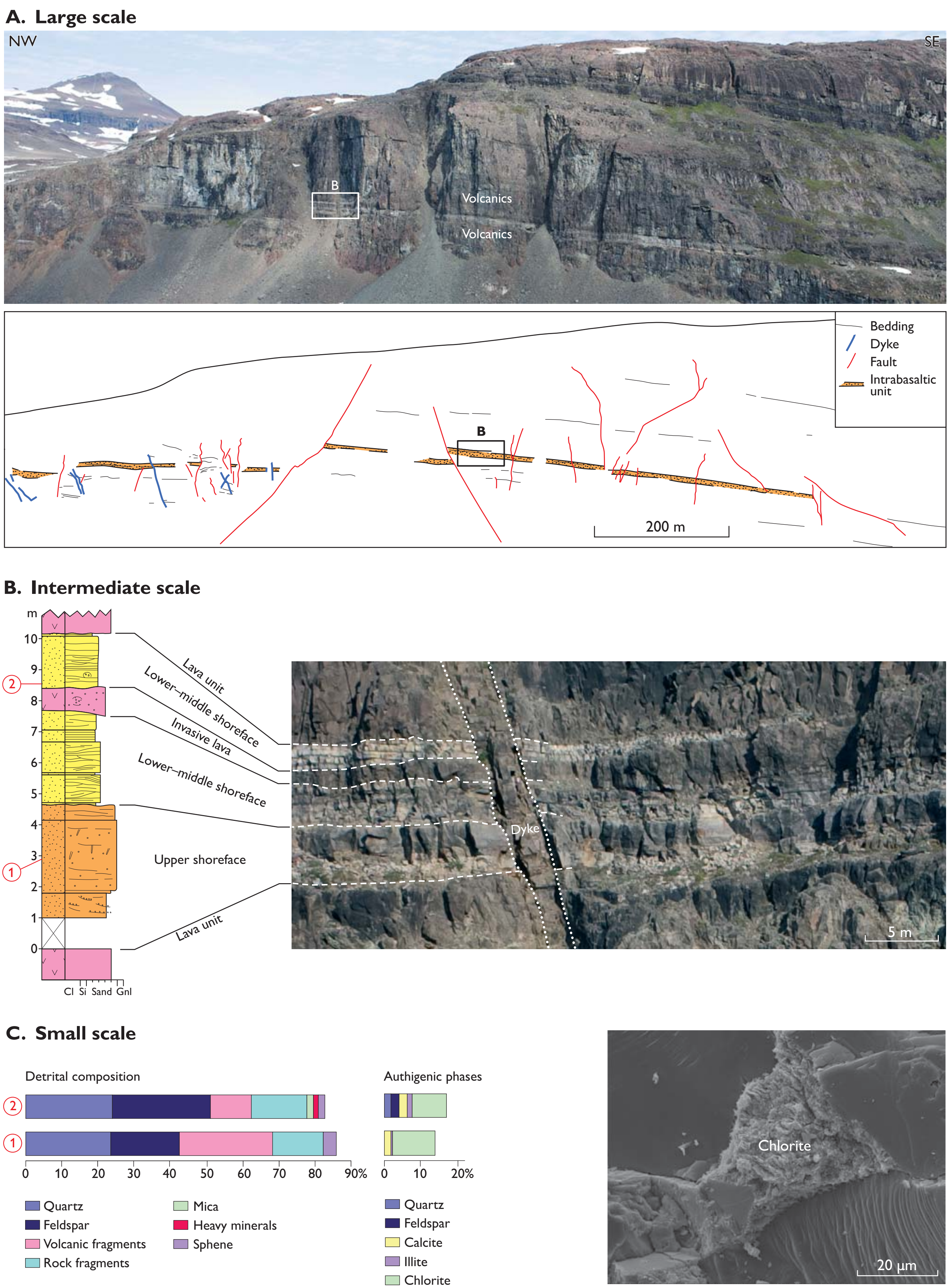


Fig. 1. Map of the Sødalen area in southern East Greenland. The red line shows the location of the profile in Fig. 2A.


A. Large scale
NW
SE
B
Volcanics
Volcanics
Bedding
Dyke
Fault
Intrabasaltic unit
B
200 m
B. Intermediate scale
m
10
9
8
7
6
5
4
3
2
1
0
2
1
Cl Si Sand Gnl
Lava unit
Lower–middle shoreface
Invasive lava
Lower–middle shoreface
Upper shoreface
Lava unit
Dyke
5 m
C. Small scale
Detrital composition
Authigenic phases
0 10 20 30 40 50 60 70 80 90%
0 10 20%
Quartz
Feldspar
Volcanic fragments
Rock fragments
Mica
Heavy minerals
Sphene
Quartz
Feldspar
Calcite
Illite
Chlorite
Chlorite
20 µm

as shape files suitable for 3-D modelling using, for example, Petrel reservoir engineering software. Moreover, using 3-D feature databases in ArcGIS, geological cross-sections can be generated automatically to obtain real representations of outcrops, and then projected onto a topographic profile, where the accuracy is as high as the resolution in the photographs. The oblique photographs used here were small-frame colour photographs taken from a helicopter flying close to the cliff faces (<800 m) and at a constant altitude along straight lines approximately parallel to the cliffs. The photographs were taken with a 60 to 80% overlap using a 22 megapixel digital camera.

On a large scale (kilometre to metre)

On a large scale, 3-D photogeology is used to study the lateral extent and geometry of the intrabasaltic sediments and volcanic rocks and boundary relationships. Evidence of compartmentalisation of the intrabasaltic reservoir analogues, caused for example by dykes, sills or faults, are mapped. Figure 2A shows an oblique view of a 1.2 km section on the eastern side of Sødalen, which is an 8 km long U-shaped valley, orientated SE–NW from Miki Fjord to 'Sødalengletscher' (Fig. 1). The photograph focuses on the stratigraphically lowest intrabasaltic, whitish sedimentary unit, which dips gently to the south-east. The geological cross-section in Fig. 2A is projected on the cliff view, and is obtained from 3-D polylines created during the 3-D photogeological work. Figure 2A illustrates several large-scale features relevant to the analogue study such as: (1) top and bottom geometry of the sandstone unit, (2) density of dykes and faults, which has a large impact on the lateral extension of the layers due to offsetting and (3) an evaluation of reservoir compartmentalisation.

Fig. 2. *(facing page)* **A**: Oblique photograph (upper) and derived geological cross-section (lower) of the eastern side of Sødalen, an 8 km long U-shaped glacial valley, extending SE–NW from 'Sødalengletscher' to Miki Fjord. For location see Fig.1. The photograph focuses on the lowest intrabasaltic sediments (whitish colour) that dip gently to the south-east. Faults and dykes are also seen. The geological cross-section below is a projection of 3-D polylines along a N–S-oriented profile, slightly different from the NW–SE orientation of the photograph. **B:** Close-up view of the white square in Fig. 2A. A field log of the section (left) labels the sedimentary facies assemblages which can be followed laterally on the photograph. Other important observations include an invasive lava bed and a dyke cutting through both lavas and intrabasaltic sediments. **C:** Detrital and authigenic mineralogical composition of the facies in the sedimentary unit. The larger amount of authigenic phases in the lower-middle shoreface sandstones compared to the upper shoreface sandstones, reflect that these sandstones originally had a larger content of unstable, glass-rich volcanic fragments. The positions of the two samples are shown on Fig. 2B.

On an intermediate scale (metre to millimetre)

On an intermediate scale, sedimentary and volcanic sections are logged in the field. Facies types are identified, their lateral distribution and vertical stacking patterns are mapped and the boundaries between sedimentary and volcanic units are studied in detail. The 3-D photogeology is also useful on this intermediate scale because the high resolution of the digital photographs allows enlargement to study decimetre-sized features. Photogeology can therefore be very helpful in mapping sedimentary facies assemblages between logged sections as well as key surfaces separating the different facies, such as sequence boundaries and marine-flooding surfaces. The overall depositional environments and the governing mechanisms for facies distribution, such as sediment transport directions, relative sea-level variations and palaeotopography can be interpreted from these studies.

An example of a study on an intermediate scale is illustrated in Fig. 2B where the photograph is an enlargement of a small area on the digital photograph (Fig. 2A). The log of the sedimentary unit of shallow marine sandstone is shown on the left side of the figure. The lower, exposed part of the unit consists of crudely and irregularly bedded sandstones, locally with vertical burrows, interpreted as deposited in the upper shoreface zone. The lower part is overlain by well-sorted, fine to medium-grained, laterally extensive sandstone sheets and wedge-shaped sandstone beds with a large variety of sedimentary structures including local vertical burrows, cross-stratification and parallel bedding. These sandstones are interpreted as deposited in the lower to middle shoreface zone, which implies that the boundary to the underlying upper shoreface sandstones represents a minor flooding surface. On the photograph (Fig. 2B) it is seen that the upper and lower to middle shoreface facies assemblages can be followed laterally for tens of metres. It is also seen that the boundary between the lava units and the sedimentary unit is slightly undulating, and that the invasive lava bed can be followed into the overlying lava to the right. The dyke that cuts through both the sedimentary unit and the lava units may have led to a possible compartmentalisation of the sandstone reservoir.

On a small scale (millimetre to micrometre)

On a small scale, petrography is used to understand diagenetically induced reductions in porosity and permeability to understand the influence of provenance, sedimentary facies and surrounding 'hot' units on diagenetic processes. Based on intensive sampling in a well-described geological framework controlled by 3-D photogeology and logged sedimentary sections, diagenetic changes are compared with detrital composition, depositional environment and effects from overlying and underlying lava units as well as dykes and sills. Provenance variations are revealed from heavy mineral analysis using computer-controlled scanning electron microscopy, zircon age distributions and petrography. Geochemistry is applied to distinguish different intrabasaltic units.

The intrabasaltic sedimentary rocks consist of a mixture of detrital siliciclastic (quartz, feldspar, mica etc.) and volcaniclastic input (Fig. 2C). The upper shoreface facies is richer in volcanic fragments than the lower-middle shoreface facies, yet it has a lower content of authigenic phases (Fig. 2C). This is unexpected as volcanic fragments traditionally have been associated with intensive alteration thereby liberating elements for extensive authigenic phases. However, the type of volcanic fragments is also crucial for the degree of diagenetic alteration. Glass-rich volcanic fragments are common in the lower-middle shoreface facies, whereas relatively stable volcanic fragments (lath-shaped plagioclase with little interstitial glass matrix) are more abundant in the upper shoreface. Glass-rich volcanic fragments, which are easily altered, result in extensive authigenic formation, including chlorite as shown in Fig. 2C. The stable volcanic fragments behave as plagioclase grains during diagenesis and have less influence on the authigenic phases than the glass-rich volcanic fragments. Consequently, the upper shoreface sandstones show better reservoir properties than the lower-middle shoreface facies.

Conclusions

The field analogue project at Sødalen integrated the three disciplines of 3-D photogeology, sedimentology and petrography, and gave detailed information from kilometre to micrometre scale. Petrographical investigations revealed the diagenetic influence on the reservoir properties. When the diagenetic changes were related to the sedimentary facies, the information on the reservoir properties could be scaled up to sedimentary bodies. The geometry of the sedimentary bodies and the probability of compartmentalisation are defined from 3-D photogeology and logged sedimentary sections. Integration and up-scaling of several types of geological data resulted in a more complete understanding of the geology of the area and can form the basic input for reservoir modelling and as field analogue for hydrocarbon discoveries in a similar, inaccessible geological setting in offshore areas.

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