The Sortlandsundet Basin, Vesterålen, northern Norway: a Jurassic basin based on erratics, seismic mapping and regional correlations

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The Sortlandsundet Basin is a half-graben with Mesozoic sediments located in Sortlandsundet between Langøya and Hinnøya in Vesterålen. The basin is defined by the Hadsselfjord Fault Zone in the southeast and by unconformable boundaries to Archaean to Palaeoproterozoic basement rocks to the northeast, northwest and southwest. The basin may have originated as an extensional basin and evolved as a transtensional basin in the Jurassic–Early Cretaceous. Sedimentary strata of probable Jurassic age within the basin are more than 400 m thick, with seismic reflectors dipping slightly to the southeast. Glacial-transported erratic blocks, assumed to derive from the Sortlandsundet Basin, are found along the shores of Sortlandsundet. The blocks comprise quartz-rich sedimentary rocks, varying from conglomerates to fine sandstones, representing terrestrial to shallow-marine deposits. Many of the erratic blocks contain common macro- and microfossils of Middle and Late Jurassic age. A syn-tectonic depositional model for the Sortlandsundet Basin with correlations to the age-equivalent strata offshore Vesterålen (Ribban Basin) and on Andøya is discussed.

Keywords: Jurassic basin, seismics, erratic rocks, correlations, Sortlandsundet

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Introduction

Local, coastal and inshore Mesozoic sedimentary basins are known from several places along the Norwegian coast, i.e., Karmsundet in Rogaland (Bøe et al., 1992, 2010); Bjørøy near Bergen (Fossen et al., 1997; Bøe et al., 2010); Griptarane off Møre (Bøe & Skilbrei, 1998), Beitstadfjorden, Edøyfjorden, Frøyfjorden and Frohavet–Vikna in Trøndelag (Carstens, 1929; Oftedahl, 1972; Bugge et al., 1976; Bøe & Bjerkli, 1989; Bøe, 1991; Thorsnes, 1995; Sommaruga & Bøe, 2002; Bøe et al., 2005, 2010; Mørk & Johnsen, 2005), off Træna and Meløy in Nordland (Bøe et al., 2008, 2010), and in Gavlfjorden, Hadsselfjorden and Sortlandsundet in Vesterålen (Davidsen et al., 2001a, b; Fürsich & Thomsen, 2005;

Bøe et al., 2010). Onshore Mesozoic rocks in Norway are only found on Andøya in Vesterålen, northern Norway (Dalland, 1975, 1979, 1981).

Erratic blocks and boulders found adjacent to the coastal and inshore sedimentary basins provide important information on the geology and stratigraphy of the basins. A Mesozoic sedimentary erratic boulder was reported from Brottøya (Hanø) in Vesterålen a century ago (Ravn & Vogt, 1915). Based on macrofossils the large block (125 kg) was assigned an Early Cretaceous age. However, Fürsich & Thomsen (2005) found that the fauna figured and described by Ravn & Vogt (1915) is not diagnostic enough to give a precise Early Cretaceous age and suggested that it may equally belong to the

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Figure 1. Geological map of the Vesterålen–Lofoten region (after Tveten, 1978, supplemented with data from NGUs bedrock database), with locations of Mesozoic sedimentary basins and positions of main structural elements (solid and stippled lines), and locations of the IKU boreholes 6814/04-U-01, 6814/04-U-02 and 6710/03-U-01 (outside map boundary). A – Austvågøy, AB – Andfjord Basin, B – Brottøya, Ef – Eidsfjorden, F – Fiskebøl, G – Gavl fjorden, Ha – Hadseløya, Hf – Hadsel fjorden, Hi – Hinnøya, La – Langøya, SB – Sortlandsundet Basin, Vf – Vesterålsfjorden

Upper Jurassic. Vogt (in Ravn & Vogt, 1915) discussed the origin of the erratic block. He suggested it could have been transported by the ice from the Ramså Basin on Andøya or possibly it could have come from an unknown sedimentary basin in the Vesterålen area.

In summer 2000, erratic boulders of Mesozoic fossiliferous sedimentary rocks were discovered along the

shoreline south of Sortland (Figs. 1 & 2) (Davidsen et al., 2001a, b), i.e., from the shore north of the present basin in Sortlandsundet. However, it should be mentioned that additional sedimentary erratics of possible Mesozoic age have been found on the shore south of Gjerstad and some kilometres southwest of the Sortlandsundet Basin. Erratics included in the present study were recovered at Strand, east of Sortland, already

Figure 2. Map of the study area and the Sortlandsundet Basin with positions of seismic lines (blue lines) and locations where Jurassic blocks and boulders have been found. Sample locations are marked by red squares. The materials included in the present study are from Natland (Nat in Fig. 7), Myrland (Myr in Fig. 7), Sortland (Sor in Fig. 7), Steiro (Ste in Fig. 7) and Strand (Str in Fig. 7). Bedding orientation of strata in the Sortlandsundet Basin is indicated by strike and dip symbols. HFZ – Hadsselfjord Fault Zone. See Fig. 1 for location.

around 1970 by Per Tore Hansen (S. Hansen, pers. comm., 2001), but these findings were not reported to the scientific community.

The erratic rocks were unmetamorphosed and distinctly different from the bedrock of the area, which consists of igneous and metamorphic rocks of Archaean to Palaeoproterozoic age (Griffin et al., 1978; Corfu,

2001, 2002, 2004; Davidsen & Skår, 2004; Mansfeld & Davidsen, 2001). Subsequent search for sedimentary erratic rocks revealed several localities along the shores of Sortlandsundet. The preliminary examinations of the erratic boulders containing fossil bivalves, belemnites, coal and plant imprints indicated that they were of Mesozoic age.

Figure 3. Interpreted seismic profile NGU 0009006 in the Sortlandsundet Basin. Position of the line is shown in Fig. 2.

The quantity and distribution of these boulders, combined with the known ice transport direction during the last phase of the last glaciations, indicated that there is a local source south of Sortland. A seismic survey conducted by NGU's research vessel F/F Seisma in September 2000 confirmed the presence of a sedimentary basin in Sortlandsundet (Davidsen et al., 2001a, b) (Fig. 3). The Sortlandsundet Basin is located in the 1–5 km-wide Sortlandsundet about 10 km south of Sortland. Sortlandsundet is the northward continuation of Hadsselfjorden, separating the island of Langøya to the west from the island of Hinnøya to the east. The basin is approximately 5 km long and 3 km wide and is fault-bounded to the south-east. Complementary fieldwork was carried out in 2001 and 2002, including collection of fossil-bearing samples and an additional seismic survey (NGU in co-operation with Statoil, Norsk Hydro and Enterprise) (Davidsen et al., 2001b).

The present paper describes the geometry and basin fill in the Sortlandsundet Basin based on seismic data and gives a documentation of the lithologies and content of microfossils (palynomorphs) in a series of erratic blocks found 3–10 km along the shores north of the basin (Figs. 2 & 4).

Geological setting and post-Caledonian development

The Lofoten–Vesterålen area is located on a thinned continental crust and represents a basement high exposed above sea level on the continental margin of the Norwegian mainland (Mjelde et al., 1993, 1996; Løseth & Tveten, 1996; Olesen et al., 1997, 2002; Bergh et al., 2007; Osmundsen et al., 2010; Hansen et al., 2012) (Figs. 1 & 2). The bounding faults of the Lofoten Ridge continue northward into the Vesterålen area.

On the northeastern side of Andøya, the northernmost island of the Vesterålen archipelago and some 70–80 km NNE of Sortland, there is a basin with Mesozoic rocks (Fig. 1) (Dalland, 1975, 1979, 1981). The total thickness of this fault-bounded sedimentary succession is estimated to more than 650 m, consisting of two major fining-upward sequences (Dalland, 1975, 1981; Brønner et al., 2017). The Mesozoic rocks extend into Andfjorden, where the up to 5 km-thick sedimentary succession is segmented into several sub-basins separated by basement ridges (Sundvor & Sellevold, 1969; Zwaan et al., 1998; Brønner et al., 2017).

The Mesozoic sequence on Andøya comprises Middle Jurassic to Lower Cretaceous strata, deposited in continental and shallow-marine and open-shelf environments. The sediments rest on a marked unconformity on the metamorphic basement, in some part consisting of deeply weathered granite with a 30 m-thick kaolinitic layer at the top (Sturt et al., 1979; Dalland, 1981; Brønner et al., 2017).

Offshore Lofoten and Vesterålen (Fig. 1) seismic surveys have revealed a thick succession of Mesozoic and younger strata (Dekko, 1975; Lien, 1976; Rokoengen & Sættem, 1983; Brekke & Riis, 1987; Løseth & Tveten, 1996; Zwaan et al., 1998; Hansen et al., 2012). Subsequent sampling and shallow drilling by IKU Petroleum Research confirmed Mesozoic ages for major parts of the succession (Rokoengen et al., 1977; Hansen et al., 1992; Smelror et al., 2001). IKU boreholes 6814/04-U-01 and -02 drilled at the northern margin of the Ribban Basin, just southwest of Langøya and 45 km west of the Sortlandsundet Basin (Fig. 1), recovered strata ranging in age from Middle Jurassic to Early Cretaceous (Smelror et al., 2001).

Offshore, formation of prominent half-grabens and horsts appears to have been initiated in the Jurassic, though seismic data also indicate remnants of pre-

Figure 4. Erratic block from Natland in Sortlandsundet (Sample Nat-01). The block contains fossil plant remains and palynomorph assemblages of Middle Jurassic age comparable to those found in the Hestberget Member (Bajocian) of the Ramså Formation on Andøya. Coin of 2.4 cm in diameter for scale. Photos of blocks from Strand are illustrated in Fürsich & Thomsen (2005). Most of the 250 blocks/samples from Sortlandsundet are now at the Tromsø Museum and registered in the database of the paleontological collection at the Department of Geology. Remaining materials are stored at the Geological Survey of Norway, Trondheim.

Jurassic basins of unknown age and history (Blystad et al., 1995; Mjelde et al., 1996; Tsikalas et al., 2001; Hansen et al., 2012). Bergh et al. (2007) proposed a model where the Vestfjorden, Træna and Havbåen sedimentary basins, and the basins in Sortlandsundet and on Andøya, may have started to develop in the Permo–Jurassic as purely extensional basins, and later (Late Jurassic–Early Cretaceous?) evolved as transtensional basins. Mesozoic sedimentation took place in an active tectonic regime with syn-sedimentary fault activity.

During the Early Cretaceous the Lofoten Ridge developed between the Ribban and Vestfjorden half-grabens (Løseth & Tveten, 1996). In borehole 6710/03-U-01 in the Ribban Basin, Upper Barremian–Upper Aptian sedimentary rocks of the Lange Formation rest with an unconformity on Upper Bathonian–Callovian sandstones which appear to be time-equivalent to the Måsmøykan Formation as defined in borehole 6814/04-U-01 off Langøya in the Nordland VII area (Fig. 6; Smelror et al., 2001; fig. 3 in Hansen et al., 2012). This suggests uplift in the Late Jurassic, or that Upper Jurassic strata were eroded during Early Cretaceous uplift.

The offshore seismic sections show large-scale bounding faults between the various basins and basement highs, mainly oriented NE–SW (Fig. 1) (Løseth & Tveten, 1996; Olesen et al., 1997; Tsikalas et al., 2001, 2005; Bergh et al., 2007; Hansen et al., 2012). The majority of these are well defined, though seismic coverage in some areas is poor (e.g., eastern border fault of the Lofoten Ridge (Løseth & Tveten, 1996)). The western border fault of the Lofoten Ridge, with a throw of at least 4 km, can be traced northwards to Hadsselfjorden west of Hadseløya (Fig. 1) (Løseth & Tveten, 1996; Hendriks et al., 2010; Davidsen et al., 2001b). There, several possibilities exist for its continuation, of which one is a splay northeastwards into Hadsselfjorden.

The Sortlandsundet Basin is fault-bounded on its southeastern side along the Hadsselfjord Fault Zone (Løseth & Tveten, 1996) (Fig. 2). Løseth & Tveten (1996) interpreted fault(s) in Hadsselfjorden between Hadseløya and Fiskebøl based on the presence of two low-velocity zones. Seismic profiles acquired by NGU at the same location show that the low-velocity zones correspond to eroded gullies in the bedrock, also indicating easily

Figure 5. Erratic bloks from Steiro and Strand in Sortlandsundet. (A) Coarse-grained sandstone with conglomeratic layers (Steiro). (B) Fine-grained and mica-rich sandstone with bivalve fragments (Steiro). (C) Fine-grained and mica-rich sandstone with fossils (Steiro - first of the samples discovered). (D) Fine- to medium-grained sandstone with cross-bedding (not analysed for palynomorphs). (E & F) Large block of sandstone, with some thin beds of conglomerate. The block contains fossil belemnites, bivalves and schapopods (Strand, sample M00 Str 13a).

eroded rocks (Davidsen et al., 2001b). In addition, they argued for a tectonic boundary between Langøya/Hadseløya and Austvågøy/Hinnøy based on regional geomorphology and geometric relationships when extrapolating offshore Mesozoic strata onto Langøya/Hadseløya. Exposures with a thick weathering zone are seen on Hadseløya (Olesen et al., 2013).

The Sortlandsundet Basin: Results of the seismic survey

Seismic data were acquired in 2000 and 2001 using NGU's 55 foot-long vessel F/F Seisma. During profiling, single-channel analogue and digital data were collected using air-guns of 15 and 40 in³ (filtered to 100–600 Hz) and an electromagnetic boomer (filtered at 600–3000 Hz). Maximum penetration for the airgun into the Mesozoic rocks is about 500 m (c. 0.3 s TWT, assuming an average sound velocity of 3.5 km/s). Positioning

was obtained using differential GPS. Bathymetric data acquired from the Norwegian Mapping Authority was used as a basis for interpretation and presentation (50 x 50 m grid). In addition to seismic mapping, magnetic data were recorded using an Overhauser GSM 19M proton magnetometer, towed 100 m behind the vessel.

The water depth in the areas covering the Sortlandsundet Basin varies between 40 m and 150 m. The basin is 5 km long and 3.5 km wide and has a spoon-shaped geometry. The extension of the basin is well constrained by a regular grid of seismic lines and the boundaries can be traced with confidence (Fig. 2). The northwestern boundary has a curved shape, whereas the southeastern boundary is defined by a normal fault, dipping to the NW towards the basin. This main fault, which controls the basin, is oriented NE–SW in the northern part and swings to an E–W orientation toward the southwest. The northern boundary is recognised as an on-lap surface.

The sedimentary succession in the basin comprises Quaternary sediments on top of sedimentary rocks of presumed Mesozoic age, which rest upon crystalline basement. The boundary between the Quaternary deposits and the Mesozoic strata is generally well displayed. The thickest Quaternary cover occurs in the centre of the basin, measuring up to about 20 m (assuming a sound velocity of 1700 m/s). The boundary between the Mesozoic strata and the basement rocks is well expressed along the boundaries of the basin (Fig. 3). The base of the sedimentary rocks in the deepest part of the basin is more difficult to define, due to multiples and restricted penetration of the seismic energy. Assuming an average sound velocity of 3.5 km/s twt, the maximum vertical thickness of the Mesozoic succession within the basin is estimated to be more than 400 m.

The sedimentary strata of presumed Mesozoic age are well bedded and shown as strong continuous reflectors on the dip seismic lines (Fig. 3). They display sub-parallel reflectors dipping a few degrees to the southeast. Some units exhibit a more discontinuous seismic reflection pattern. Internal discordances have been observed but are difficult to trace. On strike lines, the reflectors show either a flat or wavy layering. Basement appears as a rather transparent seismic unit. The contact between the Mesozoic and underlying basement rocks is sharp and generally well defined on seismic lines, although in a few lines the contact appears more diffuse.

In the seismic data, synclines, anticlines and small faults are evident, and a major syncline occurs north of the main fault. Synclines observed from strike lines have an orientation almost perpendicular to the main Hadsselfjord Fault Zone (Fig. 2). A secondary fault parallel to the main fault is recognised on a few lines. This fault appears to splay off the main fault in the southwest. Strike and dip data calculated from seismic profiles show that the basin is spoon shaped. Seismic data suggest that

the main fault in Sortlandsundet was active both during deposition of the sediments and afterwards.

Erratic blocks and boulders in Sortlandsundet

The boulders and blocks of Mesozoic sedimentary rocks along the shores of Sortlandsundet have mostly been found on the eastern shores of Langøya, from Elvenes, 4 km south of Sortland, to Selnes, 2 km north of Sortland (Fig. 2). About 3 km of the seashore around the town of Sortland is covered by constructions, so that erratics can no longer be found.

The largest concentration of erratics occurs on Sørneset at Steiro (Fig. 2), with at least 50–100 Mesozoic sedimentary blocks and boulders. Other occurrences on Langøya exist as scattered patches, with 2–10 blocks at each locality (Myrland, Natland, Sortland, Selnes, Fig. 2). On the western shores of Hinnøya, Mesozoic sedimentary boulders and blocks are found at Strand (locality Str), from the bridge crossing Sortlandsundet and 2 km northwards toward Kringelneset (Fig. 2). Here, erratic rocks are found in the whole area, but generally in low to moderate numbers (5–20 blocks per 100 m²).

In the Sortlandsundet, erratics range in size from less than 5 cm in diameter up to c. 1 m³, the largest weighing more than 2 tons. About 20–30 boulders larger than 0.5 m³ have been found. In some areas, it is obvious that some of the erratic blocks have been moved and dumped on the shore by farmers cultivating fields, or by workers constructing ditches. The boulders and blocks are variably rounded, and some are scoured. In some places, the blocks are fragmented or shattered, probably due to wave action and/or frost.

The largest concentration of boulders at Sørneset (Steiro) is found on a pronounced ridge protruding into the sea. This ridge is one of many transverse ridges visible on the seafloor between the Sortlandsundet Basin and the town of Sortland. These ridges are interpreted as retreat moraines formed during the deglaciation of the area.

Most of the sedimentary erratics consist of quartz-rich sedimentary rocks, ranging from conglomerates and sedimentary breccias to fine-grained sandstones. Coarse-grained sedimentary rocks have few structures, whereas sedimentary layering is common in medium- and fine-grained rocks. The latter samples may also be rich in fossils, particularly bivalves. Remnants of plant material, including coaly wood, are also common.

The conglomerates and some coarse-grained sandstones contain pebbles up to 10 cm in diameter, consisting of clear, well-rounded, coarse-grained quartz. A rare variety

of the conglomerates found at Sørneset consists of 5–10 cm elongated pebbles of quartz in a matrix of pyrite. A considerable number of pebbles derived from the Mesozoic erratics are spread over many of the beaches at Sortlandsundet.

Most of the sedimentary blocks have a high content of carbonate and shell remains. Calcite cementation is very common, and for the fine-grained sandstones 0.1–0.3 mm angular grains of quartz and partially resorbed K-feldspar are typically matrix-supported by calcite (up to 50%). There are no indications of quartz cementation. Muscovite is very abundant, and other commonly occurring minerals include biotite, tourmaline, epidote and coal, whereas the heavy minerals garnet, rutile, sphene and zircon occur in minor amounts. Despite the abundant carbonate cementation, there are also examples of well-sorted sandstones with up to 25–30% pore volume (estimated value).

Mesozoic erratics with plant remains are mainly found at Natland (Fig. 2). Numerous blocks of a light-greyish conglomeratic breccia and coarse-grained sandstones occur along the 100 m beach. Cleavage surfaces in the erratics contain coalified remnants of plants, including leaves/fronds and possibly cones (J.O. Vigran, pers. comm., 2000). The sandstones, and in particular the blocks of conglomeratic breccia, contain large rounded grains and pebbles of clear quartz up to 5 cm in diameter. In addition, the breccia contains some angular fragments of schistose quartzite, up to 10 cm across.

Among the various gneissic and mangeritic basement boulders found at Steiro (Sørneset), there are two very characteristic lithologies which have identifiable sources of restricted occurrence. One is a texturally distinct porphyritic amphibolite (metagabbro) known from the basement at the southern side of Risedalen on Langøya. The other is a very dark, iron-rich gabbro occurring as dolerite dykes in the Austvågøy–SW Hinnøya area (Misra & Griffin, 1972). The distribution of the latter is believed to be more widespread.

At the locality at Natland (Fig. 2), a small outcrop exposed during ebb tide comprises sub-vertically oriented Precambrian? quartzitic schist. The rock appears identical to the angular fragments in a breccia block. Both the in situ basement rocks and the Mesozoic erratics at this site contain large clusters (up to several cm) of diagenetic pyrite. Other types of Mesozoic erratics are very scarce at this locality but are found some 2–300 m farther to the north-northeast.

Fossil assemblages and biostratigraphic ages

Several of the Mesozoic sedimentary erratic blocks recovered from Sortlandsundet contain fossils (Figs. 4, 7 & 8). Macrofaunas in 250 samples from more than 50 fossiliferous erratic blocks were analysed by Fürsich & Thomsen (2005). The macrofaunas in 17 erratics from Steiro, 2 from Myrland, 2 from Natland and 12 from Strand comprise 39 identified taxa, including common bivalves, serpulids, gastropods, brachiopods and echinoid spines. Belemnites are also found in several of the sedimentary erratics (Fürsich & Thomsen, 2005).

A total of 21 samples have been analysed for organic-walled microfossils (palynomorphs). These include ten samples from Steiro (Ste), six from Strand, one from Sortland (Sor), three from Natland and one sample from Myrland (Figs. 2 & 7). Most of these samples were also analysed for macrofossils, but only a few contained macrofossils which could provide detailed and reliable age-determinations. All samples analysed for palynomorphs yielded identifiable assemblages with Jurassic species (Figs. 6 & 7), but the abundances vary considerably. Pollen and spores are most abundant, but some of the samples also contain common marine microplankton (dinoflagellate cysts, prasinophytes and acritarchs). The dominance of terrestrial palynomorphs mirrors assumed near-shore depositional environments for most of the samples.

Although marine palynomorphs are generally subordinate compared to pollen and spores, several samples contain a characteristic oligo-specific marine assemblage with common to abundant representatives of the marine acritarch genus *Cyclopsiella*. Lists of recovered palynomorphs are presented in Fig. 7 and selected species are illustrated in Fig. 8. Most focus has been put on identifying dinoflagellates since they generally provide a better means for age-determinations of Jurassic rocks than pollen and spores. Several Jurassic dinoflagellate cyst zonation schemes have been published, of which most are calibrated to the Boreal ammonite zonation (Riley & Fenton, 1982; Woollam & Riding, 1983; Riding, 1984; Smelror, 1988a; Riding & Thomas, 1992; Smelror & Below, 1993; Poulsen, 1996; Riding et al., 1999; Poulsen & Riding, 2003). Hardenbol et al. (1998) presented a comprehensive Jurassic biostratigraphy for the European basins, where the boreal dinoflagellate cyst biostratigraphic events are calibrated to the Northwest European ammonite zones, and they are also given absolute ages and calibrated to the standard chronostratigraphy.

The fossil faunas and microfloras recovered from the erratic rocks from Sortlandsundet are compared and correlated with fossil assemblages reported from the Jurassic succession on Andøya and in a borehole drilled offshore in the Nordland VII area.

Figure 6. Lithostratigraphic and sequence-stratigraphic correlation between cored successions at Andøya, Nordland VII (Ribban Basin) and Troms III (Harstad Basin). (Modified from Smelror et al., 2001 and from Bøe et al., 2010).

																				Samples	Taxa
Str-13B		x																			Bisacat pollen
Str-16A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Baculatisporites spp.
Str-16B																					Araucariscites australis
Str-16C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Anapiculatisporites sp.
Str-16D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Camerozonosporites sp.
Str-20																					Cerebropollenites macroverrucosus
Str-24	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Cerebropollenites thiergartii
Str-25	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Contignisporites problematicus
Str-30	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Deltoidospora minor
Str-37	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Densosporites spp.
Nat-01	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Foveosporites sp.
Nat-07	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Lycopodiumsp. austroclavatoides
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Lycopodiumsporites clavatoides
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Lycopodiumsporites spp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Perinopollenites elatoides
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Perinopollenites spp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Punctatisporites major
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Retusotriletes mesozoicus
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Stereisporites seebergensis
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Botryococcus spp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Adnatosphaeridium caulleryi
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Adnatosphaeridium sp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Ambonosphaera staffinensis
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Atopodinium haromense
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Chlamydotheca ectotabulata
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Chytroisphaeridia chytroides
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Cleistosphaeridium sp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Cribroperidinium sp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Ctenodinium sp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Cyclopsella sp. A
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Cyclopsella spp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Dingodinium minutum
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Dingodinium jurassicum
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Dissilodinium sp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Escharisphaeridia rudis
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Gonyaulacysta centriconnata
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Gonyaulacysta jurassica
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Gonyaulacysta pectinigera
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Nannoceratopsis pellucida
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Pareodinia ceratophora
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Pareodinia evittii
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Perisseiasphaeridium pannosum
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Rhynchodiniopsis cladophora
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Scrinodinium sp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Sentusidinium pilosum
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Sentusidinium sp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Sirmiodinium grossii
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Systematophora daveyi
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Valensiella ovula
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Valvaedinium theresae
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Tasmanites spp.
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Foraminifera linings
Nat-08	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Scolecodonts

Figure 7. List of terrestrial and marine palynomorphs recovered in erratic blocks from Sortlandsundet. (Nat – Natland, Myr – Myrland, Ste – Steiro, Str – Strand, Sor – Sortland). The locations of the sample sites are shown in Fig. 2.

The Middle Jurassic to Early Cretaceous fossil assemblages recovered on Andøya have been documented by Heer (1877), Lundgren (1894), Sokolov (1912), Johansson (1920), Bose (1959), Ørvig (1953, 1960), Manum (1968, 1987), Dalland (1975, 1979, 1981), Birkelund et al. (1978), Løfaldli & Thusu (1979), Zakharov et al. (1981), Århus et al. (1986) and Manum et al. (1991). There are few common species among the marine benthic macrofossil assemblages from Andøya and those recovered from the Sortlandsundet erratics. According to Fürsich & Thomsen (2005) this might be an artifact, as the benthic macrofauna from the Andøya Basin has never been comprehensively described. The older records of palynomorph assemblages from Andøya do not offer very detailed stratigraphic information, but new data from recent boreholes in the Ramså Basin provide a good means for age-determinations and correlations.

According to Fürsich & Thomsen (2005), most of the blocks with shelly remains appear to be of Volgian age. Furthermore, Sr-isotope analyses from two separate samples (Ste-30 and Ste-31) yielded isotope ratios supporting a late Early Volgian age (Fürsich & Thomsen, 2005). In contrast, the marine palynomorphs indicate a wider variety of Middle and Late Jurassic ages for

the erratics. Several recent studies have provided new information on the geographical distribution and stratigraphic range of Mesozoic bivalves (Ros-Franch et al., 2014), and some of the taxa used to validate a Volgian age for the erratics in Sortlandsundet have a broader stratigraphic range, with significantly older first appearances than cited by Fürsich & Thomsen (2005). A summary of ages based on palynomorphs, macrofossils and strontium-isotope analyses for the samples included in the present study is shown in Table 1.

Two of the erratic samples, Nat-01 and Ste-01, seem to lack marine palynomorphs (Fig. 7); nor have macrofossils been recorded from these erratics. The assemblages of terrestrial palynomorphs found in these samples are comparable to assemblages known from the Middle Jurassic Ramså Formation on Andøya (Birkelund et al., 1978; Manum et al., 1991). Most of the recovered species of pollen and spores in samples Nat-01 and Ste-01 have a wide stratigraphic range in the Jurassic and Early Cretaceous.

The majority of examined samples contain common to abundant specimens of the characteristic acritarch genus *Cyclopsiella* (Figs. 7 & 8). Previously, no species of this genus has been described from Jurassic strata,

Table 1. Lithologies and ages based on palynomorphs, macrofossils and strontium-isotope analyses for the samples included in the present study. (Nat – Natland, Myr – Myrland, Ste – Steiro, Str – Strand, Sor – Sortland). The locations of the sample sites are shown in Fig. 2.

Sample	Lithologies	Sr-isotopes	Macrofossils	Palynomorphs
Ste-31	Sandstone, fine-grained, fossil fragm.	147.4 Ma	Kimmeridgian-Barremian	Volgian
Ste-17	Sandstone, grey-green, some fossil fragm.		ND	Middle-Late Jurassic
Ste-10	Sandstone, mica-rich, fossil fragm.		ND	Kimmeridgian-Volgian
Ste-05	Sandstone, fine-grained, some bivalves		ND	Middle Jurassic
Ste-02	Sandstone, with mica, some fossil fragm.		ND	Kimmeridgian-Volgian
Ste-01	Sandstone, rich in fossils		ND	Middle Jurassic
Nat-08	Sandstone, coarse- to medium-grained		ND	Middle-Late Jurassic
Nat-07	Sandstone, laminated, cross-bedded		ND	Middle-Late Jurassic
Nat-01	Shale, light grey, Q-fsp., plant fragm.		ND	Middle Jurassic
Sor-01B	Sandstone, medium-grained, shell fragm.		ND	Middle-Late Jurassic
Myr-01	Sandstone, greenish-grey, fossils		ND	Middle-Late Jurassic
Str-37	Sandstone, rich in fossils		ND	Kimmeridgian-Ryazanian
Str-30	Sandstone, fossil fragm.	147.4 Ma	ND	Middle-Late Jurassic
Str-25	Sandstone, fine-grained, mica-rich, fossils		Jurassic-Valanginian	Middle-Late Jurassic
Str-24	Conglomerate, bivalves, belemnites		Volgian-Albian	Late Jurassic
Str-20	Sandstone with clasts, bivalves, belemnites		ND	Middle-Late Jurassic
Str-16D	Sandstone, silty, bivalves		Middle-Late Jurassic	Kimmeridgian-Volgian
Str-16C	Sandstone, dark grey, mica-rich, fossils		ND	Callovian-Oxfordian
Str-16B	Sandstone, dark, fine-grained, clasts, fossils		ND	Middle-Late Jurassic
Str-16A	Sandstone, rich in small bivalves		Lt. Jurassic-E. Cretaceous	Bajocian-Kimmeridgian
Str-13B	Sandstone, bivalves, scaphopodes		Lt. Jurassic-E. Cretaceous	Middle-Late Jurassic

Figure 8. Marine and terrestrial palynomorphs from Jurassic blocks found at Sortlandsundet. (A) Camarozonosporites sp., diameter 34 µm, Sample Str-37. (B) Densosporites sp., diameter 56 µm, Sample Nat-08. (C) Stereisorites seebergensis Schulz 1966, diameter 25 µm, Sample Nat-08. (D) Cerebropollentites macroverrucosus (Thiergart) Schulz 1967, diameter 42 µm, Sample Nat-08. (E) Baculatisporites sp., diameter 40 µm, Sample Nat-08. (F) Retusotriteles mesozoicus Klaus 1960, diameter 34 µm, Sample Ste-10. (G) Cyclopsella sp., width 25 µm, Sample Str-20. (H) Cyclopsella sp., width 34 µm, Sample Ste-10. (I) Tasmanites sp., diameter 125 µm, Sample Str-20. (J) Perisseiasphaeridium pannosum Davey & Williams 1966, overall diameter 102 µm, Sample Ste-10. (K) Foraminifera test-linings, Sample Str-20. (L), width 126 µm, Cyclopsella sp., width 28 µm, Sample Ste-05. Palynological slides with illustrated specimens are stored in the collections of the Geological Survey of Norway, Trondheim.

but similar species to those found in the Sortlandsundet samples are common in the upper Middle Jurassic sandstones of the Måsnykan Formation in borehole 6814/04-U-01 off Vesterålen and borehole 6703/03-U-01 in the Ribban Basin southwest of Lofoten. Recent examinations of Jurassic strata in boreholes in the Ramså Basin on Andøya have further documented the presence of *Cyclopsella* spp. in Upper Jurassic (Kimmeridgian) strata of the Ramså and Dragneset formations (Smelror, in press). Observations from the Middle and Upper Jurassic of the Ramså Basin, the offshore Ribban Basin, and the present material from Sortlandsundet suggest that acmes of *Cyclopsella* morphotypes indicate shallow-marine/near-shore, relatively high-energy depositional environments.

In addition to *Cyclopsella* spp., sample Nat-07 contains the dinoflagellate cyst *Chlamydomphorella ectotabulata* which is well known from the Middle Jurassic of the Barents Sea area (Smelror, 1989; Smelror & Below, 1993). Sample Nat-08 yielded the dinocysts *Dingodinium minutum*, *Dissiliodinium* sp., *Scriniodinium* sp., *Sentusidinium pilosum* and *Sirmiodinium grossii*, together with *Cyclopsella* spp. This assemblage of marine palynomorphs suggests a general Middle to Late Jurassic age.

Samples Sor-01B and Myr-01 contain relatively sparse marine palynomorphs, but the occurrences of *Cyclopsella* spp. indicate a Middle or Late Jurassic age. The recovery of *Sirmiodinium grossii* in sample Myr-01 is further evidence for an age not older than Middle Jurassic. No macrofossils are reported from these two samples.

Sample Str-25 contains the bivalves *Camptonectes auritus*, *Entolium orbiculare*, *Astarte* cf. *Astarte chetaensis* and *Astarte veneriformis*, together with several taxa determined at genera level (Fürsich & Thomsen, 2005). The two first species mentioned above are well documented from the Early/Middle and Late Jurassic

in Europe. *Astarte chetaensis* is previously recorded in the Volgian of Siberia, while *Astarte veneriformis* is known from the Valanginian of Siberia. The acritarch *Cyclopsella* found in Str-25 supports a Middle-Late Jurassic age for this erratic block.

Erratic Str-30 contains a macrofauna of bivalves, belemnites and brachiopods (Rhynchonellid), but none of the taxa was determined to species level (Fürsich & Thomsen, 2005). Str-30 contains common to abundant specimens of the characteristic acritarch genus *Cyclopsella*. The Sr-isotope analyses yielded isotope ratios pointing towards a late Early Volgian age for this sample (Fürsich & Thomsen, 2005).

Sample Str-16A contains *Nannoceratopsis pellucida* and *Gonyaulacysta jurassica*. The first species has a well-documented stratigraphic range from Late Bajocian to earliest Kimmeridgian (Riding & Thomas, 1992), while the latter species is known from the Late Bajocian to Volgian in NW Europe and East Greenland (Poulsen, 1991). In borehole 6814/04-U-01 off Langøya, *Gonyaulacysta jurassica* has been recovered from the Late Oxfordian (Bauhini ammonite zone) to Kimmeridgian (Kochi ammonite zone) in the Hekkingen Formation (Wierzbowski et al., 2002). *G. jurassica* has also been recovered from the Early Kimmeridgian (Cymadoce ammonite zone) in the Breisanden Member (Dragneset Formation) in the Andøya Basin (Birkelund et al., 1978). Str-16A further contains the annelida *Serpula* (*Cycloserpula*) *intestinalis* and the bivalves *Entolium* (*E.*) *orbiculare*, *Astarte* cf. *Astarte chetaensis* and *Astarte veneriformis*. None of these species contradicts a Middle–Upper Jurassic age for this erratic sample.

Sample Str-16C contains *Gonyaulacysta centricornata* which is known from the mid Callovian to Early Oxfordian (Riding & Thomas, 1992). The presence of the dinoflagellate cyst *Sirmiodinium grossii* in this sample confirms an age no older than Bathonian. No age-diagnostic macrofossils have been recovered from sample Str-16C.

Erratic sample Str-16D contains a few specimens of *Ambonosphaera staffinensis* and *Perisseiasphaeridium pannosum* pointing towards a Kimmeridgian–Early Volgian age. The latter species is restricted to the Kimmeridgian and Lower Volgian in the Sub-Boreal–Boreal realms (Riding & Thomas, 1992; Poulsen 1996). On Andøya, this species is found in the Kimmeridgian of the Ramså and Dragneset formations.

Str-16D also contains a diverse assemblage of benthic macrofossils, including *Myophorella* cf. *Myophorella* (*M.*) *intermedia*, *Discoloripes fischerianus*, *Astarte* cf. *Astarte chetaensis*, *Astarte veneriformis* and *Pleuromyra uniformis*. The macrofauna is consistent with a Late Jurassic age for this erratic, although *Pleuromyra uniformis* is also commonly found in the Middle Jurassic.

Sample Ste-01 yielded an assemblage with *Dinogodinium minutum*, *Dissiliodinium* sp., *Gonyaulacysta pectingera*, *Sentusidinium pilosum* and *Sirmiodinium grossii*, while sample Ste-05 contains *Pareodinia evittii*, *Valensiella ovula* and *Valvaeodinium theresae*. These species are also found in the Bathonian–Middle Callovian Måsnýkan Formation off Vesterålen and Lofoten and are commonly found in the lateral time-equivalent shales of the Fuglen Formation on the Barents Shelf (Smelror & Below, 1993) and Agardhfjellet Formation on Svalbard (Smelror, 1988b). The recovery of the annelida *Ditrupa* sp. in this erratic (Fürsich & Thomsen, 2005) is of no biostratigraphic significance since this genus has a wide stratigraphic range through the Mesozoic and Cenozoic.

Erratic blocks Ste-02, Ste-05 and Ste-10 contain the dinoflagellate cyst *Perisseiasphaeridium pannosum*, which points to a Kimmeridgian or Early Volgian age (Riding and Thomas, 1992; Poulsen 1996). The recovery of the dinoflagellate cysts *Adnatosphaeridium caulleryi* in sample Ste-10 may support a Kimmeridgian age. No macrofossils have been recovered from this sample.

Sample Ste-31 contains common macrofossils, including bivalves, belemnites and echinoid spines. However, most species reported by Fürsich & Thomsen (2005) are determined at genus level and are of limited biostratigraphic significance. *Camptonectes auritus* appears in the Hettangian and is widely known from Middle and Upper Jurassic deposits in Europe, including the Bajocian in the southern Baltic area (Koppa et al., 2006). Fürsich & Thomsen (2005) write that “the widespread *Enotolium* (E.) orbiculare is known from the Kimmeridgian to Albian (Kelly, 1984)”. However, this species is also known from the Callovian of Spain (Platt et al., 1991) and possibly also older Jurassic strata (Johnson, 1984). *Hartwellia* cf. *Hartwellia* (H.) *kharoschvensis* is known from the Upper Jurassic–Lower Cretaceous (Kimmeridgian to Barremian). The marine microflora recorded in this sample contains *Cyclopsiella* spp., *Dinogodinium spinosum*, *Sentusidinium* sp. and *Sirmiodinium grossii*. The Sr-isotope analyses from Ste-31 suggest a late Early Volgian age (Fürsich & Thomsen, 2005). The presence of the dinoflagellate cyst *Dinodinium jurassicum* in Ste-31 also supports a Volgian age.

Samples Ste-33 and Str-24 contain the bivalve *Camptonectes* (*Mclearnia*) *cinctus*. *Mclearnia* is typically boreal in its distribution. The Jurassic specimens, apart from rare occurrences in the Upper Volgian of East England, are generally restricted to East Greenland and northern Russia. *Camptonectes* (*Mclearnia*) *cinctus* is known to range from the Late Volgian into the Albian (Fürsich & Thomsen, 2005). Sample Ste-33 was not analysed for palynomorphs. Sample Str-24 contains *Cyclopsiella* spp. and *Cribroperidinium* sp., the latter pointing to a Late Jurassic age.

Systematophora daveyi recovered in Str-37 suggests a Kimmeridgian–Ryazanian age (Poulsen, 1996). According to Hardenbol et al. (1998), the youngest occurrence of this species gives an age of 144.7 Ma. This erratic also contains the bivalves *Camptonectes auritus*, *Entolium orbiculare*, *Myophorella* cf. *Myophorella* (M.) *intermedia* and *Astarte* cf. *Astarte chetaensis*. These species are previously well documented from Upper Jurassic strata (Fürsich & Thomsen, 2005). This sample also contains common *Cyclopsiella* spp.

Both the palynomorphs and the macrofossils found in the erratic sedimentary blocks from Sortlandsundet suggest that they represent strata deposited during the Middle and Late Jurassic. The recovery of an erratic sedimentary block with Early Cretaceous bivalves at Hanøya (Ravn & Vogt, 1915) and the presence of Lower Cretaceous strata in the Ramså Basin on Andøya, could indicate that also Lower Cretaceous marine strata may be present in the Sortlandsundet Basin.

Preliminary depositional model for the Mesozoic Sortlandsundet Basin

Sedimentation in the Sortlandsundet Basin took place in an active tectonic regime during Jurassic times. There are no drillcores from within the basin, and consequently, the model is tentative. However, the recovery of continuous cores through the Middle Jurassic to Lower Cretaceous sequence on the northeastern margin of the Ribban Basin on the adjacent shelf, some kilometres southwest of Langøya (Smelror et al., 2001), and well documented contemporaneous strata on Andøya (Dalland, 1975, 1981; Brønner et al., 2017), provide a good framework for stratigraphic correlations and for a model of the Jurassic–Early Cretaceous depositional history of the area (Fig. 9).

On the adjacent shelf, southwest of Langøya, the boundary between the Archaean–Palaeoproterozoic basement and the overlying sedimentary rocks coincides with an unconformity in the seismic sections. This is related to regional uplift in Early–early-Middle Jurassic time (Løseth & Stiberg, 1998; Løseth, 1999; Smelror et al., 2001). During this period, faulting and subsidence took place on Andøya as well as in Vesterålen and in the northern Ribban Basin (Smelror et al., 2001).

In the Late Bajocian, a major transgressive event led to significant facies changes in the basins and along the basin margins off Norway and Greenland (Surlyk, 1991; Smelror et al., 2001). In the northern Ribban Basin and on Andøya, the sea transgressed large areas of peneplained crystalline basement (Fig. 9). In some places the basement rocks are deeply weathered and are covered

Figure 9. Schematic model of Middle to Early Cretaceous structural and depositional development of the Sortlandsundet Basin, and the adjacent Andøya and northern Ribban Basin. HFZ – Hadseljord Fault Zone.

by a thin unit of continental or brackish-water sediments and restricted marine deposits in structurally controlled embayments. Off Langøya (borehole 6814/04-U-01), the basement is overlain by fluvial and restricted marine deposits, followed by transgressive shoreface sands (Smelror et al., 2001). On Andøya, the oldest Mesozoic deposits of Bajocian age comprise sandstones with beds of kaolinite shale and channel-coal, i.e., the Hestberget Member of the Ramså Formation. These sediments are interpreted as braided river deposits draining into a

lagoonal environment (Dalland, 1975, 1981; Brønner et al., 2017). Dalland (1975) found that the kaolin shales are concentrated in a very small area in the middle of the basin on Andøya, and probably represent erosional products from the kaolin-rich weathered basement. The Hestberget Member is overlain by lagoonal bituminous shale deposits assigned to the Kullgrøfta Member and fluvial sandstones of the lower Bonteigen Member (Dalland, 1975, 1981).

A similar setting may well have existed in the Sortlandsundet Basin, as suggested by the lithofacies, plant fossils and coal fragments found in many of the erratic blocks. A comparable microflora found in the Ramså Formation on Andøya (Birkelund et al., 1978; Manum et al., 1991) and in some of the erratic samples from Sortlandsundet appears to support this interpretation. The lack of kaolinite and bituminous shale as found in the deposits of the Kullgrøfta Member on Andøya may be either a result of a more high-energy setting in the Sortlandsundet Basin, or it may be due to the fact that such fine-grained materials are more easily eroded than the coarse clastic sediments.

The transgression initiated in the Late Bajocian continued through the Early Bathonian, and by Late Bathonian time fully marine conditions were established over the whole Barents Sea area and the northern margins of the Norwegian Sea (Smelror et al., 2001; Mørk & Smelror, 2001). The period of relative sea-level rise culminated in the Mid-Callovian, and in the northern Ribban Basin (borehole 6814/04-U-01 off Langøya) Upper Callovian–Lower Oxfordian deposits are missing. On Andøya, biostratigraphic information from the Bonteigen Member (upper Ramså Formation) suggests that Bathonian, Callovian and Oxfordian strata are missing in the Ramså Basin.

Several of the erratic blocks from Sortlandsundet contain dinoflagellate cyst assemblages similar to those recovered from the Upper Bathonian–(Middle?) Callovian Måsnykan Formation off Vesterålen–Lofoten (Smelror et al., 2001). This suggests an open marine connection between the Sortlandsundet Basin and the adjacent shelf areas, including the northern Norwegian Sea and southwestern Barents Sea basins during Late Bathonian–Mid Callovian times, and shallow-marine depositional environments in Sortlandsundet.

The Måsnykan Formation off Vesterålen–Lofoten correlates to the Fuglen Formation in the Harstad Basin and is also time-equivalent with the Melke Formation as defined in the Trænabanken area (Dalland et al., 1988). Farther south, on the Halten Terrace, shallow-marine sandstones of the Garn Formation backstep onto structural highs of the footwall in the Smørbukk area and are coeval with Melke Formation open marine mudstones in the depocentres (Corfield et al., 2001).

In borehole 6814/04-U-01 off Langøya, Upper Callovian–Lower Oxfordian deposits are missing, and Upper Oxfordian muddy siltstones of the Hekkingen Formation (Rauå Member) unconformably overlie the Upper Bathonian–Mid Callovian sandstones of the Måsnykan Formation (Fig. 9) (Smelror et al., 2001). The recovery of ammonites in the lower part of the transgressive shales of the lowermost Hekkingen Formation dates the initial Late Jurassic transgression to the *Amoeboceras serratum* ammonite zone (Smelror et al., 2001; Wierzbowski et al., 2002).

In the Ramså Basin on Andøya there appears to be a depositional break spanning the Bathonian–Oxfordian time interval. A general Bajocian age is inferred for the Hestberget and Kullgrøfta members (Birkelund et al., 1978; Manum et al., 1991). The marine palynomorphs found in the shallow-marine sandstones of the upper part of the Bonteigen Member (Ramså Formation) point towards an earliest Kimmeridgian age. An Early Kimmeridgian age for the overlying Breisanden Member (Dragneset Formation) is evident from ammonites belonging to the *Rasenia cymadoce* Zone. Apparently, there is a disconformity within the Bonteigen Member, probably corresponding to the transition from fluvial sediments into overlying beach and shallow-marine deposits (i.e., the ‘Callovian transgression’ of Dalland, 1981).

As suggested by several erratic samples, Kimmeridgian deposits might be present in the Sortlandsundet Basin. A more near-shore, shallow-marine setting is inferred from the erratics of the Sortlandsundet Basin compared with an open shelf environment in the northeastern Ribban Basin (borehole 6804/04-U-01). On Andøya, the Lower Kimmeridgian sandstones of the lower Breisanden Member were probably below the littoral zone in an open marine environment, while the upper part appears to have been deposited in a bay or lagoon connected to the sea (Dalland, 1975, 1981).

Maximum sea-level along the margins of the Norwegian and Barents shelves was reached in the Late Kimmeridgian (sensu gallico) *Aulacostephanus eudoxus* ammonite zone (Surlyk, 1991; Smelror et al., 2001). On Andøya, lowering of the relative sea-level is evident from the transition from the open marine to shallow-marine deposits within the Breisanden Member. The overlying Taumhølet Member is interpreted to have been deposited in a mud-flat environment or in a shallow-marine, brackish-water lagoon (Dalland, 1975). In borehole 6814/04-U-02 off Langøya (Ribban Basin) a lowering of the relative sea-level in Mid-Volgian time is inferred from a slight increase of silt in the Upper Jurassic claystone succession, and from the occurrence of more abundant carbonate beds and bivalves (Smelror et al., 2001).

On Andøya, Volgian siltstones and sandstones of the Ratjøna Member were deposited in an open marine environment. The sandstones are interpreted to represent infill deposits of small tidal channels. The dark, shaly siltstone that characterises most of the formation was probably deposited in somewhat deeper water (Dalland 1975, 1981). The Ratjøna Member contains abundant marine fossils, including ammonites, belemnites and bivalves. Middle Volgian ammonites of the Boreal *Dorsoplanites* faunas are found in the lower part of the formation (Birkelund et al., 1978). A Middle Volgian age is also supported by the presence of the bivalve *Buchia* ex. gr. *russiensis* (Zakharov et al., 1981).

Age-diagnostic Late Volgian fossils have not been found on Andøya. Ammonites document a Late Ryazanian age for the uppermost part of the member (uppermost Dragneset Formation) (Birkelund et al., 1978). Zakharov et al. (1981) have suggested the presence of a stratigraphic break spanning the Late Volgian–Early Ryazanian (Boreal Berriasian) time interval in the upper part of the Ratjønna Member. In the offshore Ribban Basin, there appear to have been a more continuous deposition of open marine fine-grained sediments through the Volgian and Ryazanian, although the sedimentary record from borehole 6801/04-U-02 off Langøya indicates a regressive phase starting in the Late Volgian and persisting into the early Late Ryazanian (Smelror et al., 2001).

According to Fürsich & Thomsen (2005), most of the boulders from Sortlandsundet with shelly remains appear to be of Volgian age. Following their model, the Middle Jurassic fossils found in many samples are most likely reworked into the Volgian shallow-marine deposits. However, some samples contain only Middle Jurassic microfloras, without any evidence of Volgian fossils. The microfloras recovered from these samples are comparable to assemblages recorded in Middle and lower Upper Jurassic strata on Andøya and in the offshore Ribban and Harstad basins and suggest that contemporaneous strata also are present in the Sortlandsundet Basin.

A tentative syn-tectonic depositional model for the Sortlandsundet Basin is shown in Fig. 9. The model relies on the limited available biostratigraphic data from Sortlandsundet, Andøya and the adjacent offshore northeastern Ribban Basin area. The model suggests that initial deposition in the Sortlandsundet Basin took place in Middle Jurassic (Bajocian?) time, in fluvial to lagoonal environments comparable to those existing during deposition of the Hestberget and Kullgrøfta members on Andøya. The basin infill was mainly from the west, as the northeastern Ribban Basin appears to have been uplifted and exposed until Bathonian times.

In the Bathonian, the sea transgressed into former exposed areas and shallow-marine sands accumulated in the Ribban Basin off Langøya and possibly in the Sortlandsundet Basin. No deposition took place in the Ramså Basin during this time. Active tectonic movements created significant lateral differences in depositional regimes. More than 120 m of Bathonian–Middle Callovian sandstones of the Måsnykan Formation are recorded off Langøya (borehole 6814/04-U-01), while only 16 m of the same unit are found at site 6710/03-U-01 farther south in the Nordland VI area. The thickness of this unit in the Sortlandsundet is not known.

In the Ribban Basin and on Andøya there is a stratigraphic break covering the Late Callovian and Early Oxfordian, and there are no records of any Late Callovian–Early Oxfordian fossils in the erratic rocks

from Sortlandsundet. This points towards a period of non-deposition over the entire area, possibly caused by uplift and erosion. The stratigraphic break corresponds to the boundary between the Måsnykan and the Hekkingen formations in the offshore area, and to a disconformity within the Bonteigen Member (upper Ramså Formation) on Andøya (Figs. 6 & 8).

In the Kimmeridgian and Volgian periods, marine depositional conditions existed throughout the northeastern Ribban Basin, Sortlandsundet Basin and Andøya. Off Langøya (borehole 6814/04-U-02) shaly and silty sediments of the Hekkingen Formation accumulated in open marine settings, and in Sortlandsundet and on Andøya shallower marine, near-shore conditions led to deposition of siltstones and sandstones. An overall lowering of the relative sea-level in the Middle Volgian may have led to restricted marine, possibly brackish conditions on Andøya. During this time, shallow-marine sandstones and conglomerates, with reworked older Jurassic sediments, accumulated in the Sortlandsundet Basin.

In the Late Volgian–Early Ryazanian, continuing local tectonic movements led to uplift and non-deposition on Andøya. Similar conditions may also have occurred in Sortlandsundet. Off Langøya, more or less continuous deposition of shales and siltstones of the upper Hekkingen Formation resumed during Late Volgian–Early Ryazanian times.

Tectonic movements continued into the Early Cretaceous. In the Late Barremian a major rift phase began, and the Lofoten Ridge developed as a horst between the Ribban and Vestfjorden basins (Løseth & Tveten, 1996). Vesterålen (Hinnøya, Langøya, Andøya) experienced rapid subsidence, and the Lofoten Ridge became an important local sediment source in the subsequent Early Cretaceous times (Løseth & Stiberg, 1998; Smelror et al., 2001). There is no firm evidence of Lower Cretaceous sediments among the Sortlandsundet erratics, although this cannot be excluded (Fürsich & Thomsen, 2005). To the north and southwest of Sortlandsundet, Lower Cretaceous sediments were deposited on Andøya and offshore Langøya (Dalland, 1975, 1981; Smelror et al., 2001). The last rifting phase initiated in the Mid-Cretaceous and terminated by continental break-up and seafloor spreading during latest Paleocene–earliest Eocene time (Løseth & Stiberg, 1998).

Kilometre-scale Mesozoic and/or younger movements along faults delineating the Sortlandsundet Basin are inferred from significant differences in Apatite Fission Track (AFT) ages recorded on the western side and the eastern side of Sortlandsundet. While AFT ages are in the range of 190–120 Ma on the western side of the basin, AFT ages on the eastern and southeastern side are significantly younger and between 100 and 70 Ma

(Hendriks et al., 2010; Osmundsen et al., 2010). This is consistent with major reactivations of the bounding faults of the Sortlandsundet Basin in Late or post-Cretaceous times, and apparently also explains the difference in topographic elevation and contrast in landscape maturity from the alpine landscape on the southeastern side of the sound to the gentler, SE-dipping topography in the northwest (Osmundsen et al., 2010).

Glacial transport of the erratic blocks

Present models for the Quaternary geology in Vesterålen and Lofoten indicate that the region was covered by an ice-sheet during the last glacial maximum at about 20,000 years BP. At that time, glaciers must have covered Sortlandsundet and most of the surrounding mountains. The ice sheet reached the shelf edge outside Lofoten and Vesterålen, and paleo-ice streams flowed along Vestfjorden to the southwest and in Andfjorden to the north (Ottesen et al., 2005, 2008) (Fig. 10).

Few details exist on the ice-flow directions, though Rasmussen (1984) indicated a radial flow from the centre of the icecap, presumably situated in the inner parts of Hinnøya (considering its distribution during subsequent glacial maxima). Regional ice-streams flowing out

Vestfjorden and Andfjorden may have influenced the glacial dynamics in southeastern Vesterålen and modified this generally radial pattern. Sortlandsundet was located close to a local ice-divide and separate ice streams were flowing out of Gavlfjorden in a northward direction and out of Hadsselfjorden in a westerly direction (Ottesen et al., 2005, 2008), especially in a late phase when topographic control would have been prominent. Evidence for this exists as roches moutonnées on the eastern shores of Hinnøya at Sortlandsundet (Kringelneset, north of Strand). Also, a northward ice-flow direction is suggested by the large whaleback morphology of the mountain Strandheia to the east of Sortland (647 m a.s.l. on Hinnøya). In addition, some of the non-Mesozoic boulders found at Steiro (Sørneset) appear to be derived from sources south of the Sortlandsundet Basin.

Deglaciation of Hadsselfjorden is believed to have been rapid and the De Geer moraines present immediately northeast of the Sortlandsundet Basin (Rasmussen, 1984) were probably deposited during small halts in the retreating icefront. These left behind the erratics in the Sortlandsundet found on the shores today. Later glacial events in the area (Skarpnes Stage: c. 12,300 years BP and Tromsø–Lyngen Stage: c. 10,500 years BP) were confined to valleys and mountains, and would not have affected Sortlandsundet directly (Rasmussen, 1984).

Figure 10. Ice-flow pattern across the area during the last glacial maximum (c. 20,000 year BP). Orange lines: possible ice-flow lines. Bathymetry and topography from Kartverket.

However, from a locality at Bø (Bøstranda) immediately north of the Sortlandsundet Basin, Rasmussen (1984) obtained shell fragments from a till, giving a minimum age of 40,000 ^{14}C years BP. This indicates that reworked material from older glaciations is also present in the area, implying that some of the recorded erratics and boulders may have had a complex transport history, spanning over several glacial periods.

Conclusions

The Mesozoic Sortlandsundet Basin covers an area of 5 x 3 km in Sortlandsundet. The basin has been mapped by high-resolution seismic profiles and is recognised as a half-graben defined by the Hadseljord Fault Zone in the southeast and by unconformable boundaries to Archaean and Palaeoproterozoic basement rocks to the northeast, northwest and southwest. The Sortlandsundet Basin may have originated as an extensional basin and evolved as a transtensional basin in the Late Jurassic–Early Cretaceous.

The basin comprises at least 400 m of Middle and Upper Jurassic infill. The seismic reflectors identify sedimentary layers dipping a few degrees to the southeast. Glacial-transported erratic blocks, assumed to derive from the basin, are found along the shorelines around the basin. The blocks comprise quartz-rich sediments, varying from conglomerates to fine-grained sandstones. Many of the erratic blocks contain macro- and microfossils of Middle and Late Jurassic ages.

A tentative depositional model for the Sortlandsundet Basin and contemporaneous strata offshore Vesterålen (northeastern Ribban Basin) and on Andøya suggests that sedimentation in the Sortlandsundet Basin took place mainly in a syn-tectonic, shallow-marine setting during different phases of rifting and block movements, superimposed on global sea-level fluctuations, in Middle and Late Jurassic (and possibly Early Cretaceous) times.

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