The Late Jurassic Bjorøy Formation: A provenance indicator for offshore sediments derived from SW Norway as based on single zircon (SIMS) data

Trine-Lise Knudsen & Haakon Fossen

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The Late Jurassic Bjorøy Formation is located in a fracture zone in granodioritic gneisses of the Øygarden Complex in the Bergen area, SW Norway. An ion-microprobe (SIMS) U-Pb zircon study has been performed on a sand sample and the granitic basement, and the data are integrated with Nd and Sr whole rock isotopes in order to identify the provenance components to the Bjorøy Fm. The detrital zircons reflect a source area that was dominated by rocks with zircon ages in Caledonian (450 and 520 Ma), Sveconorwegian (900 to 1010 Ma) and mid-Proterozoic (ca. 1450 Ma) times. One Archaean zircon at ca. 2700 Ma is recorded. The sand sample has a relatively low Nd model age of 0.5 Ga, which can be connected to an important sediment source in Caledonian rocks of intermediate and mafic compositions. These were probably derived from units related to the Minor and Major Bergen Arcs. Thus, rocks of the Upper Allochthon of the Caledonides were probably important in the sediment source area together with Proterozoic gneisses and late-Proterozoic platform sediments, which appear as tectonically intercalated slivers in the upper allochthonous units. Ordovician sediments in the provenance may explain the elevated time-corrected Sr isotope composition of the Bjorøy Fm, but it cannot be excluded that this signature is a result of interaction with seawater and/or crustal fluids during and after sediment deposition. The Bjorøy sand gives a zircon age signature of SW Norway in Mesozoic times. This is important since offshore sands with distinctly different zircon age distribution have previously been connected to a source in SW Norway.

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Introduction

Sediments store important information on dynamic geological processes in the continental crust. Their geochemical compositions record characteristics of a section of the continental crust that is no longer preserved (Taylor & McLennan 1985) and sediments deposited through time may reflect the (tectonic) changes in the upper continental crust within an area. Zircon is a resistant mineral during erosion, sediment transport and deposition, and zircon ages are not fractionated during sedimentary processes. Detrital zircon ages therefore directly reflect the age distribution of the zircon-bearing source and the zircon age pattern may serve as a fingerprint of a given provenance terrane (Morton et al. 1996; Knudsen et al. 1997b; Knudsen et al. 2001a). However, the composition of the upper continental crust is generally complex with both zircon-rich and zircon-poor lithologies. In order to document a large range of possible provenances, additional isotope tracers are useful, for example Sm-Nd and Rb-Sr whole rock data. Sm-Nd are generally not fractionated by crustal processes (McCulloch & Wasserburg 1978), a calculated Nd model age may reflect the average crustal residence time of the protolith (DePaolo 1981; Arndt & Goldstein 1987). On the other hand, surface and metamorphic processes (Gallet et al. 1996) may easily modify the Rb-Sr isotopic system. When such processes have not taken place, Sr may represent a useful provenance indicator since it is strongly fractionated between magmatic rocks (Knudsen et al. 1997a; Knudsen 2000).

The newly discovered and well-described Late Jurassic Bjorøy Formation was encountered in a subsea road tunnel between the island of Bjorøy and the mainland in the Bergen area (Fossen et al. 1997). The present paper is a provenance study of a sand sample in this rare occurrence of Mesozoic sediments in SW Norway. Its isotopic signature and detrital zircon age distribution may be characteristic of detritus that were derived from SW Norway and deposited in the North Sea basin in the Mesozoic and Cenozoic, particularly with regard to the near-shore deposits of the Horda Platform area.

Geologic setting

The West Norwegian Caledonides are the result of plate collision between Baltica and Laurentia in the early Paleozoic. During this process, Proterozoic rocks and early Paleozoic deposits were imbricated and thrust southeastward onto the western platform of Baltica (Fig. 1; Stephens & Gee 1989). In the Bergen Arcs, the middle allochthonous *Lindås Nappe* is dominated by gneisses of anorthosite, mangerite (hypersthene-monzonite), diorite, norite, and gabbro-composition. These rocks experienced a Sveconorwegian high-grade metamorphism (Austrheim 1978) at 930 to 945 Ma (U-Pb zircon ages, Boundy et al., 1997; Bingen et al., 2001). In tectonic contact with the Lindås nappe is *the Blåmannen Nappe*, consisting of Proterozoic migmatitic gneisses of the Ulriken Gneiss Complex, unconformably overlain by assumed late-Proterozoic continental margin deposits (Fossen 1989). The upper allochthonous unit comprises rocks that were formed off the continental margin: ophiolite complexes and well-preserved *island-arc volcanic and intrusive rocks* are dated at 472 to 493 Ma in SW Norway, while *Caledonian granitoids* intruded this nappe complex at 482 to 410 Ma (U-Pb zircon ages; Dunning & Pedersen 1988; Skjerlie 1992; Rb/Sr ages; Andersen & Jansen 1987; Fossen & Austrheim 1988). These rocks are stratigraphically overlain by an Ashgill-Llandoverian sedimentary cover sequence. Rocks of the Upper Allochthon are preserved in the *Major* and *Minor Bergen Arcs* of the Bergen area, where they occur intercalated with slivers of mylonitized Proterozoic gneisses and metasediments, due to tectonic movements during the Silurian-earliest Devonian Caledonian contractional history (Færseth et al. 1977; Fossen 1989). The parautochthonous Precambrian basement gneisses and migmatites of the *Øygarden Complex* of the Bergen area were considerably reworked during the Caledonian orogeny (Bering 1984; Fossen & Rykkelid 1990). Precambrian Rb/Sr ages of 1750 ± 60, 1024 ± 85, 1042 ± 92, 890 ± 15, and 800 ± 14 Ma were obtained from this complex (Sturt et al. 1975). It should be noted that the subdivision into Upper and Middle Allochthons is complicated in the Bergen Arcs, where the Middle Allochthon overlies the Upper Allochthon. This anomaly may be due to a late-stage inversion of the nappes in this region, although it cannot be ruled out that the present tectonostratigraphic status of the Lindås Nappe is incorrect.

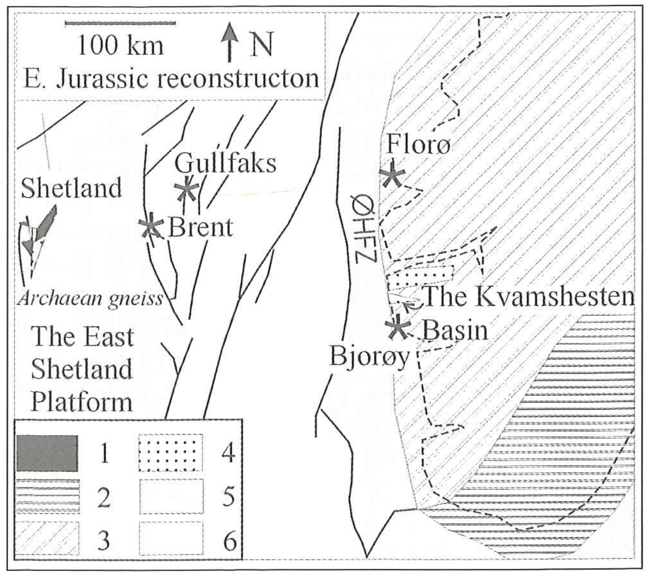

Fig. 1. Parts of the North Sea Region in an Early Jurassic reconstruction (based on Gage & Dorè, 1986; Coward, 1993; Knott et al., 1993). 1: Proterozoic metasediments (at Shetland), 2: Proterozoic rocks (S. Norway), 3: Caledonian allochthonous rocks, 4: Devonian sediments, 5: landmasses exposed in the Early Jurassic, 6: submarine.

Intramontane mid-Devonian collapse basins developed in the hangingwall of the Nordfjord-Sogn Detachment Zone of SW Norway (Séranne & Séguret 1987; Andersen et al. 1991; Andersen et al. 1994; Osmundsen & Andersen 1994) and probably also above the Bergen Arc Shear Zone (Wennberg et al. 1998). The development of these extensional structures and basins are related to a shift in tectonic regime from one of Caledonian contraction to large-scale crustal extension (Fossen 2000). The extension phase dominated the Early and Middle Devonian periods (Fossen 1992; Ar-Ar cooling ages; Chauvet & Dallmeyer 1992; Fossen & Dallmeyer 1998; Fossen & Dunlap 1998). Extension continued in the Mesozoic and Cenozoic, resulting in the formation of the North Sea basin and repeated faulting of the Caledonian basement (e.g. Doré 1992; Rohrmann et al. 1995; Færseth et al. 1995; Riis 1996; Eide et al. 1997; Dunlap & Fossen 1998; Fossen 1998).

The northern North Sea Rift originated during an episode of E-W crustal stretching in the Permian to Early Triassic (Badley et al. 1988, Gabrielsen et al. 1990). In the Late Triassic to Early Jurassic, an E-W extensional system prevailed in the Viking Graben area (Badley et al. 1988) and increased sedimentation rates caused deposition of important pre-rift, oil reservoir sandstones (including the Statfjord Formation; Olaussen et al. 1993). Rifting culminated in the Middle Jurassic to Early Cretaceous (Ziegler 1982; Glitner 1987; Badley et al. 1988) and fission-track modelling indicates that exhumation rates on the Norwegian mainland dropped by an order of magnitude at this time (Rohrman et al. 1995). At least parts of south-western Norway were flooded shortly after deposition of *the Bjorøy Formation* in the Late Jurassic (Fossen et al. 1997), and a tectonically quiet phase with gradual (thermal) rift subsidence in the Ryazanian to early Tertiary caused flooding of extensive areas of the mainland (Badley et al. 1988; Riis 1996). Subsequent uplift of the Norwegian mainland led to exhumation of the eastern margin of the North Sea basin, and deposition of major prograding Paleocene and Pliocene to recent clastic sequences close to the coast (Badley et al. 1988).

The investigated samples

The Bjorøy Formation is preserved in a 10 m-wide, pre-Jurassic fault zone in the Øygarden Complex (Fig. 2), and is located in a submarine road tunnel in the Bergen area (Fossen et al. 1997). It comprises a sedimentary breccia, grain-supported conglomerate, matrix supported conglomerate and medium- to fine-grained, quartz-dominated sand, which were deposited in the Oxfordian (at 154 to 159 Ma) in near-shore, marine environments (Fossen et al. 1997). Lithified zones in the sand can be attributed to fluid flow along the fault zone, while post-depositional fault movements caused a chaotic mixture of sand, sandstone and conglomerate (Fossen et al. 1997). Sedimentary breccia and conglomerate clast compositions suggest a main provenance in the Øygarden Complex, but fragments of rocks from the Minor Bergen Arc are also present (Fossen et al. 1997). One sand sample was used for the present study, together with three drillcore samples of a granodioritic basement rock. These samples were taken in the vicinity of the sand-filled gorge and represent relatively well-preserved samples of the Øygarden Complex.

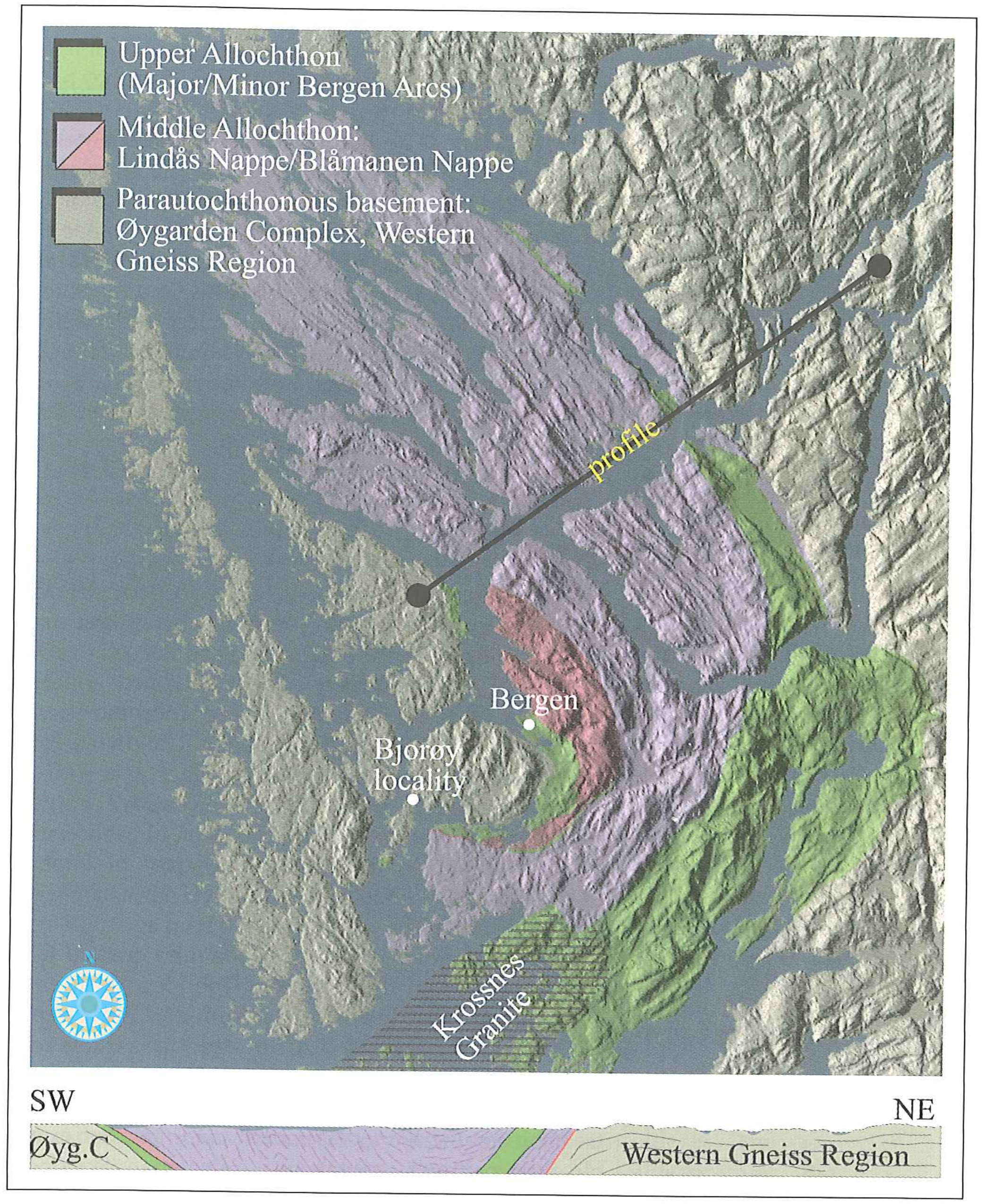

Fig. 2. Geological overview of the Bergen Arcs region, based on a digital elevation model. The Bjorøy locality is indicated where the analysed samples were collected.

Analytical data and results

Analytical techniques

A sand sample of the Bjorøy Formation (97.99Bjo) and one sample of the basement granodiorite (98.99Bjo) were selected for ion microprobe analysis. A random selection of *zircon* grains from the sand and a selection of well-preserved, non-magnetic magmatic zircons from the granodiorite were mounted in epoxy resin and polished to expose half of most zircon grains. The mounts were examined by reflected light microscopy and scanning electron microscopy, using the backscatter electron signal (BSE). U-Pb dating of zircons was performed using a CAMECA IMS1270 ion microprobe in the Nordsim laboratory located at the Swedish Museum of Natural History, Stockholm, Sweden. The location of the ana-

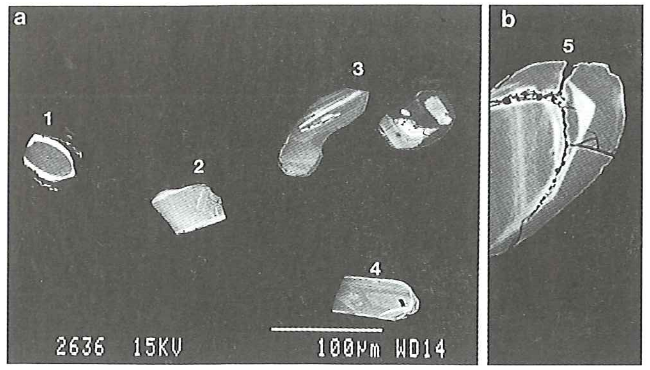

Fig.3a, b. Backscatter electron micrographs of oscillatory zoned, detrital zircons from the Bjorøy Fm. Zircon 1 and 3 are strongly discordant Sveconorwegian grains (analyses 18a and 16a, respectively, Table 1), zircon 2 has a ^{206}Pb/^{238}U age of 858 Ma (analysis 17a) and zircon 4 and 5 have ^{207}Pb/^{206}Pb ages of 1094 Ma and 2696 Ma, respectively (analyses 15a and 25a). A micrometre-wide and BSE-dark Caledonian metamorphic overgrowth can be seen on zircon no. 3 and 5. Photo b is ca. 50 µm wide.

lytical spots were selected on the basis of the BSE documentation (Fig. 3; Knudsen et al. 1997a). Details regarding the analytical procedure are described by Whitehouse et al. (1997, 1999). In this study, the Pb/U calibration was performed relative to the Geostandards zircon 91500, which has an age of 1065.4 ± 0.3 Ma (1σ) and Pb and U concentrations of ca. 15 and 80 ppm, respectively (Wiedenbeck et al. 1995). Data reduction was performed using a Nordsim developed suite of software (version 2.1).

The procedures for *Sm, Nd, Rb and Sr* extraction and *whole rock isotope analyses* are described in Knudsen et al. (1997b). Nd isotopic compositions are normalized to ^{146}Nd/^{144}Nd = 0.7219. During the period when the present analyses were made, the Johnson and Matthey batch no. S819093A Nd$_2$O$_3$ gave ^{143}Nd/^{144}Nd = 0.511101 ± 0.000013 (2σ). The NBS 987 Sr standard yielded ^{87}Sr/^{87}Sr = 0.710190 ± 0.000050 (2σ). The error of the ^{147}Sm/^{144}Nd ratio was in the order of 0.025%. Rb, Sr, Sm and Nd concentrations were determined by isotope dilution, using aliquots spiked in ^{87}Rb, ^{84}Sr, ^{148}Nd and ^{149}Sm. A VG354 mass spectrometer was used for isotope dilution and Sr isotope analyses, while the Nd isotope ratios were determined using a fully automated Finnigan MAT262 mass spectrometer. Both instruments are located in the Laboratory of Isotope Geology, Mineralogical-Geological Museum in Oslo, Norway.

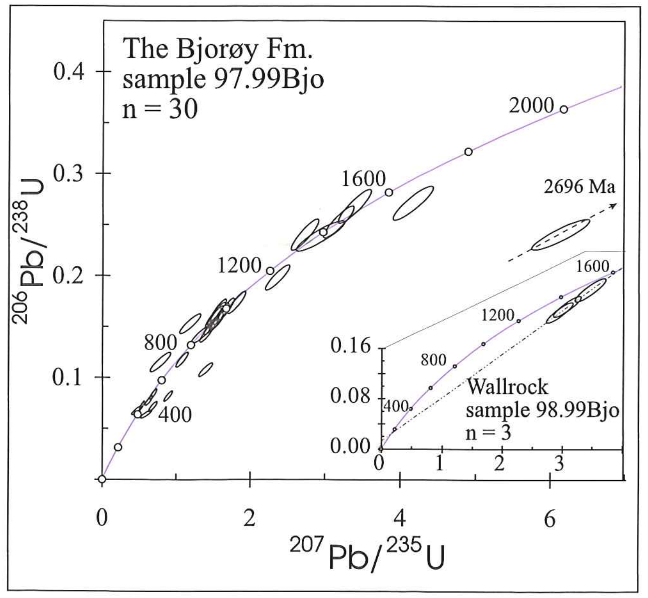

Fig.4. Concordia diagram showing SIMS zircon data on the Bjorøy Fm. The zircons form arrays with a lower intercept age at 400 Ma (Caledonian) to the present and upper intercepts in the range 900 to 1450 Ma. Inset: data on the granodiorite wallrock. It has an upper intercept age of 1620 ± 120 Ma and a lower intercept at 155 ± 610 Ma (MSWD = 0.041).

Single zircon data

Single zircon U-Pb isotope data on 30 detrital grains from the Bjorøy Formation (sandstone) and three magmatic zircons from the basement granodiorite are given in Table 1. All grains were oscillatory zoned, which is typical of magmatic zircons. No metamorphic zircons were included in the analytical data set. The zircons from the *basement granodiorite* are discordant and with an upper intercept age at 1620 ± 120 Ma (Fig. 4). Thus, the granodiorite is coeval with the intrusion of gabbro, diorite and syenite in the southwestern part of Western Gneiss Region at 1620 to 1640 Ma (U-Pb zircon ages; Skår et al. 1994; Skår 1998). These zircon ages post-date a Rb-Sr whole rock age of ~1750 Ma for a quartzo-feldspatic gneiss from the Øygarden Complex (Sturt et al. 1975) and pre-date intrusive ages from the Lindås Nappe at 1237 to 1254 Ma (U-Pb zircon and Rb-Sr whole rock ages; Austrheim 1978; Bingen et al. 1998).

There is no correlation between zircon age and crystal habit for *the Bjorøy Formation sandstone.* For example, long prismatic crystals give Caledonian, Sveconorwegian or Archaean ages. There is a high abundance of discordant grains forming arrays with a lower intercept age between ca. 400 Ma (Caledonian metamorphism) and the present, and upper intercepts in the range 900 to 1000 Ma and at ca. 1450. Discordance can be explained by composite analyses of detrital zircon cores and metamorphic overgrowths (Fig. 4; Fig. 3b), in combination with recent lead loss. Forty three per cent of the detrital zircon cores are within 100 ± 10% concordant (2σ error), suggesting that the ^{207}Pb/^{206}Pb age closely reflects the crystallization age of these grains, while the ^{206}Pb/^{238}U age is more reliable in young (< 1000 Ma) grains due to the low accumulation of ^{207}Pb in a young zircon (Ludwig 1980; Mattinson 1987). The combination of ^{207}Pb/^{206}Pb ages and ^{206}Pb/^{238}U ages are presented in a cumulative probability histogram (Fig. 5), which is useful for a comparison of the zircon age distribution between different samples. A sediment source area characterized by rocks with zircon ages in Caledonian times (450 and 520 Ma), in Sveconorwegian times (900 to 1010 Ma) and at ca. 1450 Ma, is suggested for the Bjorøy Formation (Fig. 5a). A distinct group of zircons at ca. 520 Ma may have a source in early Caledonian island arc volcanic rocks and ophiolite complexes, dated at 485 to 494 Ma (Pedersen & Dunning 1997), while a well-defined, separate Caledonian zircon peak at ca. 450 Ma may be related to plagiogranites and S-type granites that crystallized at 443 to 420 Ma (U-Pb zircon ages; Dunning & Pedersen 1988, Skjerlie 1992). Magmatism at ca. 1450 Ma is poorly known in Western Norway, but gabbro intrusions related to anorogenic magmatism at 1450 to 1462 Ma have been recorded both in the Jotun Nappe of central South Norway and in the Western Gneiss Region (U-Pb zircon and titanite ages, Tucker et al. 1990; Corfu & Emmett 1992). Also granite intrusives dated at 932 to 1014 Ma (U-Pb zircon ages, Corfu 1980; Skår 1998) appear to be common for the Caledonian nappes and the autochthonous basement (Sturt et al. 1975). Two zircons in the Bjorøy Formation with ^{207}Pb/^{206}Pb ages at 1818 Ma and 2696 Ma, are older than known intrusives from western Norway. These may represent far-transported and re-sedimented detritus from the Svecofennian (1.8 to 2.0 Ga) and Archaean domains of the Baltic Shield, and may have a provenance in the late-Proterozoic platform sediments. However, Pedersen (1992) reported

Table 1. Zircon ion-probe data on the Bjorøy Fm

													Apparent ages						
Id.	U	Th	Pb	Th/U$_{meas}$	f$_{206}$ %[1]	^{204}Pb/^{206}Pb	^{207}Pb/^{206}Pb	+/- 1σ	^{207}Pb/^{235}U	+/- 1σ	^{206}Pb/^{238}U	+/- 1σ	^{207}Pb/^{206}Pb	+/- 1σ[2]	^{207}Pb/^{235}U	+/- 1σ	^{206}Pb/^{238}U	+/- 1σ[2]	% concordance[3]
The Bjorøy Formation, sample 97.98Bjo																			
01a	386	78	104	0,20	1,37	0,0007	0,0824	0,94	2,7267	2,78	0,2401	2,61	1254	18	1336	21	1387	33	112
02a	387	186	78	0,48	0,94	0,0005	0,0684	1,20	1,5722	2,81	0,1666	2,54	882	25	959	18	993	23	114
03a	166	46	23	0,28	0,54	0,0003	0,0665	1,87	1,0792	3,17	0,1177	2,57	821	38	743	17	718	17	87
04a	462	128	137	0,28	0,16	0,0001	0,0911	0,41	3,1732	2,57	0,2527	2,54	1448	8	1451	20	1452	33	100
05a	695	83	120	0,12	0,25	0,0001	0,0727	0,54	1,5784	2,60	0,1575	2,54	1006	11	962	16	943	22	93
06a	593	191	50	0,32	0,31	0,0002	0,0540	0,97	0,5406	2,72	0,0726	2,54	370	22	439	10	452	11	123
07a	513	10	(89)	0,02	0,83	0,0004	0,0693	1,48	1,5330	2,94	0,1604	2,54	908	30	944	18	959	23	106
08a	238	81	68	0,34	3,43	0,0018	0,0890	3,67	2,9299	4,48	0,2389	2,56	1403	69	1390	34	1381	32	98
09a	216	63	69	0,29	0,64	0,0003	0,0915	0,64	3,3829	2,62	0,2681	2,54	1458	12	1500	21	1531	35	106
10a	434	339	94	0,78	0,49	0,0003	0,0692	0,84	1,5620	2,68	0,1636	2,54	906	17	955	17	977	23	108
11a	365	143	73	0,39	0,15	0,0001	0,0728	0,56	1,6803	2,60	0,1675	2,54	1007	11	1001	17	998	24	99
12a	474	83	150	0,17	1,26	0,0007	0,1112	0,63	4,1572	2,62	0,2713	2,54	1818	11	1666	22	1547	35	83
13a	210	23	(28)	0,11	6,58	0,0035	0,0496	6,29	0,7881	7,12	0,1153	3,34	175	140	590	32	703	22	418
14a	1071	215	188	0,20	0,08	0,0000	0,0722	0,34	1,5391	2,57	0,1547	2,55	990	7	946	16	927	22	93
15a	191	88	41	0,46	0,44	0,0002	0,0760	0,90	1,8196	2,70	0,1737	2,55	1094	18	1053	18	1033	24	94
16a	919	898	109	0,98	1,57	0,0008	0,0696	1,94	0,6877	3,50	0,0717	2,91	916	40	531	15	446	13	47
17a	420	169	72	0,40	0,64	0,0003	0,0682	3,28	1,3388	4,16	0,1423	2,55	876	66	863	24	858	21	98
18a	913	562	90	0,62	0,34	0,0002	0,0791	0,74	0,8937	2,65	0,0820	2,54	1174	15	648	13	508	12	41
19a	284	104	50	0,36	2,20	0,0012	0,0564	4,21	1,1892	4,93	0,1530	2,57	467	91	796	28	918	22	204
20a	445	197	88	0,44	0,22	0,0001	0,0719	0,61	1,6125	2,65	0,1626	2,57	984	12	975	17	971	23	99
21a	350	158	35	0,45	0,36	0,0002	0,0600	1,11	0,6942	2,78	0,0839	2,55	603	24	535	12	519	13	86
22a	891	472	90	0,53	2,16	0,0012	0,0593	2,10	0,6333	3,30	0,0775	2,55	577	45	498	13	481	12	83
23a	14	0	1	0,02	(3.79)	0,0020	0,0675	4,56	0,5986	5,25	0,0643	2,60	853	92	476	20	402	10	45
24a	180	103	34	0,57	0,17	0,0001	0,0709	1,02	1,4780	2,73	0,1513	2,54	954	21	921	17	908	22	95
25a	225	89	70	0,40	0,46	0,0002	0,1847	0,60	6,1352	2,61	0,2409	2,54	2696	10	1995	23	1391	32	46
26a	113	54	22	0,48	(0.24)	0,0001	0,0685	1,32	1,5001	2,86	0,1588	2,54	884	27	930	18	950	22	108
27a	241	89	56	0,37	1,30	0,0007	0,0864	1,19	2,3605	2,81	0,1981	2,54	1348	23	1231	20	1165	27	85
28a	162	77	13	0,48	1,89	0,0010	0,0498	5,33	0,4660	5,90	0,0678	2,54	188	120	388	19	423	10	230
29a	231	17	(29)	0,07	(4.04)	0,0022	0,0942	1,15	1,4002	2,80	0,1078	2,55	1513	22	889	17	660	16	41
30a	391	177	67	0,45	1,31	0,0007	0,0715	1,31	1,4185	2,86	0,1438	2,54	973	27	897	17	866	21	88
Wallrock sample 98.98Bjo																			
01a	458	330	132	0,72	(0.04)	0,0000	0,0985	0,63	2,9508	3,11	0,2174	3,04	1595	12	1395	24	1268	35	77
02a	61	53	19	0,86	(0.15)	0,0001	0,0983	0,87	3,0777	3,12	0,2270	2,99	1593	16	1427	24	1319	36	81
03a	247	162	81	0,66	0,08	0,0000	0,0992	0,50	3,4638	3,04	0,2531	3,00	1610	9	1519	24	1455	39	89

1: percentage of the ^{206}Pb contributed by common Pb, which is estimated from ^{204}Pb by assuming Stacey & Kramers (1975) model. Numbers in brackets indicate a spuriously high common lead for which no correction of ratios has been made. 2: at a 2σ level. The ^{207}Pb/^{206}Pb ratios are observed errors and the Pb/U ratios contain a dominant propogated component based upon the external error of the standard measurements.

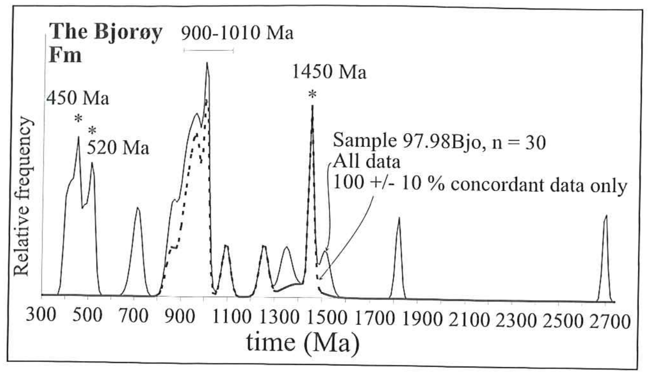

Fig. 5. A cumulative probability histogram of detrital zircon data from the Bjorøy Fm. The curve is constructed by assuming equal area Gaussian curves based on the mean value and standard deviation of the individual analyses. There are important zircon-bearing lithologies in the provenance with ages at ca. 450 Ma, 520 Ma, 900 to 1010 Ma and at ca. 1450 Ma.

Archaean ages from the island arc related West Karmøy Igneous complex in the Karmøy Ophiolite Complex, which opens the possibility that the similar ophiolitic rocks of the Bergen Arc System may be a source for the Archaean ages found in the Bjorøy Formation. The ca. 1620 Ma granodiorite and time-correlative intrusives within the Øygarden Complex/Western Gneiss Region constituted an insignificant provenance component to the sand.

Nd-Sr isotope modelling

The Sm-Nd and Rb-Sr whole rock isotopes were performed in order to obtain a better understanding of the relative amounts of material derived from zircon-poor, ophiolite lithologies in the Bjorøy Formation. This may have been an important provenance component together with Caledonian granitoids, *allochtonous* Proterozoic gneisses and late-Proterozoic platform sediments (Table 2). Included are also new data on three samples of rocks from the Øygarden Complex. The Bjorøy sand sample has a low Sm and Nd content, and a relatively low Nd model age (DePaolo 1981) of 0.5 Ga, which is consistent with a substantial provenance component of juvenile crust generated in Caledonian times. The granodiorite samples have Nd model ages of 1.2 to 1.6 Ga that overlap with the zircon age at 1620 Ma (sample 98.99Bjo), and a relatively short crustal residence time of the granodiorite precursor prior to intrusion at ca. 1620 Ma is suggested. The Sr and Nd isotope data are corrected to the time of sediment deposition at 155 Ma in Fig. 6 and compared to published data on important Caledonian lithologies. The Bømlo Ophiolite Complex, which is located some 60 km south of the Bjorøy area, shows a wide range of Nd and Sr isotope compositions, and Nd data from this complex (Pedersen & Dunning 1997) overlap with those from the Bjorøy Formation. These ophiolite and island arc related rocks have relatively high time corrected $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$ values relative to the field of Caledonian granitoids (Skjerlie 1992). Ordovician sediments of SW Norway (Skjerlie 1992) are characterized by relatively low $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$ and a wide range of $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ values at 155 Ma. The present data suggest that mafic and intermediate magmatic rocks were important Caledonian units in the sediment source area, together with granitoids. A provenance component in Ordovician sediments may explain the elevated time-corrected Sr isotope composition of the Bjorøy Fm. Alternatively, interaction with seawater and/or crustal fluids during and after deposition of the Bjorøy Fm may also explain this composition.

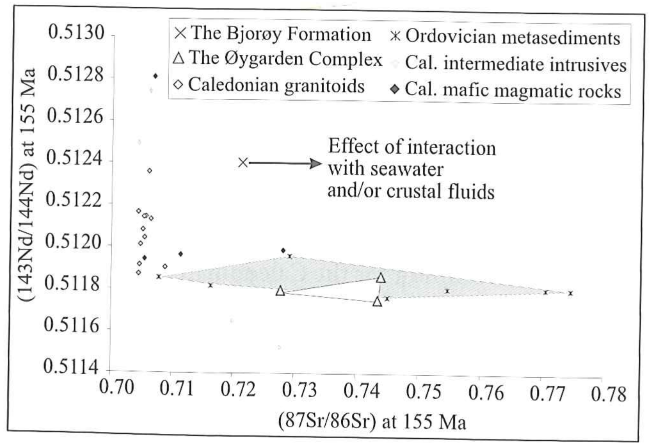

Fig. 6. Time corrected Nd- and Sr-data on the Bjorøy Fm and three samples of the basement granordiorite. Data on potential provenance components to the Bjorøy Fm are included. Cal. is Caledonian.

Discussion

Juvenile rocks added to a provenance will effectively lower the Nd model age of a sediment, while young granitoid intrusions in the provenance may change the detrital zircon age distribution without severely effecting the Nd whole rock data of the sediment. The combination of a low Nd model age of 0.5 Ga and a high abundance of Caledonian zircons at ca. 450 Ma and 520 Ma, suggest that both mafic and granitoid Caledonian rocks were important in the source area to the Bjorøy Formation. Amphibolite, metagabbro, trondhjemite and serpentinite are dominant lithologies in the Minor Bergen Arc, which probably represent remnants of a Caledonian outboard terrane (Fossen 1989), while Caledonian granitoids, including the Krossnes Granite (Ingdahl 1985; Fossen and Austrheim 1988), are more widespread in the Major Bergen Arc. The present data on the Bjorøy Formation are consistent with a composite sediment source in an upper allochthonous unit related to the Minor and particularly the lithologically diverse Major Bergen Arcs. Proterozoic gneisses and late-Proterozoic platform sediments, which are imbricated and intercalated with these rocks, may explain the high abundance of detrital zircon

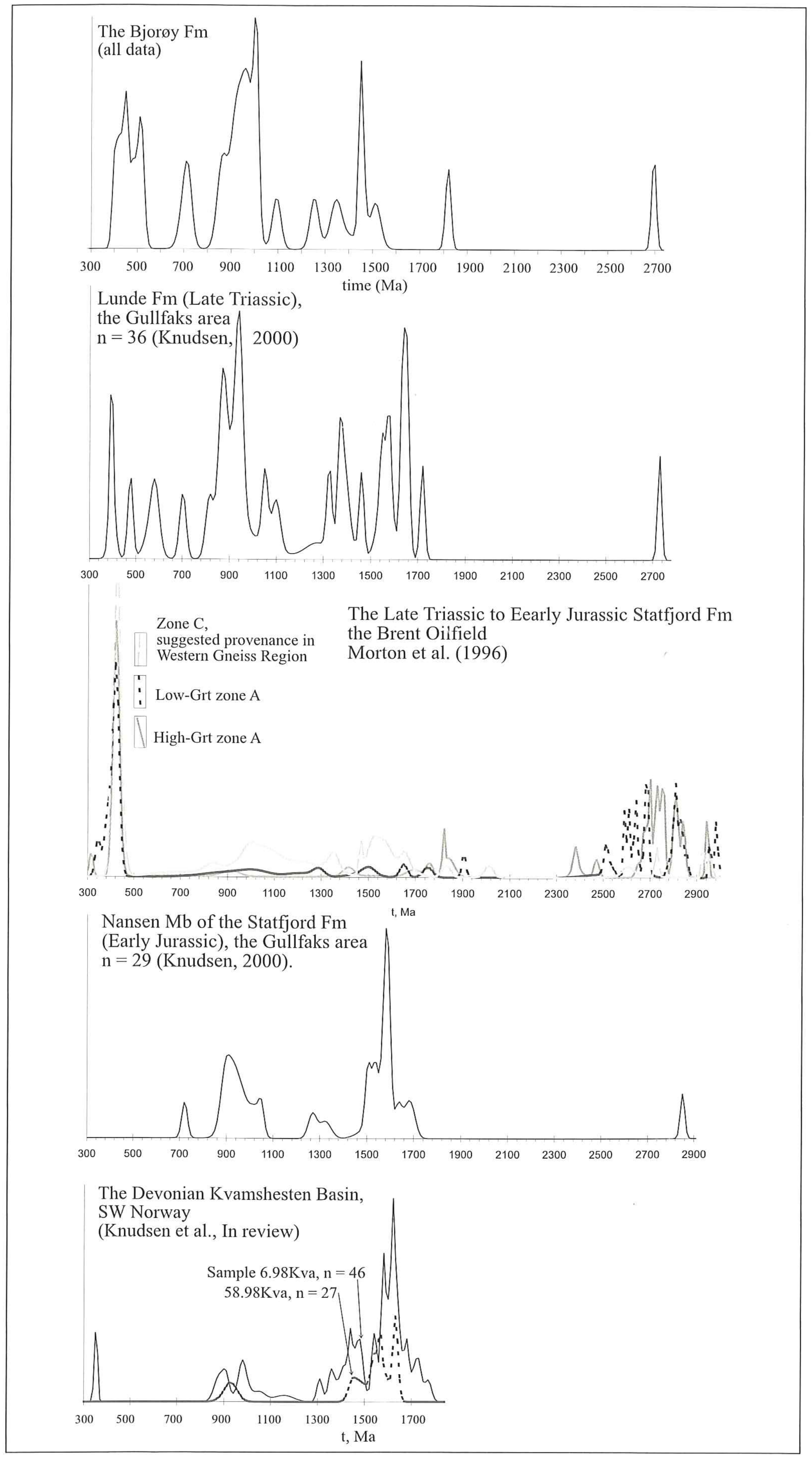

Fig. 7. A cumulative probability histogram of detrital zircon data from the Bjorøy Fm compared with data on the Lunde Fm of the Gullfaks Oilfield, the Statfjord Fm of the Brent Oilfield, the Nansen Mb of the Gullfaks Oilfield and Devonian sandstones from the Kvamshesten Basin of SW Norway.

Table 2. Whole rock isotope data on the Bjorøy Formation and the gneiss host-rock

sample	rock	Sm, ppm	Nd, ppm	Sm/Nd	^{147}Sm/^{144}Nd[1]	^{143}Nd/^{144}Nd	2σ*10^{-6}	eNd(0)	t(DM),Ga	Rb, ppm	Sr, ppm	^{87}Rb/^{86}Sr[2]	^{87}Sr/^{86}Sr	2σ*10^{-6}
97.99Bjo	sand	0,2	2,7	0,062	0,03796	0,51244	32	-3,8	0,5	73,91	47,68	4,49540	0,73133	7
95.99Bjo	granodiorite	10,7	63,8	0,168	0,10246	0,51185	8	-15,2	1,6	234,10	216,38	3,14322	0,75036	13
96.99Bjo	granodiorite	5,8	45,9	0,126	0,07720	0,51194	32	-13,6	1,2	210,29	192,92	3,16693	0,75094	13
98.99Bjo	granodiorite	7,7	52,0	0,148	0,08986	0,51189	4	-14,6	1,4	148,14	60,14	7,15175	0,74355	16

1: the error is 0.025 % of the calculated ratio. 2: the error is 0.5 % of the calculated ratio

ages at 900 to 1010 Ma and at ca. 1450 Ma. A provenance component in the middle allochthonous Lindås Nappe cannot be discarded, but the autochthonous Øygarden Complex was not an important sediment source terrane.

The Bjorøy Formation is located in an area of Lower Paleozoic/upper allochthonous rocks of various types in addition to Proterozoic basement – a setting representative of the West Norway coastal areas. In the Late Jurassic, Lower Paleozoic rocks in the area may have formed valleys where paleo-rivers were located and the data may be explained in terms of favoured erosion of Paleozoic rocks only. Alternatively, more of the Upper Allochthon was covering the basement at the time of deposition of the Bjorøy Formation than is the case today, which makes the age distribution a more regional signature of Mesozoic sediments derived from SW Norway. An overlapping detrital zircon age distribution for the Bjorøy sand and the Lunde Formation (Late Triassic) of the Gullfaks Oilfield may support this interpretation (Fig. 7). Independent of these alternative models, the zircon age distribution signature of the Bjorøy Formation can serve as a reference for offshore sands with an (ultimate) main provenance in the upper allochthonous units of SW Norway.

The Bjorøy Formation as a provenance indicator for sediments derived from SW Norway

An early stage of rifting and sediment deposition in the North Sea basin in the Late Triassic to Early Jurassic, involved an interplay of separate provenance terranes (Dalland et al. 1995). Figure 7 is a comparison of detrital zircon data on Late Triassic and Early Jurassic sands from the Gullfaks and Brent Oilfields of the North Sea, Devonian sandstones from the Kvamshesten Basin of SW Norway and the present data on the Bjorøy Formation (Morton et al. 1996; Knudsen 2001; Knudsen et al., 2001b). Sands with distinctly different age signatures have been connected to a provenance in SW Norway (Morton et al. 1996; Knudsen 2001), but a provenance signature of SW Norway may be represented by detrital zircon data on Devonian sediments and the Bjorøy Fm. To which extent the Bjorøy data are representative for Mesozoic sediments eroded from SW Norway is unknown, but the data suggest that the Bjorøy Formation and the Late Triassic Lunde Formation (from the Gullfaks Oilfield) have a related provenance in upper allochthonous rocks from SW Norway. The Early Jurassic Nansen Member may have a separate source in re-sedimented Devonian sediments from SW Norway. Overlapping zircon age distributions between these onshore and offshore sediments suggest subordinate contributions from other provenance terranes during the processes of sedimentation and sediment re-deposition during the deposition of the Triassic and Jurassic sands.

For the Statfjord Fm of the Brent Oilfield, provenances were suggested for the sand zones A and C in the East Shetland Platform and in SW Norway, respectively (Morton et al. 1996; Fig. 7). The present compilation shows that sand zone C does not have a South Norwegian source and similarities in the zircon age distributions suggest that both sand zones A and C may have a related provenance in the East Shetland Platform. Thus, zircon provenance studies of Devonian and younger sediments from the exposed landmasses surrounding the North Sea basin are important for an understanding of ultimate provenance and sediment re-deposition processes in the rift basin.

Conclusions

The detrital zircon ages and Sm-Nd whole rock data consistently suggest that the Bjorøy Formation of SW Norway has a composite provenance in lower Paleozoic rocks within the Minor and Major Bergen Arcs, and in Proterozoic gneisses and late-Proterozoic sediments which appear as tectonically intercalated slivers in these units. The fractured granodiorite in the basement of the Øygarden Complex, which hosts the Bjorøy Fm, is dated to ca. 1620 Ma and constituted an insignificant provenance component to the sand. The results imply that in the Bergen area, the autochthonous/parautochthonous units may not have been exposed to erosion in Late Jurassic times, and little erosion of this crystalline basement (the Øygarden Complex) may have taken place since the Late Jurassic. Thus, the detrital zircon age distribution of the Bjorøy Formation may be used as a provenance signature for clastic sediments derived from SW Norway in the Mesozoic and Cenozoic. This is demonstrated by data on an Upper Triassic sand unit from the Lunde Formation of the Gullfaks area in the North Sea, which has a detrital zircon age pattern suggesting a similar sediment source area for the Lunde and the Bjorøy Formations.

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