Petrophysical and thermal properties of pre-Devonian basement rocks on the Norwegian continental margin

Trond Slagstad[1], Cécile Barrére[1], Børre Davidsen[1], Randi K. Ramstad[1,2]

[1]Geological Survey of Norway (NGU), 7491 Trondheim, Norway
[2]Present address: Asplan Viak AS, Pb 6723, 7031 Trondheim, Norway
E-mail: trond.slagstad@ngu.no

This Geological note presents petrophysical and thermal properties of pre-Devonian basement rocks along the Norwegian continental margin. The dataset is the first to present ground-truth data from basement rocks along the continental margin, and can be used to constrain future geophysical and thermal models of the margin's structure.

Introduction

Gravimetric and magnetic surveys along the Norwegian continental margin has significantly improved our understanding of the margin's crustal architecture and has allowed correlations between the onshore and offshore realms (e.g., Doré et al. 1997, Olesen et al. 2002, Skilbrei et al. 2002, Lyngsie et al. 2006), in addition to yielding important information to the petroleum industry. Furthermore, the location of hydrocarbon accumulations is believed to depend on the temperature structure of the subsurface (e.g., Bjørkum and Nadeau 1998), which in turn varies with variations in thermal conductivity and radiogenic heat production. However, models based on gravimetric, magnetic and thermal methods are hampered by a lack of ground-truth data, and at present, the petrophysical and thermal properties of basement rocks along the Norwegian continental margin have to be inferred from onshore datasets and educated estimates. Here, we present new data that help characterise the basement along the Norwegian continental margin (defined here as the dominantly pre-Devonian crystalline rocks underlying the ubiquitous Mesozoic cover) in terms of mineralogical and chemical composition, and petrophysical/thermal properties. The work is based on samples from 22 wells that have penetrated basement rocks, made available by the Norwegian Petroleum Directorate and Statoil. The purpose of this brief communication is to present petrophysical data from 12 wells (15 samples) in the North Sea, 4 wells (6 samples) in the Norwegian Sea and 6 wells (12 samples) in the

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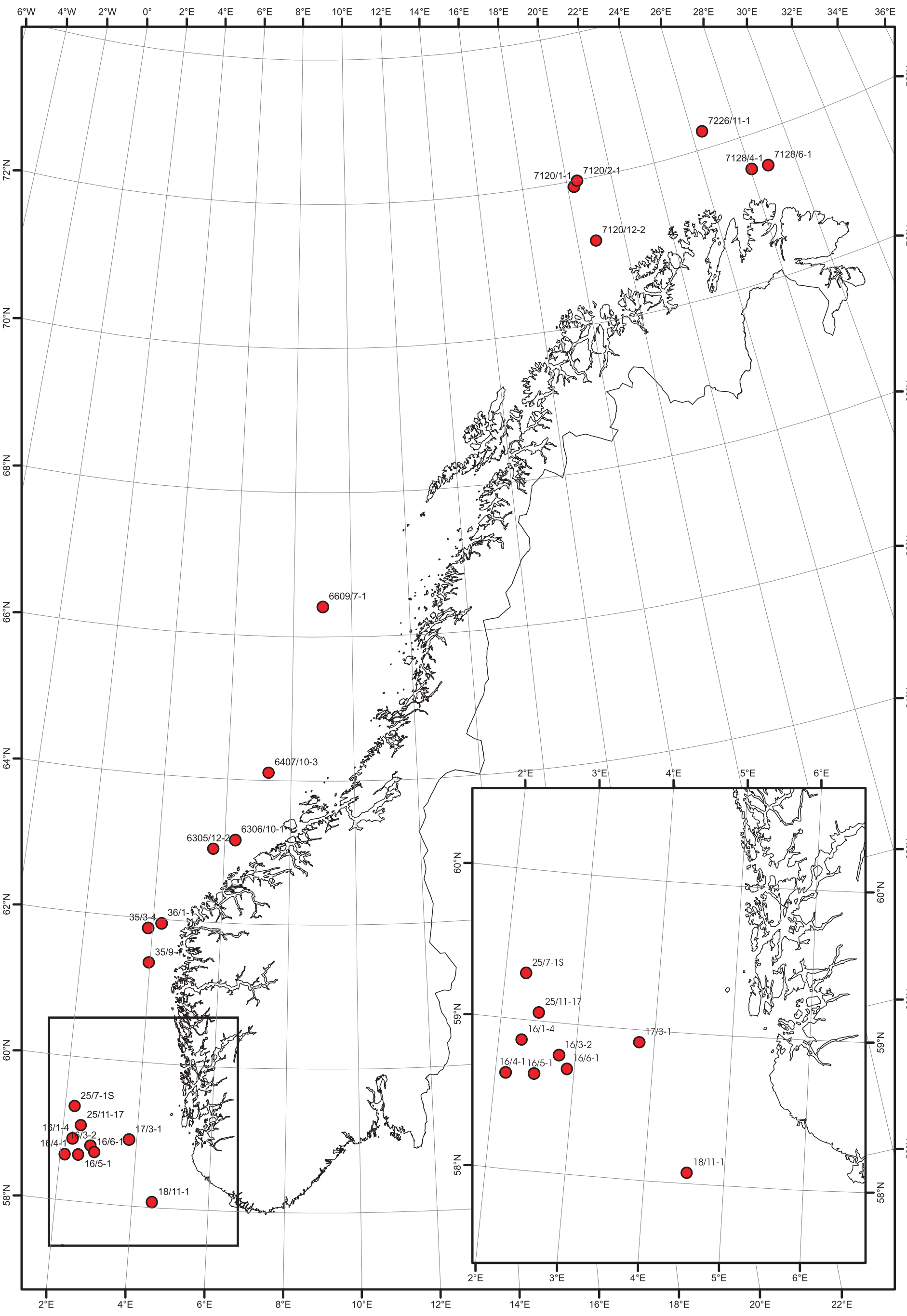

Figure 1. Map showing the locations and names of wells from which basement samples have been obtained.

Barents Sea (Figure 1). The analyses include determination of density, magnetic remanence, magnetic susceptibility, thermal conductivity and radiogenic heat production. The samples are described in Appendix 1 and a discussion on the geological significance of a subset of the samples is presented by Slagstad and Davidsen in Olesen et al. (2007). A few super-basement samples were also analysed for petrophysical properties. These samples are described in Appendix 2 and the data presented in Table 1.

Analytical methods

Petrophysical properties

Measurements of density, remanence and magnetic susceptibility are conducted following procedures described by Torsvik and Olesen (1988) and Olesen (1988).

Thermal conductivity

Measurements of thermal conductivity are conducted on 2 cm-thick circular disks. A constant heat flow is induced to the top of the sample by placing a heat source with a constant tempera-

Table 1. Petrophysical data from offshore basement samples, and some super-basement samples.

Well name	Sample depth (m)	Area	Top Basement depth (m)	Sample depth below Top Basement (m)	North	East	Lithology	Density (kg m^{-3})	Magnetic suscept. (10^{-6} SI)	Magnetic remanence (10^{-3} A m^{-1})	Electrical resistivity (ohm*m)
16/1-4	1937.0	North Sea	1864.0	73.0	58° 51` 55.20`` N	2° 17` 56.12`` E	Gabbro	2765	448.4	32.1	130
16/3-2	2017.7	North Sea	2015.0	2.7	58° 47` 12.80`` N	2° 47` 34.70`` E	Granite	2680	949.7	48.8	39845
16/4-1	2907.4	North Sea	2885.0	22.4	58° 38` 18.33`` N	2° 8` 17.03`` E	Altern. qtzite/siltstone	2778	221.3	2.8	3829
16/4-1	2908.6	North Sea	2885.0	23.6	58° 38` 18.33`` N	2° 8` 17.03`` E	Granite	2646	88	6.9	11075
16/5-1	1929.3	North Sea	1925.0	4.3	58° 38` 53.66`` N	2° 29` 39.69`` E	Granite	2662	179.8	11.3	403
16/6-1	2059.7	North Sea	2055.0	4.7	58° 42` 06.00`` N	2° 54` 44.00`` E	Porph. volcanic rock	2591	181.1	9.5	768
17/3-1	2849.5	North Sea	2811.0	38.5	58° 55` 02.50`` N	3° 48` 21.33`` E	Breccia	2750	553.3	10.3	1100
17/3-1	2850.7	North Sea	2811.0	39.7	58° 55` 02.50`` N	3° 48` 21.33`` E	Breccia	2661	58.3	0	14854
18/11-1	2082.3	North Sea	2060.0	22.3	58° 4` 21.30`` N	4° 32` 00.10`` E	Porph. volcanic rock	2639	207.4	22	1465
25/7-1S	3548.2	North Sea	n.a.	n.a.	59° 18` 35.23`` N	2° 16` 05.37`` E	Brecciated siltstone	2883	1406.8	68.7	110
25/7-1S	3554.3	North Sea	n.a.	n.a.	59° 18` 35.23`` N	2° 16` 05.37`` E	Qtz-rich sandstone	2722	48.8	9.2	553
25/11-17	2259.5	North Sea	2243.0	16.5	59° 3` 26.66`` N	2° 29` 06.59`` E	Metasiltstone	2656	291.6	0	415
35/3-4	4088.3	North Sea	4069.0	19.3	61° 51` 54.54`` N	3° 52` 26.99`` E	Bt-gneiss	2773	234.1	0	2288
35/9-1	2313.6	North Sea	2313.6	0.0	61° 23` 07.95`` N	3° 59` 03.72`` E	Breccia	2619	286.4	0	38
36/1-1	1588.7	North Sea	1568.0	20.7	61° 56` 40.36`` N	4° 15` 43.86`` E	Granitic gneiss	2676	104.3	5.2	835
6305/12-2	3158.3	Norwegian Sea	3145.0	13.3	63° 1` 11.39`` N	5° 40` 06.44`` E	Brecciated siltstone	2740	456.8	9.6	198
6306/10-1	3158.5	Norwegian Sea	2989.0	169.5	63° 9` 26.32`` N	6° 19` 41.45`` E	Quartz diorite	2767	2836.2	58.6	363
6306/10-1	3159.2	Norwegian Sea	2989.0	170.2	63° 9` 26.32`` N	6° 19` 41.45`` E	Quartz diorite	2732	1001.7	20	1403
6407/10-3	2972.1	Norwegian Sea	2959.0	13.1	64° 6` 11.66`` N	7° 18` 11.43`` E	Granite	2631	1186.7	108.9	11622
6609/7-1	1944.7	Norwegian Sea	1912.0	32.7	66° 24` 56.49`` N	9° 1` 14.91`` E	Brecciated silt-/ sandstone	2622	14.7	0	958
6609/7-1	1945.8	Norwegian Sea	1912.0	33.8	66° 24` 56.49`` N	9° 1` 14.91`` E	Altern. silt-/ sandstone	2580	24.6	11	1121
7120/1-1	4002.2	Barents Sea	3947.0	55.2	71° 55` 00.83`` N	20° 18` 07.13`` E	Amphibolite	3085	777.1	27.2	n.a.
7120/2-1	3478.0	Barents Sea	3471.0	7.0	71° 58` 57.94`` N	20° 28` 35.09`` E	Diabase	2762	42281	475.4	n.a.
7120/2-1	3479.0	Barents Sea	3471.0	8.0	71° 58` 57.94`` N	20° 28` 35.09`` E	Diabase	2727	34025.5	291.6	n.a.
7120/12-2	4675.8	Barents Sea	4664.0	11.8	71° 7` 30.30`` N	20° 48` 19.00`` E	Qtz-rich augen gneiss	2676	177.8	5	15060
7120/12-2	4678.2	Barents Sea	4664.0	14.2	71° 7` 30.30`` N	20° 48` 19.00`` E	Qtz-rich augen gneiss	2656	181.3	10.1	37368
7128/4-1	2527.0	Barents Sea	2503.0	24.0	71° 32` 27.33`` N	28° 4` 54.08`` E	Altern. silt-/ sandstone	2640	207	0	n.a.
7128/4-1	2527.2	Barents Sea	2503.0	24.2	71° 32` 27.33`` N	28° 4` 54.08`` E	Altern. silt-/ sandstone	2638	242.8	28.6	95
7128/4-1	2528.1	Barents Sea	2503.0	25.1	71° 32` 27.33`` N	28° 4` 54.08`` E	Altern. silt-/ sandstone	2617	260.4	46.1	177
7128/6-1	2540.5	Barents Sea	2534.0	6.5	71° 31` 04.99`` N	28° 49` 03.41`` E	Metasandstone	2689	124.8	11	1722
7128/6-1	2541.73	Barents Sea	2534.0	7.7	71° 31` 04.99`` N	28° 49` 03.41`` E	Metasandstone	2622	125.8	0	n.a.
7226/11-1	5198.3	Barents Sea	5137.0	61.3	72° 14` 18.16`` N	26° 28` 44.78`` E	Biotite-rich schist/gneiss	2783	315.8	5	n.a.
7226/11-1	5198.8	Barents Sea	5137.0	61.8	72° 14` 18.16`` N	26° 28` 44.78`` E	Biotite-rich schist/gneiss	2794	337.9	6.5	2295

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Table 1. Contined

Non-basement samples

Well name	Sample depth (m)	Area	Top Basement depth (m)	Sample depth below Top Basement (m)	North	East	Lithology	Density (kg m^{-3})	Magnetic suscept. (10^{-6} SI)	Magnetic remanence (10^{-3} A m^{-1})	Electrical resistivity (ohm*m)
7120/2-1	2239.35	Barents Sea	n.a.	n.a.	71° 58` 57.94`` N	20° 28` 35.09`` E	Polymict conglomerate	2738	444.6	10.7	n.a.
7120/2-1	2242.35	Barents Sea	n.a.	n.a.	71° 58` 57.94`` N	20° 28` 35.09`` E	Polymict conglomerate	2495	345.9	0	n.a.
7120/2-1	2230.65	Barents Sea	n.a.	n.a.	71° 58` 57.94`` N	20° 28` 35.09`` E	Polymict conglomerate	2642	241.8	2.8	n.a.
7120/2-1	2235	Barents Sea	n.a.	n.a.	71° 58` 57.94`` N	20° 28` 35.09`` E	Reddish brown, fine-grained conglomerate or ignimbrite(?)	2656	328.5	8.4	n.a.
7120/2-1	2645	Barents Sea	n.a.	n.a.	71° 58` 57.94`` N	20° 28` 35.09`` E	Conglomerate, silty and sandy matrix	2556	151.2	0	n.a.
7120/2-1	2641.35	Barents Sea	n.a.	n.a.	71° 58` 57.94`` N	20° 28` 35.09`` E	Breccia	2587	421.4	3.9	n.a.

ture approximately 10 mm above the top surface of the sample. The heat is transferred as radiation. The sample is insulated on all other surfaces and the temperature is measured at the base of the sample. The thermal conductivity (K) is calculated from Equation 1 based on measured thermal diffusivity (α) and density (ρ), and assumed specific heat (Cp) of the sample. The specific heat capacity is assumed to be 850 J kg^{-1} K^{-1} for all rock types.

$$K = \rho C_p \alpha \tag{1}$$

Radiogenic heat production

Radiogenic heat production is calculated from U, Th and K concentrations determined by standard XRF and LA–ICP–MS techniques at NGU and measured densities (ρ) using Equation 2 (Rybach 1988).

$$A = \rho * (9.52C_U + 2.56C_{Th} + 3.48C_K) * 10^{-5} \tag{2}$$

where C_U and C_{Th} represent U and Th concentrations in ppm, respectively, and C_K represents K concentration in wt.%.

Petrophysical and thermal properties

The petrophysical and thermal data are presented in Tables 1 and 2, respectively. Compilations of onshore petrophysical data show that most geological units display highly varied magnetic properties, typically ranging between 2 and 3 orders of magnitude (Skilbrei 1989), greatly limiting the value of a small dataset with poor geological control (due to pinprick offshore sampling). However, despite the difficulties in extending these very localised measurements to a larger rock volume, they represent additional information to the onshore petrophysical database at NGU. The main purpose of this contribution is therefore to disseminate the available data so that they are available to other researchers who may find them useful. For the same reason, we limit ourselves to a very brief and general discussion.

Most of the offshore samples are relatively low magnetic, which is compatible with the geological information (Slagstad and Davidsen, in Olesen et al. 2007) suggesting that the shallow basement along much of the continental margin consists of rock types that may be correlated with the Caledonian Uppermost Allochthon on land (cf., Olesen et al. 2002). In particular, the granites encountered in wells 16/3-2, 16/4-1, 16/5-1 and 6407/10-3 yield Caledonian ages and may be correlated with the low-magnetic Bindal batholith (Olesen et al. 2002). The diabase from well 7120/2-1 confirms the presence of thick mafic dykes within the basement of the Loppa High. This is in agreement with the joint interpretation of potential field modelling (Barrére et al. 2007) that proposes a tongue of basement affected by mafic dykes all along the fault complexes bordering the west of the Loppa High.

Table 2. Thermal data from offshore basement samples.

Well name	Depth (m)	Area	Top Basement depth (m)	Sample depth below Top Basement (m)	North	East	Lithology	Thermal conductivity (W m^{-1} K^{-1})	n	K (wt.%)	Th (ppm)	U (ppm)	Heat production (µW m^{-3})
16/1-4	1937.0	North Sea	1864.0	73.0	58° 51` 55.20`` N	2° 17` 56.12`` E	Gabbro	2.38	1	2.80	2.83	8.37	2.7
16/3-2	2017.7	North Sea	2015.0	2.7	58° 47` 12.80`` N	2° 47` 34.70`` E	Granite	3.12	1	2.25	8.70	2.62	1.5
16/4-1	2907.4	North Sea	2885.0	22.4	58° 38` 18.33`` N	2° 8` 17.03`` E	Altern. qtzite/ siltstone	2.51 (2.17–2.94)	4	3.82	10.8	3.64	2.1
16/4-1	2908.6	North Sea	2885.0	23.6	58° 38` 18.33`` N	2° 8` 17.03`` E	Granite	3.18	1	3.11	11.5	1.11	1.3
16/5-1	1929.3	North Sea	1925.0	4.3	58° 38` 53.66`` N	2° 29` 39.69`` E	Granite	3.23	1	2.89	10.7	2.89	1.7
16/6-1	2059.7	North Sea	2055.0	4.7	58° 42` 06.00`` N	2° 54` 44.00`` E	Porph. volcanic rock	2.89	1	2.26	0.34	0.96	0.5
17/3-1	2849.5	North Sea	2811.0	38.5	58° 55` 02.50`` N	3° 48` 21.33`` E	Breccia	2.69	1	0.04	1.81	0.60	0.3
17/3-1	2850.7	North Sea	2811.0	39.7	58° 55` 02.50`` N	3° 48` 21.33`` E	Breccia	3.93	1	0.05	1.59	0.55	0.3
18/11-1	2082.3	North Sea	2060.0	22.3	58° 4` 21.30`` N	4° 32` 00.10`` E	Porph. volcanic rock	3.25	1	0.11	7.14	2.12	1.0
25/7-1S	3548.2	North Sea	n.a.	n.a.	59° 18` 35.23`` N	2° 16` 05.37`` E	Brecciated siltstone	2.42	1	0.11	2.96	0.91	0.5
25/7-1S	3554.3	North Sea	n.a.	n.a.	59° 18` 35.23`` N	2° 16` 05.37`` E	Qtz-rich sandstone	4.69	1	2.67	3.65	0.96	0.8
25/11-17	2259.5	North Sea	2243.0	16.5	59° 3` 26.66`` N	2° 29` 06.59`` E	Metasiltstone	2.04	1	4.81	9.00	1.56	1.5
35/3-4	4088.3	North Sea	4069.0	19.3	61° 51` 54.54`` N	3° 52` 26.99`` E	Bt-gneiss	2.00	1	3.16	9.13	2.22	1.5
35/9-1	2313.6	North Sea	2313.6	0.0	61° 23` 07.95`` N	3° 59` 03.72`` E	Breccia	2.34 (2.25–2.47)	3	1.27	3.31	1.19	0.6
36/1-1	1588.7	North Sea	1568.0	20.7	61° 56` 40.36`` N	4° 15` 43.86`` E	Granitic gneiss	2.70 (2.54–2.80)	3	3.89	11.9	1.75	1.6
6305/12-2	3158.3	Norwegian Sea	3145.0	13.3	63° 1` 11.39`` N	5° 40` 06.44`` E	Brecciated siltstone	2.85	1	0.72	0.11	0.29	0.2
6306/10-1	3158.5	Norwegian Sea	2989.0	169.5	63° 9` 26.32`` N	6° 19` 41.45`` E	Quartz diorite	2.76	1	1.29	4.66	2.68	1.2
6306/10-1	3159.2	Norwegian Sea	2989.0	170.2	63° 9` 26.32`` N	6° 19` 41.45`` E	Quartz diorite	2.94	1	1.60	7.08	1.96	1.2
6407/10-3	2972.1	Norwegian Sea	2959.0	13.1	64° 6` 11.66`` N	7° 18` 11.43`` E	Granite	3.56	1	4.41	58.3	2.65	5.0
6609/7-1	1944.7	Norwegian Sea	1912.0	32.7	66° 24` 56.49`` N	9° 1` 14.91`` E	Brecciated silt-/ sand-stone	5.15 (4.95–5.44)	3	1.66	3.25	0.92	0.6
6609/7-1	1945.8	Norwegian Sea	1912.0	33.8	66° 24` 56.49`` N	9° 1` 14.91`` E	Altern. silt-/ sandstone	3.58	1	2.76	7.84	2.34	1.3
7120/1-1	4002.2	Barents Sea	3947.0	55.2	71° 55` 00.83`` N	20° 18` 07.13`` E	Amphibolite	2.69	1	0.93	3.42	1.07	0.7
7120/2-1	3478.0	Barents Sea	3471.0	7.0	71° 58` 57.94`` N	20° 28` 35.09`` E	Diabase	n.a.	0	n.a.	n.a.	n.a.	n.a.
7120/2-1	3479.0	Barents Sea	3471.0	8.0	71° 58` 57.94`` N	20° 28` 35.09`` E	Diabase	n.a.	0	n.a.	n.a.	n.a.	n.a.
7120/12-2	4675.8	Barents Sea	4664.0	11.8	71° 7` 30.30`` N	20° 48` 19.00`` E	Qtz-rich augen gneiss	2.72 (2.60–2.82)	3	1.69	16.2	4.85	2.5
7120/12-2	4678.2	Barents Sea	4664.0	14.2	71° 7` 30.30`` N	20° 48` 19.00`` E	Qtz-rich augen gneiss	2.94	1	2.90	4.29	0.40	0.7
7128/4-1	2527.0	Barents Sea	2503.0	24.0	71° 32` 27.33`` N	28° 4` 54.08`` E	Altern. silt-/ sandstone	n.a.	0	n.a.	n.a.	n.a.	n.a.
7128/4-1	2527.2	Barents Sea	2503.0	24.2	71° 32` 27.33`` N	28° 4` 54.08`` E	Altern. silt-/ sandstone	n.a.	0	4.18	21.2	5.51	3.2
7128/4-1	2528.1	Barents Sea	2503.0	25.1	71° 32` 27.33`` N	28° 4` 54.08`` E	Altern. silt-/ sandstone	n.a.	0	3.68	19.3	4.62	2.8
7128/6-1	2540.5	Barents Sea	2534.0	6.5	71° 31` 04.99`` N	28° 49` 03.41`` E	Metasandstone	4.90	1	1.47	2.58	0.87	0.5
7128/6-1	2541.73	Barents Sea	2534.0	7.7	71° 31` 04.99`` N	28° 49` 03.41`` E	Metasandstone	n.a.	0	n.a.	n.a.	n.a.	n.a.
7226/11-1	5198.3	Barents Sea	5137.0	61.3	72° 14` 18.16`` N	26° 28` 44.78`` E	Biotite-rich schist/gneiss	n.a.	0	n.a.	n.a.	n.a.	n.a.
7226/11-1	5198.8	Barents Sea	5137.0	61.8	72° 14` 18.16`` N	26° 28` 44.78`` E	Biotite-rich schist/ gneiss	3.75 (3.70–3.81)	3	2.43	12.6	2.55	1.8

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