Mineral deposits

Mineral raw materials in Greenland occur in a series of different geological environments that include sedimentary deposits, metamorphic crystalline rocks, and volcanic and plutonic rocks. An overview of selected mineral occurrences with their place names are shown in Fig. 54.

Mining activities have been carried out in Greenland since the middle of the 19th century, with the cryolite mine at Ivittuut as the only long-term mine; it was in operation for a period of 130 years. The cryolite deposit was associated with a granite intrusion in the Mesoproterozoic Gardar Province of South Greenland (p. 38), and represents an example of a very rare type of mineralisation, of which there are only very few similar deposits in the world (Pauly & Bailey 1999). Other mining activities in Greenland have exploited more common types of mineralisation. The two most important ones were both lead-zinc deposits – one at Mestersvig in East Greenland was associated with quartz veins of probable Palaeogene age, and the other at Maarmorilik in central West Greenland was a stratabound mineralisation in the Palaeoproterozoic Mârmorilik Formation (p. 27). Most recently a gold occurrence in Kirkespirdalen in the Palaeoproterozoic Ketilidian orogen, South Greenland, has been mined (Nalunaq Gold Mine, see below).

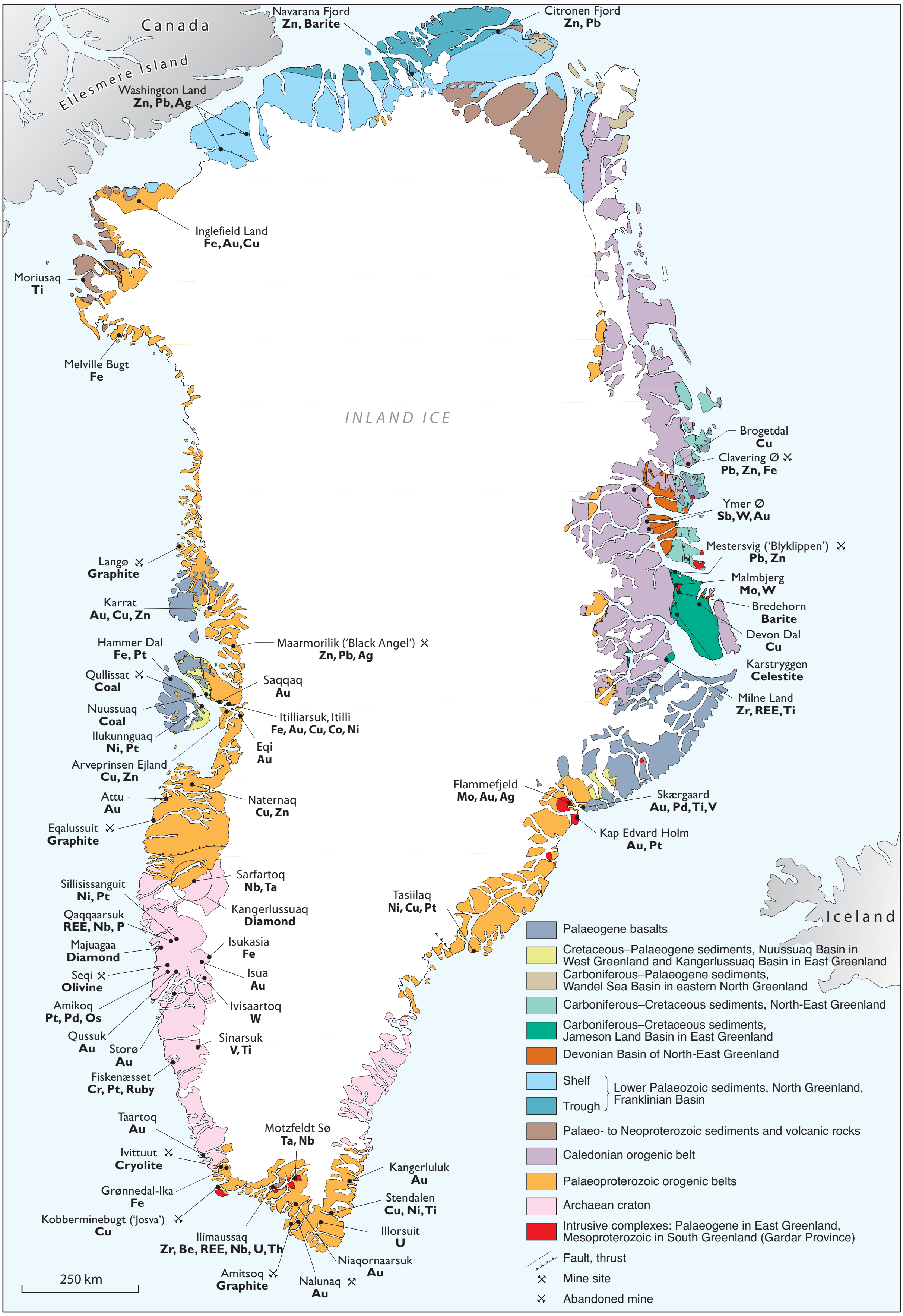
Mining activities have so far been very limited in Greenland considering the expected potential of such a large area. However, systematic exploration did not commence until the late 1950s when new legislation governing the mineral sector was introduced to encourage the mining industry to undertake exploration. This was intensified with the introduction of Home Rule status for Greenland in 1979.

In recent years exploration activities have concentrated on prospecting for gold, base metals, platinum elements, molybdenum, iron ore and diamonds. Gold exploration has focused on the Archaean and Palaeoproterozoic Precambrian shield of West Greenland and the Palaeogene Skaergaard layered gabbro intrusion (p. 62) in southern East Greenland (Andersen *et al.* 1998; Secher *et al.* 2007). A major new gold province in the Palaeoproterozoic Ketilidian orogen forming the southern tip of Greenland (Steenfelt 2000; Stendal & Frei 2000; Stendal & Secher 2002) was first recognised by panning of stream sediments, and in 1992 visible gold was found in quartz veins transecting mafic supracrustal rocks. The Nalunaq Gold Mine in Kirkespirdalen (a valley north-east of Nanortalik) operated from 2004 to 2008, but the mine is presently (2009) placed on 'care and maintenance'. Another find substantiating the interpretation of the Ketilidian orogen as a gold province was made in southernmost South-East Greenland, where gold mineralisation was found in a quartz-bearing shear zone cutting a sequence of mafic to andesitic extrusives and intrusives and associated sedimentary rocks. The promising gold mineralisations in South Greenland are situated at the southern border of the Julianehåb batholith (p. 29), which is also the root zone of a former volcanic arc (Chadwick & Garde 1996; Garde *et al.* 1998, 2002; McCaffrey *et al.* 2004).

Exploration for base metals in recent years has focused on showings in the Lower Palaeozoic Franklinian Basin and Ellesmerian fold belt of North Greenland. A massive sulphide deposit with lead and zinc was discovered in 1993 at Citronen Fjord in Peary Land (Fig. 54; van der Stijl & Mosher 1998). It occurs as stratiform sheets in a folded sequence of dark argillaceous rocks of the Upper Ordovician to Lower Silurian Amundsen Land Group. The Citronen Fjord deposit is located at the eastern end of the Franklinian Basin, which extends across North Greenland into Arctic Canada and is known to be a significant prospective zone which includes the Polaris zinc-lead mine in Canada.

Diamond exploration has focused on the Archaean and Palaeoproterozoic crystalline shield areas of West Greenland. The kimberlite province in this region includes the Archaean craton and areas of Archaean rocks farther north reworked during the Palaeoproterozoic. The province contains various Meso–Neoproterozoic ultramafic lamprophyres (UML) as well as Mesozoic UML-intrusions.

Facing page
Fig. 54. Map of known mineral occurrences in Greenland. The presentation combines the geological map with the knowledge of mineral prospects and deposits gathered over more than 150 years. The main geological divisions on the geological map cover periods from Archaean to Palaeogene and are summarised in the legend. From GEUS Department of Economic Geology.


Canada
Ellesmere Island
Washington Land
Zn, Pb, Ag
Navarana Fjord
Zn, Barite
Citronen Fjord
Zn, Pb
Inglefield Land
Fe, Au, Cu
Moriusaq
Ti
Melville Bugt
Fe
INLAND ICE
Brogetdal
Cu
Clavering Ø
Pb, Zn, Fe
Ymer Ø
Sb, W, Au
Mestersvig ('Blyklippen')
Pb, Zn
Malmbjerg
Mo, W
Bredehorn
Barite
Devon Dal
Cu
Karstryggen
Celestite
Milne Land
Zr, REE, Ti
Langø
Graphite
Karrat
Au, Cu, Zn
Hammer Dal
Fe, Pt
Maarmorilik ('Black Angel')
Zn, Pb, Ag
Qullissat
Coal
Saqqaq
Au
Nuussuaq
Coal
Itilliarsuk, Itilli
Fe, Au, Cu, Co, Ni
Ilukunnguaq
Ni, Pt
Eqi
Au
Arveprinsen Ejland
Cu, Zn
Flammefjeld
Mo, Au, Ag
Skærgaard
Au, Pd, Ti, V
Attu
Au
Naternaq
Cu, Zn
Kap Edvard Holm
Au, Pt
Eqalussuit
Graphite
Sarfartoq
Nb, Ta
Sillisissanguit
Ni, Pt
Kangerlussuaq
Diamond
Tasiilaq
Ni, Cu, Pt
Iceland
Qaqqaarsuk
REE, Nb, P
Isukasia
Fe
Majuagaa
Diamond
Isua
Au
Seqi
Olivine
Amikoq
Pt, Pd, Os
Ivisaartoq
W
Qussuk
Au
Storø
Au
Sinarsuk
V, Ti
Fiskenæsset
Cr, Pt, Ruby
Taartoq
Au
Motzfeldt Sø
Ta, Nb
Ivittuut
Cryolite
Kangerluluk
Au
Grønnedal-Ika
Fe
Stendalen
Cu, Ni, Ti
Kobberminebugt ('Josva')
Cu
Ilímaussaq
Zr, Be, REE, Nb, U, Th
Illorsuit
U
Niaqornaarsuk
Au
Amitsoq
Graphite
Nalunaq
Au
250 km
Palaeogene basalts
Cretaceous–Palaeogene sediments, Nuussuaq Basin in West Greenland and Kangerlussuaq Basin in East Greenland
Carboniferous–Palaeogene sediments, Wandel Sea Basin in eastern North Greenland
Carboniferous–Cretaceous sediments, North-East Greenland
Carboniferous–Cretaceous sediments, Jameson Land Basin in East Greenland
Devonian Basin of North-East Greenland
Shelf
Trough
Lower Palaeozoic sediments, North Greenland, Franklinian Basin
Palaeo- to Neoproterozoic sediments and volcanic rocks
Caledonian orogenic belt
Palaeoproterozoic orogenic belts
Archaean craton
Intrusive complexes: Palaeogene in East Greenland, Mesoproterozoic in South Greenland (Gardar Province)
Fault, thrust
Mine site
Abandoned mine

A large number of these intrusions contain diamonds, and intensive exploration activity has been in progress since the 1990s (Secher & Jensen 2004; Jensen *et al.* 2004; Nielsen *et al.* 2009). At present more than 1000 occurrences of diamondiferous kimberlite dykes have been found, and the largest diamond so far discovered is of 2.5 carat. The Archaean block also contains three large intrusive carbonatite complexes with a resource potential for various speciality commodities such as niobium and tantalum.

Mineral occurrences in specific geological settings

Significant occurrences of a broad range of metallic and industrial minerals are present in all the principal geological provinces in Greenland, ranging in age from Archaean to Quaternary (Fig. 54; Schønwandt & Dawes 1993; Stensgaard & Thorning 2009). In broad terms these can be related to five main settings:

Archaean–Palaeoproterozoic high-grade regions
Mesoproterozoic intracratonic intrusions
Palaeozoic orogenic belts
Upper Palaeozoic – Mesozoic basins
Late Phanerozoic intrusions.

The following description covers the principal active and former mines and some significant prospects (Fig. 54); at present (2009) there are two active mines, although one is 'on hold'. On the printed map sheet the locations of only four abandoned mines are shown (Ivittuut cryolite mine in South-West Greenland, Maarmorilik zinc and lead mine in central West Greenland, Mestersvig lead mine in central East Greenland and Qullissat coal mine in central West Greenland). Promising prospects are a large Zn-Pb mineral occurrence in Citronen Fjord in North Greenland, a banded iron occurrence at Isukasia in the Nuuk region, a zirconium and rare-earth element prospect/deposit in the Ilímaussaq complex in South Greenland and the Malmbjerg molybdenum deposit in central East Greenland. Information about a large number of mineralised localities is available in the continually updated Greenland Mineralisation Data Bank at the Survey (see: www. geus.dk/gmom: Greenland Mineral Occurrence Map on-line).

Archaean–Palaeoproterozoic high-grade regions

At Isukasia (Isua supracrustal sequence [**69**]; Fig. 54) north-east of Nuuk, a major Archaean banded iron formation is composed of interlayered magnetite and chert (Fig. 5). The deposit, which is partly covered by the Inland Ice, has been drill tested and a minimum tonnage of 1900 million tonnes grading 32.9% Fe is estimated (Nielsen 1976; Appel 1991).

The Nuuk region in southern West Greenland has revealed a good potential for gold mineralisations (Stensgaard & Stendal 2007). The gold occurs in the supracrustal parts of the Archaean craton, which largely consists of amalgamated islands arcs, which gradually merged into micro-continental blocks (Windley & Garde 2009). The supracrustal belts reflect both island-arc and ocean-floor environments, and also contain ultramafic to mafic magmatic intrusions. Gold showings occur in a NNE-trending belt along the fjord Nuup Kangerlua (Godthåbsfjord) from Nuuk to Isukasia, and a multidisciplinary approach has now resulted in division of the occurrences into three main groups (Stensgaard & Stendal 2007). The occurrences contain up to 3–7 g/t Au with local grades of up to 20 g/t Au. Intensive exploration with drilling both north and south of the fjord has been undertaken since 2003.

A series of gold occurrences has also been found in the crystalline basement rocks of the Nagssugtoqidian orogen north-east of Disko Bugt, central West Greenland. Here Archaean orthogneisses with their Archaean and Palaeoproterozoic cover rocks have been variably affected by the *c.* 2.0 to 1.75 Ga Nagssugtoqidian orogeny. The gold is hosted in Archaean metasedimentary and metavolcanic rocks and may be either stratabound or located in veins, breccias or shear zones (Steenfelt *et al.* 2004). The gold values are modest with only a few ppm in the mineralised zones, but there is a potential for further occurrences in the investigated region.

A folded and metamorphosed Archaean anorthosite complex [**85**] at Qeqertarsuatsiaat/Fiskenæsset, southern West Greenland (the Fiskenæsset complex; Fig. 54) hosts widespread chromite-bearing layers (Ghisler 1976). The complex, which has a strike length of more than 200 km and an average thickness of 400 m, has an estimated potential of 100 million tonnes of low-grade chromium ore. Enhanced precious metal values have been reported from the ultramafic parts of the complex (Appel 1992). Ruby-bearing rocks occur at several localities in the Fiskenæsset complex, where the corundum/ruby occurs in zones close to the contact between anorthosite and

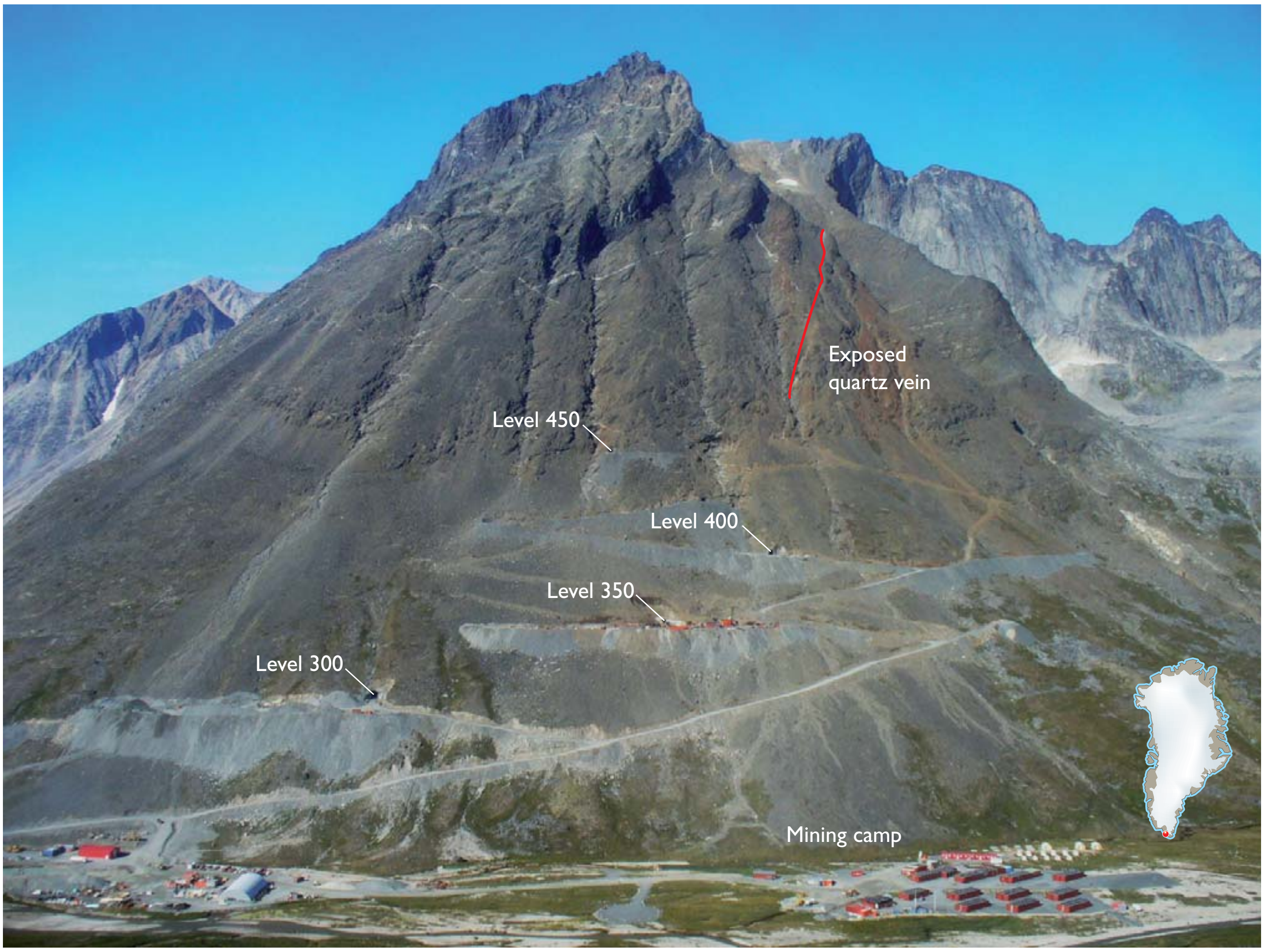


Fig. 55. View of the mining area around the Nalunaq Gold Mine in South Greenland. Access to the underground mine is at four levels of 300, 350, 400 and 450 m. The mine was opened in 2004. Photo: Bureau of Minerals and Petroleum, Nuuk.

amphibolite/ ultrabasite. A mining company has obtained an exclusive exploration licence for rubies, and tests have shown that some types of ruby and sapphire are of gem quality (Secher & Appel 2007).

A Neoarchaean iron province occurs in the coastal areas along Melville Bugt in North-West Greenland. Geographically it is the largest iron province in Greenland (Dawes 2006) and is traceable in a WNW–ESE-trending belt for *c*. 350 km. The belt contains magnetite and hematite in quartz-banded iron formation (BIF), massive lenses and layers with iron oxides and disseminated iron minerals in schists. BIF occurs in units of varying thickness, ranging from less than a metre to 40 m where iron concentrations typically are 30–35%.

At Maarmorilik, central West Greenland, the Black Angel (Fig. 54) zinc-lead ore bodies hosted in Palaeoproterozoic marble (p. 27; lower part of [**62**]) were mined in the period 1973–1990. Production totalled *c*. 11 million tonnes ore grading 4.0% Pb, 12.6% Zn and 29 ppm Ag. The deposits were almost exhausted in that period, but a re-establishment of the mine is planned for 2010–2011, based on the remaining ore in pillars in the mine combined with other marble-hosted lead-zinc prospects in the area (Thomassen 1991, 2006; MINEX 2008b). Prior to the Pb-Zn mining, some 8000 tonnes of marble were quarried at Maarmorilik in 1936–1971.

The Nalunaq Gold Mine in Kirkespirdalen, north-east of Nanortalik, South Greenland (Figs 54, 55) is a small, high-grade gold deposit associated with up to 1.8 m wide quartz-veins in a major shear zone. The deposit is an orogenic-type gold mineralisation (mesothermal lode gold) hosted in Palaeoproterozoic amphibolite facies volcanic rocks within the Ketilidian orogen. The mine was opened in 2004, but mining was placed on 'care and maintenance' by the owner at the end of 2008. In 2009 a new company is negotiating to take over the mine and start production again. Production in 2006 totalled 108 000 tonnes of ore with an average gold grade of 17.9 grams per tonne (Secher *et al.* 2008).

Several large, homogeneous, olivine-rich (dunitic) bodies occur in the Archaean gneiss terrain some 90 km north of Nuuk. An opencast mine, the Seqi Olivine Mine, was opened in 2005 in the northernmost part of the Niaqunngunaq/Fiskefjord fjord system (see Fig. 54).This homogeneous deposit contains at least 100 million tonnes of high-quality olivine.

Mesoproterozoic intracratonic intrusions

Cryolite hosted in a Gardar granite stock (part of [**56**]) at Ivittuut, South-West Greenland (Fig. 54) was worked from 1858 until 1987, and a total of 3.7 million tonnes ore grading 58% cryolite was quarried from an open pit. In addition to cryolite, galena, chalcopyrite and siderite were extracted as by-products. The main ore body is now exhausted, but there are indications of deep-seated reserves in the area (Bondam 1991).

In the Gardar Ilímaussaq alkaline intrusion (part of [**56**]; see Fig. 19; Fig. 54) east of Narsaq in South Greenland, a deposit with rare metals such as niobium, tantalum, zirconium, yttrium, rare-earth elements, lithium and beryllium and accessory uranium and thorium has been delimited by diamond drilling, indicating a reserve of 56 million tonnes of U with a grade of 365 ppm (Nyegaard 1979). The rare-earth and other special elements are concentrated in the final, highly volatile, products of the magmatic differentiation. The last rocks to solidify are therefore relatively rich in elements such as niobium, tantalum, zirconium and rare-earth elements (Bondam 1995). The Motzfeldt centre east of Narsarsuaq is another of the large intrusive syenite complexes in the Gardar Province. This centre has preserved accumulations of the mineral pyrochlore which has a high content of tantalum and niobium. The deposit has been explored and is rated as a 'low-grade – large tonnage' type of resource, with 600 million tonnes of ore with 120 g/t tantalum and 130 million tonnes of ore with 1400 g/t niobium. The deposit is believed to be one of the largest tantalum deposits in the world (H. Sørensen *et al.* 2006b).

Late Neoproterozoic (604–555 Ma old) *in situ* kimberlite intrusions and ultramafic lamprophyre dykes are widespread as dykes and sheets in the region around the fjord Kangerlussuaq / Søndre Strømfjord, West Greenland (Secher *et al.* 2009). They are found on both sides of the boundary between the Archaean craton to the south and the Palaeoproterozoic Nagssugtoqidian orogen to the north. The intrusions have been known since the mid-1960s and the first microdiamonds were found in stream sediments in the Sarfartoq river. The finds of microdiamonds led to intensive prospecting, and at present several microdiamond sites have been reported from outcropping kimberlitic rocks (MINEX 2002, 2007a, 2008a, b; Secher & Jensen 2004). Diamonds and diamond indicator minerals have since been found in numerous samples of stream sediments, in boulders and in situ kimberlites, both in the Sarfartoq area and in the Maniitsoq/Sukkertoppen area (65°N). In the Sarfartoq area exploration has resulted in finds of commercial-sized diamonds of up to 2.5 carats, and in 2008 the exploration company reported the recovery of another large diamond of *c.* 4 carat from a dyke. In the Maniitsoq area recent field work has resulted in recognition of a large kimberlite dyke system with a combined length of more than 10 km.

The known carbonatite intrusions of Sarfartoq, Qaqarssuk and Tikiusaaq (legend numbers [**59**] and [**61**] on the 1: 2 500 000 map) within the alkaline province south of Kangerlussuaq / Søndre Strømfjord have a recognised potential for accumulations of niobium and rare-earth elements (Secher & Jensen 2004; Kolb & Stensgaard 2009). Tikiusaaq was found in 2005 (Steenfelt *et al.* 2006) and is thus not indicated on the map.

Palaeozoic orogenic belts

South of Citronen Fjord (Fig. 54) in Peary Land, North Greenland, a large sulphide-rich zone hosts a major lead-zinc-bearing, Sedex-type, massive sulphide deposit in Ordovician black shales (part of [**24**]) (Kragh *et al.* 1997). Diamond drilling since the discovery in 1993 and up to 2008 has yielded 44 km of core and has indicated a resource of more than 102 million tonnes grading 4.7% Zn + Pb at a 2% Zn cut-off grade (van der Stijl & Mosher 1998; MINEX 2007b, 2008b). The deposit is located north of a prominent palaeo-escarpment separating carbonate shelf sedimentary rocks to the south from deep-water trough sedimentary rocks to the north. The prospect is currently (2009) under evaluation for opening of a mine in the near future.

Another discovery of zinc-lead-silver mineralisation in the same province has been made in Washington Land, western North Greenland, where a galena occurrence is hosted in evaporitic Lower Ordovician carbonates in the platform succession (Jensen 1998).

Upper Palaeozoic – Mesozoic basins

At Qullissat (Fig. 54) on Disko, central West Greenland, Cretaceous sub-bituminous coal was mined during the period 1924–1972. A total of about 570 000 tonnes of coal was shipped before the mine was closed due to the low coal quality (Schiener 1976). On nearby Nuussuaq, more than 180 million tonnes of sub-bituminous coal distributed in layers more than 0.8 m thick have been indicated by surface investigations and limited drilling (Shekhar *et al.* 1982).

Late Phanerozoic intrusions

The 54.5 Ma old Skaergaard layered gabbro intrusion (Fig. 54) at Kangerlussuaq, north-east of Ammassalik in southern East Greenland, hosts a major deposit of low-grade palladium, platinum and gold (Bird *et al.* 1991). Intensive diamond drilling totalling 42 drill holes with a combined length of more than 21 km, has shown a resource of more than 1520 million tonnes grading 0.21 ppm Au, 0.61 ppm Pd and 0.04 ppm Pt (Thomassen & Nielsen 2006; Secher *et al.* 2007). The mineralisation is hosted in a 100 m thick zone with gold and platinum-group elements accumulated in five intervals with thicknesses of several metres. In these intervals concentrations of gold and platinum-group elements are much higher than the average figures given above. Titanium, vanadium and iron are important additional commodities in the middle of the mineralised zone, and a test profile across the deposit indicates average contents of 6.6% TiO_2, 0.13% V_2O_5 and 19% Fe_2O_3. Similar mineralisation is known in other nearby intrusions.

Lead-zinc-bearing quartz veins, probably of Palaeogene age, occur in Lower Permian sediments near Mestersvig in East Greenland (Fig. 54). One of these occurrences, the Blyklippen deposit, was mined in the period 1956–1962. After production of 560 000 tonnes ore grading 11.1% Pb and 8.6% Zn the deposit was exhausted (Harpøth *et al.* 1986; Thomassen 2005).

A large porphyry-molybdenum deposit of Miocene age occurs at Malmbjerg (Fig. 54) south of Mestersvig, East Greenland, hosted in an intrusive complex [53]. Ore resource calculations were based on 22 km of diamond drill cores which indicate a tonnage of 150 million tonnes grading 0.23% MoS_2 and 0.02% WO_3 (Harpøth *et al.* 1986). A re-evaluation of the deposit was initiated in 2004 and has confirmed the earlier tonnage estimates. A mining company obtained an exploitation licence in 2009 and aims at opening an open pit mine in the near future with a production rate of *c.* 10 000 tonnes molybdenum per year (MINEX 2007b, 2008b). Other less well-investigated porphyry-molybdenum occurrences exist in the East Greenland Palaeogene volcanic province (Geyti & Thomassen 1984).

Petroleum potential of Greenland

The petroleum potential of Greenland is confined to the sedimentary basins of Phanerozoic age. Onshore, such basins occur in North Greenland, North-East and central East Greenland, and central West Greenland. Offshore, large sedimentary basins are known to occur off both East and West Greenland (Fig. 56). No proven commercial reserves of oil or gas have been found to date (2009), but so far only seven exploration wells have been drilled, six offshore southern West Greenland between latitudes 63°49´N and 68°N, and one onshore, on Nuussuaq at 70°28´N in central West Greenland (Christiansen *et al.* 1997; Pulvertaft 1997). In recent years there has been much interest in petroleum exploration mainly offshore West Greenland, where a number of exploration licences (Fig. 57) have been granted to consortia of both large and small oil companies (F.G. Christiansen, personal communication 2009). In the coming years focus will also be directed towards Baffin Bugt off North-West Greenland. Recent investigations include acquisition of geophysical data (seismic and airborne magnetic/gravity surveys) and seabed sampling. Another main target for future oil and gas exploration will be the shelf areas of North-East Greenland, where geophysical investigations have revealed the existence of a number of large sedimentary basins (Hamann *et al.* 2005). Based on data from the adjacent onshore areas it may be assumed that source rocks, reservoirs and seals are likely to occur here, and that several play types are present. The geophysical investigations in North-East Greenland both onshore and offshore have up to now only been carried out at reconnaissance level, and the area must still be characterised as essentially unexplored for oil and gas.

The greatly increased interest in recent years for petroleum exploration in Greenland has been supported by its relatively high ranking given by the Arctic Petroleum Appraisal of the United States Geological Survey. Here, North-East Greenland was selected as a prototype for an evaluation of this and similar other areas in the circum-arctic region (F.G. Christiansen, personal communication 2009). The undiscovered resource estimates for both oil and gas are quite high and the Danmarkshavn Basin (see p. 74) in particular is mentioned as a promising area (Gautier *et al.* 2009). A brief summary of the petroleum-geological features of the main sedimentary basins is given on the follow pages.

Onshore basins

Franklinian Basin, North Greenland (80–83°N)

The Franklinian Basin of North Greenland (see p.45) is the eastern continuation of the Cambrian–Devonian Franklinian Basin of the Canadian Arctic Islands. It consists of a belt of flat-lying, shallow-water carbonate rocks to the south and a northern belt of deep-water folded sedimentary rocks. Good type II (oil-prone) shaly source rocks are known in both Lower–Middle Cambrian and Lower Silurian outer shelf terrigenous and carbonate mudstones. Potential reservoirs include Lower and Middle Cambrian shelf sandstones and Lower Silurian reef and platform margin carbonate build-ups (Stemmerik *et al.* 1997). The rocks in the north are probably postmature due to the thermal influence of the Ellesmerian orogeny (see p. 49), but oil has been preserved in the southern areas and can now be seen as asphalt residues in pores and fractures in various carbonate rocks. The most promising play involves long-distance migration up-dip from Middle Cambrian source rocks into Lower Cambrian shelf sandstones (Christiansen 1989).

Late Palaeozoic – Mesozoic basins, eastern North Greenland (80–83°N)

Deposits in the Wandel Sea Basin comprise a succession of sedimentary rocks which were laid down along the northern and north-eastern margin of the Greenland shield (see p. 54). The development spans a period from Early Carboniferous to Palaeogene and includes three main phases of basin formation. The region is transected by a major NW–SE fault zone dividing the area into two blocks with different structural, depositional and thermal histories and hydrocarbon potential (Stemmerik

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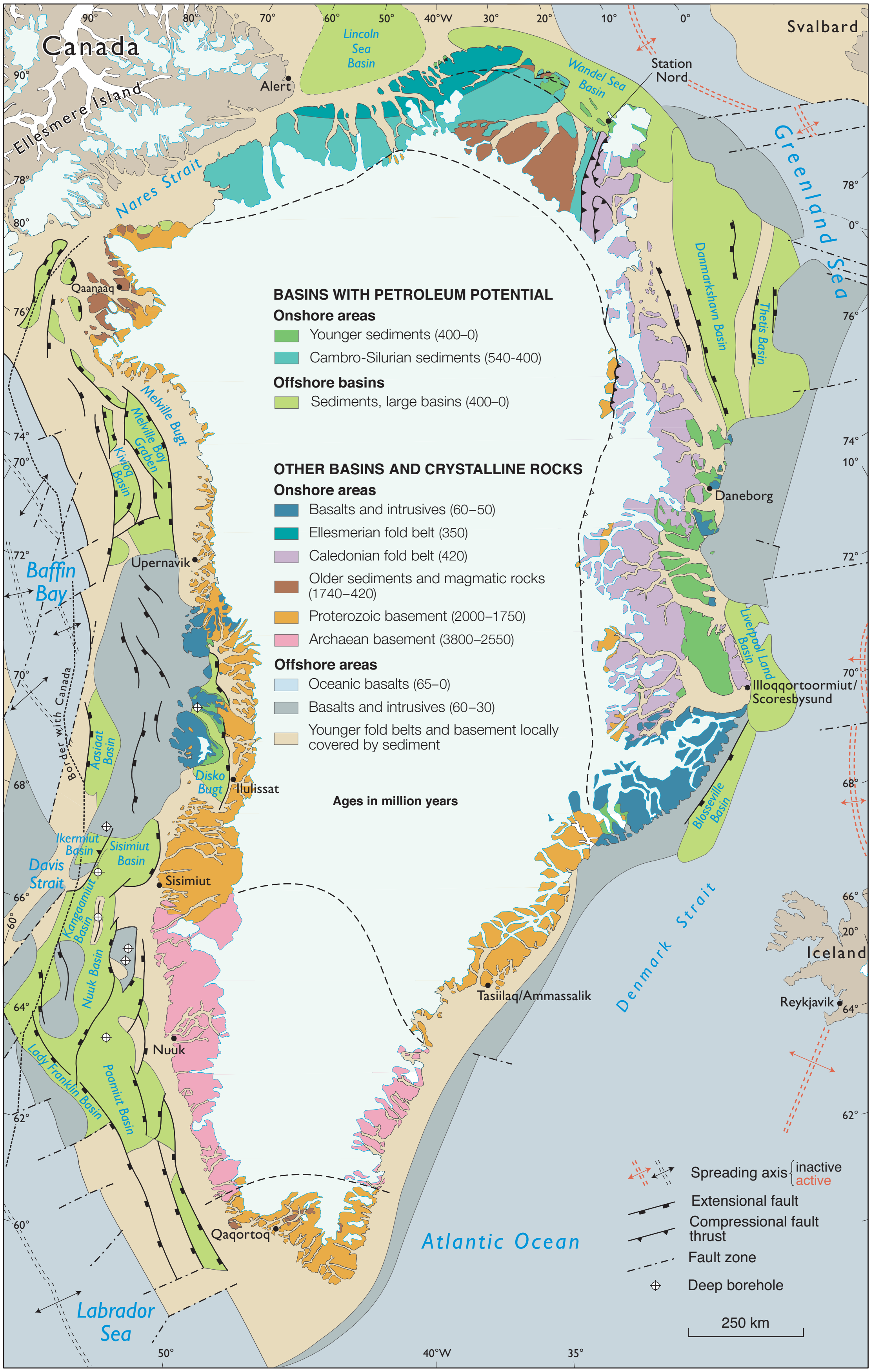
Fig. 56. Simplified map showing the onshore and offshore sedimentary basins with petroleum potential of Greenland. Distribution of crustal types can be seen in Fig. 48 A. Ellesmere Island (Canada), Iceland and Svalbard are shown as light brown: undifferentiated. Map based on Henriksen *et al.* (2000), Chalmers & Pulvertaft (2001) and Hamann *et al.* (2005).


Canada
Ellesmere Island
Nares Strait
Lincoln Sea Basin
Alert
Wandel Sea Basin
Station Nord
Svalbard
Greenland Sea
Danmarkshavn Basin
Thetis Basin
Qaanaaq
Melville Bugt
Melville Bay Graben
Kivioq Basin
Upernavik
Baffin Bay
Daneborg
Liverpool Land Basin
Illoqqortoormiut/ Scoresbysund
Aasiaat Basin
Border with Canada
Disko Bugt
Ilulissat
Blosseville Basin
Ikermiut Basin
Sisimiut Basin
Davis Strait
Sisimiut
Kangaamiut Basin
Nuuk Basin
Nuuk
Lady Franklin Basin
Paamiut Basin
Denmark Strait
Iceland
Reykjavik
Tasiilaq/Ammassalik
Qaqortoq
Atlantic Ocean
Labrador Sea
BASINS WITH PETROLEUM POTENTIAL
Onshore areas
Younger sediments (400–0)
Cambro-Silurian sediments (540-400)
Offshore basins
Sediments, large basins (400–0)
OTHER BASINS AND CRYSTALLINE ROCKS
Onshore areas
Basalts and intrusives (60–50)
Ellesmerian fold belt (350)
Caledonian fold belt (420)
Older sediments and magmatic rocks (1740–420)
Proterozoic basement (2000–1750)
Archaean basement (3800–2550)
Offshore areas
Oceanic basalts (65–0)
Basalts and intrusives (60–30)
Younger fold belts and basement locally covered by sediment
Ages in million years
Spreading axis inactive active
Extensional fault
Compressional fault thrust
Fault zone
Deep borehole
250 km
90° 80° 70° 60° 50° 40°W 30° 20° 10° 0°
78° 76° 74° 72° 70° 68° 66° 64° 62° 60°
35°

et al. 2000). To the north of the fault zone the pre-Paleocene sedimentary rocks are considered postmature with respect to petroleum generation and of limited economic interest. This is also likely to be the case on the nearby shelf in eastern North Greenland where a similar sedimentary succession is expected to be present. In contrast, onshore sedimentary rocks in the coastal region south of the fault zone are early mature to immature and therefore there might be a prospective zone in the offshore region along the expected continuation of the fault zone at *c.* 80°N (Fig. 37). Carboniferous and Permian reservoir rocks occur onshore, but source rocks have not been identified.

Late Palaeozoic – Mesozoic rift basins, North-East Greenland (72–76°N)

The main source rocks in these North-East Greenland basins are: (1) Upper Carboniferous type I–II (highly oil-prone – oil-prone) mudstones with very high generative potential but restricted lateral extent, (2) Upper Permian type II marine mudstones with wide areal extent and high generative potential, and (3) Upper Jurassic (Kimmeridgian) marine mudstones which are mainly gas-prone in onshore outcrops but are likely to be highly interesting oil-prone source rocks on the continental shelf to the east (Hamann *et al.* 2005).

Reservoir lithologies include Upper Carboniferous fluvial sandstones, Upper Permian carbonates, Upper Jurassic sandstones, and uppermost Jurassic – Lower Cretaceous syn-rift conglomerates and sandstones. The basins are partially fault bounded and tilted, and there are both stratigraphical and structural plays. From regional mapping and maturity considerations an area of about 6000 km^2 is considered to have potential prospectivity (Stemmerik *et al.* 1993), but at present there are no seismic data on which to base a more stringent evaluation. A more detailed understanding of the Jurassic biostratigraphy and depositional models with their potential for source and reservoir lithologies has been gained in recent years (Ineson & Surlyk 2003; Stemmerik & Stouge 2004).

Jameson Land Basin, central East Greenland (70°30′–72°N)

The Jameson Land Basin, which extends over an area of about 10 000 km^2, is covered by a 1798 km seismic survey, carried out by Atlantic Richfield Company (ARCO) in 1985–89, and consequently is better known than the basins to the north. The structural history of the basin is also different in that rifting began in the Devonian and ended in the mid-Permian; Late Permian – Mesozoic deposition in the basin was governed by thermal subsidence. In addition to the source rock intervals known to the north (Christiansen *et al.* 1992), an important lowermost Jurassic lacustrine type I–II source rock (highly oil-prone – oil-prone) occurs in Jameson Land (Dam & Christiansen 1990). Potential reservoirs are Upper Carboniferous (and possibly older) fluvial sandstones, Upper Permian carbonates, and Lower Jurassic deltaic sandstones. Apart from an Upper Carboniferous tilted fault block play, play types are stratigraphic. ARCO stopped their exploration activities at a time when the potential seemed restricted to a Permian play in northwest Jameson Land. Later reinterpretation by GEUS of the seismic data, supplemented by new field work, analyses of source and reservoir rocks and modelling also suggest a possible Lower Jurassic play in central Jameson Land (Dam *et al.* 1995). The main risk factor in the Jameson Land Basin is the effect of Palaeogene and Neogene uplift that amounts to 2 km or more (Mathiesen *et al.* 1995).

Cretaceous–Palaeogene basin, central West Greenland (69–72°N)

Source rocks in outcrop are mainly gas-prone, but the discovery of surface oil showings in vesicular basalts over a large area extending from northern Disko to south-east Svartenhuk Halvø, as well as the occurrence of oil in three of the five core holes drilled on western Nuussuaq in 1993–1995, prove that source rocks capable of generating oil occur in this region. A 3 km deep wild-cat well (GRO#3) was drilled in 1996 on south-western Nuussuaq by the small Canadian company grønArctic Energy Inc. The logs yield some indications of oil and gas, but without giving sufficient background for a continuation of the work (Christiansen *et al.* 1999). In the region as a whole, biomarkers in the oils indicate that five types of oil are present, with source rocks of Cretaceous–Paleocene age (Bojesen-Koefoed *et al.* 1999). Reservoirs in the area may be either Cretaceous deltaic sandstones or uppermost Cretaceous – lower Paleocene turbiditic sandstones.

Offshore basins

North-East Greenland shelf (75–80°N)

An area of more than 125 000 km^2 offshore North-East Greenland is believed to have considerable petroleum potential. This view is based on extrapolation from the adjacent onshore area, where oil source rocks are present at several levels, and also from the northern North Sea, West Norwegian shelf and south-west Barents Sea, areas which were contiguous with the North-East Greenland shelf before the opening of the Greenland–Norwegian Sea (Tsikalas *et al.* 2005). The KANUMAS reconnaissance seismic survey of the shelf area confirmed that thick sedimentary basins occur on the shelf comprising possible Devonian to Neogene deposits with a thickness of up to *c.* 13 km (Hamann *et al.* 2005). Interpretation of the gravity and seismic data furthermore indicates that Upper Carboniferous – Lower Permian salt deposits are widespread between *c.* 77–79°N (Stemmerik & Worsley 2005), as shown on the geological map and on Fig. 50A. The East Greenland succession on the shelf almost certainly includes Upper Jurassic and other source rocks. In the Danmarkshavn Basin (see Fig. 50B) the Jurassic sediments have been buried deeply enough to generate hydrocarbons. The succession is expected to include extensive, excellent quality source rocks, and trap structures include large-scale fault blocks (Hamann *et al.* 2005). Possible source rocks are correlatives of the following onshore occurrences: 1) organic-rich marine shales from the Upper Permian Ravnefjeld Formation considered to be good to excellent source rocks (Christiansen *et al.* 1993), 2) marine Jurassic shales of Kimmeridgian age known as the Hareelv Formation in central East Greenland (Christiansen *et al.* 1992, 1993; Surlyk 2003) and other equivalents to the world class Upper Jurassic source rocks known from the North Atlantic region (Christiansen *et al.* 1993; Hamann *et al.* 2005), 3) Upper Triassic – Lower Jurassic lacustrine organic-rich shales from the Kap Stewart Formation in central East Greenland and 4) other source rocks may be found in lacustrine deposits of Late Palaeozoic age and from equivalents of Middle Jurassic coal deposits found onshore North-East Greenland.

The Arctic Petroleum Appraisal of the United States Geological Survey has rated the North-East Greenland shelf region an area with major potential for oil and gas; most of the undiscovered resources are likely to be in the Danmarkshavn Basin (Gautier *et al.* 2009).

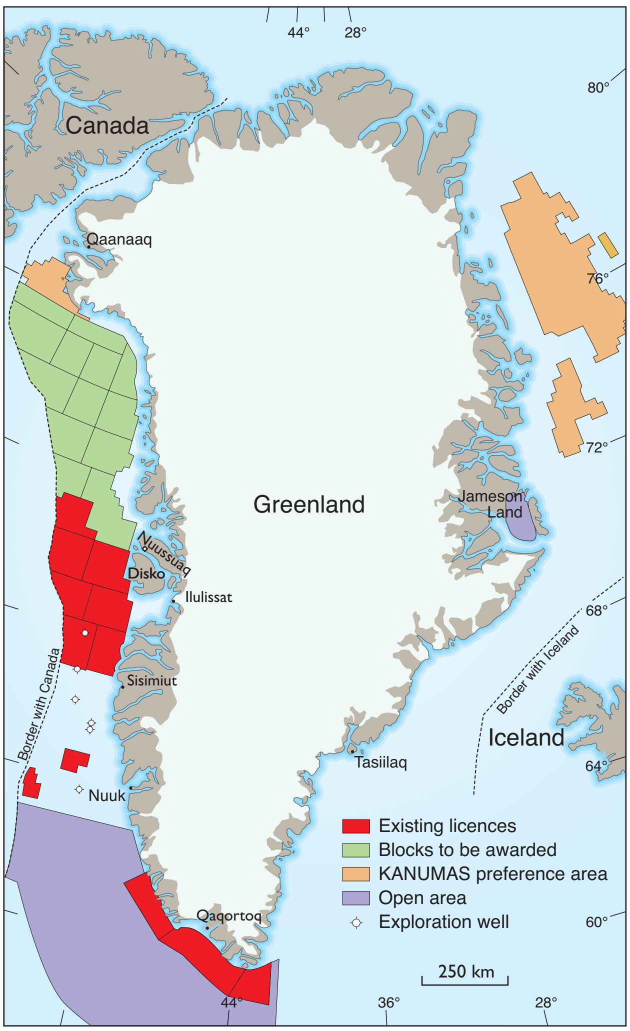


Fig. 57. Summary map of Greenland showing the state of concession agreements for hydrocarbon exploration at the end of 2008 (awarded licence areas shown in red). Licensing rounds were held in 2002, 2004, 2006 and 2007. Licences in two smaller areas west of Nuuk were awarded in 2003 and 2005, and a large region west of Disko was awarded in seven block areas in 2007 to four groups of oil companies. The green areas are blocks to be awarded in connection with a licence call round in 2010. The violet areas are covered by a so-called 'open-door' policy where oil companies can apply for concessions at any time. The yellow areas show where a group of companies (the KANUMAS companies) have preferential positions, but where exploration is not expected to take place in the near future. From Bureau of Minerals and Petroleum, Nuuk.

Liverpool Land Basin, central East Greenland (69°30′–72°N)

Up to 6 km of Cenozoic sedimentary rocks unconformably overlie block-faulted Upper Palaeozoic – Mesozoic sedimentary rocks in the inner (landward) part of the Liverpool Land Basin. In the outer part of this basin oceanic crust occurs beneath a thick wedge of Neogene and Plio–Pleistocene sedimentary rocks (H.C. Larsen 1990; Hamann *et al.* 2005). Source rocks are likely to occur at several levels in the pre-Cenozoic sedimentary rocks, but are probably postmature. Nothing can be deduced about the nature of mudstones in the Palaeogene. Only a few weak structures have been observed in the Cenozoic section, and the best traps are likely to be stratigraphic.

Blosseville Kyst Basin, East Greenland (67–69°30′N)

Only the post-basalt Cenozoic sedimentary rocks in the Blosseville Kyst Basin are considered likely to have any potential for petroleum, since any sedimentary rocks underlying the basalts will be thermally postmature. The outermost sedimentary rocks overlie oceanic crust. Trap structures occur where the sediments drape buried volcanic edifices, and it is likely that there are also stratigraphic traps. Submarine fan sandstones fed from the land areas to the north and north-west are likely to be the best potential reservoirs in the area. Source rocks are most likely to occur in the Eocene – Lower Oligocene sedimentary rocks, which were deposited at a time when the area had only limited connections with the early Atlantic Ocean, a factor that would favour oxygen-deficient conditions (H.C. Larsen 1985).

West Greenland

Southern West Greenland was the first offshore area where companies were awarded exclusive licenses for hydrocarbon exploration. About 37 000 km of seismic data were acquired in the shallower parts of the area (water depths <500 m) in the early 1970s, and five wells were drilled. One well (Kangâmiut-1, *c.* 66°N) encountered wet gas (Chalmers *et al.* 1995), but the others were dry. With hindsight it can be seen that only the Kangâmiut-1 well tested a viable structure (Chalmers & Pulvertaft 1993). In the 1990s exploration was resumed in the region, and more than 23 000 km of additional seismic data were acquired, extending knowledge of the geology into deeper water areas which appear to be the most prospective. A sixth well (Qulleq-1, west of Nuuk) was drilled by Statoil in 2000; this yielded important new stratigraphic information but was dry (Christiansen *et al.* 2001). In the last ten years, interest for oil and gas exploration in West Greenland has been driven by the documentation of live petroleum systems onshore between 70°12′ and 71°29′N (Bojesen-Koefoed *et al.* 1999), the identification of large sedimentary basins and structures offshore, and high oil prices. A number of licensing rounds have been held with the result that at present (2009) 11 blocks covering more than 125 000 km^2 have been awarded to company consortia (Fig. 57; F.G. Christiansen, personal communication 2009). In some areas outside the licensing areas an 'open door' policy has been introduced in order to encourage data acquisition while accepting higher risk. The result of the last ten years' exploration activity is that there is now a modern regional data coverage of the region between *c.* 62° and 76°N, including more than 50 000 km non-exclusive seismic data and also airborne magnetic and gravity data covering very large areas.

South and South-West Greenland (*c.* 57–62°N)

The shelf south of 62°N is relatively narrow with a steep, locally unstable, slope towards the ocean floor in the Labrador Sea. Seismic data coverage is sparse, but new data acquisition in the recently awarded licence blocks (Fig. 57), combined with investigations within the scope of the Danish Continental Shelf Programme, will provide a greatly improved data base in coming years.

With the limited existing data base, assessment of the potential for oil and gas and possible play types is very speculative. However, there are indications of Mesozoic rifting in the few available seismic lines, and a 141 Ma old onshore coast-parallel dyke swarm bears witness of the initiation of rifting in the earliest Cretaceous (Watt 1969; L.M. Larsen *et al.* 2009).

Southern West Greenland (*c.* 62–68°N)

This region is the site of extensive and deep basins with thick successions of Mesozoic–Cenozoic sediments. Knowledge of the region is based not only on extensive seismic, magnetic and gravity surveys and seabed sampling but also on the data obtained from five wells drilled in the late 1970s:

Nukik-1, 65°32′N, 54°46′W
Nukik-2, 65°38′N, 54°46′W
Kangâmiut-1, 66°09′N, 56°11′W
Ikermiut-1, 66°56′N, 56°35′W
Hellefisk-1, 67°53′N, 56°44′W

and a sixth well drilled in 2000:

Qulleq-1,63°49′N, 57°27′W

No well penetrated the deepest sediments in the region; the oldest sediments encountered being those at the base of the Qulleq-1 well which are of Santonian age (Christiansen *et al.* 2001). In consequence interpretation of the age and lithologies of the deepest sediments is based largely on analogies with the Labrador shelf where many more wells have been drilled.

A prerequisite for petroleum prospectivity is the presence of a good source rock. Although none of the wells sampled a good source rock, the live oil showings in vuggy Paleocene basalts on the Nuussuaq peninsula prove that such rocks exist in central West Greenland (Christiansen *et al.* 1996; Bojesen-Koefoed *et al.* 1999). The source rocks most likely to occur offshore southern West Greenland are 1) lacustrine mudstones and coals in the Lower Cretaceous syn-rift Kitsissut and Appat sequences, 2) Cenomanian–Turonian organic-rich mudstones at or near the base of the post-rift Kangeq sequence. These are correlatives of the marine Cenomanian–Turonian source rock interpreted as having given rise to the Itilli oil type, one of the five oil types occurring in the live oil showings on Nuussuaq (Bojesen-Koefoed *et al.* 1999), 3) Paleocene deltaic mudstones, correlatives of the Cretaceous–Paleocene source rocks in central West Greenland from which three of the five oil types in live showings was derived (Bojesen-Koefoed *et al.* 1999) and 4) mudstones deposited distally relative to prograding Palaeogene sequences that were described by Dalhoff *et al.* (2003)

The main play type involves block-faulted and tilted reservoir sandstones of the Kitsissut and Appat sequences with oil (and/or gas) derived from Cenomanian–Turonian source rocks and sealed by Cenomanian–Campanian mudstones of the Kangeq Formation or Paleocene mudstones that drape the fault blocks (Chalmers *et al.* 1993). Anticlinal structures generated locally by transpression along the Ungava Fracture Zone (Fig. 48B) provide another potential for traps. New interpretations of the Paleocene–mid-Eocene seismic sequences combined with stratigraphic correlations with well data have shown that within the Palaeogene succession there are sandy basin-floor fans and turbidite channel complexes encased in basin mudstones that could act as stratigraphic traps (Dalhoff *et al.* 2003).

From the Kangâmiut-1 well wet gas (up to C5) was reported by Chalmers *et al.* (1995), but the drill stem test produced only water from the drilling mud, not formation fluid (Skaarup 2007). Thus the possibility remains that a significant, untested, hydrocarbon field exists in the Kangâmiut structure.

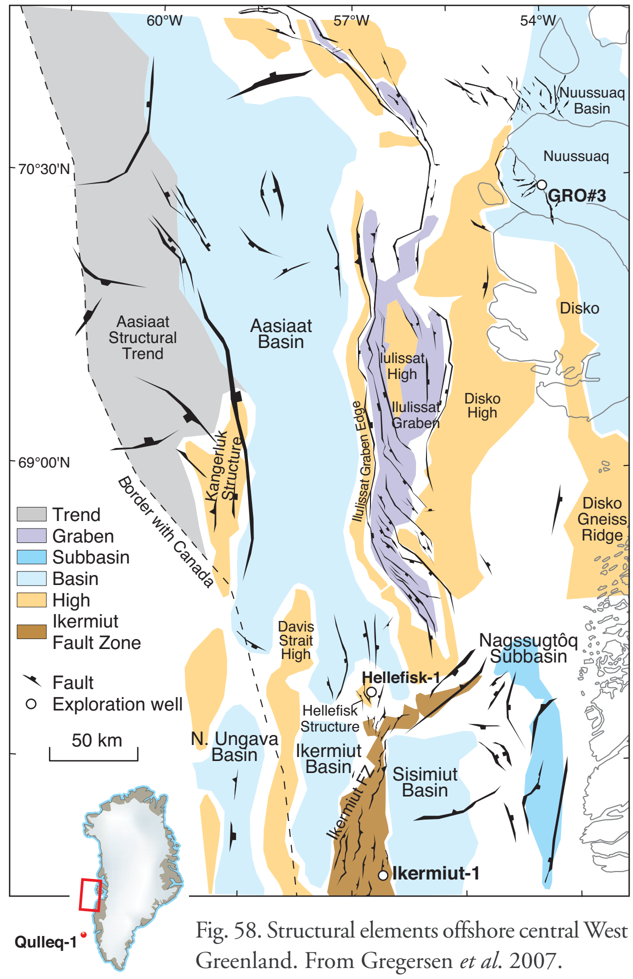


Fig. 58. Structural elements offshore central West Greenland. From Gregersen *et al.* 2007.

Central West Greenland (*c.* 68–73°N)

In this region Palaeogene basalts are widespread which hampers interpretation of Early Paleocene and older sediments. However, since the 1:2 500 000 map was printed in 1995, a wealth of new data has been acquired in this region, allowing greatly improved interpretations and the compilation of an overview map showing the main structural elements in the area (Fig. 58; Gregersen *et al.* 2007). Interest in acquiring new data in this area was stimulated by the discovery of live oil seeps in the adjacent onshore area (Christiansen *et al.* 1996; Bojesen-Koefoed *et al.* 1999). Five oil types have been identified in these seeps, three likely to have been derived from Cretaceous and Paleocene prodelta source rocks and a fourth, the Itilli oil type, from dysoxic to anoxic marine shales, probably of Cenomanian–Turonian or older age. All these source rocks can be expected to occur in the offshore region.

The new data have clearly revealed the existence of a number of deep basins with Mesozoic and Cenozoic sedimentary successions and also several large structures and closures that could provide traps (Gregersen & Bidstrup 2008). The structures were initiated during Early to mid-Cretaceous rifting. Syn-rift sediments deposited during this phase are likely to be sandstones with potential reservoir properties. During the subsequent Late Cretaceous quiet phase, a thick basinal mudstone unit was deposited, the equivalent of the Kangeq sequence farther south. This may well contain source rocks that correlate with the source of the Itilli oil type. Renewed tectonic activity in the latest Cretaceous – Early Paleocene caused uplift and formation of large structures, some of which could provide traps for hydrocarbons. Prodelta Paleocene source rocks equivalent to the suggested sources of three of the oil types identified in onshore seeps could be present. Late Paleocene – Eocene transpression related to the Ungava Fracture Zone (Fig. 49B) led to the formation of anticlinal structures that have a potential as traps. Finally, during the Eocene and especially during the late Miocene and Pliocene, the offshore basins subsided rapidly, and large sedimentary wedges prograded towards the west and south.

Direct hydrocarbon indicators (DHIs) such as bright spots in some seismic lines are encouraging signs that this segment of Greenland waters hosts live petroleum systems (Gregersen *et al.* 2007).

North-West Greenland (73–77°N)

The region is the site of some of the largest structures and deepest rift basins anywhere offshore West Greenland (Fig. 53; Whittaker *et al.* 1997). This was first shown by the results of the KANUMAS reconnaissance seismic survey carried out in 1992; later public domain surveys carried out in north-east Baffin Bay in 2000 have provided a more detailed picture of this part of the rift system (Gregersen 2008). In addition, recent gravity and magnetic surveys have supplemented knowledge of the deep basins and structural highs.

No wells have been drilled in this region, so interpretation of the age and character of the sedimentary fill of the basins is based on analogies with onshore areas in north-east Canada (Bylot Island) and central West Greenland (the Nuussuaq Basin), and with the Labrador Sea. The bulk of the up to 12 km thick sedimentary fill is likely to be of Cretaceous–Neogene age. Rifting probably started in the Early Cretaceous (Whittaker *et al.* 1997), and sandstones deposited in the early syn-rift stage could be good reservoirs for hydrocarbons. During subsequent thermal subsidence a transgressive unit was deposited that is analogous to the latest Cenomanian–Turonian Kanguk Formation in the Canadian Arctic Islands. Near the base of this formation there are oil-prone, marine shale source rocks which, however, in this area are thermally immature (Núñez-Betulu 1993). If the analogy to the Kanguk Formation holds, a similar marine source rock can be expected near the base of the transgressive unit in north-east Baffin Bay. Support for this suggestion has been obtained by submitting samples of the source rock shales in the Kanguk Formation to hydrous pyrolysis. This yielded bitumen that shares a number of important characteristics with the Itilli oil type occurring in vuggy basalts and fractures onshore central West Greenland (Bojesen-Koefoed *et al.* 2004). The Itilli oil type was generated from marine source rocks of presumably Cenomanian–Turonian age (Bojesen-Koefoed *et al.* 1999). Marine source rocks usually have a wide areal distribution, so this source rock may well occur offshore north of 73°N and even tie up physically with the Kanguk Formation source rocks. The mudstones of the transgressive unit could also provide a seal to hydrocarbons trapped in the underlying sandstones in tilted fault blocks and anticlinal inversion structures.

Three of the other oil types described by Bojesen-Koefoed *et al.* (1999) were derived from Cretaceous and Paleocene prodelta source rocks. Similar source rocks could also occur locally in north-east Baffin Bay. Hydrocarbons generated from these source rocks could be trapped in the cores of anticlines formed during inversion and transpression, particularly in the northern part of the area. Reservoir could be provided by depositional systems such as turbidite fan lobes shed off the inversion highs (Whittaker *et al.* 1997).

Western North Greenland (north of 80°N)

Lincoln Sea (Lincoln Hav on the map) north of North Greenland and Ellesmere Island (Canada) contains an extensive shelf region (almost 500 × 200 km) with water depths below 500 m. The sea is normally covered by thick multi-year sea ice, and our present knowledge of the subsurface geology stems from two recent seismic refraction profiles (Dahl-Jensen *et al.* 2006) and earlier magnetic and gravity data. Interpretation of the geophysical data suggests that the basin underlying the Lincoln Sea comprises a sedimentary sequence with a thickness of more than10 km.

Based on modelling from the seismic data it is assumed that the sedimentary succession in the Lincoln Sea Basin is comparable with the deposits in the Mesozoic–Cenozoic Sverdrup Basin of Arctic Canada. By comparison with known petroleum indications in the Sverdrup Basin it is inferred that strata in the Lincoln Sea Basin may contain source rocks of marine shales of mid-Triassic – latest Jurassic and also marine type 2 source rocks of Upper Jurassic age (K. Sørensen, personal communication 2009). Mesozoic reservoir rocks may be widespread and intervening shales could form potential seals.

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