Fig. 53. Sorte Engel (Black Angel), the locality which hosted the Maarmorilik lead-zinc deposit at *c.* 71°N in central West Greenland. The two small black spots just beneath the left wing of the angel-like figure (marked by the arrow) are cable car entrances to the mine *c.* 500 m a.s.l. Photo: B. Thomassen.

was mined during the period 1924–1972. A total of about 570 000 tons of coal was shipped before the mine was closed because it was unprofitable (Schiener 1976). On nearby Nuussuaq, more than 180 million tons 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 magmatic rocks

The 55 Ma old Skaergaard layered gabbro intrusion [57] (Fig. 52, locality 9) at Kangerlussuaq, north-east of Ammassalik in southern East Greenland, hosts a major deposit of palladium, platinum and gold (Bird *et al.* 1991). Initial diamond drilling has indicated a resource of more than 43 million tons grading 2.4 ppm Au and minor platinum group elements. Similar mineralisation is known in other nearby intrusions.

Lead-zinc-bearing quartz veins (Fig. 52, locality 10) are hosted in Lower Permian sediments near Mestersvig in East Greenland. One of these, the Blyklippen deposit, was mined in the period 1956–1962. After production of 545 000 tons ore grading 9.3% Pb and 9.9% Zn the deposit was exhausted (Harpøth *et al.* 1986).

A large porphyry-molybdenum deposit of Miocene age occurs at Malmbjerg (Fig. 52, locality 11) south of Mestersvig, East Greenland, hosted in an intrusive complex [53]. Ore resource calculations based on 22 000 m diamond drilling indicate a tonnage of 150 million tons grading 0.23% MoS_2 and 0.02% WO_3 (Harpøth *et al.* 1986). Other less well investigated porphyry-molybdenum occurrences exist in the East Greenland Tertiary 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. 54). No proven commercial reserves of oil or gas have been found to date (1999), but so far only six exploration wells have been drilled, five offshore southern West Greenland between latitudes 65°30′ and 68°N, and one onshore, on Nuussuaq at 70°28′N in central West Greenland (Pulvertaft 1997). The untested areas of Greenland are still very large. A brief summary of the petroleum-geological features of the main sedimentary basins is given below.

Onshore basins

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

The Franklinian Basin of North Greenland is the eastern continuation of the Cambrian–Devonian Franklinian Basin of the Canadian Arctic Islands. Good type II (oil-prone) 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 (e.g. Stemmerik *et al.* 1997). 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 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 mudstones which are gas-prone in onshore outcrops but are likely to be oil-prone on the continental shelf to the east.

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.

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, has been investigated by a 1798 km seismic survey carried out by Atlantic Richfield Company (ARCO) in 1985–89, and hence 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. The main risk factor in the Jameson Land Basin is a consequence of a Tertiary uplift of 2 km or more (Mathiesen *et al.* 1995).

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

Source rocks in outcrop are mainly gas-prone, but the recent discovery of surface oil showings in vesicular basalts over an area extending from northern Disko to south-east Svartenhuk Halvø, and the occurrence of oil in three of the five slim core wells drilled in western Nuussuaq in 1993–1995, proves that source rocks capable of generating oil occur in this region. 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

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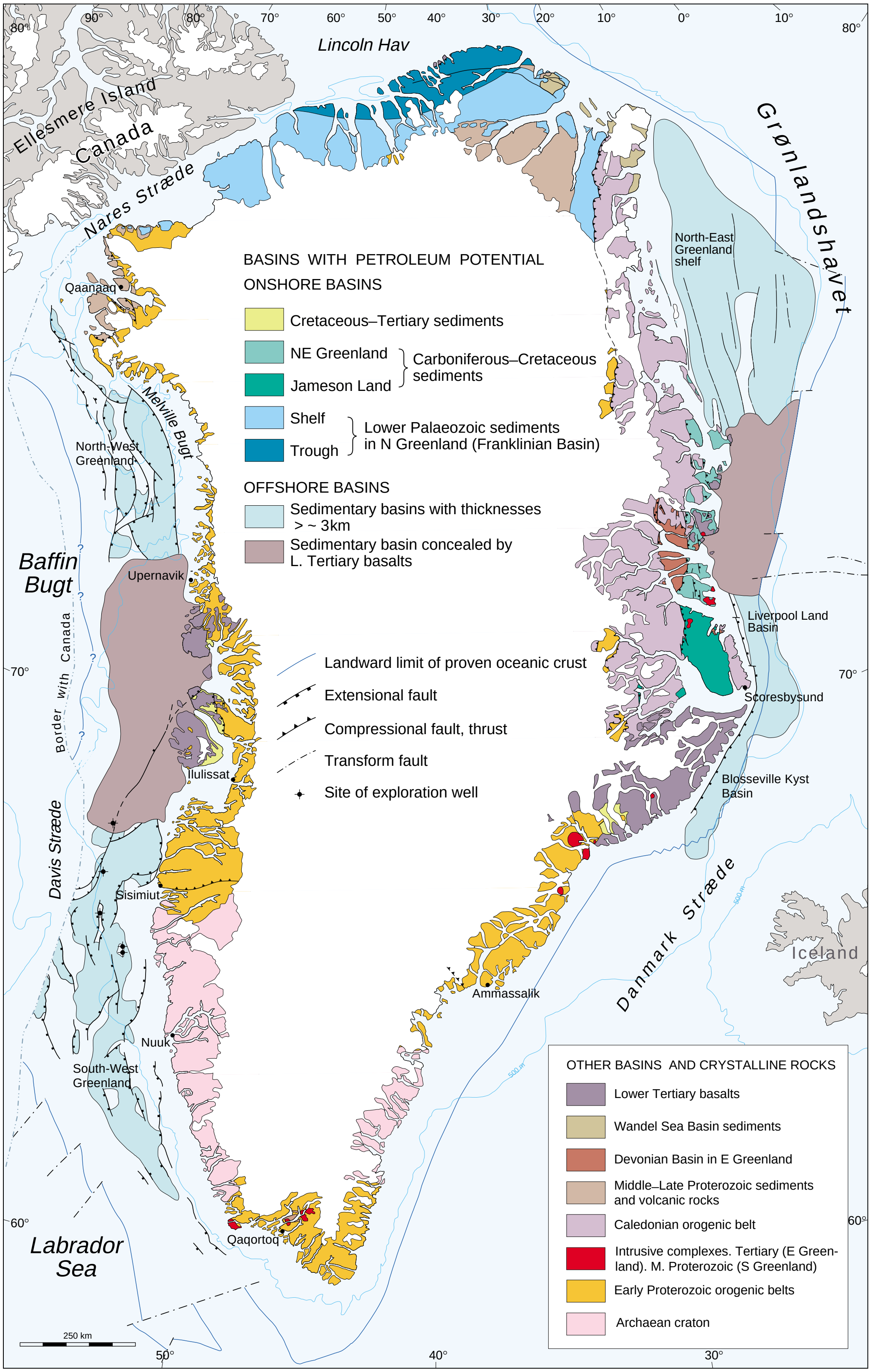
Fig. 54. Onshore and offshore sedimentary basins of Greenland. Ellesmere Island (Canada) and Iceland are shown as grey: undifferentiated. The bathymetric contour shown is at 500 m.



BASINS WITH PETROLEUM POTENTIAL
ONSHORE BASINS
Cretaceous–Tertiary sediments
NE Greenland
Jameson Land
Carboniferous–Cretaceous sediments
Shelf
Trough
Lower Palaeozoic sediments in N Greenland (Franklinian Basin)
OFFSHORE BASINS
Sedimentary basins with thicknesses > ~ 3km
Sedimentary basin concealed by L. Tertiary basalts
Landward limit of proven oceanic crust
Extensional fault
Compressional fault, thrust
Transform fault
Site of exploration well
OTHER BASINS AND CRYSTALLINE ROCKS
Lower Tertiary basalts
Wandel Sea Basin sediments
Devonian Basin in E Greenland
Middle–Late Proterozoic sediments and volcanic rocks
Caledonian orogenic belt
Intrusive complexes. Tertiary (E Greenland). M. Proterozoic (S Greenland)
Early Proterozoic orogenic belts
Archaean craton
Lincoln Hav
Ellesmere Island
Canada
Nares Stræde
Grønlandshavet
Qaanaaq
Melville Bugt
North-West Greenland
North-East Greenland shelf
Baffin Bugt
Upernavik
Border with Canada
Liverpool Land Basin
Scoresbysund
Ilulissat
Blosseville Kyst Basin
Davis Stræde
Sisimiut
Danmark Stræde
Iceland
Ammassalik
Nuuk
South-West Greenland
Labrador Sea
Qaqortoq
250 km
80°
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
10°
80°
70°
70°
60°
60°
50°
40°
30°

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. The KANUMAS reconnaissance seismic survey of the shelf area has confirmed predictions that thick sedimentary basins occur in the shelf, and indicate furthermore that salt deposits of presumed Late Palaeozoic age are widespread.

Liverpool Land Basin, central East Greenland (70°–72°N)

Up to 6 km of Tertiary sediments unconformably overlie block-faulted Upper Palaeozoic – Mesozoic sediments in the inner (landward) part of the Liverpool Land Basin and oceanic crust in the outer part (Larsen 1990). Source rocks are likely to occur at several levels in the pre-Tertiary sediments, but are probably overmature. Nothing can be deduced about the nature of mudstones in the Tertiary. Structures in the Tertiary section are weak, and the best traps are likely to be stratigraphic.

Blosseville Kyst Basin, East Greenland (67°–70°N)

Only the post-basalt Tertiary sediments in the Blosseville Kyst Basin are considered likely to have any potential for petroleum, since any sediments underlying the basalts will be overmature. The outermost sediments overlie oceanic crust. Trap structures occur where the sediments drape buried volcanic edifices, and there is a likelihood 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 sediments, 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 (Larsen 1985).

Southern West Greenland (c. 63°–68°N)

Southern West Greenland is the only offshore area where industry has held exclusive licences for hydrocarbon exploration. About 37 000 km of seismic data were acquired in the shallower parts of the area (water depths < 500 m) during exploration in the 1970s, and five wells were drilled. One well (Kangâmiut-1, 66°09′N) struck wet gas, but the others were dry. With hindsight it can be seen that these wells did not test viable trap structures (Chalmers & Pulvertaft 1993). Since 1990 more than 23 000 km of new seismic data have been acquired, mainly by the Survey, extending knowledge of the area into deeper water areas which are apparently the most prospective. Oil source rocks are interpreted as most likely to occur at the base of a widespread Upper Cretaceous (Cenomanian/Turonian – Campanian) mudstone, a level not penetrated by any of the wells. Another possible source is in the Paleocene; much of the oil in the live oil showings on the Nuussuaq peninsula is believed to have been derived from lower Paleocene source rocks. Reservoir is likely to be provided by syn-rift Lower Cretaceous sandstones and by both fan and deltaic Paleocene sandstones.

The main play type involves block-faulted and tilted Lower – mid-Cretaceous sandstone reservoirs sourced by Cenomanian/Turonian mudstones and sealed by both Cenomanian/Turonian mudstones and Paleocene mudstones which drape the fault blocks (Chalmers *et al.* 1993). Direct hydrocarbon indicators in the form of flat-spots have been observed in this type of structure in seismic data acquired south-west of Nuuk/Godthåb (Bate *et al.* 1995). If these flat-spots represent gas–liquid contacts, very large reserves of gas are present in this area. Compressional structures west of the Ikermiut-1 well (67°N) may also provide good traps, and a major delta has been identified which could provide stratigraphic traps (Chalmers *et al.* 1995).

North-West Greenland (73°–77°N)

The KANUMAS reconnaissance seismic survey carried out in 1992 in the Melville Bugt area has shown that there are both large sedimentary basins and also large potential trap structures, both tilted fault blocks and anticlines generated during inversion. The bulk of the sedimentary fill is likely to be Cretaceous–Recent in age, and older sediments can be expected in places. The live oil showings on the Nuussuaq peninsula and the oil seep reported from the Baffin Island shelf off Scott Inlet (71°23′N; MacLean *et al.* 1981) point to the likelihood that oil source rocks are present in the area. Reservoir sandstones are likely to be present throughout the syn-rift, presumed Cretaceous, sections.

Sedimentary basins concealed by volcanic rocks

In two areas, one off East Greenland between latitudes 72° and 75°N and the other between 68° and 73°N off West Greenland, there are extensive Tertiary volcanic rocks which are known in places to overlie thick sedimentary successions. It is difficult on the basis of existing seismic data to learn much about these underlying sediments, but extrapolation from neighbouring onshore areas suggests that oil source rocks are present.

Seismic data acquired west of Disko in 1995 have revealed an extensive direct hydrocarbon indicator in the form of a 'bright spot' with a strong AVO (Amplitute Versus Offset) anomaly, which occurs in the sediments *above* the basalts in this area. If hydrocarbons are indeed present here, they could either have been generated below the basalts and have migrated through the fractured lavas into their present position (Skaarup & Chalmers 1998) or, alternatively, be derived from a source rock in the presumably upper Paleocene – lower Eocene sediments above the lavas and down-dip from the bright spot (see Fig. 50).

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