The Cambrian Henson Gletscher Formation: a mature to postmature hydrocarbon source rock sequence from North Greenland

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During the 1985 field season the Cambrian Henson Gletscher Formation in central North Greenland was studied in detail with the aim of evaluating its potential as a hydrocarbon source rock. The formation contains organic rich shale and carbonate mudstone which are considered to be potential source rocks. These are sedimentologically coupled with a sequence of sandstones and coarse carbonates which might be potential reservoir rocks or migration conduits. Most of the rocks exposed on the surface are, however, thermally mature to postmature with respect to hydrocarbon generation, leaving only few chances of finding trapped oil in the subsurface of the area studied in detail.

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The main purpose of project 'Nordolie' is to study the presence and distribution of potential hydrocarbon source rocks in central and western North Greenland and to evaluate patterns of thermal maturity (Christiansen & Rolle, 1985). Preliminary organic, geochemical and palynofacies analyses on samples collected in the 1984 reconnaissance field season showed that some intervals in the Cambrian shelf sequence and in the Silurian slope sequence can be considered as potential source rocks (Christiansen *et al.*, 1985). Cambrian and Ordovician trough sequences are also rich in organic matter but with respect to hydrocarbon generation they are thermally postmature throughout the region. Consequently, during 1985 attention was concentrated on the Cambrian Henson Gletscher Formation (Ineson & Peel, in press) and the Silurian Lafayette Bugt Formation and Wulff Land Formation (Hurst & Surlyk, 1982), combining detailed field work and shallow core drilling (Christiansen *et al.*, 1986). Field work was carried out from June to August 1985 by a team of two geologists, a drilling team of three technicians (J. Boserup, A. Clausen, J. Bojesen-Koefoed) and a drill site geologist. Thirteen holes with a total length of 345 m were drilled and source rocks were

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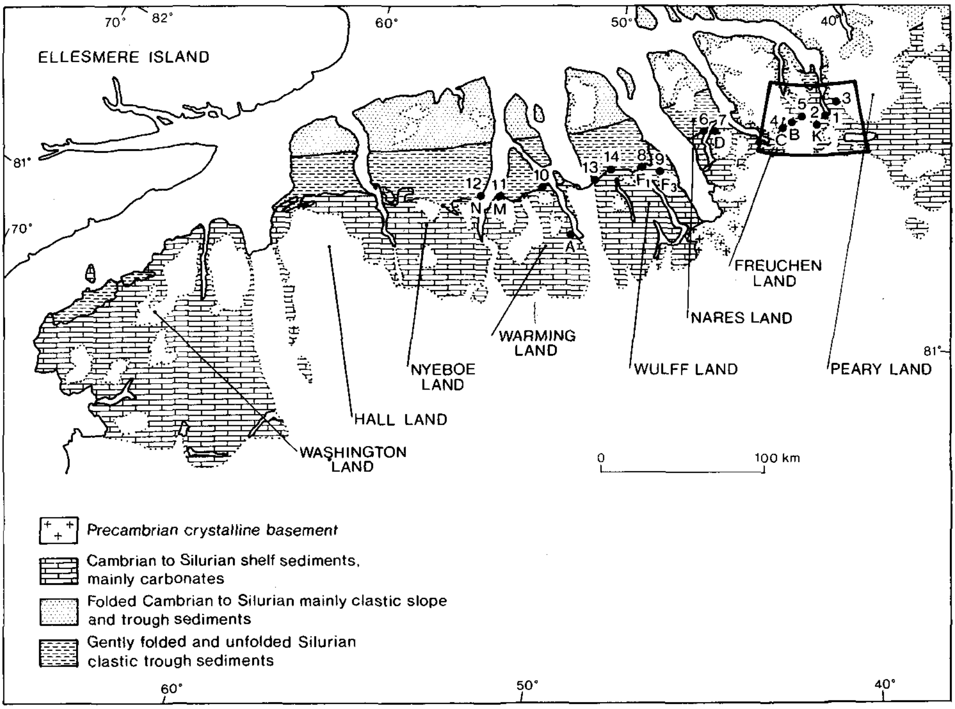

Fig. 1. Camps (numbers) and drill sites (letters) during the 1985 field season. The map is modified from Dawes (1976).

studied from 14 field camps (fig. 1, see Christiansen *et al.* (1986) for further details of the programme).

The present paper concentrates on a brief description of the sedimentary facies and evaluation of the thermal maturity of the Cambrian Henson Gletscher Formation using screening methods such as LECO, Rock Eval, and Thermal Alteration Index (TAI) determinations.

Regional setting, stratigraphy and studied sections

The Lower Palaeozoic of North Greenland was deposited within a series of east–west striking facies belts (fig. 1) which are exposed over a length of 800 km.

Within the studied region, Lower Palaeozoic shelf sediments fringe Precambrian crystalline basement which only outcrops close to the Inland Ice in south-eastern Wulff Land (fig. 1). At least 3 km of mainly shallow marine carbonates are present, forming a 100 km wide belt immediately north of the basement areas. Lower Palaeozoic deep-water basin sediments outcrop north of the shelf sequence and consist of up to 8 km of sandstone turbidites with minor shales and carbonate conglomerates. The boundary between the shelf and the rapidly subsiding deep-water basin was apparently structurally controlled during much of the Early Palaeozoic (Hurst & Surlyk, 1984; Surlyk & Hurst, 1984). During the Early Cambrian, this shelf margin was located just offshore from the northern coast of Freuchen Land, Wulff Land and Nyeboe Land, but during the Ordovician and Silurian it back-stepped to a position extending from central Freuchen Land to northernmost Hall Land. Subsequently, at the end of the Early Silurian, deep-water basin deposition was extended even farther southwards, almost completely inundating the shelf sequences as currently known.

The deep-water sediments were folded during the Ellesmerian Orogeny in the Late Devonian or Early Carboniferous (Dawes, 1976; Higgins *et al.*, 1982); this episode probably also affected the southern shelf sediments thermally. Late faulting and dyke intrusion occurred especially in the northern part of North Greenland during Late Cretaceous to Early Tertiary time (Soper *et al.*, 1982), but north–south striking dykes have also been observed in the J. P. Koch Fjord area.

The Cambrian shelf sequence, which is the main subject of the present paper, is exposed in the southern part of the Peary Land to Warming Land region. The Lower Cambrian dolomites of the Portfjeld Formation (Jepsen, 1971; O'Connor, 1979) and overlying shales and sandstones of the Buen Formation (Jepsen, 1971; Christie & Peel, 1977) occur throughout this area. The overlying Lower, Middle and Upper Cambrian carbonates are lithostratigraphically divided into an eastern and a western area with a borderline at Nordenskiöld Fjord (fig. 3) between the land area south of Nares Land and Freuchen Land. To the west, strata are referred to the Ryder Gletscher Group (Peel & Wright, 1985; Ineson & Peel, 1987) whereas the eastern sequence is assigned to the Brønlund Fjord Group and the Tavsens Iskappe Group (Ineson & Peel, 1980, in press) (fig. 2).

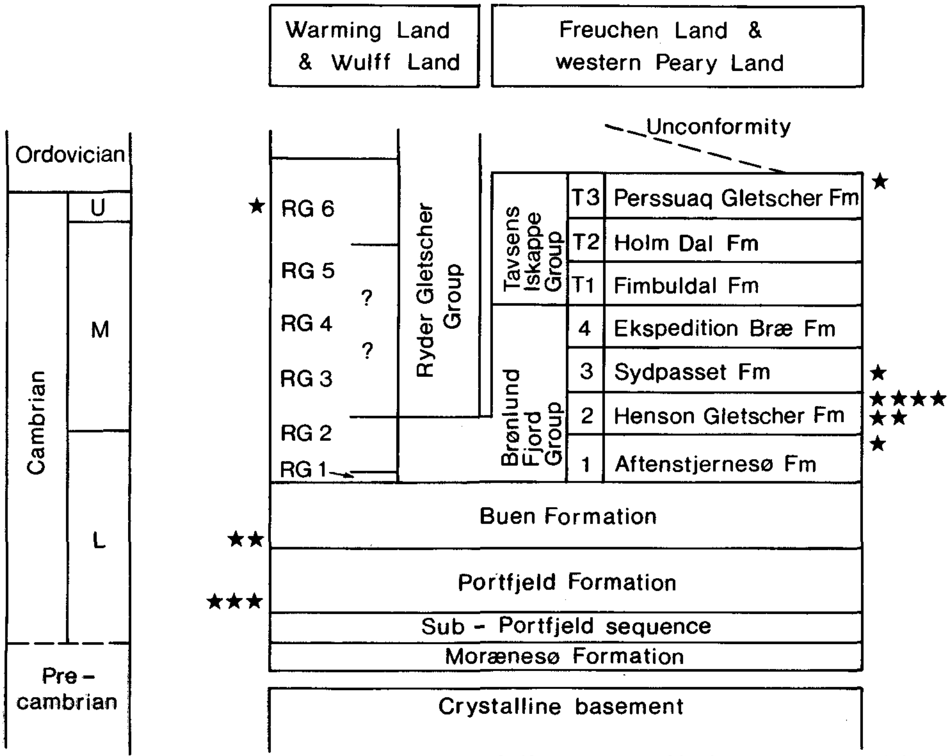

Fig. 2. Stratigraphic nomenclature of the Cambrian shelf sequence used in the present paper. Adopted from Henriksen (1985) and Peel & Wright (1985) with modification from Ineson & Peel (1987). The stars indicate the tentatively estimated abundance of migrated hydrocarbons.

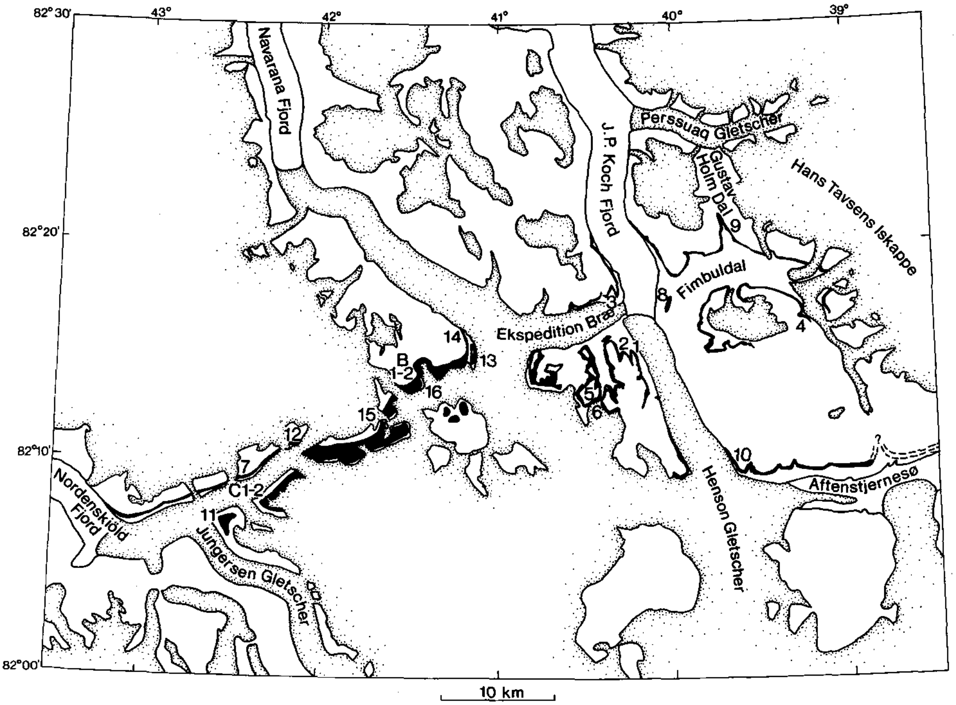

Fig. 3. Detailed map showing exposures of the Henson Gletscher Formation and the measured 1985 sections (numbers) and drill sites (letters). See fig. 1 for location.

The Henson Gletscher Formation is of particular interest from a petroleum geological point of view since it contains both potential source and reservoir rocks. The dark laminated carbonate mudstone, which mainly occurs in the lower part of the formation, is considered as a good source rock, whereas the coarser dark petroleum-stinking sandstones and carbonates in the central and upper part of the formation are likely to be good reservoir rocks or migration conduits. The Portfjeld, Buen, Aftenstjernesø and Sydpasset Formations, the latter two enclosing the Henson Gletscher Formation, display signs of migrated hydrocarbons, either as oil-impregnated sandstones or as asphalt and bitumen filled veins. The upper part of the Tavsens Iskappe Group, just below the sub-Wandel Valley Formation unconformity (Peel, 1979), and formation RG6 in the Ryder Gletscher Group also occasionally contain bitumen (fig. 2).

In the studied area, the Henson Gletscher Formation only outcrops in the southern part of Freuchen Land and in the south-western part of Peary Land (figs 1 and 3). Further east, in Peary Land, the formation can be traced for about 100 km. The formation outcrop within the studied area has a strike of approximately 60° with a shallow northerly dip (1.5° to 6°).The formation is recessive compared to the enclosing cliff-forming formations (figs 4 and

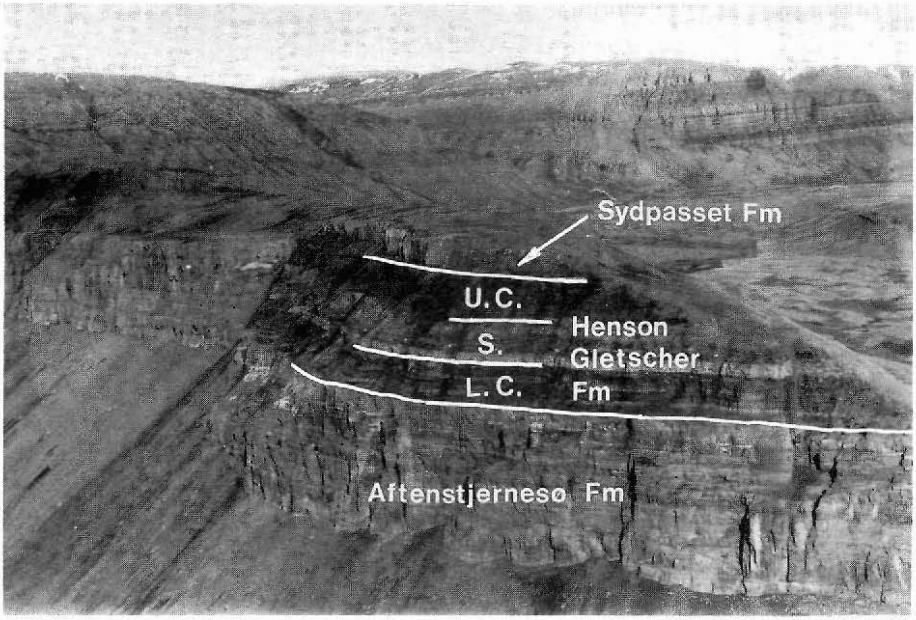

Fig. 4. Typical exposure of the Henson Gletscher Formation between the cliff-forming Aftenstjernesø Formation and Sydpasset Formation. Section 1985–8. L. C. = lower carbonate unit, S. = siliciclastic unit, U. C. = upper carbonate unit. Henson Gletscher Formation is 39 m thick.

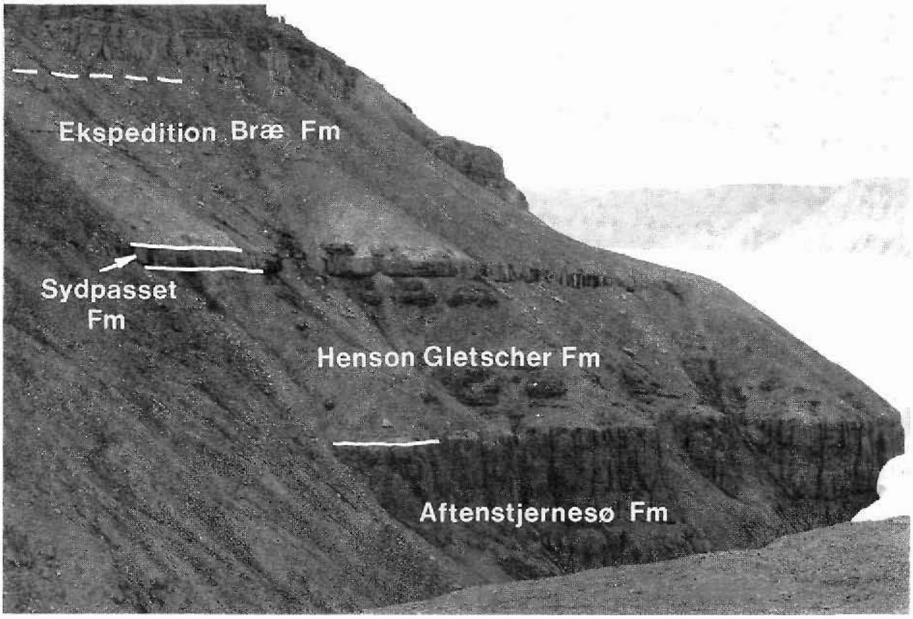

Fig. 5. Typical exposure of the Henson Gletscher Formation between the cliff-forming Aftenstjernesø Formation and Sydpasset Formation. Section 1985–14. Henson Gletscher Formation is 56 m thick.

5) and is generally poorly exposed. Consequently, it has only been possible to find two drill localities, where four holes have been drilled (fig. 3) (Christiansen *et al.*, 1986).

Most of the accessible sections through the formation, in total 16, have been sampled and studied in various degrees of detail (fig. 6). In all, 145 surface samples and 82 m of core are available for detailed analyses in addition to the small number of samples collected in 1980 and 1984 (Rolle, 1981; Christiansen *et al.*, 1985).

Sedimentary facies

The stratigraphy and sedimentology of the Henson Gletscher Formation, and the Cambrian shelf sequence in general, are described in the comprehensive study by Ineson (1985). In the following discussion the most interesting facies from a petroleum geological point of view are briefly mentioned within a framework of three main units. In the field, as well as in evaluation of laboratory data, it has been convenient to subdivide the Henson Gletscher Formation into a lower carbonate unit, a middle siliciclastic unit, and an upper carbonate unit. They are easily distinguished, even at a distance, due to the pale weathering colour of the siliciclastics (fig. 4). The variation in thickness of each unit, measured wherever possible (fig. 6), forms the basis for the evaluation of source and reservoir rock potential.

It must be emphasised that the upper carbonate unit also includes the basal part of the Sydpasset Formation, at least in the southernmost sections (J. R. Ineson, personal com-

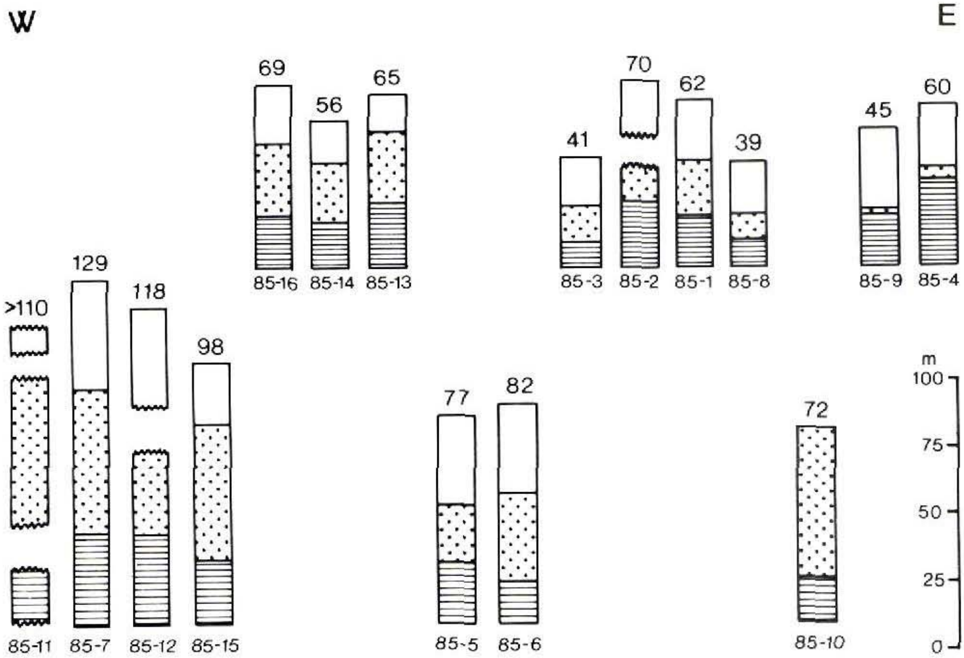

Fig. 6. Simplified measured sections of the Henson Gletscher Formation and the basal part of the Sydpasset Formation showing the total thickness and the thickness of the three units: lower carbonate (horizontal hatching), siliciclastic (dotted), and upper carbonate (blank) units. Section number is indicated below, and thickness in metres above the section columns.

munication, 1986) (see fig. 8, where the formation boundary is tentatively indicated). For convenience in the present study, the base of the impressive pale cliff-forming dolomite breccias of mass-flow origin is considered to form the formation boundary. This boundary is well exposed and defined throughout the area, whereas the more logical boundary between lime mudstone and coarser dolomites as used by Ineson is difficult to trace in the often poorly exposed terrain.

Lower carbonate unit

The lower carbonate unit is characterised by carbonate mudstone facies with minor intercalations of laminated carbonate wackestone (see description of upper carbonate unit). The thickness of this unit varies beteen 11 m and 35 m in the area studied, decreasing in thickness towards the north, as is also the case with the total thickness of the Henson Gletscher Formation (fig. 6).

Fine laminated carbonate mudstone, often with shaly or cherty intervals, is the most common facies in the lower carbonate unit. Lime mudstone is slightly more abundant than dolomite mudstone and dolomitisation is mainly observed in the lowest part.

The lime mudstone is dark grey to black and produces a flaky friable dark material during weathering. The pervasive fine lamination (typically 0.1 to 1 mm), caused by minor compositional variation, is deflected at the margins of pre- to syncompactional concretions of carbonate and chert.

The carbonate mudstone is organic rich and typically contains 1 to 2% total organic carbon (TOC). The interbedded shales (less than 50% calcite + dolomite) are richer in organic matter, typically between 1.5% and 5% TOC.

Bioturbated dolomite mudstone occurs throughout the region as decimetre to metre thick beds in the lowest part of the lower carbonates. No limestone equivalents have been found. This facies has pale grey or yellow weathering colours and forms massive exposures. Mottling and a discontinuous wavy lamination are common, often with a parallel stylolitic bedding. Burrows are filled with pyrite or dolospar. TOC values from this facies are always lower than 1%.

Siliciclastic unit

The siliciclastic unit of the Henson Gletscher Formation is highly variable in facies development and thickness. It is usually composed of four facies: sheet sandstone, cross-bedded or laminated sandstone with ripple marks, laminated siltstone, and bioturbated silt or sandstone. Carbonate rocks are often intercalated with these facies, and sandstone beds also occasionally occur in the upper carbonate sequence.

Sheet sandstone dominates the siliciclastic sequence. This facies occurs with a characteristic pale yellow or creamy weathering colour, but rocks are often dark on fresh surfaces due to hydrocarbon staining.

The sandstone is well-sorted and fine-grained and mainly occurs as structureless beds, a few centimetres to several metres thick, which are separated by discrete millimetre thick silt laminae. On a few occasions diffuse lamination or grading has been observed internally in the beds.

The sandstone was strongly cemented during diagenesis with a drastic loss of the presumably high initial permeability and porosity. Fourteen analysed samples give an average porosity of 6.0% (range 1.6% to 12.2%) and ten of these have a permeability lower than 0.001 mD.

Cross-bedded or laminated sandstone, occasionally with wave ripples, is sometimes observed above the sheet sandstone. This facies has been found in sections 7, 13, 14 and 15, where it is associated with siltstone facies.

Laminated siltstone occurs interbedded with the sandstones or the bioturbated facies, and forms units up to several metres in thickness. This facies is particularly abundant in the central and upper part of the clastic sequence. Lamination is well developed and the weathering product is dark and fissile.

Bioturbated sandstone and siltstone form units from less than one centimetre to tens of metres thick. The thin units occur interbedded with the laminated siltstones whereas thicker thoroughly bioturbated units are common in the southern part of the area (e.g. section 11). The grain size ranges from fine silt to fine sand and the degree of bioturbation varies from the occurrence of discrete burrows in wispy laminated siltstone to a completely mottled sediment.

Upper carbonate unit

The upper carbonate unit is characterised by coarser grained facies than those of the lower carbonate unit. Laminated wackestone, laminated or cross-laminated packstone and grainstone, rudstone, and breccias dominate.

The *laminated wackestone* is dark with a thin wavy or irregular lamination. Bioturbation is common in both limestone and dolomite.

The *laminated or cross-laminated packstone or grainstone* mainly occurs as thin beds or lenses a few centimetres thick in the wackestone, or as decimetre thick graded units. These facies are rich in skeletal fragments, mainly derived from trilobites.

The various types of *rudstone or breccia* occur as units varying in thickness from a few centimetres to several metres, mainly in the upper part of the upper carbonates; the thicker units are often cliff-forming. Most of the breccias are clast supported with a massive appearance, without grading or lamination.

All these carbonate facies have a rather low content of organic matter, typically with TOC values lower than 1%. Only samples with macroscopically observable bitumen (e.g. fig. 3 in Christiansen *et al.* (1986)) or a strong petroliferous odour display higher values.

Fine laminated carbonate (mainly lime) *mudstone and shale* are typically intercalated with the coarser facies as millimetre thin laminae or layers several centimetres thick. In the northernmost area the lime mudstones form sequences many metres thick. The shale is rich in organic carbon (1–4%).

Depositional environment

The spatial distribution of the above mentioned facies, combined with data from Ineson & Peel (1980, 1987, in press), Ineson (1985), J. R. Ineson & F. Surlyk (personal communication, 1986), and our own observations, allow the construction of the following depositional model.

The carbonate mudstone and shale facies are deposited in a low-energy, outer shelf environment with a slow sedimentation rate and anoxic conditions. The bioturbated sediments represent periods of higher oxygenated bottom conditions probably due to increased water circulation or lower organic production.

The distinctive change in type of sedimentation between the siliciclastic and the carbonate units was mainly controlled by clastic sediment influx from the south. During a regional regression, emergence of the carbonate platform existing south of the area, would have resulted in a drastic reduction of carbonate production. Consequently, mainly siliciclastic material would have been transported to the coastal zone and redeposited. Erosion of Precambrian basement and/or Proterozoic to Lower Cambrian siliciclastic rocks would have provided a suitable source for the siliciclastic material.

Most of the siliciclastic unit is formed as outer-shelf deposits, with only the upper part towards the south bearing evidence (bioturbation, cross-bedding) of a shallow water coastnear environment.

In the upper carbonate unit the coarser packstone, grainstone and breccia (Sydpasset Formation, J. R. Ineson, personal communication, 1986) are assumed to represent a northward-prograding slope sequence.

Distribution of potential source and reservoir rocks

The thickness variation indicated on the isopach map (fig. 7) and the simplified profile of facies distribution (fig. 8) can be applied in the prediction of the volume of potential source and reservoir rocks. The Henson Gletscher Formation is sandwiched between impressive cliff-forming dolomite breccias of mass flow origin and displays a drastic increase in thickness from north to south (figs 7 and 8).

The lower carbonate unit with potential source rocks such as carbonate mudstone or shale, decreases in thickness from approximately 30 m in the south to approximately 15 m towards the northernmost exposures. The southern, and probably most shallowly deposited part is often pervasively bioturbated and of poor source rock quality, so the thickness of source rocks only shows a minor decrease from south to north. The upper carbonate unit is very thick towards the south, but in this area it is dominated by coarse dolomites with only thin intervals of shale or carbonate mudstone. Towards the north, the thickness of the sequence decreases but the amount of source rocks increases to almost 100%. The cumulative thickness of source rocks from the upper and lower carbonates varies between 25 m and 40 m with a roughly estimated average of 30 m.

The most likely intraformational reservoir rocks are the sheet sandstone and the coarse dolomite facies. For the latter, the diagenetic history (primary and secondary dolomitisation) is of great importance in evaluating their reservoir potential but it is not considered in any detail here. It must be noted that most of the secondary white dolospar veins and vugs with bitumen fillings are observed in dolomite breccias and grainstones close to the top of the Henson Gletscher Formation. These two facies mainly occur in the southern part of the area (e.g. section 7, fig. 3).

The sheet sandstones are important as potential migration conduits since they occur in close spatial relationship to source rocks in very large areas. They continue further north as thin layers into the outer shelf and slope equivalent of the Henson Gletscher Formation, which is observed in the Navarana Fjord antiform (F. Surlyk & J. R. Ineson, personal communication, 1986). Towards the south, the sandstones reach thicknesses of potential reser-

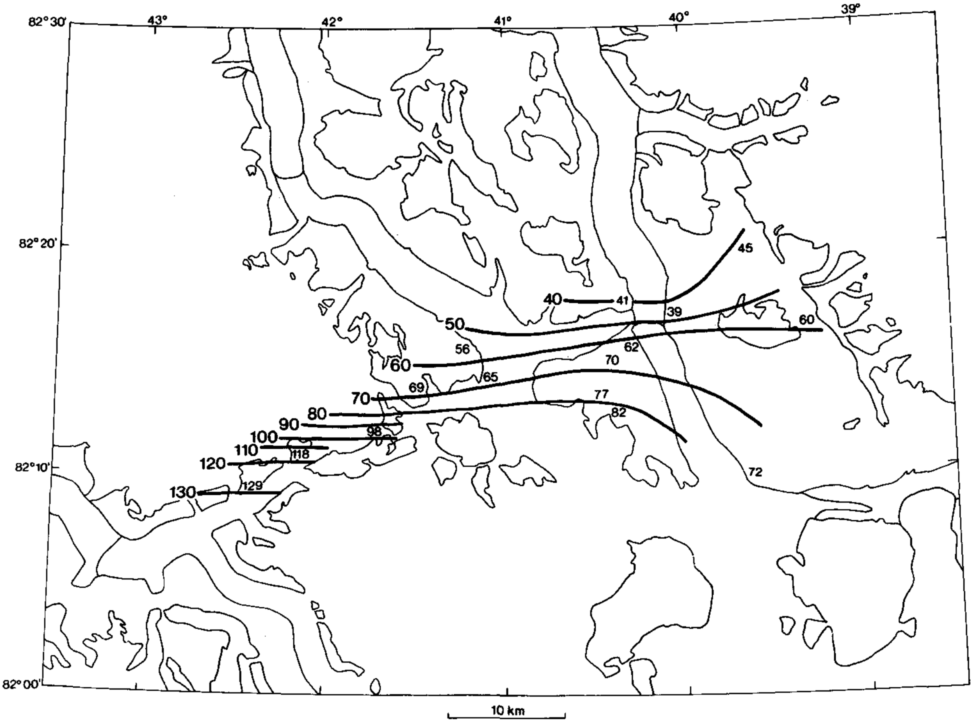

Fig. 7. Isopach map of the Henson Gletscher Formation including the basal part of the Sydpasset Formation. The small numbers show the actual measured thickness (in metres).

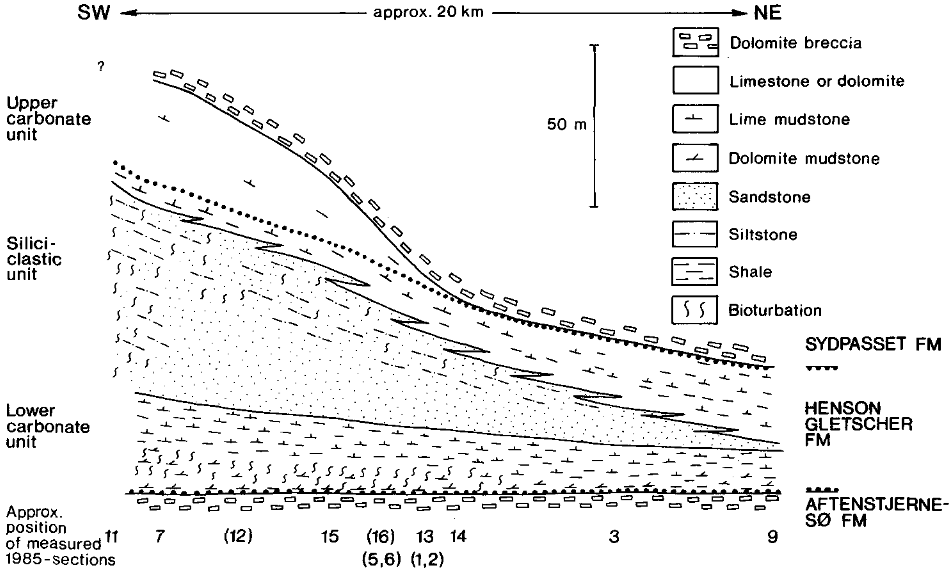

Fig. 8. Simplified SW–NE sedimentological profile of the Henson Gletscher Formation and the basal part of the Sydpasset Formation showing the facies and thickness variation. The dotted lines show the formation boundaries in the sense of Ineson (1985).

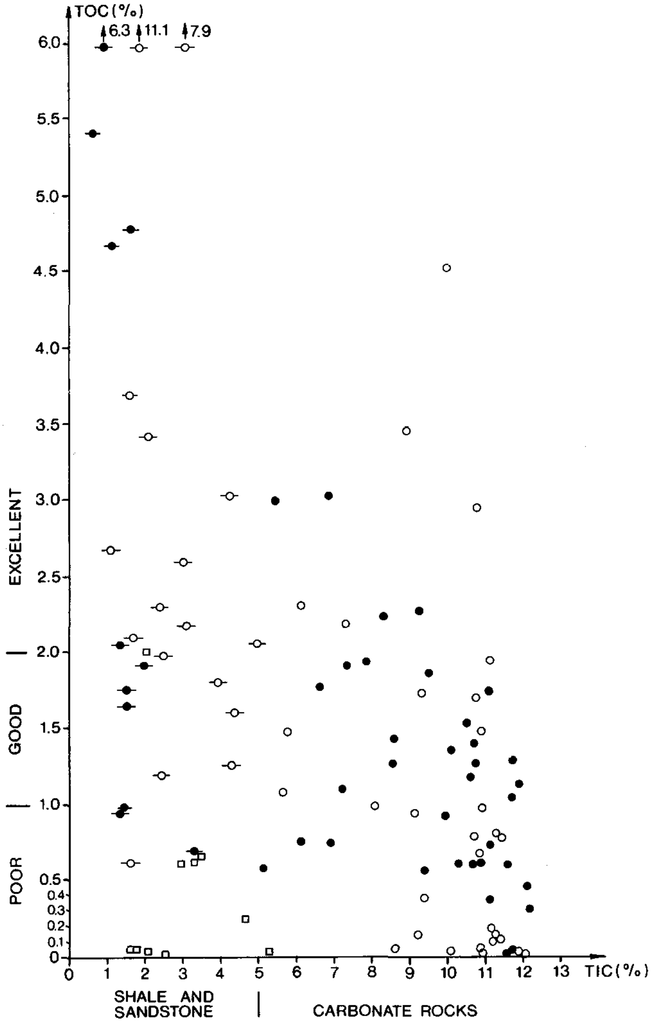

Fig. 9. Plot of Total Inorganic Carbon (TIC) versus Total Organic Carbon (TOC). Pure dolomite corresponds to *c.* 13% TIC, pure calcite to 12% TIC. Filled circles: lower carbonate unit, filled circles with bars: shale from lower carbonate unit, squares: siliciclastic unit, open circles: upper carbonate unit, open circles with bars: shale from upper carbonate unit.

voir size (fig. 8). The upward and southward facies transition to laminated, often bioturbated, silt- and sandstones with an expectedly low primary permeability favours a possible stratigraphic trapping of migrated hydrocarbons.

The thick sandstone sequence of the more easterly outcropping Sæterdal Formation (Ineson, 1985; Ineson & Peel, in press) is also considered as a potential reservoir for hydrocarbons generated from contemporaneously deposited source rocks in the Henson Gletscher Formation.

Analytical results

Preliminary geochemical analyses (LECO, Rock Eval) have been carried out in the source rock laboratories of the Geological Survey of Denmark and the Geological Survey of Green-

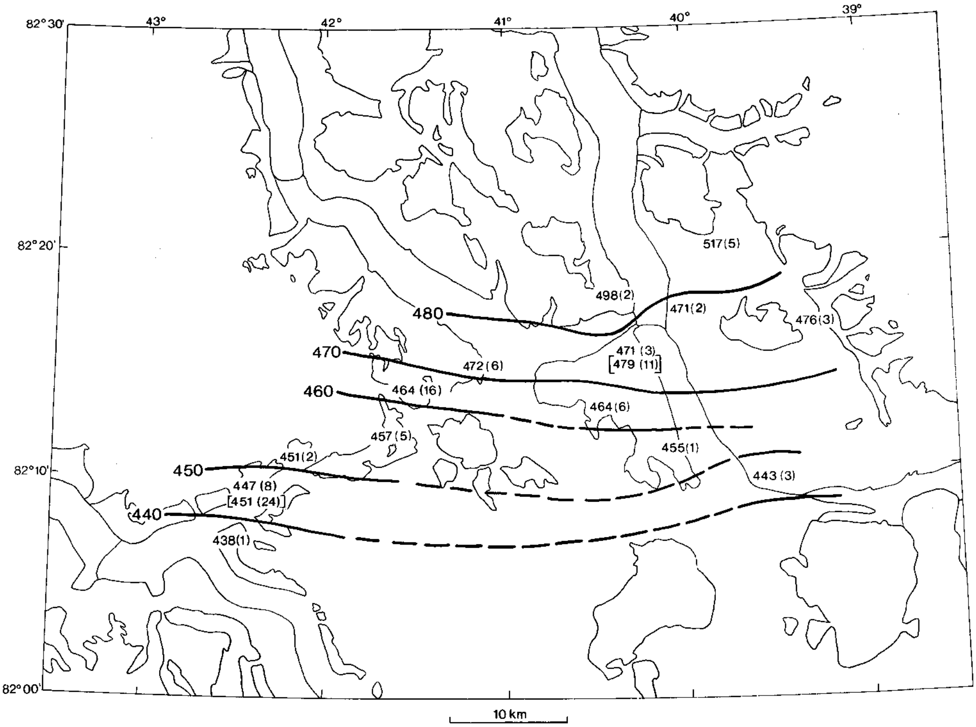

Fig. 10. Averages of measured $T^{\circ}_{\max}$ values (number of values in parenthesis) from the Henson Gletscher Formation with tentatively drawn contour lines. $T_{\max}$ values of 437°C and 460°C correspond to the onset and end of petroleum generation, respectively.

land and combined with optical studies on kerogen concentrates. The techniques employed and sample preparation are described in detail by Christiansen *et al.* (1985).

Organic matter

A source rock sequence might, as a first approximation, be characterised by its content of organic carbon (TOC). Both the shales and carbonates of the lower and upper carbonate unit are so rich in organic matter that they can be considered as good to excellent potential source rocks (figs 9 and 12). Especially some of the shales are rich in organic matter (fig. 9), whereas the poorest TOC values are mainly from the coarse clastic carbonates. Most of the carbonate mudstones have TOC values between 1% and 2%. In this context it should be noted that carbonate rocks, under favourable conditions, should contain at least 0.3% TOC to qualify as source rocks in contrast to the 0.5% value for clastic rocks (Tissot & Welte, 1978).

Under the microscope the kerogen is observed as finely disseminated organic matter and granular to spongy amorphous organic matter. Structured palynomorphs such as acritarchs are not recorded.

The precursor of the amorphous kerogen is not known, but is most likely to be of algal origin. The genus *Girvanella,* a blue green alga, is abundant in the upper carbonate sequence

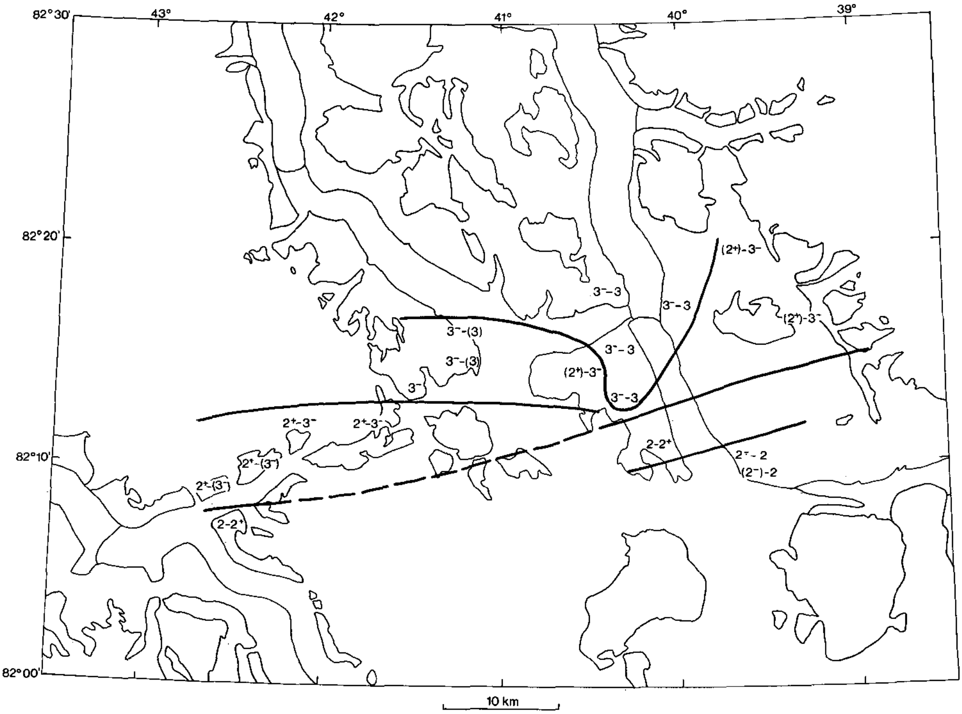

Fig. 11. Measured TAI (Thermal Alteration Index) values from the Henson Gletscher Formation with tentatively drawn contour lines. Values of 2^- to 2 and 3^- to 3 correspond to the onset and end of petroleum generation, respectively.

(N. H. Larsen, personal communication, 1986) which also contains a second blue green alga resembling the recent genus *Hyella*, (Larsen, 1985a,b).

Maturity

The thermal maturity of the Henson Gletscher Formation has been estimated from 87 T_{max} values (fig. 10) and 40 TAI values (fig. 11) from the 16 measured sections, the four drill cores and a minor number of reconnaissance localities. There is only small variation in values of T_{max} in each section, and the average value has been applied for further evaluation. However, in sections 1 and 2 the three best defined values give a considerably lower average (471°C) than the average of all eleven defined values (479°C). This variation may be due to local thermal effects from numerous faults in this area or to the occurrence of basic dykes. Also in the area of section 7 and drill site C_1 and C_2, the best defined T_{max} values give a lower average than the average of all values (fig. 10). T_{max} values higher than 480°C are poorly defined, and especially samples from sections 3 and 9 display scattered results.

With only one exception (see below) there is no major difference in the thermal maturity variation evaluated by the optical and the geochemical methods. In this context, it must be emphasised that the TAI definition is originally based on spore colouration (Staplin, 1969), whereas the present study applies the colouration of amorphous kerogen.

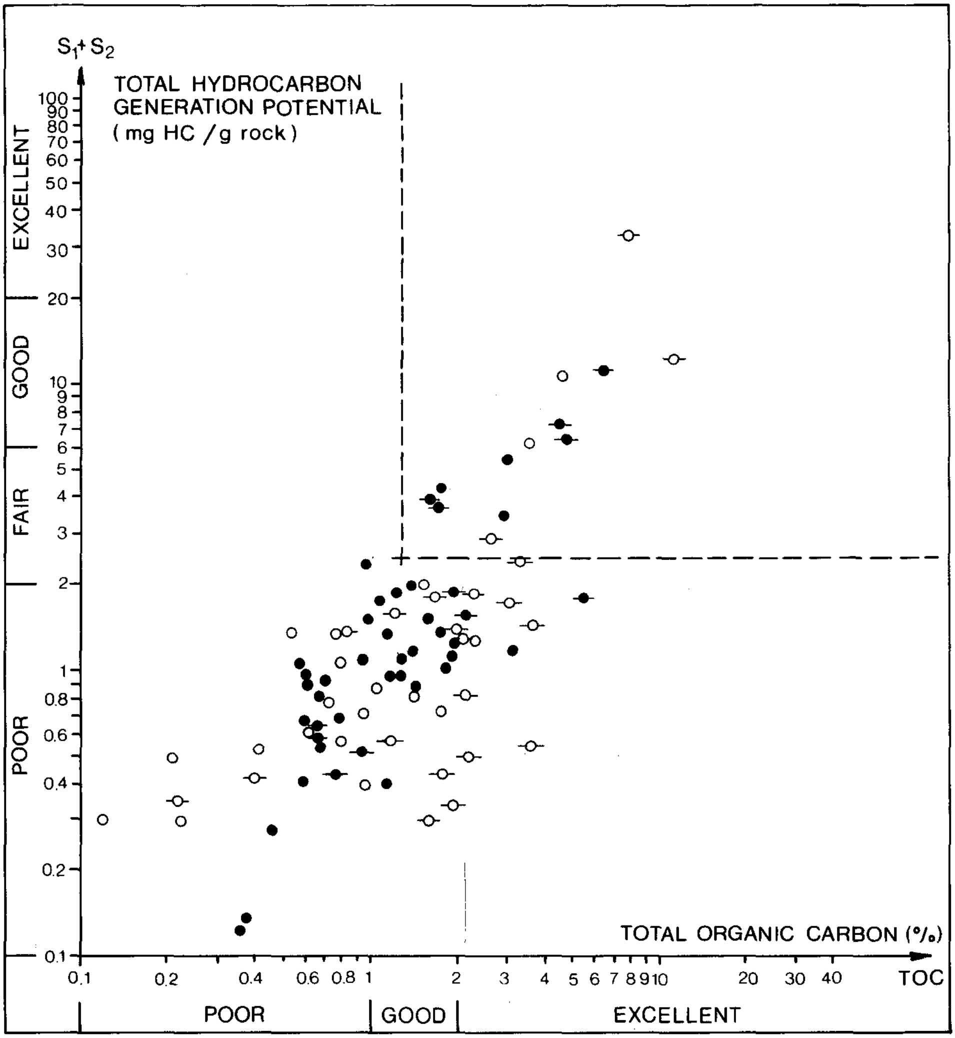

Fig. 12. Plot of Total Organic Carbon versus Total Hydrocarbon Generation Potential. Same symbols as fig. 9.

With respect to hydrocarbon generation the surface exposures of the Henson Gletscher Formation are divided into a northern thermally postmature area and a southern mature area (figs 10 and 11). Sections 10 and 11 are early mature and sections 7, 12 and 15 reflect peak generation conditions. Sections 5, 6, 13, 14 and 16 are close to the end of oil generation or postmature, whereas sections 1, 2, 3, and 8 are thermally postmature. Section 9 is problematic, since the kerogen is observed as orange brown to brown coloured amorphous matter, which suggests thermal maturity. In contrast, the T_{max} values (491°, 510°, 524°, 529°, 531°) and small S_2 values (generated hydrocarbons during pyrolysis) compared to high TOC values suggest that this area is thermally postmature.

Hydrocarbon potential

The hydrocarbon source rock potential of the analysed surface samples is generally poor (fig. 12), despite the high organic carbon content of the shale and carbonate mudstone facies. Only samples from the early mature area towards the south have reasonably good source rock parameters. Since the organic matter is of algal origin (oil-prone type I and II kerogen), the low potential is interpreted as a maturity effect rather than a compositional effect.

During the period of deepest subsidence and strongest thermal alteration most of the potential hydrocarbons in the area north of the 460° T_{max} isoline (fig. 10) were generated and expelled. The generated petroleum has either been thermally degraded or has migrated southwards, probably through the shallowly northward dipping sandstones. In the area south of the 460° T_{max} isoline it is possible, at least from a thermal point of view, that trapped hydrocarbons have been preserved. However, most of the Henson Gletscher Formation is eroded away in this area or buried only a few hundred metres below the topographic surface.

Conclusion

The present study has clearly demonstrated that the Henson Gletscher Formation, prior to subsidence and thermal alteration, formed an interesting coupled reservoir and source rock sequence. The source rocks are of good quality with a high primary organic carbon content of mainly marine algal origin, a thickness of approximately 30 m, and a regional distribution over several thousands of square kilometres.

Unfortunately, thermal maturity data indicate that most of the area is mature to postmature at the surface, leaving only few chances of finding trapped hydrocarbons in the subsurface. Generally, the maturity parameters are highly consistent within each section defining a strong maturity gradient increasing from south to north. This variation is unlikely to be caused by differential subsidence but must be due to an increase in the thermal gradient (heat flow) approaching the fold belt towards the north.

Future modelling will concentrate on the evaluation of generated volumes of hydrocarbons. Obviously very large quantities have formed, and relicts are often observed as bitumen minerals and as oil staining in sandstones. The possibility of long distance migration to immature areas towards the south must also be considered in detail. The observed asphalt seep in the southern part of Wulff Land (Christiansen *et al.*, 1986) might be biodegraded oil which originally was generated from Henson Gletscher Formation source rocks. Future detailed geochemical studies might provide the necessary correlation data to test this hypothesis.

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