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G.L. Williams

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Palynological analysis of Aquitaine *et al.* Hekja O-71, Saglek Basin, Davis Strait, offshore eastern Canada

G.S.C. Locality No.: D-208

Location: 62°10'86"N, 62°58'78"W

Elevation Sea level to R.T.: 12.5 m

Water Depth: 350.8 m

Total Depth: 4566 m

Spud Date: 17 July 1979

Interval Studied: 890-4566 m

Casing Points: 762 mm at 415.5 m; 508 mm at 714 m; 340 mm at 1670 m; 244.5 mm at 3252 m

Introduction

Aquitaine *et al.* Hekja O-71 is on the northwestern margin of the Saglek Basin in the southern part of the Davis Strait that separates Baffin Bay from the Labrador Sea (Figure 1). The well was a discovery, with natural gas and condensate were recovered from the Gudrid Formation between 3212 and 2351 m.

Biostratigraphy

The biostratigraphy in my study is based on the palynological analysis of 219 cuttings samples, seven conventional cores and one sidewall core, covering the interval 4566-890 m. Seventy-three slides of cuttings samples examined were processed by GEUS. I am indebted to the Canada-Newfoundland and Labrador Offshore Petroleum Board for providing the unwashed cuttings samples from which many of the slides were prepared.

Figure 2 presents a summary of the stratigraphy of Hekja O-71. My ages and paleoenvironments are based on dinoflagellate cysts (dinocysts), spores and pollen. To assist in interpretation of the data, I also show the Last Appearance Datum (This - the highest, latest or youngest occurrence of a taxon in a well or surface section - is commonly denoted by the acronym LAD. The First Appearance Datum - the lowest, earliest or oldest occurrence of a taxon in a well or surface section - is commonly denoted by the acronym FAD) of species, as well as occurrences representing reworking and significant fluctuations in relative abundances.

Age interpretations for Hekja O-71 are based primarily on the known stratigraphic ranges of dinocysts in European sections (Powell, 1992; Bujak, 1994; Williams *et al.*, 1999, 2001, 2004) and from other wells and coreholes from offshore eastern Canada and western Greenland (Williams, 1975; Williams and Brideaux, 1975; Williams and Bujak, 1977; Barss *et al.*, 1979; Williams *et al.*, 1990; Sønderholm *et al.*, 2003; Nøhr-Hansen, 2003a, 2003b).

Throughout this paper, I use the time scale published in Gradstein and Ogg (1996). Bujak-Davies Group (1987) and Nøhr-Hansen (2003a) have published biostratigraphic interpretations for Hekja O-71: the former is based on palynology (spores, pollen and dinocysts) and foraminifera; the latter relies on dinocysts. Paleoenvironmental studies of the well, using foraminifera, were undertaken by Bujak-Davies Group (1987). Miller and d'Eon (1987), in a geological study, also provided paleoenvironmental interpretations.

At its total depth of 4566 m, Hekja O-71 is in basalt, which extends up to 3545 m. Thus, the lowermost 1021 m in the well is basalt. Surprisingly there are age diagnostic changes in the dinocysts in this interval but determining their significance is difficult.

Two age diagnostic taxa are *Alisocysta circumtabulata* at 4400-4390 m and *Impletosphaeridium delicatulum* at 4260-4250 m. Williams *et al.* (2004) gave the LAD for *Alisocysta circumtabulata* as 58.53 Ma for Northern Hemisphere mid latitudes. This places it well within the Selandian. Nøhr-Hansen, Fensome and Williams (pers. comm.), in an appraisal of the LADs of dinocyst taxa in 17 Labrador Sea wells, have equated the LAD of *Alisocysta circumtabulata* with that of *Alisocysta margarita* and the Selandian-Thanetian boundary. In Hekja O-71, the LAD of *Alisocysta circumtabulata* must be suspect, however, because of its occurrence in the thick basaltic sequence. "*Impletosphaeridium delicatulum*", according to Nøhr-Hansen, Fensome and Williams (pers. comm.) has its LAD in the Selandian. Other supporting evidence for a Selandian age is the presence of the dinocyst species *Palaeocystodinium bulliforme* and *Palaeoperidinium pyrophorum* in the sample at 3940-3930 m. Williams *et al.* (2004) placed the LAD of *Palaeoperidinium pyrophorum* at 58.04 Ma, which is close to the Selandian-Thanetian boundary. *Palaeocystodinium bulliforme* has its LAD at 57.9 Ma (Williams *et al.*, 2004). Thus it would initially seem reasonable to consider from 3930 m to total depth to be Selandian, but this interval is basalt.

A plausible explanation for this dilemma may be found in Nøhr-Hansen (2003a). He questionably included from total depth to 3660 m in his *Palaeoperidinium pyrophorum* interval (P4). This is the lowest of his three Thanetian intervals. The other two are the *Areoligera gippingensis* interval (P5) and the *Apectodinium acme* (P6). In Hekja O-71, Nøhr-Hansen (2003a) assigned from 3660 to 3380 m to his *Areoligera gippingensis* interval and from 3380 to 3150 m to his *Apectodinium acme* interval.

What happens higher up in the well? The top of the Thanetian appears to be immediately above the cuttings sample at 3360-3350 m. I conclude this from the occurrence of the dinocyst *Cerodinium speciosum* in the cuttings sample at 3370-3360 m. According to Williams *et al.* (1999), *Cerodinium speciosum*, of which *Cerodinium "glabrum"* was formerly a subspecies, has its LAD at 53.96 Ma. Gradstein and Ogg (1996) placed the Thanetian-Ypresian boundary at 54.8 Ma, which is less than one million years earlier. The youngest Paleocene zone in both Gradstein and Williams (1976) and the Bujak-Davies Group (1987) was the *Cerodinium speciosum* Zone. An identical LAD was assigned by Nøhr-Hansen, Fensome and Williams (pers. comm.), who also consider *Cerodinium "glabrum"* to have its LAD at the Thanetian-Ypresian boundary. Further confirmation comes from Nøhr-Hansen (2004), who placed the LAD of *Cerodinium speciosum* subsp. "*glabrum*" in the late Thanetian. I am using the above evidence to confirm that the LAD of *Cerodinium "glabrum"* occurs at the top of the Thanetian.

In the Paleocene of Hekja O-71, the Bujak-Davies Group (1987) gave the following breakdown: 4545-3770 m, *Palaeoperidinium pyrophorum* Zone (early Paleocene); 3750-3350 m, *Cerodinium* (as *Ceratiopsis*) *speciosum* to *Alisocysta circumtabulata* Zone (late Paleocene). The designation of *Palaeoperidinium pyrophorum* as a zonal index species for the early Paleocene causes a distortion in the ages. As noted above, *Palaeoperidinium pyrophorum* has its LAD close to the top of the Selandian. However, it is standard practice to consider only the Danian as early Paleocene. The Selandian and Thanetian can be considered as mid and late Paleocene respectively or both can be included in the late Paleocene. Thus, the *Palaeoperidinium pyrophorum* zone, as recognized by the Bujak-Davies Group (1987) in Hekja O-71, equates in large part with my Selandian.

Even more remarkable is the Bujak-Davies Group placement of the top of the Paleocene at 3350 m. This is identical to the LAD of *Cerodinium glabrum*, which I regard as denoting the top of this epoch.

How serious is the discrepancy with the Paleocene-Eocene boundary as given in Nøhr-Hansen (2003b)? The problem is not in the dinocyst species observed but rather in the interpretation of their ranges and significance. In the early Eocene samples I have analyzed I noted the following LADs: *Apectodinium parvum* in the cuttings sample at 3260-3250 m and in a core at 3258.5 m; *Apectodinium hyperacanthum* at 3130-3120 m; frequent *Apectodinium homomorphum* at 3149-3139 m; *Deflandrea oebisfeldensis* at 3190-3180 m; and *Areoligera gippingensis* at 3100-3090 m.

Williams *et al.* (1999) cited the range of *Apectodinium parvum* as 55.54-54.31 Ma. The LAD of *Deflandrea oebisfeldensis*, according to Williams *et al.* (2004) is 52.85 Ma in Northern Hemisphere mid latitudes. The same authors gave an LAD of 57 Ma for *Areoligera gippingensis* in Northern Hemisphere mid latitudes, which would place it in the Thanetian. But there is much confusion over what is a true *Areoligera gippingensis*. Williams (2003a, b, c) referred to the taxon *Areoligera cf. medusettiformis*, which appears to be identical to *Areoligera gippingensis*. If this interpretation is correct, the LAD of *Areoligera gippingensis* in offshore eastern Canada is within the Ypresian.

I am including the interval from 3350 to 3120 m in the basal Eocene as opposed to Nøhr-Hansen (2003b), who assigns it to his *Apectodinium* acme interval of late Paleocene age. The top of the basal Eocene reflects the LAD of *Apectodinium hyperacanthum*, whose precise age is uncertain. Perhaps a better pick would be at 3180 m, in which occurs the LAD of *Deflandrea oebisfeldensis*. This would agree with my findings in Gjoa G-37 (Williams, in press b).

The sparse assemblages make it difficult to subdivide the Eocene in Hekja O-71. However, there are some useful indicators, one of which is the relative abundance of the freshwater fern *Azolla*. This genus reaches a peak at 2430-2420 m and occurs consistently and frequently up to 2240-2230 m. My use of *Azolla* as a marker for the Ypresian-Lutetian boundary agrees with my findings in Gjoa G-37 (Williams, in press b). Brinkhuis *et al.* (2006) stated that *Azolla* is abundant in basal middle Eocene marine sediments of Nordic seas. In a study of an ACEX (Arctic Coring Expedition) core taken on the Lomonosov Ridge, Brinkhuis *et al.* (op. cit.) considered the high concentrations of this fern to reflect in situ growth in the Arctic. But in the Labrador Sea the specimens are reworked.

Under supplementary information, Brinkhuis *et al.* (2006) listed one well from the Saglek Basin (Karlsefni A-13) and three from the Hopedale Basin (Bjarni O-82, North Leif I-05, Snorri J-90) as having earliest middle Eocene abundances of *Azolla*. But they did not reference Hekja O-71, Ralegh N-18 and Gjoa G-37, the three wells in which *Azolla* is most abundant. All three wells are in the northern Saglek Basin and presumably lie closer to the *Azolla* source than the other Labrador Sea wells.

Species with their LADs in the Ypresian of Hekja O-71 include: *Areoligera gippingensis* (3100-3090 m); "*Taurodinium granulum*" (3010-3000 m); *Apectodinium fleximorphum* (2530-2520 m); and *Komewuia? "unicornis"* (2530-2520 m). Another important horizon seems to be the abundance peak of *Trithyrodinium? "circellum"* between 3150 and 3045 m. The LADs of three of the above species show good agreement with the plots generated by Nøhr-Hansen, Fensome and Williams (pers. comm.). These palynologists have determined that the peak of "*Taurodinium granulum*" is in the earliest Ypresian and the LADs of *Apectodinium fleximorphum* and *Komewuia? "unicornis"* are in the late Ypresian. I also noted a *Trithyrodinium? "circellum"* peak in the earliest Ypresian.

A comparison of my pick for the Ypresian-Lutetian boundary shows some disagreement with that of the Bujak-Davies Group (1987). These authors considered the interval from 3330 to 2436 m to be early to middle Eocene, including it in four zones: these are from oldest to youngest the *Areoligera senonensis* Zone, the *Dracodinium condylos* Zone, the *Trinovantedinium* #LA Zone, and the *Eocladopyxis* #LA Zone. Unfortunately there is no further subdivision that would permit delineation of the zones.

Nøhr-Hansen (2003a) included from about 3150 to 2440 m in the early Eocene. From 3150 to 2670 m he assigned to the E2 interval and from 2670 to 2440 m he assigned to the E3 interval: he called these assignments questionable. Nøhr-Hansen (2003b) defined seven intervals in the Ypresian; these were based on the zonation of Bujak (1994) for the North Sea. In ascending order the intervals are: E1, the *Cerodinium dartmoorium-Deflandrea oebisfeldensis* interval; E2a, the *Wetzeliiella astra-Fibrocysta bipolaris* interval; E2b, the *Dracodinium condylos* interval; E2c, the *Areoligera medusettiformis* interval; E3a, the *Eatonicysta furensis* interval; E3b, the *Charlesdowniea columna* interval; and E3c-d, the *Eatonicysta ursulae* interval. The top of the Ypresian was considered to be within the *Eatonicysta ursulae* interval. Obviously Nøhr-Hansen (2003a) considered the early Ypresian to be missing in Hekja O-71.

Defining the Lutetian in Hekja O-71 is difficult. Initially I considered it absent but believe I can now distinguish it on the basis of the fungal spore abundances. Nøhr-Hansen, Fensome and Williams (pers. comm.) in their compilation of LADs for Labrador Sea palynomorphs, record a mid Lutetian peak for fungal spores. From this, I conclude that from 2310 to 1930 m is Lutetian but that much of the early and all the late Lutetian is absent.

The Bujak-Davies Group (1987) and Nøhr-Hansen (2003b) came to different conclusions in part reflecting different approaches. Neither Lutetian nor Bartonian were recognized by the Bujak-Davies Group (1987), who simply referred to a middle to late Eocene *Areosphaeridium fenestratum* Zone, which extended from 2416 to 1460 m. Nøhr-Hansen (2003a) presented a zonation for the Lutetian and the Bartonian but did not apply this in Hekja O-71. Instead he considered the interval from 2440 to 1400 m to be middle to late Eocene.

Recognition of the Eocene stages in Hekja O-71 is not possible if based solely on the dinocysts. One must use the pollen and spores which provide much needed control, especially in the middle and late Eocene. For example, I designated the interval from 1910 to 1390 m as Bartonian, based on the LAD of *Extratropipollenites* occurring in the cuttings sample at 1400-1390 m. This is substantiated by the LAD of *Cicatricosisporites auritus* at 1470-1460 m. Nøhr-Hansen, Fensome and Williams (pers. comm.) consider the LAD of this taxon to be within the Bartonian, just below the LAD of *Pistillipollenites mcgregori*. In Hekja O-71 *Pistillipollenites mcgregori* has a suppressed LAD in the Lutetian.

Other species with LADs in the Bartonian are: *Spiniferites pseudofurcatus* (1390-1400 m), *Cicatricosisporites "labatus"* (1500-1490 m), *Gothanipollis* (1530-1520 m), *Trithyrodinium?"circellum"* (1620-1610 m), *Retitricolpites maximus* (1620-1610 m) and *Retitricolpites vulgaris* (1620-1610 m). The surprising number of pollen taxa highlights the need for more integration of the spore/pollen with the dinocyst data.

I consider the interval 1370-1150 m to be Priabonian, based on the LAD of *Deflandrea "borealis"* at 1150-1150 m. Nøhr-Hansen, Fensome and Williams (pers. comm.) considered the LAD of *Deflandrea "borealis"* to equate with that for *Lentinia serrata*, which is close to the Priabonian-Rupelian boundary according to Williams *et al.* (1999) and Williams (2003c). Thus, in Hekja O-71 it seems reasonable to assume that the top of the Priabonian is at 1160-1150 m with the LAD of *Lentinia "glabra"*, which is at 1370-1360 m, being depressed.

The Rupelian (early Oligocene) extends from 1130 to 950 m in Hekja O-71. I say this with some confidence in view of the LAD of *Enneadocysta "magna"* being in the cuttings sample at 960-950 m. This species, as *Enneadocysta "cingulomagna"* has its LAD in the Rupelian of several Grand Banks wells (Williams, 2003a, 2006): it is one of the most consistent marker species in offshore eastern Canada.

In Hekja O-71, other taxa with LADs in the Rupelian are *Pterocaryapollenites* (960-950 m), *Microsphaeridium ancistroides* (1070-1060 m) and *Eocladopyxis peniculata* (1130-1120 m). *Microsphaeridium ancistroides*, originally described from the late Oligocene by Benedek (1972), appears to be a consistent Oligocene marker in the Labrador Sea.

Bujak-Davies Group (1987) included the interval 1200 to 950 m in their *Areosphaeridium arcuatum* Zone of early Oligocene or Rupelian age. This shows close agreement with my findings.

One sample at 930-920 m seems to be assignable to the Chattian. This is based on the occurrence of *Chiropteridium galea*. Williams *et al.* (2004) gave the stratigraphic range of *Chiropteridium galea* as 33.5 to 22.36 Ma in Northern Hemisphere mid latitudes. According to Gradstein and Ogg (1996), the Oligocene extends from 33.7 to 23.8 Ma. Therefore the LAD of *Chiropteridium galea* is 1.5 million years later than the Oligocene-Miocene boundary. I consider this close enough to regard the LAD of *Chiropteridium galea* as equating with the top of the Oligocene.

The Bujak-Davies Group (1987) include the single cuttings sample at 930-920 m in their late Oligocene *Chiropteridium mespilanum* Zone. This agrees with my results. *Chiropteridium mespilanum* is a taxonomic junior synonym of *Chiropteridium galea*, so the index species is the same for both the Bujak-Davies Group and my determinations.

I examined two samples above 920 m: the lower at 900-890 m; and the higher at 810-800 m. At 900-890 m the only significant LAD was the acritarch *Cyclopsiella vieta*, originally described from the Oligocene by Davies and Loeblich (1967). However, Williams and Brideaux (1975) recorded *Cyclopsiella* cf. *vieta* from the Plio-Pleistocene in some shallow coreholes, the Grand Banks of Newfoundland. Perhaps more informative is the presence of *Lingulodinium machaerophorum* in the sample at 810-800 m. Williams (1975) gave the LAD for this species on the Scotian Shelf as late Miocene, and Williams and Bujak (1977) placed its LAD in the middle to late Miocene. Because *Lingulodinium machaerophorum* is living today, the above LADs are questionable. But it may be that in the vicinity of Hekja O-71, *Lingulodinium machaerophorum* has a restricted stratigraphic range. With this in mind, I questionably assign a Miocene age to the interval 900-800 m.

My conclusion regarding the age of the top two samples is not that dissimilar to the findings of the Bujak-Davies Group (1987). They include 900-800 m in their *Operculodinium centrocarpum* Zone to *Systematophora ancyrea* Zone of middle to late Miocene age. Examination of their analyses suggest that the age is based on the presence of *Osmundacidites claytonites*, which Williams and Bujak (1977) regarded as having an LAD in the middle to late Miocene of the Labrador Shelf.

Reworked Cretaceous dinocysts occur occasionally throughout Hekja O-71, but are surprisingly sparse. Reworked older Paleogene taxa also seem to be rare, although it is difficult to recognize those. A possible explanation for the relatively low numbers is that it reflects the paleoenvironments: this will be explained in the next section.

Paleoenvironments

Interpreting paleoenvironments from dinocyst and pollen/spore abundances has been attempted on pre-Quaternary subsurface sections. The problem is that dinocysts represent the encysted stage of the motile dinoflagellate, which is a planktonic organism. Consequently the tautology for many years was that dinocyst distribution patterns will not reflect water depths. This is correct literally but dinoflagellates and hence the corresponding dinocysts do show distinct environmental preferences, such as non-marine, lagoonal, coastal, close to shore and more offshore and open ocean settings. By assuming, for example, that open ocean equates with a deeper water or bathyal setting, some meaningful paleoenvironment

determinations can be made.

Initial control, based on other fossil groups and lithostratigraphy will ultimately lead to development of a relatively precise paleoenvironmental model for dinocyst. This has been ably demonstrated in the pioneering studies of Gocht (1969), Downie *et al.* (1971), Islam (1984) and Köthe (1990). Prior research led to the realization that both qualitative and quantitative analyses were needed to obtain results that were reproducible. Thus, the mode advanced by Brinkhuis (1992), which represented a major advancement in knowledge, must be married to quantitative values and must be informative at the species level. In his study of the Priabonian, Brinkhuis (op. cit.) depicted lateral changes in dinocyst composition across a continental margin, which passed laterally from a lagoonal to coastal to shelfal to open ocean setting. This model has been modified by Sluijs *et al.* (2005) and is used as a working hypothesis for some of the conclusions presented for the Hekja O-71 well. The two major differences are my utilization of quantitative data and my inclusion of spore and pollen data.

Generation of a paleoenvironmental curve for a well poses major problems not faced in studies of surface sections. The first concern is sample type. Rarely in a well are there conventional core samples and sidewall cores are not common. Predominantly, the palynologist has a choice between cuttings and cuttings. Such samples do not necessarily provide true counts, since caving is a major problem. This means that quantitative data cannot always be taken at face value.

Another concern with cuttings is the spacing. If one is lucky, samples represent 5 m composites that hopefully are taken continuously. But, when processing for palynomorphs only a small sample is collected and it may not be representative. For Hekja O-71, I had to rely exclusively on composite 10 m cuttings samples from 5 to 20 m apart.

Regardless of the drawbacks, generalizations can be made from the cuttings samples about paleoenvironments. For Hekja O-71, I used almost exclusively quantitative data, where possible counting 200 specimens. However, the low number of specimens in some samples restricted the number of specimens counted.

The paleoenvironmental curve is shown in Figure 1. I have not included the spore-pollen to dinocyst ratio, which provides useful information that I have summarized in the text.

In Hekja O-71, the paleoenvironments were predominantly shallow water (inner neritic) to marginal marine throughout the Tertiary. The problem is where to take the oldest sample, since the lowermost 1020 m are basalt. I picked as my starting point the cuttings sample from 3546 m. This sample is dominated by *Pinuspollenites*, with only 4 dinocysts. These are all *Cerodinium*. Also present is melanogen, phyrogen and hylogen plus one *Azolla*. I interpret this paleoenvironment as innermost neritic.

Innermost neritic to coastal settings predominate in the Thanetian and within the early Eocene (3546 to 3040-3030 m). Counts rarely provided the minimum of 200 specimens, but there are still environmental indicators. From 3546 to 3300 m, *Pinuspollenites* is invariably the dominant pollen and the dominant palynomorph. At 3280-3270 m, there is a marked change, with an influx of *Spiniferites* spp. and *Operculodinium centrocarpum*. The abundance of these two genera continues upwards to the cuttings sample at 3220-3210 m. I interpret this as denoting a farther offshore, inner shelf setting.

Dinocyst counts are minimal in the cuttings samples from 3210 to 3180 m but change at 3150-3140 m, with an influx of *Trithyrodinium*? "*circellum*". I do not know what are the paleoenvironmental preferences of this species but, from the accompanying taxa, I am assuming it is inner neritic to marginal

marine.

The *Apectodinium* peak is between 3149 and 3120 m. According to Bujak and Brinkhuis (1998) *Apectodinium homomorphum*, the most abundant species in this interval, is a warmer water species. Crouch *et al.* (2001) have shown that the onset of *Apectodinium*-dominated assemblages seems to be synchronous on a global scale. One such peak occurred during the Paleocene-Eocene thermal maximum (PETM), which lasted for about 220 ky at about 55 Ma. This can be correlated with the carbon isotope excursion (CIE), a benthic foraminifera extinction event and a calcareous nannofossil zonation. The *Apectodinium* influx denotes higher sea-surface temperatures and a major increase in marginal marine, surface water productivity. Correspondingly, a decline in *Apectodinium* abundance presumably indicates cooler water conditions. Thus, I postulate that warmer water conditions existed during deposition of the interval 3149-3120 m, which is close to the Paleocene-Eocene boundary.

Hekja O-71 differs from other wells in the Saglek Basin, such as Gjoa G-37 and Gilbert F-53, in having low numbers of *Areoligera gippingensis*. This must reflect the paleoenvironmental setting, which I interpret as marginal marine to innermost neritic. This shows that Heilmann-Clausen (1994) was correct when he considered *Areoligera gippingensis* as indicating offshore marine environments.

From 3120 to 2330 m, the top of the Ypresian, the paleoenvironments are predominantly marginal marine to coastal, with more marine conditions at 2950-2940 m, a brief interval of innermost neritic between 2700 and 2640 m, and a non-marine setting between 2390 and 2330 m. *Trithyrodinium?* "*circellum*" is dominant to frequent in samples from 3130 to 3030 m, indicating innermost shelf paleoenvironments. I postulate this on the low numbers of other dinocyst taxa and the presence of the green alga *Pediastrum* and "*Taurodinium*" in the cuttings sample at 3040-3030 m. Nøhr-Hansen, Fensome and Williams (pers. comm.) use the informal generic name "*Taurodinium*" for Paleogene ceratiaceans that differ from *Nyktericysta* in not having lateral horns. We are assuming that the paleoenvironmental signals for the two genera are similar, so I interpret "*Taurodinium*" as indicating marginal marine to lacustrine environments.

Azolla occur in the cuttings samples between 2620 and 2600 m and in the conventional core at 2587 m. The paleoenvironment represented by the cored interval appear to be innermost neritic. The major influx of *Azolla*, however, is between 2445 and 2320 m. High pollen counts and the one or two dinocysts indicate a marginal marine setting.

What are the findings of the Bujak-Davies Group (1987) and Miller and d'Eon (1987) on the prevailing paleoenvironments in the vicinity of Hekja O-71 during the Thanetian-Ypresian? The Bujak-Davies Group determined the paleoenvironments for the interval 4465-2330 m as: 4465-3600 m, inner neritic to transitional to non-marine; 3585-3180 m, inner to outer neritic; 3160-3150 m, middle to outer neritic; 3130-3120 m, inner to middle neritic; 3100-3020 m, transitional to inner neritic; 3000-1180 m, non-marine to transitional to inner neritic. Miller and d'Eon (1987), based on lithologic variations, came up with the following conclusions: 4566-3847 m, inner shelf; 3845-3544 m, marginal marine, mixed subaerial and subaqueous; 3544-3364 m, inner to mid shelf; 3364-3332 m, marginal marine, barrier beach; 3323-3286 m, marginal to non-marine, lagoonal; 3286-3200 m, marginal marine, fluvial channel meanders in estuary?, some swamp/marsh deposits; 3200-3100 m, inner to mid shelf; 3100-2972 m, inner shelf; 2972-2950 m, marginal marine, barrier beach; 2927-2859 m, marginal to non-marine, lacustrine/lagoonal; 2859-2628 m, marginal to non-marine, lacustrine/lagoonal; 2628-2436 m, marginal marine, brackish, interdeltaic; 2436-2254 m, non-marine, lacustrine/marginal lacustrine, varves, turbidites, deltaic. Condensing this down, the general trend is variable inner shelf to non-marine, with shelfal conditions from 4566 to 3847 m, 3544-3364 m, 3200-2972 m. From 2972 to 2254 m is generally marginal marine to non-marine. The general trend therefore is shallowing, which agrees with my data.

My only difficulty with the interpretations of the Bujak-Davies Group (1987) and Miller and d'Eon (1987) is that they postulate paleoenvironmental conditions during formation of the basalts. This is extremely difficult with the palynomorphs, many of which are dark brown. If the few present are in situ, the paleoenvironments appear to have fluctuated between marginal marine and inner neritic during extrusion of the basalts.

According to my data, the paleoenvironments did not vary too much in the middle Eocene (Lutetian-Bartonian) to early Oligocene (Rupelian). In the Lutetian, there were alternating episodes of marginal marine to non-marine conditions. In the Bartonian to Rupelian, coastal to marginal marine paleoenvironments predominated, with occasional non-marine interludes. I base my conclusions on the dominance of the spores and pollen in most of the samples, with their percentage of the total palynomorph count being over 90%. There are also high concentrations of herbaceous and woody material in several samples. Slightly more marine conditions seem to characterize the intervals 1730-1690 m, 1610-1580 m, 1390-1360 m, 1240-1180 m, 1160-1120 m, and 930-920 m. This is based on the influx of low numbers of dinocysts.

The two uppermost samples at 900-890 m and 810-800 m, provisionally considered to be Miocene, represent a marginal marine to innermost shelf environment.

As noted previously, Bujak-Davies Group (1987) considered 3000-1180 m to be non-marine to transitional to inner neritic. For above 1180 m they provided the breakdown: 1180-970 m, inner neritic; 950-910 m, inner to middle neritic; 890-880 m, inner neritic; 860-815 m, inner neritic; 810-735 m, non-marine to transitional. From 2254 m upwards, Miller and d'Eon (1987) recognized the following paleoenvironments: 2254-2177 m, non-marine, delta front, distributary channel/mouth bar complex; 2177-2121 m, non-marine, meandering fluvial, delta plain; 2121-2042 m, non-marine, marginal lacustrine/delta front; 2042-2016 m, non-marine, deltaic, distributary channel/mouth bar complex; 2016-1804 m, non-marine, lacustrine/prodelta, turbidites?; 1804-1564 m, non-marine, marginal lacustrine/delta front, alluvial fan delta; 1564-1416 m, non-marine, braided fluvial, delta plain, alluvial fan?; 1416-1400 m, non-marine?; 1400-1016 m, marginal marine to inner shelf, estuarine delta front? transgressive zone; 1016-890 m, inner shelf, delta front, distributary mouth bar complex?, tidal; 890-696 m, non-marine, braided delta plain.

My paleoenvironmental curve for the Lutetian (2310 m) to the Miocene (800 m) is intermediate between the findings of Miller and d'Eon (1987) and the Bujak-Davies Group (1987). My interpretation of marginal marine is based on the presence of occasional dinocyst taxa, which are marine. The two previous studies and I agree, however, in recognizing very shallow water to non-marine paleoenvironments for much of the Paleogene in Hekja O-71.

Correlation of Palynology and Lithostratigraphy

Figure 1 presents the lithostratigraphy of Hekja O-71, as interpreted by Moir (1987). This author used the term "unnamed basalts" for the interval 4566 (total depth) to 3545 m. Williamson *et al.* (2001) gave an age of 48.7 ± 1.3 Ma for a sample taken from an unspecified depth in the basalts. This would put it close to the Ypresian-Lutetian boundary, much younger than the ages of the overlying rocks, as determined from the biostratigraphy. However, Williamson *et al.* (2001) stated that they considered the 48.7 Ma age unreliable until replicated. The 59.5 ± 1 Ma and 59.2 ± 1.8 Ma ages (Selandian-Thanelian) that Williamson *et al.* (2001) gave for the basalts in Gjoa G-37 are much more in accord if compared with the biostratigraphy in Hekja O-71. By that I mean my provisional Selandian age for the interval 3930-4566 m and my Thanelian age for the interval 3940-3350 m.

According to Moir (1987), the basalt is overlain by the "Gudrid tongue" which is from 3364-3212 m.

McWhae *et al.* (1980) recognized a lower Gudrid tongue between the Markland and Cartwright formations and an upper Gudrid tongue between the Cartwright and Kenamu formations. Unfortunately, Moir (1987) did not specify which of the two “Gudrid tongues” he was discussing. Since this author indicated that the Cartwright Formation overlies the Gudrid tongue in Hekja O-71, I am assuming that he is including the interval 3364-3212 m in the lower Gudrid tongue.

Umpleby (1979) introduced the term Gudrid Sand Member of the Cartwright Formation. He considered the age of the Gudrid Member to be Paleocene to earliest Eocene. McWhae *et al.* (1980) raised the Gudrid to formation status and considered it “completely equivalent laterally to the Cartwright Formation” as defined by them. They considered the dominant lithology to be quartzose and felspathic sandstone. The sandstone was believed to be a turbiditic deep sea fan deposited in an outer shelf to bathyal (slope or rise) paleoenvironments (Gradstein and Srivastava, 1980). In Hekja O-71, I consider the age of the “lower Gudrid tongue” to be Thanetian to basal Eocene. The age of the unit indicates that it is the lower Gudrid tongue.

The Cartwright Formation, excluding the Gudrid tongue, extends from 3212 to 3104 m (Moir, 1987). As defined by Umpleby (1979), the Cartwright Formation is a claystone-siltstone sequence with thin sandstone and carbonate beds. Umpleby (1979) considered the paleoenvironments to be marginal to shallow marine. McWhae *et al.* (1980) disagreed, considering the sands to be turbidites and the lutites to be outer shelf or upper slope.

In Hekja O-71, the Cartwright Formation (including the Gudrid tongue) is Thanetian to early Ypresian and represents deposition in a close-to-shore, inner neritic environment. There are no obvious hiati in the formation. The age shows good agreement with the middle Paleocene to early Eocene age as determined from the foraminifera (McWhae *et al.*, 1980). But the paleoenvironments are much shallower, reflecting the basin-margin location of the well.

Moir (1987) included 3104-2175 m in the Kenamu Formation, with the Leif Member being from 2428 to 2175 m. McWhae *et al.* (1980) defined the Kenamu Formation as an Eocene shale, siltstone, sandstone sequence that can be glauconitic and calcareous and was deposited in outer shelf to slope environments. The Leif Sandstone Member was named by Umpleby (1979), who included it in his Saglek Formation. McWhae *et al.* (1980) renamed the unit the Leif Member and placed it in the upper part of the Kenamu Formation. These authors regarded the age as late Eocene to earliest Oligocene. The sandstone was believed to represent inner neritic, possibly tidal, deposition.

In Hekja O-71 the age of the Kenamu Formation is Ypresian-Lutetian and the Leif Member is latest Ypresian to Lutetian. These ages show remarkable agreement with the ages for the Kenamu Formation and Leif Member in Gjoa G-37 (Williams, in press b). The paleoenvironmental settings differ with those in Hekja O-71, however, which are marginal to non-marine, apart from two inner neritic interludes. In Gjoa G-37 the Kenamu Formation, including the Leif Member, represents outer shelf deposition.

The Kenamu Formation is successively overlain by the Mokami (2175-1730 m) and Saglek (1730-363 m) formations in Hekja O-71. McWhae *et al.* (1980) defined the Mokami Formation as a predominantly claystone and soft shale unit of Eocene to middle Miocene age. The formation was deposited during a period of shallowing, representing inner shelf to marginal marine deposition and increasingly cooler temperatures (Gradstein and Srivastava, 1980).

In Hekja O-71, the Mokami Formation is Lutetian-Bartonian and was deposited in a marginal marine to non-marine environment. This is much closer to shore than in Gjoa G-37. The thin Lutetian and absence of dinocyst index species suggest that there is missing section. Based on the bioevents chart produced by

Nøhr-Hansen, Fensome and Williams (pers. comm.), I consider that much of the early Lutetian is missing, indicating that there may be a hiatus at the base of the Mokami Formation.

Umpleby (1979) defined the Saglek Formation as a sequence of variably silty and sandy mudstones and suggested that it was a series of turbidites, with water depths corresponding to an inner to outer neritic environment in the Miocene. He considered the age to be Eocene to Plio-Pleistocene. McWhae *et al.* (1980) restricted the Saglek Formation to mid to late Miocene to Pliocene sediments. The formation consists of unconsolidated sandstones, some conglomeratic, with siltstones and claystones, with at its base the Beaufort Unconformity.

Moir (1987) placed the base of the Saglek Formation at 1730 m in Hekja O-71. This means that the age of the formation is Bartonian or younger, which is at odds with the definition of McWhae *et al.* (1980). I would prefer to extend the top of the Mokami Formation to 950 m. Regardless, the late Oligocene is attenuated in Hekja O-71. And the presence of *Wetzeliella symmetrica* in the single sample indicates to me that it is primarily the upper part of the Chattian that is absent. It also appears that the Early Miocene is missing. This hiatus could be equated with the Beaufort Unconformity.

McWhae *et al.* (1980) and McWhae (1981) recognized five regional unconformities in the Cretaceous-Cenozoic rocks of the Labrador Shelf. These were: the Labrador Unconformity, 130 to 120 Ma, which is Barremian-Aptian; the Avalon Unconformity, 100 to 85 Ma, which is Cenomanian-Santonian; the Bylot Unconformity, 63 to 60 Ma, which is Danian-Selandian; the Baffin Bay Unconformity, 28-34 Ma, which is latest Bartonian to Ypresian; and the Beaufort Unconformity, 20 to 10 Ma, which is Burdigalian to Tortonian. Thus, the Beaufort Unconformity would be late Early to early Late Miocene.

Summary

Hekja O-71 contains a ?Selandian to Miocene section, with suggested hiatus in the Lutetian and late Chattian-early Miocene. Correlation of the LADs with the dinocyst and spore/pollen bioevent plot of Nøhr-Hansen, Fensome and Williams (pers. comm.) has resulted in more reliable age determinations in the Paleocene and Eocene. This has been fortuitous because of the low number and diversity of the dinocysts, especially in the early and middle Eocene (Ypresian, Lutetian, Bartonian). The Nøhr-Hansen *et al.* (pers. comm.) chart provided control for some of the spore/pollen LADs that dominate the Eocene assemblages in Hekja O-71.

The sediments in Hekja O-71 were deposited in inner neritic to non-marine environments, with a general upward shallowing. My interpretations, which show good agreement with those of the Bujak-Davies Group (1987) and Miller and d'Eon (1987), will permit refinement of my model for Paleogene inner neritic to non-marine dinocysts occurrences and for dinocyst to spore/pollen ratios. A practical application of this model would be the analysis of the nearby Raleigh N-18 well. This study should be done immediately.

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Figures

Figure 1 Location of wells discussed in text.

Figure 2 Stratigraphy and paleoenvironments of Aquitaine *et al.* Hekja O-71.

Appendix A

Palynomorph taxa recorded in Hekja O-71. References for dinocyst citations are from Fensome and Williams (2004). Informal taxa will be illustrated in one of the proposed palyatlases.

Achomosphaera alvicornu (Eisenack, 1954b) Davey and Williams, 1966a
Adnatosphaeridium vittatum Williams and Downie, 1966c
Alisocysta circumtabulata (Drugg, 1967) Stover and Evitt, 1978
Altercidinium sp.
Apectodinium "fleximorphum"
Apectodinium homomorphum (Deflandre and Cookson, 1955) Lentin and Williams, 1977b
Apectodinium hyperacanthum (Cookson and Eisenack, 1965b) Lentin and Williams, 1977b
Apectodinium parvum (Alberti, 1961) Lentin and Williams, 1977b
Apectodinium quinquelatum (Williams and Downie, 1966b) Costa and Downie, 1979
Areoligera cf. *coronata* (O. Wetzel, 1933b ex Deflandre, 1937b) Lejeune-Carpentier, 1938a
Areoligera gippingensis Jolley, 1992
Areoligera cf. *senonensis* Lejeune-Carpentier, 1938a
Azolla spp.
Baltisphaeridium "scalenoformatum"
Batiacasphaera hirsuta Stover, 1977
Callimothallus pertusus Dilcher, 1965
Camaronosporites insignis Norris, 1967
Caryapollenites imparalis Nichols and Ott, 1978
Caryapollenites veripites (Wilson and Webster, 1946) Nichols and Ott, 1978
Casuarinidites sparsus Frederiksen and Christopher, 1978
Cerodinium denticulatum (Alberti, 1959b)
Cerodinium diebelii (Alberti, 1959b) Lentin and Williams, 1987
Cerodinium "glabrum"
Cerodinium sp.
Cerodinium speciosum (Alberti 1959b) Lentin and Williams, 1987
Cerodinium speciosum subsp. *"brevicornum"*
Cerodinium striatum (Drugg, 1967) Lentin and Williams, 1987
Chatangiella tripartita (Cookson and Eisenack, 1960a) Lentin and Williams, 1976
Chiropteridium galea (Maier, 1959) Sarjeant, 1983
Cicatricosisporites hallei Delcourt and Sprumont, 1955
Cicatricosisporites "labatus"
Cicatricosisporites sp.
Cicatricosisporites auritus
Cinguliriletes Pierce, 1961
Cleistosphaeridium diversispinosum Davey et al., 1966
Cleistosphaeridium diversispinosum subsp. *"brevispinum"*
Cleistosphaeridium urbinii subsp. *"brevispinum"*
Comasphaeridium cf. *cometes*
Cordosphaeridium cantharellus (Brosius, 1963) Gocht, 1969
Cordosphaeridium fibrospinosum Davey and Williams, 1966b
Cribroperidinium giuseppi (Morgenroth, 1966a) Helenes, 1984
Cupaneidites spp.
Cycadopites sp.
Cyclopsiella vieta Drugg and Loeblich Jr., 1967
Dapsilidinium pastielsii (Davey and Williams, 1966b) Bujak et al., 1980
Dapsilidinium? simplex (White, 1842) Bujak et al., 1980

Deflandrea heterophlycta Deflandre and Cookson, 1955
Deflandrea hialina Baltes, 1969
Deflandrea oebisfeldensis Alberti, 1959b
Densosporites sp.
Dicellaesporites sp.
Diporicellaesporites liaoningensis Ke and She ex Sung et al., 1978
Enneadocysta "magna"
Eocladopyxis peniculata Morgenroth, 1966a
Extratropipollenites spp.
Glaphyrocysta divaricata (Williams and Downie, 1966c) Stover and Evitt, 1978
Glaphyrocysta ordinata (Williams and Downie, 1966c) Stover and Evitt, 1978
Glaphyrocysta pastielsii (Deflandre and Cookson, 1955) Stover and Evitt, 1978
Glaphyrocysta retiintexta (Cookson, 1965a) Stover and Evitt, 1978
Gothanipollis Krutzsch, 1959
Hafniasphaera hyalospinosa Hansen, 1977
Heteraulacacysta pustulata Jan du Chêne and Adediran, 1985
Homotryblium abbreviatum Eaton, 1976
Homotryblium tenuispinosum subsp. "*brevispinum*"
Horologinella sp.
Hystrichokolpoma spinosum Wilson, 1988
Hystrichosphaeridium tubiferum (Ehrenberg, 1838) Deflandre, 1937b
Hystrichosphaeridium tubiferum subsp. *brevispinum* (Davey and Williams, 1966b) Lentin and Williams, 1973
Hystrichostrogylon membraniphorum Agelopoulos, 1964
Juglanspollenites sp.
Komewuia? "unicornis"
Lacrimasporonites permagnus Parsons and Norris, 1999
Lejeunecysta hyalina (Gerlach, 1916) Artzner and Dörhöfer, 1978
Lejeunecysta sp.
Lentinia "glabra"
Lingulodinium "brevispinosum"
Lingulodinium machaerophorum (Deflandre and Cookson, 1955) Wall, 1967
Lingulodinium multivirgatum de Verteuil and Norris, 1996a
Lingulodinium sp.
Liquidamberpollenites sp.
Lycopodiumsporites sp.
Membranophoridium aspinatum Gerlach, 1961
Microsphaeridium aneistroides Benedek, 1972
Momipites actinus Nichols and Ott, 1978
Momipites coryloides Wadehouse, 1933
Momipites tenuipolus Anderson, 1960
Momipites ventifluminis Nichols and Ott, 1978
Momipites wyomingensis Nichols and Ott, 1978
Multicellaesporites sp.
Myrtaceaepollenites sp.
Nematosphaeropsis rigida Wrenn, 1988
Nyssapollenites spp.
Odontochitina costata Alberti, 1961
Oligosphaeridium complex (White, 1842) Davey and Williams, 1966b
Oligosphaeridium totum Brideaux, 1971

Operculodinium centrocarpum (Deflandre and Cookson, 1955) Wall, 1967
Operculodinium tiara (Klump, 1953) Stover and Evitt, 1978
Osmundacidites sp.
Ovoidinium cinctum (Cookson and Eisenack, 1958) Davey, 1970
Ovoidinium verrucosum (Cookson and Hughes, 1964) Davey, 1970
Palaeocystodinium bulliforme Ioannides, 1986
Palaeoperidinium basilium Drugg, 1967
Phelodinium kozlowskii (Górka, 1963) Lindgren, 1984
Phelodinium magnificum (Stanley, 1965) Stover and Evitt, 1978
Phelodinium sp.
Pluricellaesporites sp. C Parsons and Norris, 1999
Podocarpidites sp.
Polysphaeridium sp.
Quercoidites sp.
Retitricolpites georgensis Brenner, 1963
Retitricolpites maximus Singh, 1971
Retitricolpites vulgaris Pierce, 1961
Schizocystia rugosa Cookson and Eisenack, 1962a
Senoniasphaera protrusa Clarke and Verdier, 1967
Sepispinula huguoniottii (Valensi, 1955a) Islam, 1993
Sequoapollenites sp.
Spiniferites bentorii (Rossignol, 1964) Wall and Dale, 1970
Spiniferites crassipellis (Deflandre and Cookson, 1955) Sarjeant, 1970
Spiniferites "digitatus"
Spiniferites "furcosus"
Spiniferites pseudofurcatus (Klumpp, 1953) Sarjeant, 1970
Spiniferites pseudofurcatus subsp. "*brevispinus*"
Stiphrosphaeridium dictyophorum (Cookson and Eisenack, 1958) Lentin and Williams, 1985
Sumatradinium sp.
Surculosphaeridium longifurcatum (Firtion, 1952) Davey et al., 1966
Svalbardella sp.
"Talladinium coleothryptum"
"Tauradinium granulatum"
Tenua hystrix Eisenack, 1958a
Thalassiphora pelagica (Eisenack, 1954b) Eisenack and Gocht, 1960
Tiliaepollenites spp.
Trinovantedinium sp.
Trithyrodinium? "*circellum*"
Tritonites pandus Marshall and Partridge, 1988
Tsugaepollenites? *pseudomassulae* Mädler, 1964b
Veryhachium formosum Stockmans and Willièrè, 1960
Veryhachium trispinosum (Eisenack, 1938a) Stockmans and Willièrè, 1962a
Vitreisporites sp. Singh, 1972
Wetzeliiella articulata O. Wetzel in Eisenack, 1938b
Wetzeliiella symmetrica Weiler, 1956
Wilsonidium compactum Michoux, 1988
Zlivisporis sp.

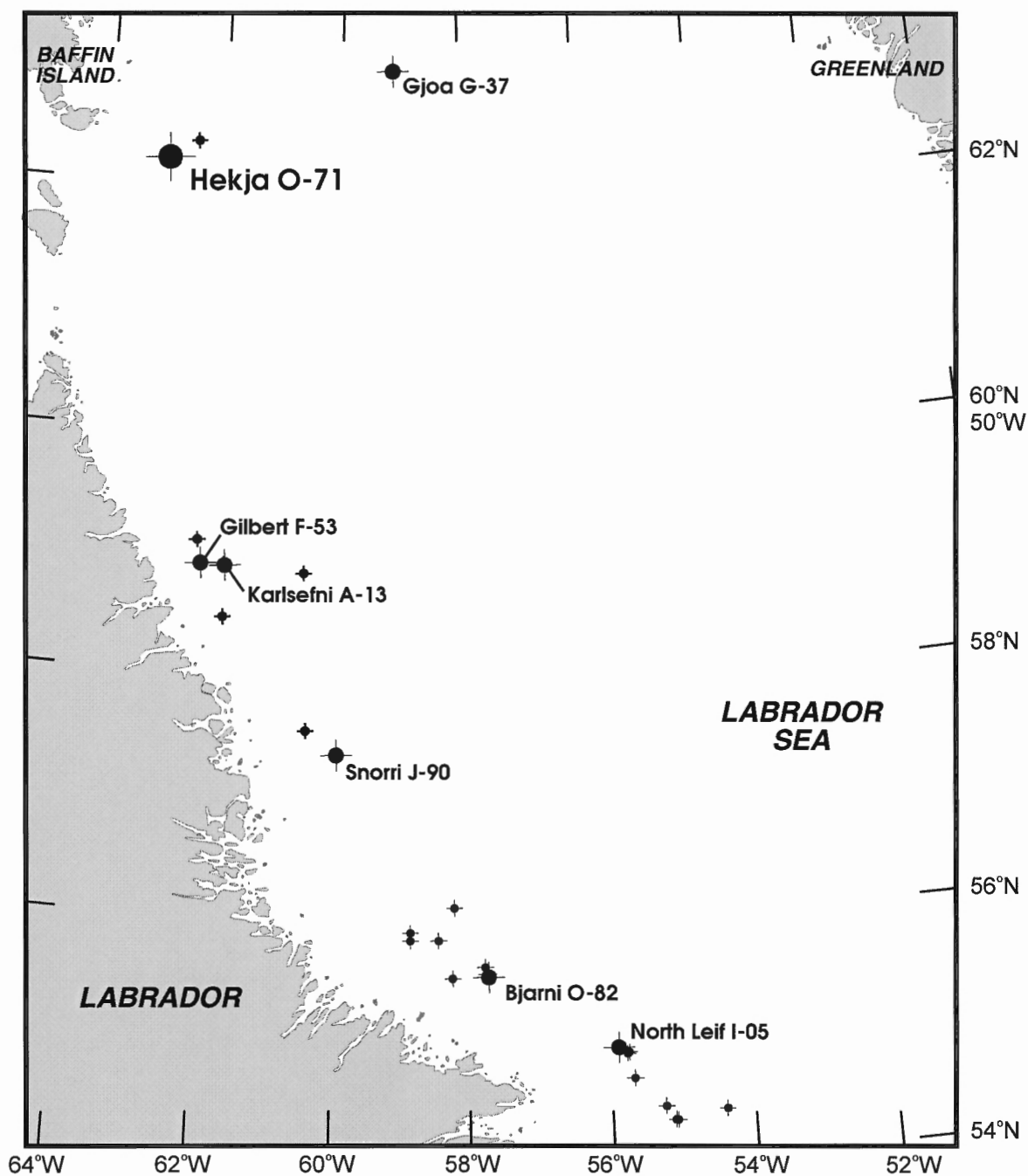


Figure 1. Location of wells discussed in text.