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The Tectonic Evolution of Nares Strait: Implications of New Data

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Abstract: The plate tectonic setting of the research area is well constrained by magnetic anomaly patterns in the surrounding oceans. Greenland as part of Eurasia separated from North America during the Late Cretaceous and the Paleocene, which implied sinistral strike-slip motion in the present Nares Strait region. The direct field evidence for this postulated transform, the Wegener Fault, however, was not very convincing. We provide new data acquired during the Nares Geocruise 2001 and mapping activities on Ellesmere Island in the seasons before.

In the northern part of Nares Strait, from the Lincoln Sea to Dobbin Bay, there is consistent evidence for substantial strike-slip motion between Greenland and Ellesmere Island, i.e. for the existence of the Wegener Fault. Onshore, a significant sinistral fault system has been mapped, and dated as Paleocene, i.e. as having been active at the time of Greenland – North America plate motion. Pull-apart basins associated with this fault system can be traced offshore, and the aeromagnetic data also indicate a crustal boundary west of Nares Strait. However, the motion along these faults is not sufficient to accommodate the total opening of Baffin Bay, and intra-plate extension and deformation within the North American Plate is suggested as the source of the remainder. In the Kennedy Channel region, the plate boundary is delineated by a down-faulted sedimentary basin along the coast of Ellesmere Island, where the Greenland Plate is over-thrust by the Eocene to Oligocene Eurekan fold belt. In this region, and in the onshore area to the NW, evidence for strike-slip motion may have been over-ridden by subsequent convergence.

In the southern part of the region, it is more difficult to reach a consistent interpretation. The aeromagnetic data from Kane Basin show that there is no significant offset within the basin itself. Whether they permit such an offset along the Ellesmere Island coast remains a matter for discussion. Fission track data suggest that the area was subject to tectonic activity, and seismic data south of Smith Sound also provides evidence in favour of strike-slip motion. It is not yet possible to resolve definitively how motion was partitioned between the Strait itself and the interior of the present North American Plate. A possible alternate route of the Wegener Fault west of the Inglefield Uplift encounters major problems in the Grisefjord area for the structural link with the oceanic Baffin Bay.

Zusammenfassung: Der plattentektonische Rahmen des Untersuchungsgebiets ist durch die magnetischen Lineationsmuster in den umgebenden Ozeanen klar umrissen. In der obersten Kreide und im Paläozän trennte sich Grönland als Teil Eurasias von Nordamerika. Dieser Vorgang erforderte eine sinistrale Seitenverschiebung im Gebiet der heutigen Nares Strait. Direkte Feldbelege für die postulierte „Wegener-Transform-Störung“ waren jedoch schwer zu finden. Wir präsentieren hier neue Ergebnisse von einer Messfahrt in der Nares Strait 2001 und von Kartierarbeiten auf dem benachbarten Ellesmere Island in den Jahren zuvor.

Im nördlichen Abschnitt der Nares Strait zwischen Lincoln Sea und Dobbin Bay gibt es schlüssige Belege für eine bedeutende Lateralbewegung zwischen Grönland und Ellesmere Island, d.h. für die Existenz der Wegener-Störung. An Land wurde ein größeres sinistrales Blattverschiebungssystem paläozänen Alters kartiert, das zeitlich in die Spanne der Plattenbewegung zwischen Grönland und Nordamerika passt. Pull-apart-Becken, die an diese Störungen gebunden sind, können unter dem Wasser der Nares Strait geophysikalisch verfolgt werden. Die aeromagnetischen Daten deuten außerdem auf eine Krustengrenze im Gebiet unmittelbar westlich der Nares Strait hin. Der Versatz an diesen Störungen ist jedoch nicht groß genug, um den Öffnungsbetrag der Labrador-See auszugleichen. Hierfür wird Intraplatten-Deformation in der nordamerikanischen Platte vorgeschlagen. Im Kennedy Channel wird die Plattengrenze auf der Seite der Ellesmere Island durch ein küstenparalleles Sedimentbecken nachgezeichnet und zwar genau in dem Gebiet, in dem die Grönland-Platte durch den eozänen bis oligozänen Eureka-Faltengürtel überschoben wurde. In dieser Region und weiter nordwestlich an Land können die Spuren der Blattverschiebung durch die spätere Kompression verhüllt worden sein.

Im südlichen Abschnitt der Nares Strait ist es schwieriger, eine schlüssige Interpretation zu finden. Die aeromagnetischen Daten über dem Kane Basin zeigen in diesem Meeresbecken selbst keinen Versatz. Es wird aber diskutiert, ob sie einen solchen entlang der Ellesmere-Küste zulassen. Spaltspuren-Ergebnisse zeigen, dass das Gebiet zur fraglichen Zeit tektonisch aktiv war, und seismische Ergebnisse südlich des Smith Sound liefern Hinweise auf Lateralbewegungen. Es ist zur Zeit noch nicht möglich, die Aufteilung der Bewegung zwischen der Nares Strait selbst und dem Innern der nordamerikanischen Platte abzuschätzen. Ein diskutierter Alternativ-Verlauf der Wegener-Störung westlich des Inglefield Uplifts im südlichen Ellesmere Island trifft auf Probleme bei der nötigen Verbindung zur ozeanischen Baffin Bay im Gebiet von Grisefjord.

INTRODUCTION

It is perhaps paradoxical that a feature that appears at first sight to be a clear case of simple lateral continental motion, and was interpreted as such by both TAYLOR (1910) and WEGENER (1912) in developing the hypothesis of continental drift, should turn out to be so complex and controversial (DAWES & KERR 1982). We believe that the work described in the papers of this volume makes a major contribution to resolving some of the problems of the area, although there are still many unanswered questions. Here, we summarise some of the most significant results, and attempt a synthesis for the entire Strait. It should be noted that this is not intended to be a complete summary of the work carried out in connection with the Nares 2001 project; the contributions in fields such as surficial marine geology, oceanography and geodesy are important especially for the recent glacial history of the area, but do not bear directly on its tectonic evolution. In addition, observations can often be interpreted in various ways, and in some cases our attempt to take an overall view results in an interpretation that differs to some extent from that of the authors of the individual papers.

TECTONIC SETTING

The history of plate motion between Greenland and North America is well constrained by magnetic anomaly patterns in the North Atlantic and Arctic Oceans, as well as the Labrador Sea (HINZ et al. 1979, SRIVASTAVA 1985, SRIVASTAVA & TAPSCOTT 1986, ROEST & SRIVASTAVA 1989, CHALMERS & LAURSEN 1995). Greenland, as part of Eurasia, separated from Labrador and Baffin Island in the early stages of North Atlantic opening, with implied strike-slip motion in the present Nares Strait region (Fig. 1). Subsequent development of the North Atlantic spreading axis to the east of Greenland resulted in a

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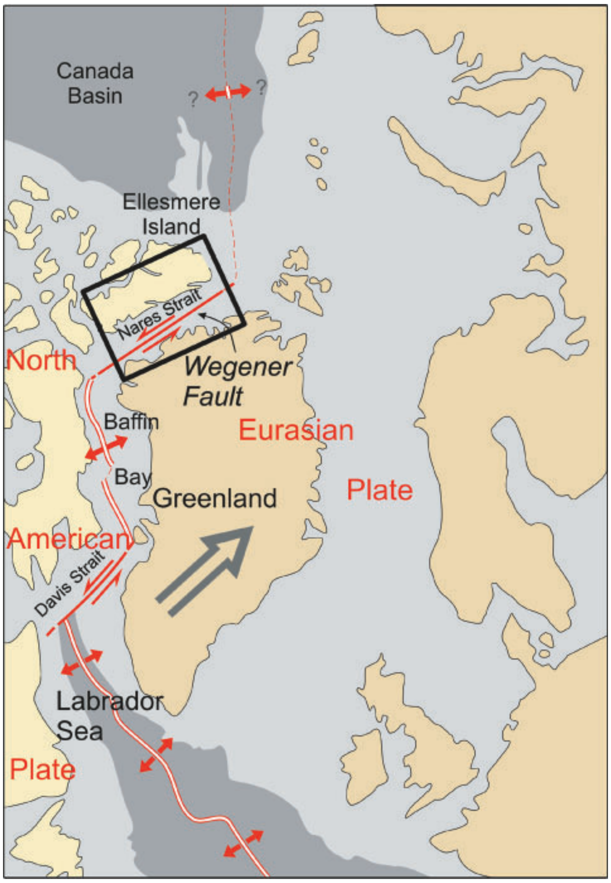

Fig. 1: Plate Tectonic Setting during the Late Cretaceous to Paleocene. During opening of Labrador Sea and Baffin Bay, the Greenland plate as part of the Euasian plate moved to the NE, causing sinistral strike-slip faults in the area of Davis and Nares straits.

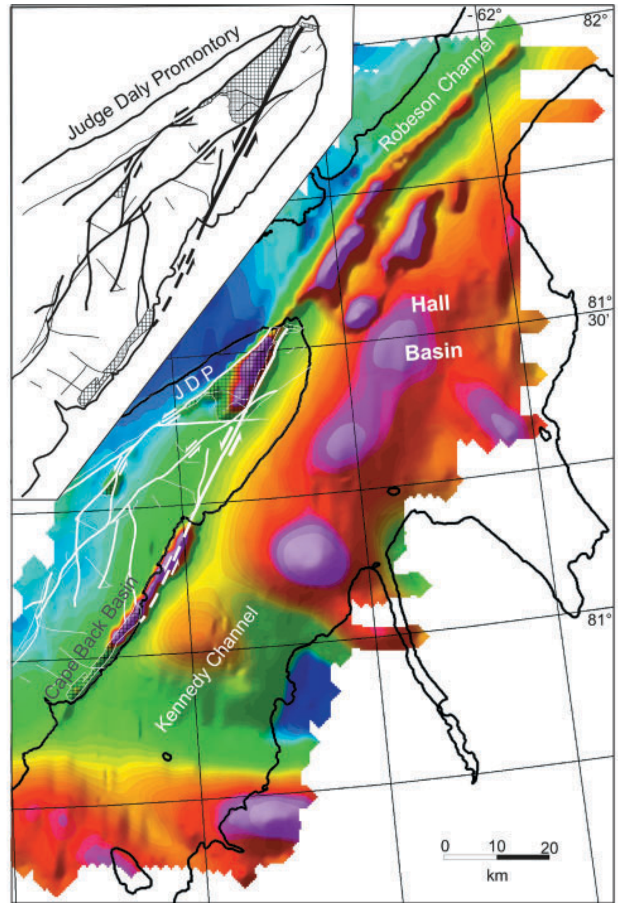

Fig. 2: Aeromagnetic map of the Hall Basin area from Damaske & Oakey (this vol. 2006), combined with selected geological features (inset) onshore. Paleocene sedimentary basins (crosshatched) contain volcanogenic sandstones with strong magnetic signature, which continues offshore to the north and south. The signature stops in the southernmost (Cape Back) basin, where thick limestone conglomerates replace the sandstone facies.

change of motion, with northward motion of Greenland producing convergence and compression between Greenland and Ellesmere Island, which is manifested geologically in the Eurekan fold belt to the northwest of Nares Strait.

The plate reconstructions themselves show that the interpretation of the Strait as a simple strike-slip fault, the "Wegener Fault" of Wilson (1965) is an oversimplification. It is therefore not surprising that the geological evidence for such a fault is, at best, fragmentary. Harrison (this vol. 2006) provides an overview of the geological evidence for and against lateral offsets, and finds significant differences between the northern and southern parts of the Strait. Since these were the two regions that were particularly investigated by the Nares 2001 project, we will consider the new geophysical and geological data from each of these separately, before attempting an overall synthesis.

NORTHERN NARES STRAIT

Strike-slip faults with a substantial amount of sinistral offset have been identified on northeast Ellesmere Island (Mayr & DeVries 1982, Mayr et al. in press). Based on a number of assumptions, Harrison (this vol. 2006) estimates the total amount of slip on the Judge Daly fault system to be 65-75 km, and interprets it as the local geological expression of the Wegener Fault. An implication of this interpretation is that part of the Greenland plate is in fact exposed on Ellesmere Island. If this is the case, the basement of northern Nares Strait, in the Kennedy Channel region, should be continuous with that of Greenland.

The new geophysical data (Damaske & Oakey this vol. 2006) provides strong evidence in favour of this interpretation. The aeromagnetic survey shows a systematic variation in the amplitude of the regional magnetic anomalies (Fig. 2). They are positive over Greenland and as far west as the coast of Ellesmere Island. These anomalies have been attributed to Archean basement rocks overlain by nonmagnetic Silurian and Devonian carbonates. The contrasting negative magnetic anomalies of Ellesmere Island suggest a different basement. The change in amplitudes from positive to negative can be interpreted as supporting evidence of a crustal boundary in Nares Strait. This boundary can be traced from the Lincoln Sea to the vicinity of Franklin Island in Kennedy Channel.

The magnetic data also provide evidence for offshore extension of the Judge Daly fault system. Geological investigations of the region associated with two parallel linear magnetic anomalies on the Judge Daly Promontory found that basaltic clasts in sedimentary basins bounded by sinistral faults are responsible for the anomalies. These linear anomalies and, by implication, the associated fault-bounded basins, can be readily traced offshore. They have a shallow source of a kilometre or less, and are located to the east of the transition from mainly positive to mainly negative anomalies that is interpreted as the crustal boundary. The association of the magnetic lineations with onshore sinistral strike-slip faults, and dating of the clasts as Paleocene, provide a sharp delineation in space and time of the distal edge of the Ellesmere Island plate.

Fission track measurements from the Judge Daly Promontory (Grist & Zentilli this vol. 2006) provide valuable information on the timing of the movements. The fission track ages from the Pavy Formation of Cape Back are indistinguishable from volcanic provenance ages of 58.5-61.2 Ma (Estrada et al. in press), and are consistent with active volcanism that could be related to rift transform volcanism. The fault-bounded Pavy River system may therefore represent the exposed portion of the Wegener Fault system, parts of which may be thrust-overridden further south. The fission track data are compatible with extensive strike-slip motion during the late Paleocene (Grist & Zentilli this vol. 2006).

Seismic data are obviously crucial for determining the nature of the Nares Strait basement and the location of any offshore faults. The seismic reflection survey completed during this project (Jackson et al. this vol. 2006) succeeded in determining several important characteristics of the seabed and subsea floor in north-eastern Kane Basin, Kennedy Channel and Hall Basin (Fig. 3). Adjacent to the coast of Ellesmere Island at Cape Lawrence, a continuation of the Franklin Pierce sedimentary basin is present (Fig. 3b). The basin is fault-bounded and asymmetric, deepest near the Ellesmere Island coast. A vertical throw of over a kilometre is required on the coastal fault scarp. Industry seismic data (Rendell & Craig 1976) show that the Franklin Pierce Basin in north western Kane

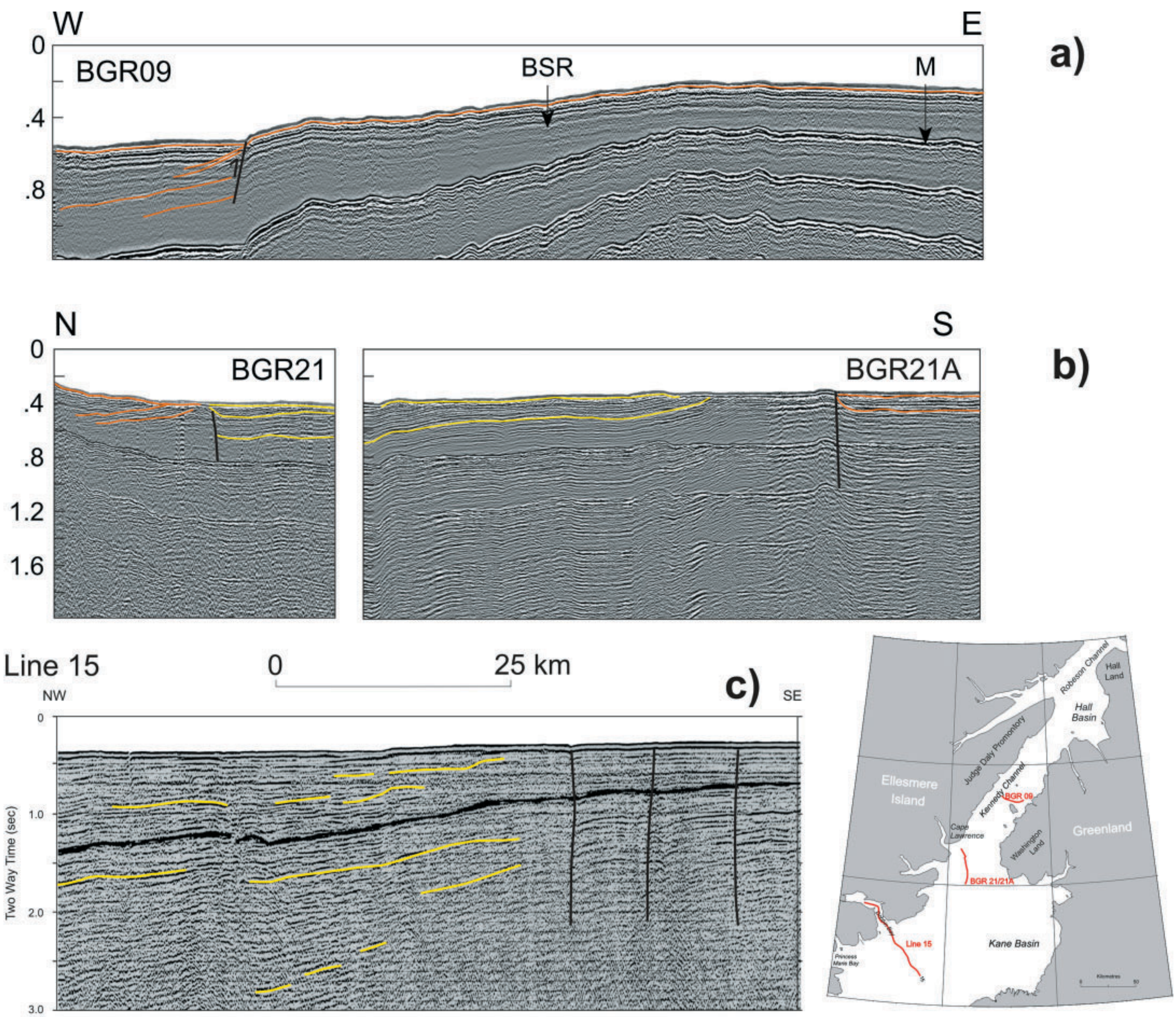

Fig. 3: Selected seismic lines in Kennedy Channel after Jackson, Dehler et al. (this vol. 2006). Line BGR 09 shows contact between front thrust of Ellesmerian system in contact with carbonate platform of Greenland side. Line BGR 21-21a runs almost N–S, but crosses diagonally an offshore sedimentary basin south of Cape Lawrence. Line 15 from Rendell & Craig (1976) crosses the same basin near Dobbin Bay.

Basin is also asymmetric, and deepest near the Ellesmere Island coast (Fig. 3c). A steep coastal fault terminates the Eurekan thrusts sheets in the Dobbin Bay area.

Ice conditions further north in Kennedy Channel prevented surveying near the Ellesmere Island coast, so it was not possible to establish the presence of a corresponding basin here. In the area surveyed, the Strait is underlain by a reflector with a hard surface and no internal structure. Refraction data (Funck, Dehler et al. this vol. 2006) indicate velocities of 5.8 km s^{-1} at the surface in the east of the area and 6.1 km s^{-1} in the west. These velocities are consistent with a carbonate platform, dipping away from the Greenland coast that extends across most of the channel (Fig. 3a). Carbonate platform and reefal mounds are exposed on Hans Island and along the Greenland coast. In the central and eastern part of Kennedy Channel there is no evidence of faulting. The reflection and refraction results support the interpretation that the crust across most of Nares Strait is of Greenland affinity.

The new geophysical information: magnetics, seismic reflection and refraction profiles, together with fission track data and recent publications on the geology of the Judge Daly Promontory (Mayr et al. in press), allow the faulted contact between Greenland and Ellesmere Island crust to be traced along the coast of Ellesmere Island from the Lincoln Sea into north-eastern Kane Basin. The observed sinistral offset of the Judge Daly Fault System supports identification of this as a primary locus of strike-slip motion along the Strait. However, the 65-75 km offset suggested by Harrison (this vol. 2006) is not sufficient to account for the offset required for the opening of Baffin Bay. Harrison (this vol. 2006) suggests that the remainder of the offset may be taken up further inland, in the Sverdrup Basin, and by extension across Lancaster and Jones Sounds, effectively decoupling Ellesmere Island from the rest of North America. There is also the possibility that much of the evidence for strike-slip motion was obliterated by the thrusting associated with convergence of the Eurekan orogeny. Nevertheless, this feature, which matches most closely the original definition of the Wegener Fault, can be identified with some confidence in the nothern part of Nares Strait.

SOUTHERN NARES STRAIT

To the south, in the region of Kane Basin and Smith Sound, it is more difficult to find an interpretation that is consistent with all the observations. A complete aeromagnetic survey was made of southern Kane Basin and nearby onshore areas (Oakey & Damaske this vol. 2006). The general magnetic pattern (Fig. 4) reflects the geology. Short-wavelength anomalies in areas of crystalline basement and thin Proterozoic cover are replaced by more subdued, long-wavelength anomalies over southern Kane Basin, which is believed to be underlain by Proterozoic sedimentary rocks of the Thule Supergroup. The observation that has the greatest bearing on the present discussion is the presence of several narrow, continuous anomalies that cross the otherwise magnetically quiet Kane Basin. One of these in particular, which can be correlated with an early Proterozoic dyke at Kap Leiper on Greenland and thus predates the more recent tectonic activity, can be traced with confidence almost to the Ellesmere Island coast. Thus it convincingly rules out the possibility of major strike-slip motion associated with a Wegener Fault through Kane Basin itself. Oakey & Damaske (this vol. 2006) make some additional correlations of magnetic anomalies across the Ellesmere Island coast, and interpret these to refute the existence of a Wegener Fault in this region. They and Harrison (this vol. 2006) suggest that the strike-slip motion is accommodated further inland, with the Inglefield uplift in south-eastern Ellesmere Island belonging to the Greenland plate. In our view, the fact that the Kap Leiper Dyke cannot be traced onto Ellesmere Island, and that the other correlations are not sufficiently constrained to be conclusive, means that some amount of strike-slip motion at or near the Ellesmere Island coast, as is the case further north, cannot be definitely ruled out.

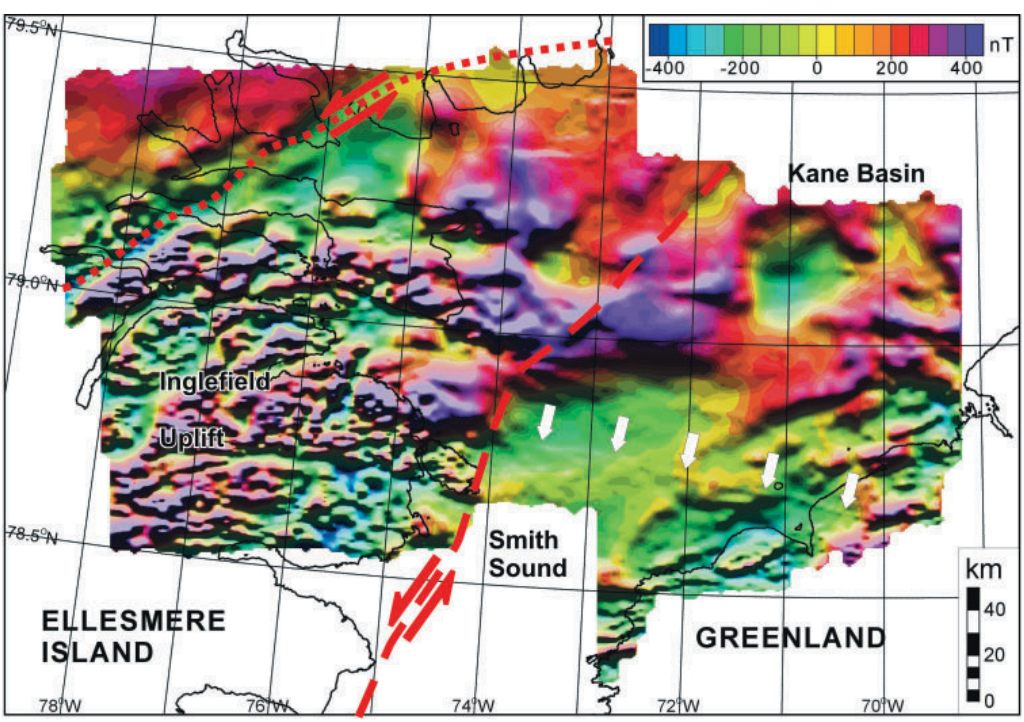

Fig. 4: Aeromagnetic map of the Smith Sound – Kane Basin area from Oakey & Damaske (this vol. 2006). White arrows indicate trace of Cape Leiper Dyke. Following the seismic evidence from the south, a possible continuation of the Wegener Fault is projected near the coast of Ellesmere Island. Coming from the North, the broken line indicates the alternate track of the fault, which would make the Inglefield Uplift a part of the Greenland plate.

Thermal models for samples from sea level dykes from around Smith Sound suggest a period of Late Cretaceous – Paleocene heating prior to the final cooling during the Paleocene (Grist & Zentilli this vol. 2006). These observations tend to oppose the implication of Harrison's (this vol. 2006) model, in which Smith Sound is entirely within the Greenland plate, and remote from any tectonic activity at this time.

Additional important evidence is provided by the seismic reflection data (Neben et al. this vol. 2006) that were acquired south of Smith Sound. This region has experienced regional tectonism, creating faulted and folded sedimentary basins and uplifted areas where basement, either Thule Supergroup or Archean, is exposed. Three major basins are identified on the seismic profiles (Fig. 5): one north–south and two northeast–southwest. They show fundamentally different character in stratigraphy and deformation.

Differing axes of stratigraphic thickening and unconformities in the northeast–southwest basins suggest several periods of tectonic movement. The larger of these, the Kiatak basin, is dominated by a number of extensional faults, which are replaced by folds to the west.

The north–south North Water Basin is V-shaped and characterized by many short incoherent seismic reflectors (Fig. 6) The close spacing of the faults and their fan-like pattern suggests a pull-apart basin or flower structure (Dooley et al. 1999). Immediately to the south, flower structures have been identified on the west flank of the Carey Basin (Jackson et al. 1992). We suggest that the North Water Basin structures are the northward continuation of those of the Carey Basin, and that the flower structures, indicative of strike-slip motion, delineate the Wegener Fault in this area. It is not possible from the seismic data alone to make any estimate of the amount of strike-slip motion associated with these features. The other

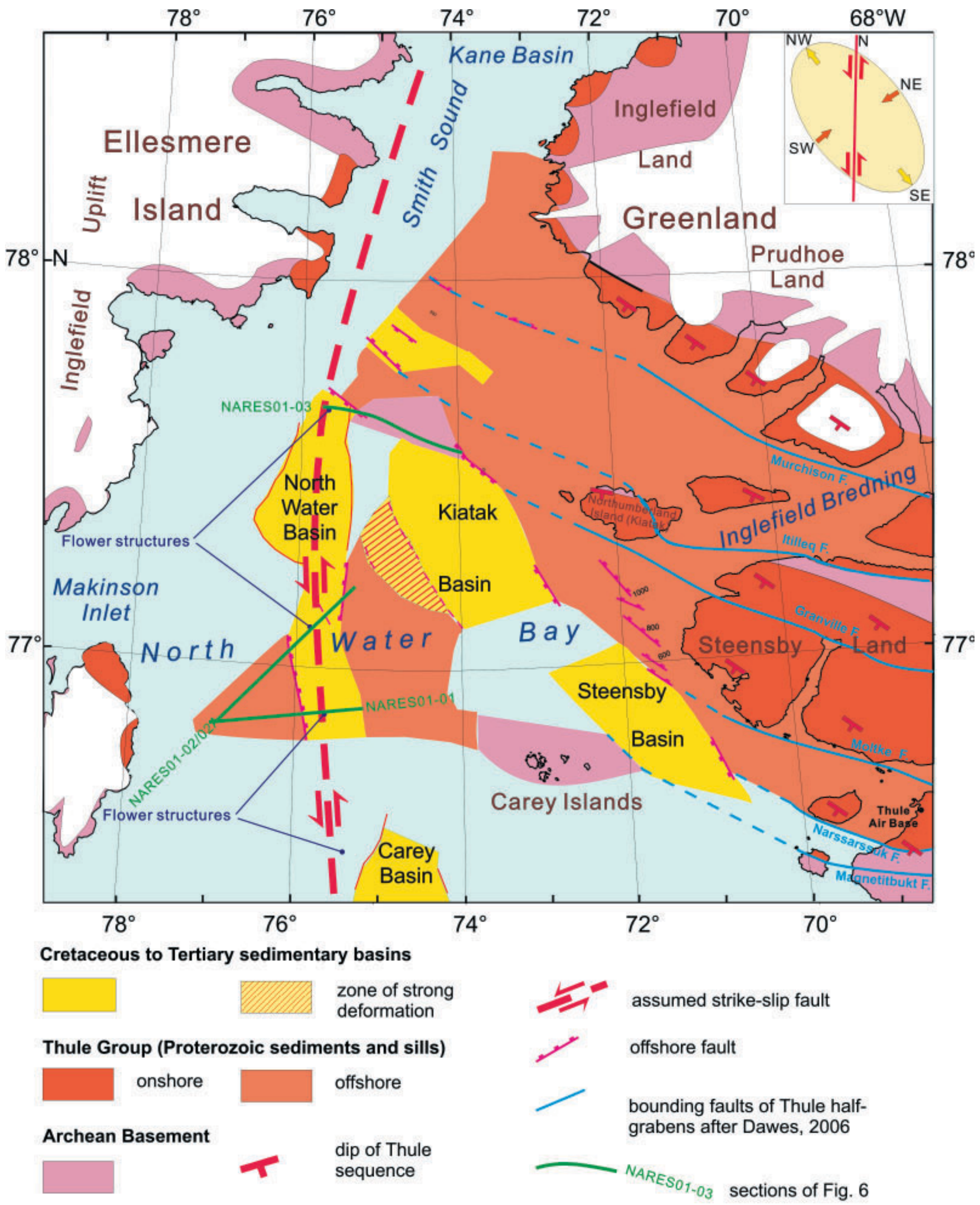

Fig. 5: Interpretative map of the North Water Bay indicating young sedimentary basins downfaulted in a large area of Proterozoic Thule Super Group rocks, simplified from Neben et al. (this vol. 2006). The narrow elongate North Water Basin is thought to represent a pull-apart basin strongly deformed by a set of flower structures. Three seismic sections of Fig. 6 are marked green.

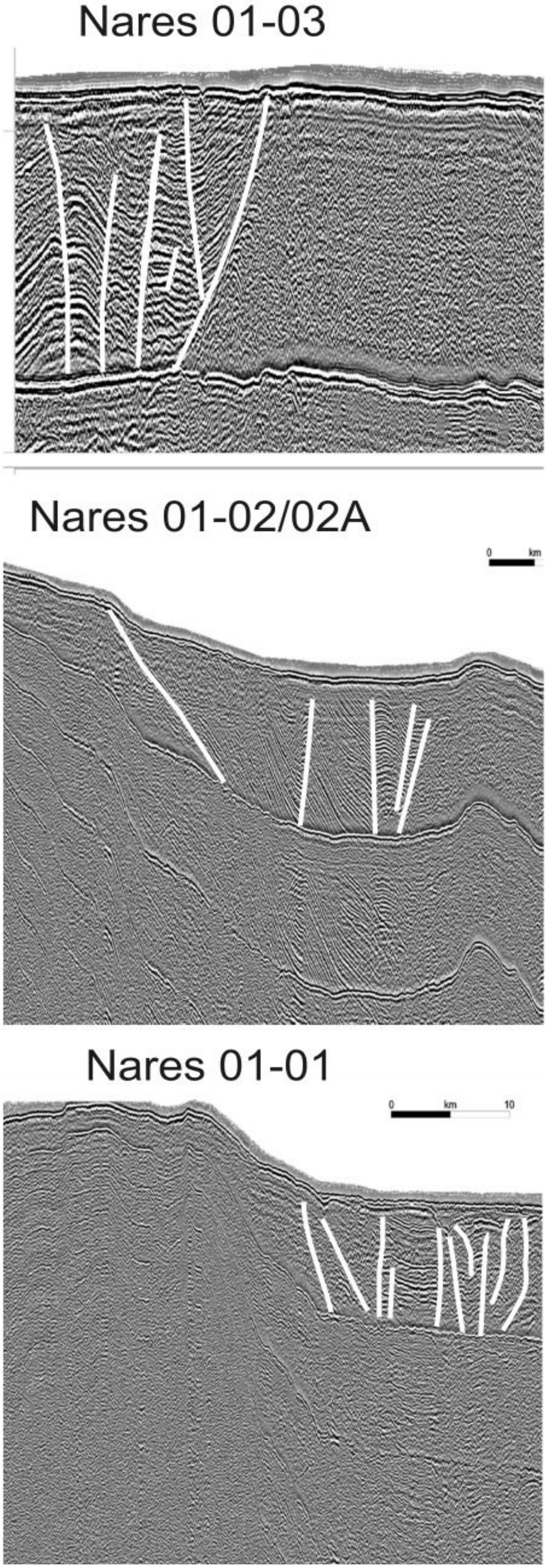

Fig. 6: Three sections across the North Water Basin (see Fig. 5 for location) from Neben et al. (this vol. 2006). The deep V-shaped basin is cut by sets of fairly close-spaced faults. The sedimentary layers between the faults are more or less strongly deformed.

two basins fit into the same stress field, but they may well be older because of the much thicker sedimentary infill.

The crustal refraction profile in this area also provides data that may be consistent with a boundary south of Smith Sound. There is a subtle change in the velocity structure of the upper and middle crust that coincides with the flower structure of the North Water Basin. The lower crustal velocity structure and thickness are general uniform, apart from a local shallowing of Moho east of the North Water Basin. The Carey Island uplift is positioned over the shallow Moho. These velocity and thickness variations are consistent with the position of the Wegener Fault as interpreted on the seismic reflection profile.

Another deep refraction profile crosses northern Baffin Bay, 100 km to the south, across the Carey Basin (Reid & Jackson 1997). Here, too, there is a thinning of the crust to the east of the basin, much more pronounced in this case. We suggest that the crustal thinning is a continuous feature, which is strongest in the south, towards the continent-ocean boundary of Baffin Bay, and continues northward towards Smith Sound, becoming weaker as the overall crustal thickness increases to normal continental values.

Fission track data from a mafic dyke on the Carey Islands yielded a fission track age of 253 Ma, but are consistent with thermal overprinting in Late Cretaceous time (Grist & Zentilli this vol. 2006). We suggest this may be associated with the uplift of the Carey Islands by the earliest translation motions of Greenland, which would be consistent with the position of the uplift near the flower structure and the thinned crust.

DISCUSSION

The classic Nares Strait problem, whether there is or is not major strike slip along Nares Strait, associated with the opening of Baffin Bay, is in a sense obsolete. It has become clear that the tectonic history of the region is considerably more complex than this, involving various stages of rifting, lateral motion, and convergence. It is therefore to be expected that the geological evidence of motion will be correspondingly complex. Recent investigations, particularly that associated with the Nares Strait 2001 project and summarised briefly above, have greatly increased our knowledge and understanding of the area (Fig. 7). However, there remain a number of questions on which there is not yet full consensus, particularly in the southern part of the region.

In the northern part of Nares Strait, from the Lincoln Sea to Dobbin Bay, there is consistent evidence for substantial strike-slip motion between Greenland and Ellesmere Island, i.e. for the existence of the Wegener Fault. Onshore, a significant sinistral fault system has been mapped, and dated as Paleocene, i.e. as having been active at the time of Greenland-North America plate motion. Pull-apart basins associated with this fault system can be traced offshore, and the aeromagnetic data also indicate a crustal boundary west of Nares Strait. However, the motion along these faults is not sufficient to accommodate the total opening of Baffin Bay, and intra-plate extension and deformation within the North American plate is suggested as the source of the remainder. In the Kennedy Channel region,

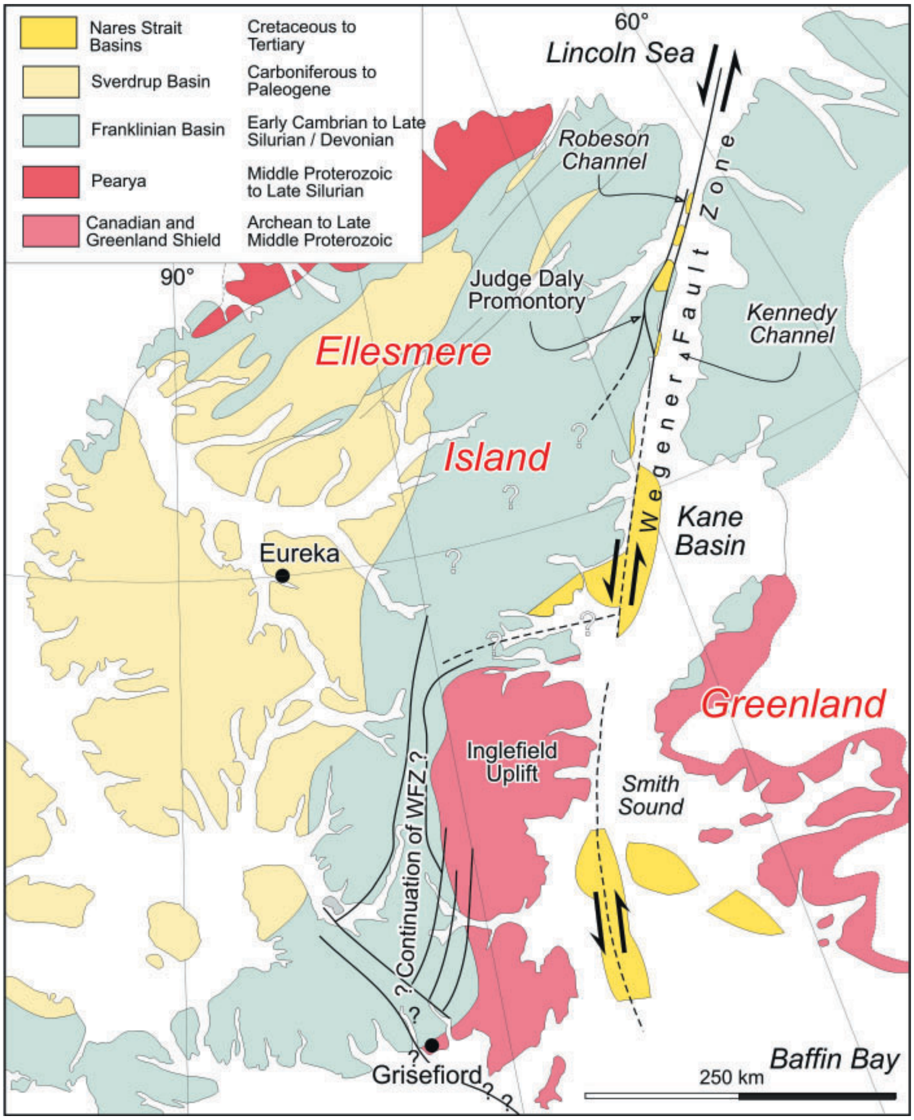

Fig. 7: Summary of results and present state of Nares problem. The northern part of the Wegener Fault Zone appears to be well established, whereas the southern continuation is less clear. Problem areas exist mainly across and around the basement areas on either side of Smith Sound.

the plate boundary is delineated by a downfaulted sedimentary basin along the coast of Ellesmere Island where the Greenland plate is overthrust by the Eurekan fold belt. In this region, and in the onshore area to the NW, evidence for strike-slip motion may have been overridden by subsequent convergence.

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