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Cretaceous Magmatism South and East of Svalbard: Evidence from Seismic Reflection and Magnetic Data

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THEME 1: Magmatic Provinces around the Eurasian Basin: Interplay with Tectonism

Summary: In the Svalbard archipelago, late Mesozoic magmatic rocks in the form of basaltic sills and dykes are recorded from the land areas between central and eastern Spitsbergen and the Hinlopen Strait. In addition, tholeiitic flood basalts are identified on Kong Karls Land, where they typically form the summit plateaus of the main islands, and in Franz Josefs Land in the Russian Arctic. Seismic mapping, combined with the forward modelling of magnetic anomalies, has revealed the extent of the magmatic province in the offshore area to the south and east of Svalbard. Sills and dykes are identified within sedimentary sequences of Permo-Carboniferous, Triassic, Jurassic, and Cretaceous age. The evolution of the basalt province was related to the initial break-up of the Eurasian-Laurentian supercontinent. This event involved extension and volcanism associated with the opening of the Canada Basin and subsequent formation of the basaltic Alpha Ridge, presently situated in the Arctic Ocean. The mapping of this province has important implications for the thermal evolution of petroleum source rocks, and the evaluation of the hydrocarbon potential of the northern Barents Sea.

REGIONAL GEOLOGY

The purpose of this paper is to present the results of the Norwegian Petroleum Directorate's (NPD) preliminary mapping of the distribution of magmatic rocks associated with early Cretaceous volcanism in the Norwegian sector of the northern Barents Sea (Fig. 1). The mapping of magmatic rocks has been made possible by seismic interpretation and constrained by magnetic data, field studies on the Svalbard archipelago, and shallow stratigraphic boreholes on the continental shelf GROGAN et al. (1999).

The Barents Sea shelf is an intra-cratonic basin bounded by the passive North Atlantic and Arctic margins in the west and northwest respectively, and by the Eurasian basin in the north (GUDLAUGSSON et al. 1998). The platform areas situated south and east of Svalbard comprise an underlying rift system containing Devonian and Early to Middle Carboniferous sedimentary rocks overlain by relatively flat-lying or gently folded sequences of Late Palaeozoic (Late Carboniferous and Permian), and Mesozoic (Triassic, Jurassic and Cretaceous) age. Tectonic activity was characterised by regional extension in the Late Early to Middle Carboniferous, and locally throughout the Permian (NØTTVEDT et al. 1992), Early Triassic, and also locally in the Late Jurassic and Early Cretaceous (FALEIDE et al. 1993). In the Late Jurassic, the Kong Karls Land Platform and Sentralbanken High (Fig. 1) underwent compression resulting in the inversion of Palaeozoic rift basins, and the gentle folding of overlying Mesozoic sequences. Cycles of Cenozoic burial and uplift related to sea floor spreading in the west, and glacio-isostatic rebound in the Quaternary, have combined to remove any late Lower and Upper Cretaceous and Tertiary sediments that may have been deposited. As a result, Lower Cretaceous strata of Aptian to Albian age are probably the youngest subcropping sequences below the thin Quaternary cover (Fig. 1).

The region has been affected by several phases of tectonism since the establishment of its basement foundation during the Early Devonian (STEEL & WORSLEY 1984, NØTTVEDT et al. 1992). Three pre-late Devonian orogenies; the Precambrian Baikalian, the Caledonian (Ordovician to Silurian), and the Early to Middle Devonian Innuitian events (DORÉ 1991, ALSGAARD 1992) have each produced distinct lineament patterns. The initial opening of the Canadian Basin and the formation of the predominantly basaltic Alpha Ridge in the early Cretaceous (LANE 1997, TARDUNO 1998) led to large scale crustal updoming and extensive magmatic activity. These events are now manifest as lavas observed on and adjacent to Kong Karls Land (Fig. 1), and as sills and dykes emplaced into the sedimentary sequence.

THE KONG KARLS LAND BASALTS

In 1992 the NPD conducted field work in the Kong Karls Land archipelago (LARSSEN 1992) (Fig. 2). One of the main objectives was to map the distribution of basaltic extrusive and intrusive rocks, and their effect on the maturation of source rocks. The archipelago is situated within the The Kong Karls Land Platform (Fig. 1) which is characterised by elongate north-northeasterly trending flexures at Mesozoic levels. These flexures developed above Palaeozoic normal fractures reactivated as reverse faults in the Late Mesozoic and Tertiary. The largest island of the group, Kongsøya (Fig. 2), is located above a fold of this type. Field relations and evidence from seismic mapping of parallel anticlines situated offshore, suggest that flexuring was probably initiated in one or more discrete phases of compression and transpression in the Late Jurassic and Early Cretaceous. The present day structural configuration is probably the result of further compression in the Tertiary.

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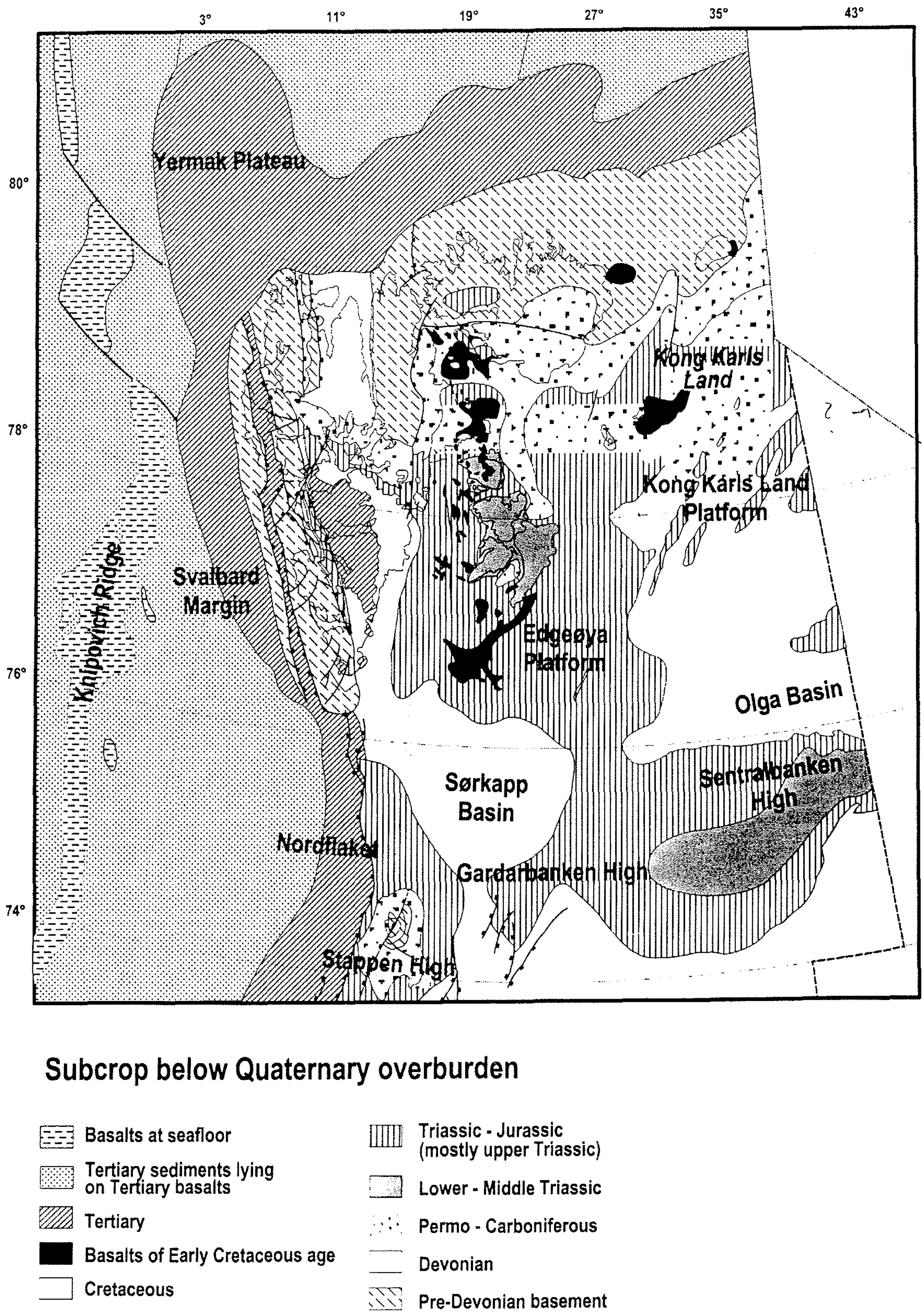


Fig. 1: Geological map of the Norwegian Sector of the northern Barents Sea.

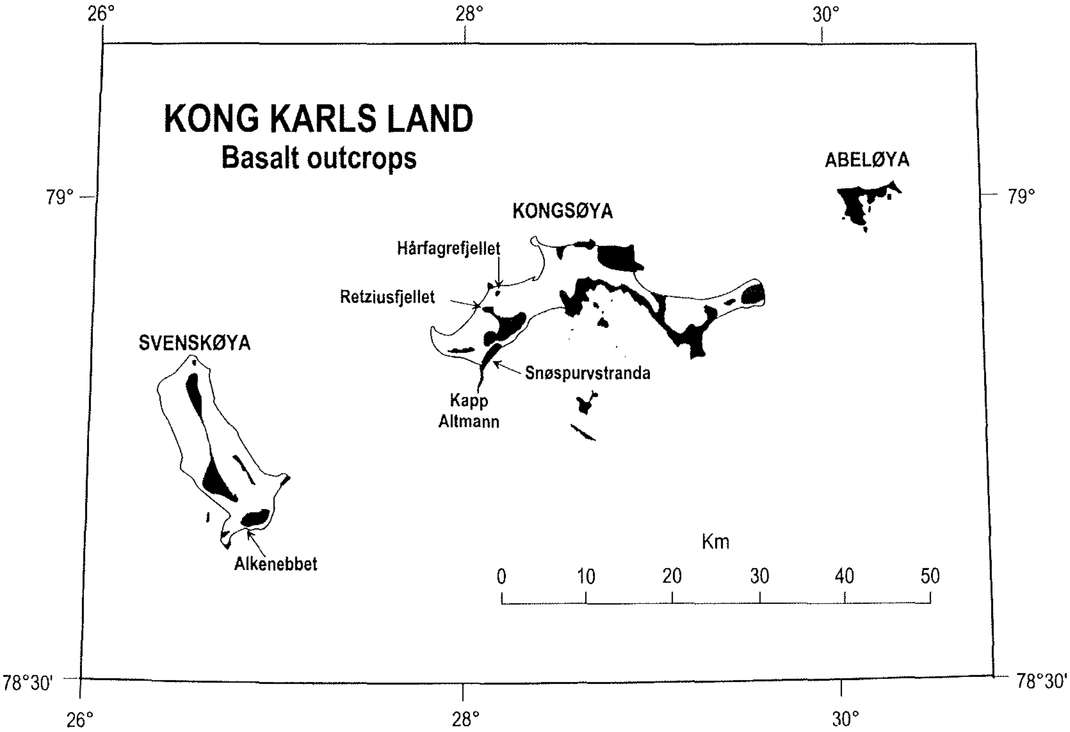


Fig. 2: Basalt outcrops on the Kong Karls Land Archipelago.

The most prominent exposures of the Kong Karls Land basalts are on the mountain tops (at between 150-300 m above sea level), and their presence has served to protect the underlying and surrounding sediments from erosion. They occur both as extrusive lavas and as intrusives. Petrographically they are typical plateau flood basalts, comprising a single geochemical population classified as low-Al, low-K tholeiitic to quartz-tholeiitic basalts. Biostratigraphic data constrain the volcanism only within the period Ryazanian to Cenomanian, whereas preliminary Ar/Ar isotope dating studies give a Barremian to Albian age for the basalts.

The basalts are divided into three main units. The two most dominant occur within the Lower Cretaceous (Hauterivian and younger) Helvetiafjellet Formation, which are the youngest rocks exposed on the islands. The two units are emplaced at stratigraphically distinct levels and it is considered likely that they were emplaced as sills. Basalts which may have been extruded as lavas are restricted to Retziusfjellet and Hårfagrefjellet on the island of Kongsøya (Fig. 2), and field relations suggest that the lavas appear to have flowed out over an almost flat landscape.

A third unit, most probably an intrusive body, is also recorded locally in the Helvetiafjellet Formation. Intrusions are also observed within the Upper Jurassic Agardhfjellet Formation and in older sequences on both Kongsøya and Svenskøya islands (Fig. 2). Many intrusions appear to have been emplaced at depths of less than 100 m into relatively unconsolidated sediments which makes it difficult at many localities to distinguish them from lavas. At Snøspurvstranda on Kongsøya (Fig. 2) the landscape exhibits a distinctive hummocky relief, where the hummocks are interpreted to represent the more massive parts of a large intrusive body. At other localities, for example at Alkenebbet on Svenskøya (Fig. 2), intrusive magma appears to have pushed and distorted the host rock sediments of the Agardhfjellet Formation.

Evidence indicating that the lavas were extruded over a relatively flat landscape constrains the volcanism to after the initial phases of formation of the Kongsøya anticline when the resulting relief was infilled by the fluvial sediments of the lower part of the Helvetiafjellet Formation. This is confirmed by unconformities on seismic data in the offshore areas which indicate that neighbouring anticlines were initiated in the Late Jurassic during deposition of the Agardhfjellet Formation.

THE OFFSHORE BASALT PROVINCE

The majority of The NPD's seismic data on the Kong Karls Land Platform were acquired in 1990, 1994 and 1996, but lines acquired during the 1980's have also been utilised in interpretation work. High resolution seismic has also been acquired, both as single channel, and as multifold data recorded with a 500 m long shallow streamer. These data have supported the correlation with land geology and in some areas have enabled the identification of detailed features associated with the morphology of the basalts. The resolution of the Upper Palaeozoic and Mesozoic sequences is generally good in this area, but poor data quality resulting from limited penetration of the seismic signal is common and often diagnostic for the presence of basalts.

The seismic expression of the basalts in the offshore (Figs. 3, 4) may be classified into five types; a) sills and lavas within the

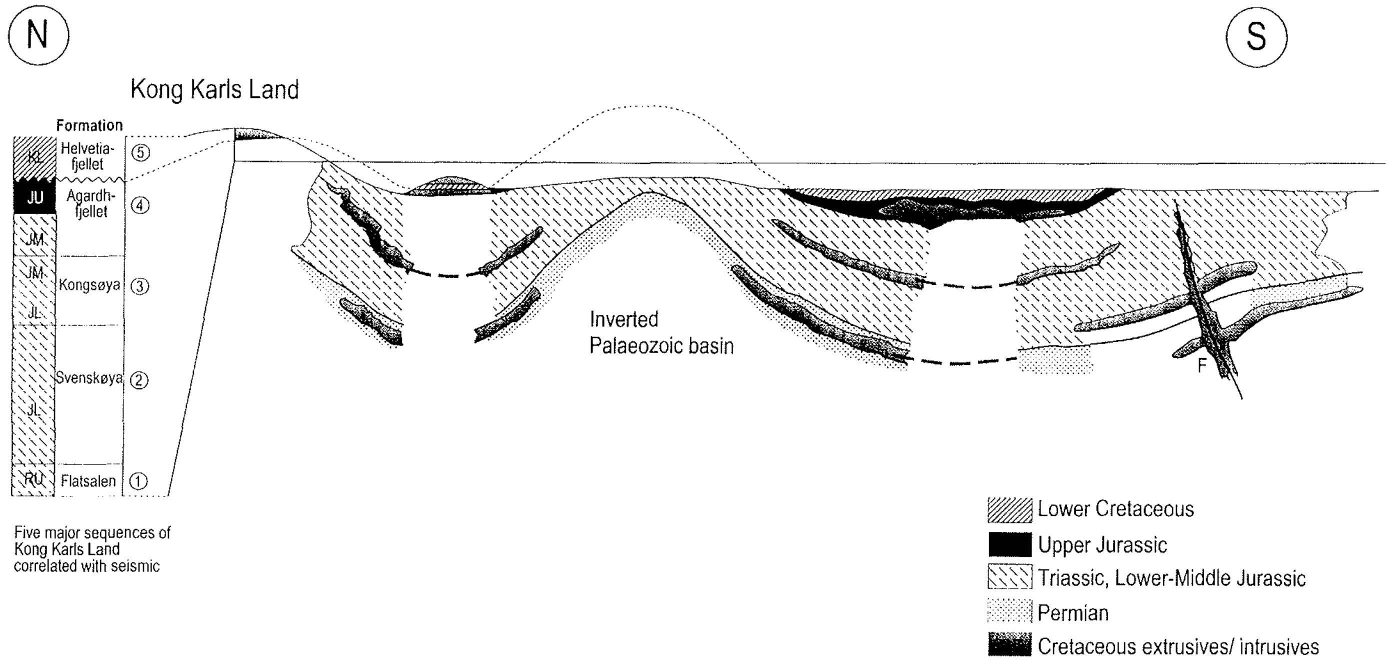


Fig. 3: Schematic profile showing the seismic expression of basalts (not to scale).

Lower Cretaceous expressed as bathymetric highs, b) sills within the Upper Jurassic, c) sills within the Triassic, d) sills within the Upper Palaeozoic, and e) vertical or steeply dipping intrusions.

Sills and lavas within the Lower Cretaceous expressed as bathymetric highs.

The sea floor over an area of approximately 2000 km^2 to the south and east of Kongsøya and Abeløya (Fig. 2) is characterised by tabular bathymetric highs (Fig. 5), which are interpreted to be erosional remnants of basalts emplaced within the Lower Cretaceous Helvetiafjellet Formation. The impedance contrast at the sea floor across these features is high and only multiples are observed beneath them. The poor data quality is probably exacerbated by the presence of intrusions within Upper Jurassic sequences immediately below the Cretaceous. It is not possible to determine whether these are extrusive lavas or sills, but being the southernmost evidence on seismic for basalts within the Lower Cretaceous, they also represent the only candidates for extrusive lavas in the offshore areas.

Sills within the Upper Jurassic

Basalts are apparently absent from the Lower Cretaceous sequences in the other synclines of the Kong Karls Land Platform (Fig. 1). However, these synclines are characterised by a discontinuous hummocky topography developed within the sequence immediately below the Base Cretaceous unconformity, often deforming the unconformity itself (Fig. 6a). This phenomenon is interpreted to result from sills emplaced into the Upper Jurassic Agardhfjellet Formation. The hummocky topography and deformation of the Base Cretaceous are reminiscent of field relations previously described on both Kongsøya and Svenskøya.

The seismic character of these intrusions is variable. Although most have hummocky and discontinuous tops (Fig. 6b), others are apparently flat and smooth over considerable distances. They also lie at different intervals within the unit. The intrusions appear to be restricted to the synclines where the Agardhfjellet Formation is thickest. They become thinner and die out towards the syncline flanks and are nowhere observed to be eroded at the sea floor. This confirms observations in the field on Kongsøya, where intrusions are not observed on the main anticline, but are well developed on the flanks (e.g at Kapp Altmann and Snøspurvstranda; Fig. 2). It appears that the basalts have followed a path of least resistance and are preferentially emplaced into the thicker Agardhfjellet Formation which invariably includes black shales. These sills cover an area of between 15 000 - 20 000 km^2 (Fig. 4) south and east of Kong Karls Land.

Sills within the Triassic

High amplitude reflectors interpreted as sills are observed at different levels within Triassic sequences on the Kong Karls Land Platform (Fig. 4). Those in the middle and upper part of the sequence occur closest to the archipelago (Fig. 7a, b). The form and lateral extent of sills are often well demonstrated on seismic lines in this area and their masking effect is minimal, suggesting that they may be relatively thin (less than 30 m thick). Those further south are more continuous and apparently thicker (50 m or more), and occur more commonly in Lower Triassic sequences, often just above the near top Permian reflector. They commonly mask the underlying Palaeozoic reflectors and gene-

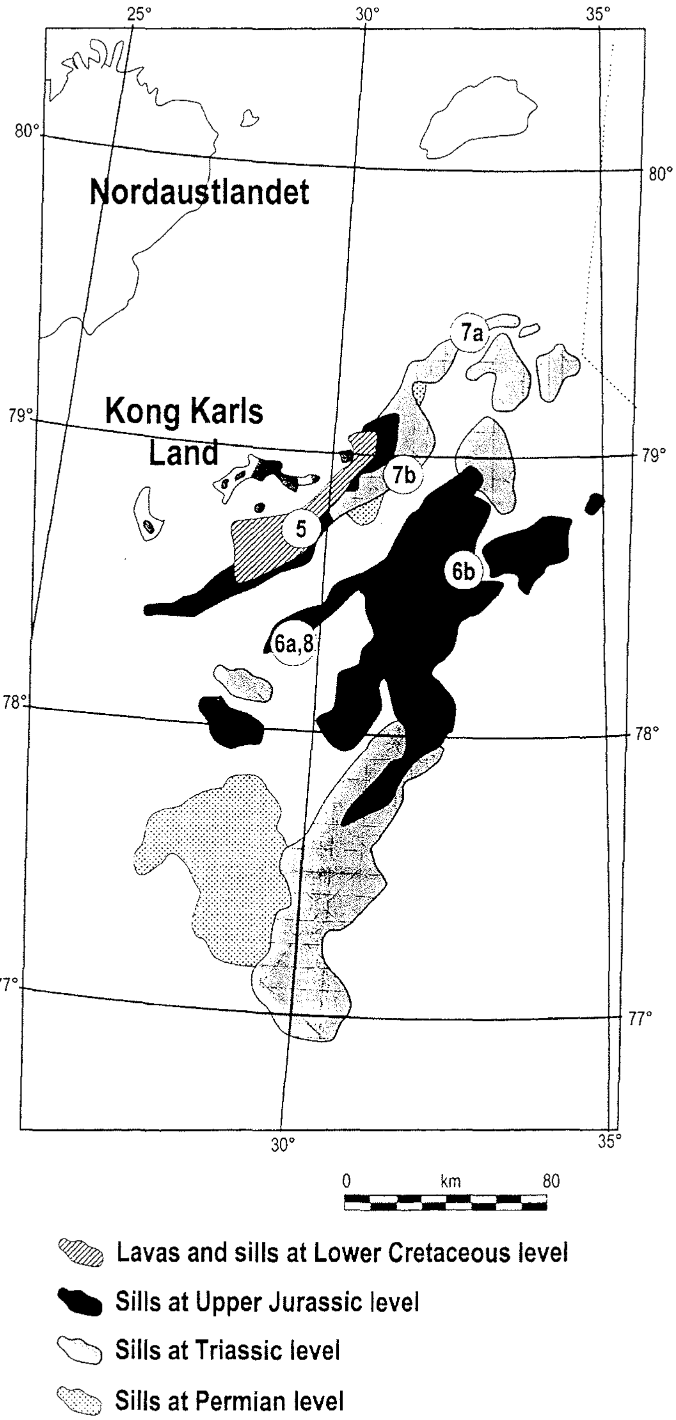


Fig. 4: Distribution of Cretaceous basalts identified on seismic on the Kong Karls Land Platform. Numbers refer to locations of seismic lines of Figures 5 to 8.

rate significant multiple energy. There is insufficient data regarding the detailed lithostratigraphy of the Triassic in this area to confirm whether these intrusions are preferentially emplaced into shales, although field evidence from Svalbard would suggest that this is likely. Although Triassic sediments continue to subcrop the sea floor north to approximately 79°° 50' N, there are no significant amplitude anomalies observed north of 79°° 25' N.

Sills within the Upper Palaeozoic

The presence of sills at shallower Mesozoic levels has resulted in poor imaging of the Palaeozoic sequences over large areas of the northern part of the Kong Karls Land Platform. Close to Kong Karls Land however, high amplitide, low frequency reflectors within the Upper Permian can be correlated with magnetic anomalies and are interpreted as bedding-parallel intrusions (Fig. 8). Sills within the Permian are more easily identified southeast of Hopen where there are no apparent shallower intrusions. In this area the form and lateral extent of the sills are well defined on seismic data.

Vertical intrusions

At various locations on the Kong Karls Land Platform, reflector continuity within Mesozoic sequences is disturbed by vertical discontinuities which cannot be explained by seismic artefacts. Their close association with bedding-parallel phenomena described above makes them candidates for subvertical, dyke-like intrusions, and this can normally be confirmed by correlation with high amplitude magnetic anomalies. Some, but not all, of these features are associated with reactivated Palaeozoic faults.

The aeromagnetic data used in this study comprise over 250 000 line kilometres acquired by diverse institutions since the late 1960's and reprocessed and compiled in 1993. The mapping and modelling of magnetic anomalies utilises the magnetic properties of basaltic rocks and, combined with the constraints provided by seismic interpretation, provides the basis for the identification of sills and dykes. The modelling process compares residual potential field anomalies with the response of an input model based on seismic interpretation. High-pass filtering is applied in an attempt to remove components derived from deep crustal structures and the relief at the top of the Moho. The same filter is applied to both the observed data and the model response. Iterative adjustment of the model and fine tuning of filters makes it possible to focus on a particular depth interval at any one time, and for the depth to magnetic sources to be estimated. Depth estimates to individual magnetic sources are determined by the "half-slope" method described by Peters (1949). The identification of sources at different depths enables them to be classified as near-surface, intra-sedimentary or basement-related.

On the Kong Karls Land Platform, seismic observations may be correlated with magnetic anomalies which have sources in the upper 4-6 km of the sedimentary sequence. The ability to achieve accurate correlation is invariably dependant on the imaging resolution of the seismic. In areas where seismic data are poor it may not be possible to identify the sources of the observed magnetic anomalies. High frequency and high amplitude magnetic anomalies are commonly observed north of 77° °N. The anomalies have variable wavelength and correlate with seismic observations at different depths and stratigraphic

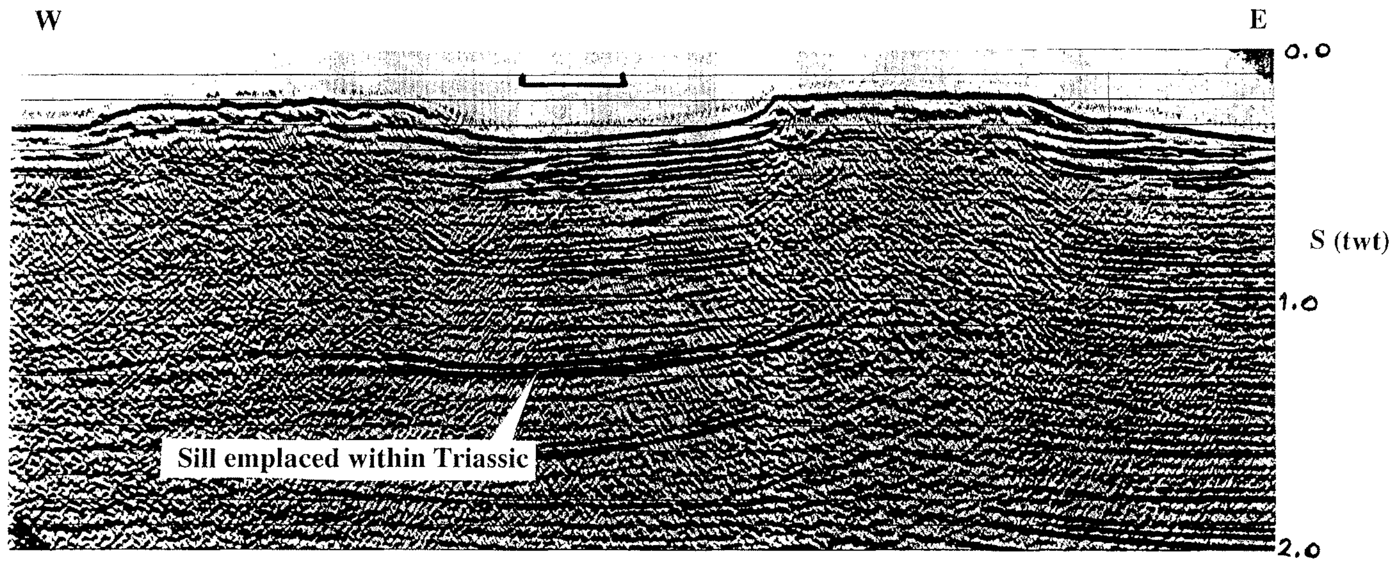


Fig. 5: Seismic section illustrating tabular bathymetric highs resulting from basalts emplaced as either lavas or sills within the Lower Cretaceous. For location see Figure 4. Scale bar is 1 km.

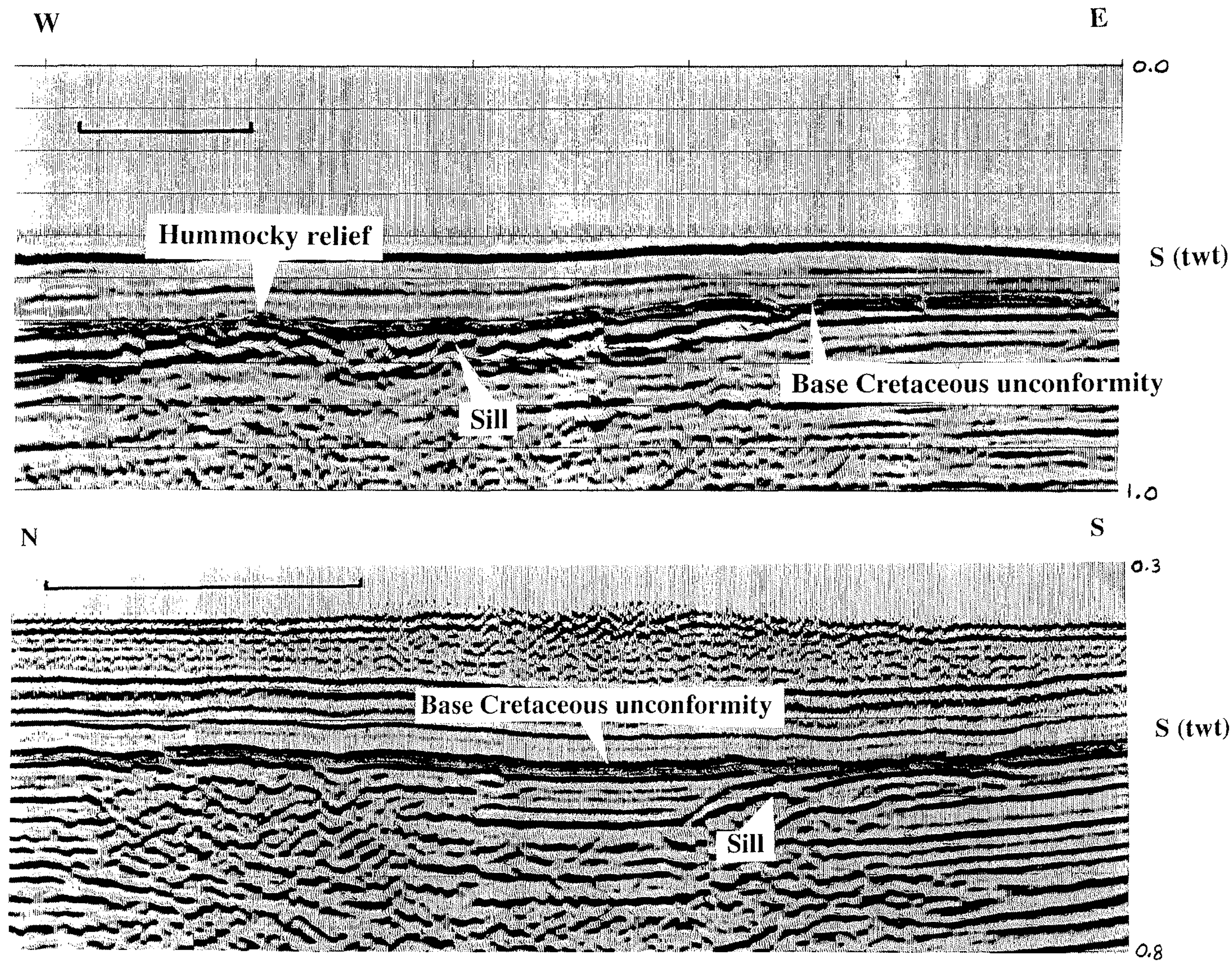
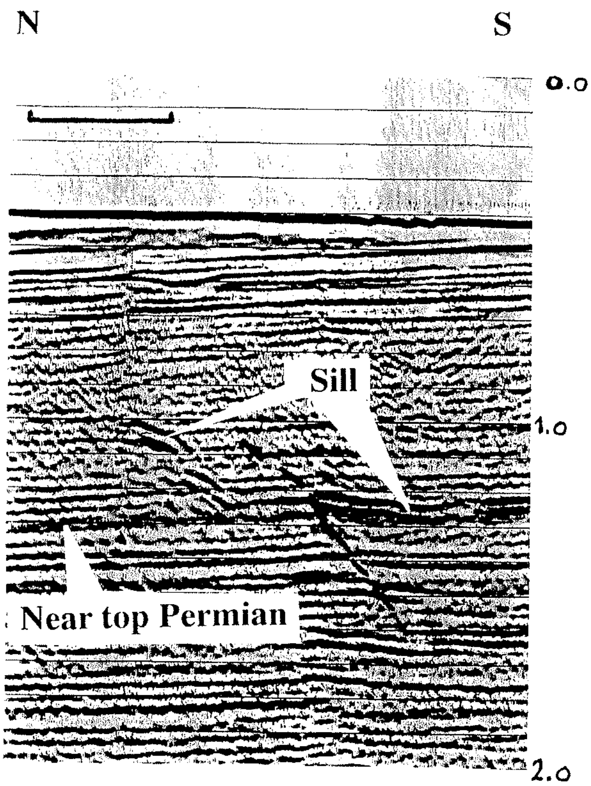


Fig. 6: (a and b) Seismic sections illustrating the discontinuous and hummocky morphology resulting from basalts emplaced as sills within the Upper Jurassic. For location see Figure 4. Scale bar is 1km.



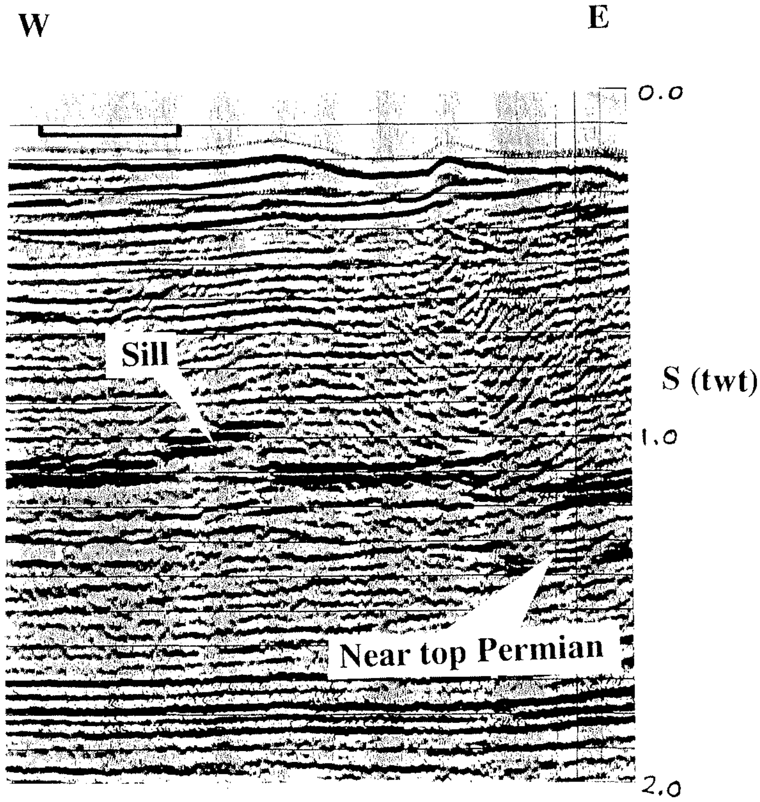


Fig. 7: (a and b) Seismic sections illustrating sills emplaced in the Triassic. For location see Figure 4. Scale bar is 1 km.

levels; lavas and sills at or near the sea floor (in Cretaceous sediments), intrusives in Upper Jurassic sediments and sills and dykes in Triassic and Late Palaeozoic sediments. Intra-sedimentary magnetic anomalies may be usefully classified into two groups which also reflect the relative reliablity of correlation to seismic data with depth.

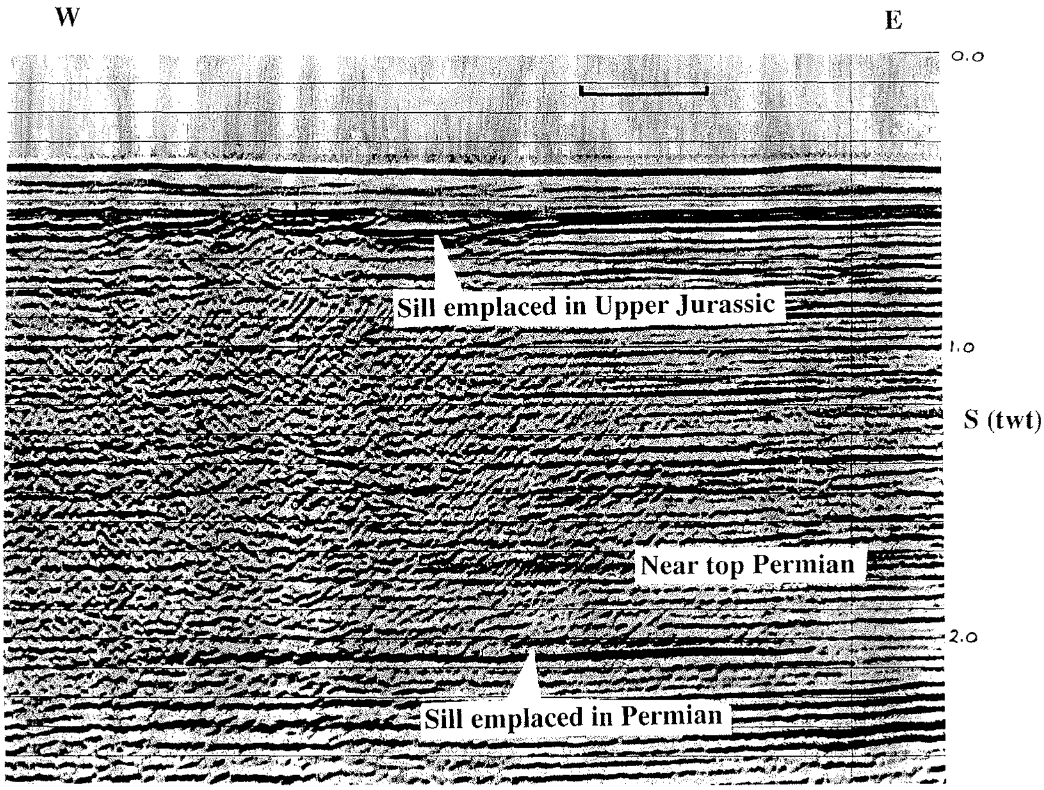


Fig. 8: Seismic section illustrating a sill within the Permian, emplaced below a complex of sills within the Upper Jurassic. For location see Figure 4. Scale bar is 1 km.

ANOMALIES WITH SOURCE DEPTHS IN THE RANGE 0-1 KM

On the Kong Karls Platform there is excellent correlation between the distribution of shallow magnetic sources and possible lavas and sills within Lower Cretaceous and Upper Jurassic sequences (Fig. 9a). These sources give rise to high frequency magnetic anomalies with variable, but generally low, amplitudes. The intensity of these anomalies decreases south of about 78° 40' N, although shallow intrusions are still identified on seismic as far south as 77° 40' N. Anomalies sourced at shallow depths die out north of approximately 79° 10' N, which correlates well with seismic observations. In areas of intensive magmatism, such as the northern part of the Kong Karls Land Platform, many anomalies result from sources at different depths, which are effectively interfering with each other.

West of 26° E, towards the Edgeøya Platform, anomalies from shallow sources are related to intrusives emplaced within Triassic sequences. Individual anomalies within and south of Storfjorden exhibiting relatively low amplitudes (in the range 5-10 nT), are correlated with the offshore extension of the Tusenøya skerries which are situated south of Edgeøya. This pattern continues in Svalbard and is correlated with dolerites observed at different stratigraphic levels on land.

ANOMALIES WITH SOURCE DEPTHS IN THE RANGE 1-4 KM.

Jurassic and Cretaceous rocks are only rarely encountered deeper than 1000 m in the northern Barents Sea, and anomalies from greater than these depths probably arise from intrusions within Triassic and older sequences (Fig. 9b). In general, it is much more difficult to establish reliable correlations between sources from these depths and seismic observations. Often these sources are poorly imaged on seismic data, particularly where they are masked by shallower sills as in the northern Kong Karls Land Platform. In areas where sediment cover is relatively thin (less than 4 km), these sources will be associated with the top of magnetic basement.

The occurrence of linear, high amplitude anomalies indicates the presence of vertical intrusions within Triassic sequences, and these frequently correlate with mapped Palaeozoic faults. Magnetic sources of this type on the Kong Karls Land Platform

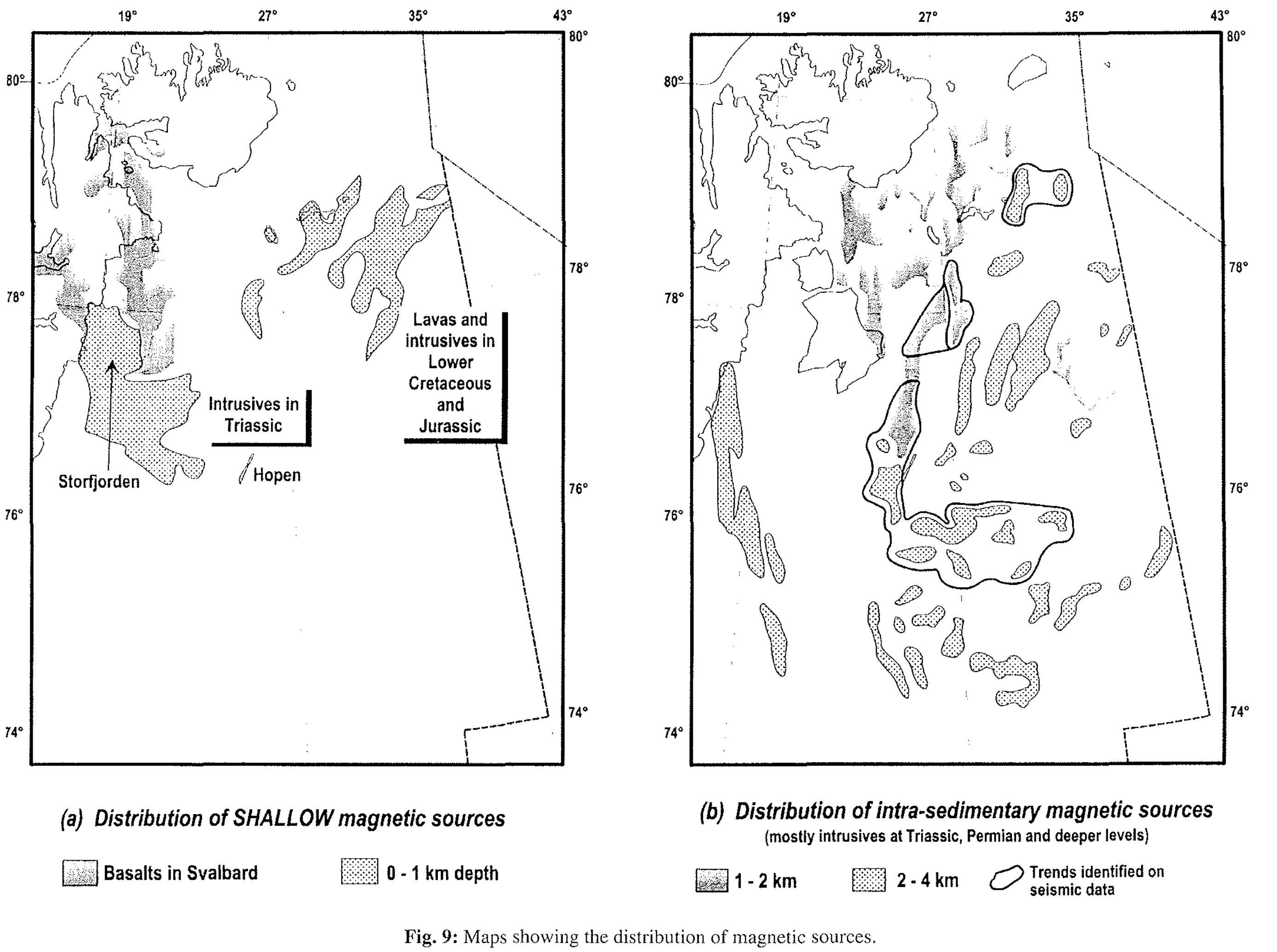


Fig. 9: Maps showing the distribution of magnetic sources.

exhibit a distinct NE-SW trend, extending from northwest of the island of Hopen towards the eastern part of the Kong Karls Land archipelago. North of 77° N, low amplitude magnetic anomalies reveal the presence of extensive, bedding-parallel intrusions at various levels within the Triassic sequence which correlate well with seismic observations. These sills are commonly observed on seismic, but exhibit only subtle magnetic signatures at their edges. The correlation of sills in Palaeozoic rocks is more problematic. In some cases apparent sills on seismic produce only poorly defined or discontinuous magnetic signatures, whereas in other areas apparent magnetic sources are not identified on seismic. The latter can probably be explained by the relatively low impedance contrasts between magmatic rocks and carbonate host rocks.

South of 77° N, along the flanks of the Olga Basin and Sentralbanken High (Fig. 1), magnetic anomalies exhibit an E-W trend, which reflects the underlying Palaeozoic rift system and demonstrates the presence of intrusives along its controlling faults. Similar patterns are observed around the Sørkapp Basin and Gardarbanken High (Fig. 1). In these areas, the high frequency character of the anomalies becomes more sporadic, but the faults are easily identified on seismic data. This close association of magnetic anomalies with fault trends is a good indication that the faults have been utilised as conduits for rising magma, although it is rare for these intrusives to be recognised on seismic.

DISCUSSION

The Kong Karls Land lavas appear to form the western extension of an extrusive magmatic province which extends eastward to Franz Josefs Land (Fig. 10; Solheim et al. 1998, Ntaflos & Richter 1998). Taken as a whole, the volcanic province inclusive of intrusive dykes and sills extends west across Nordaustlandet, Barentsøya, Edgeøya and into central Spitsbergen. Throughout the province, the dating of basalts by K-Ar methods is inconclusive due to a combination of poor K-content and hydrothermal alteration, but a concentration of ages in the range 160-80 my has emerged from the literature (Burov et al. 1976, Campsie et al. 1988, Bailey & Rasmussen 1997).

The Kong Karls Land basalts form part of an extensive magmatic province whose evolution was related to the initial break-up of the Eurasian-Laurentian supercontinent, resulting in widespread basaltic volcanism over large areas of the present day Arctic Basins during the Mesozoic. This event involved extension and volcanism associated with the opening of the Canada Basin and subsequent formation of the basaltic Alpha Ridge, presently situated in the Arctic Ocean. In the Sverdrup Basin in the Canadian Arctic, basaltic magmatism persisted throughout much of the Cretaceous (Embry & Osadetz 1988, Embry 1991, Tarduno 1998). The Kong Karls Land basalts correlate stratigraphically most closely to the Paterson Island (Valanginian to early Barremian) and Walker Island members

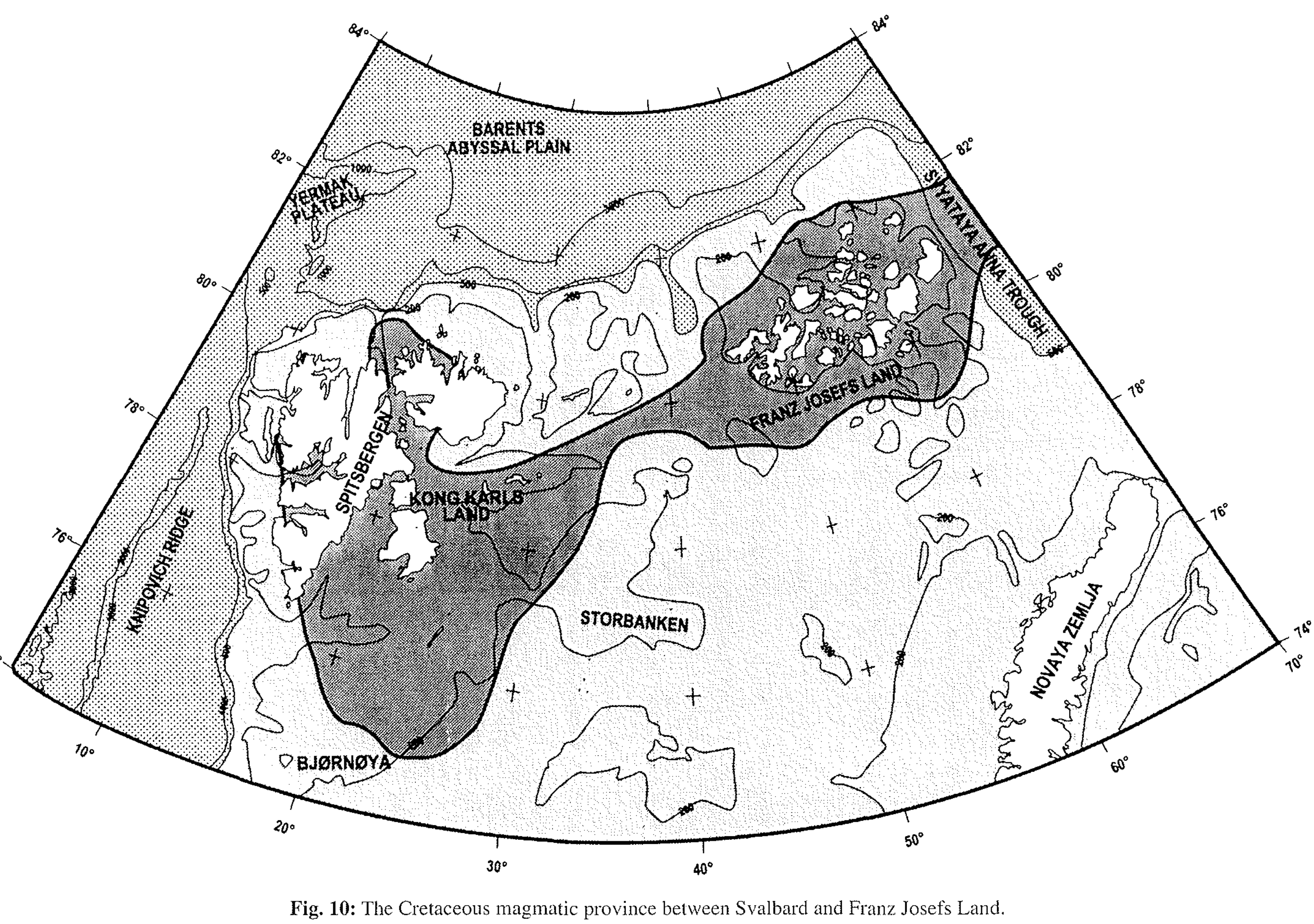


Fig. 10: The Cretaceous magmatic province between Svalbard and Franz Josefs Land.

(Barremian to Aptian) of the Isachsen Formation. In both Franz Josefs Land and in the Canadian basins, the lava sequences are many hundreds of metres thick and are accompanied by sills and extensive dyke swarms, suggesting that the present Kong Karls Land archipelago was situated at the periphery of the province.

The early Cretaceous magmatic event has important implications for the petroleum geology of the region, particularly for the maturation of source rocks and the timing of hydrocarbon generation. This not least because both field and seismic observations indicate that the basalts tend to be emplaced within Jurassic, Triassic and possibly also Upper Palaeozoic shales which represent potential hydrocarbon source rocks. Field observations on Svalbard and subsequent analyses indicate that the thermal contact metamorphic effects of sills on maturation can locally be very great. The intensity of the thermal effect with distance from the interface with the host rock is generally proportional to the thickness of the sill, but will be modified by other factors such as the temperature of the magma and the temperature difference between the magma and the host rock. Because of surface area considerations, many thin sills may have a similar effect to a single, thicker intrusion. The regional thermal effect is likely to have been been minimal for Upper Jurassic and Cretaceous shales lying at or near the surface, since they had a significantly lower temperature than either extrusive lavas or intrusive magma during the emplacement of the basalts. For Triassic and older shales at greater depths, and at relatively elevated temperatures, magma may be able to trigger "early" generation of hydrocarbons in a source rock which is already heated by burial to near the oil window.

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