GRØNLANDS GEOLOGISKE UNDERSØGELSE
RAPPORT Nr. 54

The Geological Survey of Greenland
Report No. 54

Seismic velocity and sediment thickness investigations by refraction soundings in Nûgssuaq, West Greenland

by

P. Vallabh Sharma

KØBENHAVN 1973

Grønlands Geologiske Undersøgelse

(The Geological Survey of Greenland)
Østervoldgade 10, DK-1350 Copenhagen K

Reports

No. 32 Géologie d'un secteur situé entre les fjords de Sermiligârssuk et Arsuk (SW du Groenland). 1971 *par* L.-F. Bonnard. D.kr. 14.00.

No. 33 Beryllium mineralization in the Ilímaussaq intrusion, South Greenland, with description of a field beryllometer and chemical methods. 1971 *by* J. Engell *et al.* D.kr. 25.00.

No. 34 Preliminary account of the geology of south-east Renland, Scoresby Sund, East Greenland. 1971 *by* B. Chadwick. D.kr. 8.00.

No. 35 Report of activities, 1970. 1971. D.kr. 12.00.

No. 36 Short explanation to the Quaternary map of Greenland. 1971 *by* A. Weidick. D.kr. 3.00.

No. 37 Report on the 1970 geological expedition to Scoresby Sund, East Greenland. 1971. D.kr. 12.00.

No. 38 Field observations on the kakortokites of the Ilímaussaq intrusion, South Greenland, including mapping and analyses by portable X-ray fluorescence equipment for zirconium and niobium. 1971 *by* H. Bohse *et al.* D.kr. 15.00.

No. 39 An electronic data processing system for geological field and laboratory data. The E.D.P. system Agto. 1971 *by* S. W. Platou. D.kr. 10.00.

No. 40 The composition of sands from the Fiskenæsset region, South-West Greenland, and its bearing on the bedrock geology of the area. 1971 *by* F. Kalsbeek. D.kr. 3.00.

No. 41 Holocene shore-lines and glacial stages in Greenland – an attempt at correlation. 1972 *by* A. Weidick. D.kr. 12.00.

No. 42 U – Pb istotopic ages of zircons from Precambrian rocks of South Greenland. 1971 *by* R. Chessex *et al.* D.kr. 3.00.

No. 43 The possibility of ilmenite placers in the Thule district, North Greenland. A preliminary examination of the heavy fractions of some sands. 1971 *by* M. Ghisler & B. Thomsen. D.kr. 4.50.

No. 44 Helium in the thermal springs of Ũnartoq, South Greenland. 1972 *by* F. Persoz *et al.* D.kr. 9.00.

No. 45 Report of activities, 1971. 1972. D.kr. 15.00.

No. 46 Regional geology of early Precambrian high-grade metamorphic rocks in West Greenland. Part 1: Kângnaitsoq to Ameralik. 1972 *by* B. F. Windley. D.kr. 15.00.

No. 47 Geoelektriske resistivitetsmålinger ved permafrostundersøgelser i Holsteinsborg. Grønland. 1972 *af* K. Klitten & O. B. Olesen. D.kr. 10.00.

No. 48 Report on the 1971 geological expedition to Scoresby Sund, East Greenland. 1972. D.kr. 30.00.

No. 49 Notes on Greenland trace fossils. 1972 *by* R. G. Bromley & U. Asgaard. D.kr. 8.00.

No. 50 Results from a geological reconnaissance around Svartenhuk Halvø, West Greenland. 1972 *by* V. Münther. D.kr. 9.00.

No. 51 Progress report on the geology of the Fiskenæsset region, South-West Greenland. 1973. D.kr. 22.00.

No. 52 Precambrian structures of the Ikorfat peninsula, Agto region, West Greenland. 1973 *by* L. Skjernaa. D.kr. 12.00.

No. 53 Geological results of the 1971 e.pedition to central West Greenland. 1973.

No. 54 Seismic velocity and sediment thickness investigations by refraction soundings in Nûgssuaq, West Greenland. 1973 *by* P. Vallabh Sharma.

GRØNLANDS GEOLOGISKE UNDERSØGELSE
RAPPORT Nr. 54

Seismic velocity and sediment thickness investigations by refraction soundings in Nûgssuaq, West Greenland

by

P. Vallabh Sharma

1973

Abstract

Interpretation of refraction soundings made along the coastal strip of north Nûgssuaq indicates the presence of high velocity sediments (4.3 km/s) below Cretaceous beds of velocity 3 km/s. On the assumption of a simple three-layer model the depth to the top of the Precambrian basement refractor of velocity 5.6 km/s is estimated to be around 2500 m below sea level. Complex geology and irregular topography along the coastal strip severely limit the effective application of continuous refraction profiling.

CONTENTS

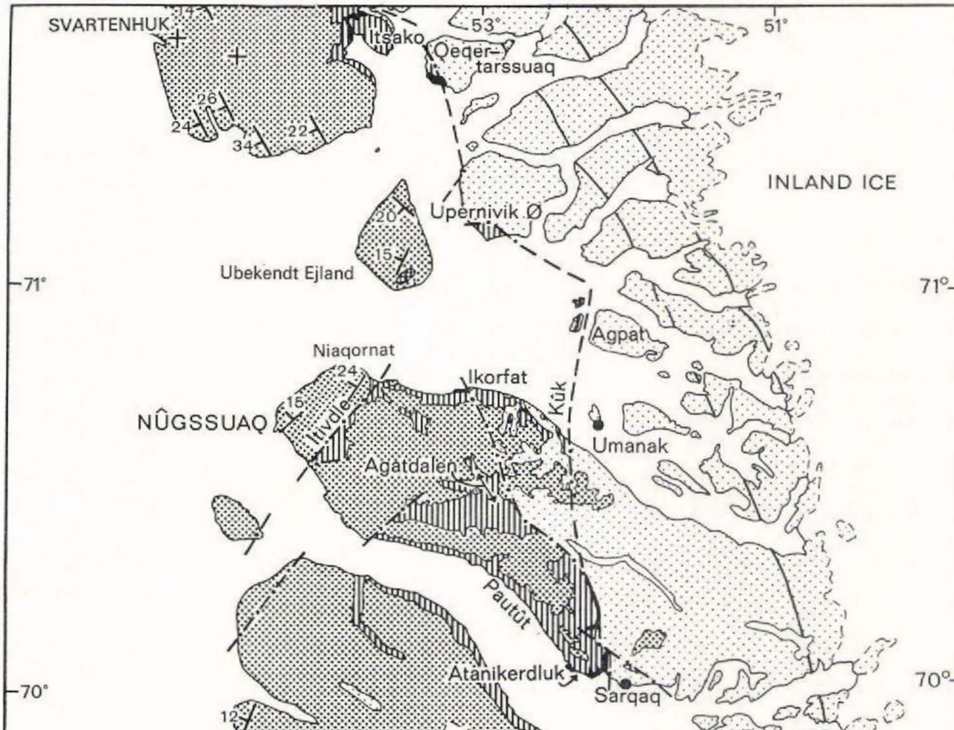

Fig. 1. Map showing the distribution of Cretaceous-Tertiary rocks in West Greenland.

INTRODUCTION

During recent years there has been a rapidly growing interest shown by oil companies in the oil and gas prospects of West Greenland, in particular the West Greenland continental shelf. During this period the Geological Survey of Greenland (GGU) has continued regional mapping in the onshore area of central West Greenland and initiated geophysical work on land in the Nûgssuaq peninsula to obtain additional information on the thickness of the sedimentary section in this part of the West Greenland basin. The geology of the basin has recently been discussed by Rosenkrantz & Pulvertaft (1969), Henderson (1969) and Rosenkrantz (1970).

The geophysical exploration programme in the area started in 1969 with a reconnaissance magnetic and gravity survey in the Itivdle valley of Nûgssuaq. The results of this survey (Sharma, 1973) indicated the thickness of the sediments to be around 1500 m or more in the south-western part of the Itivdle valley. Because of the disturbing effects of thick basaltic cover flanking the valley, an extension of the magnetic and gravity work to the northern part of the valley was not considered feasible.

It was with this background that the refraction seismic investigations were started on the north coast of Nûgssuaq in the summer of 1971. The object of the programme was to determine the seismic velocities of the rocks exposed at the surface in the area and to determine the depth to the Precambrian basement.

This report gives an account of the seismic refraction investigations made along the north coast of Nûgssuaq in the 30 km long strip between Sangmissoq (lying 3 km west of the Itivdle valley) and Ikorfat (figs. 1 and 2). Various operational problems encountered in the effective application of the refraction survey in an area beset with difficult field conditions are also discussed.

In all eleven profiles were shot, eight for velocity measurements and three for basement depth investigations. Despite some spread in velocity values within some formations, correlation of velocities with the geological formations has been attempted. Velocity determinations were made with charges of 1 to 5 kg. Depth soundings were made with shot-to-geophone distances ranging from 6 to 13 km and with explosive charges varying from 60 to 100 kg of dynamite. Commercially available explosives were used.

GEOLOGICAL SETTING

Sediments outcropping onshore on Nûgssuaq and adjoining areas range in age from Cretaceous to lowermost Tertiary Danian (fig. 1). The thickest sections of marine sediments are exposed along the north coast of Nûgssuaq where the total thickness, on the basis of exposed sediments, is at least 1500 m consisting mainly of sandstones and shales. The Ikorfat fault on western Nûgssuaq shows a downthrow to the south-west displacing Maastrichtian marine sediments by 900 m. Precambrian basement is exposed along the coast east of Ikorfat.

The sediments along the north coast of Nûgssuaq are overlain for a considerable part by Tertiary basalts which attain a thickness of over 1000 m in the central part of the north coast. To the west of the Itivdle valley the sediments are faulted against basalts which are several thousand metres thick. This puts a severe restriction on the size of the area in which the effective application of geophysical methods is possible. In addition, there are dykes and sills which occur in lavas and sediments, but their distribution in the area is not known in detail. The topography of the area is in general very rugged and unfavourable for ground geophysical work.

LAY-OUT OF THE SEISMIC PROFILES

In a virgin area knowledge of seismic velocities of rock formations is imperative for correlation of velocities with the geological formations and for depth determinations. With this objective, eight short profiles were planned for velocity shootings at localities where good surface outcrops of the rocks could be seen. These localities are shown in fig. 2.

Three velocity profiles were shot near Tuperssuartâ in the delta which forms the northern edge of the Itivdle valley. This valley is floored by Quaternary deposits overlying the Cretaceous sediments. Two profiles were shot in the vicinity of Sangmissoq where a good section of basalts is exposed along the coast line. Three profiles were shot at Ikorfat where the Precambrian basement is exposed. All the velocity profiles were reversed, i.e. they were shot on both ends of the geophone spread.

For basement depth investigations three long profiles were planned, one at Niaqornat and two at Tuperssuartâ. The geophone spread in each of these profiles was 990 m with 90 m spacing between the geophones. Due to practical difficulties only two profiles could be reversed where the shot-to-geophone distance was $\leqslant$ 6 km. The choice of sites for the long profiles was dictated by the following practical considerations:

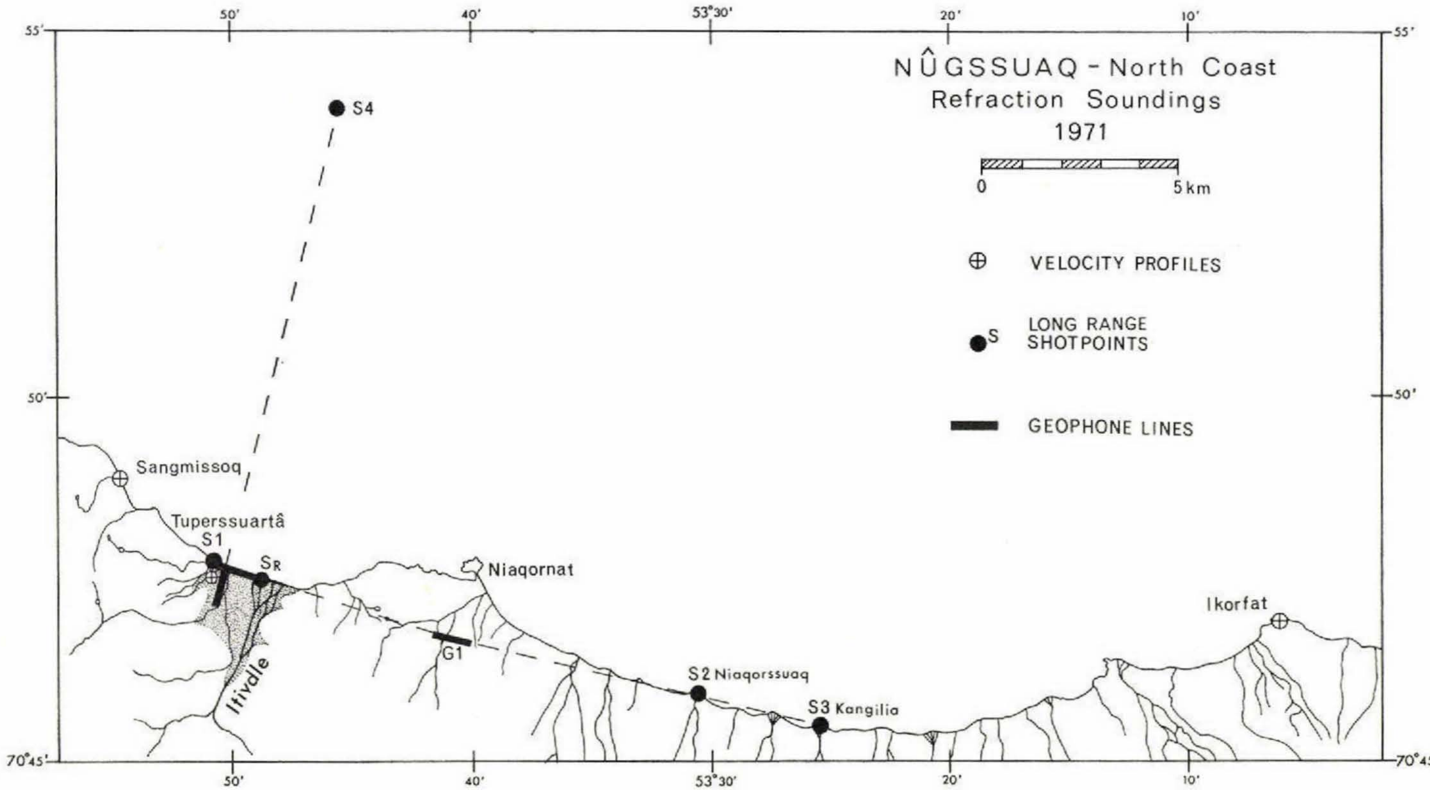

Fig. 2. Map showing the locations of velocity shootings and refraction profiles along the north coast of Nûgssuaq.

(1) Areas with basaltic cover were to be avoided.
(2) Availability of a fairly gentle topography for the geophone line.
(3) Ease of transport for the seismic cable and the recording unit.

For practical reasons all shot points were laid along the coast line. Here again great care had to be exercised in order to exclude the possibility of basalt masses lying below the shot points or between the shot-geophone line.

SEISMIC EQUIPMENT AND FIELD PRACTICE

A portable 12-channel ABEM Trio refraction unit (belonging to the Geophysical Institute of the University of Copenhagen) was used for recording of seismograms (fig. 3). For velocity profiles with small shot-to-geophone distances, standard SM-1 geophones (14 hertz) were used.. However, for deep refraction soundings involving long shot-to-geophone distances, low frequency GSC-8D geophones (4.5 hertz) were employed which yielded a better signal response. The long shot-to-geophone distances (ranging from 6–13 km) necessitated radio-shooting which was accomplished with the aid of a radio relay shot-box designed at the Electronics Division of the Danish Atomic Energy Commission, Risø.

The field crew consisted of a group of four persons from Copenhagen whose respective assignments were geophone line surveying, shooting, recording and interpreting of seismograms. In addition, local Greenlanders equipped with a motor boat were employed for field transport of the instrument and cable units. The laying of seismic cable over the long profile lines (about 1 km in length) was quite a formidable task. For ease of transport, two cable units each of about 550 m length with 6 take-outs were used. The recording unit was placed midway and offset from the geophone line. The long profile lines were laid with the aid of a theodolite and the relative elevation between the geophone positions was measured roughly with a hand level. The difference in elevation between the shot point and the geophone line was estimated from the Geodetic Institute's topographic maps (1:50 000) of the area.

For shooting velocity profiles on land, the normal practice was to place the explosive charge in a polythene bag filled with water in a hand-dug hole about 50 cm deep. For deep refraction soundings, all the shot points were positioned in shallow water along the coast, and the explosive charge contained in polythene bags was suspended about 1–2 m below the water surface with the aid of plastic floats.

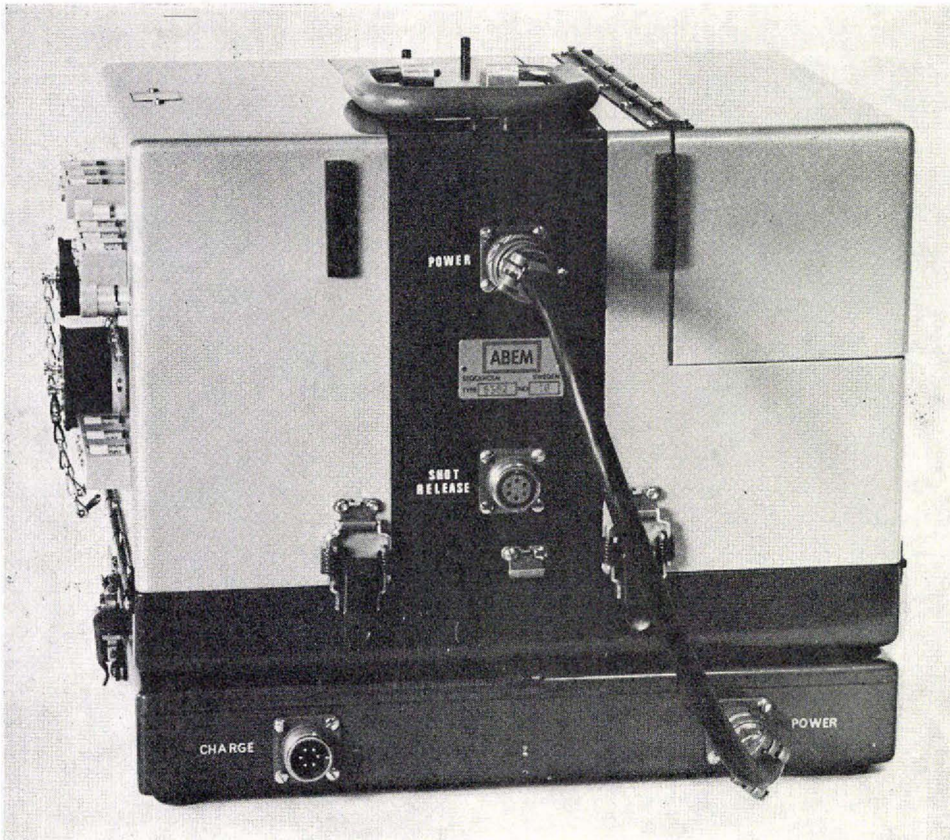

Fig. 3. Photograph of the ABEM seismic unit used for refraction soundings in Nûgssuaq.

SPECIFIC OPERATIONAL PROBLEMS

Some of the operational problems concerning the equipment used and other practical difficulties encountered because of the special field conditions in the coastal area of Nûgssuaq are now briefly mentioned. These points may be of importance for further refraction work in the onshore areas of the West Greenland basin.

Radio shooting

Most of the operational difficulties were encountered with radio shooting. The problems encountered were due partly to the unfavourable topography along the coast line, which made it difficult to maintain a radio contact between the shooter and the recorder, and partly to the inadequate power of the radio shot-box transmitter. Along the north coast of Nûgssuaq, reliable radio shooting with the VHF Storno set (operating at 150 MHz) was rarely possible beyond 6 km.

Occasionally, the drifting of massive icebergs close to a shot point (loaded with heavy charge) created unpredictable situations.

The problems relating to the radio detonation could be minimised by using a more powerful field radio system radiating 15–20 watts in the frequency range of 10–20 MHz.

Recording speed of seismograms

For seismic soundings involving shot-to-geophone distances greater than 10 km, a few seconds elapse before the refracted events are recorded. Even with the lowest recording speed of the ABEM seismograph unit the transit time would yield seismogram records of over 10 m length. Such a large output of paper length interferes with the paper drive mechanism, the instantaneous collection of large paper lengths often blocking the paper drive motor.

It should be possible to overcome this difficulty by using a suitable low-geared paper drive motor for long distance refraction shootings.

Reverse shooting of long profiles

The sediments are overlain by basalts for a considerable part of the coastal area surveyed. Quite clearly localities with basaltic cover had to be excluded as shot points. In practice this was a limiting factor in the choice of sites for shots and thus only two of the three long profiles could be shot on both ends. The other major consideration was to avoid permafrost zones below the shot points as a permafrost zone has a relatively high seismic velocity and therefore acts as a physical barrier for the deep penetration of seismic energy.

Among other factors limiting the choice of location of shot points for reversing of profiles which deserve mention were the lack of suitable equipment for the drilling of shot holes on land, non-availability of rivers with sufficiently deep water near the proposed shot points, and above all the formidable problem of inland transport in the area.

DETERMINATION OF SEISMIC VELOCITIES

In a virgin area it is necessary to determine the seismic velocities in the various formations at the surface to permit subsequent identification of the various seismic horizons at depth. The problem of variation of seismic velocity with rock type and lithology has been discussed by several authors. Based on extensive studies of velocity data from well surveys in North America, Faust (1951, 1953) deduced an empirical relationship between velocity, depth, age and lithology of sedimentary formations. However, true formation resistivities required by Faust as lithological parameters are nowhere available in Nûgssuaq, and hence his relationships are not applicable for making velocity estimates.

For ease of interpretation, seismic wave velocities are best measured *in situ*. For refraction surveys, the velocities computed from the first arrival events are applicable. In the area studied suitable outcrops of the various formations were available for making surface velocity measurements. The geophone spread for velocity profiles, in most cases, was 110 m with 10 m spacing and wherever possible geophone lines were run both parallel and normal to the strike direction.

Correlation of seismic velocities with the known formations was possible despite some spread in velocity values. The assigned velocity ranges for rocks outcropping at the surface are shown in fig. 4. It should however, be mentioned that the presence of a high velocity sedimentary layer (4100–4500 m/s) overlying the basement was indicated in the Niaqornat profile (see fig. 2) which was shot for basement depth investigations. The geological age of the high velocity sediments is unknown and these are not exposed on land.

It is important to note that refraction arrivals from the sediments are transmitted preferentially along high velocity layers and thus the refraction method gives an inherent bias to higher velocities in comparison with the reflection method. This difference is further affected by the anisotropy of a rock unit possessing layering and a preferred orientation of flaky minerals. In stratified formations the seismic velocity parallel to the strata is generally greater than that normal to the strata by about 10–15 %.

EFFECT OF UNIFORM INCREASE OF VELOCITY WITH DEPTH

Another point of importance in relation to the velocity data of sediments is the variation of velocity with depth. Because of lack of time in the 1971 field season, this effect could not be studied for the sediments on the north coast of Nûgssuaq.

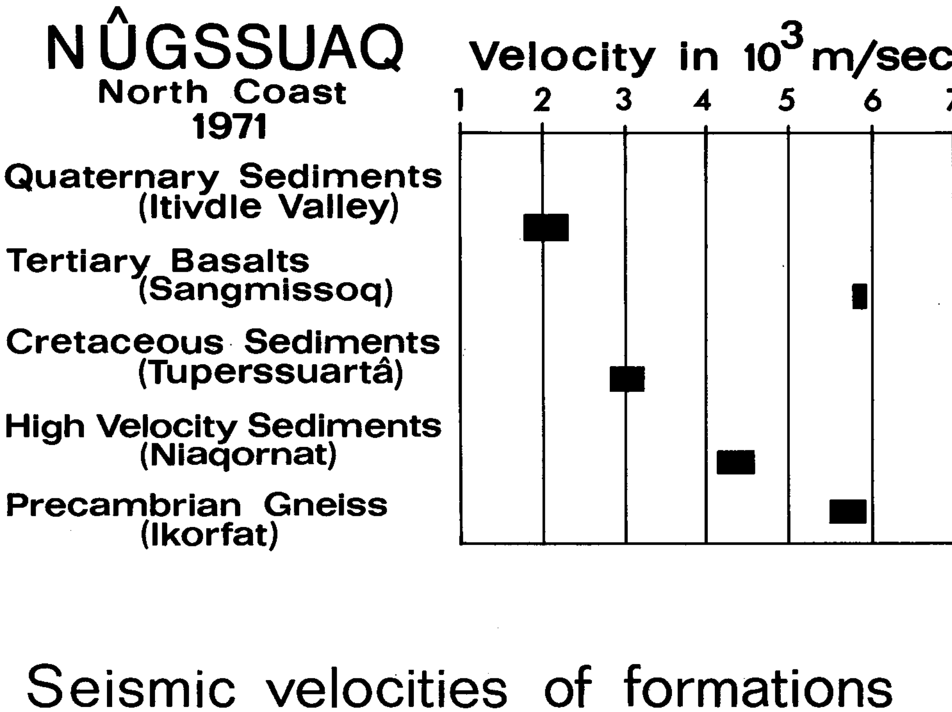

Fig. 4. Seismic velocities of the formations on the north coast of Nûgssuaq.

Common rates of increase of velocity with depth in sedimentary sequences, range from 0.3 to 1 m/s/m. The effect of depth on velocity is expected to be greater for younger rocks which may still be undergoing compaction, while older rocks which have suffered a long history of vertical movements and compaction may possess velocities largely independent of the present depth of burial.

In most cases where there is a linear variation of velocity with depth, the velocity at depth Z could be computed by the simple relation

$$V = V_0 + k . Z$$

where V_0 is the velocity at zero depth and k a constant.

A geological section in which the velocity increases continuously with depth is likely to cause problems of depth penetration in refraction studies. For a uniform increase of velocity with depth the maximum depth of penetration is given by

$$Z_{max} = V_0/k \left\{ [1 + (kX/2 V_0)^2]^{1/2} - 1 \right\}$$

If V_0 is taken to be 3000 m/s for the Nûgssuaq Cretaceous sediments and k as 0.5, table 1 shows the depths of maximum penetration as a function of the shot-to-geophone distance X.

Table 1. Penetration depth of a curved ray trajectory

($V_0 = 3000$ m/s; $k = 0.5$ m/s/m)

X m	Maximum depth Z m	Penetration Z/X %
1000	20	2
2000	85	4
5000	500	10
8000	1210	15
10000	1810	18
15000	3600	24
20000	5660	28
25000	7860	31

The figures show that there is no significant penetration for a curved ray path for shot-to-geophone distances of the order of 5 km. Thus a deep sedimentary basin with monotonic increase of velocity will not be a promising object for refraction studies. In oil exploration, refraction survey is useful only where there is some definite discontinuity in seismic velocity that can be detected or mapped. This condition may exist in geological situations where a continuous series of sands and shales is deposited on a crystalline basement or over a massive limestone with a relatively high velocity. That such a situation exists in the area surveyed is indicated by the identification of two refractors with velocities of about 4.3 km/s and 5.6 km/s respectively on the Niaqornat profile.

DEPTH DETERMINATIONS FROM REFRACTION PROFILES

Tuperssuartâ profile 1

The first refraction profile shot for depth investigations was at the north-eastern end of the Itivdle valley beside the river delta. The azimuth of the profile was 108° and the 990 m long geophone line was laid along the coast. The profile was shot on both ends. Fig. 5 shows the travel time sections for the profile. The first segments give the velocity (1780–2250 m/s) of the Quaternary sediments and glacio-fluvial deposits flooring the Itivdle valley. The second segments represent an

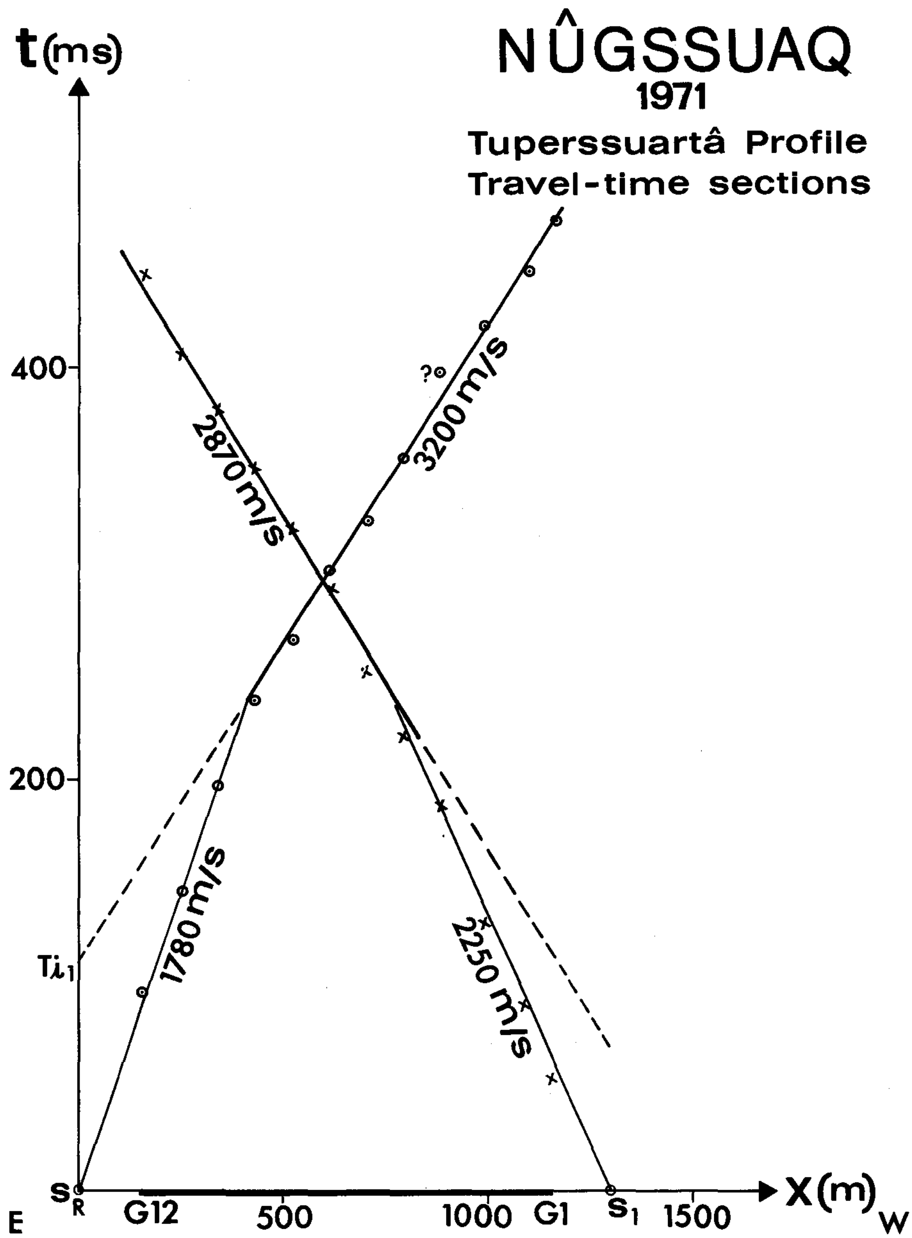

Fig. 5. Tuperssuartâ profiles 1: travel-time sections.

underlying refractor with an average velocity of around 3000 m/s, which is probably the interface marking the top of the Cretaceous sediments.

Simple calculations based on the two-layer model give depths to the top of the second layer of about 140 m and 90 m on the eastern and western ends of the profile respectively. The apparent eastward dip (about 3°) for the refractor suggested by the above depth figures may not be representative of the true dip of the underlying Cretaceous sediments, for the variations in depth could have been caused partly by the erosion of the valley.

As expected, no information about the total thickness of the Cretaceous sediments could be obtained from this profile.

Niaqornat profile

The second long profile, which was also the most important profile shot with the objective of basement depth investigation, was laid on Cretaceous sediments south of Niaqornat. The azimuth of the profile was about 103°. The shot-to-geophone line distance was about 6 km (see fig. 2). It should be noted that for various practical reasons (mentioned earlier) S_1 could not be placed in line with the geophone line. This bend of about 6° between S_1G_1 and S_2G_1 would mean that simple calculations used in the reverse shooting of a profile are not strictly valid. Further it also implies that the apparent velocity disregarding any dip in the refractor will be greater than if S_1 had been on a straight line passing through the geophone line.

Analysis of the seismograms showed a sequence of first arrivals after about 1.8 sec reckoned from the shot instant. The average velocity of about 4.3 km/s (fig. 6) for the first arrivals suggested that so far no refraction signals had been received from the basement. This led to the speculation as to what geological horizon is represented by this relatively high velocity marker. Without going further into geological speculations, a depth estimate to the top of this high velocity sedimentary layer could be made. Since there is no evidence of any other distinct refractor lying between the Cretaceous sediments (3 km/s) and the high velocity layer (4.3 km/s) a 2-layer model can be safely assumed. From the average intercept time of about 0.52 sec the depth Z_1 to the top of the high velocity refractor can be computed. Without taking into consideration the effect of the dip, the computed value of Z_1 comes to about 1100 m. On taking into account the elevation difference E of about 240 m between the geophone line and the shot points (S_1, S_2), the depth to the top of the high velocity layer (4.3 km/s) as reckoned from the mean level of the Niaqornat profile would be $Z_1 + E/2$, i.e. about 1200 m. Thus on the assumption of a simple 2-layer model and disregarding the effect of any continuous variation of velocity with depth for the Niaqornat sediments, the above estimate of 1200 m should give the thickness of the Cretaceous sediments overlying the high velocity refractor.

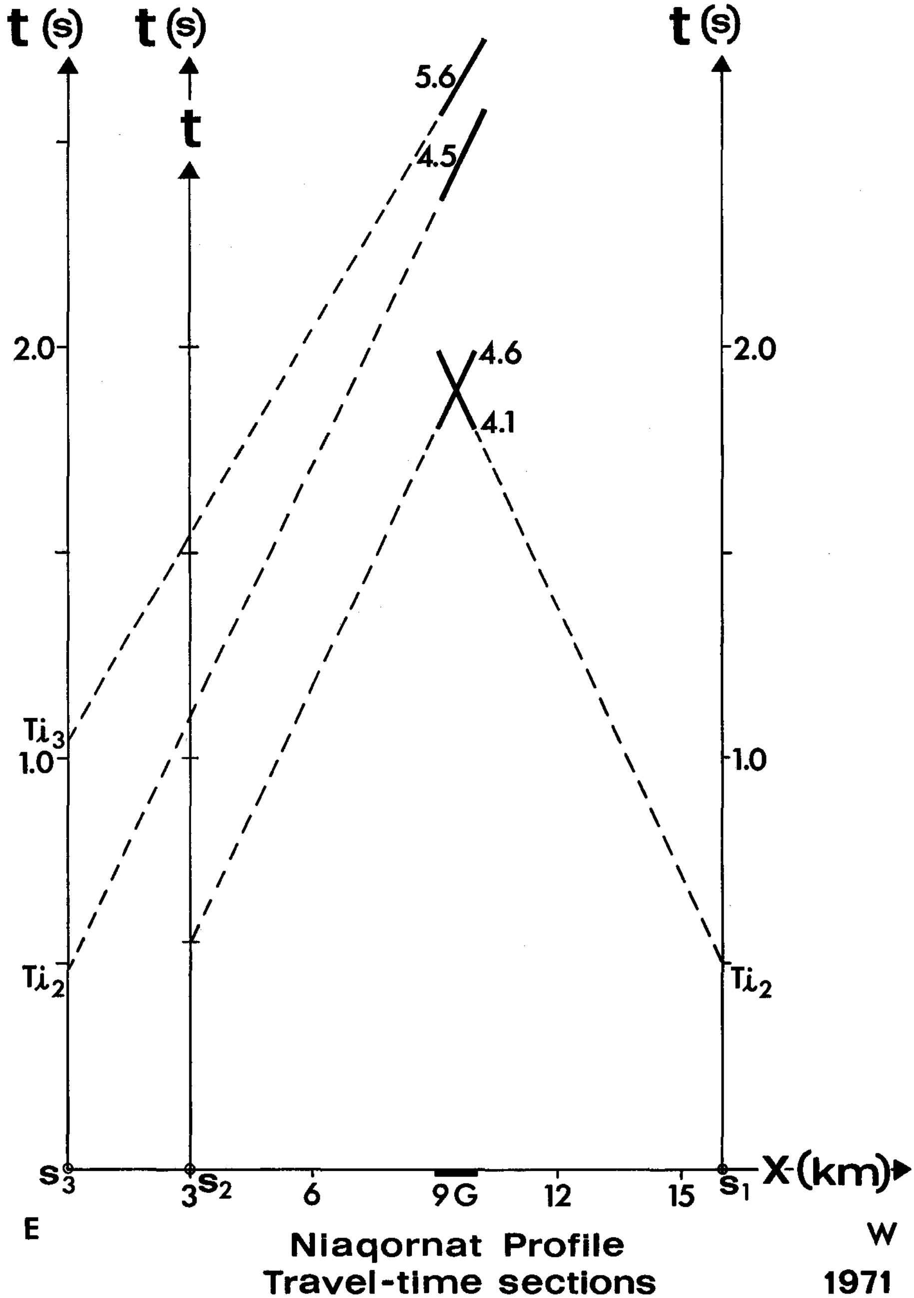

Fig. 6. Niaqornat profile: travel-time sections.

Since it became apparent that a shot-to-geophone distance of the order of 6 km was not adequate for receiving refraction signals from the basement an increase in this distance was necessary. The easiest solution seemed to be the moving of shot points. Moving S_1 towards the west seemed problematic in view of the intervening topography and complications because of faulting at Tuperssuartâ. On the other hand moving the shot point S_2 eastwards seemed feasible. It became evident that a reversal of the profile was not possible. S_3 was then placed beside the stream mouth of Kangilia and the profile was shot from the east end. The first events on the seismogram showed again a high velocity refractor with an apparent velocity of about 4.5 km/s (fig. 6) which most probably represents the eastward continuation of the 4.3 km/s (sedimentary) layer detected earlier. However, following the sequence of first events there was another line-up of events (second arrivals) with an apparent velocity of about 5.6 km/s which strongly suggested that the later events could be from the basement.

For determining depth to the top of the 5.6 km/s refractor a simple 3-layer model with two horizontal interfaces could be assumed. In effect the problem is reduced to computing the thickness Z_2 of the second layer (4.3 km/s) since the thickness Z_1 of the first layer (Cretaceous beds) has already been estimated to be about 1200 m. Using the intercept time method (Dobrin, 1960) and disregarding the effect of dip, the computed value of Z_2 comes to about 1500 m. This makes the estimate of the total thickness of sediments south of Niaqornat to be in the order of 2700 m.

Tuperssuartâ profile 2

At this stage it became apparent that if refraction signals from the 5.6 km/s layer were to be registered as first events, a further increase in the distance between the shot point and geophone line was necessary. Moving S_3 further east of Kangilia by a few kilometres in the profile direction did not seem feasible. The alternative solution of moving the geophone line back to the Tuperssuartâ delta was preferred and the shot was placed about 12 km from the geophone line. At this distance the radio communication was so poor that no shooting was possible. As an act of desperation shooting was attempted without radio by synchronizing the two wrist watches used by the shooter and the recorder. The synchronization was not sufficiently precise, and the result was a wastage of explosive charge without any recording of signals. This led to the abandonment of all further plans for long range shooting along the coast line.

Finally, with the availability of a more reliable radio on board the GGU boat 'Steenstrup', it was decided to try offshore shooting of a cross profile placing the geophone line normal to the coast at Tuperssuartâ. The azimuth of the profile (see fig. 2) was about 15° and the shot distance as measured by the ship's radar was about 13 km. The sequence of first arrivals showed an apparent velocity of about 5.1 km/s. As the reversal of the profile was not possible, it is difficult to correlate this apparent velocity with any of the deep seismic horizons so far identified. In all probability the first events arriving with a velocity of 5.1 km/s may be from the basement refractor, and the apparent decrease in velocity may have been caused by a southward dip of the basement. Because of the various unknown parameters involved, i.e. the thickness and dips of the overlying layers, a quantitative interpretation of the unreversed profile is not attempted.

SOURCES OF ERRORS IN REFRACTION INTERPRETATION

A knowledge of factors causing errors in refraction interpretation is basic to any reliable estimate of depths to the geological horizons. Errors in refraction interpretation can be classified under two general headings: (a) errors due to incorrect reading of the data, (b) errors due to incorrect assumptions.

Errors due to incorrect reading of the data

The principal error is usually the incorrect identification of the inception of the signals on the seismograms. The possibility of this error occurring increases with increase in the shot-to-geophone distance. The signal not only decreases in amplitude but also has a longer period as the offset distance increases. In practice the error leads to a parallel shift in the intercept time segment and will primarily cause an error in the depth of the refractor. The error D_e in depth determination is directly proportional to the error T_e in the intercept time for a given velocity contrast, as can be seen from the following relationship:

$$D_e = T_e/2 \cdot V_1 V_2 \, (V_2^2 - V_1^2)^{-1/2}$$

For example, a shift of 20 ms in the total intercept time of about 500 ms for the refractor segment of 4.3 km/s (see fig. 6) would cause a proportionate error of about 4 % in the depth of the refractor. Even for the long offset distance of about 9 km for the Niaqornat profile the error due to this cause is not expected to exceed 5 % in the depth estimates.

The other source of error is in the approximation of the time-distance curve with straight line segments whose slopes affect not only the velocity of the refractor but also the dip and depth computations. The method of least squares (Steinhart & Meyer, 1961) does not solve the problem completely. The effect of using incorrect apparent velocities (V_d, V_u) for calculations of dip α and refractor velocity (V_2) can best be understood from the following relation:

$$V_1/V_d + V_1/V_u = 2 \cdot (V_1/V_2) \cos \alpha$$

From this it is evident that to a first approximation the true velocity V_2 of the refractor can be determined as the reciprocal of the average slope of the time-distance segments for a reversed profile (see fig. 5). The error made in this approximation is proportional to cos α, and for dips less than 10° the error in V_2 is less than 2 %. The resulting errors in depth computation by use of average velocities have been worked out by Savit (1967), and for dips less than 10° the errors in depth computation do not exceed 9 % for velocity contrasts (V_1/V_2) from 0.5 to 0.8.

Errors due to incorrect assumptions

The errors caused by incorrect assumptions are sometimes greater than those due to incorrect reading of the data.

One assumption usually made is that no decrease of velocity occurs with depth and this assumption cannot be tested by only refraction surveying. The effect of the existence of an intermediate low velocity layer would result in an overestimation of depth for the underlying refractor, the overestimation being determined by the thickness of the low velocity layer and the velocity contrast involved. However, it is unknown whether such low velocity zones exist in the sedimentary succession along the north coast of Nûgssuaq.

Even where the velocity increases with depth, the assumption that all layers ($V_n > V_{n-1}$) are recognizable may not necessarily be true. If one of the layers is thin in comparison with depth, the refracted wave from it may never reach the surface as a first arrival. This can lead to a misinterpretation if only first arrivals are recorded. The error due to the hidden bed (blind zone) makes the computed depth too shallow, as the overburden is assumed to be less than it actually is. The condition for the maximum error is one where the hidden layer just fails to appear as first arrival breaks (Hawkins & Maggs, 1961). Since the ABEM refraction unit used on Nûgssuaq was capable of registering also the later arrivals (second refraction events), any possibility of a hidden bed remaining undetected seems very remote.

Another source of error is in the assumption of the true vertical velocity of the overburden. Horizontal velocities in sand-shale sequences tend to be 10–15 % higher than the vertical velocities (Hagedorn, 1954). This error leads to computed depths being too great if refraction-derived velocities are used. On the other hand if vertical velocities (obtainable from well data or reflection surveys) are used, computations would tend to give depths which are too shallow. This is due to the fact that in a refraction survey the trajectory through the overburden is neither vertical nor horizontal. In practice, for an oblique ray path the actual error in depth computation by using horizontal velocities would be much less than 10 %.

Thus subject to the assumption that no reversal of the velocity with depth occurs in the area surveyed, the errors in depth computation could be due partly to the incorrect reading of data and partly to the anisotropy in seismic velocity of the north Nûgssuaq sediments. Taking these two factors into consideration, it is estimated that the depth determinations made from the interpretation of the seismograms may be subject to errors of about 10 to 15 %.

SUMMARY OF RESULTS AND CONCLUSIONS

The results of the 1971 seismic reconnaissance programme could be summarized as follows.

(1) The velocity shootings on the surface outcrops in north Nûgssuaq show sufficient velocity contrasts among the known geological formations to make the application of the refraction method possible for structural studies.

(2) The Quaternary deposits flooring the Itivdle valley east of Tuperssuartâ show a considerable variation in velocity with an average of about 2 km/s. Along the coast their thickness is about 100 m increasing eastwards.

(3) The thickness of Cretaceous sediments (3 km/s layer) south of Niaqornat is about 1200 m and they rest on a succession of older sediments (4.3 km/s layer) whose thickness is estimated at around 1500 m. The geological age of the 4.3 km/s layer is unknown.

(4) The total thickness of sediments at Niaqornat overlying the basement refractor (5.6 km/s layer) is estimated to be about 2500 m below sea level. Since the reverse shooting of long profiles was not possible, the above estimate is based on the assumption of a three-layer model with two horizontal refractors.

(5) In view of the possible sources of errors in refraction interpretation, the above depth estimates might well be subject to errors of 10–15 %. In addition, if serious structural complications (faulting, or dips over 10°) are present, the above interpretation may not be reliable.

(6) Practical problems of long range shooting on land limit the effective application of refraction surveying in the complex geological conditions of northern Nûgssuaq. Nevertheless, the first results indicating the presence of a high velocity marker (5.6 km/s) at a depth of about 2500 m, suggest a sufficiently deep sedimentary section to warrant further exploration.

(7) The total thickness of sediments at Tuperssuartâ could not be determined due to long range shooting problems. This is a key area whose structure should be studied in detail both by refraction and reflection methods, especially to follow up the westward extension of the 4.3 km/s and 5.6 km/s layers. Marine geophysical studies, in particular seismic and magnetic work, off the coast of north Nûgssuaq should be invaluable for the tie-up of the onshore data.

Acknowledgements

The writer would like to express his sincere thanks to all those who collaborated in the planning and execution of the seismic field programme, and in particular to the crew members C. Mohr, S. Lauge Petersen and E. Johannsen who despite various hazards strove hard to get results.

Thanks are also due to skipper A Viðstein for assistance in the long range offshore shooting. A team from the Geodetic Institute led by J. Olson kindly assisted in establishing the position of some lines and shot points.

The writer is deeply indebted to Professor Henry Jensen of the Geophysics Institute for the loan of the ABEM refraction unit and the low frequency geophones. The radio shot-box was designed by E. Johannsen of the Danish Atomic Energy Commission at Risø.

Thanks are due to G. Henderson for assisting with geological information, and to L. Denham for helpful discussions on various points.

Max Schierling kindly assisted with the drawing of figures in the manuscript.

The topographic maps are reproduced with the permission (A649/72) of the Geodetic Institute.

REFERENCES

Dobrin, M. 1960: *Introduction to geophysical prospecting.* New York, McGraw Hill, 435 pp.

Faust, L. Y. 1951: Seismic velocity as a function of depth and geological time. *Geophysics* **16,** 192–206.

Faust, L. Y. 1953: A velocity function including lithologic variation. *Geophysics* **18,** 271–288.

Hagedorn, J. G. 1954: A practical example of an anisotropic velocity-layer. *Geophys. Prospect.* **2,** 52–60.

Hawkins, L. V. & Maggs, D. 1961: Nomograms for determining maximum errors and limiting conditions in seismic refraction survey with a blind-zone problem. *Geophys. Prospect.* **9,** 526–532.

Henderson, G. 1969: Oil and gas prospects in the Cretaceous-Tertiary basin of West Greenland. *Rapp. Grønlands geol. Unders.* **22,** 63 pp.

Henderson, G. 1973: The geological setting of the West Greenland basin in the Baffin Bay region. *Pap. geol. Surv. Canada* **71–23.**

Rosenkrantz, A. 1970: Marine Upper Cretaceous and lowermost Tertiary deposits in West Greenland. *Bull. geol. Soc. Denmark* **19,** 406–453.

Rosenkrantz, A. & Pulvertaft T. C. R. 1969: Cretaceous-Tertiary stratigraphy and tectonics in northern West Greenland. *Mem. Amer. Ass. Petrol. Geol.* **12,** 883–898.

Savit, C. H. 1967: Refraction profiling using average velocity to near-horizontal beds. *In* Musgrave, A. W. (edit.) *Seismic refraction prospecting,* S.E.G. volume, 330–336. Tulsa Oklahoma.

Sharma, P. V. 1973: Magnetic and gravity surveys in the Itivdle valley of Nûgssuaq, West Greenland. *Pap. geol. Surv. Canada* **71–23.**

Steinhart, J. S. & Meyer, R. P. 1961: Minimum statistical uncertainty of the seismic refraction profile. *Geophysics* **26,** 574–587.