THE STRUCTURE OF THE ARCHEAN CRUST IN SW GREENLAND FROM SEISMIC WIDE-ANGLE DATA: A PRELIMINARY ANALYSIS

Karsten Gohl[1], Scott B. Smithson[1], and Yngve Kristoffersen[2]

Abstract. An extensive seismic wide-angle and vertical-incidence experiment was conducted over Archean crust in SW Greenland. 15 PASSCAL REFTEK recorders were placed on 35 locations along the coast and fjords recording 6000 cu.in. air-gun shots from offsets as far as 350 km. 100-150 m shot spacing allows one to identify several unaliased pre- and post-critical coherent phases from throughout the crust and uppermost mantle. The most prominent P-wave phases consist of Pg- and PmP-arrivals, mid- and lower crustal (PlP) reflections, and Pn-arrivals. Excellent quality PlP and PmP-phases can be traced from near-vertical to post-critical distances. S-wave arrivals include Sg and SmS (or SlS)-phases, and a strong Sn-phase at offsets between 200 and 280 km. To obtain local one-dimensional estimates of the velocity structure, an extremal inversion method was applied. All receiver gathers were slant-stacked and semblance-filtered. Pre- and post-critical arrivals were picked in the tau-p domain and inverted. Depth bounds show that velocities exceed 6.0 km/s at depths below 4 to 6 km, followed by a low gradient to the bottom of the crust where velocities exceed 7.0 km/s. The Moho depth is estimated to be 30 - 40 km with increasing depth northward. Depth bounds derived for two of the stations show a major discontinuity appearing between 6 and 8 km above the Moho. Mafic material, possibly accreted during the opening of the Labrador Sea, might be responsible for the high velocities between both reflectors.

Introduction

In September 1989, an extensive seismic vertical-incidence and wide-angle experiment was conducted along the coast and two fjords of SW Greenland (Fig. 1) to investigate the structure of the ancient Archean crust. Participants were the University of Wyoming, the University of Bergen, IRIS, the Geodetic Institute of Denmark, and Victor McGregor from Greenland. Some of the oldest rocks in the world [McGregor, 1973] are exposed in the Archean block in SW Greenland. One goal of the experiment was to trace Archean sutures from surface observations down into the crust and to obtain constraints on a possible assembly of Archean terranes [Nutman et al., 1989]. A more general purpose was to invert and model seismic normal-incidence and wide-angle data for velocity structure of oldest Archean crust that possibly underwent extension during rifting of the Labrador Sea and Davis Strait in the Cretaceous and Tertiary [Srivastava, 1978; Hinz et al., 1979]. This study focuses on a preliminary analysis and a one-dimensional inversion of densely-spaced wide-angle recordings.

Geology and Previous Geophysical Studies

The Archean block in southern Greenland consists of 3.8 BA old rocks affected by younger events and contains several Archean sutures [McGregor, 1973, 1979; Bridgwater et al., 1976; Brown et al., 1981; McGregor et al., 1986; Robertson, 1986]. Nutman et al. [1989] describe four terranes with ages of 2750 to 3820 MA that assembled between 2750 and 2550 Ma. All terranes underwent amphibolite to granulite facies metamorphism and were intensively folded.

The Archean block in Greenland was separated from its counterpart in Canada, the Nain Province, by rifting between Greenland and North America. Rifting started in the southern Labrador Sea in the Late Cretaceous, continued in the northern Labrador Sea in the Early Paleocene, and ended in the Davis Strait and Baffin Bay in the Early Oligocene [Srivastava, 1978; Srivastava and Tapscott, 1986].

Previous geophysical investigations in SW Greenland include gravity and magnetic studies in the Godthaabfjord region [Thorning, 1986; Geological Survey of Canada, 1988a,b; Woodside and Verhoef, 1989; Forsberg, unpublished data; Speece, unpublished data]. Gravity maps show a decrease in the long-wavelength Bouguer anomaly field northward of the western Godthaabfjord region, indicating a

1) Program for Crustal Studies, Department of Geology and Geophysics University of Wyoming, Laramie, WY 82071

2) Seismological Observatory, University of Bergen, N-5007 Bergen

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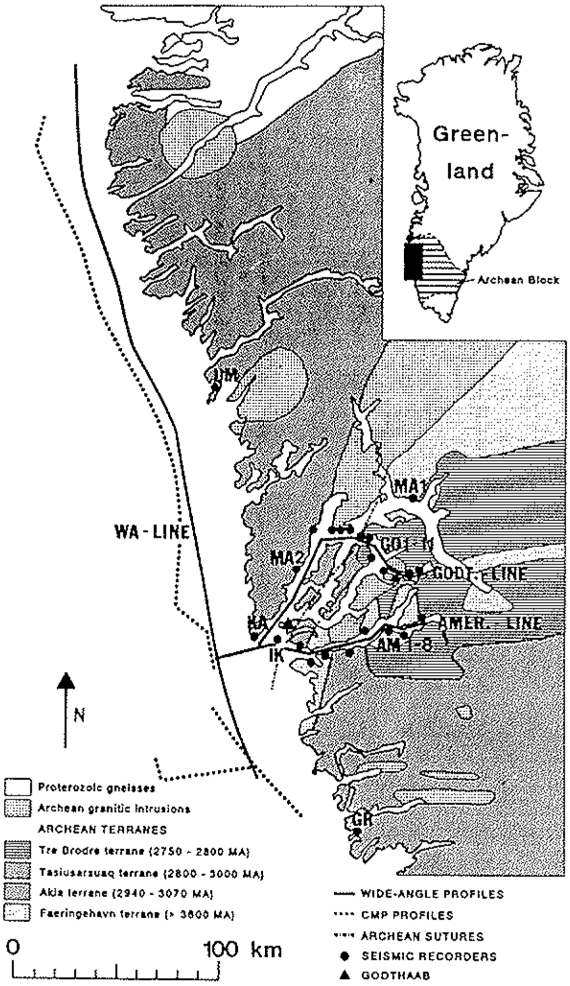

Fig. 1. Location map of shots and receiver stations of the seismic experiment in SW Greenland. Solid lines: positions of source array for wide-angle recordings consisting of 5 air-guns, shot interval 60 s; thick-dotted lines: positions of CMP lines, source array consisted of 3 air-guns, shot interval 30 s, 48-channel streamer with 50 m spacing; land-station (REFTEK instruments): UM Uman, KA Kangeq, IK Ikaarisat, GR Graedefjord, MA Manitsoq (2 stations), GO Godthaabs-fjord (11 stations), AM Ameralikfjord (8 stations), BA Base; star: Godthaab; thin-dotted lines: boundaries of Archean terranes [from Nutman et al., 1989]; striped area in inlet map marks Archean Block.

north dipping Moho. A steep gradient in the Bouguer anomaly follows the continental slope along the passive margin.

Data Acquisition

15 REFTEK recorders were placed on 35 locations along the coast, fjords, and farther inland. An array of 6000 cu.in. air-guns was fired along a north-south striking offshore line (WA) covering offsets up to 350 km, and along the Godthaab- (GOD) and Ameralik- (AM) fjords to obtain data farther inland (Fig. 1). For the first time, these broadband instruments, designed and built for the PASSCAL project as part of IRIS, were used for a large-scale controlled source experiment. To avoid the danger of losing data due to instrument failure in their first deployment, two recorders were placed on key locations. The shot interval from line WA was 1 minute, for the CMP-lines 30 seconds. A portion of the CMP-shooting was recorded by land-stations as well. We chose a recording length of 30 seconds to record up to six days without servicing. The positions of the land-stations were located using the Global Positioning System (GPS). Positions off-shore were obtained by an integrated navigation system.

Wide-Angle Data

Receiver gathers show excellent quality arrivals at offsets to 280 km (Fig. 2 and 3). All receivers were corrected for elevation statics with sea-level as datum. Also, high and low frequency noise was eliminated by a band-pass filter of 6 to 30 Hz. Dominant frequencies for most phases lie between 8 and 10 Hz. All phases show strong reverberations from the bubble effect and sea-bottom multiples. Most of the reverberations were eliminated by applying a predictive deconvolution operator designed for the dominant arrival (Fig. 2).

Major vertical component phases recorded along the coast show, even after statics correction, a first break (Pg) with highly varying apparent velocities between 5.4 and 7.1 km/s due to drastic changes in sea-bottom topography and lateral velocity variations as well as dip effects within the uppermost crust. One of the most prominent features of the vertical component of stations IK and KA is a strong, continuous lower crustal pre- and post-critical reflection (PlP) crossed by an equally strong Moho reflection (PmP) (Fig. 2). The PlP- and PmP events can be correlated through interfering S-wave arrivals to near-vertical offsets with few interruptions in their continuity. Mid-crustal phases were identified in all recordings of profile WA. Their coherency is very weak at pre-critical distances and increases with offset. A refracted upper mantle phase (Pn) with an apparent velocity of 8.1 to 8.3 km/s appears at far offsets at station IK (Fig. 2).

Other prominent features include strong shear-wave arrivals, originated from mode conversions at the water-seafloor contact. A strong, multi-cyclic direct S-wave (Sg) phase appears in all recordings. Stations IK and KA show a band of coherent S-wave energy reflected from the lower crust (SlS) or Moho (SmS). Unfortunately, this phase can not be traced farther due to a limited recording window. As a result of wrap-around recordings of previous shots, energy could be recorded at travel times corresponding to 60 to 90 seconds at offsets as far as 280 km. Within that window, all stations, except

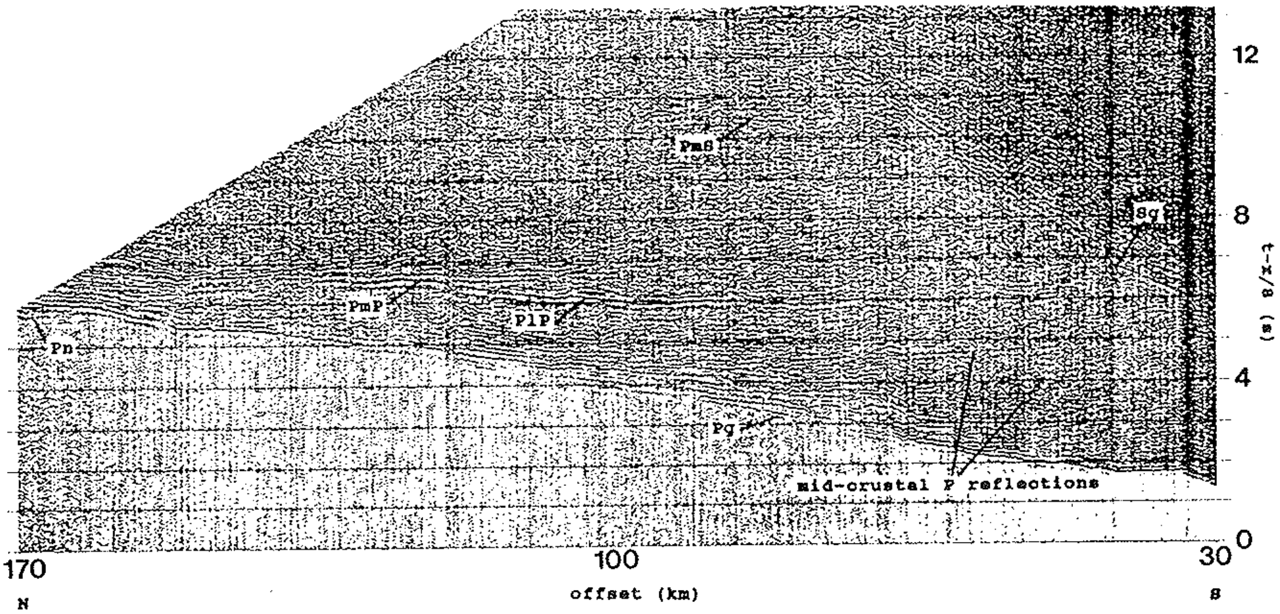

Fig. 2. Receiver gather from station IK (shot profile WA), vertical component, traveltime reduced with 8 km/s, predictive deconvolution applied.

UMAN, show coherent energy within a multi-cyclic band, identified as a shear-wave refraction from the upper mantle (Sn) with an apparent velocity of 4.1 to 4.3 km/s (Fig. 3). After rotation has been applied, it appears that the transverse component contains a more coherent Sn-phase than the radial component, an unexpected result.

Processing

As a preliminary step in our interpretation of densely spaced wide-angle data, we performed an inversion of individual receiver gathers to estimate depth bounds assuming local 1-D velocity structures. Although the bounds are probably biased to some extent by local dip effects, the inversion results provide useful starting points for deriving more realistic models. Each receiver gather was split into overlapping windows of 200 traces and then transformed into the tau-p domain. A ray-parameter increment of 0.002 s/km was used, starting from ray-parameter zero and ending at 0.35 s/km, so that the ray-parameter range for S-wave arrivals were included. After multiplying by a coherency filter derived from the smoothed semblance (Stoffa et al., 1981), the individual panels were summed to form a composite tau-p section.

The envelope of the composite slant stack of station KA (Fig. 5) shows a strong P-wave branch and a weaker S-wave branch. Several arrivals can be matched with the respective time-offset gather. The Pg-phase consists of several high-amplitude clusters between ray-parameters 0.185 and 0.125 s/km indicating variations in the first break alignment of the offset gather. Several mid-crustal phases show strong amplitudes when they reach post-critical angles. The tau-p gathers for stations KA and IK show clear images of pre- and post-critical reflections from the lower crust and Moho.

Extremal Inversion

Picks in the tau-p domain were made at the onset of each arrival. Uncertainties assigned to the intercept-time picks were based on the reciprocal bandwidths and S/N ratio of the arrivals. They did not incorporate scatter due to local dip effects. These uncertainties ranged between 0.08 and 0.2 s.

The model parameterization consisted of a stack of layers of constant slownesses with slownesses decreasing (velocities increasing) with depth. The

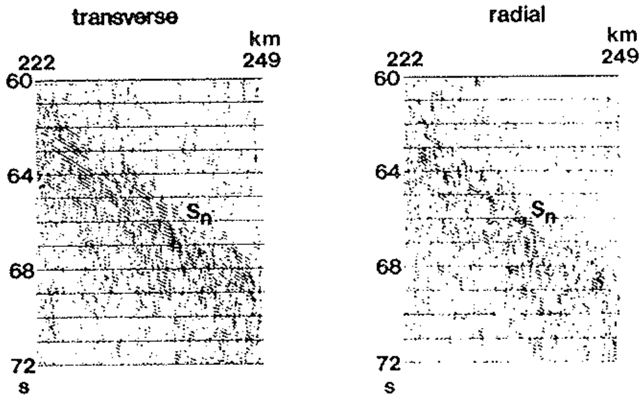

Fig. 3. Rotated horizontal components (transverse and radial) of far offset recordings from station KA (shot profile WA), containing multi-cyclic Sn.

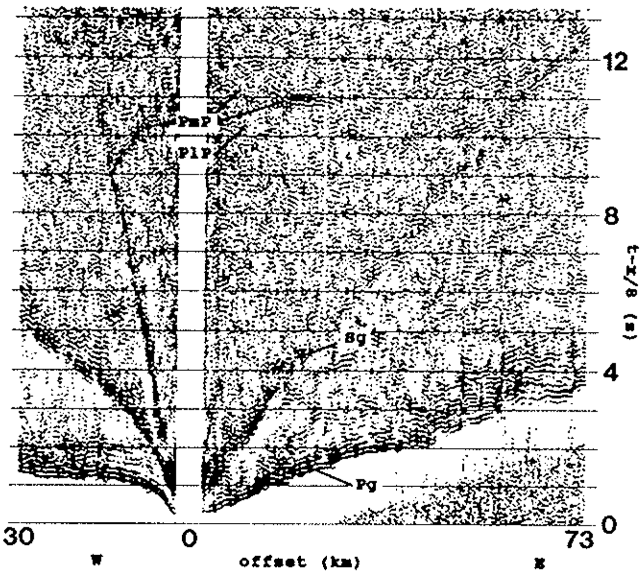

Fig. 4. Receiver gather from station IK (shot profile AM), vertical component, travel-time reduced with 8 km/s. Note the strong dip of PmP.

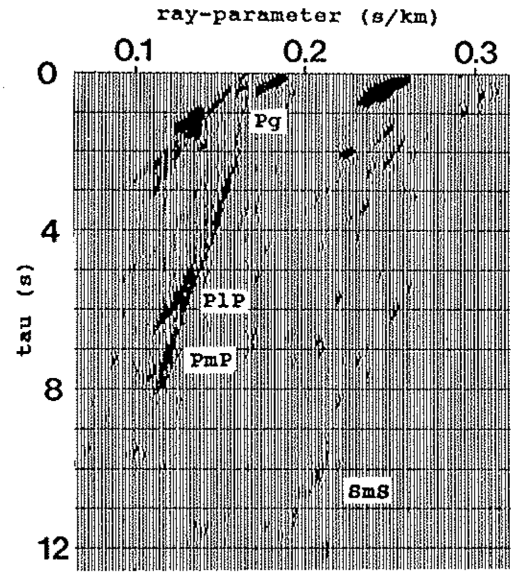

Fig. 5. Envelope plot of coherency-filtered slant stack from the vertical component of station KA-North (shot profile WA), containing strong P-wave and weaker S-wave branches. Threshold for the semblance-filter was set to level where correlation of P-wave arrivals display best. Notice the high amplitude PlP and PmP arrivals.

slowness for the uppermost layer (0.19 s/km) was chosen from the near-offset first break velocities. A minimum slowness of 0.125 s/km was chosen to allow for the possibility of high velocities near the base of the crust. The model is parameterized such that the number of layers is larger than the number of data picks to more closely approximate the real earth. Input data include refractions and post-critical reflections. Pre-critical reflections were also included wherever they could be traced back from the critical point; this helped to contrain depth bounds for specific target slownesses [Hawman and Phinney, submitted paper].

The extremal method produces a 1-D inversion (Fig. 6) of data acquired over a large offset range on a crust that is probably extremely heterogeneous. Localized depth bounds show a northward increase in crustal thickness from 30 to 40 km, in agreement with gravity data [Speece, unpublished data]. Several mid-crustal discontinuities appear at varying depths between 5 and 25 km, indicating a complex structure with lateral heterogeneities. A first order discontinuity, 6 to 8 km above the Moho, can be derived from the strong, coherent PlP-phase of stations KA and IK. A high velocity gradient for the uppermost crust is observed. Velocities exceed 6.0 km/s below depths of 4 to 6 km for most recordings, but, thereafter, the gradient remains low for the larger part of the crust. The bottom of the crust appears to consist of a high-velocity layer with a large gradient from 7.0 to 7.6 km/s.

The WA profile was located parallel to the continental margin. A first study of data from the Ameralikfjord indicates a Moho with local dip angles of 20 to 30 degrees eastward (Fig. 4). Therefore, the results of the inversion may be biased by a slope of the Moho perpendicular to the profile.

The observation of a distinct high-velocity zone at the bottom of the transitional crust suggests that mantle-derived material might have intruded and accreted to the Archean crust in SW Greenland during the beginning of the Labrador Sea rifting process. This interpretation implies that the rifting of the region was more volcanic than previously thought (White and McKenzie, 1989).

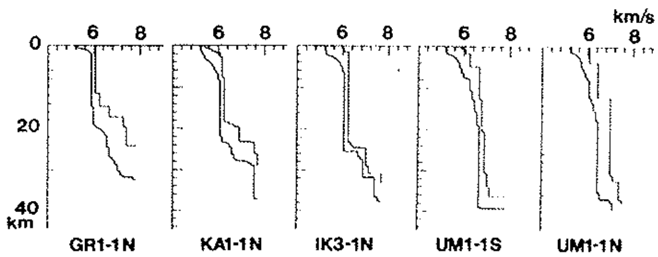

Fig. 6. Results from extremal inversion using tau-p picks. Profiles represent minimum and maximum depth bounds for each slowness, here displayed as layer velocity. Depth bounds are narrow for the upper and lowermost crust, because more coherent phases exist. Note the increase in crustal thickness toward northern recordings.

Conclusions

1. Densely spaced 3-component seismic wide-angle data were acquired from the Archean crust in SW Greenland covering offsets of up to 350 km. Prominent P-wave phases observed in the receiver gathers include strong Pg, PmP, PlP (lower crustal reflection), and several pre- and post-critical mid-crustal arrivals as well as a Pn-phase. Strong coherent S-wave arrivals include Sg, SmS (or SlS) phases, and a surprisingly coherent Sn phase at 200 to 280 km offset.

2. Extremal inversion of composite tau-p data of the coastline data assuming local 1-D structures show an increase in crustal thickness from 30 to 40 km northward that is consistent with results from gravity surveys. The results are strongly affected by the complicated 3-D structure of an Archean crust in proximity of a passive continental margin. Depth bounds of mid-crustal discontinuities are wide and vary among the station recordings, indicating intense lateral heterogeneities in the mid- and upper crust. The velocity profiles show a high velocity gradient for the uppermost crust where velocities exceed 6 km/s below depths of 4 to 6 km and a rather low gradient to lower crustal depths. Several profiles show a distinct high-velocity layer (7.0 to 7.6 km/s) at the bottom of the crust.

3. The observation of a 3 to 8 km thick high-velocity zone at the bottom of the Archean transitional crust implies that the SW Greenland margin was affected by more active volcanic rifting than previously thought. Mafic and ultra-mafic material might have been underplated as part of the rifting process.

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