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PLANNED EXPLOSION SEISMIC EXPERIMENTS IN EAST QUEEN MAUD LAND USING A PENETRATOR

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Abstract: In order to compare crustal velocity structures of East Queen Maud Land with those of Enderby Land, large explosion seismic experiments are planned along 24°E, for a 400 km profile from Breid Bay through Asuka Station toward inland of the Nansen Ice Field. We are now developing an easily deployable (expendable) seismograph from the helicopter (Antarctic penetrator) to install 40–50 seismic stations along the profile with the elevation range from 0 to 3000 m in a limited operational schedule. The penetrator must have memories to store the digital seismic records. The recorded data have to be transmitted by radio-telemetry to the central data acquisition system on the helicopter.

This report briefly summarizes scientific objectives of the planned explosion experiments, and the status of the development of the Antarctic penetrator.

1. Introduction

During 1980–1981 years, the 21st Japanese Antarctic Research Expedition (JARE-21) made explosion seismic experiments to deduce the crust and upper mantle velocity structure of the Mizuho Plateau, East Antarctica. The observation system consisted of a vertical seismograph of 2-Hz natural frequency (Mark Products *L-22D*), slow-speed (2.3756×10^{-4} m/s) direct-analog-recording (DAR) tape recorder with an internal clock, and alkaline batteries to keep the system running for 30 days. Since the calibration of the internal clocks among 30 stations at intervals of 10 km had to be made by using 4 master clocks which were carried by oversnow vehicles, and since these 4 master clocks had to be calibrated by an NNSS-receiver recovered UTC (SHIBUYA and KAMINUMA, 1982), the field operation became rather difficult and time-consuming (ITO *et al.*, 1983).

Since 1983, the research field of the JARE earth science programs has been shifted to the Sør Rondane Mountains region, and explosion seismic experiments are also being planned for the JARE-37 (1995–1996 austral summer) mission. As seismic explosions are usually made in the end phase of each regional survey, we briefly summarize here

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earth science studies in the region concerned. We then introduce the penetrator system which is now being designed as an expendable and deployable seismic observation equipment from a helicopter.

2. Outline of the Earth Science Studies over the Mizuho Plateau and East Queen Maud Land

2.1. *Ground studies*

Figure 1 illustrates a compile map of the ground studies in the region concerned. Four geological complexes are noted in the coastal zone between 20°E and 70°E. The Napier complex has the Precambrian metamorphic age of 3100–3500 Ma. The Rayner Complex is remetamorphosed from the Napier Complex 1000 Ma before the present. There is a geological boundary near the Sinnan Rock between the Rayner Complex and the adjacent Late Proterozoic Lützow-Holm Complex. Recent geological studies (HIROI *et al.*, 1986) revealed progressive metamorphism from lower-grade (low *P-T*) eastern part to higher-grade (high *P-T*) western part in the Lützow-Holm Complex. Though the Yamato-Belgica Complex has the same metamorphic age (500–700 Ma) as that of the Lützow-Holm Complex, crustal evolution of the former is believed different from

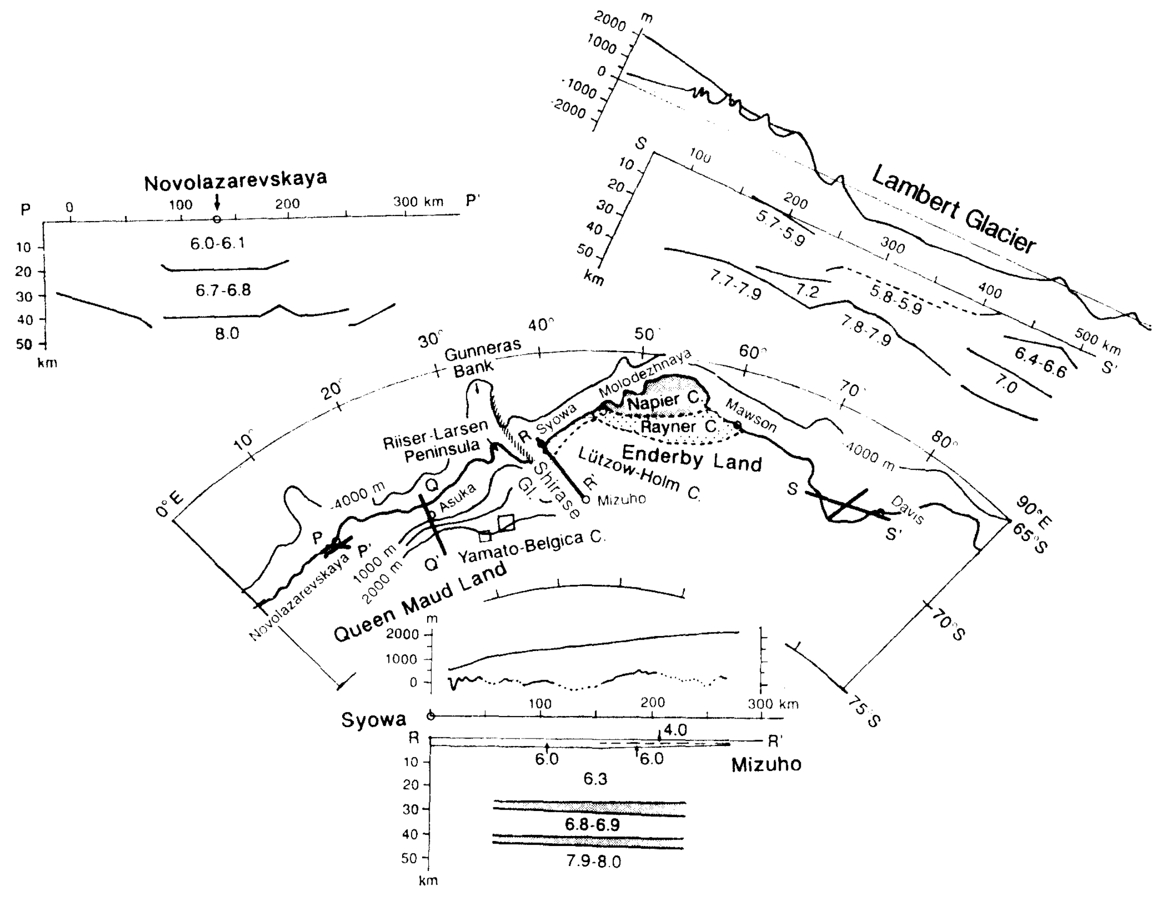

Fig. 1. Compile map of geological complexes, sea bottom and ice sheet topography, and crustal P-wave velocity structures in the region 0°–90°E, East Antarctica. For details, see text.

the latter from the comparison of the initial $^{87}Sr/^{86}Sr$ ratios (SHIBATA *et al.*, 1986).

At the boundary between the Lützow-Holm and the Yamato-Belgica Complexes, there is a 200-km long ridge on the ice sheet along 34°E from the Riiser-Larsen Peninsula towards inland. The above topographic rise continues seaward to the Gunneras Bank, constituting a ridge of 600 km total length. From the seismic reflection surveys, the Gunneras Bank is known to have a seismic velocity structure of continental type (SAKI *et al.*, 1987) which has been emplaced between the sandwiching oceanic crusts.

All the ground studies support that the Gunneras Bank, Riiser-Larsen Peninsula, Shirase Glacier, and the Yamato Mountains region constitute a large structural boundary between Enderby Land and East Queen Maud Land in the East Antarctic shield.

2.2. Satellite studies

TAKENAKA *et al.* (1991) obtained the crustal magnetic anomalies in and around the Antarctic region by applying the MPDF (Mean Polar Disturbance Field) correction method to MAGSAT data. As illustrated by black contours (2 nT interval) in Fig. 2, Enderby Land is covered with positive anomalies (solid contours; dotted region) which attain to 6 nT, while East Queen Maud Land is covered with negative anomalies (broken contours; shaded region) of −8 nT. The transition from positive to negative anomaly (0 nT contour) occurrs along 32°E; somewhat shifted westward to the Shirase Glacier region. Since positive crustal magnetic anomalies generally correspond to thick crust, and *vice versa*, Enderby Land is believed to have thicker crust than that of East Queen Maud Land.

Red curves (2.5 m interval) in Fig. 2 illustrate geoidal undulation (FUKUDA *et al.*,

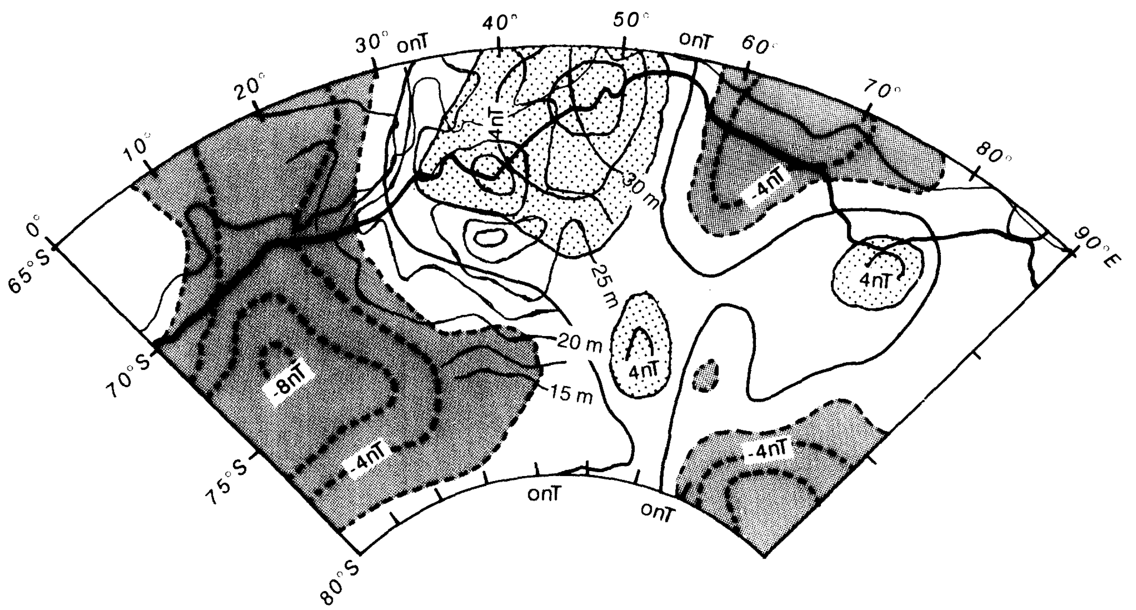

Fig. 2. MAGSAT crustal magnetic anomalies and GEOSAT geoidal undulations over Enderby Land and East Queen Maud Land, East Antarctica. Black contours are drawn at intervals of 2 nT, where broken contours (shaded region) indicate negative and solid contours (dotted region) indicate positive. Red curves indicate geoidal undulations on the OSU86D Earth Ellipsoid (a=6378137 m, f=1/298.257) at intervals of 2.5 m. Edited from TAKENAKA *et al. (1991) and* FUKUDA *et al. (1990).*

1990) obtained from GEOSAT altimeter data and ground gravity data. Geoid heights increase toward east with northwest-to-southeast trends. The Shirase Glacier area has local lows, while the Yamato Mountains region has local highs. Higher geoid anomaly generally corresponds to emplacement of larger mass, and the above two eyes also suggest change of crustal structure between east (Mizuho Plateau) and west (Sør Rondane Mountains) of the transition zone (from the Shirase Glacier to the Yamato Mountains).

2.3. *Summary of explosion seismic experiments*

Thick segments in Fig. 1 show profiles of large explosion seismic experiments ever made by Japan and the USSR. The deduced velocity structures around Novolazarevskaya Station (profile P-P′; KURININ and GRIKUROV, 1982) are generally in good agreement with those over the Mizuho Plateau (profile R-R′; IKAMI *et al.*, 1984). Both have 40 km crustal thickness, 6.0 or 6.3 km/s *P*-wave velocity for the upper crust, 6.8 km/s *P*-wave velocity for the lower crust, and 8.0 km/s P_n velocity for the Moho, with typical continental shield structures. The slight difference may be in thickness of the lower crust.

The deduced velocity structures over the Prince Charles Mountains and the Lambert Glacier (profile S-S′; KURININ and GRIKUROV, 1982) are rather different from those discussed above. The thickness of the crust sandwiching the Lambert Glacier is generally thin ($\sim$30 km) as compared with 40 km thickness for the former two profiles. The Moho depth is at 20 km beneath the Lambert Glacier area with slower P_n velocity of 7.8–7.9 km/s. It is remarkable that the *P*-wave velocity of the upper crustal layer is below 5.8–5.9 km/s, which corresponds to that of the unconsolidated sediments. The layer with the 6.8 km/s velocity, which corresponds to the lower crust, is lacking. The Lambert Glacier area is interpreted as the failed rift zone (MASOLOV *et al.*, 1981)

3. Planned Explosion Seismic Experiments

3.1. *Profile along 24°E*

Satellite studies suggested thicker crust over Enderby Land than that over East Queen Maud Land. Ground studies supported difference of the crustal structures between east and west of the boundary zone characterized by the Gunneras Bank, Riiser-Larsen Peninsula and Yamato Mountains region. However, the explosion seismic experiments along the profiles P–P′ and R–R′ did not show significant difference between the corresponding crustal velocity structures. In order to examine in detail the above regional characteristics, large explosion seismic experiments along 24°E (profile Q–Q′ in Fig. 1) are required.

The upper part of Fig. 3 illustrates ice surface topography and bedrock topography along 24°E obtained by NISHIO *et al.* (1988). There are large areas of marine ice sheet in the downstream of the Sør Rondane Mountains, indicating plain bedrock topography with an extent of 100 km (Breid Bay—Asuka Station) towards inland from the continental shelf. Bedrock rise from Asuka Station to Brattnipene is greater than 1.0×10^{-1} inclination with several steep fjords. The Sør Rondane Mountains act as a dam for the upstream Nansen Ice Field, where ice sheet gradually thickens to 2000 m at 300 km

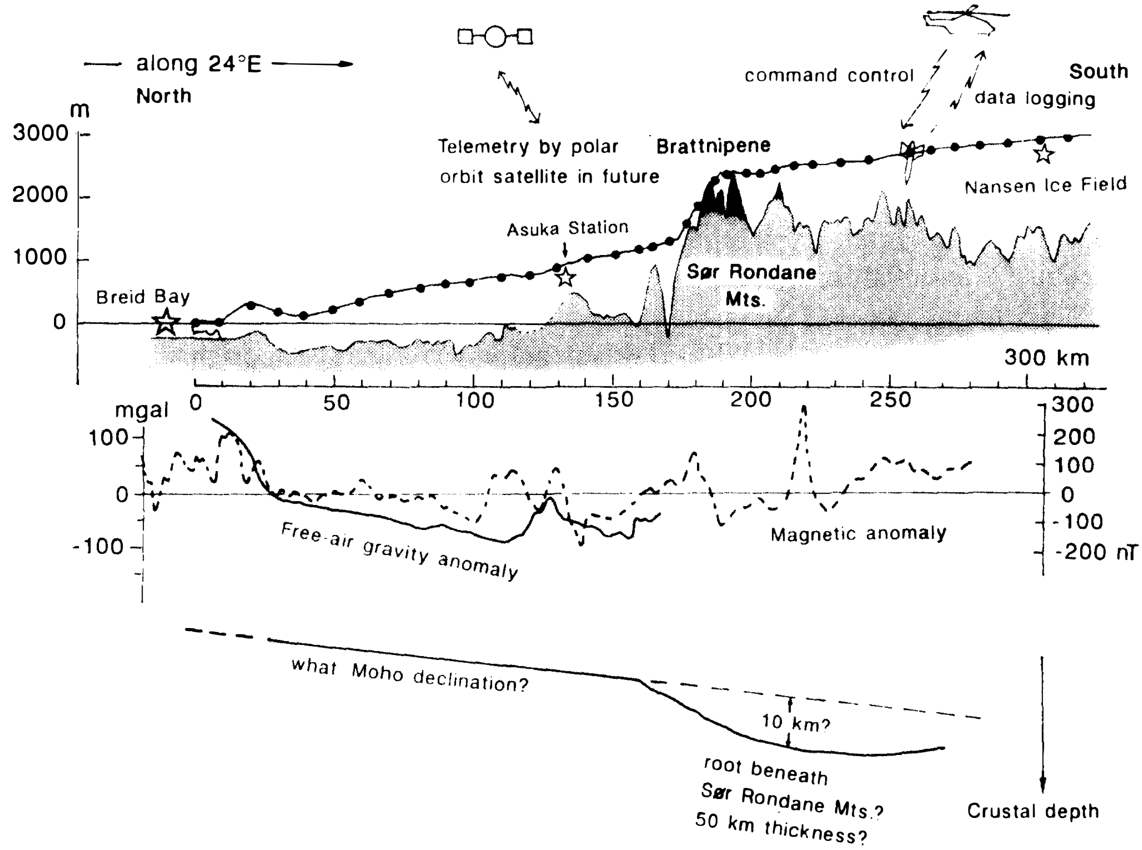

Fig. 3. Model profile along 24°E (from Breid Bay to the Nansen Ice Field) for future explosion seismic experiments in East Queen Maud Land. Surface topography and ice thickness are compiled from NISHIO *et al. (1988). Magnetic anomaly and free-air gravity anomaly profiles are compiled from* SHIBUYA *et al. (1991a). Solid circles on the ice surface indicate expendable Antarctic penetrators deployed from the helicopter. Penetrator intervals are planned as 5 km in the Sør Rondane Mountains region and 10 km on the ice sheet. More than 40 penetrators will be installed along the 400 km profile. Three stars indicate 1 to 3-t shots at both ends and middle point on the profile. Digital waveform data memorized in the penetrator must be recovered by radio-telemetry. The system must be developed by taking future satellite link into consideration.*

distance from Breid Bay.

The middle part of Fig. 3 illustrates magnetic anomaly (broken curve) and free-air gravity anomaly (solid curve) obtained by SHIBUYA *et al.* (1991a). Both anomalies suggest local mass concentration in Breid Bay. Decreasing trend in the free-air gravity anomaly towards inland is common to other research areas of Antarctica and suggests thickening of the crust.

As schematically illustrated in the lower part of Fig. 3, the scientific objectives of the planned explosions along 24°E are to detect (1) declination of the Moho toward south, (2) where on the profile does the crustal thickness attain to 40 km? (3) is P_n velocity greater than 8.0 km/s? and (4) is there a crustal root (local thickening) beneath the Sør Rondane Mountains?

3.2. Design of the penetrator system

More than 40 stations (small solid circles on the ice surface profile of Fig. 3) may be required at intervals of 5–10 km to deduce crust and upper mantle velocity structures from the 3 shots (stars in Fig. 3) at both ends and middle point on the profile Q–Q′. Installation of such many stations by the oversnow vehicle in a crevassed area (0–3000 m elevation range) is operationally unrealistic, and development of easily deployable (expendable) seismograph (Antarctic penetrator) and remote data logging system on a helicopter is essential for the planned seismic explosions.

3.2.1. Sensor

Figure 4a illustrates the V241-M seismograph which has been originally developed for the moon penetrator (MIZUTANI *et al.*, 1990). This sensor has an output sensitivity of $1.8 \times 10^2 V_{pp}$/m/s with the natural frequency of around 3.5 Hz (depending on each seismograph). Though the velocity amplitude response of V241-M seismograph is slightly shifted to higher frequencies than those of the signals expected from planned 4-t

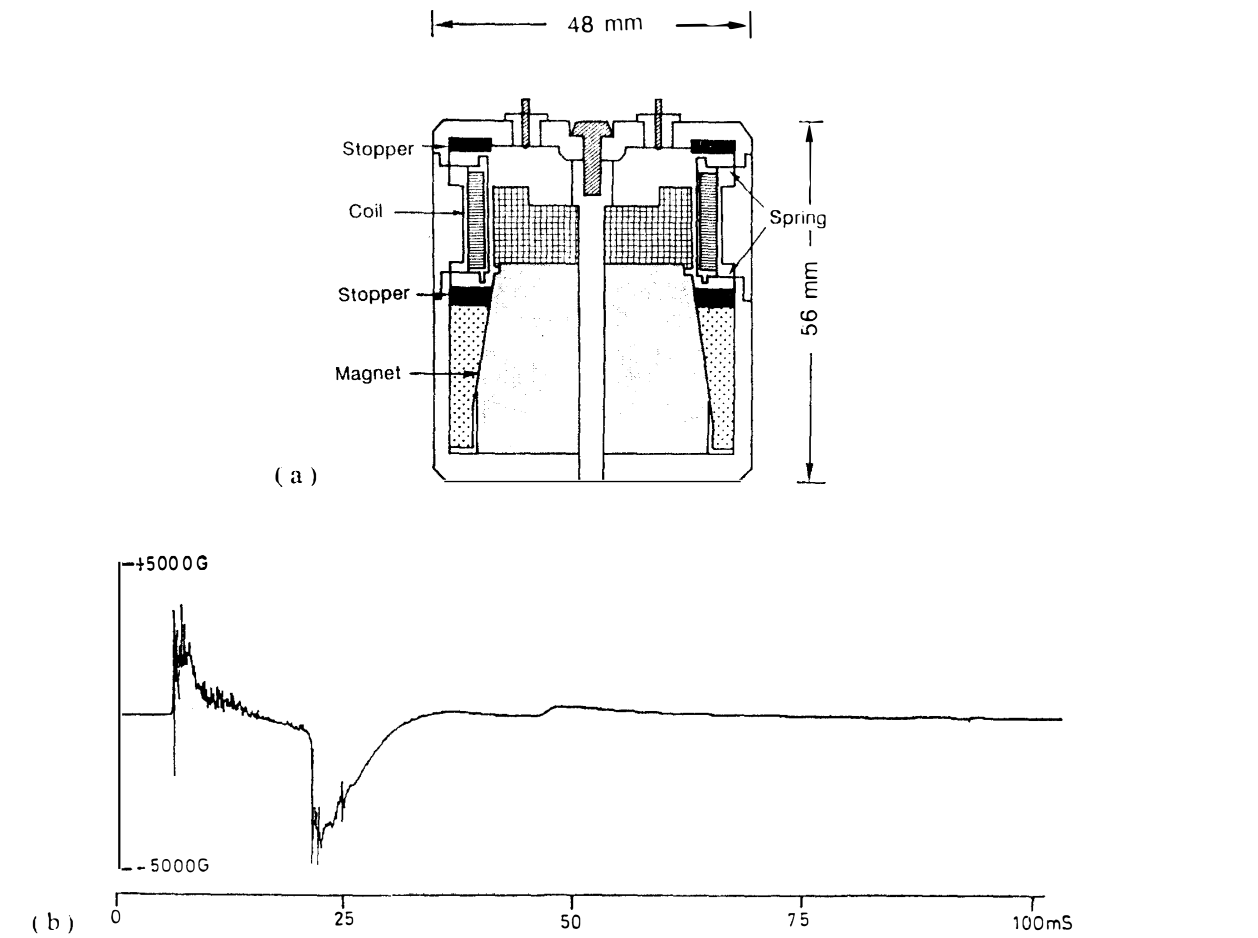

Fig. 4. (a) V241-M type vertical-component seismograph can be integrated in the Antarctic penetrator, (b) the seismograph can endure accelerations ranging from −5000 G to 5000 G, which resulted from the collision of the test penetrator into sands (hardness 20–100×10⁵ N/m²; collision velocity ~220 m/s). Redrawn from YAMADA *et al. (1990).*

sea shot and 1-t ice shot (for reference, see IKAMI *et al.*, 1981), recovered digital waveform of impulse response from each deployed penetrator can be used to calibrate the frequency characteristics of explosion signals.

According to the shock test made at the Noshiro Rocket Center (YAMADA *et al.*, 1990), the seismograph was proven to endure ± 5000 G (1G=9.8 m/s^2) shock (Fig. 4b) by the collision (impact velocity $\sim$220 m/s) of the penetrator into sands (hardness 20–100$\times 10^5$ N/m^2).

3.2.2. Hardness parameter of snow

Penetration depth d in meters of the Antarctic penetrator depends on the hardness parameter s of snow, which can be expressed (FUJIMURA, personal communication, 1988) as

$$d=10^{-3}sNA^{-1/2}\sqrt{m}V, \qquad (1)$$

where

- s: hardness parameter of snow (non-dimensional),
- N: configuration parameter of the penetrator cone (non-dimensional),
- A: cross sectional area of the penetrator measured perpendicular to fall direction (m^2),
- m: weight of the penetrator (kg),
- V: collision velocity (m/s).

In order to estimate s for the glazed surface snow on the Antarctic ice sheet, a fall test of the dummy loads from 600 m above the ground was made at Asuka Station (Fig. 5a). Though the smaller dummy load (Fig. 5b) was not found, the larger dummy load (Fig. 5c) was recovered. Since $N=1.08$, $m=8.75$ kg, $A=2.78\times 10^{-2}$ m^2, V$\sim$105 m/s and d was measured as 1.63 m (unrecovered core was presumed to have no strength), hardness parameter of snow can be estimated as $s=8.3$. It is true that s has regionality and must be small in the blue ice area, however, this parameter can be used to design controlled burial depth of the antenna element for radio telemetry.

3.2.3. Telemetry

Because of long span (400 km) and rugged topography (3000 m height difference), real-time data transfer from the penetrator by radio-telemetry to the central recording station is not certain. Pickup of the deployed penetrator is also uncertain because it may not even be found. Thus the penetrators must have memories to store the explosion signals, and the digital waveforms must be radio-telemetered to the data acquisition system by command control. Figure 6 schematically illustrates the block diagram of planned aerial link. The FM coded data are transmitted on a VHF radio wave. They are decoded and recorded on a memory of the central data acquisition system.

Considering previous shots in the Mizuho Plateau, the required record length per shot is 90 s. For a rate of 200 samples per second, the memory size will be 200 samples/s $\times$16 bits/sample$\times$90 s=288 kbits. When 4 memory banks are installed in the penetrator, all the data for transmission is 288 kbits$\times$4=1152 kbits, which, by a transfer rate of 8 kbits/s, can be transferred to the data acquisition system on the helicopter in 1152 kbits$\div$8 kbits/s=144 s$\sim$2.5 min.

Detailed design of commands and data formats for radio-telemetry is now being

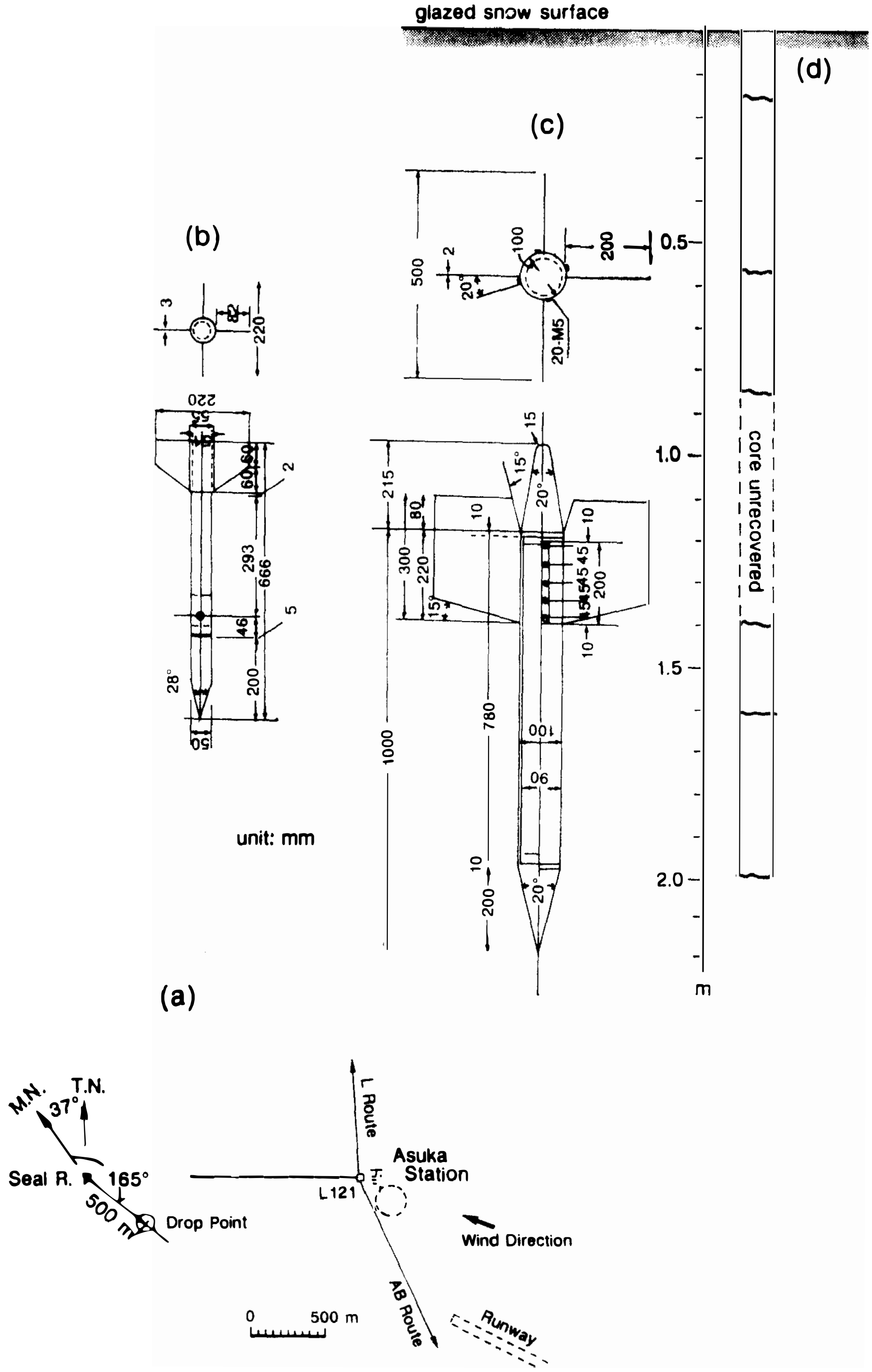

Fig. 5. A fall test of the dummy penetrator from 600 m above the snow ground at Asuka Station: (a) Location map of the test site. (b) The small dummy load was not found. (c) The tip of the large dummy load stopped at 2.2 m depth from the glazed snow surface. (d) Snow core was sampled near the drop point.

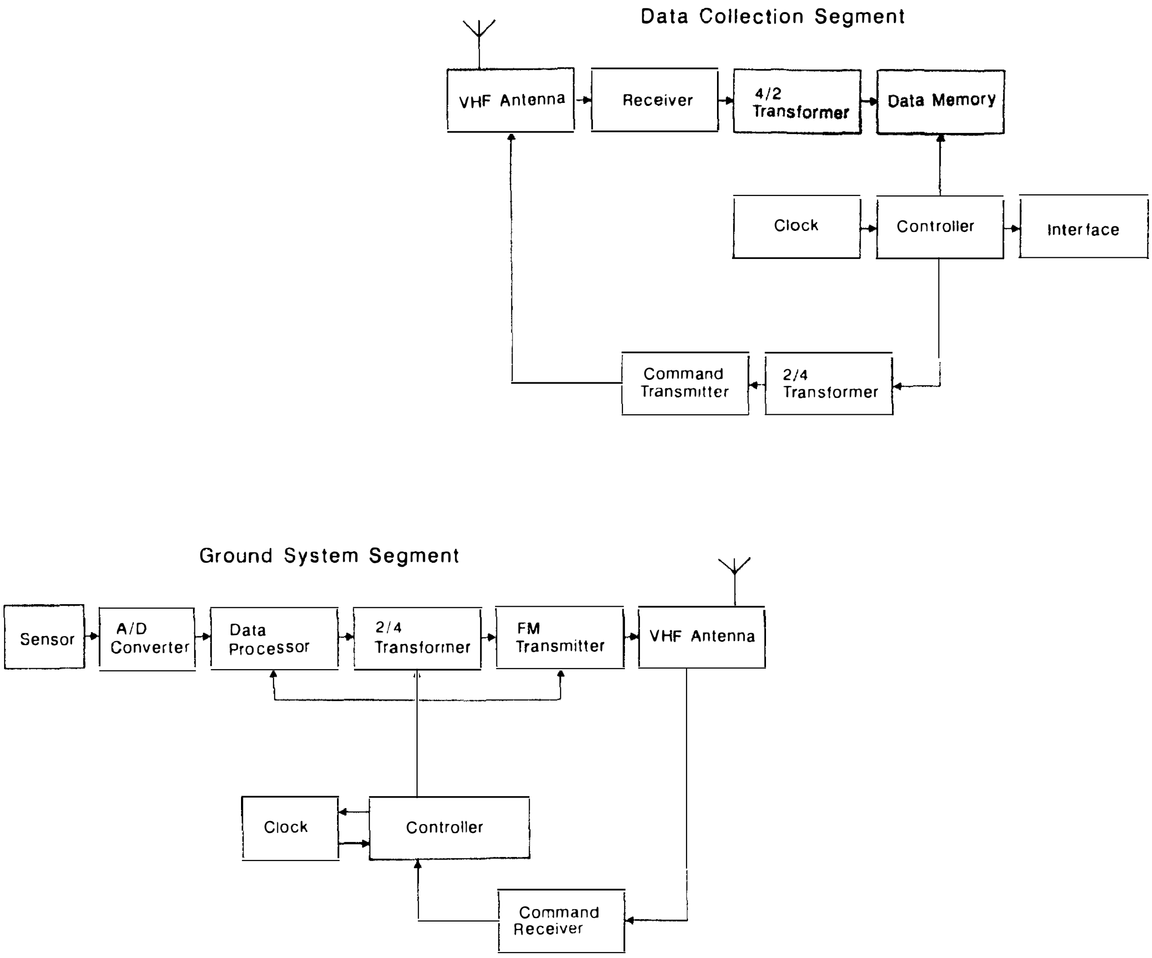

Fig. 6. Block diagram of aerial link for data transmission from the deployed penetrator to the data acquisition system on the helicopter.

made. Some discussion is given by SHIBUYA *et al.* (1991b). Other problems to be solved urgently are (1) accurate positioning (~30 m rms) of the deployed penetrator by a passive method, and (2) synchronization of the penetrator clock to the standard time base (UTC) within an offset of 1 ms by command control. These problems must be solved by an application of GPS differential positioning and GPS time transfer.

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