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Initial Field Report: U.S. Geological Survey participation in the 1993/94 Antarctic Crustal Profile (ACRUP) Seismic Project, Ross Sea area, Antarctica

by

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Abstract

During the 1993/94 austral summer, the U.S. Geological Survey recorded wide-angle refraction data along three east-west, deep-crustal transects in the Ross Sea region as part of an international project. One transect was across the Transantarctic Mountains extending about 230 km along latitude 76 degrees South. Fifty three seismic stations were deployed and four shooting locations were used. The other two transects were in the southern Ross Sea, and extended back-to-back for 650 km along latitude 77 degrees 6 minutes South, starting at a point directly north of Ross Island. Fifty-six ocean-bottom seismometers were deployed, and a seismic source of 71 liters was fired every 240 meters along the combined transect. Data from the three transects are now being digitized and analyzed. Initial interpretations from seismic stations should be available by mid-1994. Good logistic and science cooperation between the U.S. and Italian Antarctic programs resulted in a highly successful field season.

Introduction

In January and February 1994, the U.S. Geological Survey conducted seismic investigations in the Ross Sea and adjacent Transantarctic Mountains, as part of the international Antarctic Crustal Profile (ACRUP) project to map the crustal structure of the West Antarctic Rift system. The ACRUP project was conducted under the logistic coordination of the Italian National Antarctic Research Program (PNRA), with planned involvement of six research organizations from four countries including USA, Germany, Italy, and Japan. The U.S. Geological Survey participated with the logistic and science-grant assistance of the U.S. Antarctic Program, Office of Polar Programs in the National Science Foundation.

The ACRUP project had a land component, coordinated from Starr Nunatak Camp near Terra Nova Station (Italy), and a marine component, conducted aboard the R/V OGS EXPLORA (Italy). The purpose of this preliminary report is to give a general overview of the ACRUP project and describe the activities and contributions of the U.S. Geological Survey during the field operations. Complete descriptions of the land and marine field operations for the ACRUP project are reported by the Italian National Antarctic Research Program (Bacigalupi and Ramorino, 1994).

The objective of the ACRUP project is to study the structure of the crust and upper mantle of the Ross Sea region using geophysical measurements along onshore and offshore transects. The Ross Sea is part of the West Antarctic Rift system (WRS). The WRS has a 2500 to 5000-m-high rift shoulder (Transantarctic Mountains (TAM)) on the west, and is underlain in the Ross Sea by numerous large rift basins now filled with thick sedimentary sections (Cooper et al., 1991; Behrendt et al., 1991). A deep sedimentary basin, the Victoria Land basin, and an active rift (Terror rift) are mapped along the western side of the Ross Sea adjacent to the TAM (Cooper and Davey, 1987; Cooper et al., 1987). The rift structures of the Ross Sea are believed to have formed initially with the Mesozoic breakup of Gondwana, and later with late Mesozoic and Cenozoic extension across the Ross Sea and uplift of the Transantarctic Mountains (Fitzgerald et al., 1986; Cooper et al., 1991; Lawver et al., 1991). The age of the Mesozoic and Cenozoic rifting is poorly known because rocks from deep within the rift basins have not been sampled (Cooper et al., 1991). Also, the crustal structure and mechanism(s) of rifting are not known because few refraction data exist, although many models for the evolution of the WRS and uplift of the TAM have been proposed (e.g. Gleadow et al., 1984; Fitzgerald et al., 1986; Stern and tenBrink, 1989; Cooper et al., 1991; Tessensohn and Worner, 1991; Behrendt et al., 1991; Behrendt and Cooper, 1991; Fitzgerald, 1992). The ACRUP experiments are designed to determine deep-crustal structures in the Ross Sea region to help resolve the mechanisms, and relative timings, of rifting events.

Initially, two ACRUP transects were planned for the 1993/94 field season: 1) an E-W transect along latitude 76° S, extending about 400 km from the polar plateau of the Transantarctic Mountains to about 200 km offshore in the Ross Sea; this transect would cross the flank of the West Antarctic Rift system (i.e. boundary between East and West Antarctica along the TAM) and the adjacent offshore Victoria Land basin and Terror rift; and 2) a 200- km-long, N-S transect along the axis of the Victoria Land Basin (longitude 164° W); this transect would examine the crustal structure of the 14-km-thick sedimentary section and underlying thin(?) crust of the basin and active Terror rift.

Unusually bad ice conditions were encountered in the western Ross Sea during January and February 1994. More than 80% of the planned operating areas were covered by heavy pack ice. Consequently, the locations of offshore crustal transects had to be changed, and the planned onshore-offshore long-range seismic experiment could not be done. In addition, the Japanese ship R/V Hakurei-Maru was unable to join the ACRUP project at the last minute due to the bad ice conditions in their other working area of the Ross Sea, and due to heavy pack ice across the entrance to the Ross Sea. The offshore ACRUP transects were subsequently relocated to the southern Ross Sea to cross the deep rift structures beneath these areas. Two transects were done, back-to-back, yielding a continuous transect that extends nearly 650 km across about 70% of the southern Ross Sea along latitude 77^{o} 06^{o} S from near Ross Island (168^{o} E) to the middle of the Eastern basin (longitude 167^{o} W). The onshore part of the ACRUP project was done as planned, and several additional seismic stations were placed on the fast ice along a seaward extension of the profile out to about 30 km from shore, over the Victoria Land basin (Figures 1 and 2).

Many different types of geophysical surveys were conducted during the onshore and offshore parts of the ACRUP field program. Scientists from each of the three countries participated and contributed equipment for use in the field program. The overall logistics for the operation were coordinated and principally sponsored by Italy. Tables 1 to 3 list the general contributions to the science program by each country and organization; the contributing organizations; and participants in the ACRUP field work.

Table 1: Science contributions to ACRUP project by country

Science Program	USA	Germany	Italy
Onshore field work:			
Seismic experiment	X	X	X
Gravity stations	-	X	X
Aeromagnetic surveys	-	X	-
Radio echo sounding	-	X	X
Downhole heat flow	-	-	X
Offshore field work:			
Ocean bottom seismometers	X	X	X
MCS seismic reflection	-	-	X
Seagravimeter	-	-	X
Marine magnetometer	-	-	X
Bathymetry	-	-	X

Table 2: Organizations and researchers participating in ACRUP project fieldwork

Participating Organizations and Researchers	Country	Onshore	Offshore
German Geological Survey (BGR) V. Damm, G. Delisle, G. Reitmayr	Germany	X	
Inst. Geophysik, University of Hamburg F. Hinrichs, D. Woodtke M. Bahnhoff, F. Egloff	Germany	X	X
National Institute for Geophysics M. Chiappini	Italy	X	
Osservatorio Geofisco Sperimentale (OGS) G. Brancolini F. Coren	Italy	X	X
University of Genova E. Bozzo, G. Caneva	Italy	X	
University of Siena C.A. Ricci	Italy	X	
University of Trieste **B. Della Vedova (Project Coordinator)** G. Pellis	Italy	X	X
U.S. Geological Survey (USGS) (See Table 3)	USA	X	X

Table 3: U.S. Participants in ACRUP project - 1993/94 field season

U.S. Participant	Affiliation	Location	Field location
Dr. Alan Cooper	Geophysicist, USGS - Pacific Marine Geology	Menlo Park, CA	R/V EXPLORA
Mr. Gregory Miller	Marine Technician, USGS - Atlantic Marine Geology	Woods Hole, MA	R/V EXPLORA
Mr. Jie Zhang	PhD Student - Earth Resources Laboratory, MIT	Cambridge, MA	Starr Nunatak Camp

The following sections of the report give details for the field operations for the offshore and onshore parts of the USGS involvement in the ACRUP project. The offshore sections are outlined in greater detail, because the principal scientist and first author of this report participated in the EXPLORA cruise, and was not directly involved in the daily activities of the onshore field work. The reader is directed to the comprehensive field-report, now in preparation by the Italian National Program, for greater detail of the onshore and offshore parts of the experiment. Scientific results will be presented in later publications after data processing and analysis.

Cruise Narrative

Transit to Antarctica

The U.S. scientific staff for the offshore part of the 1994 Antarctic Crustal Profile (ACRUP) project (i.e. Dr. Alan Cooper and Mr. Gregory Miller) departed the United States for Antarctica on January 1. After stopping in Christchurch for Antarctic clothing issue, the staff continued to Dunedin, New Zealand to prepare for arrival of the R/V OGS EXPLORA. Upon arrival of the ship, the staff loaded the 5800 pounds of U.S. Geological Survey Ocean Bottom Seismometer (OBS) equipment aboard during the period of January 7-10, 1994. On January 10, the ship departed for the Ross Sea, Antarctica, arriving at the entrance to the sea on January 16. Due to heavy ice conditions, the entrance was closed by up to 9/10 pack ice, and the EXPLORA could not enter. By good fortune, the USCG POLAR SEA was escorting the tanker-ship MATHESSIAN into the Ross Sea, and provided ice-breaking assistance for the EXPLORA to enter the Ross Sea on January 17 and 18. The EXPLORA then proceeded to the Italian Terra Nova Station, thru heavy pack ice, to offload supplies. On January 20 EXPLORA left Terra Nova Station and proceeded to Franklin Island area, arriving on January 21 to deploy equipment for commencing seismic transects.

Multichannel seismic reflection operations

Due to heavy ice cover of the western Ross Sea, from the coast to Franklin Island, it was not possible to deploy OBS equipment across nearly all of the Victoria Land basin, E-W along the planned ACRUP-1 transect of the Transantarctic Mountains and westernmost Ross Sea along 76° S. Open water east of Franklin Island allowed four OBSs (2 from Italy and 2 from Germany) to be deployed at the far east end of the ACRUP transect at 10-km-intervals. The westernmost OBS was deployed about 1 km from the edge of the ice pack. Thereafter, the EXPLORA deployed seismic gear to begin an E-W multichannel seismic-reflection (MCS) profile across the Ross Sea. The equipment and parameters used included

- 3000-m-long, 120-channel, seismic streamer, 15-second record length, 4 msec sample rate, 50 m shots
- 36-airgun array (one string of 17 guns and one string of 19 guns with a total volume of 71.5 litres)
- marine gradiometer
- seagravimeter
- 12-kHz bathymetry
- integrated GPS navigation system

Following deployment and testing of the MCS equipment, which required about 29 hours, a sequence of 40 airgun shots at 120 sec intervals were made while the ship was circling to begin the MCS profile. These shots were intended to be recorded by land seismic stations along the ACRUP transect in the Transantarctic Mountains. The EXPLORA recorded an E-W MCS profile between January 24 and January 27. Thereafter, a second MCS profile was recorded heading NW until January 28. The two MCS profiles were recorded for the University of Trieste as part of the Italian Antarctic Research Program (Figure 1).

Offshore ACRUP Transects

From January 28 to February 17, the EXPLORA conducted OBS operations as part of the international ACRUP project. Two offshore-only transects were recorded, each about 300 km long. The two transects, end to end, with a center-point near 180 degrees longitude, extend from the eastern flank of the Victoria Land basin (directly north of Ross Island) to the middle of the Eastern basin (Figure 1). The ACRUP transect in the eastern Ross Sea was recorded first, followed by that in the western Ross Sea. The complete transect is located directly over previously recorded MCS seismic line USGS 404 (USA) and BGR 2 (Germany).

ACRUP-ERS Transect - Eastern Ross Sea

The ACRUP-ERS transect commenced on January 30 directly following a bad storm and long transit from the end-position of MCS profile 2. Twenty-six OBS stations (6 from USA, 6 from Italy, and 14 from Germany) were deployed along the 300-km long transect with a station spacing of 10 km, and with gaps of 30 and 40 km at the west and east ends of the transect, respectively. After OBS deployment, the full complement of geophysical gear was deployed (see above) in about 6 hours. A 1500 m-long-streamer (120 channels) was used instead of the 3000-m-long streamer. Shooting of the ACRUP-ERS transect began on January 31 and ended on February 2. The first phase of OBS recovery, during which all but 5 OBS were recovered, started February 2 and ended on February 4. On February 5, necessary repairs and tests were made to ship, MCS, magnetometer, and side-scan sonar equipment. The final phase of OBS recovery was completed on February 6, during which all but 2 OBS (both from Germany) were recovered.

Following completion of the ACRUP-ERS transect, the EXPLORA transited to Franklin Island to recover the four OBSs set out earlier. On February 7, three OBS were recovered, but the fourth OBS (from Italy) could not be reached because the ice-front had moved 7 km east and now covered the OBS station. Thereafter, EXPLORA transited to a point about 30 miles north of Ross Island to be refueled from the ship ITALICA on February 8.

ACRUP-WRS Transect - Western Ross Sea

The ACRUP-WRS transect commenced in the evening of February 8 with OBS deployment about 6 km from the edge of heavy brash ice north of Mt. Terror on Ross Island. Thirty OBS stations (6 from USA, 7 from Italy, and 17 from Germany) were set out at 10-km intervals along the E-W transect, which followed a latitude of about 77° 06' S. The position of several OBS stations had to be moved 2 to 3 miles north of the transect line to avoid a) the advanced position of the Ross Ice Shelf (17 km north of charted position) and b) concentrations of heavy brash ice near the advanced Ice Shelf. OBS deployment was completed on February 9. Prior to shooting the OBS line, Scott Base was contacted to determine the possibilty of using the downhole seismometers near Lake Vanda in the Dry Valleys (i.e. about 77° 35' S and 161° 30' E) to attempt to record the offshore seismic shots. The principal contractor for the seismometers, Allied Signal Company in Albequerque, New Mexico, said that this would not be possible on short notice because 3-4 days were required to recalibrate the equipment for the 0-25 Hz frequency range needed for the experiment.

In preparation for shooting the OBS transect, it was discovered that extreme cold weather and ice had caused several problems (frozen winches, snapped air hoses, and airguns filled with ice), causing an 8 hour delay for repairs. The shooting phase began on February 10, and was done with the same geophysical equipment as used on the eastern Ross Sea transect (see above). During the shooting of the first half of the ACRUP-WRS profile, the OBS data over more than one-half of the transect were corrupted by external seismic noise, which originated from the nearby (i.e. within 0 to 10 miles of the transect) shooting of seismic-reflection equipment on the R/V N.B. PALMER. The PALMER arrived at the ACRUP transect site 2 days earlier than previously agreed. After shooting along a converging track to a point directly on top of the ACRUP profile, PALMER stopped shooting their airgun. PALMER then did coring operations close to the ACRUP profile for 4 hours and resumed their seismic shooting away from the ACRUP area as EXPLORA circled for 5-6 hours. Shooting of the ACRUP-WRS transect was completed without further problems on February 12, at a point about 40 km west of Station 101.

The OBS recovery phase began on February 12, following about 7 hours of seismic-streamer repairs. High-velocity (30 Kt) catabatic winds and resulting bad sea conditions near Mt. Erebus caused great difficulty with recovery of the first eight OBS stations. Thereafter, conditions improved and OBS recovery was completed in the early morning of February 17 following a delay of more than a day to repair and test ship and science equipment. All but seven OBSs were recovered, with losses of 5 OBS by Germany and 2 OBSs by Italy. All

USGS OBS were recovered. EXPLORA then proceeded to McMurdo Station to disembark four members of the science staff (Cooper, 1 Italian, 2 Germans) to fly to New Zealand. EXPLORA remained at McMurdo Station for a 4-hour visit and guided tours by U.S. Antarctic Program staff before departing for New Zealand. Greg Miller remained on the EXPLORA to insure the well being of the USGS OBS equipment during the long transit. The EXPLORA arrived in New Zealand on March 3, at which time the USGS OBS equipment was offloaded and shipped back to the U.S.

Throughout the 1993/94 field season, the U.S. Antarctic Program was highly responsive to requests from the EXPLORA staff (forwarded by Alan Cooper) for assistance with logistic support for the ACRUP science program. Such help included a) assistance by the USCG POLAR SEA in getting EXPLORA into the Ross Sea and in offering to pickup US and foreign scientists on EXPLORA and transport them to McMurdo Station (NB: the offer of transport help was not used because ice conditions improved at the last moment); b) regular assistance with providing ice and weather reports to the EXPLORA in the Ross Sea; c) providing cold-weather clothing for foreign scientists from EXPLORA and flying them (with Cooper) to New Zealand; d) hosting EXPLORA at McMurdo Station; and e) many other smaller requests throughout the field season. Without such timely cooperation, the planned ACRUP science program could not have been done as safely, successfully, and effectively as accomplished, especially in the offshore areas.

Cruise Data

Two ACRUP transects were recorded, each with several types of geophysical data (see cruise narrative above). Ocean bottom seismometer (OBS) data were the principal data recorded offshore by the USGS. The following sections provide details of the OBS data and operations. The characteristics and locations of the offshore segments of the ACRUP transects are given in Tables 5 to 8.

Table 5: Characteristics of the offshore ACRUP profiles

Characteristic	ACRUP-WRS (Profile 2)	ACRUP-ERS (Profile 1)	ACRUP-TAM (Far east end)
Total length (including "off-end" shooting)	355 km	300 km	80 km
Shooting distance off west / east ends	40 / 25 km	0 / 0 km	0 / 50+ km
Total number OBS deployed	30	26	4
Total number OBS recovered	23	24	3
USA: OBSs deployed / recovered	6 / 6	6 / 6	-
Germany: OBSs deployed / recovered	17 /12	13 / 11	2 / 2
Italy: OBSs deployed / recovered	7 /5	7 / 7	2 / 1
OBS station spacing	10 km	10 km with gaps at ends of transect	10 km
Gaps between stations: west/east ends	0 / 0 km	30 / 40 km	0 / 0 km
Airgun array: no. guns / total volume (L)	36 / 71.5	36 / 71.5	36 / 71.5
Shot spacing: seconds / m	120 / 240	120 / 240	40 shots: 120 / 240 then, MCS: 20 / 50
Ship speed during shooting	4 kt	4 kt	4 kt, then 5 kt
Other data recorded	N, MCS, G, M, B	N, MCS, G, M, B	N, MCS, G, M, B

Abbreviations:
N - Integrated GPS and Transit satellite navigation system
MCS - Multichannel seismic-reflection (Sercel 120 channel, 1500 m Prakla streamer, 15 sec record length, 4 msec samples
G - Bodenseewerk (Germany) gravity meter
M - Overhauser (Canada) magnetic gradiometer
B - 12 Khz bathymetry

Location of transects:

Two ACRUP transects were planned in the Victoria Land basin (VLB); however, new locations had to be chosen for the ACRUP transects after it became clear that ice conditions would not permit surveys of the VLB. New ACRUP locations were selected in the southern Ross Sea (Figure 1). Several criteria were used to select the new locations and design the refraction experiments. The criteria included geologic objectves, amounts of available ship time and OBS instruments, likely ice conditions, and requirements of the three participating national Antarctic programs. Multichannel seismic-reflection (MCS) profiles that had previously been collected in the Ross Sea by Germany, Italy and the US were examined to find the most clearly defined rift structures that could be reached, within the restriction of the ship operating in ice-free waters. MCS lines BGR-2 and USGS-404 were selected because they join and extend east-west across all major rift basins, including the Victoria Land basin and Eastern basin, which had no prior OBS refraction studies. The southern Ross Sea transect was also selected to a) complete the southernmost part of the Central trough OBS surveys done by a prior GANOVEX expedition; b) to examine the active rift structures near Ross Island; and c) to study possible "interior" continental-rift structures and decollemont zones.as far landward of the continental shelf edge as possible. Ray-trace models for the two transects were made aboard ship based on MCS profiles, prior gravity model studies, and sonobuoy-refraction velocities for shallow crustal layers. From the model studies, a station-spacing of 10 km was selected to give regional coverage for mantle arrivals and to provide good lateral-velocity control for some smaller rift structures (i.e. 20-30 km across) seen in MCS data. A shot-spacing of 60 sec (120 m) was desired for high-density seismic-trace recording; however, a decision was made to use a 120 sec fire rate (240 m at 4 kt survey speed) to avoid the possiblity of "overwriting" deep-crustal and mantle arrivals at a horizontal offset of about 80 to 100 km by the "direct arrival" from the previous shot. Approvals for changing field operating areas were requested and obtained from the national programs.

The following tables give the exact locations of the OBS stations. Two station numbering systems are given, "station numbers" (used aboard ship) and "location numbers" (used for entire project). For the ACRUP-TAM transect, noted in the above table, the EXPLORA's "shot-line" was a standard MCS profile that extended east for several hundred km from the OBS stations. The OBS stations along ACRUP-TAM were deployed principally to attempt to record the large explosive shots in the Transantarctic Mountains, rather than the shots from the MCS line.

Maps of the Ross Sea showing exact locations for OBS stations and for shotpoints along profiles ACRUP-ERS and ACRUP-WRS, based on the following tables 6 thru 9, are given in Figure 2.

Table 6: Locations and water depths for OBS stations on profile ACRUP-WRS - Western Ross Sea

Location No.	Station No.	Dist. km	OBS*	Deployment Position	Water depth (m)**
WRS-1	101	0	G	not recovered	
WRS-2	102	10	U (A3)	77°05.632'S 169°13.537'E	886
WRS-3	103	20	G	77°06.108'S 169°37.063'E	841
WRS-4	104	30	I	77°06.127'S 169°59.150'E	815
WRS-5	105	40	G	not recovered	
WRS-6	106	50	U (A1)	77°04.295'S 170°46.382'E	775
WRS-7	107	60	I	77°03.236'S 171°10.821'E	732
WRS-8	108	70	G	77°03.309'S 171°34.785'E	696
WRS-9	109	80	G	77°03.849'S 171°59.258'E	670
WRS-10	110	90	U (A2)	77°04.301'S 172°23.165'E	658
WRS-11	111	100	I	77°04.531'S 172°47.293'E	612
WRS-12	112	110	G	77°05.349'S 173°12.190'E	562
WRS-13	113	120	G	not recovered	
WRS-14	114	130	U (C9)	77°06.329'S 174°00.286'E	448
WRS-15	115	140	I	not recovered	
WRS-16	116	150	G	not recovered	
WRS-17	117	160	G	77°06.313'S 175°12.927'E	379
WRS-18	118	170	G	77°06.313'S 175°37.299'E	370
WRS-19	119	180	I	77°06.298'S 176°01.562'E	355
WRS-20	120	190	G	77°06.297'S 176°25.472'E	352
WRS-21	121	200	U (C4)	77°06.307'S 176°49.548'E	424
WRS-22	122	210	G	77°07.328'S 177°14.363'E	454
WRS-23	123	220	G	77°07.291'S 177°38.217'E	511
WRS-24	124	230	I	not recovered	
WRS-25	125	240	G	77°07.285'S 178°26.726'E	513
WRS-26	126	250	G	77°07.367'S 178°50.880'E	620
WRS-27	127	260	G	not recvovered	
WRS-28	128	270	G	77°07.228'S 179°39.577'E	687
WRS-29	129	280	U (B1)	77°07.305'S 179°56.204'W	742
WRS-30	130	290	I	77°07.385S 179°32.163'W	686

* Country code: U is USA, with number of OBS; G is Germany; and I is Italy

** Water depths based on 1425 m/sec

Table 7: Locations and water depths for OBS stations on profile ACRUP-ERS - Eastern Ross Sea

Location no.	Station no.	Dist. km	OBS*	Coordinates	Water depth m**
ERS-1	1	0	U (A3)	77°07.1'S - 179°23.2'W	635
ERS-2	2	10	I	77°07.1'S - 178°58.9'W	617
ERS-3	3	20	I	77°07.2'S - 178°35.0'W	608
ERS-4	4	50	G	77°07.0'S - 177°22.7'W	591
ERS-5	5	60	U (A1)	77°07.0'S - 176°59.4'W	619
ERS-6	6	70	G	77°07.1'S - 176°33.2'W	600
ERS-7	7	80	G	not recovered	
ERS-8	8	90	G	77°07.1'S - 175°41.2'W	563
ERS-9	9	100	G	77°07.2'S - 175°15.3'W	543
ERS-10	10	110	I	77°07.2'S - 174°51.0'W	546
ERS-11	11	120	G	77°07.2'S - 174°26.7'W	518
ERS-12	12	130	G	77°07.3'S - 174°02.2'W	513
ERS-13	13	140	U (B1)	77°07.3'S - 173°38.2'W	508
ERS-14	14	150	I	77°07.3'S - 173°13.9'W	501
ERS-15	15	160	G	77°07.3'S - 172°49.6'W	499
ERS-16	16	170	G	77°07.3'S - 172°26.1'W	485
ERS-17	17	180	U (C9)	77°07.3'S - 172°01.6'W	478
ERS-18	18	190	I	77°07.3'S - 171°37.2'W	452
ERS-19	19	200	G	77°07.3'S - 171°12.6'W	432
ERS-20	20	210	U (C4)	77°07.3'S - 170°48.8'W	466
ERS-21	21	220	G	77°07.3'S - 170°24.6'W	524
ERS-22	22	230	G	77°07.4'S - 170°00.4'W	528
ERS-23	23	240	U (A2)	77°07.3'S - 169°36.6'W	523
ERS-24	24	250	I	77°07.3'S - 169°11.9'W	519
ERS-25	25	290	G	77°07.3W - 167°30.1W'	496
ERS-26	26	300	G	not recovered	

* Country code: U is USA, with number of OBS; G is Germany; and I is Italy
** Water depths based on 1425 m/sec

Table 8: Locations and water depths for OBS stations on profile ACRUP-TAM (far east end only)

Location no.	Station no.	Dist. from coast (km)	OBS*	Coordinates	Water depth m**
TAM-22	1-22		I	not recovered	
TAM-23	1-23		G	76°00.0'S - 169°33.7'E	557
TAM-24	1-24		G	76°00.0'S - 169°51.7'E	581
TAM-25	1-25		G	76°00.0'S - 170° 09.6'E	597

* Country code: U is USA; G is Germany; and I is Italy
** Water depths based on 1425 m/sec

Table 9: Locations for start and end of shooting points for offshore ACRUP profiles

Profile	Description	Shot Point	Date (UTC)	Time (UTC)	Latitude	Longitude
ACRUP-ERS	Start shot-line	100	1/31/94	0126	77° 07.3' S	166° 58.2' W
	End shot-line	1411	2/1/94	2108	77° 07.2' S	179° 27.2' W
ACRUP-WRS	Start shot-line	100	2/9/94	1322	77° 07.2' S	178° 27.6' W
	End shot-line	1680	2/11/94	1802	77° 07.3' S	167° 15.9' E
ACRUP-TAM (east end only)	Start MCS line	100	1/23/94	1401	76° 00.0' S	170° 10.0' E
	End MCS line	9961	1/25/94	1907	75° 29.7 S	171° 56.4 W

OBS Systems:

Two different OBS systems were used during the ACRUP profiles. Both systems have been used extensively in field operations over the past several years. One system, used by Italy and Germany, was designed and built by the Institute of Geophysics (IG), directed by Prof. Janis Makris, at University of Hamburg, Germany. The other system was designed and built by the U.S. Geological Survey (USGS). The basic parameters of the two systems are described in the following table.

Table 10: Characteristics of OBS equipment used on the ACRUP profiles

OBS Characteristic	IG (Germany) design	USGS (USA) design
Geophone configuration	3-component (V, H, H)	3-component (V,H,H), but only V used for ACRUP to increase bottom-record time
Geophone type	4.5 Hz	4.5 Hz
Hydrophone	None	1 Pressure compensated
Analog filter	No filtering	35 Hz anti-alias; Butterworth with 48 db/oct rolloff
Recording design	Analog: 2 analog recorders each with a different gain setting	Digital: Gain ranging, 10 msec sampling, 200 MByte storage
Recording style	Continuous from OBS closing	Continuous from preset time
Recording time	10 days	7 days for ACRUP setup
Time standard	Crystal oscillator	Oven-compensated oscillator
Maximum bottom time	4 weeks	10 days
Maximum depth	6000 m	2 OBS: 500m; 4 OBS: 5000 m
Enclosure type	Glass sphere	Aluminum sphere
Anchor style for coupling	Open metal frame	1-m circular plate
Approx. weight	~ 25 kg	2 OBS: ~30kg; 4 OBS: ~50kg
Ranging options	Ranging while on seafloor only	Ranging while on seafloor and during ascent during recovery
Release mechanism	Benthos (on demand) and timer for preset "pop-up"	Benthos (on demand)
Search aids	Radio transmitter and 2 flags	Strobe light and orange color
Time calibration (clock drift)	Set and checked by GPS clock	Set and checked by GPS clock

OBS data

OBS data recorded during the ACRUP field experiment must be processed and merged with shot-navigation information before the amount and quality of the data can be accurately assessed. Aboard ship, raw OBS data were read from the digital recording systems of USGS instruments to verify that data had been recorded by OBSs along the ACRUP profiles. However, the far-offset distances to which seismic arrivals were recorded along the transect was not possible to determine from the raw field data. An example of raw field data recorded by a USGS OBS at station ERS-20 is shown in Figure 3. For OBS instruments made by Institute of Geophysics, the analog data tapes could not be read aboard ship. The tapes were taken to Germany, to be digitized and processed.

Several environmental factors are likely to affect the data quality of OBSs along the ACRUP profiles. These fall into four catagories: 1) water noise; 2) ice-related noise; 3) external seismic noise; and 4) biologic noise.

Water noise is generally controlled by weather and sea conditions, although water depths of 400 to 900 m along the profile may be sufficiently large to minimize these effects. Weather conditions were generally quite good during the seismic-shooting phase of the OBS transects, with only short periods of high-winds and rough (> 9 foot) seas. Hence, background water noise is expected to be quite low on OBS data.

Ice-related noise is likely to come from "echo-shots" generated by air-gun energy reflected from the sides of large icebergs and the Ross Ice Shelf. Near-vertical side of these ice features may extend up to several hundred meters below the sea-surface, and provide an excellent reflection surface at the water to ice interface. Solid ice has a velocity of about 3.9 km/sec. Such ice-related noise is likely to be common along the eastern half of the ACRUP-WRS profile, where large tabular icebergs were common and the front of the Ross Ice Shelf was only 4 to 15 miles from the OBS stations.

External seismic noise is expected from only one source, that of the seismic shooting by the R/V PALMER along nearly one half of the ACRUP-WRS profile at distances of from 0 to 15 miles from the profile (see cruise narrative above). The effect of the noise is expected to increase as the PALMER converged on the ACRUP profile, shooting a 50 cu in airgun at 5 second intervals. OBS data will be degraded at close shooting distances by the PALMER. A second, and less likely, seismic noise source is microseismic events from volcanoes on Ross Island and along the Terror rift, at the west end of the ACRUP-WRS transect. Mt. Erebus on Ross Island is an active volcano.

Biologic noise can be expected, but the extent is unknown. Whales are known to cause large noise bursts on OBS data (Trehu, personal communication), and whales were occassionally observed nearby. Seafloor life is also a possible source of noise. On recovery of one OBS along the ACRUP-ERS profile, a large octopus (nearly three feet long) was tightly wrapped around the OBS sphere (Station ERS-20). The noise effect of such seafloor biota is unknown, but should be recognized as a potential source.

Onshore narrative

The U.S. part of the onshore ACRUP work is under the overall direction of one of the report authors (UTB). The data collection, processing and analysis is being done by Mr. Jie Zhang, who is a PhD candidate at the Massachusetts Institute of Technology. The 12 REFTEK seismic instruments used for the U.S. part of the experiment were provided by the IRIS PASCALL Project.

U.S. field activities

Mr. Zhang departed from the U.S. on December 31, and after a layover in New Zealand for clothing issue, he continued to McMurdo Station via C-130, arriving on January 5. After completing survival training, Mr. Zhang was taken to the remote field camp, Starr Nunatak camp, from which the onshore logistic operations were being done. From January 10 to February 3, he remained at the camp to prepare, test, deploy, and recover the U.S. seismic instruments. In addition to deploying instruments for the principal seismic transect (i.e. ACRUP-TAM), Mr. Zhang also conducted other field experiments near the camp to measure ice-quakes and seismic velocities in ice. Following the shooting of the ACRUP-TAM transect, the digital data from the U.S. and Italian REFTEK instruments were downloaded, copied and data-tapes exchanged. Mr. Zhang and all U.S. equipment were transferred to McMurdo by helicopter and ship ITALICA for transport back to New Zealand on February 9 by C-130. Mr. Zhang returned to the U.S. on February 12 to begin data processing and analysis.

ACRUP Transect - Transantarctic Mountains

The onshore ACRUP-TAM Transect was under the overall logistic management of the Italian National Program. Logistic support was coordinated and run principally from the Italian Terra Nova Station. The field operations were conducted from the remote field camp (Starr Nunatak) at which most scientists stayed. The field operations at Starr Nunatak camp commenced on December 19, 1993 and ended with the closure of the camp on February 3, 1994. During the field period, several geophysical experiments were conducted along and near the ACRUP-TAM profile. The experiments included seismic, gravity, aeromagnetic, topographic, heat flow, and radio-echo-sounding measurements (see Table 1).

For the ACRUP-TAM transect, 48 three-component seismic stations were deployed at 3-km intervals along a line transverse to the axis of the Transantarctic Mountains (Figure 1; Table 11). Ten of these seismic stations were placed offshore on the 1-2-meter thick fast ice to a distance of about 30 km from the coast. In addition, four OBS instruments were placed along the offshore projection of the transect about 200 km from the coast near Franklin Island (see cruise narrative above).

Table 11: Locations of onshore recording stations for the ACRUP-TAM transect

Station	Country	Latitude (S)	Longitude (E)
TAM-00	I	-75 53 54.00	162 34 42.60
TAM-01	I	-75 52 46.65	162 46 38.32
TAM-02	G	-75 52 01.80	162 39 35.40
TAM-03	U	-75 52 32.74	162 37 38.58
TAM-04	G	-75 52 41.70	162 27 06.92
TAM-05	G	-75 52 33.95	162 17 45.69
TAM-06	G	-75 52 30.13	162 13 07.67
TAM-07	U	-75 52 23.10	162 06 17.96
TAM-08	G	-75 52 19.08	161 57 54.56
TAM-09	I	-75 52 00.79	161 51 03.59
TAM-10	G	-75 51 54.52	161 47 21.22
TAM-11	G	-75 51 49.78	161 40 20.36
TAM-12	G	-75 51 38.66	161 33 16.46
TAM-13	U	-75 51 24.75	161 26 13.24
TAM-14	G	-75 51 11.63	161 18 44.66
TAM-15	I	-75 51 00.08	161 12 34.39
TAM-16	G	-75 50 48.26	161 05 45.11
TAM-17	G	-75 50 38.37	160 59 12.47
TAM-18	U	-75 50 25.04	160 52 47.61
TAM-19	G	-75 50 11.55	160 46 05.22
TAM-20	I	-75 50 03.03	160 39 31.13
TAM-21	I	-75 49 52.80	160 29 48.82
TAM-22	G	-75 49 36.02	160 25 32.33
TAM-23	U	-75 49 24.18	160 18 19.81
TAM-24	G	-75 49 12.62	160 12 08.97
TAM-25	I	-75 49 01.01	160 05 02.90
TAM-26	G	-75 48 48.37	159 58 17.58
TAM-27	U	-75 48 36.05	159 52 10.03
TAM-28	G	-75 48 18.01	159 45 30.10
TAM-29	G	-75 48 02.17	159 38 13.66
TAM-30	I	-75 47 46.07	159 32 01.89
TAM-31	G	-75 47 30.24	159 25 05.03
TAM-32	U	-75 47 17.86	159 18 04.14
TAM-33	G	-75 47 08.50	159 45 30.10
TAM-34	G	-75 46 54.33	159 04 46.82
TAM-35	U	-75 46 36.26	158 57 53.35
TAM-36	G	-75 46 25.35	158 51 22.66
TAM-37	I	-75 46 06.77	158 44 55.10
TAM-38	G	-75 45 47.88	158 38 49.53
TAM-39	G	-75 45 32.29	158 31 27.02
TAM-40	U	-75 45 17.41	158 25 02.50
TAM-41	I	-75 44 58.23	158 18 45.23
TAM-42	G	-75 44 35.27	158 08 30.96
TAM-43	I	-75 44 14.43	157 58 44.64
TAM-44	G	-75 43 54.05	157 48 07.84
TAM-45	U	-75 43 16.40	157 35 16.46
TAM-46	G	-75 42 29.19	157 18 15.58
TAM-47	I	-75 42 02.60	157 05 02.26

Code:

I -Italian REFTEK station *U-USGS REFTEK station* *G -German LOBS station*

Four land explosions, each with an array of drill holes, were used for the experiment (Table 12; 530 kg dynamite, 80, 150, and 300 kg pentrite). The total length of the "onshore" ACRUP-TAM transect is about 200 km, which includes the 153 km of seismic stations and an "offend" shot about 50 km west of the instruments. The shooting was done on January 25.

Table 12: Locations of onshore shots for the ACRUP-TAM transect

Shot	Latitude (S)	Longitude (E)
A	-75 53 09.11	162 31 34.50
B	-75 49 52.83	160 29 58.40
C	-75 64 58.23	158 18 45.23
D	-75 42 02.59	155 05 02.26

In general, the weather for the experiment was excellent, with only one bad weather day (no-fly day) out of the 45 days of helicopter operations. The land parties collected more data than anticipated, largely due to the good weather and flying conditions.

Land data

Among 48 three-component seismic stations, there were 26 digital stations (12 USGS stations, 14 Italian stations), all with the same internal recording system (REFTEK). The digital stations used a sampling rate of 100 samples/sec. A total of 22 analog stations (Germany) were deployed along the transects. The data from these instruments will be digitized at a rate of 50 samples/sec. A SUN computer workstation, provided by the US PASSCAL group, was used at the remote field camp to examine the data from the REFTEK instruments immediately after the instruments were recovered.

There were two waveform patterns that were immediately observed from the land digital data. Within 70 km of the coast, the recordings from explosion A are similar to those often seen in other continental experiments, i.e., showing typical long refracted wavefield responses. Pg wave comes first with a velocity of 5.8 km/sec. However, further inland, the recordings from explosions B, C and D were strongly influenced by the shallow ice cap: the body waves were strongly attenuated and the surface waves were large with strong dispersion. For these three explosions, P* waves came first with the ice velocity 3.8 km/sec within 10 to 15 km. Pg waves with velocity of 6.00 km/sec were also clearly observed at further distance.

Environmental noise was not a problem with the good weather, but induced microseismic noise due to scattering was a major factor at distances within 70 km of the shore. One of the 12 stations deployed by the USGS did not record data because of a mistake made during the deployment. The remaining 11 stations worked properly, using the power supply from one auto battery and one solar panel for each station.

Icequake monitoring experiment (Jan. 17, 1994)

Upon request by Mr. Zhang, Italian program coordinator offered 3 helicopter hours for deploying and recovering 5 USGS stations near an icequake active zone at the boundary of Harbord Glacier (75.54S, 162.30E). The deployment was difficult, because there were many crevasses in the area. One Italian military officer helped deploy the stations. Two other USGS stations were also deployed near Starr Nunatak by skidoo. The 7 stations had a circular geometry, and were in good locations to monitor the nearby icequakes. During 3-day continuous recordings with a samplying rate of 100 samples/sec, about one hundred icequakes were recorded with high quality.

The data show a unique waveform pattern with narrow band of frequency. Particle motion studies suggest that these icequakes often produced S-wave polarized anisotropy due to the firn and ice. These data are useful for analyzing the detailed waveforms, investigating icequake source mechanisms, and their relation with the glacier motion. Until now, few studies have been done on this topic.

Small-scale refraction experiment (Jan. 30, 1994)

As suggested by Mr. Zhang, a small-scale refraction experiment was conducted after the ACRUP land experiment for better understanding seismic wave propagation, source coupling, receiver coupling in the harsh Antarctic environment. 10 Italian stations were deployed near Starr Nunatak. A sampling rate of 500 samples/sec and station interval of 100 meters was used. All stations recorded continuously for one day. Three shotpoints of 1 kg dynamite each, were located in 25-27 meter deep holes drilled in the solid ice, and one shot of 1 kg dynamite was located near the surface in the firn layer. Preliminary analysis suggests that a low-velocity firn layer about 25 meters thick lies above high-velocity ice beneath 5 stations; and a high velocity ice layer lies at the surface, beneath the other 5 stations.. The near surface firn layer strongly attenuates the amplitude and modulates the frequency of the incoming wavefield. For a source in the solid ice, the amplitude of P*-wave received by the stations directly located on the ice layer can be 4-5 times larger than those recorded on the firn layer at the same distance. Moreover, the amplitude of a shot in solid ice can be 6-7 times larger than one in the firn layer for the same station. During the experiment, 4 earthquakes and 6 icequakes were recorded, with the waves passing the array from both ends. The earthquake and icequake data provide useful information of the medium structure and the low-frequency attenuation.

Summary

During the 1993/94 austral summer, the U.S. Geological Survey participated in onshore and offshore geophysical transects of the Ross Sea region. Three transects were accomplished under the overall direction of the Italian National Research Program. For the single onshore transect, the USGS deployed 12 seismic stations, and for each of the two offshore transects, the USGS set out six ocean bottom seismometers. The results of the three seismic transects should provide new information on the deep crustal structure of the Transantarctic Mountains and the offshore Ross Sea sedimentary basins, all of which are part of the extensive West Antarctic Rift system.

Acknowledgements

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References

Bacigalupi, L. and Ramorino, M.C., 1994, Rapporto sulla Campagna Antarctica Estate Australe 1993-94, ENEA - Progetto Antartide, Via Anguillarese 301, c.p. 2400, 00100 Roma A.D., Italy, 511p.

Behrendt J.C. & Cooper A.K., 1991, Evidence of rapid uplift of the shoulder escarpment of the Cenozoic West Antarctic Rift System and a speculation on possible climate forcing. Geology, 19, pp. 315-319.

Behrendt J.C., LeMasurier W.E., Cooper A.K., Tessensohn F., Tréhu A., & Damaske D. 1991, Geophysical studies of the West Antarctic Rift system. Tectonics, 10, No 6, pp. 1257-1273.

Cooper A.K. and Davey F.J., 1987, The Antarctic Continental Margin: Geology and geophysics of the Western Ross Sea. Published by the Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, Huston, Texas, 5B,

Cooper, A. K., Davey, F. A., & Hinz, K., 1991, Crustal extension and origin of sedimentary basins beneath the Ross Sea and Ross Ice Shelf, Antarctica, In Thomson, M. R. A., Crame, J. A., and Thomson, J. W., editors, Geological Evolution of Antarctica: Cambridge, Cambridge University Press, p. 285-291.

Cooper, A. K., Davey, F. J., & Behrendt, J. C., 1987, Seismic stratigraphy and structure of the Victoria Land basin, western Ross Sea, Antarctica, In Cooper, A. K., and Davey, F. J., editors, The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea (Earth Science Series): Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, p. 27-66.

Fitzgerald P.G., 1992: The Transantarctic Mountains of the Southern Victoria Land: The Application of Apatite Fission Track Analysis to a Rift Shoulder Uplift. Tectonics, **11**(3), 634-662.

Fitzgerald P.G., Sandford M., Barrett P.J. and Gleadow A.J.W., 1986, Asymmetric extension associated with uplift and subsidence in the Transantarctic Mountains and Ross Embayment. Earth and Planetary Science Letters, 81, pp. 67-78.

Gleadow A.J.W., McKelvey B.C., Ferguson K.U., 1984, Uplift history of the Transantarctic mountains in the Dry Valleys area, southern Victoria Land from apatite fission track ages. N.Z.J. geol. geophys. 27, pp. 457-464.

Lawver L.A., Royer J.Y., Sandwell D.T., Scotese C.R., 1991, Evolution of the Antarctic continental margins. M.R.A. Thomson, J.A. Crame & J.W. Thomson eds. Cambridge University Press, pp. 533-540.

Stern T.A.& ten Brink U.S., 1989, Flexural Uplift of the Transartarctic Mountains. Journal of Geophysical Research, 41, pp. 10.315-10.330.

Tessensohn F. & Worner G., 1991, The Ross Sea rift system, Antarctic: structure, evolution and analogues. In: Geological Evolution of Antarctica; M.R.A. Thomson, J.A. Crame & J.W. Thomson eds. Cambridge University Press, pp. 273 - 277.

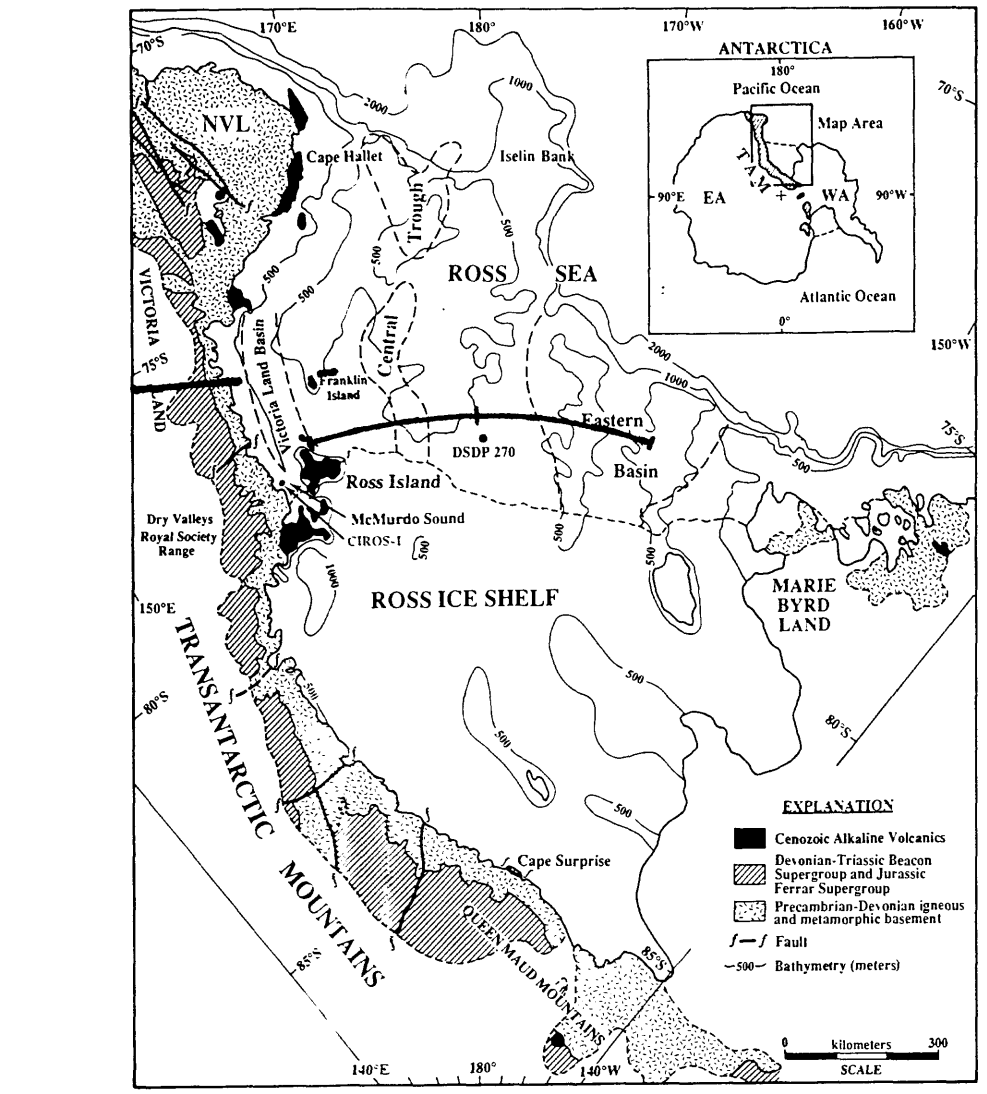
FIGURE CAPTIONS

Figure 1: Index maps of Ross Sea region showing locations of seismic profiles collected by the ACRUP project in January/February 1994. A) Map of Ross Embayment with locations of refraction profiles (bold lines). One profile is 200 km long and crosses the Transantarctic Mountains. Two back-to-back profiles, each about 320 km long, cross the rift basins of the southern Ross Sea. Base map modified from Fitzgerald et al. (1991); B) Bathymetric map of the Ross Sea showing locations of multichannel seismic reflection profiles (IT-126,127) and OBS refraction profiles (ACRUP-ERS,WRS).

Figure 2. Maps of the southern Ross Sea. A) locations of OBS stations for profiles ACRUP-ERS and ACRUP-WRS; and B) locations of shotpoints for the two offshore ACRUP profiles.

Figure 3. Example of raw field data collected by USGS OBS at station ERS-20 (near longitude 171 W).

FIG. 1


ANTARCTICA
Pacific Ocean
Map Area
Atlantic Ocean
EA
WA
NVL
Cape Hallet
Iselin Bank
Trough
ROSS SEA
VICTORIA LAND
Victoria Land Basin
Central
Franklin Island
Eastern
Basin
DSDP 270
Ross Island
McMurdo Sound
CIROS-1
Dry Valleys
Royal Society Range
ROSS ICE SHELF
MARIE BYRD LAND
TRANSANTARCTIC MOUNTAINS
Cape Surprise
QUEEN MAUD MOUNTAINS
EXPLANATION
Cenozoic Alkaline Volcanics
Devonian-Triassic Beacon Supergroup and Jurassic Ferrar Supergroup
Precambrian-Devonian igneous and metamorphic basement
Fault
Bathymetry (meters)
kilometers
SCALE

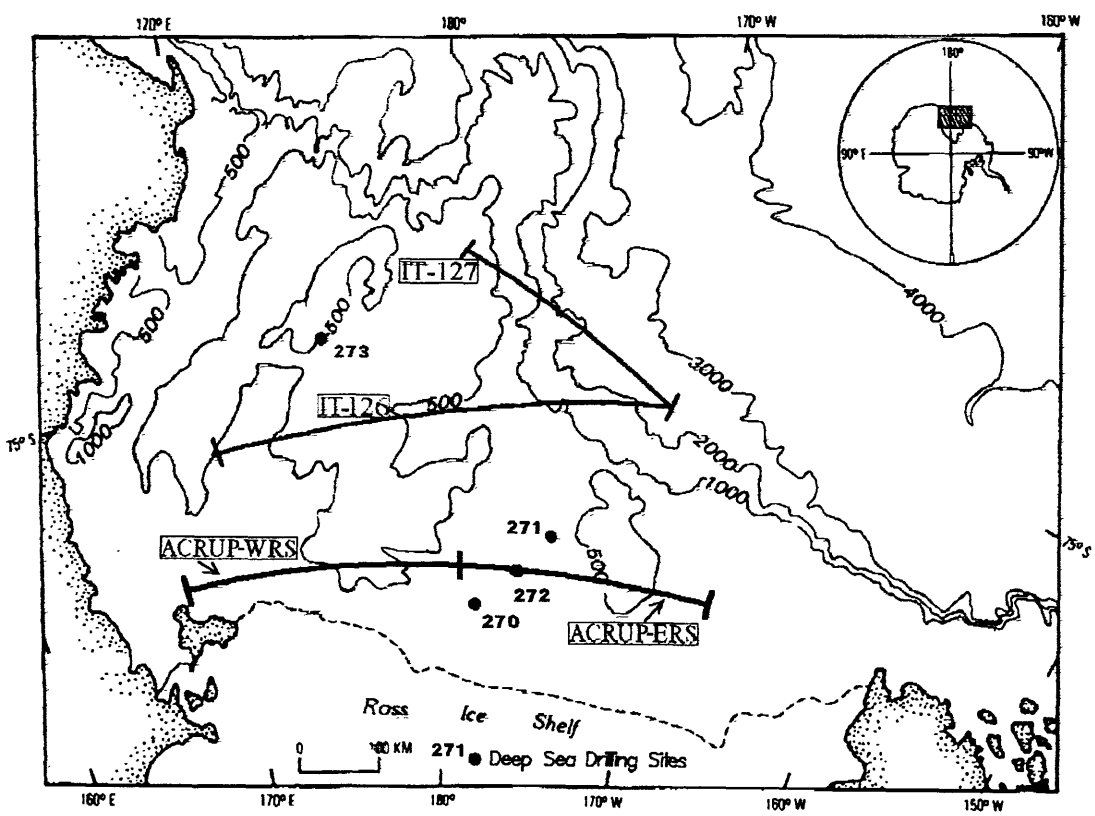
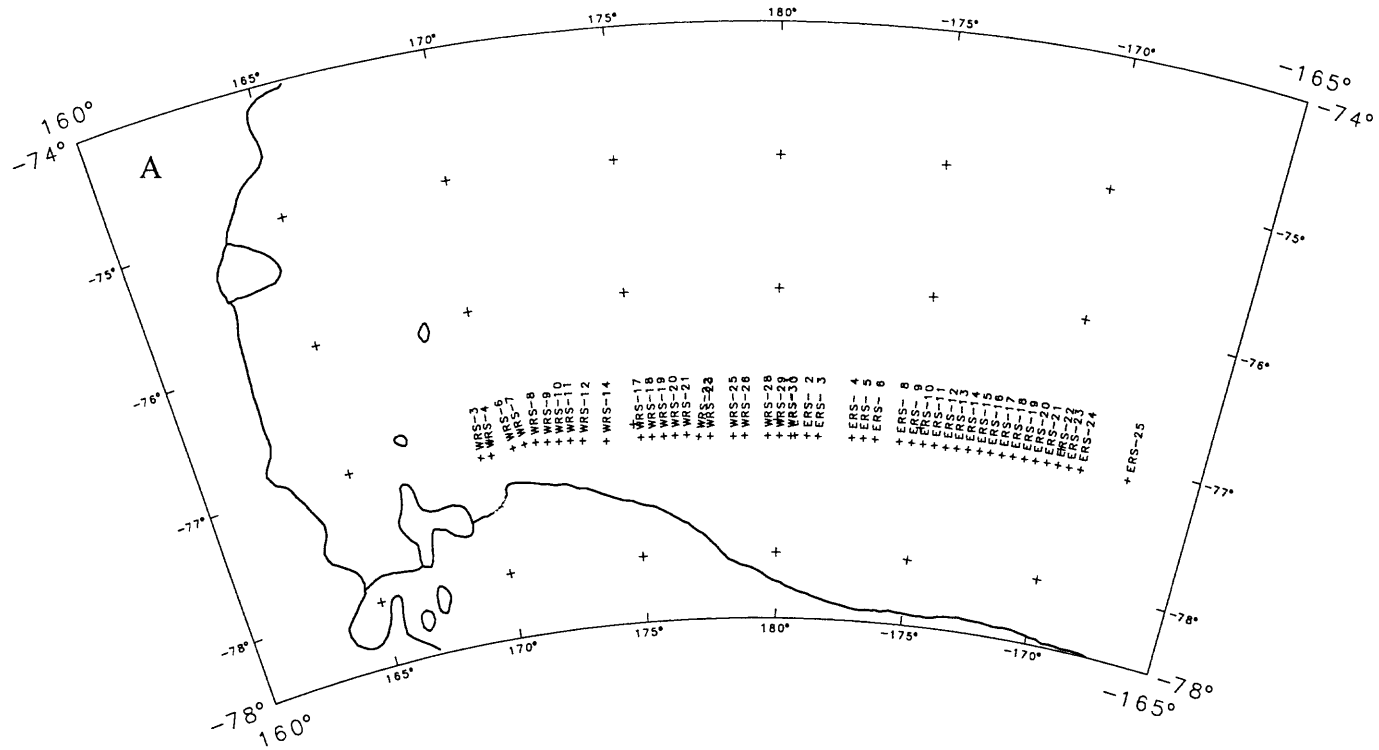

IT-127
IT-126
ACRUP-WRS
ACRUP-ERS
273
271
272
270
Ross Ice Shelf
271 Deep Sea Drilling Sites

FIG. 2


A
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165°
170°
175°
180°
-175°
-170°
-165°
-74°
-75°
-76°
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-78°
160°
-78°
165°
170°
175°
180°
-175°
-170°
-165°
-78°
-77°
-76°
-75°
+ WRS-3
+ WRS-4
+ WRS-6
+ WRS-7
+ WRS-8
+ WRS-9
+ WRS-10
+ WRS-11
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+ WRS-14
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+ WRS-19
+ WRS-20
+ WRS-21
+ WRS-25
+ WRS-26
+ WRS-28
+ WRS-29
+ WRS-30
+ ERS- 2
+ ERS- 3
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+ ERS- 5
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+ ERS-21
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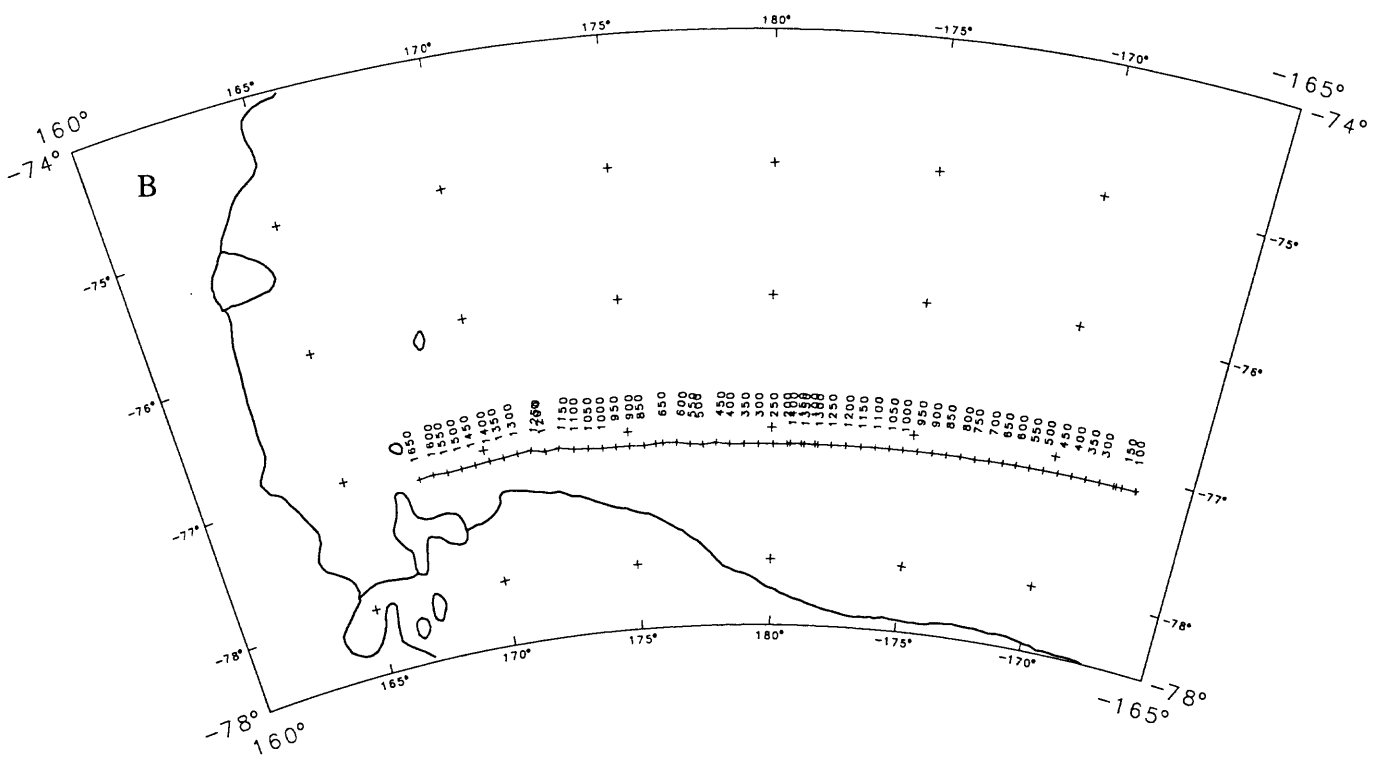
+ ERS-24
+ ERS-25


B
160°
-74°
165°
170°
175°
180°
-175°
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-74°
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160°
-78°
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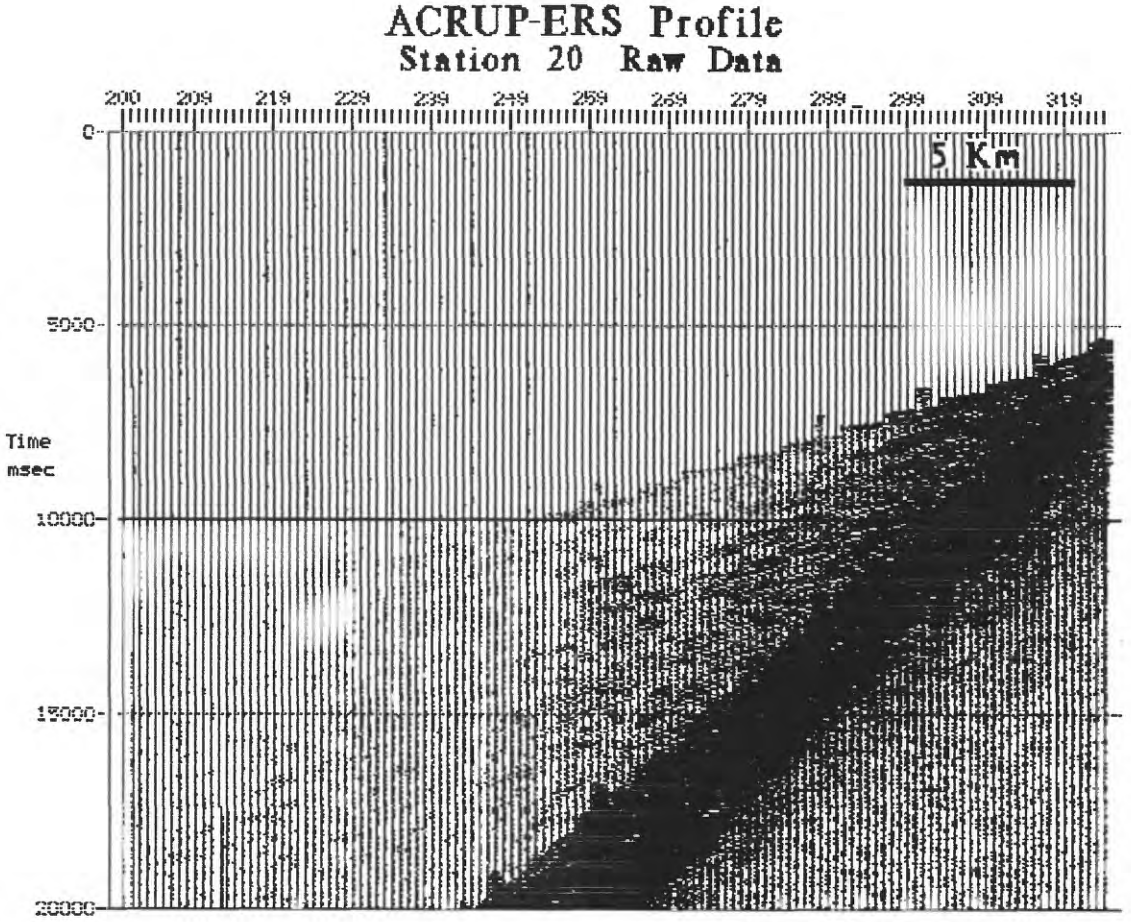
-77°
-76°
-75°

FIG. 3


ACRUP-ERS Profile
Station 20 Raw Data
200
209
219
229
239
249
259
269
279
289
299
309
319
0
5000
10000
15000
20000
Time
msec
5 Km