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DATA REPORT FOR ONSHORE-OFFSHORE WIDE-ANGLE SEISMIC RECORDINGS IN THE BERING-CHUKCHI SEA, WESTERN ALASKA AND EASTERN SIBERIA

Submitted by
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and Brian K. Galloway

USGS, U. of Durham, U. of Alaska, Auburn and Stanford

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ABSTRACT

This report presents fourteen deep-crustal wide-angle seismic reflection and refraction profiles recorded onland in western Alaska and eastern Siberia from marine air gun sources in the Bering-Chukchi Seas. During a 20-day period in August, 1994, the **R/V Ewing** acquired two long (a total of 3754 km) deep-crustal seismic-reflection profiles on the continental shelf of the Bering and Chukchi Seas, in a collaborative project between Stanford University and the United States Geological Survey (USGS). The **Ewing**'s 137.7 liter (8355 cu. in.) air gun array was the source for both the multichannel reflection and the wide-angle seismic data. The **Ewing**, operated by the Lamont-Doherty Earth Observatory, steamed northward from Nunivak Island to Barrow, and returned, firing the air gun array at intervals of either 50 m or 75 m. About 37,700 air gun shots were fired along the northward directed Lines 1 and 2, and more than 40,000 air gun shots were fired along the southward directed Line 3. The USGS and the University of Alaska, Fairbanks (UAF), deployed an array of twelve 3-component REFTEK and PDAS recorders in western Alaska and eastern Siberia which continuously recorded the air gun signals fired during the northward bound Lines 1 and 2. Seven of these recorders also continuously recorded the southward bound Line 3. These wide-angle seismic data were acquired to: (1) image reflectors in the upper to lower crust, (2) determine crustal and upper mantle refraction velocities, and (3) provide important constraints on the geometry of the Moho along the seismic lines. In this report, we describe the land recording of wide-angle data conducted by the USGS and the UAF, describe in detail how the wide-angle REFTEK and PDAS data were reduced to common receiver gather seismic sections, and illustrate the wide-angle seismic data obtained by the REFTEKs and PDAS's. Air gun signals were observed to ranges in excess of 400 km, and crustal and upper mantle refractions indicate substantial variation in the crustal thickness along the transect.

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INTRODUCTION

The Bering Shelf-Chukchi Sea region comprises over half of the total continental shelf area of the United States of America, and forms part of the vast system of continental shelves that encircle the Arctic Ocean and link the Alaskan and Russian mainlands. In August, 1994, two long north-south trending deep-crustal seismic-reflection profiles were acquired in the Bering and Chukchi seas (Figure 1) in a collaborative project between Stanford University and the United States Geological Survey (USGS) (Galloway and Shipboard Scientific Party, EW94-10, unpublished manuscript, 1994; Galloway et al., 1994). These seismic lines are approximately perpendicular to several major structural features including the foreland (Arctic Platform), the fold-thrust belt (Colville Basin and Brooks Range), a region of possible late-to post-orogenic collapse (Seward and Chukotshiy), the accreted terranes of the Bering Shelf "collage", and the abandoned subduction zone (Beringian margin). In addition, the seismic lines imaged the deep-crustal structure beneath several major sedimentary basins developed across these various tectonic belts. The transect was designed to provide another deep-crustal transect of the North American continent from ocean basin to ocean basin, similar to the Trans-Alaska Crustal Transect (TACT), which ran from the northern Gulf of Alaska to the North Slope, following the Alaskan Highway .

Parts of the transect were selected to (1) specifically address the nature of the boundaries or transition between segments of the orogenic belt with different known histories, (2) couple surface studies with seismic imaging of the deep crust in order to study better the magmatic and tectonic processes that shape continental crust at depth beneath orogenic belts, and (3) image key structures in the crust and mantle that accommodated significant shortening or extension between Eurasia and North America in the Cretaceous and Tertiary. Deep-crustal seismic-reflection profiling was conducted using a 20-element 137.7 liter (8355 cu. in.) air gun array and a 4.2-km-long digital streamer towed by the **R/V Ewing** on leg EW94-10.

Additional reasons for choosing the general location of the seismic reflection lines included crossing perpendicular (or as closely as possible) to major structures, to be close to the coast to facilitate geological correlation and to allow in-line wide-angle recording (Figure 2), to tie to COST wells and accessible industry seismic grids, to remain in water deep enough for the **Ewing** to work safely in the ice-free near-coastal waters of the Beaufort Sea and to remain outside the 3-mile limit whilst in U.S. waters in order to be exclusively in Federal waters which simplified permitting issues with respect to marine mammals.

During a 20-day period in August, the **Ewing** acquired two long (a total of 3754 km) deep-crustal seismic-reflection profiles. The profiles started in the south at the July 1994 **Ewing** seismic-reflection survey of the Aleutian Island and Bering Sea (McGeary et al., 1994) in the vicinity of Nunivak Island (Figure 1), traversed northward to the east of Saint Lawrence Island, across the Norton Basin, through the Bering Straits, across the Hope Basin, hugged the coastline as it crosses the Herald Arch, Brooks Range Orogen and Colville Foredeep, and finished at the shelf edge of the Canada Basin. A parallel profile to the west returned through the Bering Straits, hugged the International Border east of the Chukotshiy Peninsula, passed just west of Saint Lawrence Island and across the Navarin Basin tying to the Navarin Basin COST well, ending oceanward of the Cretaceous Beringian margin. The **Ewing** fired the air gun array along these profiles at intervals of 50 or 75 m. About 37,700 air gun shots were fired along the northward directed Lines 1 and 2, and more than 40,000 air gun shots were fired along the southward directed Line 3.

We describe the acquisition and reduction of the wide-angle seismic data recorded onshore in western Alaska and eastern Siberia during this seismic reflection transect. The USGS deployed an array of eight three-component REFTEK recorders in western Alaska which continuously recorded the air gun signals fired during northward-bound Lines 1 and 2 (Figure 3). Three REFTEK recorders also continuously recorded the return profile Line 3. In addition, the UAF deployed four recorders in the Chukotshiy Peninsula, eastern Siberia, which recorded both Lines 1 and 3. The recordings, made at an average interval of about 150 km along the western shore of Alaska and Siberia, were designed to provide reconnaissance-level seismic refraction information about average crustal velocities and thicknesses along the seismic reflection profiles.

DATA ACQUISITION

R/V Ewing Instrumentation and Operations

The **R/V Ewing** acquired marine reflection profiles with a 50 m (sometimes altered to 75 m) shot-spacing (40 or 27 fold) and record lengths between 16 and 23 seconds. Principal instrumentation included a 4.2-km, 160-channel digital streamer and a 137.7 liter (8355 cu. in.), 20-chamber air gun source (Galloway and Shipboard Scientific Party, EW94-10, unpublished manuscript, 1994; Galloway et al., 1994). The ship's schedule was chosen to maximize the chances of being able to extend the seismic lines northwards over the rifted passive margin into the Canada Basin during optimal sea ice conditions. Water depths were generally between 25 and 50 m for most of the cruise, deepening only at both ends of the lines.

The northbound leg (Lines 1 and 2) started at 2220 Local time (L) Monday August 8th (Julian Day (JD) 220 at 0620 Universal Coordinated Time (UCT)) and reached the northern end of the survey at 0645L Thursday August 18th (JD 230 1445 UCT). The southbound leg (Line 3) ended at 1700L Tuesday August 30th (JD 243 at 0100 UCT). Together both legs yielded about 3754 km of multichannel seismic-reflection data. Table 1 presents the latitude, longitude, and time of the starting and end points of each of the reflection line segments acquired during the survey. Note that Line 1 was composed of seven segments (a, c-h), Line 2 consists of 5 segments (a-e), and Line 3 consists of six segments (a-f). These tracks represented all the pre-cruise plans apart from the optimistic northerly extensions into the Chukchi Sea (prevented by pack ice), and work in Russian waters (replaced by sub-parallel lines on the US side of the Convention Line).

The geometry of the air gun deployment from the **R/V Ewing** is presented in Figures 4 and 5. The air gun array, composed of Bolt air guns, was generally towed at depths between 8 and 10 meters. Eight guns were towed on each side of the ship from large retractable booms that are swung out abeam of the ship (Figure 4). The remaining four air guns were deployed from an A-frame on the stern of the ship. The ship-to-gun distances were staggered to minimize fouling the air guns and to optimally separate the air bubbles created by the air gun array: the center of the air gun array was towed approximately 39.6 m behind the stern of the ship (Figure 4). The width of the air gun array across the beam of the ship was roughly 33.8 m (111 feet) (Figure 5). The Magnavox Global Positioning Satellite (GPS) receiver for the ship was located above the ship's bridge about 47.8 m forward of the stern of the ship, roughly 87.4 m forward of the center of the air gun array. The source-receiver ranges placed in the trace headers were not corrected for this minor offset between the air gun array and GPS receiver. The sizes of the air gun chambers were varied from 2.4 liter (145 cu. in.) to 14.2 liter (850 cu. in.) to provide a tuned outgoing source wavelet.

Air gun shot times recorded in the navigation files represent the air gun fire command time determined from a Magnavox GPS clock. These shot times are considered accurate to within a millisecond. Files containing smoothed navigation and shot times were transmitted daily from the **Ewing** via e-mail.

Approximately 44 sonobuoys were deployed from the **Ewing** during the cruise (Galloway and Shipboard Scientific Party, EW94-10, unpublished manuscript, 1994). These were expendable military sonobuoys which self-scuttled after 8 hours. Table 2 summarizes the launch times and locations of the sonobuoys; they were launched every 6 hours at the start of the cruise and every 12 hours later on in the cruise. Additional geophysical data acquired during the cruise included gravity, magnetics, and 3.5 kHz bathymetry (Galloway and Shipboard Scientific Party, EW94-10, unpublished manuscript, 1994). Weather data were also continuously recorded on the **Ewing**.

Wide-Angle Recording

The USGS deployed eight 3-component REFTEK recorders on the western coast of Alaska between St. Lawrence Island and Point Lay (Figure 1) during the **Ewing** cruise (stations 1-8). The station sites were chosen based on: (1) their proximity to the seismic reflection lines, (2) the ability to reach the site via charter aircraft, and (3) the desire to obtain deep-crustal information between St. Lawrence Island and Cape Lisburne (Figure 3). Little Diomede Island, King Island,

and the Northeast Cape on St. Lawrence Island are all located in the Bering Strait and northern Bering Shelf, and all are located directly on the seismic lines, to try to record arrivals reflected from the middle to lower crust. We recorded three-component seismometers to improve our chances of recording converted shear-wave arrivals.

The station sites were generally reached via fixed wing aircraft, although the stations at Little Diomede and King Islands were reached by helicopter. The REFTEK stations were generally located close to landing strips. Instruments were housed in plastic containers and buried as much as possible to minimize disruption by wildlife. All cabling was buried wherever possible. Roughly half of the instruments were left recording when deployed, the other half were programmed to turn on at a later time. Four of the sites were located on islands in the Bering Straits/Sea, and four were located on the western Alaskan coast. Table 3 provides a list of the stations, their locations and elevations, and indicates when they were each deployed and retrieved. Station latitudes and longitudes in Table 3 represent averages from 8-days of recording GPS data on the hour. Estimated uncertainties of the station latitudes and longitudes are generally less than 40 m. Station elevations were determined from USGS topographic maps once the horizontal locations were fixed by GPS. The eight sites were used to record signals generated along Lines 1 and 2. Two recorders were redeployed at Gambell and Tin City to record Line 3.

Poor flying conditions between August 10 and August 16 (JD 222-229) made it impossible to retrieve any REFTEK stations during that week, but ultimately did not lead to any loss of data. Stations were deployed to the north and south of the base station at Nome, Alaska, using a combination of fixed wing and helicopter charter aircraft.

The digital REFTEK recorders deployed (primarily models 07G) consist of four major components (PASSCAL, 1991). These components include the (1) Data Acquisition System (DAS), (2) internal hard disk drive, (3) internal GPS Clock, and (4) 3-component 4.5-Hz seismometers. For continuous recording it was necessary to supplement a small internal battery with an external 12-V truck battery. Each REFTEK DAS was controlled by a Hand Held Terminal (HHT), which was used to program the DAS, determining such parameters as the start and end times of recording, the sample rate (100 Hz in our case), mode of recording (continuous in our case), and number of channels to record (3 in our case). The GPS receiver clocks had a duty cycle of 5 minutes per hour. Recording was performed at 10 msec sample rate in compressed REFTEK data format.

The University of Alaska, Fairbanks (UAF), with Russian collaborators, deployed four additional stations on the eastern shore of the Chukotshiy Peninsula in Russia (Table 3). The digital recorders deployed by the UAF group in Russia were all Teledyne PDAS units. The data were recorded on external SCSI hard drives, and a sampling rate of 50 Hz was used. Stations at Novoye Chaplino, Lavrentiya, and a station at Provideniya used 3-component L22 seismometers. Another station at Provideniya recorded a Guralp broad-band seismometer. The two Provideniya stations and the Novoye Chaplino station ran continuously for at least two days before and after the closest approach of the **Ewing**. The Lavrentiya station shut itself down at irregular intervals and did not write data to the external SCSI drive. The data that were collected are presumably stored in the 8 Mbyte internal memory, but at the present time it is not possible to make the system boot.

All the PDAS's had GPS clocks that checked the timing every hour. The GPS clocks also allowed the stations to be located accurately with respect to latitude and longitude. The altitude for the two Provideniya sites were obtained using a hand held Garmin GPS receiver. The altitude of the Novoye Chaplino site was estimated visually since it was only about 2m above sea level and within about 200 m of the coastline. GPS position information for Lavrentiya is locked up in the internal memory, and the position quoted in Table 3 is based on local maps, whilst altitude was estimated visually compared with the nearby estuary.

A second station was operated at Provideniya using a Guralp 40T broad band instrument. Because of limited memory, this instrument was run in event-detect mode for the northbound legs of the **Ewing**, but was run in continuous mode for the time of passage of the **Ewing** on its southbound leg.

TABLE 1. R/V **Ewing** Seismic Reflection Line Endpoints

UCT Day:HR:MIN:SEC	Lat. (N) Deg. Minute	Long. (W) Deg. Minute	Line No.
220:00:00:13.766	58 57.4170	169 31.0150	test25
220:03:48:53.934	58 47.7070	169 35.8248	test25
220:06:20:01.186	58 47.5825	169 32.4891	1a
221:03:16:49.460	60 22.0099	169 09.7851	1a
221:05:56:34.279	60 20.4038	169 10.0437	1c
221:17:35:53.892	61 20.6420	168 55.0994	1c
221:17:36:56.059	61 20.7396	168 55.0821	1d
223:14:35:49.868	62 10.2248	168 42.8187	1d
223:14:49:09.875	62 11.1615	168 42.5296	1e
225:06:49:31.684	65 26.4702	168 19.6007	1e
225:06:50:03.443	65 26.5177	168 19.6006	1f
225:19:44:26.998	66 42.2436	168 02.8101	1f
225:19:44:38.981	66 42.2613	168 02.8008	1g
226:01:20:44.826	67 09.4709	167 53.5477	1g
226:01:20:54.058	67 09.4825	167 53.5457	1h
229:01:39:42.797	70 29.6770	163 01.1523	1h
229:02:06:29.019	70 30.6319	162 55.6997	2a
229:04:46:27.863	70 34.9162	162 35.7926	2a
229:04:50:24.790	70 34.8438	162 36.6105	2b
229:05:46:14.549	70 33.4930	162 48.2117	2b
229:05:54:04.903	70 33.2420	162 49.7473	2c
229:18:07:47.453	70 50.6397	160 11.2175	2c
229:18:10:58.606	70 50.7305	160 10.4242	2d
230:06:12:59.665	71 23.6895	157 06.7564	2d
230:06:13:33.151	71 23.7190	157 06.6012	2e
230:15:51:30.082	71 47.2073	154 17.1128	2e
232:08:52:15.116	71 23.2144	162 59.6374	3a
233:04:45:30.128	70 30.9559	166 42.1906	3a
233:04:46:12.271	70 30.9238	166 42.3021	3b
236:06:01:01.869	65 32.3711	168 50.1773	3b
236:06:01:37.237	65 32.3286	168 50.1736	3c
236:08:33:48.244	65 36.9222	168 48.4346	3c
236:08:34:40.904	65 36.8564	168 48.4057	3d
240:23:59:45.445	58 41.4294	177 49.9741	3d

TABLE 2. Sonobuoy Launch Times and Locations

Sonobuoy No.	Line, FFID*	Launch Time JD:Hr:Mn:Second	Latitude (N) Deg. Minute	Longitude (W) Deg. Minute
46	1A, 2754	220:23:05:53.027	60 02.6129	169 14.6611
47	1C, 280	221:06:56:10.223	60 25.5245	169 08.9543
48	1C, 1331	221:12:29:12.483	60 53.4262	169 02.1449
49	1D, 155	221:18:04:29.205	61 23.3408	168 54.3576
50	1D, 757	221:22:22:13.713	61 47.1694	168 48.5531
51	1D, 1874	222:06:41:46.194	62 31.8642	168 36.8780
52	1E, 539	223:19:29:46.560	62 32.7838	168 36.6422
53	1E, 556	223:19:37:57.213	62 33.4572	168 36.4720
54	1E, 1793	224:05:33:22.191	63 22.6162	168 25.3647
56	1E, 3242	224:18:01:35.740	64 20.4298	168 22.5858
57	1E, 3873	224:22:56:53.750	64 45.6120	168 21.1411
59	1E, 4659	225:05:01:50.920	65 16.9759	168 19.5657
60	1F, 1067	225:13:05:10.331	66 05.2475	168 15.2221
61	1F, 1901	225:19:00:30.420	66 38.2316	168 04.1369
62	1H, 3249	226:20:17:45.963	66 53.0658	167 59.1615
63	1H, 4525	227:03:38:27.235	67 26.7191	167 47.5404
64	1H, 5218	227:07:33:14.440	67 44.9814	167 41.0680
65	1H, 6062	227:12:24:33.189	68 06.8259	167 28.6702
66	1H, 7027	227:17:51:36.006	68 30.9059	167 04.5035
67	1H, 7277	227:19:14:39.265	68 37.1354	166 58.3267
68	1H, 7520	227:20:37:32.723	68 43.1411	166 52.0148
69	1H, 9140	228:05:58:15.952	69 20.6415	165 54.6541
71	1H, 10070	228:11:18:19.003	69 40.8244	165 13.7520
72	2A, 122	229:02:14:08.902	70 30.8092	162 54.0149
73	2D, 1222	230:02:00:00.318	71 11.6201	158 08.0937
74	3A, 1472	232:17:00:47.543	71 01.7400	164 32.1451
76	3B, 2726	233:20:49:52.719	69 43.0020	168 50.3030
77	3B, 4051	234:04:47:07.493	69 07.8195	168 49.8271
78	3B, 4236	234:05:54:13.295	69 02.8869	168 50.1111
79	3B, 4597	234:08:04:24.046	68 53.2804	168 49.7482
80	3B, 6630	234:20:32:11.795	67 59.2258	168 49.8901
81	3D, 944	236:13:42:16.699	65 18.4330	169 19.1057
82	3D, 1561	236:17:28:05.508	65 05.7327	169 43.8790
83	3D, 1729	236:18:27:36.503	65 02.3173	169 50.6827
84	3D, 3730	237:06:26:07.348	64 21.3826	171 10.2002
85	3D, 5234	237:15:42:54.094	63 49.8212	172 06.3357
86	3D, 5465	237:17:05:47.577	63 44.4311	172 12.7717
87	3D, 7583	238:05:58:43.443	62 54.7880	173 12.3095
88	3D, 9499	238:17:42:27.788	62 09.8748	174 04.4808
90	3D, 11118	239:03:37:02.365	61 31.8635	174 47.7129
91	3D, 16638	240:13:18:57.810	59 22.3224	177 08.2287
92	3D, 18046	240:22:00:00.463	58 49.2104	177 42.3537
93	3F, 2511	242:16:56:59.889	58 26.8964	175 31.2589
94	3F, 3199	242:21:05:13.829	58 42.9563	175 14.3087

*Sonobuoy, line, and FFID numbers from Galloway and Shipboard Scientific Party, EW94-10 (unpublished manuscript, 1994).

TABLE 3. REFTEK Station Locations and Elevations

Station No.	Station Name	DAS No.	Latitude (N) Deg.	Longitude (W) Deg.	No. GPS Obs.	Elevation (m)	Dates and Times of Deployment (1994)
1	Lietnik	7279	63.322742	168.979082	242	5	219/2000-229/1900
2	Gambell	7282	63.771725	171.733129	223	2	219/2000-229/2000
3	King Island	7296	64.964777	168.057411	239	300	219/2000-229/2000
4	Tin City	7300	65.561635	167.924010	259	80	219/2000-231/0000
5	Little Diomede	7289	65.745256	168.925760	337	305	219/2000-233/2000
6	Point Hope	7281	68.353425	166.795966	288	1	221/2200-233/2000
7	Cape Lisbourne	7294	68.875000	166.113333	0	80	221/2300-233/1900
8	Point Lay	7301	69.730050	163.023758	285	2	222/0000-233/2000
9	Lavrentiya%	PDAS	65.590	171.008		3	225-230,234-238
10	Novoye Chaplino%	P159	64.4958	172.8583		2	218-240
11	Provideniya%	P180	64.4242	173.2324		50	217-228,235-243
12	Provideniya%	Grlp	64.4242	173.2324		50	217-228,235-243

*REFTEK was programmed to record continuously from the time of deployment.
%Coordinates for stations at Provideniya and Novoye Chaplino are from GPS coordinates, coordinates for station at Lavrentiya are from a 1:200,000 Russian military topographic map. Elevations for Russian stations are estimated from GPS for the two sites at Provideniya, from the nearby sea level for Novoye Chaplino, and from a map for Lavrentiya and are thought to be accurate to within a few meters.

DATA REDUCTION

REFTEKs digitally recorded seismic data using 1 Gbyte hard-disks in compressed format. After retrieving the REFTEKs from the field, the digital seismic data was downloaded onto DAT tapes in "refdump" format using a Sun workstation (see Appendix 2). The seismic data were then converted to SEG-Y format using a PASSCAL program called "ref2segy". Finally, we converted these SEG-Y data into SEG-Y-formated, common receiver gathers using the PASSCAL program "segygather" (see Appendix 2). Data from the PDAS's were converted from PDAS format to AH format and sent to the PASSCAL Instrument Facility, Palo Alto, to be converted to SEGY using a modified version of "ref2segy". Common receiver gathers were processed and plotted using ProMAX (Appendix 3).

SEG-Y Tape Format

The common receiver gathers generated from the digital REFTEK tapes are stored in a unreduced travel time format. Sixty seconds of data were saved for each trace in the common receiver gather (6001 data samples per trace). The sample interval is 10 msec. The number of traces saved for each common receiver gather varies with each station due to the particular signal-to-noise characteristics of each site. The common receiver gathers obtained were written in SEG-Y format to Exabyte tape using the "segygather" program. Data from all three geophone components were converted to SEG-Y format. SEG-Y trace header formats described by Barry and others (1975) were modified slightly, as described in Appendix 4. The header is in EBCDIC format, and the data are in IBM floating point format. See Appendix 3 for a description of the ProMAX flows used to process the SEG-Y data.

DESCRIPTION OF THE DATA

We next describe the wide-angle seismic data for the two major lines acquired during the Chukchi-Bering Sea experiment. Common receiver gathers are shown in Figures 6 to 19 for stations which recorded useful data. Data are presented in the order they were recorded, from south to north for Line 1 and north to south for Line 3. In these figures the data have been bandpass filtered between 6 and 13 Hz, linearly reduced (moved out) to 8 km/s, deconvolved with a spiking operator, and stacked (mixed) over five adjacent traces (for details of the processing parameters see Appendix 3). Only vertical component data are shown. Negative ranges are shown for air gun shots to the south of the receiver, positive ranges are for air gun shots to the north of the receiver. In general, data quality are slightly lower than we had expected due, at least in part, to the poor weather and high wind conditions experienced for much of the study. The geophone coupling for the receiver at King Island, a rocky outcrop, was poor, and resulted in very poor data which are not shown here.

Eight sites provided useful recordings of the northbound multichannel seismic (MCS) reflection transect (Lines 1 and 2). The best data were recorded at the northernmost three stations; the lowest quality data were obtained by the southernmost three REFTEK stations. Data recorded at Leitnik, on the eastern end of St. Lawrence Island, are low quality, showing only faint crustal arrivals (Pg) for air gun shots north of St. Lawrence Island to ranges of about 100 km (Figure 6). The strongest arrivals on this record appear to be PmP reflections at ranges between 60 and 160 km. Faint Pn arrivals indicate that Pn crosses over Pg arrivals at a range of about 125 km. Data recorded at Gambell on the western end of St. Lawrence revealed no crustal arrivals (this data is not shown).

Stations at Provideniya and Novoye Chaplino both recorded Line 1 in a highly-oblique geometry. At both stations arrivals could be traced at offsets of more than 250 km (Figures 7 and 8).

Wide-angle data recorded at Tin City were of high quality (Figure 9). Pg arrivals with an apparent velocity close to 6 km/s can be traced discontinuously up to 180 km south of Tin City. Probable mid-crustal reflections can be observed at ranges between 40 and 60 km. Pn arrivals recorded at Tin City could be traced to ranges in excess of 160 km south of Tin City, and show that Pn crosses over Pg arrivals between 110 and 120 km. The apparent Pn velocity at Tin City is

8.5 km/s. The record obtained at Tin City shows a clear PmP arrival which can easily be traced to within 60 km of the receiver. Data quality for shots north of the station at Tin City, is not as high as those from south of the station, and arrivals can be observed to ranges of about 100 km.

Pg arrivals recorded at Little Diomede Island can be traced to ranges of about 150 km north and south of the island (Figure 10), although the data recorded at this site are considerably noiser than those obtained at Tin City. The crossover of Pn occurs at a range of about 125 km. Faint Pn arrivals are consistent with a slight southerly dip on the Moho. PmP can be observed both north and south of the station.

Recordings made at Point Hope were the highest quality obtained during our study, yielding Pg arrivals that could easily be traced to offsets in excess of 200 km for air gun shots north of the Cape (Figure 11). Pn arrivals at Point Hope appear to cross over Pg arrivals at a distance of about 200 km, implying a much thicker crust at Point Hope than in the vicinity of Tin City and Little Diomede Island. A prominent mid-crustal reflection can be observed for air gun shots between 60 and 120 km north of the receiver. Exceptionally strong converted shear-wave arrivals, having apparent velocities between 2 and 3 km/s, were recorded at this site.

The REFTEK deployed at Cape Lisbourne recorded large amplitude arrivals to ranges as much as 180 km (Figure 12). Unfortunately, the internal GPS clock failed to lock onto the GPS satellites, so the internal clock was free running. Correlation of lower crustal reflections with the seismic reflection line collected on the Ewing, however, suggests that the drift of the internal clock probably did not exceed 0.5 s prior to the acquisition of Line 1. Furthermore, the drift of the internal clock during the acquisition of Line 1 was probably minor, being less than 200 msec. Thus the apparent velocities are likely to be accurate. This record is very similar in appearance to those from Point Hope and Point Lay, except that Pn crossover for shots north of Cape Lisborne is close to 120 km. A strong reflection, interpreted as PmP, is observed at ranges between 85 and 145 km. Pg arrivals, having an apparent velocity of 6 km/s, can be traced to ranges in excess of 100 km.

The record obtained at Point Lay is more complex than records obtained at other stations (Figure 13). The recorder at Point Lay provided useful data to offsets in excess of 200 km, although the recorder was located more than 60 km east of the reflection line. Pg arrivals can be traced to offsets of about 100 km, and PmP or Pn arrivals appear to cross over in the range of 120 km, at least north of the station. Data acquired for the shots south of the station show considerable complexity for ranges in excess of 120 km.

The records made at Point Hope, Cape Lisbourne, and Point Lay provide reversed refraction coverage along that portion of the northern line. The available data unfortunately do not reverse the wide-angle coverage between Tin City and Point Hope.

Useful wide-angle data were acquired for the southward bound MCS Leg (Line 3) at six sites. These include stations at Point Lay, Tin City, Novoye Chaplino, two sites at Provideniya, and Gambell. The station at Point Lay recorded data in a highly-oblique geometry at ranges between 150 and 200 km from shots along Line 3 (Figure 14). The arrivals appear to be either Pn or PmP arrivals, but they can be traced only over short distances.

High quality data were recorded at Tin City, where Pn arrivals could be traced about 400 km to the north and and Pg arrivals could be traced at least 300 km to the south of the receiver, respectively (not shown in Figure 15). The arrivals recorded at Tin City during this southbound leg are very similar to those recorded on the northbound leg. In most cases, however, the data recorded during the southern leg have a higher signal-to-noise ratio than those recorded during the northern leg.

Data recorded by PDAS's at Novoye Chaplino and Provideniya for Line 3 were also very high quality (Figures 16 and 17). Arrivals could be traced in excess of 250 km, and frequently in excess of 300 km. Both records obtained at these stations show clear Pg arrivals as well as Pip or PmP reflections. Data recorded by the Guralp at Provideniya is of poorer quality than those recorded at the adjacent PDAS (Figure 18). This difference presumably reflects the substantially different frequency response of the two recorders.

Gambell recorded relatively poor quality data from the southern transect (Figure 19). Pg arrivals can be traced only to ranges less than 70 km from air gun shots north and south of Gambell. These arrivals include a prominent reflection branch (centered at offsets of about 60 km) for shots north of the station.

All the records obtained show pronounced statics along Pg and Pn branches introduced by topography of seismic basement. These undulations can reach amplitudes of several hundred milliseconds. We believe that these statics originate from variations in the thickness of sedimentary basins along the reflection lines.

We show the seismic ray coverage obtained during our experiment in Figure 20. This figure illustrates where useful wide-angle data were obtained, and shows that the best sampled regions lie in the Chukchi Sea between Point Hope and Point Lay and in the vicinity of the Bering Strait, near the Cape Prince of Wales (Tin City and Little Diomedes Island). The crust between St. Lawrence Island (Gambell) and Eastern Siberia was also well sampled. The crust near Lietnik was sampled to a lesser degree by our wide-angle recording.

Apparent latitudinal variations in wide-angle data quality primarily reflect differences in wind speed conditions during the survey. Wind force and wave height conditions were continuously measured on the **Ewing** during the survey (Figure 21), and there is a clear correlation between the quality of the wide-angle data and the weather conditions. This correlation is most apparent with the data recorded at Lietnik, because the weather was very bad before the ship arrived offshore Lietnik and gradually improved as the ship steamed north past the station. Looking at the receiver gather for Lietnik useful data can only be seen to the north of the station. The weather was as follows (Figure 21): very stormy to improving past Lietnik, worsened again on the north side of Tin City, and was bad north of Diomede. It then improved north of Point Hope, Cape Lisburne and Point Lay. The weather remained calmer (wind force conditions were generally 3-4) as the ship steamed south past Point Lay and Tin City and then worsened again (wind force normally 5-6) as the station at Gambell was passed. The REFTEK installations at all three of these latter sites were comparable, strongly suggesting that wind speed variation accounts for the lower quality data obtained by the recorder at Gambell.

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APPENDIX 1. R/V **Ewing** Airgun Firing Times and Locations

UCT Day:HR:MIN:SEC	Lat. (N) Deg. Minute	Long. (W) Deg. Minute
Line test25		
220:00:00:13.766	58 57.4170	169 31.0150
220:03:48:53.934	58 47.7070	169 35.8248
Line 1a		
220:06:20:01.186	58 47.5825	169 32.4891
220:07:00:04.832	58 50.4688	169 31.7986
220:08:00:18.263	58 54.9298	169 30.6585
220:09:00:19.524	58 59.3619	169 29.7341
220:10:00:03.257	59 03.7191	169 28.6058
220:11:00:14.790	59 08.1805	169 27.7057
220:12:00:02.212	59 12.6918	169 26.5110
220:13:00:18.033	59 17.3369	169 25.4878
220:14:00:16.803	59 21.8599	169 24.3466
220:15:00:16.681	59 26.3319	169 23.3703
220:16:00:13.534	59 30.8312	169 22.1159
220:17:00:05.195	59 35.3194	169 21.0497
220:18:00:07.257	59 39.8281	169 20.1189
220:19:00:01.763	59 44.3819	169 19.0067
220:20:00:09.059	59 48.8408	169 18.0339
220:21:00:01.104	59 53.2905	169 16.8929
220:22:00:09.652	59 57.7273	169 15.7528
220:23:00:31.610	60 02.2120	169 14.7467
221:00:00:03.626	60 06.7511	169 13.5386
221:01:00:11.207	60 11.2909	169 12.5509
221:02:00:19.370	60 15.9263	169 11.3047
221:03:00:01.222	60 20.7365	169 10.0356
221:03:16:49.460	60 22.0099	169 09.7851
Line 1c		
221:05:56:34.279	60 20.4038	169 10.0437
221:06:00:01.554	60 20.6750	169 09.9741
221:07:00:17.505	60 25.9081	169 08.8639
221:08:00:10.735	60 31.1853	169 07.6007
221:09:00:03.892	60 36.2750	169 06.3233
221:10:00:16.149	60 41.2278	169 05.2144
221:11:00:09.355	60 46.0489	169 03.9810
221:12:00:21.463	60 51.0391	169 02.7480
221:13:00:14.714	60 56.0721	169 01.3202
221:14:00:07.745	61 01.2188	169 00.1198
221:15:00:00.740	61 06.4034	168 58.7856
221:16:00:12.632	61 11.7745	168 57.3610
221:17:00:05.701	61 17.2770	168 55.9946
221:17:35:53.892	61 20.6420	168 55.0994
Line 1d		
221:17:36:56.059	61 20.7396	168 55.0821
221:18:00:23.472	61 22.9558	168 54.4906
221:19:00:11.186	61 28.6843	168 53.0807
221:20:00:20.006	61 34.1837	168 51.7275
221:21:00:09.628	61 39.7630	168 50.5031
221:22:00:01.238	61 45.1985	168 49.0389
221:23:00:02.929	61 50.5507	168 47.7493
222:00:00:20.261	61 55.7795	168 46.3065
222:01:00:17.451	62 00.9640	168 45.0168
222:02:00:16.278	62 06.2210	168 43.6796
222:03:00:00.179	62 11.4316	168 42.3632
222:04:00:00.131	62 16.8809	168 40.6677
222:05:00:12.752	62 22.4038	168 39.2881
222:06:00:18.082	62 28.0032	168 37.8094
222:07:00:24.029	62 33.5179	168 36.3416
222:08:00:21.907	62 36.7310	168 39.8798
222:09:00:01.427	62 37.2039	168 46.3539
222:10:00:06.319	62 37.4618	168 52.8498
222:11:00:14.067	62 37.5579	168 59.1902
222:12:00:00.258	62 37.5092	169 05.8892
222:13:00:22.499	62 37.2986	169 13.4768
222:14:00:14.597	62 36.9756	169 21.9737
222:15:00:16.467	62 36.9030	169 31.4505
222:16:00:10.566	62 34.4857	169 34.6157
222:17:00:20.757	62 31.0626	169 31.6544
222:18:00:13.887	62 27.8271	169 28.7277
222:19:00:20.640	62 24.7060	169 25.4577
222:20:00:12.260	62 21.7218	169 21.7412
222:21:00:05.776	62 18.6255	169 17.5017
222:22:00:16.182	62 15.3872	169 12.8431
222:23:00:24.135	62 12.0066	169 08.1616
223:00:00:09.763	62 08.3657	169 03.8838
223:01:00:09.230	62 04.9975	169 00.1515
223:02:00:09.959	62 01.4322	168 56.7789
223:03:00:09.314	61 57.8703	168 53.6076
223:04:09:49.363	61 53.6594	168 50.3017
223:05:00:09.398	61 50.8209	168 49.9794
223:06:00:09.441	61 47.4351	168 49.0764
223:07:00:09.482	61 43.8931	168 48.3563
223:08:08:29.540	61 40.0306	168 48.1601
223:09:00:09.595	61 42.9695	168 50.2913
223:10:00:09.637	61 48.0220	168 48.7404
223:11:00:10.282	61 52.9847	168 47.4639
223:12:00:09.739	61 57.8188	168 46.4848
223:13:00:09.780	62 02.6707	168 45.2168
223:14:00:09.832	62 07.4768	168 43.7032
223:14:35:49.868	62 10.2248	168 42.8187
Line 1e		
223:14:49:09.875	62 11.1615	168 42.5296
223:15:00:28.832	62 11.9546	168 42.2789
223:16:00:10.712	62 16.2274	168 41.0407
223:17:00:28.334	62 20.8479	168 39.8133
223:18:00:29.592	62 25.5726	168 38.4649
223:19:00:00.703	62 30.3759	168 37.1363
223:20:00:27.221	62 35.3145	168 35.9518
223:21:00:02.219	62 40.3401	168 34.5227
223:22:00:17.812	62 45.5436	168 33.2258
223:23:00:25.066	62 50.6122	168 31.9847
224:00:00:01.623	62 55.7404	168 30.6724
224:01:00:03.329	63 00.9606	168 29.4563
224:02:00:02.465	63 05.7300	168 28.1250
224:03:00:18.246	63 10.2782	168 26.7530
224:04:00:12.625	63 14.7809	168 25.8734
224:05:00:25.890	63 19.7492	168 25.5196
224:06:00:09.779	63 25.0078	168 25.4424
224:07:00:22.949	63 30.3546	168 25.2293
224:08:00:22.544	63 35.5818	168 24.8951
224:09:00:21.875	63 40.4219	168 24.3780
224:10:00:05.174	63 44.8018	168 24.5476
224:11:00:16.114	63 49.1648	168 24.4713

224:12:00:30.465	63 53.3647	168 24.3232
224:13:00:02.606	63 57.5147	168 23.6604
224:14:00:13.340	64 01.6827	168 23.6346
224:15:00:26.347	64 06.0032	168 23.2419
224:16:00:22.867	64 10.5542	168 23.0614
224:17:00:13.741	64 15.3313	168 22.7728
224:18:00:10.100	64 20.3082	168 22.5847
224:19:00:19.938	64 25.4061	168 22.1963
224:20:00:13.054	64 30.5029	168 21.9681
224:21:00:27.504	64 35.6824	168 21.5567
224:22:00:00.607	64 40.7583	168 21.2796
224:23:00:17.885	64 45.9029	168 21.1162
225:00:00:00.968	64 50.9257	168 20.7476
225:01:00:07.328	64 56.0360	168 20.5212
225:02:00:11.561	65 01.2553	168 20.4469
225:03:00:22.022	65 06.5664	168 20.1397
225:04:00:20.908	65 11.8162	168 19.6723
225:05:00:21.806	65 16.8511	168 19.5757
225:06:00:16.272	65 22.0422	168 19.1514
225:06:49:31.684	65 26.4702	168 19.6007

Line 1f

225:06:50:03.443	65 26.5177	168 19.6006
225:07:00:11.086	65 27.4183	168 19.4884
225:08:00:01.402	65 32.9454	168 18.4641
225:09:00:12.508	65 39.5244	168 18.4819
225:10:00:00.514	65 46.6673	168 17.4618
225:11:00:10.403	65 53.0527	168 17.5765
225:12:00:20.303	65 58.9848	168 17.0459
225:13:00:15.823	66 04.7966	168 15.3287
225:14:00:11.947	66 10.3676	168 13.7833
225:15:00:14.799	66 16.0320	168 11.7951
225:16:00:26.289	66 21.5686	168 09.8436
225:17:00:02.439	66 27.0689	168 07.9474
225:18:00:11.580	66 32.4672	168 06.1284
225:19:00:04.957	66 38.1939	168 04.1518
225:19:44:26.998	66 42.2436	168 02.8101

Line 1g

225:19:44:38.981	66 42.2613	168 02.8008
225:20:00:01.056	66 43.6378	168 02.2314
225:21:00:25.684	66 48.8252	168 00.5172
225:22:00:05.345	66 53.9502	167 58.6461
225:23:00:08.276	66 59.0440	167 56.9271
226:00:00:22.706	67 03.5082	167 55.6222
226:01:00:10.633	67 07.9490	167 54.1054
226:01:20:44.826	67 09.4709	167 53.5477

Line 1h

226:01:20:54.058	67 09.4825	167 53.5457
226:02:00:03.594	67 12.1154	167 52.0566
226:03:00:08.468	67 13.1759	167 40.1932
226:04:00:06.965	67 13.2145	167 27.9209
226:05:00:09.896	67 13.0444	167 15.6636
226:06:00:17.858	67 12.8142	167 03.4709
226:07:00:02.499	67 12.7181	166 50.8695
226:08:00:06.449	67 12.2680	166 38.6157
226:09:00:13.939	67 09.2387	166 36.8168
226:10:00:14.112	67 05.6871	166 39.8405
226:11:00:17.553	67 01.8469	166 43.4992
226:12:00:15.430	66 58.3781	166 46.2653
226:13:00:03.676	66 54.4430	166 49.5310
226:14:00:10.917	66 50.0590	166 53.1837
226:15:00:02.720	66 49.2623	167 02.8859
226:16:00:18.831	66 49.4385	167 14.1982
226:17:00:17.731	66 49.4605	167 25.7019
226:18:00:14.634	66 49.5478	167 37.2267
226:19:00:12.724	66 50.2228	167 48.6113
226:20:00:20.026	66 51.7594	167 58.9102
226:21:00:12.717	66 56.3416	167 57.8058
226:22:00:11.988	67 01.0138	167 56.3411
226:23:00:08.909	67 05.4226	167 54.8704
227:00:00:07.442	67 09.9774	167 53.6068
227:01:00:03.142	67 14.5990	167 51.9116
227:02:00:19.512	67 19.1342	167 49.9197
227:03:00:07.746	67 23.7647	167 48.6725
227:04:00:04.177	67 28.3867	167 46.8703
227:05:00:03.547	67 32.9782	167 45.5370
227:06:00:13.131	67 37.6533	167 43.4529
227:07:00:18.557	67 42.4036	167 41.6787
227:08:00:19.499	67 47.0603	167 40.2948
227:09:00:12.931	67 51.7503	167 38.6660
227:10:00:16.092	67 56.2766	167 36.6707
227:11:00:14.596	68 00.8502	167 34.6728
227:12:00:06.469	68 05.0956	167 30.4481
227:13:00:16.246	68 09.4004	167 26.0563
227:14:00:13.098	68 13.8409	167 22.1911
227:15:00:01.809	68 18.0817	167 17.3671
227:16:00:03.039	68 22.5477	167 13.0785
227:17:00:13.333	68 27.1328	167 08.4644
227:18:00:38.829	68 31.5588	167 03.8857
227:19:00:06.414	68 36.0787	166 59.5100
227:20:00:19.903	68 40.4885	166 54.7595
227:21:00:03.076	68 44.7056	166 50.5856
227:22:00:19.974	68 48.8714	166 46.5616
227:23:00:16.320	68 53.0439	166 42.1305
228:00:00:15.710	68 57.4002	166 37.8607
228:01:00:03.912	69 01.4984	166 31.8440
228:02:00:15.641	69 05.4401	166 24.6441
228:03:00:07.685	69 09.1281	166 17.2742
228:04:00:12.447	69 12.9349	166 09.3887
228:05:00:01.609	69 16.7898	166 01.7288
228:06:00:01.650	69 20.7596	165 54.4308
228:07:00:19.731	69 24.3936	165 46.8664
228:08:00:08.852	69 28.2606	165 39.2429
228:09:00:03.305	69 32.0224	165 31.5887
228:10:00:14.213	69 35.8492	165 24.0995
228:11:00:15.245	69 39.6838	165 16.2449
228:12:00:08.958	69 43.5177	165 08.7142
228:13:00:20.228	69 47.3285	165 00.7944
228:14:00:11.172	69 51.0813	164 53.4016
228:15:03:40.301	69 55.0070	164 44.8809
228:16:00:08.263	69 58.5942	164 37.9027
228:17:00:18.532	70 02.0079	164 28.6984
228:18:01:48.545	70 05.2924	164 18.5503
228:19:00:11.089	70 08.3803	164 08.7070
228:20:04:15.682	70 11.8373	163 57.9004
228:21:00:19.147	70 14.8005	163 48.5951
228:22:00:16.168	70 18.0396	163 38.2479
228:23:00:17.976	70 21.2241	163 27.9009
229:00:00:05.853	70 24.4026	163 18.0424
229:01:07:12.683	70 27.9240	163 06.6306
229:01:39:42.797	70 29.6770	163 01.1523

Line 2a

229:02:06:29.019	70 30.6319	162 55.6997
229:03:00:10.265	70 31.9971	162 43.8666
229:04:27:51.172	70 35.2195	162 31.9849
229:04:46:27.863	70 34.9162	162 35.7926

Line 2b

229:04:50:24.790	70 34.8438	162 36.6105
229:05:00:09.176	70 34.7078	162 38.6489
229:05:46:14.549	70 33.4930	162 48.2117

Line 2c

229:05:54:04.903	70 33.2420	162 49.7473
229:06:00:18.319	70 32.8708	162 50.5364
229:07:00:03.081	70 32.5849	162 39.3848
229:08:00:03.891	70 34.1650	162 25.8618
229:09:00:19.654	70 35.8247	162 12.8495
229:10:00:19.438	70 37.3973	161 59.6025
229:11:00:16.453	70 39.0326	161 46.4405
229:12:00:14.368	70 40.6214	161 33.3538
229:13:00:01.736	70 42.2698	161 20.2060
229:14:04:25.390	70 43.9839	161 05.8921
229:15:00:11.820	70 45.5250	160 53.6559
229:16:00:11.680	70 47.1033	160 40.4021
229:17:00:18.743	70 48.7793	160 27.0134
229:18:00:09.985	70 50.4268	160 13.1395
229:18:07:47.453	70 50.6397	160 11.2175

Line 2d

229:18:10:58.606	70 50.7305	160 10.4242
229:19:00:13.494	70 52.5250	159 57.1666
229:20:00:23.573	70 55.3386	159 41.2811
229:21:00:22.937	70 58.1938	159 25.1856
229:22:00:06.420	71 01.0044	159 09.5529
229:23:00:22.266	71 03.7200	158 54.0096
230:00:00:08.761	71 06.3587	158 38.6679
230:01:00:03.520	71 08.9932	158 23.6542
230:02:00:00.318	71 11.6201	158 08.0937
230:03:00:05.746	71 14.4247	157 53.2767
230:04:00:00.089	71 17.4034	157 38.2913
230:05:00:14.547	71 22.2678	157 28.2366
230:06:00:18.972	71 23.0516	157 10.2152
230:06:12:59.665	71 23.6895	157 06.7564

Line 2e

230:06:13:33.151	71 23.7190	157 06.6012
230:07:00:02.217	71 25.9405	156 53.2221
230:08:00:19.439	71 28.6814	156 34.6972
230:09:00:20.082	71 31.3541	156 15.1960
230:10:00:08.612	71 34.4531	155 55.9543
230:11:00:15.915	71 36.4751	155 36.0666
230:12:00:09.434	71 38.4054	155 15.1228
230:13:00:13.548	71 41.0417	154 56.1195
230:14:00:10.419	71 45.6743	154 42.4355
230:15:00:07.100	71 49.5476	154 27.2656
230:15:51:30.082	71 47.2073	154 17.1128

Line 3a

232:08:52:15.116	71 23.2144	162 59.6374
232:09:00:07.517	71 22.8530	163 01.1572
232:10:00:15.722	71 20.1622	163 12.9918
232:11:00:19.801	71 17.5874	163 24.5778
232:12:00:05.748	71 14.9170	163 35.6979
232:13:00:04.117	71 12.2483	163 47.0312
232:14:00:18.436	71 09.6822	163 58.6137
232:15:00:05.108	71 07.0277	164 09.3064
232:16:00:13.939	71 04.4098	164 20.6877
232:17:00:05.633	71 01.7718	164 32.0047
232:18:00:00.965	70 59.2115	164 43.4299
232:19:00:08.602	70 56.4570	164 54.9343
232:20:00:04.665	70 53.7220	165 06.6961
232:21:00:02.619	70 51.0188	165 18.1570
232:22:00:12.668	70 48.2735	165 29.4346
232:23:00:04.569	70 45.6773	165 40.6854
233:00:00:06.999	70 43.0749	165 51.9092
233:01:00:13.370	70 40.3744	166 03.2407
233:02:00:18.237	70 37.8246	166 13.4383
233:03:00:09.142	70 35.4405	166 23.8425
233:04:00:00.234	70 32.9098	166 34.6277
233:04:45:30.128	70 30.9559	166 42.1906

Line 3b

233:04:46:12.271	70 30.9238	166 42.3021
233:05:00:04.834	70 30.3829	166 44.5719
233:06:00:18.415	70 28.1269	166 54.3868
233:07:00:21.746	70 25.6802	167 04.2617
233:08:00:04.661	70 23.2649	167 14.6804
233:09:00:07.088	70 20.6091	167 25.2406
233:10:00:18.312	70 18.0625	167 36.3024
233:11:00:13.011	70 15.4910	167 46.9839
233:12:00:18.706	70 13.0782	167 57.0563
233:13:00:19.042	70 10.4589	168 06.9464
233:14:00:10.150	70 07.8560	168 17.7218
233:15:00:07.495	70 05.3213	168 28.5261
233:16:00:02.408	70 02.6854	168 39.2889
233:17:00:08.409	69 59.8163	168 49.2558
233:18:00:15.359	69 55.4329	168 50.1120
233:19:00:05.830	69 51.1240	168 49.9172
233:20:00:13.805	69 46.7288	168 49.8095
233:21:00:09.045	69 42.2238	168 50.3193
233:22:00:03.496	69 37.7868	168 50.0631
233:23:00:17.997	69 33.2865	168 50.1374
234:00:00:02.618	69 28.9179	168 50.0681
234:01:00:16.636	69 24.6373	168 49.7556
234:02:00:19.991	69 20.0805	168 50.3852
234:03:00:08.749	69 15.6726	168 49.7737
234:04:00:19.361	69 11.2370	168 49.8281
234:05:00:17.214	69 06.8463	168 49.8216
234:06:00:08.763	69 02.4604	168 50.0877
234:07:00:02.917	68 58.0692	168 49.7928
234:08:00:09.395	68 53.5963	168 49.7412
234:09:00:04.748	68 49.1857	168 50.1225
234:10:00:22.234	68 44.8462	168 50.1418
234:11:00:05.351	68 40.7364	168 50.1048
234:12:00:11.702	68 36.3657	168 49.9636
234:13:00:09.002	68 31.9318	168 49.8248
234:14:00:00.842	68 27.5155	168 49.9841
234:15:00:18.285	68 22.9826	168 50.2730
234:16:00:11.393	68 18.5813	168 50.3490
234:17:00:34.423	68 14.2658	168 50.0143
234:18:00:05.136	68 10.0441	168 49.8397
234:19:00:03.959	68 05.8083	168 49.9139

234:20:00:12.750	68 01.5021	168 49.9154
234:21:00:08.802	67 57.1902	168 49.9526
234:22:00:20.079	67 52.6977	168 50.0324
234:23:00:05.045	67 48.2814	168 49.9570
235:00:00:18.306	67 43.8234	168 49.8928
235:01:00:00.646	67 39.4223	168 50.1947
235:02:00:07.946	67 34.9017	168 49.8689
235:03:00:12.869	67 30.3785	168 49.9324
235:04:00:05.411	67 25.8513	168 49.8223
235:05:00:13.362	67 21.3545	168 49.9240
235:06:00:10.342	67 16.8021	168 49.9464
235:07:00:13.992	67 12.2737	168 49.8946
235:08:00:03.522	67 07.8526	168 50.0117
235:09:00:08.794	67 03.4746	168 50.1279
235:10:00:13.630	66 59.3075	168 50.1241
235:11:00:18.095	66 55.0972	168 50.0788
235:12:00:03.049	66 50.7379	168 50.0763
235:13:00:13.257	66 46.1651	168 50.0478
235:14:00:06.589	66 41.7767	168 49.9383
235:15:00:17.721	66 37.2586	168 50.1316
235:16:00:10.783	66 32.7842	168 49.8447
235:17:00:22.363	66 28.4321	168 49.8774
235:18:00:18.764	66 23.9598	168 50.1027
235:19:00:09.603	66 19.8517	168 50.1088
235:20:00:09.444	66 15.8054	168 50.0194
235:21:00:16.699	66 11.4436	168 50.0238
235:22:00:01.340	66 07.0658	168 50.0282
235:23:00:04.721	66 02.8250	168 50.1230
236:00:00:01.933	65 58.5910	168 50.0836
236:01:00:00.193	65 54.1033	168 49.8605
236:02:00:18.754	65 49.6399	168 50.0209
236:03:00:19.166	65 45.2004	168 50.0620
236:04:00:10.907	65 40.8488	168 50.2592
236:05:00:15.019	65 36.6133	168 49.8656
236:06:00:16.577	65 32.4242	168 50.1831
236:06:01:01.869	65 32.3711	168 50.1773

Line 3c

236:06:01:37.237	65 32.3286	168 50.1736
236:07:00:13.479	65 32.9043	168 54.7633
236:08:00:10.089	65 37.4912	168 52.6093
236:08:33:48.244	65 36.9222	168 48.4346

Line 3d

236:08:34:40.904	65 36.8564	168 48.4057
236:09:00:22.822	65 35.2694	168 50.3106
236:10:00:08.604	65 31.4980	168 55.6088
236:11:00:11.114	65 27.7129	169 00.9162
236:12:00:13.646	65 24.1987	169 07.5773
236:13:00:11.757	65 20.8530	169 14.3581
236:14:00:15.652	65 17.4559	169 21.1220
236:15:00:13.722	65 14.0924	169 27.6577
236:16:00:16.260	65 10.6204	169 34.6382
236:17:00:12.931	65 07.2862	169 40.7744
236:18:00:08.566	65 03.8957	169 47.5074
236:19:00:03.836	65 00.4417	169 54.2993
236:20:00:02.031	64 57.0533	170 00.8919
236:21:00:15.807	64 53.6281	170 07.6849
236:22:00:04.196	64 50.1916	170 14.3142
236:23:00:05.261	64 46.8421	170 21.0452
237:00:00:18.541	64 43.4566	170 27.5717
237:01:00:01.416	64 40.0622	170 34.2177
237:02:00:12.363	64 36.6175	170 40.8751
237:03:00:02.219	64 33.1236	170 47.7073
237:04:00:01.669	64 29.6097	170 54.3058
237:05:00:11.220	64 26.1994	171 00.9872
237:06:00:11.650	64 22.7918	171 07.4238
237:07:00:16.750	64 19.4757	171 13.8305
237:08:00:09.296	64 16.0281	171 19.9986
237:09:00:08.550	64 12.8955	171 25.9944
237:10:00:13.102	64 09.7835	171 32.1162
237:11:00:02.378	64 06.5888	171 38.0223
237:12:00:18.530	64 03.3222	171 44.2420
237:13:00:06.694	63 59.9228	171 50.8903
237:14:00:21.294	63 56.5049	171 57.5221
237:15:00:15.703	63 52.7478	172 02.8490
237:16:00:02.017	63 48.6718	172 07.7231
237:17:00:08.767	63 44.7676	172 12.3145
237:18:00:00.587	63 41.0340	172 16.9306
237:19:00:10.110	63 37.3134	172 21.5381
237:20:00:21.230	63 33.4002	172 26.0128
237:21:00:16.877	63 29.5242	172 30.8241
237:22:00:06.722	63 25.8462	172 35.3414
237:23:00:01.104	63 21.9939	172 39.6878
238:00:00:07.159	63 18.1045	172 44.5731
238:01:00:02.859	63 14.1537	172 49.2482
238:02:00:11.336	63 10.2028	172 53.8445
238:03:00:09.557	63 06.2359	172 58.5125
238:04:00:13.610	63 02.3898	173 03.3711
238:05:00:10.293	62 58.5770	173 07.8625
238:06:00:09.163	62 54.6955	173 12.4283
238:07:00:16.102	62 50.7730	173 16.8720
238:08:00:11.072	62 46.9351	173 21.4187
238:09:00:09.735	62 43.0703	173 25.9834
238:10:00:05.077	62 39.2065	173 30.4107
238:11:00:16.651	62 35.3602	173 34.9947
238:12:00:11.598	62 31.5185	173 39.4115
238:13:00:06.459	62 27.6792	173 43.8458
238:14:00:00.751	62 23.8400	173 48.3765
238:15:00:01.405	62 20.0085	173 52.7925
238:16:00:05.723	62 16.2042	173 57.0005
238:17:00:02.179	62 12.4780	174 01.3540
238:18:00:01.389	62 08.7684	174 05.7420
238:19:00:17.697	62 04.9349	174 09.9966
238:20:00:11.398	62 01.1042	174 14.4005
238:21:00:04.610	61 57.3373	174 18.5898
238:22:00:00.101	61 53.5608	174 22.9322
238:23:00:03.202	61 49.8305	174 27.2065
239:00:00:06.421	61 45.9903	174 31.6805
239:01:00:11.884	61 42.0456	174 36.1413
239:02:00:10.415	61 38.1036	174 40.4134
239:03:00:03.987	61 34.2263	174 44.8023
239:04:00:19.005	61 30.3294	174 49.4830
239:05:00:20.019	61 26.4264	174 53.6910
239:06:00:14.962	61 22.5937	174 58.0084
239:07:00:00.563	61 18.7114	175 02.2263
239:08:00:08.785	61 14.8346	175 06.5091
239:09:00:03.770	61 11.1324	175 10.5871
239:10:00:01.590	61 07.5093	175 14.6529
239:11:00:14.176	61 03.7214	175 18.8073
239:12:00:14.301	60 59.9061	175 23.0734
239:13:00:13.272	60 56.1520	175 27.1837
239:14:00:07.830	60 52.4600	175 31.3517
239:15:00:19.150	60 48.5951	175 35.6280
239:16:00:07.243	60 44.6680	175 39.8703
239:17:00:14.203	60 40.8098	175 44.1253

239:18:00:02.946	60 36.8713	175 48.5247
239:19:00:00.581	60 32.9236	175 52.8377
239:20:00:18.390	60 28.9437	175 56.9400
239:21:00:10.970	60 25.0967	176 01.2524
239:22:00:12.403	60 21.2027	176 05.4180
239:23:00:07.301	60 17.3948	176 09.4819
240:00:00:12.238	60 13.6034	176 13.5582
240:01:00:15.783	60 09.8020	176 17.7511
240:02:00:15.845	60 05.8674	176 21.7853
240:03:00:01.592	60 01.9387	176 26.1156
240:04:00:17.539	59 58.0938	176 30.5154
240:05:00:05.342	59 54.1757	176 34.4722
240:06:00:13.634	59 50.3307	176 38.5725
240:07:00:07.112	59 46.4691	176 42.5910
240:08:00:08.836	59 42.6094	176 46.8192
240:09:00:20.476	59 38.8079	176 50.9534
240:10:00:00.779	59 35.0689	176 54.6944
240:11:00:20.897	59 31.2910	176 58.7159
240:12:00:13.511	59 27.3641	177 02.7935
240:13:00:15.199	59 23.5603	177 07.0336
240:14:00:04.454	59 19.6941	177 11.0093
240:15:00:17.164	59 15.8418	177 14.8933
240:16:00:20.727	59 12.1119	177 19.0464
240:17:00:21.013	59 08.1911	177 22.9487
240:18:00:22.377	59 04.5316	177 26.8321
240:19:00:13.131	59 00.6860	177 30.7879
240:20:00:12.374	58 56.9012	177 34.5654
240:21:00:18.163	58 53.0418	177 38.3707
240:22:00:00.463	58 49.2104	177 42.3537
240:23:00:06.517	58 45.2878	177 46.1648
240:23:59:45.445	58 41.4294	177 49.9741
241:00:00:08.175	58 41.4052	177 49.9950
241:01:00:06.797	58 37.4453	177 53.7768
241:02:00:02.712	58 33.5280	177 57.4223
241:03:00:15.780	58 29.7334	178 01.2484
241:04:00:03.862	58 26.0051	178 04.7171
241:05:00:08.543	58 22.2150	178 08.5961
241:06:00:03.236	58 18.2753	178 12.2596
241:07:00:20.278	58 14.5977	178 15.9798
241:08:00:16.338	58 10.9005	178 19.6589
241:09:00:10.827	58 07.2042	178 23.0790
241:10:00:04.940	58 03.4194	178 26.7943
241:11:00:02.812	57 59.5999	178 29.9499
241:12:00:12.912	57 57.4165	178 22.1967
241:13:00:03.596	57 55.7673	178 13.6323
241:14:00:15.965	57 53.9254	178 05.2801
241:15:00:11.749	57 51.9076	177 57.3071
241:16:00:15.742	57 49.9054	177 49.1219
241:17:00:25.943	57 47.8423	177 40.9336
241:18:00:14.560	57 45.7126	177 32.6754
241:19:00:19.171	57 43.5602	177 24.2885
241:20:00:11.914	57 41.5669	177 15.8495
241:21:00:02.666	57 39.3209	177 07.2511
241:22:00:29.854	57 37.4188	176 59.3426
241:23:00:12.922	57 35.8369	176 53.3236
242:00:00:10.209	57 34.1795	176 46.6654
242:01:00:08.981	57 32.3909	176 39.6994
242:02:00:30.487	57 30.6499	176 32.6193
242:02:29:26.429	57 30.4673	176 29.5107

Line 3f

242:02:30:53.043	57 30.5312	176 29.3772
242:03:00:04.352	57 32.3851	176 27.8434
242:04:00:14.760	57 36.2442	176 23.6233
242:05:00:08.487	57 40.1317	176 19.5473
242:06:00:15.446	57 44.0561	176 15.7931
242:07:00:11.045	57 47.8611	176 11.7137
242:08:00:18.281	57 51.6764	176 07.8046
242:09:00:10.877	57 55.4807	176 03.9141
242:10:00:19.619	57 59.3939	175 59.7446
242:11:00:08.332	58 03.2829	175 55.7562
242:12:00:20.713	58 07.2068	175 51.7376
242:13:00:03.204	58 11.1655	175 47.5156
242:14:00:07.949	58 15.2681	175 43.5441
242:15:00:05.536	58 19.2322	175 39.1712
242:16:00:14.310	58 23.1504	175 35.0306
242:17:00:15.597	58 27.1064	175 31.0421
242:18:00:01.561	58 30.9635	175 27.0073
242:19:00:15.250	58 34.8017	175 23.0172
242:20:00:06.194	58 38.7118	175 18.9931
242:21:00:32.885	58 42.6534	175 14.6570
242:22:00:07.317	58 46.6011	175 10.4102
242:23:00:33.047	58 50.6593	175 06.1026
243:00:00:08.108	58 54.5497	175 02.0644
243:01:00:15.151	58 58.2263	174 57.7964

APPENDIX 2: CONVERTING REFTEK FORMAT DATA TO RECEIVER GATHERS

Below is a step by step description of the processes necessary to convert the continuously recorded REFTEK data into SEG-Y format common receiver gathers. Ths reduction was carried out at the Stanford PASSCAL Instrument facility. To cut 1 day of data with a 100 Hz sample rate and 20 s air gun repetition rate requires about 20 minutes of wall clock time. For more detail, please consult the online manual page for segygather.

1. Download compressed data from REFTEK hard drive.

After retrieving the REFTEKs from the field, we downloaded the digital seismic data onto DAT tapes in refdump format using both a Sun workstation and a PASSCAL field DAT drive. The procedure followed for the field DAT drive consisted of the following. A power supply or battery and a hand-held terminal (HHT) were connected to each DAS unit, and SCSI cables were connected from the DAS to the field DAT drive. The field DAT drive was also connected to a power supply. For each station a new DAT tape was inserted into the field DAT drive. Using the HHT the DAT tape was then formated by the following steps: press F5 (Data Menu), press 5 (SCSI Format), press 1 (Format Tape), and press F10 (Start Procedure). With the HHT and power supply still connected to the DAS, and the SCSI cable still connected to the DAT drive, the REFTEK data on the DAS was then written to DAT tape using the following steps: F5 (Data Menu), press 2 (Copy Data), press 8 (Copy Disk to Tape), and press F10 (Start Procedure). Repeating this procedure resulted in 8 DAT tapes, one for each station. We attempted to repeat this procedure twice for each station, one using the field DAT drive and the other using the Sun workstation. For some DAS units, however, it was possible to download the data using the field DAT drive.

If using a Sun workstation, type **refdump -d /dev/sd5c /dev/rst1**

2. Convert REFTEK formatted data tapes to SEG-Y formatted tapes

use **tar xvf /dev/nrst1** to read the refdump file from tape and write it to disk

Type:

```
mkdir XXXX            (where XXXX is the station number)
cd XXXX
mt -f /dev/rstY/ rewind
ref2seg -t /dev/rstY         (where Y is the tape device number)
```

If prompted, enter the sampling rate and gains in dB for each channel

3. Check REFTEK functioning and obtain station coordinates

These checks were made using the logview program to view the information contained in the REFTEK log file. A plot of the GPS coordinates obtained every hour can be obtained using the GPS tool. The average of these positions is used for the station location. Clock performance can also be assessed via plots of clock phase locking.

First, type **logview filename** where filename is a REFTEK logfile e.g. **94:231.7300.log.**

Second, click on **GPS: Clock** window in **logview.** A plot of all GPS coordinates and statistics on these locations will be provided.

4. Generate shot times file

This file should be in the format:

```
shot time lat lon
300976 94:222:00:00:48.732 61.9303267 -168.7716050
300977 94:222:00:01:17.243 61.9310033 -168.7714167
300978 94:222:00:01:45.873 61.9316867 -168.7712133
```

This information is obtained from the shotfile generated on board the **EWING** (for shotfiles lon is negative in the western hemisphere). A detailed example of how to do this is given below:

1) Combine all shot information into one big file: e.g. **big.shot.**

2) Edit **(vi) timeflt.awk** to select needed dates for shottimes.

3) Type **awk -f timefilt.awk big.shot >tmp**. Puts output into tmp.

4) Type **awk -f degmin2degdec.awk tmp >220_228.shotfile** where **220_228.shotfile** is an example of a shotfile name

5) Type **head 220_228.shotfile** to look at first few lines of shotfile

6) Type **tail 220_228.shotfile** to look at last few lines of shotfile

7) **vi 220_228.shotfile** to delete s.ts.n220: from files
   vi 220_228.shotfile to change "94-" to "94:"
   vi 220_228.shotfile to change "94+" to "94:"
   vi 220_228.shotfile to header line "shot time lat lon" in lower case

   e.g. :%s/94+/894:/g in **vi**

8) **awk '{print $1, $2}' 220_228.shotfile >220_228.starttime**

5. Generate Receiver File (RCVR file)

This file should be in the format:

```
number DAS/C  lon          lat          elevation
# Lietnik
1      7279/1  -168.979082   63.322742     15
2      7279/2  -168.979082   63.322742     15
3      7279/3  -168.979082   63.322742     15
# Point Hope
4      7281/1  -166.795962   68.353427     5
5      7281/2  -166.795962   68.353427     5
```

```
6      7281/3  -166.795962    68.353427      5
```

number = arbitrary station number
DAS = REFTEK unit number
C = Channel (1=vertical, 2=N-S Horizontal, 3=E-W Horizontal)
lon = negative in the western hemisphere
elevation = elevation in meters

Note: The hash sign means the cshell ignores that line

6. Write cshell to produce start times list and cut data.

e.g. segygather.csh

The same cshell can be used for both operations. First a start times list must be created. This list was created by appending the lists produced for each day in step 2. Secondly the continuous data was cut using segygather. The format is:

```
segygather    -i ../starttimes -s ../shottimes -g
        ../rcvrfile -d device -n record_length -o
        output_device
```

An example c-script for Gambell is:

```
ls /breck/data3/Gambell/R220.01/*.1>/breck/data4/lst/Gambell220_225.1.lst
ls /breck/data3/Gambell/R221.01/*.1>>/breck/data4/lst/Gambell220_225.1.lst
ls /breck/data3/Gambell/R222.01/*.1>>/breck/data4/lst/Gambell220_225.1.lst
ls /breck/data3/Gambell/R223.01/*.1>>/breck/data4/lst/Gambell220_225.1.lst
ls /breck/data3/Gambell/R224.01/*.1>>/breck/data4/lst/Gambell220_225.1.lst
ls /breck/data3/Gambell/R225.01/*.1>>/breck/data4/lst/Gambell220_225.1.lst

segygather -i /breck/data4/lst/Gambell220_225.1.lst -s
/breck/data4/shottimes/220_225.shottimes -g /breck/data4/receivers -d 7282/1 -n
60 -o /dev/nrst$1
```

The first six lines produce a list of all the start times for days 220 to 225 (the period the **EWING** was within a reasonable range). The 1s are for component 1, the same procedure is necessary for all three components. Segygather is then run using the start times list generated (Gambell220_225.1.lst), the shot file (220_225.shottimes), the receiver file (receivers), the REFTEK unit number and component (7282/1). The data was cut to 60 sec, this means that a 60 sec slice of the continuous data was cut for each shot. The shots were separated by 20 to 30 sec resulting in more than one shot being recorded on each trace. The cut traces are then downloaded to tape.

Make one **segygather** line per line and per channel

When finished editing, type **chmod +x segygather.csh** to make it executable

Put a new, labeled Exabyte tape in the Exabyte tape drive.

Run program by typing **segygather.csh**

7. Load into ProMAX

The data is now in a format suitable to be loaded into ProMAX. Appendix 2 lists the necessary input parameters. Read tape using ProMAX software and make screen display to verify **segygather** worked properly.