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Physical Environment of the Underground Nuclear Test Site on Novaya Zemlya, Russia

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PHYSICAL ENVIRONMENT OF THE RUSSIAN UNDERGROUND NUCLEAR TEST SITE ON NOVAYA ZEMLYA, RUSSIA

ABSTRACT

The former Soviet Union conducted 132 nuclear tests on the Arctic islands of Novaya Zemlya between September 21, 1955 and October 24, 1990. This includes 87 explosions in the atmosphere (one explosion on the land surface; three explosions on the water surface; and 83 air bursts); three underwater explosions between 1955 and 1962; and 42 underground tests between 1964 and 1990. The underground nuclear test site, located along the Matochkin Shar strait that divides Novaya Zemlya into two main islands, is the only former Soviet nuclear test site that is presently declared under the 1963 Threshold Test Ban Treaty (TTBT). An underground site on the southern part of the islands was deactivated in 1975. Underground tests average one or two per year between 1964 and 1990. At the Matochkin Shar test site 36 tests occurred during this period. U.S. estimates of the yields for underground tests at both sites range from 2 kt to 4 mt; the estimated yield of the largest test at the Matochkin Shar site is 2 mt. Russian data indicate that the scaled depth of burial for tests at both sites ranges from 90 to over 400 $m/kt^{1/3}$, averaging 123 $m/kt^{1/3}$; the average for tests at the Matochkin Shar site is 114 $m/kt^{1/3}$. The Matochkin Shar site is composed of bedded, fractured and faulted sedimentary rocks which dip to the northwest, but are near vertical in Mt. Lasareff, along the strait, where some testing has occurred. Deformation of the rocks in the test area is due primarily to thrust faulting, though folding also occurs. The tests have occurred in low-porosity rocks of middle Paleozoic age, described as mostly shale, siltstone, sandstone, quartzite, and conglomerate with lesser amounts of limestone and dolomite. Descriptions of sericite and chlorite schists and quartzites at Matochkin Shar suggest that the rocks are metamorphosed to the Greenschist facies. The largest granitic intrusion on Novaya Zemlya is located on the northern side of the strait, about 20 km to the west of the current testing region, but no underground tests are known to have occurred in the granite. Novaya Zemlya is located in the zone of continuous permafrost, which is up to 600 meters thick in the higher mountains, but it is uncertain if the tests have occurred within or below the permafrost.

INTRODUCTION

Purpose

Personnel of the U.S. Geological Survey participated in the first US-Soviet nuclear test Joint Verification Experiment (JVE) in Kazakhstan, USSR, in 1988, and are expected to participate in subsequent verification exercises. The responsibility of the USGS teams in these exercises is to independently verify the geologic and geophysical data of the testing medium that is supplied by the Russians, and also to collect and analyze additional data on site to aid in this verification, as outlined under the protocols of the TTBT and the Peaceful Nuclear Explosions Treaty (PNET). With the closing of the Semipalatinsk underground nuclear test site in Kazakhstan in August 1991, the only currently declared Russian test site is located on Novaya Zemlya in the Russian Arctic. This paper is intended to provide researchers of Russian nuclear tests and testing practices with a basic understanding of the geologic environment of the underground nuclear test site on Novaya Zemlya. The paper reviews geologic data on Novaya Zemlya that was published in various books and journals over a period of about 70 years. In addition to providing geologic information for on-site inspections, these data are also useful for estimating the coupling characteristics of the rock at the test site, the potential for decoupling, interpreting the seismic signals originating from Novaya Zemlya, and in comparisons with the geology of other nuclear test sites worldwide.

Location

Novaya Zemlya consists of two large islands located approximately 450 kilometers north of the Arctic Circle. Situated between 70° and 77° north latitude and 51° to 69° east longitude, the two islands together are over 800 km in length and average 100 km in width (see Figure 1). The islands are bordered on the east by the Kara Sea and on the west by the Barents Sea. Administratively, they fall within the Arkhangel'skaya Oblast' of the Russian Republic of the former Soviet Union. Novaya Zemlya is the site of two Russian underground nuclear test sites; a southern and a northern site.

The northernmost nuclear test site is located about 73° 25' north latitude and 54° 45' east longitude, along the Matochkin Shar strait on the northern end of the South Island. The southernmost site is located on the southwest coast of the South Island, about 70° 45' north latitude and 54° east longitude (Andrianov and others, 1992, p. 17). In this paper only the Matochkin Shar test site is described in detail, as this is the only currently active site. No tests appear to have been conducted at the southern site since October, 1975 (Sykes and Ruggi, 1989, Table 10.2; Andrianov and others, 1992; NEIC, 1990a). At the Northern site, the Matochkin Shar strait was formed by the headward erosion and joining of two fjords, subdividing Novaya Zemlya into its constituent North Island and South Island. The strait is about 125 kilometers long, two to four kilometers wide, and ranges up to 350 meters in depth (Glazovskiy, 1989, p. 26). The large bays and inlets that characterize both coasts of Novaya Zemlya are also glacially scoured, drowned fjords.

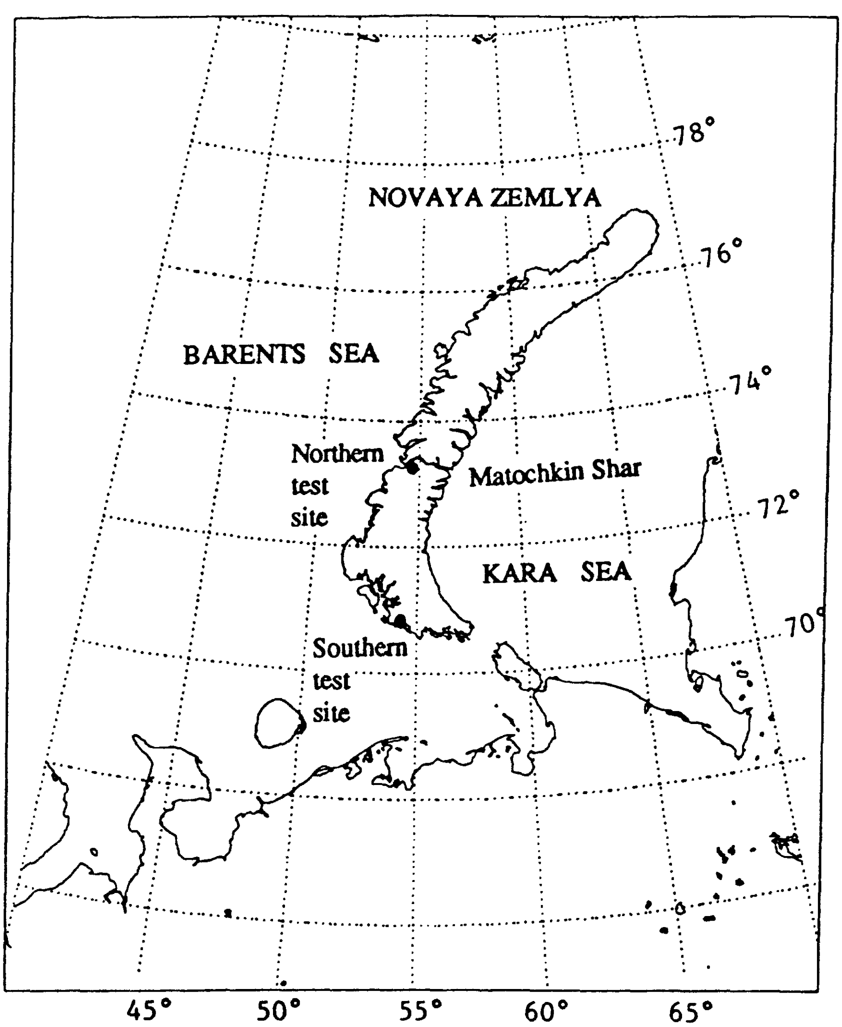


Figure 1.
Locations of the northern (Matochkin Shar) and southern test sites on Novaya Zemlya.

Sources

The main sources on the geology of the test site come from the Russian geologic literature available at the USGS library in Reston, Virgina. This literature includes descriptions from general reconnaissance and paleontological expeditions to Novaya Zemlya from the 1920's through the 1980's. In the early 1920's, a Norwegian scientific expedition traveled through Matochkin Shar, making on-site investigations on both shores (Holtedahl, 1930). The cross sections and some of the geologic descriptions in this paper are adapted from that early work. Geologic field trips were conducted on the southern part of the South Island, as part of the 17th International Geological Congress, held in 1937 (Samoilovich and Yermolaev, 1937). The descriptions from these excursions cover much of the area of the southern test site, but do not extend to the area of the northern test site. Small scale regional geologic maps, as well as some limited larger scale geologic maps from the Russian geologic literature, were also utilized in the preparation of this report. Important descriptions of individual underground tests come from Andrianov and others (1992), in a compilation discussing underground testing on Novaya Zemlya, containment procedures, and contamination concerns.

Climate

A summary of weather conditions reported for the station at Malye Karmakuly, about 130 km south of Matochkin Shar on the west coast of Novaya Zemlya, is given in Table 1. The data in this table are extracted from Lydoph, 1977, and US Department of Commerce, 1990.

Novaya Zemlya is characterized by a severe climate, with frequent, extremely strong winds ("Bora") which accompany lower temperatures and cause snow or dust storms. The Bora are caused by extreme air pressure differences between the Barents and Kara Seas (the Murman current, a branch of the Gulf Stream, flows into the Barents Sea and along the western coast of Novaya Zemlya, thereby causing the Barents Sea to be somewhat warmer than the Kara Sea). The monthly mean wind speed averages about 8 m/sec over the year, with mean annual peak gusts about 32 m/sec.

On Novaya Zemlya, summers are cold and short, starting in June and continuing until September. Temperatures can rise to a maximum of 24^{0} C (75^{0} F) in July, but the average mean summer temperature is about 4.2^{0} C (40^{0} F). The mean relative humidity averages 80 percent. Rain is frequent but light. Thunderstorms are rare but may occur during late spring and summer. The surface frost-free period is less than 45 days, from early July to middle August, but night frosts can occur during any of the summer months. During May, June and July the sun does not set and dense fogs can occur. Clear days are rare, ranging from one to four days per month in the summer, to three to nine days per month in the winter. By mid-October both the mean and average maximum daily temperatures are below freezing.

Winter begins in late October or early November and generally continues into April. Temperatures rarely rise above freezing, with daily mean temperatures averaging -13^{0} C (8^{0} F). Precipitation greater than 0.1 mm occurs on about one half of the winter days. Snow cover averages only 0.31 meters deep annually. January through April are the least cloudy months, but even then contain only seven to nine clear days. During November, December, and January the sun does not rise. The average temperatures drop to about -12^{0} C (10^{0} F). The coldest month on the island is March, during which temperatures can drop to -44^{0} C (-47^{0} F). In spite of these temperatures, Novaya Zemlya is somewhat milder than northern Siberia because of the warming influence of the Murman current.

Mean annual precipitation is about 317 mm (12.5 inches). About half the annual precipitation falls in the warm period, the maximum occurring in August and September as cold, prolonged

Table 1. Weather and climate summary, Malye Karmakuly, Novaya Zemlya

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Temperature (degrees C)													
mean	-15	-14.5	-15.4	-10.8	-4.5	1.4	6.4	6.3	2.7	-2.7	-9	-13	-5.7
maximum	1	1	1	6	13	20	24	20	17	10	3	2	24
minimum	-41	-40	-44	-32	-24	-17	-10	-1	-13	-18	-34	-36	-44
Precipitation (mm)													
mean	26	18	19	18	20	24	30	36	41	35	26	24	317
maximum						59	82	95	88				
minimum						2	2	7	8				
max in 24 hrs.						28	27	27	28				
Mean relative humidity (%)													
	78	77	79	75	80	84	81	82	85	82	80	78	80
Wind													
mean speed (m/sec)	10.3	10.4	9.2	8.1	7.2	6.9	6.3	6.9	7.1	7.9	9	10.4	8.3
(prevailing direction)	SE	SE	SE	SE	N	N	N	N	SE	SE	SE	SE	SE
mean peak gusts (m/s	27.1	26.7	25	27	22.3	22.9	22.2	21.4	22.7	20.6	24.9	28.9	32.6
Mean sea level pressure (mbar)													
	1007.2	1010.8	1012.3	1012.8	1015.9	1012.2	1013.3	1012.2	1007.9	1007.8	1005	1002.3	1010
Cloud cover													
Mean cloudiness (tent	7.1	6.4	6.7	7.6	8.3	8.1	7.6	8.5	8.6	8.2	7.8	7.3	7.7
Avg number of clear days													
(based on a 30 day m	9	7	7	8	3	2	4	3	1	3	5	6	
Mean sunshine (hrs)													
	0	21	95	155	175	178	194	146	76	44	2	0	1086
Actual evaporation (mm)													
	0	0	0	0	0	15	18	15	9	8	0	0	65
Frost-free period (days)													
													68
Number of days with:													
wind (>15 m/sec)	15.7	13.8	13.9	11	8.2	7	5.5	5.4	7.4	10.2	12.1	14	124.2
precipitation > 0.1 mr	19.7	14	18.3	15.3	14.2	12.5	12.7	16.9	17.8	17	14.8	17.9	191
fog	0.5	1	0.7	3	5	7	10	8	5	3	2	1	46.2
thunderstorms						0.3	0.5	0.5	0.04				1.3
clouds (8-10 tenths)	14	11.6	12.5	17.4	21.4	19.1	18.5	22.4	21.2	19.2	17.2	16.7	211.2
snow cover													238
Snow cover max. 10-day avg. depth (cm)													
													31

rain. The minimum precipitation occurs February to April. Almost two-thirds of the precipitation runs off the islands during the summer months since annual evaporation rates are low. The water does not percolate into the ground because of the underlying permafrost; floods continue throughout the summer months. In winter, surface runoff is lacking since rivers, lakes and swamps are completely frozen.

The occurrence of sea ice varies significantly between the Barents and Kara seas throughout the year. Due to the presence of the warm Murman current, much of the Barents Sea remains open throughout the year. However, ice cover does occur along the west coast of Novaya Zemlya from November to May, with scattered ice remaing in the area through the first half of June. In contrast, the Kara Sea, which is insulated from the Murman current by Novaya Zemlya, is characterized by much more extensive ice cover. The Kara Sea in the region of Matochkin Shar is free of ice only from late August to about the first half of October. These differences in ice cover between the seas also influence the occurrence of ice in the Matochkin Shar strait. The western entrance to the strait is ice-free for about four and a half months, from late June through October, while the eastern entrance is ice-free for about two and a half months, from early August to mid October. Thus, the western half of the strait may be ice free at a time when the eastern half is still plugged with ice.

UNDERGROUND NUCLEAR EXPLOSIONS

Basic data on the 42 underground nuclear tests at Novaya Zemlya, from 1964 to 1990, are given in Andrianov and others (1992) and presented in Table 2. Additional data are extracted from the U.S. Geological Survey National Earthquake Information Center, 1990a, 1990b; and Sykes and Ruggi, 1989. Of the 42 tests, 36 occurred at the northern, Matochkin Shar test site, 6 occurred at the southern site. The table indicates that about 85 percent of the tests have occurred during the months of August, September, and October. U.S. yield estimates for all underground tests on Novaya Zemlya range from 2 kilotons (kt) to about 4.1 megatons (mt). The largest test at the Matochkin Shar site was 2.1 mt. The scaled depths of burial (SDOB) given in Table 2 are provided by Andrianov and others (1992). For all tests on Novaya Zemlya, the SDOB ranges from 90 to over 400 $m/kt^{1/3}$, with an average value of 123 $m/kt^{1/3}$. The average SDOB for only those tests that occurred at the Matochkin Shar site is 114 $m/kt^{1/3}$. These averages are comparable to the 120 $m/kt^{1/3}$ used for planning purposes at the Nevada Test Site (NTS) in the US. The 18 October 1975 and 11 October 1980 events may each have been two simultaneous explosions spaced several kilometers apart (Lilwall and Marshall, 1986; Stewart and Marshall, 1988). There are also two test numbers and SDOB's assigned to these dates by Andrianov and others (1992), as well as to the events of 21 October 1967, and 14 October 1969, perhaps suggesting that these were all double events. Two test numbers are given for the event of 27 October 1966 but only one SDOB. Additionally, Andrianov and others (1992) lists an event on 27 July 1972, which is not reported elsewhere.

The data in Andrianov and others (1992) indicate seepage of radioactive inert gases into the atmosphere at both test sites on Novaya Zemlya. The data indicate that for all underground tests on Novaya Zemlya, 28 of the 42 tests (67 percent) leaked; the number increases to 26 of 36 tests (72 percent) at Matochkin Shar. Much of the leakage is described as emanating from the "explosion zone; " seepage along fractures or faults in the rock is specifically described at only four of the Matochkin Shar tests. Only two tests are acknowledged by Andrianov and others (1992, p. 44) as venting larger than expected amounts of radioactive material, on 14 October 1969 (no. A-9), and 2 August 1987 (no. A-37A), which caused an "abnormal radiation environment" at each site. In addition, data presented by V. Adushkin at a 1993 conference at the Center for Seismic Studies (CSS) in Virgina, indicate that the 27 September 1973 test also resulted in significant venting (Leith, personal communication, 1993). The Russians have not considered the seepage of

Table 2. Underground nuclear explosions, Novaya Zemlya.

Test date	North Latitude	East Longitude	Russian test number	Russian SDOB (m/kt 1/3)	Magnitude (mb)	Est. Yield (kt)	Test site	Venting (Yes; No)	Location no. in Figure 7
18-Sep-64	73.20	54.40	G	~100	4.30	2	northern	Y	1
25-Oct-64	73.39	53.90	B	~200	4.90	8.4	northern	Y	2
27-Oct-66	73.40	54.57	A-1	~90	6.39	422	northern	Y	3
			A-2					Y	
21-Oct-67	73.40	54.42	A-4	~90	5.92	93	northern	Y	4
			A-5	~120				N	
7-Nov-68	73.39	54.58	A-3	~140	6.02	119	northern	Y	5
14-Oct-69	73.39	54.50	A-7	~120	6.09	140	northern	N	6
			A-9	~100				Y#	
14-Oct-70	73.31	54.89	A-6	~90	6.60	1001	northern	Y	7
27-Sep-71	73.39	54.91	A-8	>90	6.47	586	northern	Y	8
27-Jul-72			Yu-3	>400				N	
28-Aug-72	73.39	54.65	A-16	~90	6.33	329	northern	Y	9
12-Sep-73	73.32	54.97	V-1	~95	6.78	2099	northern	Y	10
27-Sep-73	70.80	53.42	Yu-4	~190	5.95	100	southern	Y##	
27-Oct-73	70.80	53.92	Yu-1	~120	6.94	4055	southern	N	
29-Aug-74	73.41	54.93	A-11	~120	6.43	497	northern	Y	11
2-Nov-74	70.81	53.91	Yu-5N	~120	6.78	2099	southern	N	
23-Aug-75	73.34	54.50	A-10	~90	6.42	477	northern	Y	12
18-Oct-75	70.84	53.53	Yu-6N	~110-120	6.66	1281	southern	Y	
			Yu-7				southern	N	
21-Oct-75	73.32	54.93	A-12	~90	6.43	497	northern	Y	13
29-Sep-76	73.41	54.50	A-14	~95	5.80	70	northern	Y	14
20-Oct-76	73.40	54.47	A-15	~140	5.10	13	northern	N	15
1-Sep-77	73.37	54.41	A-17	~150	5.70	55	northern	N	16
9-Oct-77	73.47	53.98	A-7N	~100	4.60	4.1	northern	Y	17
10-Aug-78	73.31	54.70	A-18	~110	5.90	89	northern	Y	18
27-Sep-78	73.38	54.44	A-19	~100	5.60	44	northern	N	19
24-Sep-79	73.37	54.58	A-32	~120	5.70	55	northern	Y	20
18-Oct-79	73.34	54.73	A-20	~120	5.80	70	northern	Y	21
11-Oct-80	73.36	54.82	A-25	~120	5.70	55	northern	N	22
			A-30	~140				Y	
1-Oct-81	73.32	54.55	A-23	>120	6.00	113	northern	N	23
11-Oct-82	73.37	54.34	A-37	>120	5.60	44	northern	Y	24
18-Aug-83	73.38	54.87	A-40	>>120	5.90	89	northern	Y	25
25-Sep-83	73.35	54.38	A-21	>120	5.80	70	northern	Y	26
26-Aug-84			A-100	~110				N	
25-Oct-84	73.37	54.96	A-26	~115	5.90	89	northern	Y	
2-Aug-87	73.29	54.71	A-37A	~95	5.80	70	northern	Y#	
8-May-88	73.36*	54.44*	A-24	>120	5.6*		northern	Y	
4-Dec-88	73.39*	55.00*	A-27	>120	5.9*		northern	N	
24-Oct-90	73.36*	54.71*	A-13N	>>120	5.7*		northern	N	

Notes:

1. Dates, test numbers, venting, and scaled depth of burials (SDOB) from Andrianov and others, 1992.
2. Latitudes, longitudes, magnitudes and yields from Sykes and Ruggi, 1989, except where noted.
3. #Significant venting (containment failure), Andrianov and others, 1992.
4. ##Significant venting (containiment failure), W. Leith, personal communication, 1993: presentation by Adushkin at Center for Seismic Studies, 16 June, 1993.
5. *Data from U.S. Geological Survey, National Earthquake Information Center, 1990a, 1990b.

radioactive inert gases to be a violation of the 1963 LTBT since these leaks do not result in radioactive "fallout," as specified in the Russian version of the treaty[1].

Presumed test locations are plotted on the topographic map in Figure 2 and the geologic map in Figure 7. The Lilwall and Marshall (1986) locations are used in these figures because they are restrained to the mountains on the south side of the strait by using a Joint Epicenter Determination method, as described in their paper. This results in epicenter relocations that are an average of nine kilometers to the east of the ISC locations. The spread of the ISC locations is much wider, with events plotting on both sides of the strait, and two events plotting in the Barents Sea. The extreme right-hand column in Table 2 correlates the Matochkin Shar events in the table with the locations plotted in Figure 7, with the exception of Location 1, which falls beyond the limits of the map.

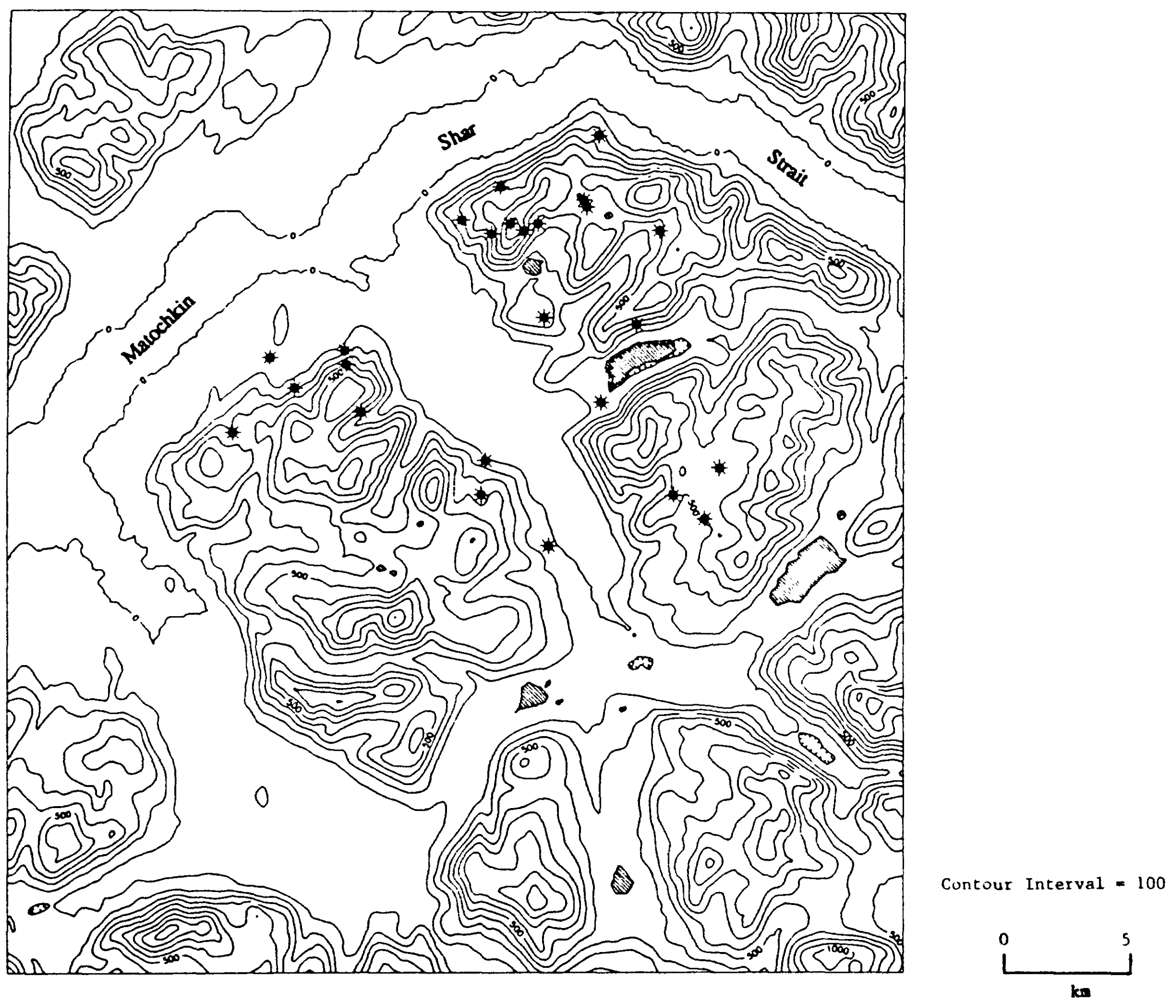


Figure 2. Contour map of a digital terrain model for part of the Matochkin Shar test area, Novaya Zemlya. The controur interval is 100 meters. The stars mark the locations of underground nuclear explosions, as plotted by Lilwall and Marxhall, 1986. Map adapted from Leith and others, 1990.

[1]The text of the Russian language version of the treaty prohibits radioactive "fallout" while the English language version prohibits radioactive "debris." In Russian, "fallout" can be regarded as "sediment," or that material which accumulates and remains after the event. Therefore, radioactive gases released by an event, which circulate and dissipate in the atmosphere, do not violate the LTBT (Andrianov and others, 1992).

The region of the Matochkin Shar test site appears to be characterized by a lack of frequent *natural* seismicity, since only one of the seismic events listed in the USGS database, during the 24 year period from 1964 to 1990, appears to have been an earthquake. This particular event occurred 01 August 1986, with coordinates of 72.91^0 N by 55.86^0 E, at a depth of 10 km, and magnitude of 4.7 mb (National Earthquake Information Center, 1990a). Also, Andrianov and others (1992, p. 126) describes Novaya Zemlya as an aseismic region. For a fuller treatment of seismic investigations of the area, the reader is referred to papers by Burger, Burdick, and Lay, 1986; Burger, Lay, Wallace, and Burdick, 1986; McCowan, Glover and Alexander, 1978; and Sykes and Wiggins, 1986.

Maximum relief in the mountainous area of the northern part of the South Island and a significant part of the North Island, is about 1600 m (Pecherkin and others, 1990, p. 38). The local relief in the area of the Matochkin Shar test site is approximately 650 meters in the mountains along the coast (as measured from a topographic map constructed by registering a SPOT image of the area to a digital terrain model derived from DTED digital terrain data from the U.S. Defense Mapping Agency - see Figure 2). The stars in Figure 2 represent the location of underground nuclear tests, as plotted by Lilwall and Marshall, 1986. The mountain towards the northern end of the test site, in which some tests have occurred, is identified as Mt. Lasareff on maps presented in Holtedahl, 1930 (see also Figure 7).

STRUCTURE

Regional Crustal Structure

Novaya Zemlya lies on the continental shelf, which extends from the mainland's coastline to just north of Franz Josef Land and Severnaya Zemlya (about 400 km north of Novaya Zemlya). On the Barents shelf, west of Novaya Zemlya, deep seismic refraction studies have inferred a continental crust 25 to 35 km thick. This has been confirmed by surface wave studies, which have also inferred an upper mantle with no low-velocity zone and very thick sediment accumulations in the southeast, approaching 10 km (Chan and Mitchell, 1985).

Estimates of the crustal thickness of Novaya Zemlya itself range from about 30 to 45 km in the literature. As seen on recently published Russian maps, presented in Figure 3, the crustal thickness in the area of the southern test site, near Krasino, is indicated to be 45 km on one map (Shipilov and Senin, 1988); in the Matochkin Shar area the crust is indicated to be 40 km thick on another map (Gramberg, 1988). McCowan and others (1978) used Rayleigh-wave dispersion data to infer a crust of about 45 km, between Krasino and Matochkin Shar (see Figure 4). By comparison, the crustal thickness in the Ural Mountains ranges from 37- 50 km (Piwinskii, 1979, p. 33).

Local Structure

The Matochkin Shar test site occurs within a region referred to as the *Mozaichnaya* (Mosaic) tectonic area. This 140 km long by (up to) 45 km wide area is characterized by intensive block movement (Sidorenko, 1970, p. 189). Here, many faults are exposed, which reveal fold structures transverse to their strike. Some faults are of more recent Mesozoic-Cenozoic age, while others may be structures related to Hercynian (middle Paleozoic to early Mesozoic) or Caledonian (early to middle Paleozoic) deformation. There are many shear fractures in the sandy-shaley sequences, along which displacement is either insignificant or absent (Sidorenko, 1970, p. 190). In the Matochkin Shar area, thrust faulting may predominate over folding. Thrust planes, cutting bedding planes, were observed in Mt. Ludlow by Holtedahl's expedition through the strait (Holtedahl, 1930). The minor folding that is often displayed in the Paleozoic rocks is commonly tight, isoclinal, and overturned. In many folds, shale beds are complexly contorted near crests and troughs.

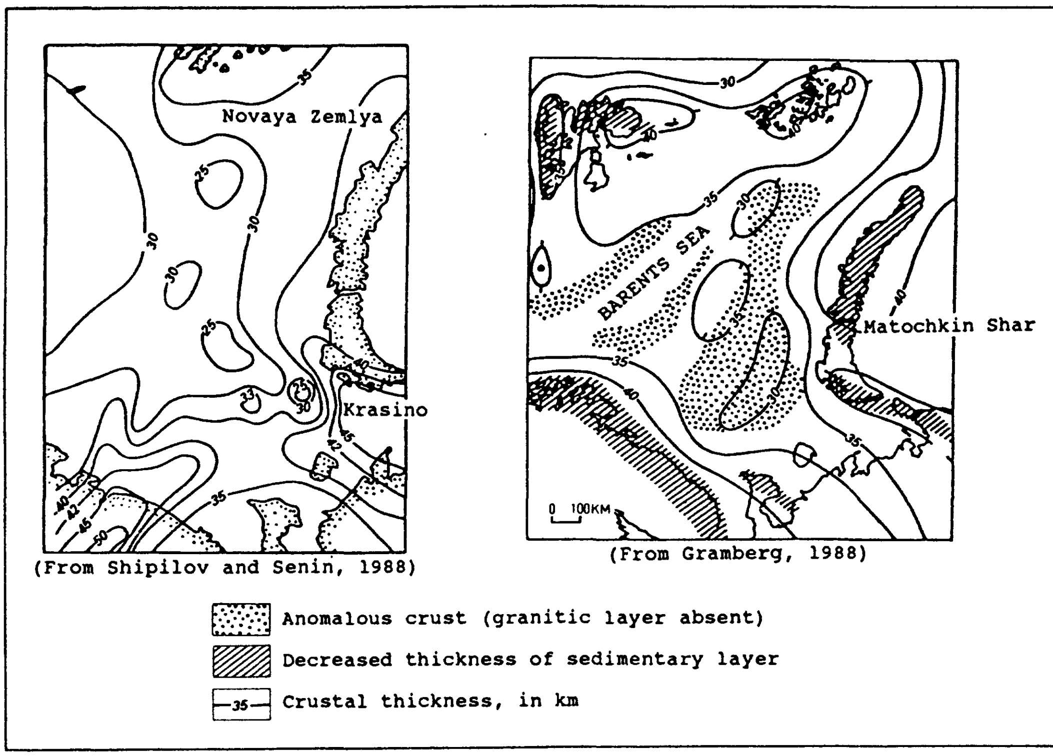


Figure 3. Thickness of the crust in the Barents Sea and surrounding areas, in kilometers. The thickness of the crust in the area of the southern test site is indicated to be 45 km, while it is 40 km thick at the Matochkin shar test site.

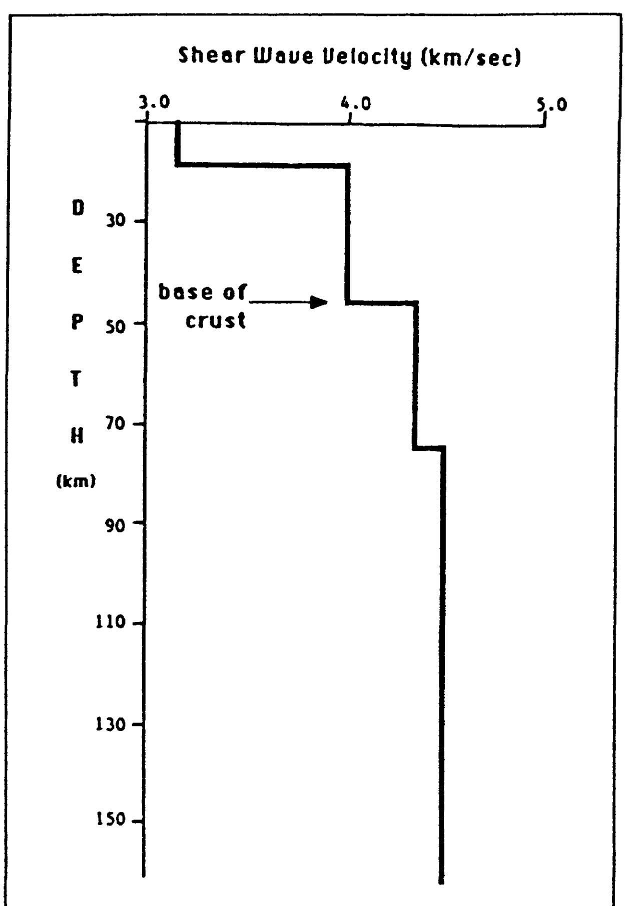


Figure 4.
Crustal and upper mantle shear-wave velocity profile for Novaya Zemlya. From McCowan and others, 1978, p. 1656.

The general nature of the geologic structure is indicated in the cross sections of Figure 5. These diagrams indicate that most of the bedded sedimentary rocks in the Matochkin Shar area are dipping to the northwest, but at Mt. Lasareff, where some underground nuclear testing is believed to have taken place, the sandstone beds comprising part of the mountain are near vertical.

Neotectonics

The primary neotectonic process occurring at Novaya Zemlya is uplift (see Figure 6). The Russian literature estimates more than 1,000 meters of total uplift since mid-Tertiary time at the center of the islands (Nikolayev and Shul'ts, 1959). The most recent component of that uplift is due to glacial isostatic rebound, and appears to account for about 200 meters of the uplift of the islands. The existence, magnitude, and rate of this component of the uplift is inferred by the study of uplifted marine terraces along the present shore line of Novaya Zemlya. These studies indicate uplift rates of about 1 to 1.5 cm/year, which are comparable to Scandinavian uplift rates (Holtedahl, 1930; Pecherkin and others, 1990). However, in Scandinavia, there is evidence both for recent faulting and for low magnitude seismicity associated with the process of glacial rebound. Thus, similar tectonic effects might be expected at Novaya Zemlya, but no data have yet been found to confirm this hypothesis. The earlier (mid-Tertiary) component of the uplift, which accounts for about 800 meters of the present uplift, may be due to erosional isostatic compensation.

Faulting

Faulting follows two main trends on Novaya Zemlya. The principal trend is parallel to the fold axes of the sedimentary beds, generally following the elongate structure of the islands. A second trend runs perpendicular ("cross strike") to the first. Many of the fjords appear to have developed along these weaker cross strike fault or fracture zones, to be subsequently widened by glacial and marine erosion. A major fault (the Main Novozemel'skaya fault) runs along the length of both the South and North Islands, along the western side, generally paralleling the trend of the fold axes. This fault, considered by early investigators to be a result of the late Caledonian (Devonian) orogenic event, has localized the intrusion of the largest granite massif exposed on Novaya Zemlya, known as Mityushev Kamen'. More recent work (Korago and Chukhonin, 1984; 1988) considers the intrusion to be a Precambrian-aged structure. Other smaller Paleozoic- and Mesozoic-aged intrusions occur scattered about on Novaya Zemlya.

The anticlinoria and synclinoria of the North Island are broken up by many high angle thrust faults which dip to the east. The displacement is usually tens, less commonly, few hundreds of meters (Ustritskiy, 1985, p. 40).

Orientation of bays and river valleys is often controlled by faults transverse and diagonal to the general longitudinal structural trend of Novaya Zemlya. Often, geologic structures can be correlated across river valleys or across the strait. Matochkin Shar (as well as Karskiye Vorota - between Novaya Zemlya and Vaygach; and Yugorskiy Shar - between Vaygach and Pai-Khoi) originated along similar transverse faults (Sidorenko, 1970, p. 189-190).

GEOLOGY

The formation of the Novaya Zemlya - Pai Khoi fold system occurred under geosynclinal conditions, at the conclusion of the Baikalian, Caledonian, and Hercynian-early Kimmerian tectonic cycles.

The Russian literature does not contain many detailed descriptions of the rock formations in the immediate region of the Matochkin Shar test site. Consequently, descriptions are used from

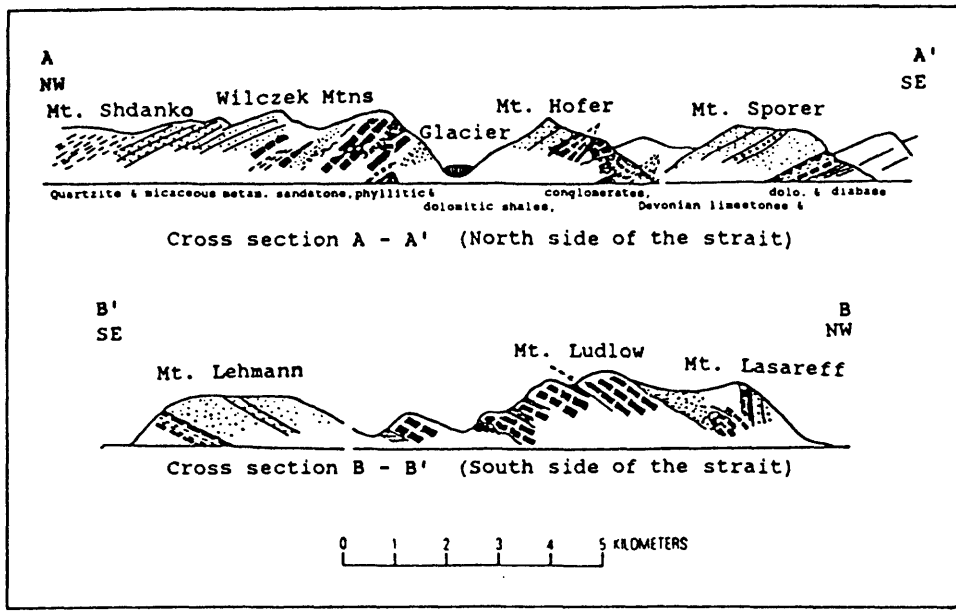


Figure 5. Geologic cross sections on the north side of Matochkin shar (A-A') and the south side (B-B'), in the region of the Matochkin Shar test site. The brick pattern represents limestone and dolomite; the dot pattern sandstone. For locations of the profiles, see the geologic map in Figure 7. From Holtedahl, 1930.

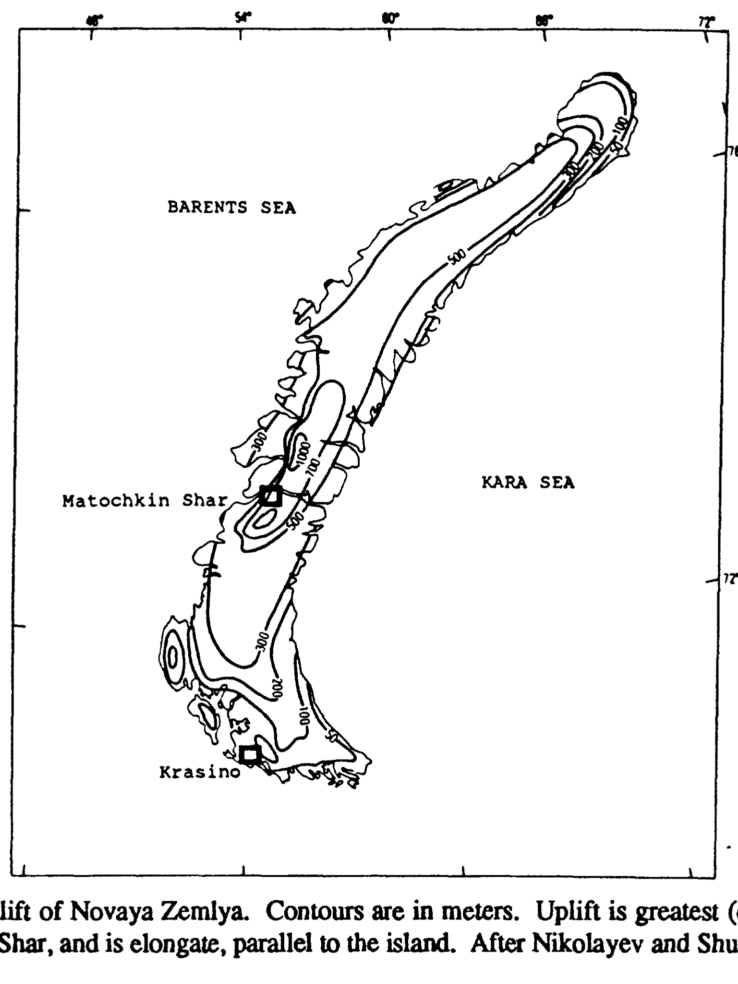


Figure 6. Late Tertiary uplift of Novaya Zemlya. Contours are in meters. Uplift is greatest (over 1,000 meters) near Matochkin Shar, and is elongate, parallel to the island. After Nikolayev and Shul'ts, 1959.

adjacent regions where the same geologic formations occur, to compile representative descriptions of the rocks at the test site. These source regions include Mityushikha, Melkiye, Krestovaya and Sul'meneva Bays; 30, 65, 90, and 115 kilometers north, respectively, and Gribovaya Bay 60 kilometers south of Matochkin Shar, on the west coast. The descriptions of rocks from the Lower Silurian, Ordovician and Cambrian systems are from the Bakan Bay and Pomorskaya Bay areas at the western entrance to Matochkin Shar, which is the only place in the immediate area of interest where these rocks are exposed at the surface.

A composite stratigraphic column (Figure 8) covering the Lower and Middle Paleozoic section, is constructed for the Matochkin Shar area. This column is based on rock descriptions from the various areas described above. The column covers the Upper Devonian (D_3) to Middle and Lower Cambrian (Cm_{1-2}) systems. For completeness, all of the stratigraphic units are described here, even though some are not mapped in the area of immediate interest, as outlined in Figure 7 (e.g., the Lower to Middle Cambrian; the Givetian stage of Middle Devonian; and the Famennian stage of Upper Devonian are not represented on the geologic map).

The age of the exposed bedrock in the test site as outlined in Figure 7, ranges from middle and late Cambrian at Pomorskaya Bay and Cape Matochka at the western end of Matochkin Shar strait, to early and middle Devonian further east. The rocks are metamorphosed and recrystallized to varying degrees, with micas and chlorite replacing some minerals in the clastic rocks. Locally, the bedrock may have a thin cover of unconsolidated material on mountain slopes and tops. Due to the frost action on the bedrock, the exposed rock surfaces on hills and slopes can be very fractured and broken. Particularly when water-saturated, such an unstable mass can become subject to downslope mass movement.

Andrianov and others (1992, p. 42) lists the following geologic criteria used in selecting a location for a nuclear test:

- the absence of faults and fractures in the rock up to a radius of 100 $m/kt^{1/3}$ from the device location
- the gas content of the rock at $1{,}000^0$ C must be $\leq$ 15% of the mass
- the absence of carbonates and "carbonaceous" rocks in the region of the thermal blast (radius $\leq$ 4 $m/kt^{1/3}$)
- the absence of water-bearing horizons that have a high free-water exchange
- the "hydraulic conductivity" of the rocks must be no greater than 10^{-3} to 10^{-4} m/day
- distance of the devise emplacement point from previous detonations

If the Lilwall and Marshall (1986) data are used as the current best estimates of locations of explosion epicenters, then 16 of the 25 epicenters (64 percent) plotted in Figure 7 are located in the Middle Devonian section, described as mostly shale, siltstone, sandstone, quartzite, gritstone, and conglomerate, metamorphosed to schists and quartzites; and possibly some minor amounts of carbonates. Six epicenters (24 percent) are plotted on the Lower Devonian section, described as mostly limestone and dolomite. Only three epicenters (12 percent) plot in the Upper Silurian section, described as sandstone and gritstone. Altogether, 76 percent of the epicenters are located in the metamorphosed clastic rocks. All of these stratigraphic units are described in the sections below.

The rock descriptions below start with the younger Upper Devonian (Fammenian) and end with the older Lower-Middle Cambrian. The source region for each description is given, as well as the thickness of the section in that source region. Limestones and dolomites of the Hercynian-Lower Kimmerian structural complex (late Devonian to late Triassic) have a silica content to 17 percent and graphite content occasionally to 20 percent.

Upper Devonian

D_3fm Famennian (Mityushikha-Krestovaya Bays): Limestone, gray and dark gray, usually thinly laminated, "clean" and dolomitized varieties. Beds of fossiliferous, sandy limestone in upper part of section. Thickness 300 to 400 meters. (Nalivkin and others, 1973, p. 319, 329; Sidorenko, 1970, Table 4).

D_3fr Frasnian (Mityushikha-Krestovaya Bays): Upper part composed of dark gray and light, clayey, fossiliferous limestones; lower part composed of basic extrusives interbedded with quartz sandstone, shale, and fossiliferous limestone. Sandstones contain a small admixture of plagioclase, and are often metamorphosed to "quartzo-sandstone" with preserved relicts of the parent rock (blastopsammitic structure). The sandstones are characterized by a gray or greenish tint. Thickness of (mostly) clastic facies may be up to 1200 meters. (Nalivkin and others, 1973, p. 319; Pecherkin, et. al., 1990, p. 42; Sidorenko, 1970, Table 4).

Middle Devonian

D_2gv Givetian (Matochkin Shar to Sul'meneva Bay): Dark colored clastic-carbonate rocks, locally with intrusions of diabase.

(Mityushikha-Krestovaya Bays): Interbedded black and dark gray shales, with black and dark gray sandstone and fossiliferous limestone. Thickness in Mityushikha-Mel'kaya Bay region is about 700 meters. (Nalivkin and others, p. 319, 326; Sidorenko, 1970, p. 134).

D_2e Eifelian ***TEST FORMATION*** (Northern part of South Island, and North Island): Composed primarily of metamorphosed varieties of shale, siltstone, sandstone, quartzite, gritstone, and conglomerate (thickness of the conglomerates can be measured in terms of hundreds of meters). Rocks are metamorphosed to sericite and chlorite schists, and quartzite.

(Mityushikha-Krestovaya Bays): The upper part of the Eifelian consists of interbedded green or variegated shale, sandstone, quartzite and conglomerate. The conglomerates contain well rounded pebbles to 15 cm, with arkosic gritstone cement. The lower part consists of black to dark gray shale with beds of siltstone and fossiliferous limestone. Thickness in Matochkin Shar to Mityushikha and Krestovaya Bay area is about 700 meters. (Nalivkin and others, 1973, p. 324; Sidorenko, 1970, p. 132-134).

Lower Devonian

D_1 ***TEST FORMATION*** (Matochkin Shar area): Primarily clean and dolomitized bedded limestone, with a large and varied fossil assemblage, especially in the upper part of the section. There is a increasing amount of dolomite and a decreasing number of bioherms downwards in the section. Dolomitized zones can be enriched in bitumen. The Lower Devonian is divided into three horizons (top to bottom):

Val'nevskiy horizon (Possibly Coblenzian and lower Zlichovian stages): Carbonates, mostly limestone, lesser amounts of dolomite. Bioherms and fossils common.

Guba Morzhevoi horizon (Possibly Gedinnian stage, along with Guba Kamenki horizon):

Beds of fossiliferous limestone, increase in amount of dolomite over Val'nevskiy horizon. In the Mityushikha Bay area, consists of black limestone; dolomite is more rare.

Guba Kamenki horizon (Possibly Gedinnian stage, along with Guba Morzhevoi horizon):

Rhythmically interbedded sequence, mostly carbonates among which dolomites and dolomitized limestones dominate. Poorly fossiliferous.

The thickness of the Lower Devonian is not less than 200 meters and up to about 300 meters in the Matochkin Shar area. The apparent thickness of this unit increases to about 400 meters on the south shore of Griboviy Bay, which is located about 35 kilometers south of the test site (Nalivkin and others, 1973, p. 317-322; Sidorenko, 1970, p. 131-132). The thickness of this formation is insufficient to contain the events that are mapped on this unit in Figure 7 (epicenters no. 7, 8, 10, 11, 21, 23). Because Figure 7 shows formations as mapped on the ground surface, there is some uncertainty as to the actual, underlying formations in which the tests were probably emplaced, but they may have been something other than carbonate rocks.

Upper Silurian

S_2ld Ludlovian ***TEST FORMATION*** (Mityushikha and Krestovaya Bays region): Upper Ludlovian: Grebenskaya horizon, composed mostly of sandstone, possibly some shale and limestone with variable fossil assemblage. Thickness is about 350 meters. Lower Ludlovian: Composed of sandstone, gritstone, possibly some shale, rare fossiliferous marl. Thickness about 350 meters. The Silurian to early Devonian sandstones and quartz-sandstones are often sheared. (Sidorenko, 1970, p. 129; Table 3).

Lower Silurian

S_1w Wenlockian (Middle Novaya Zemlya structural-facies zone; Mityushikha and Krestovaya Bays region): Few examples of the Wenlockian stage are seen in this area. Described as fossiliferous limestone, with thickness about 100 meters. (Sidorenko, 1970, p. 127; Table 3).

S_1ln Llandoverian (Pomorskaya Bay [western entrance to Matochkin Shar]): Interbedded conglomerate and sandstone, with chlorite and sericite schist, basic extrusives and tuffs. Thickness 500 meters. (Sidorenko, 1970, p. 114, section V).

(Ruch'evaya Bay, north shore Matochkin shar): Interbedded conglomerate and sandstone beds, some dolomite, shale, phyllite; chlorite and sericite schists. Possibly includes some Upper Silurian rocks. (Sidorenko, 1970, p. 114, section VI).

(Mityushikha and Krestovaya Bays region): Fossiliferous limestone and dolomite, thickness more than 150 meters. (Sidorenko, 1970, p. 127; Table 3).

Ordovician

O (Matochkin Shar area, western entrance, south coast): Undifferentiated, composed of schistose, conglomeratic beds, possibly tuffaceous to some extent, often with red, green, yellow colors; coarse sandstone or fine-grained conglomerate (with chlorite and secondary muscovite), shale and phyllite. Some highly contorted limestone described in Cape Stolbovoi area, as well as local occurrences of strongly altered basic extrusive rocks (porphyry and others). Thickness about 350 meters. (Holtedahl, 1930, plate 33, Figure 5; Sidorenko, 1970, p. 114 , section V; p. 115).

(Ruch'evaya Bay, north shore of Matochkin Shar): Thick sequence of metamorphosed polymictic sandstone, with mostly calcareous cement. Thickness 350 meters. (Sidorenko, 1970, p. 114, section VI; p. 115).

Upper Cambrian

Cm_3kr Karpinskiy fm (Pomorskaya Bay, Matochkin Shar): Composed of dark foliated shale, with interbedded siltstone, quartzite-like sandstone, and lenses of sandy, fossiliferous limestone. Holtedahl also describes quartz-schists. Conformably underlain by the Snezhnogorskaya formation. Thickness 260 to 310 meters. (Solov'ev and others, 1986, p. 74, Holtadahl, 1930)

Middle Cambrian

Cm_2sn Snezhnogorskaya fm (Pomorskaya Bay, Matochkin Shar): Variegated sandstone conformably overlying the Astaf'evskiy formation. Alternating with subordinate quartz sandstone and arkosic gritstone with thin interbeds (to three meters thick) of siltstone and phyllitic-like shales Fine-grained quartz conglomerate present, also sandstone beds with small nodules or spines of phosphate. Sandstone and shale is somewhat metamorphosed. Surfaces of layered rocks often show ripple marks, desiccation crack, and worm burrows (?). Thickness 290 to 320 meters. (Solov'ev and others, 1986, p. 70).

Middle - Lower Cambrian

$Cm_{1-2}as$ Astaf'evskiy fm (Pomorskaya Bay, Matochkin Shar): Phyllitic-like schist and siltstone, fossiliferous. Thickness more than 120 meters. (Solov'ev and others, 1986, p. 69).

Igneous Rocks

Two large granitic intrusions are shown on geologic maps, in the area of Matochkin Shar. They are located in the Lutke Mountains, about 15 km west of the mouth of the Shumilikha River, and Mityushev Kamen', approximately 20 km to the northwest; both intrusions occur on the North Island. Mityushev Kamen' is the largest granitic intrusion mapped on Novaya Zemlya.

Korago and Chukhonin (1988) apparently consider the granites of Mityushev Kamen' and Lutke Mountain to be separate outcrops of the same intrusion, the Lutke Mountains being the southernmost outcrop. Overall, the intrusion consists of four outcrops, extending about 40 km in a north east direction, with outcrop widths up to 3-8 km. The main body of the Mityushev Kamen' intrusion is more than 50 square kilometers in area, with a thickness up to 5 km. It is fractured and faulted, with the faults dipping steeply to the east. The faults are expressed as zones of crushing or shearing, schistosity, cataclasis, and mylonitization. The dominant lithology is coarse-grained alaskite. This rock type also makes up part of the Degelen Mountain intrusion in Kazakhstan (Chirkov, 1985, p. 131), where nuclear testing has been conducted in tunnels (Bocharov and others, 1989, p. 211). The rock is high in silica (75 percent), low in iron and manganese, with total alkali around 9 percent, and with limited occurrence of potassium. It is composed of large quartz grains (20-35 percent), feldspar (microcline-perthite, 15-60 percent; acidic plagioclase, 0-15 percent), and chloritized biotite (up to 3-5 percent), cemented by a finely-crushed aggregate of feldspar and quartz, with subordinate amounts of biotite of a strong green tint, ore minerals, and sericite. Accessory minerals include apatite, sphene and zircon; more rarely, orthite and fluorite. The cataclastic texture of the rock reflects the mechanical stresses imposed on it during metamorphism. Locally, plagiogranite or granodiorite occurs at the margins of the granitic intrusions, along fractures. These are gneissic rocks with striae of biotite and, occasionally, some amphibole. Muscovite, when encountered, is usually in association with biotite.

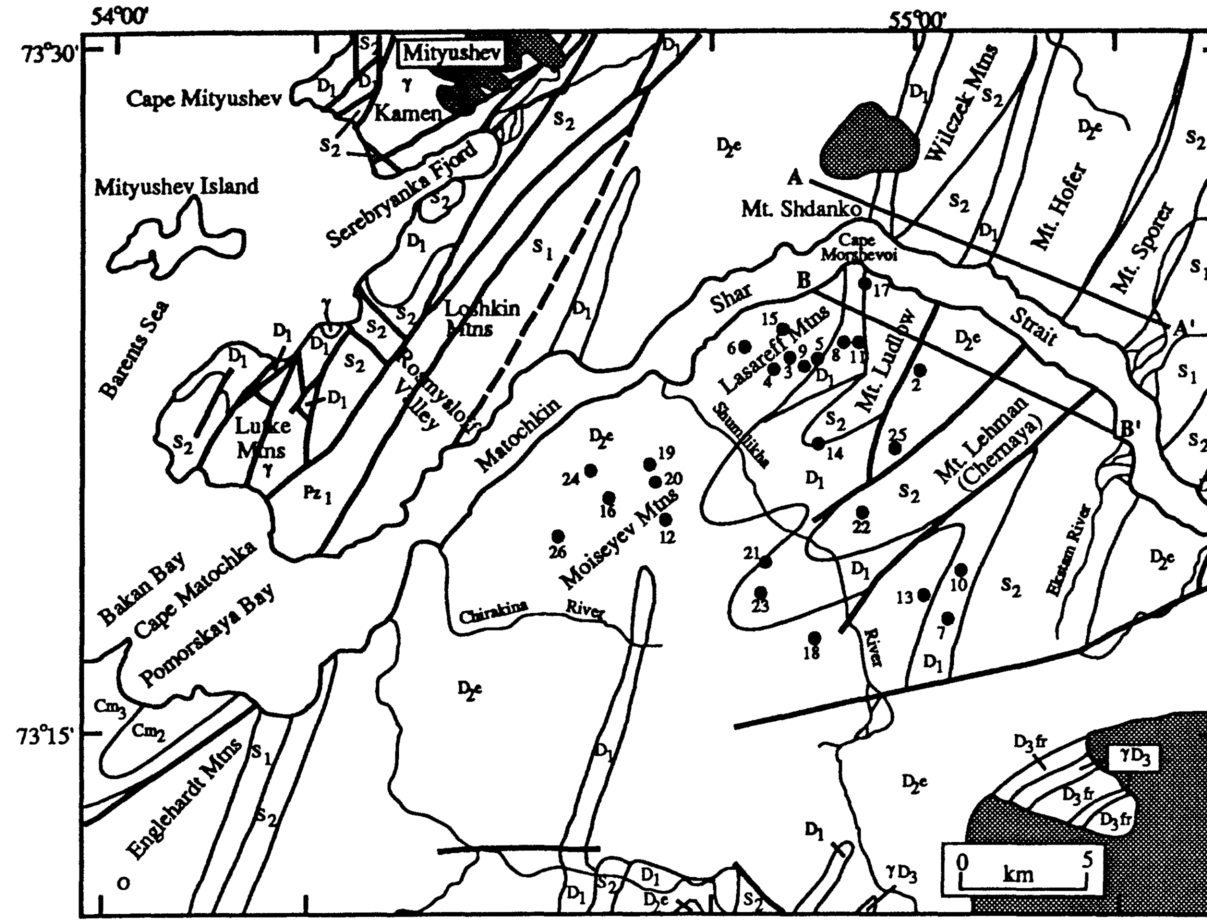
The Lutke Mountains are, at least in part, a laccolithic igneous intrusion which occupies an area of about 17 square kilometers. The dominant lithology is coarsely-porphyritic amphibole-biotite plagiogranite-granodiorite, containing quartz (20-30 percent), sericitized oligoclase (40-60 percent) and microcline-perthite feldspars (up to 15 percent), biotite (5-20 percent), and amphibole (0-15 percent). The phenocrysts (up to 4 cm) are composed of microcline, microcline-perthite and, more rarely, albite. The peripheral zone is made up of granodiorite, described by Sidorenko (1970, p. 168) as coarse-grained, grayish green and gray granite with a gneissic texture. It is composed of quartz, plagioclase (from albite-oligoclase to oligoclase-andesine) and potassium feldspar (mostly microcline, some orthoclase), with lesser amounts of micas (biotite and muscovite) and hornblende. Secondary minerals include chlorite, epidote, and zoisite, among others. It is characterized by a cataclastic structure, with a relict porphyritic texture.

Associated with the intrusions are small aplite and thin (up to 30 cm) pegmatitic veins. Lamprophyre veins occur in the Lutke Mountains. Larger dikes range from several to 60 meters in thickness. There are also diabase and gabbro-diabase dikes in the general area (Sidorenko, 1970, p. 169).

The Mityushev complex has been considered to be of Devonian or even early Mesozoic age. However, based on U-Pb dating of the zircon, Korago and Chukhonin (1984; 1988) showed the absolute age of the granite to be Precambrian (Proterozoic) at 680 to 735 million years ($\pm$ 50 million years).

HYDROLOGY

Ground water occurs at shallow depths in the unconsolidated deposits and in fractures in hard rock. In the unconsolidated sediments, the water table in the summer months generally occurs at depths of 0.5 to 2 meters. In the mountains, the ground water table may occur at about 3 meters, possibly less. During the cold months, ground water is frozen except in taliks (a talik is a layer of unfrozen ground above, within, or below the permafrost). In the warm months (July-September), ground water is available from the thin active layer, which acts as a perched water table. Downward percolation of the ground water is limited by permafrost. The presence of permafrost and the low evaporation rates result in most of the rainfall and snowmelt becoming surface runoff. Deeper ground water aquifers probably occur beneath the permafrost but, due to restricted circulation, the water here is likely to be more highly mineralized.



Legend

γ	Precambrian: granitic rocks (mostly alaskite)
D_3fr	Upper Devonian (Frasnian): limestone, shale, sandstone, conglomerate
γD_3	Upper Devonian: diabase and gabbro-diabase
D_2e	Middle Devonian (Eifelian): mainly clastics, some carbonates, thickness ~700 m
D_1	Lower Devonian: mostly limestone, lesser amounts of dolomite. Thickness 200 - 300 m
S_2	Upper Silurian: sandstone and gritstone. Thickness ~350 m
S_1	Lower Silurian: limestone, dolomite, with some clastic materials. Thickness 600 - 700 m
O	Ordovician: basal conglomerate, overlain by sandstone. Thickness ~700 m
Cm_3	Upper Cambrian: quartzitic sandstone, phyllite, schist/slate, some conglomerate. Thickness ~500 m
Cm_2	Middle Cambrian: phyllite, argillaceous and calcareous schists/slates, some conglomerates. Thickness ~450 m
Pz_1	Lower Paleozoic, undifferentiated: mostly clastics

Snow, ice fields

Contacts

Faults

A——A' Line of cross section (see Figure 5)

18 Underground nuclear test epicenter, as plotted by Lilwall and Marshall, 1986

Figure 7. Geologic map of the region of the Matochkin Shar test site, Novaya Zemlya. The location of the two profiles of Figure 5 are indicated on the map. The dots represent the locations of underground tests, as plotted by Lilwall and Marshall, 1986. Map after Sidorenko, 1970; and Holtedahl, 1930.

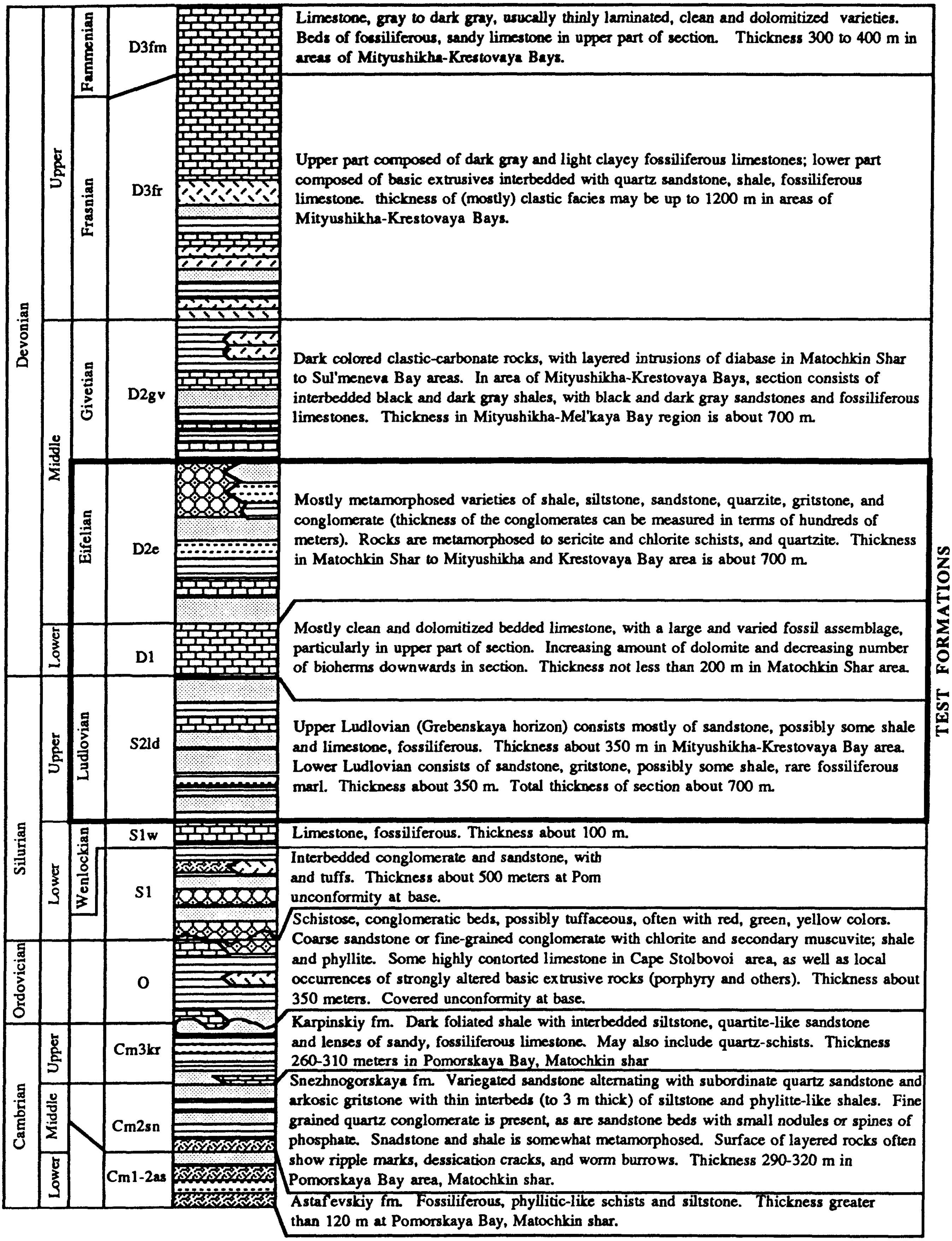


Figure 8. Composite stratigraphic column for the area of the Matochkin Shar test site, Novaya Zemlya. The test beds are composed of the D_2e, D_1, and S_2ld stratigraphic units.

METAMORPHISM

Regional metamorphism ranges from"not evident to weakly evident" in belts along both the east and west coasts, to the greenschist facies in the central part of the island (Holtedahl, 1930, plate 38), where the Matochkin Shar test site is located. The occasional descriptions in the Russian literature, of quartzite, marble, and chloritized and sericitized shale in the stratigraphic sequence also suggests that the rocks are probably better described as low-grade metamorphic rocks, rather than unaltered sedimentary rocks. In this area, the term "shale," as used in the Russian literature, may actually be referring to chlorite or sericite schists, of the greenschist facies, reflecting conditions of low temperature (300^0 to 500^0 C) and, commonly, high shearing stress. Russian data presented at a Canadian symposium on the environmental impact and containment of nuclear weapons tests cites a density of 2.7 g/cc for sandstones and shales, and velocities of 5.0 to 5.3 km/sec, presumably for sandstones and shales, at the Matochkin Shar test site on Novaya Zemlya (Mikhailov and Chernyshev, 1991). These numbers are high for undeformed shales, but are consistent with compaction and regional metamorphism of these rocks to the greenschist facies.

PERMAFROST

Novaya Zemlya falls within the zone of continuous permafrost. The thickest permafrost can be found in the higher mountains. At elevations up to 500 meters, permafrost in the Matochkin Shar area may be as much as 100 meters thick in valleys and 400 meters thick on watersheds. At elevations to 1,000 meters, the thickness may increase to as much as 600 meters in the mountains. The active layer is only 0.3 to 3 meters thick, depending on the soil type and condition, and the vegetation cover, and thaws in the two to three months of warmer temperature (July-September). The elevation and topography of the base of the permafrost is not known; the base may be a subdued reflection of the topography of the land surface. The base of the permafrost may extend to depths below sea level in some areas, particularly along the strait. The stable ground temperature (at that horizon in which seasonal temperature fluctuations cease) ranges -5^0 to -7^0 C at 400 to 1,000 meters elevation; at the 100 to 500 m elevations, the stable temperature is -3^0 to -5^0 C (Kondrat'eva, 1978, p. 45).

The frozen zone can be subdivided into three horizons, according to Pecherkin (Pecherkin and others, 1990, p. 46), distinguished essentially by their different electrical properties and ice content. The upper horizon consists of Quaternary deposits and disintegrated bedrock, with a high ice content and electrical resistivity. The middle horizon is confined to the contemporary weathering zone of the bedrock, which may occur to depths of 50 to 70 meters (see also Trepettsov and others, 1978, p. 152). Here, fractures and voids in the rock are almost completely ice-filled, but even so, the ice content of the rock is only tenths to a couple of percent. The lower horizon likely forms the bulk of the frozen sequence in the mountainous areas, where the permafrost is thickest. This horizon is characterized by an extremely low ice content and the presence of fractures in the rock which contain easily soluble salt, mostly mirabilite (decahydrate sodium sulfate).

A frost-shattered zone very likely exists at least to the depth of the active layer, and possibly extends to a few tens of meters into the permafrost zone as well. Within the active layer, thermal expansion of the rock and ice expansion contribute to the fracturing and weathering of the bedrock, thereby reducing its strength. Solifluction, thermokarst, and landslides are possible, due to the fluctuating temperatures, occurrence of slopes and escarpments, presence of plastic (frozen) layers, and the high moisture content of the soil. In finer-grained soils, about 30 percent of the water in the soil may remain unfrozen due to capillary action, even at temperatures several degrees below freezing. Thus, within a single soil mass, ice could form in the larger voids while water could remain in the smaller voids at the -3 to -7^0 C temperatures found in the permafrost (Johnson, 1981, p. 74).

In a permafrost area with high relief and a deep (main) water table, such as is postulated for Matochkin Shar, the ice-saturated permafrost zone itself may contain air voids (as gas "impurities" taken up in the open crystalline structure of ice-I). Below the permafrost zone, and above the main water table, a non-frozen zone may occur, also containing abundant air-filled voids.

A recent Russian paper (Sedov and Luchinina, 1988, p. 149, 152) dealing with the seismic wave field in permafrost conditions suggests that rocks in the permafrost zone have better coupling characteristics than "thawed or thawing" rocks, due to high acoustic rigidity. The same paper also says that decreasing the thickness of frozen, friable deposits increases the frequency of the P wave.

KARST

Karst dissolution may be occurring within the carbonates, within the active layer and in areas where taliks occur, which have access to the atmosphere ("open" taliks). Such taliks can occur under larger rivers, deeper bays, and the strait itself, or in zones of deep regional faults, which act as zones of thermal conductivity. (One such fault, the Novozemel'skaya fault, cuts both islands, about 20 km west of the Shumilikha River). Taliks under lakes can be 30 to 35 meters thick, containing sulfate-bicarbonate-calcium-sodium water throughout the year (Percherkin and others, 1990, p. 47).

Paleo-karst, developed before the Pleistocene, may possibly exist deeper in the carbonates, well within the permafrost. However, any voids within the permafrost layer will be ice filled, the exception being the rare talik. Within these "closed" taliks, dissolution of carbonates is probably not taking place due to restricted circulation of the (presumably) highly mineralized water and an effective lack of a renewable CO_2 supply.

Descriptions suggestive of carbonate dissolution are encountered for rocks on the west coast of the North Island, in the area of the Gorboviy Islands (located approximately 325 km north along the coast, from Matochkin Shar). Here, part of the stratigraphic section is described as 380 meters of "porous and brecciated" gray Lower Carboniferous (Visean) limestone (Sidorenko, 1970, p. 143). On the South Island, porous limestone is described in a recent publication (Pecherkin and others, 1990, p. 42) to a depth of several hundred meters. The dimensions of the pores here do not exceed several millimeters in diameter, and they are often filled with calcite. In spite of these rare descriptions of secondary porosity development, there is no unequivocal evidence in the literature surveyed to date, for the existence of very large caverns in the Matochkin Shar area of Novaya Zemlya, with the potential to partially decouple a large (greater than 150 kt) nuclear explosion. Data presented in Stevens and others (1991) indicate that a fully decoupled explosion as small as 1.5 kt requires an air-filled spherical cavity 64 meters in diameter. In view of the lack of evidence in the literature for large, well developed karst-cavern systems in the carbonates of Novaya Zemlya, a cavity of 64 meters diameter is not anticipated. It cannot be ruled out, however, that voids a fraction of this size may exist, which may have some potential to partially decouple an explosion much smaller than the 150 kt ceiling defined by the TTBT and PNET. Such voids would be ice-filled if they occur within the permafrost zone; they may conceivably be air- or water-saturated if they occur below the base of the permafrost.

PHYSICAL PROPERTIES

Until recently, physical property data specifically for Matochkin Shar were lacking in the literature, therefore estimates of properties were initially based on studies of similar lithologies in the Ural Mountains and the Pechora region on the mainland. More recent investigations (Pecherkin and others, 1990) present some very limited data on rocks from the South Island of Novaya Zemlya which are consistent with the mainland analog values. Limited, generalized data for Novaya Zemlya are also published in Andrianov and others, 1992.

The physical properties data on Novaya Zemlya from Pecherkin and others (1990, p. 42) indicate that, in general, the clastic rocks of the Caledonian complex (Ordovician to middle Devonian) are resistant to weathering and are characterized by a high (bulk) density of 2.55 to 2.60 g/cm^3. Early Carboniferous limestone from the South Island, from 9-17 meters depth, has a grain density of 2.65 g/cm^3 (three measurements), bulk density of 2.63 g/cm^3, and uniaxial compressive strength of 87 MPa (water saturated). The limestone underwent 50 freeze/thaw cycles with no change in strength. Limestone samples collected from the surface of the South Island have a bulk density of 2.61 to 2.65 g/cm^3, water absorption of 0.39 to 0.20 %, compressive strength (air-dried) to 68 - 96 MPa, water saturated to 68-82 MPa. These reported densities, and particularly the compressive strengths, are lower than the estimated values given in Table 3. The estimated properties in Table 3 should be regarded as generic values representative of competent, unfractured samples of the rock types listed. The porosities were constrained to 2 percent or less to take into account limited statements by the Russians (Leith, 1993, personal commumication), as well as the limited data in Pecherkin and others (1990) that the porosities for the rocks on Novaya Zemlya are "less than 2 percent" or "less than a few percent." The generalized data from Andrianov and others (1992, p. 126) are included at the base of Table 3. In addition, this source indicates that the moisture content of the rocks reach 1%, and the gas content 15%.

Table 3. Estimated Physical Properties

Lithlogy	Grain density (g/cc)	Dry bulk density (g/cc)	Porosity (%)	Compressive strength (MPa)	Vp (km/sec)
Sandstone	2.72	2.67	2	250	6.0
Conglomerate	2.72	2.58	5	80	5.5
Limestone	2.72	2.67	2	175	6.0
Dolomite	2.81	2.67	5	150	5.5
Marble	2.75	2.74	0.5	200	6.0
Quartzite	2.66	2.63	1	300	6.0
Phyllite	2.81	2.78	2	140	5.5
Schist	2.77	2.74	1	300	6.0
Slate	2.80	2.74	2	145	5.5
Sandstone*					
Siltstone*		2.5-2.7			2.2-5.3
Shale*					

*From Andrianov and others, 1992, p.126

Papers by Mellor (1971) and Timur (1968) discuss tests run on the mechanical and seismic properties of Berea Sandstone, Indiana Limestone, Barre Granite, and black, siliceous shale (composed mostly of amorphous silica and chert), under frozen conditions. All four of these lithologies are represented on Novaya Zemlya. The papers show that the strength of unfrozen rock is a function of the rock's water content. Higher water contents result in decreased compressive and tensile strength, such that the strength of water-saturated (unfrozen) rock can be as little as 75 percent of the strength of dry rock. Additionally, the compressive and tensile strength of saturated rock increases significantly upon freezing; the strength of saturated, frozen rock is about twice that of unsaturated, frozen rock. Seismic velocity of rocks and soils is also influenced by temperature. The compressional velocity in saturated, porous rock increases dramatically with a decrease in temperature. Upon freezing, the velocity in saturated carbonate rock increases by 24 to 31 percent, and by 23 to 51 percent in saturated sandstone.

Because increased porosity weakens rocks, induced fracturing in a dry, porous, weaker limestone would extend to greater distances than it would in the same rock, in which the porosity is ice-supported[2] (Robertson, 1989). Under this scenario, explosion-induced fracturing in porous carbonate rock above the permafrost table may be more extensive than fracturing induced in the same rock within the permafrost zone. Robertson (1989, p. 5) suggests that dense limestone (or porous limestone, saturated with ice) could have a strength approaching that of granite, (or, could even be stronger) and might also have a similar fracturing pattern. At Matochkin Shar, the undisturbed bedrock below the frost-shattered and weathered zones is low-porosity rock with low ice content, thus the strengths and velocities of the bedrock are probably not significantly affected by the occurrence of permafrost.

In a nuclear explosion, an effect similar to strain hardening may occur, in which the shock wave may act to moderately increase the confining pressure in the far-field zone of fracturing, thereby increasing the compressive strength of the rock two to five times (Robertson, 1989, p. 2). Rzhevskiy and Novik (1971, p. 78) also state that the strength of a fine-grained sandstone will increase with temperatures up to 800^0 C. Also to be considered in a nuclear explosion are the effects of vaporization of ice and water, the generation of CO_2 during the vaporization of limestone, and the effect of potential phase changes in limestone at high pressures.

SUMMARY AND CONCLUSIONS

The site at Matochkin Shar, Novaya Zemlya, is the only presently declared underground nuclear testing area in the former Soviet Union. Between 1964 and 1990, 36 underground tests have been conducted at this site, averaging only one or two tests per year in the late summer or fall. The Matochkin Shar site has not been as active as the test sites in eastern Kazakhstan, which were deactivated in August 1991. The maximum estimated yield for a test at Matochkin Shar is about 2.1 mt.

Underground nuclear testing at the Matochkin Shar site occurs in low-porosity, metasedimentary, fractured and faulted rocks in a permafrost environment; conditions under which the U.S. has no previous test experience. The majority of tests appear to have been conducted in clastic rocks, though some mapped test epicenters are located on stratigraphic units composed mostly of carbonates. In spite of scaled depths of burial similar to those used at the U.S. test site, a large number (72 percent) of tests at Matochkin Shar resulted in seepage of radioactive inert gases

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[2]In the lower pressures and temperatures of the far-field zone of a nuclear explosion, limestone tends to act brittle, rather than ductile (as it does under high pressures and temperatures). Some of the energy of a shock wave is spent in collapsing pores as the wave passes through a high porosity, dry limestone; some is spent in inducing fractures.

into the atmosphere, suggesting that the testing media do not provide reliable, complete containment of radioactive explosion products.

REFERENCES

Andrianov, K. N., Bazhenov, V. N., Vyskrebentsev, V. V., Doskoch, Ya. Ye., Dubasov, Yu. V., Dumik, V. P., Zolotukhin, G. Ye., Ivanov, V. I., Karimov, V. I., Kasatkin, V. V., Kaurov, G. A., Kozlov, Ye. P., Krasilov, G. A., Krivokhatskiy, A. S., Kudryavtsev, G. G., Kulikov, V. I., Maltsev, A. L., Matushenko, A. M., Mikhailov, V. N., Myasnikov, K. V., Pichugin, A. V., Ramzayev, P. V., Safronov, V. G., Strukov, V. G., Filippovskiy, V. I., Filonov, I. P., Kharitonov, K. V., Tsyrkov, G. A., Chernyshev, A. K., Chugunov, V. V., and Shipko, Yu. Ye., 1992, Yadernye vzryvy v SSSR, vyp. 1, Severnyi ispitatel'nyi poligon, spravochnaya informatsiya (Nuclear explosions in the USSR, vol. 1, Northern test site, information handbook), Moscow, 195 p.

Belikov, B. P., 1961, Uprugiye i prochnostnye svoista gornykh porod (Elastic and strength properties of rocks), *in* Issledovaniya fiziko-mekhanicheskikh svoistv gornykh porod (Studies of the physical-mechanical properties of rocks): AN SSSR, Moscow, vyp. 43, p. 47-110.

Bocharov, V. S., Zelentsov, S A., and Mikhailov, V. N., 1989, Kharakteristiki 96 podzemnykh yadernykh vzryvov na Semipalatinskom ispytatel'nom poligone (Characteristics of 96 underground nuclear tests at the Semipalatinsk test site): Atomnaya Energiya (Atomic Energy), T. 67, Vyp. 3, September, p. 210-214.

Burger, R. W., Lay, T., Wallace, T. C., and Burdick, L. J., 1986, Evidence of tectonic release in long-period S waves from underground nuclear explosions at the Novaya Zemlya test sites: Bulletin of the Seismological Society of America, v. 76, no. 3, pp. 733-755.

Burger, R. W., Burdick, L. J., and Lay, T., 1986, Estimating the relative yields of Novaya Zemlya tests by waveform intercorrelation: Geophysical Journal of the Royal Astronomical Society, v. 87, Blackwell Scientific, p. 775-800

Chan, W. W., and Mitchell, B. J., 1985, Surface wave dispersion, crustal structure, and sediment thickness variations across the Barents shelf: Geophysical Journal of the Royal Astronomical Society, no. 80, p. 329-344.

Chirkov, V. G., (ed.), 1985, Varistsiiskii granitoidnyi magmatizm Kazakhstana (geologiya, formatsii, geneticheskiye modeli) (Variscan granitoid magmatism of Kazakhstan [geology, formation, genetic models]): VSEGEI, Leningrad, "Nedra," 251 p.

Glazovskiy, A. F., 1989, Vzaimodeistviye lednikovykh pokrovov s lozhem v predelakh materikovykh okrain (Ice sheet-bedrock interaction on the continental margins): Mezhdyvedomstvennii geofizicheskii komitet AN SSSR, Moscow, 121 p.

Gramberg, I.S., (ed.), 1988, Barentsevskaya shel'fovaya plita (Barents shelf platform): Trudy, PGO Sevmorgeologiya, T. 196, "Nedra", Leningrad

Holtedahl, O., (ed.), 1930, Report of the scientific results of the Norwegian expedition to Novaya Zemlya, 1921: Det-Norske Videnskaps-Akademi, Oslo.

Johnston, G. H., (ed.), 1981, Permafrost, engineering design and construction: John Wily and Sons, 540 p.

Kondrat'eva, K. A., 1978, Glacial thickness and cryolithozones of Novaya Zemlya: mapping on a scale of 1:2,500,000: Moscow University, Geology Bulletin, (Vestnik Mosk. Univers. Geol.), v. 33, no. 6, p. 57-69 (Translated by Allerton Press, trans. p. 40-49).

Kondratov, A. B., and Malinin, A. G., 1984, Issledovaniye fiziko-mekhanicheskikh svoistv porod Ural'skikh rossypnykh mestorozhdenii primenitel'no k zadacham shakhtnovo stroitel'stba (Study of physical-mechanical rock properties of Ural placer deposits for the purpose of mining engineering), *in* Inzhenernaya Geologiya (Engineering Geology), v. 6: "Nauka", Moscow, p. 42-50.

Korago, Ye. A., and Chukhonin, A. P., 1984, Novye dannye o geologicheskom stroenii i vozraste granitoidov massiva Mityushev kamen' (Novaya Zemlya) (New data on the geologic structure and age of granitoids of the Mityushev kamen' massif, Novaya Zemlya): Doklady ANSSSR, v. 277, no. 2, July, p. 445-448.

Korago, Ye. A., and Chukhonin, A. P., 1988, Granitoidnye formatsii Novoi Zemli (Granitoid formations of Novaya Zemlya): Izvestiya, AN SSSR, Moscow, Seriya Geologicheskaya, no. 10, October, p. 28-35.

Leith, W., Matzko, R., Unger, J., and Simpson, D. W., 1990, Geology and image analysis of the Soviet nuclear test site at Matochkin Shar, Novaya Zemlya, U.S.S.R: Proceedings, DARPA/AFGL Seismic Research Review., U.S. Air Force, Cambridge, 8 p

Lilwall, R. C., and Marshall, P. D., 1986, Body wave magnitudes and location of Soviet underground explosions at the Novaya Zemlya test site: Atomic Weapons Research Establishment, AWRE Report No. O-17/86

Ludwig, W. J., Nafe, J. E., and Drake, C. L., 1970, Seismic refraction, *in* A. E. Maxwell, ed., The sea, ideas and observations on progress in the study of the seas, v. 4, New concepts of sea floor evolution, Part I: Wiley - Interscience, p. 53-74.

Lydolph, P. E., 1977, Climates of the Soviet Union, v. 7 *of* World Survey of Climatology: Elsevier, New York, p. 392

McCowan, D. W., Glover, P. and Alexander, S., 1978, A crust and upper mantle model for Novaya Zemlya from Rayleigh-wave dispersion data: Bulletin of the Seismological Society of America, v. 68, no. 6, p. 1651-1662.

Mellor, M., 1971, Strength and deformability of rocks at low temperatures: Cold Regions Research and Engineering Laboratory (CRREL), US Army Corps of Engineers, Hanover, New Hampshire, Research Report 294, (MAY), 73 p.

Mel'nikov, N. V., Rzhevskiy, V. V., and Protod'yakonov, M. M., (eds.), 1975, Spravochnik (kadastr) fizicheskikh svoistv gornykh porod (Handbook [cadaster] of the physical properties of rocks): "Nedra," Moscow, 277 p.

Mikhailov, V. N., and Chernyshev, A., 1991, Novaia Zemlia, untitled report, general region characteristics; and, On the preparation for conducting nuclear explosions at the Northern test site; As given to the Canadian Center for Arms Control, translated by E. Bykowskiy, SRF/DNA, 66 p.

Nalivkin, D. V., Rzhonsnitskaya. M. A., and Markovskiy, B. P., 1973, Stratigrafiya SSSR, Devonskaya Sistema, kn. 1 (Stratigraphy of the USSR, Devonian System, Book 1): Nedra, Moscow, (VSEGEI), 520 p.

Nikolayev, N. I., and Shul'ts, S. S., (eds.), 1959, Karta noveyshey tektoniki SSSR (Neotectonic map of the USSR), scale 1:5,000,000: AN SSSR.

Pecherkin, I. A., Dubeikovskiy, S. G., and Bochkarev, V. P., 1990, Inzhenernaya geologiya SSSR, Ural, Taimir i Kazakhskaya skladchataya strana (Engineering geology of the USSR, Ural, Taimir, and Kazakh folded region), Moscow: Nedra, p. 37-49

Piwinskii, A. J., 1979, Deep structure of the Earth's crust and upper mantle in the USSR according to geophysical and seismological data, Part I: Lawrence Livermore Laboratory, UCID-18099, 69 p.

Robertson, E. C., 1989, Report on explosion effects on granite and limestone in dry-warm and wet-cold environments (unpublished manuscript).

Rzhevskiy, V., and Novik, G., 1971, The physics of rocks: Mir, Moscow, (translated by A.K. Chatterjee), 320 p.

Samoilovich, R. L., and Yermolaev, M. M., (eds.), 1937, The Novaya Zemlya excursion, International Geological Congress, XVII Session, USSR, Part I (General) and Part II (Routes): Leningrad, Part I - 134 p., Part II - 117 p.

Sedov, B. M., and Luchinina, A. V., 1988, Pole seismicheskikh voln v blizhnei i dal'nei zonakh ot promyshlennykh vzryvov v mnogoletnemerzlykh porodakh (The seismic wave field in the near and far zones of industrial explosions in permafrost rocks), *in* Ob'emnye modeli struktury zemnoi kory i vernei mantii (Volumetric models of the structure of the Earth's crust and upper mantle): Magadan, p. 149-163.

Shipilov, E. V., and Senin, B. V., 1988, Glubinnoye stroeniye dna Barentseva Morya (Deep structure of the floor of the Barents Sea): Geotektonika (Geotectonics), no. 6, November-December.

Sidorenko, A. V., (ed)., 1970, Geologiya SSSR, T. XXVI, Ostrova Sovetskoi Arktiki, geologichesoye opisaniye (Geology of the USSR, v. 26, Islands of the Soviet Arctic, geologic descriptions): "Nedra," Moscow, 547 p.

Solov ev, I. A., Trufanov, G. V., Korago, Ye. A., Vinogradova, O. N., Matveev, V. P., and Shemyakin, Ye. V., 1986, Kembriiskie otlozheniya Novoi Zemli (Cambrian deposits of Novaya Zemlya): Sovetskaya Geologiya (Soviet Geology), no. 3, p. 65-76.

Stewart, R. C., and Marshall, P. D., 1988, Seismic P-waves from Novaya Zemlya explosions: seeing double: Geophysical Journal, v. 92, p. 335-338

Stevens, J. L., Rimer, N., Murphy, J. R., Barker, T. G., Bailey, E., Halda, E. J., Proffer, W. J., Rogers, S. H., and Shkoller, B., 1991, Simulation of seismic signals from partially coupled nuclear exolosions in spherical and ellipsoidal cavities: Maxwell, S-Cubed Division, SSS-FR-12735, August, 1991, 101 p.

Sykes, L. R., and Wiggins, G. C., 1986, Yields of Soviet underground nuclear explosions at Novaya Zemlya, 1964-1976, from seismic body and surface waves, *in* Proceedings, National Academy of Sciences, USA, v. 83, p. 201-205.

Sykes, L. R., and Ruggi, S., 1989, Soviet Nuclear Testing, *in* Cochran, T. B., Arkin, W. M., Norris, R. S., and Sands, J. I., eds., Nuclear Weapons Databook, Volume IV: Soviet nuclear weapons: Harper and Row, New York, p. 332-382

Timur, A., 1968, Velocity of compressional waves in porous media at permafrost temperatures: Geophysics, v. 33, no. 4 (August), Society of Exploration Geophysicists, p. 584-595

Trepettsov, E. V., Popov, I. V., and Tereshkov, G. M., (eds.), 1978, Inzhenernaya geologiya SSSR, Tom pyatyi, Altai, Ural (Engineering geology of the USSR, Volume five, Altai, Ural): Izdat. Moskovskovo Universiteta, 220 p.

United States Department of Commerce, 1990, International station meterological climate summary CD-ROM, version 1.0: Federal Climate Complex, Ashville, NC

U.S. Geological Survey, National Earthquake Information Center, 1990a, Global hypocenter datbase CD-Rom: U.S. Geological Survey World Data Center A for Seismology, Denver, CO

U.S. Geological Survey, National Earthquake Information Center, 1990b, October, Monthly listing, Preliminary Determination of Epicenters, US GPO, Washington, D. C.

Ustritskiy, V. I., 1985, The relationship between the Urals, Pai -Khoi, Novaya Zemlya, and Taimyr: Geotectonics, v. 19, no. 1, p. 35-42.