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SUMMARY AND REVIEW OF THE TECTONIC STRUCTURE OF EURASIA PART I

ILENE R. SAMOWITZ

DAVID M. HADLEY

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INTRODUCTION

An extensive search of the available geologic and geophysical literature dealing with the crust and upper mantle properties of the U.S.S.R. and Eurasia has been conducted. During the past 25 years a vast amount of deep seismic sounding has been done in the U.S.S.R. This review has attempted to fully use source material from the Soviet literature that has resulted from this massive campaign. Additionally, previously unavailable Russian data that has been organized and critiqued by Piwinskii (1979) has been reviewed and included in this report. Vol'vovskii and Vol'vovskii (1978) have published numerous cross sections from deep seismic sounding profiles that were extremely valuable in the synthesis of this report.

From this broad data base the U.S.S.R. was subdivided into eleven distinct tectonic provinces, Figure A. The boundaries for these provinces were drawn after considering geologic evolution. Seismic activity, heat flow, Moho properties, crustal properties, seismic wave velocities, attenuation, gravity, regional phase propagation and upper mantle structure. However, the main emphasis in this regionalization has been on seismic properties. It is important to point out that crustal properties are not uniform in each individual province but that each region represents a coherent evolutionary unit. The provinces within the

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An extensive search of the available geologic and geophysical literature dealing with the crust and upper mantle properties of the U.S.S.R. and Eurasia has been conducted. During the past 25 years a vast amount of deep seismic sounding has been done in the U.S.S.R. This review has attempted to fully use source material from the Soviet literature that has resulted from this massive campaign. Additionally, previously unavailable Russian data that has been organized and critiqued by Piwinskii (1979) has been reviewed and included in this report. Vol 'vovskii and Vol'vovskii (1978) have published numerous

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) cross sections from deep seismic sounding profiles that were extremely valuable in the synthesis of this report. From this broad data base the U.S.S.R was subdivided into eleven distinct tectonic provinces. The boundaries for these provinces were drawn after considering geologic evolution, seimic activity, heat flow, Moho properties, crustal properties, seismic wave velocities, attenuation, gravity, regional phase propagation and upper mantle structure. However, the main emphasis in this regionalization has been on seismic properties.

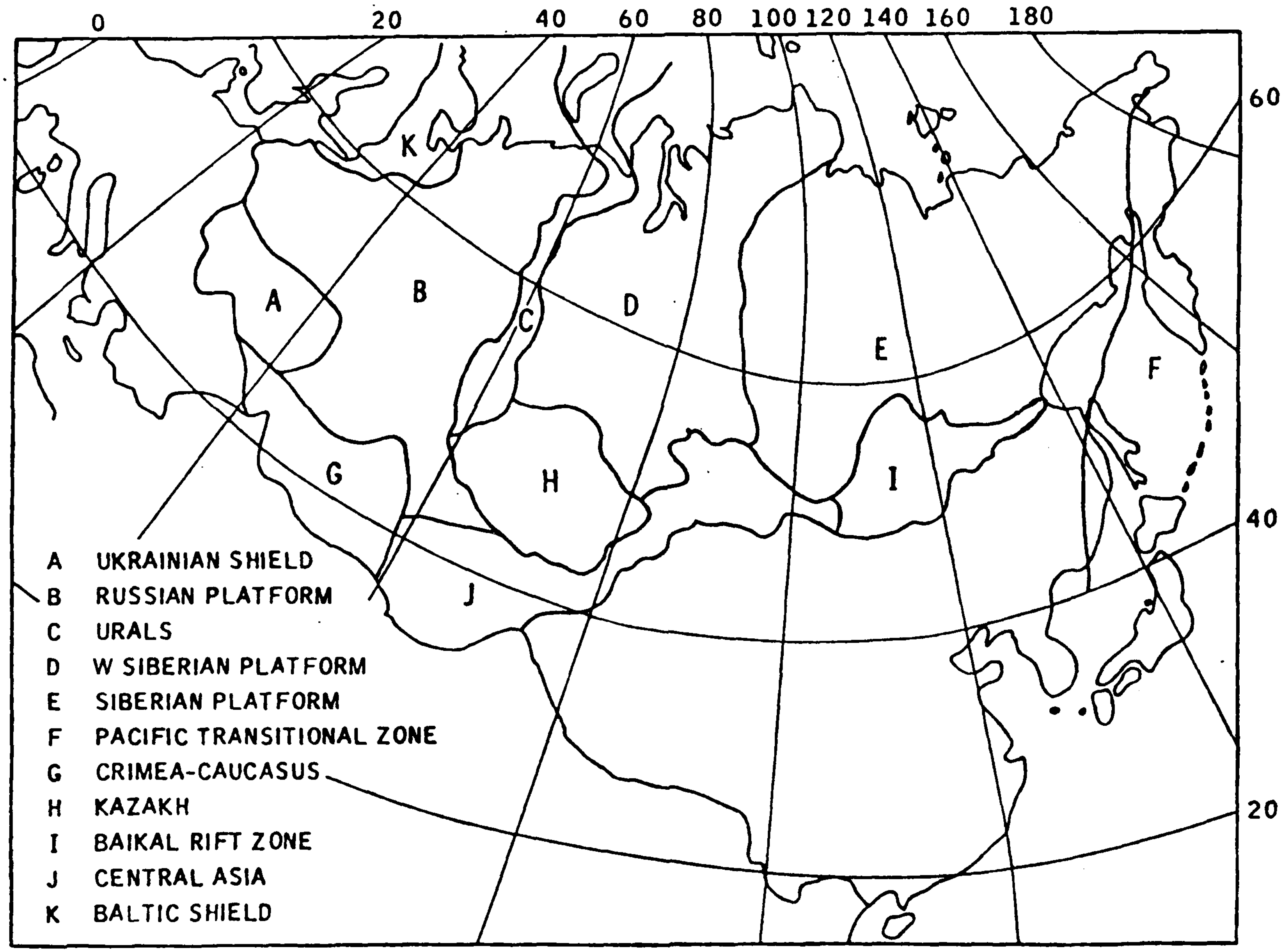

Figure A. The eleven tectonic provinces of the U.S.S.R.

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U.S.S.R. are extremely diverse, for example, there are old stable regions such as the Baltic and Ukrainian Shields as well as extremely young and active regions such as the Pacific Transitional Zone and Soviet Central Asia. Properties of these regions vary significantly. For example, Moho depths range from 8 km in the Pacific Transitional Zone to 80 km in Central Asia. Pn velocities vary from 7.6 km/sec in the Baikal Rift Zone to 8.5 km/sec in Kazakh.

In reviewing deep seismic sounding data, many ambiguities arise from the different methods of sounding as well as interpreting the data. When reviewing each province, the data values found most frequently for the region were considered to be the norm. Areas with slightly differing tectonic backgrounds or geophysical characteristics were categorized as subregions. In provinces where information was scarce, subregions were not developed. Further studies are underway in order to facilitate the labeling of subregions as well as help interpret the inconsistencies of the current data base. These results will be addressed in a subsequent report.

This report has been divided into eleven sections in order to fully critique each province. Hopefully this format will allow the reader to rapidly identify useful information when studying particular wave paths or tectonic areas.

Currently, Sierra Geophysics is studying regional wave propagation within the USSR and examining this data in comparison to the models presented here. For several provinces, Rayleigh wave group and phase velocity curves have been obtained for periods ranging from 10 to 100 sec. Sources located within the USSR and recorded at stations bordering the Soviet Union have paths generally less than 2500 km. The derived phase velocities for these paths are inverted to obtain the crust and upper mentle structure for each of these regions. Our subsequent technical report will compare the structures obtained from inverting data with the data collected from this literature review.

RUSSIAN PLATFORM

The Russian platform is located to the east of the Ukrainian Shield. The region has several structural units, most of which are basins. Platforms are tectonically stable and are characterized by smooth gentle crustal interfaces. Crustal thicknesses range between 35 and 50 km. There are many deep faults that penetrate the crust and upper mantle.

The Russian platform began forming in the Proterozoic when large areas of consolidated Archean platform folded. Extensive subsidence and sedimentation occurred in most regions primarily in the Paleozoic. The North Caspian Basin subsided throughout the Permian and Mesozoic when it received 4-10 km of sediments. The whole platform was gently uplifted in the Quaternary. The Dnieper-Donetz aulacogen formed in the Riphean as a result of stretching in the upper part of the consolidated crust. During the Paleozoic, the stretching process became reactivated. As a result of the stretching, a Hercynian graben formed over the Riphean troughlike structure. The Dnieper-Donetz trench is thought to be an analogue of an ancient rift (Kosminskaya and Pavlenkova, 1979 and Borodulin, et al., 1978). It is often compared with the Red Sea.

Beliayevsky, et al. (1968) summarize deep seismic sounding (DSS) studies done in the northern part of the platform and find three crustal layers. The sedimentary layer is usually less than 3 km with an average velocity of 4.2 km/sec. The granitic layer averages 16 km with P wave velocities ranging between 5.8 and 6.4 km/sec. The basaltic layer, which is the thickest crustal layer, is usually approximately 20 km thick. It forms more than half of the crust and has an average velocity of 6.8 km/sec. The average crustal thickness is 39 km. Pn velocities range between 8.0 and 8.2 km/sec.

Vol'vovskii and Vol'vovskii (1978) published several crustal studies in this region. Figure 1 shows the result of a 1958 DSS continuous profile study along Ural'sk Cheremshan which shows the typical crustal structure of the region.

Little deep seismic sounding has been done on the North Caspian Basin, however, Rodriguez (1969) postulates that it is analogous to the Mississippi Embayment. In the map published by Elias, et al. (1966) the North Caspian Basin is a region abundant with salt domes. Vinnik and Ryaboy (1980) claim that the central part of this depression is devoid of a granitic layer while the sedimentary layer reaches down to 20 km.

Vol'vovskii and Vol'vovskii (1978) have published one profile in this region which shows a crustal section just to the northwest of the Caspian Sea (Figure 2). In this profile, the sedimentary layer ranges between approximately 8 and 18 km with P velocities ranging from 2.5-4.7 km/sec. The second layer is approximately 30 km thick and has an average velocity of 5.9 km/sec. The Moho lies at a depth of approximately 45-50 km with a Pn velocity of 8 km/sec.

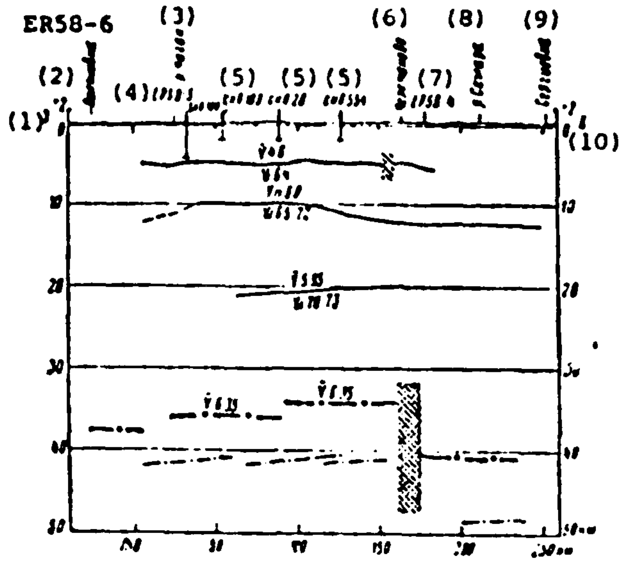

Figure 1. Seismic section of crust along Pervomaiskii-Orenburg DSS profile (ER58-6). DSS continuous profiling (CMRW). Performed by VNIIGeofizika of USSR MG (1958). Authors: Yu. N. Godin, A. V. Egorkin, N. P. Ivanova, M. V. Margot'eva, A. P. Pankratov., I. V. Pomerantseva, E. D. Tagai, et al. (12,60). 1 = W; 2 = Polyakovka; 3 = Chagan River; 4 = ER58-5; 5 = borehole; 6 = Cherepanovo; 7 = ER58-4; 8 = Samara River; 9 = Sergievka; 10 = E. (Taken from Vol'vovskii and Vol'vovskii, 1978.)

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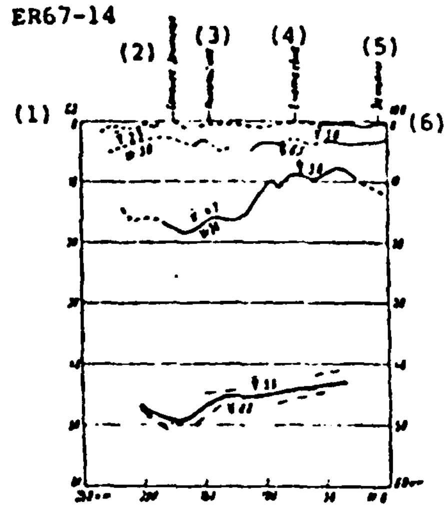

Figure 2. Seismic section of crust along Astrakhan'-Volgograd DSS profile (ER67-14). DSS continuous profiling (CMRW). Performed by Central Geophysical Trust of RSFSR MG (1967). Authors: D. P. Kasatkin et al. 1 = NW; 2 = salty flood plain; 3 = Nikol'skoe; 4 = Enotaevka; 5 = Zam'yany; 6 = SE. (Taken from Vol'vovskii and Vol'vovskii, 1978.)

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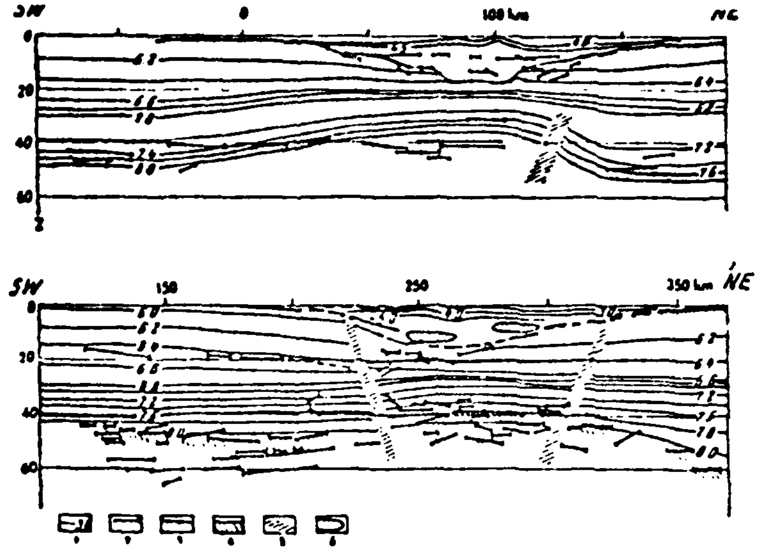

Figure 3. Crustal cross-sections of the Dnieper-Donetz depression (Pavlenkova, 1973). Legend: 1 = velocity isolines, 2 = reflecting areas, 3 = top of crystalline basement, 4 = Moho, 5 = fault zones, 6 = low velocity zones. (Taken from Kosminskaya and Pavlenkova, 1979.)

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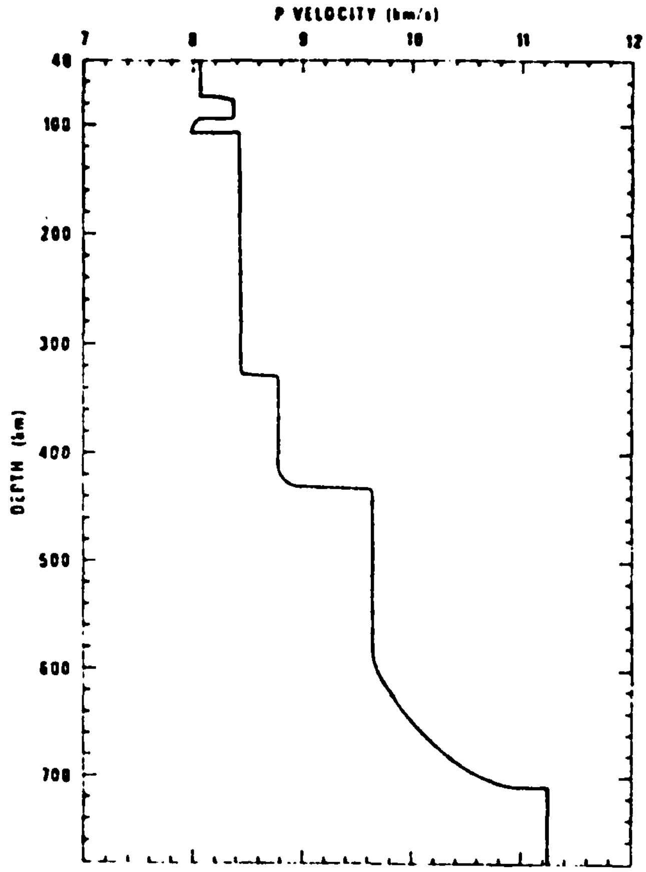

Figure 4. Upper mantle P velocity model beneath Scandinavia and Western Russia. (Modified from Massé and Alexander, 1974.)

The crust of the Dnieper-Donetz trench has been studied extensively. Pavlenkova (1979) consider it to be a typical graben. Figure 3 shows two cross sections published by Kosminskaya and Pavlenkova (1979) of this depression. It has sediments with thicknesses greater than 15 km (Vp = 4-4.5 km/sec.). In the graben, the crustal layer with velocities of 6 to 6.2 km/sec is usually absent. This large accumulation of sediments is compensated by a high velocity crust and a rise in the Moho (approximately 40 km). The crust directly below the depression (Figure 3) has a steep velocity gradient. P velocities rise from 6.4 km/sec to 7.4 km/sec within 20 kilometers. In neighboring regions, this increase of 1 km/sec in velocity usually occurs at depths greater than 30 km. There is a decrease in Pn velocities directly under the depression to 7.8-7.9 km/sec compared to Pn velocities of 8.0-8.2 km/sec in nearby regions. However, Kosminskaya and Pavlenkova (1979) think that this effect may be due to the artifact of the data.

There are several studies that model the upper mantle in this region. Masse and Alexander (1974) claim that the upper mantle P velocity is the same as that beneath the Canadian Shield. Figure 4 shows their upper mantle P velocity model. They found a Pn velocity of 8.13 km/sec and discontinuities at approximately 74, 107, 328, 431, and 710 km. They included a 10 km low velocity layer at 100 km with a P velocity of 8 km/sec. Figure 5 compares Given and Helmberger (1980) model K8 with King and Calcagnile (1976)

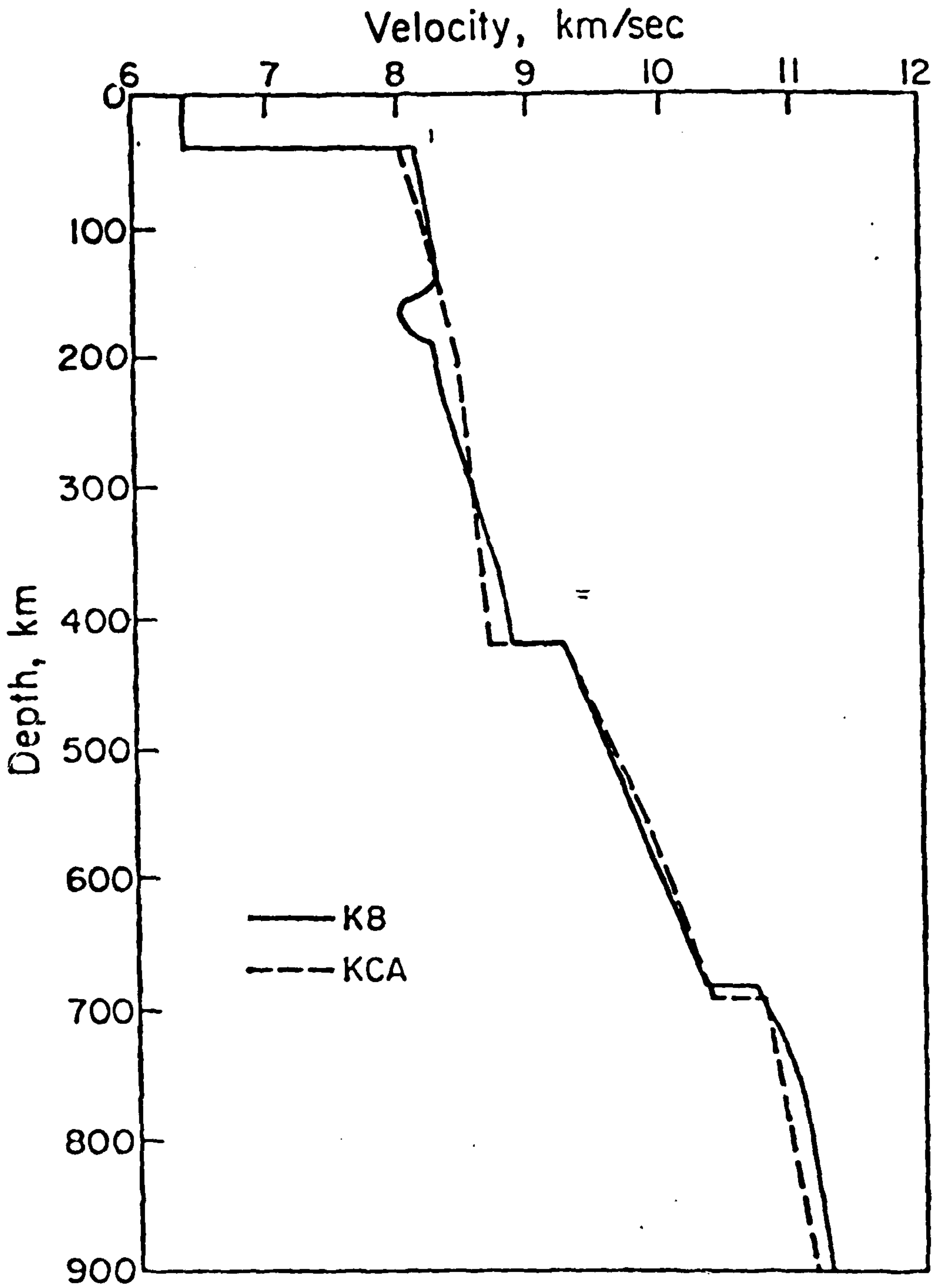

Figure 5. Model K8 (derived by Given and Helmberger, 1980) and Model KCA (King and Calcagnile, 1976) for northwest Eurasia. (Modified from Given and Helmberger, 1980.)

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model KCA of the upper mantle. Given and Helmberger (1980) concluded that a low velocity zone exists in the upper mantle between 150 and 200 km with P velocities of 8 km/sec. Vinnik and Ryaboy (1980) found pronounced differences in the uppermost mantle between the northeast Russian platform and the North Caspian depression. In the Russian platform, they found a low velocity layer at a depth of 60 to 110 km with a P wave velocity of 8.0 km/sec. In the North Caspian depression they found this (10-20 km) low velocity layer at 60-70 km with a P wave velocity of 8.1 km/sec.

Pomeroy and Nowak (1978) have used WWSSN records recorded outside of the USSR to see how Lg propagates in the Russian platform. They used both explosions and earthquakes located in Kazakh, the Urals, the Caucasus, and the Black and Caspian seas. They found that Lg amplitudes are significantly lower relative to P wave amplitudes for all of the events used. This differs significantly from the eastern United States where Lg amplitudes are consistently 5-10 times greater than P wave amplitudes.

THE URAL FOLD SYSTEM

The Ural fold system is located to the east of the Russian platform and consists primarily of ultrabasic rocks and their associated gabbros and amphibolites. The Urals' analogue in North America is the Appalachians. The Urals and the Appalachians are similarly situated relative to ancient platforms and are broken up into two segments by deep faults. In both regions the miogeosyncline is in the west and the eugeosyncline is in the east. According to Peyve (1973), the transformation from oceanic crust to continental crust is the major process in their development.

From deep seismic sounding in the Urals, Khavelin (1972) points out that a close relationship exists between the mantle structure and the development of the crust. For example, beneath the axial regions the dip on the Moho indicates the presence of a slight root zone. Additionally, in the axial zone the most outstanding feature is a sub-meridional positive gravity anomaly which corresponds to the subsidence of the Moho and indicates a higher density crust.

According to deep seismic sounding, the crustal thickness ranges from 38-50 km, with a mean value of 42 km. Figure 6 from Vol'vovskii and Vol'vovskii (1978) shows a crustal section that was derived from continuous profiling along the Izh River in the west to Beldyrevka in the east. A summary of deep seismic sounding profiles found in Vol'vovskii and Vol'vovskii (1978) indicates that the average thickness of the top layer is approximately 7 km with an average P velocity of 5.5 km/sec. A thin high velocity layer, Vp=6.7-7.0 km/sec, thickness of 12 km, is intermittently found within the region at a depth of 7-8 km. The third layer has a thickness of approximately 10 km with a mean P velocity of 6.4 km/sec. Pn velocities range from 8.2

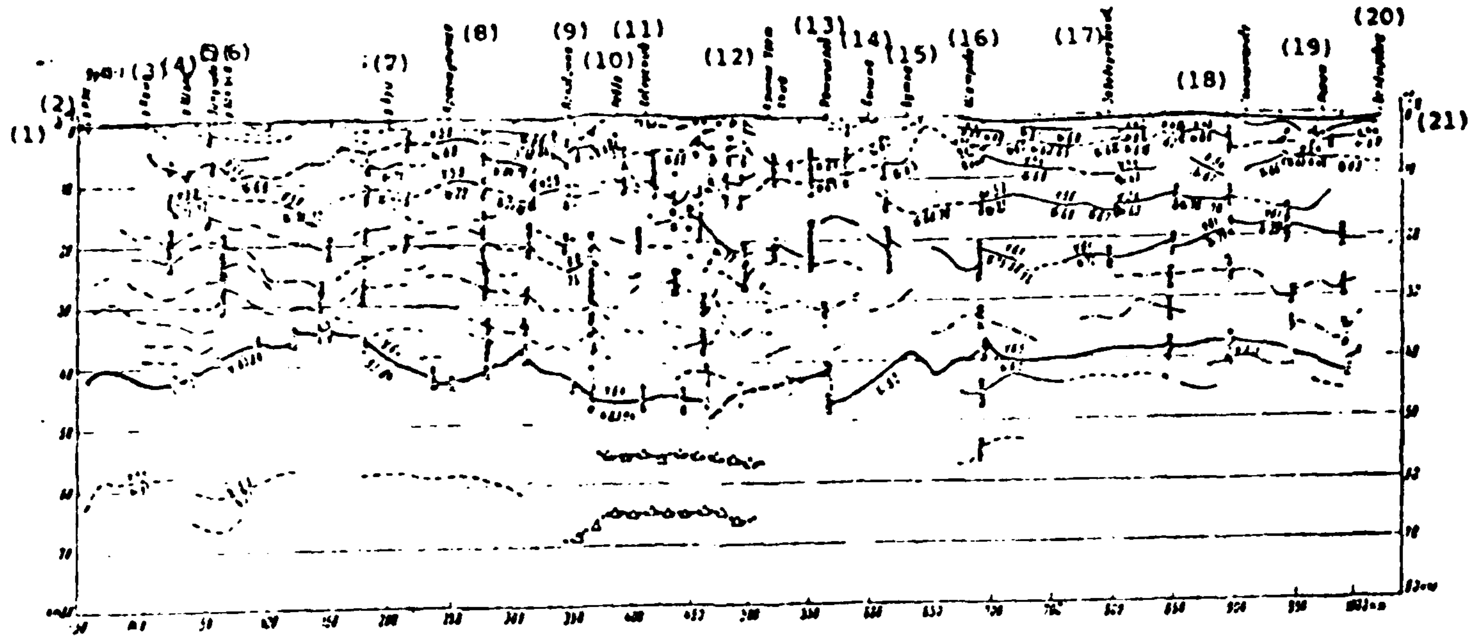

Figure 6. Seismic section of crust along Izhevsk-Ishim DSS profile (Ur65-1). DSS continuous profiling (CMRW, RWM). Performed by BEG of Ural State University of RSFSR MG and IG UNTs* of USSR AS (1965). Authors: V. N. Aleksashenko, D. A. Belikova, B. Ya. Broslavskii, V. S. Druzhinin, V. T. Gontar', O. V. Guseva, L. N. Kazachikhina, E. A. Nezolenova, V. M. Rybalka, N. I. Khalevin, F. F. Yunusov, et al. (24,43,65,96,109).

Key: 1 = W; 2 = Izh River; 3 = Kama River; 4 = Shola River; 5 = Zipunova; 6 = Bol'shaya Vsa River; 7 = Ari River; 8 = Krasnoufimsk; 9 = Polovinka; 10 = Revda; 11 = Severskii; 12 = Kamensk-Ural'skii; 13 = Kamyshlov; 14 = Pyshma; 15 = Butka; 16 = Shatrovo; 17 = Zarodoukovskii; 18 = Tolyshmanova; 19 = Ishim; 20 = Beldyrevka; 21 = E. (Taken from Vol'vovskii and Vol'vovskii, 1978.)

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km/sec to 8.3 km/sec. Additionally, two reflecting boundaries were located at 15 km and 60 km with boundary velocities of 7. and 9.1 km/sec respectively.

Piwinskii (1979) summarizes the results of DSS in the following way. In the Sverdlovsk Region he concludes that the crustal thickness varies between 37 and 50 km with many deep fractures penetrating the crust and upper mantle forming blocklike structures. In the northern Urals, he finds positive gravity anomalies contrasting the southern Urals where negative anomalies are more common. Additionally, in the axial portion of the Urals, the intensity of the gravity field increases with the thickness of the earth's crust. In the Gai-Orsh Region he concludes that the crustal thickness ranges between 38 to 50 km with several deep fracture systems penetrating the crust and upper mantle. Additionally, in some regions the Moho is not well defined indicating transition zones in the lower crust. Pn velocities are reported to be 8.1 km/sec.

McCowan, et al. (1978) model the crust and upper mantle for Novaya Zemlya (Figure 7). There is little available information on this region, but it is believed to be a northern extension of the Urals. Their model has a 45 km thick crust, a Pn velocity of 8.18 km/sec, and shear wave low velocity zone in the upper mantle.

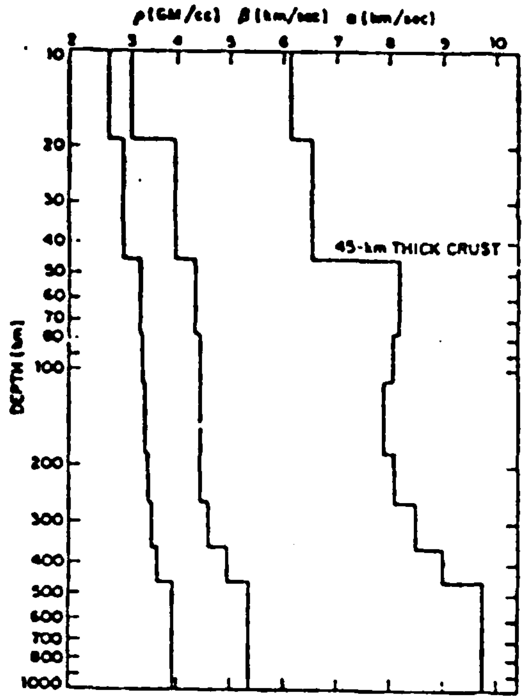

Figure 7. Logarathmic scale plot of the layer parameters from McCowan, et al. (1978) Novaya Zemlya structural model beginning at 10 km. (Modified from McCowan, Glover, and Alexander, 1978.)

KAZAKH

Kazakh is located to the southwest of the Urals and consists primarily of extensive areas of Archean and Proterozoic gneiss, schist, amphibolite with smaller amounts of quartzite and marble. This region began in the Riphean and Paleozoic as a geosyncline. By the Silurian, this region was largely mountainous with intermittent basins of continental sedimentation and extensive terrestial volcanism. The region is considered to be relatively stable since the Paleozoic.

Khrychev, et al. (1968) summarize the findings of a 1500 km long deep seismic profile crossing most of the major structural units of central and northwest Kazakh, the Urals, and the eastern Russian platform. Figure 8 from Khrychev, et al. (1968) shows the cross section of this profile. The three tectonic systems are separated by transitional zones with the Turgay basin separating Kazakh from the Urals. A deep-seated fault zone and an abrupt upward rise of lines of equal velocities towards the Urals occurs in the central part. Six major blocks were identified within this area of Kazakh (Figure 9). The principal criteria for identifying the smaller tectonic elements were constant velocity and constant thickness of crust within a block. Additionally, these blocks are separated by faults that penetrate the crust and upper mantle and by P velocities that often form steplike structures.

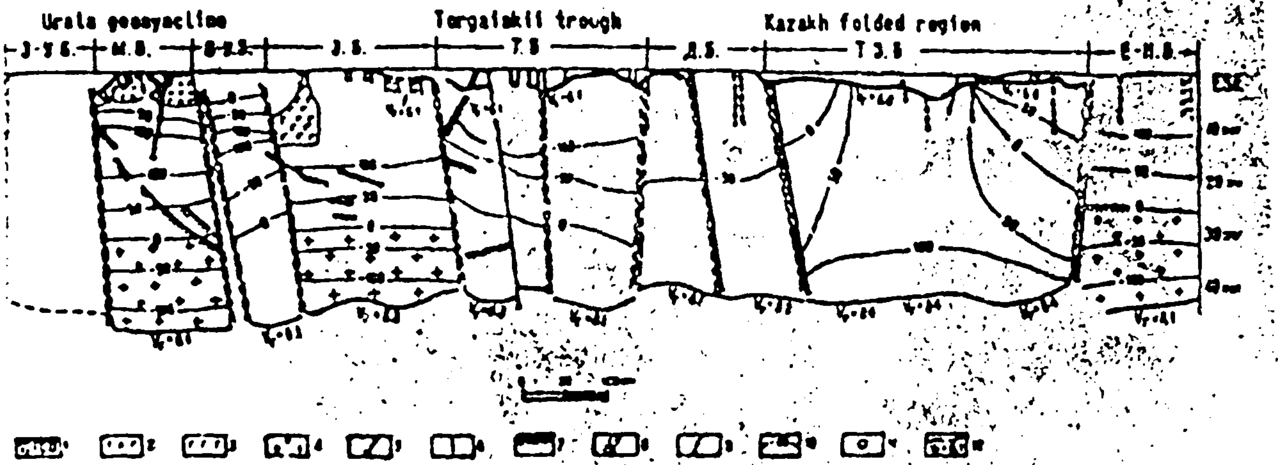

Figure 8. Scheme of the distribution of the velocity anomalies of longitudinal waves in the crust. 1 = refracting boundary with $V_b \approx 6.0$ km/sec; 2 = magmatic formations of intermediate and basic composition; 3 = ditto of basic and ultrabasic composition; 4 = negative velocity anomalies in the lower parts of the crust; 5 = subvertical reflecting elements; 6 = faults; 7 = regions of aggregation of elements constructed from dominant reflections; 8 = zones of deep dislocations; 9 = deep dislocations from gravimetric data; 10 = isomers of velocity anomalies; 11 = diffraction centers; 12 = Mohorovicic discontinuity (M). (Modified from Khrychev, Vakulin, and Tolmanov, 1973.)

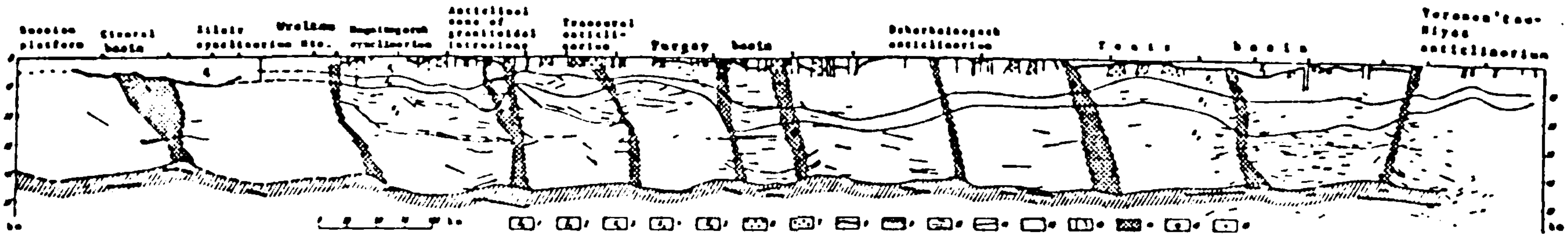

Figure 9. Seismic section of the earth's crust along the Temirtau-Kuybyshev profile. 1 = Primarily post-Devonian sedimentary deposits in the Urals and Kazakstan; 2 = sedimentary deposits within the Russian platform; 3-5 = consolidated crust with the following seismic wave velocities: 3 = K_1 -5.5-6.5 km/sec; 4 = K_2 -6.5-6.7 km/sec; 5 = K_3 -6.7-7.2 km/sec; 6^1 = acidic intrusions; 7 = basic intrusions; 8 = top of the consolidated crust; 9 = Mohorovicic discontinuity; 10 = reflectors; 11 = reflectors constructed from predominant waves; 12 = arbitrarily constructed reflectors; 13 = faults; 14 = fault zones; 15 = diffraction points; 16 = shot points. (Taken from Khrychev, Lysyakov, Al;ter, and Ivanov, 1968.)

The Eastern Teniz block has its basic rocks beginning at a depth of 23 km. This layer, Vp = 6.7-7.2 km/sec, is characterized by low velocities and does not include basic volcanic intrusions. Crustal thickness here is 43 km. The West Teniz block has a crustal thickness of 44 km. The top of the basaltic layer is at 14-15 km and the top of the acidic layer is at 4 km. Dzharkainagach differs from West Teniz by a deeper occurrence of the acidic layer at approximately 12 km. East Turgay is characterized by a deeper depth to the Moho at approximately 44 km. Central Turgay is similar to East Turgay but shows an uplift in the equal velocity layers acting as a transition to the Urals.

There has been an extensive deep seismic sounding program in Kazakh. The crustal thickness throughout all of Kazakh varies between 40 and 60 km. Beliayevsky, et al. (1968) found the average Kazakh crust to be 50 km thick and composed of a 22 km thick granitic layer with P velocities of 5.9-6.2 km/sec and a 28 km basaltic layer with a velocity range of 6.9-7.0 km/sec. The average crustal velocity is 6.6 km/sec. Pn values range between 8.1 and 8.5 km/sec with a mean value of 8.4 km/sec.

Piwinskii (1979) summarizes the deep seismic sounding studies done in Kazakh into four regions. Southeast Kazakh is reported to have a crustal thickness that varies between 40 and 60 km. There are several deep fracture systems that penetrate the earth's crust and upper mantle. The Charsk is one of the deepest fracture systems and extends to a depth of 130 km.. Due to the abundance of these fracture systems, the earth's crust is broken into block structures. The Moho in this region is characterized by mild relief and the Pn velocity is reported to be 8.1 km/sec. Piwinskii (1979) also reports the existence of a large negative gravity anomaly in the Issyk-Kul region.

Piwinskii (1979) reports that crustal thickness in Central Kazakh ranges from 40 to 54 km and that there are many deep fracture systems that penetrate down into the upper mantle creating block structures. Pn velocities are reported to range from 8.0-8.5 km/sec. There are several crustal sections published that are in this region. However, there is considerable variation in these profiles. For instance, along the Issyk-Kul-Saksaul'skii profile (Figure 10) published by Vol'vovskii and Vol'vovskii (1978) the crustal layers are almost continuously defined. Both the Conrad and the Moho can be traced through the profile until the northernmost end. In this area, the Moho varies from a depth of approximately 42 to 50 km and Pn velocities range between 8.0 to 8.1 km/sec. The Conrad varies from a depth of approximately 18 to 22 km and the associated P boundary velocity is 6.7 to 6.8 km/sec. The deepest fault in this profile extends to a depth of approximately 25 km. The Arys'-Lake Balkhash profile (Figure 11) also published by Vol'vovskii and Vol'vovskii (1978) runs southwest to northeast and has significantly different features. The first layer is not continuous. When it exists, it is found to vary between 1 and 4 km and has P velocities that range

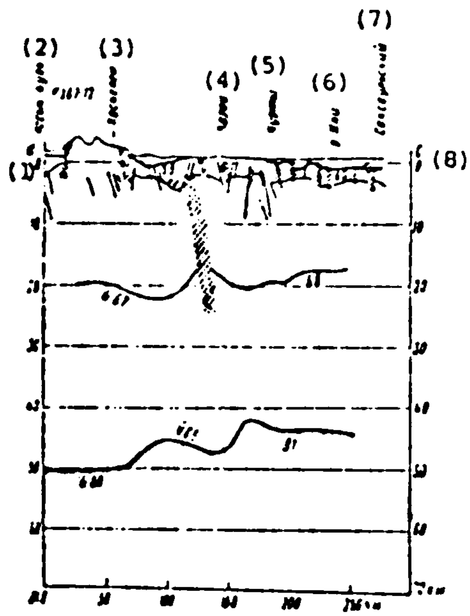

Figure 10. Seismic section of crust along Kaskelen DSS profile (Kz67-12). DSS continuous profiling (CMRW). Performed by Kazgeofizika Trust of Kazakh SSR MG (1967). Authors: V. A. Koktov, V. I. Shatsilov, et al. (3). 1 = S; 2 = Issyk-Kul'; 3 = Kaskelen; 4 = Karoi; 5 = Kurty; 6 = Ili River; 7 = Saksaul'skii; 8 = N. (Taken from Vol'vovskii and Vol'vovskii, 1978.)

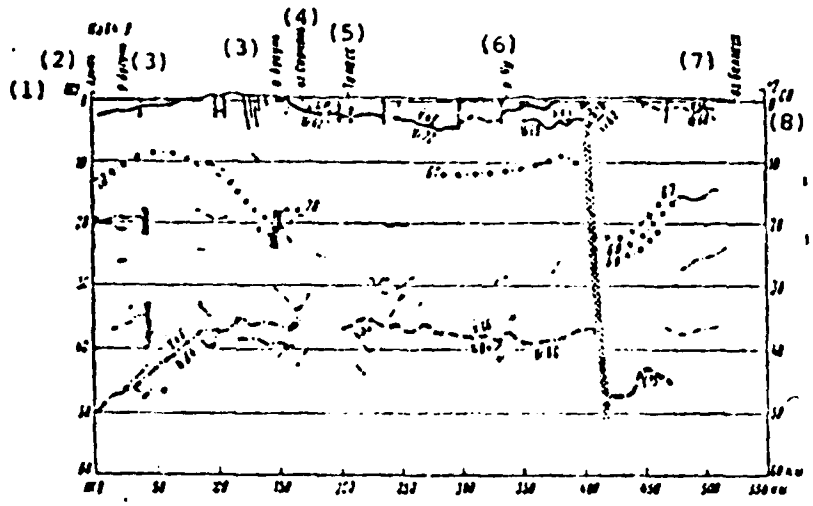

Figure 11. Seismic section of crust along Arys'-Balkhash DSS profile (Kz64-9). DSS continuous profiling (RWM). Performed by Kazgeofizida Trust of Kazakh SSR MG (1964). Authors: A. P. Ivanov, S. V. Lipskaya, I. K. Pushkarev, V. I. Shatsilov, et al. (3,39). 1 = SW; 2 = Arys'; 3 = Bugun' River; 4 = Lake Sarkol'; 5 = Talass; 6 = Chu River; 7 = Lake Balkhash; 8 = NE. (Taken from Vol'vovskii and Vol'vovskii, 1978.)

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between 4.3 to 4.6 km/sec. Vol'vovskii and Vol'vovskii (1978) place the Conrad at the bottom of this layer. The P velocity associated with this Conrad varies from 6 to 7.2 km/sec. The second layer makes up the rest of the crust and has a thickness of 33-47 km and an average P wave velocity of 6.6 km/sec. Discontinuous boundaries are found in this profile at a depth of 20 to 30 km. P velocities associated with these reflectors are 6.7 to 7.0 km/sec. The deepest fracture in this profile penetrates into the upper mantle. The crustal thickness in this profile ranges from 38 to 50 km with Pn velocities of 8.0 to 8.6 km/sec.

Piwinskii (1979) reports that the crustal thickness varies between 35 to 50 km in West and Southwestern Kazakh. As in the other subregions, there are several deep fracture systems that break the crust into blocks. Vol'vovskii and Vol'vovskii (1979) published a seismic section along the Yuzhno-Turgaiskii DSS profile (Figure 12). There are two deep fractures that penetrate down into the upper mantle. There is not much layering of the crust in this profile. Along part of this profile there is a very thin discontinuous layer that is between 1 to 2 km thick. The average P velocity of this layer is 3 km/sec. The rest of the crust is one layer with a reflector at a depth of 30 km. Average P velocities in this profile are 6.1 to 6.4 km/sec. The Moho has little relief and is found at a depth of 40 to 46 km. Pn velocities range between 7.9 to 8.5 km/sec.

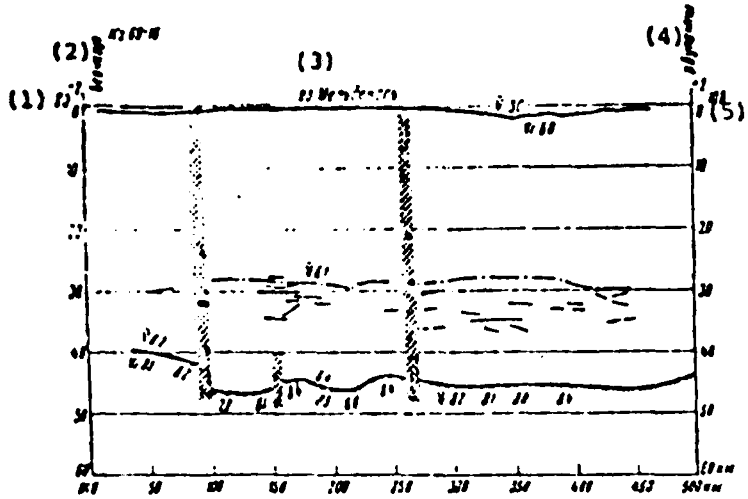

Figure 12. Seismic section of crust along Yuzhno-Turgaiskii DSS profile (Kz69-15). DSS piece continuous profiling (RWM). Performed by Kazgeofizika Trust of Kazakh SSR MG (1969). Authors: V. G. Chistyakov, N. Ya. Kunin, et al. (103). 1 = NW; 2 = Berchogur; 3 = Lake Mel'dekol'; 4 = Bulanty River; 5 = SE. (Taken from Vol'vovskii and Vol'vovskii, 1978.)

In Northwest Kazakh, Piwinskii (1979) reports the existence of many salt domes in the upper 5 kilometers of the crust. The crustal thickness in this region is also reported to range between 38 to 42 km indicating the flattest Moho in the entire Kazakh province. There are also fewer deep fracture systems in this region.

Alekseev, et al. (1973) report on the findings of Ryaboy and Matveeve which indicate that Kazakh has an average Pn velocity of 8.4 km/sec and a 10 km thick low velocity layer with velocity 8.0 km/sec at a depth of approximately 15-25 km below the Moho.

UKRAINIAN SHIELD

The Ukrainian Shield is located to the west of the Russian platform and consists of crystalline and highly metamorphic rocks in which granitoids, gneisses, migmatites, and granites of Archean-Proterozoic age are predominant. The crustal thickness in this province ranges from 30 km to 50-65 km. Areas that have thick crusts are associated with roots of mountain systems which existed in Proterozoic time. Places in which the Moho does not exceed 30-40 km are considered to be ancient platform areas. The Moho in this province correlates well with these tectonic features. However, outside the shield, in areas of younger folding, the correlation is less pronounced.

Sollogub, et al. (1973) believe that deep seismic sounding proved the main structural features of the Moho that formed over two billion years ago have been preserved. Sollogub, et al. (1973) find evidence for this in a DSS profile that runs east-west across the shield which cuts into major Lower Proterozoic structures (Figure 13). In some areas of this section one can find several Moho boundaries. Sollogub, et al. (1973) suggest that they are relics of the ancient bottom of the crust dating back to the period of Early Proterozoic origins. The Conrad cannot be traced continuously along this profile but when it is found it has a P velocity ranging between 6.7 to 7.0 km/sec. In addition, there are many reflecting boundaries found throughout the crust in both the granitic and basaltic layers. They believe that the uppermost boundary (V_p = 6.2-6.4 km/sec) found between 5 to 8 km is connected with the bottom of the sedimentary metamorphic complex.

The earth's crust in the Ukraine is crudely layered. The average velocity in the sedimentary layer is 2.5 km/sec, in the granitic layer 6.3 km/sec, and in the basaltic layer 7.0 km/sec yielding an average crustal velocity of 6.7 km/sec (Vol'vovskii, 1978). These are average velocities in each layer, however, the velocities increase with depth. There are several fault systems which penetrate the crust and upper mantle forming a blocklike structure.

Sollogub, et al. (1978) report on the longest profile in the Ukraine. The profile (Figure 14) runs approximately

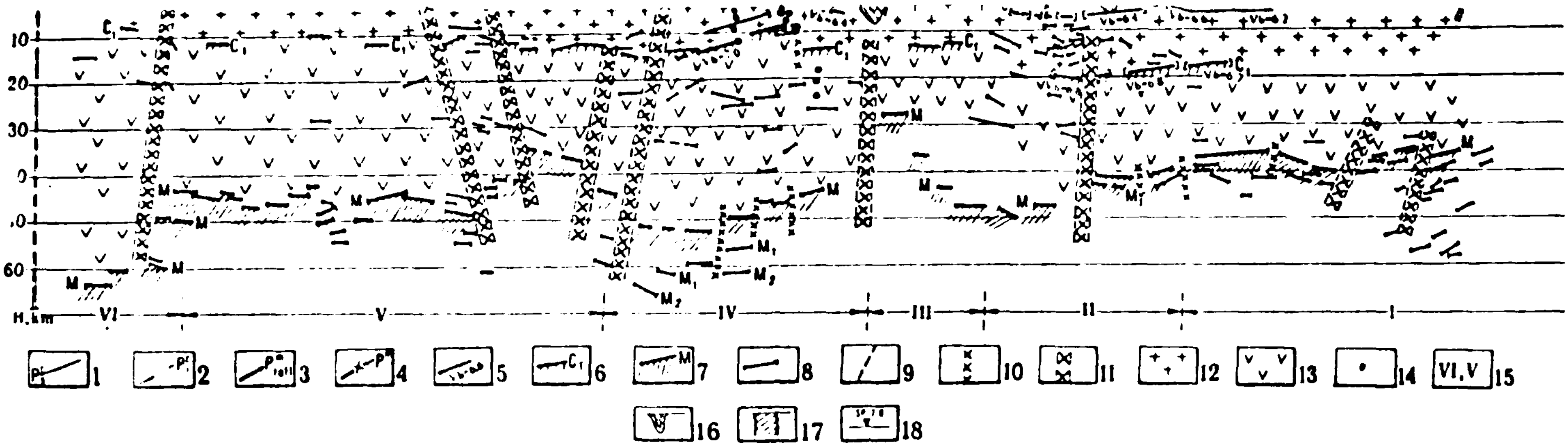

Figure 13. System of travel-time curves and crustal cross-section along profile 8 (Uman-Kirograk-Taganrog, Ukrainian Shield). Legend: 5 = refractors within the "granitic" layer, boundary velocity V_b given in km/sec; 6 = Conrad (C_1) surface; 7 = Mohorovicic (M) surface; 8 = reflectors within the consolidated crust; 9 = faults (from geologic evidence); 10 = dislocations with break in continuity; 11 = deep faults; 12 = "granitic" layer; 13 = "basaltic" layer; 14 = diffraction points; 15 = tectonic zones and blocks: I = Priazov massif, II = Orekhovo-Pavlograd Early Proterozoic geosynclinal system, III = Zaporoghje Median Massif, IV = Krivoy Rog-Kremenshug Early Proterozoic geosynclinal system, V = Kirovograd block of protoplatform type, VI = Odessa-Talnov Early Proterozoic geosynclinal system; 16 = near-surface synclinal structure (from geologic evidence); 17 = alkaline massif (salt dome; 18 = shotpoints. (Modified from Sollogub, Litvinenko, Chekunov, Ankudinov, Ivanov, Kalyuzhnaya, Kokorina, and Tripolsky, 1973.)

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Read v_r	as	$v_{boundary}$
$v_{пл}$		v_{layer}
$v_{отр}$		$v_{reflected}$
$v_{пр}$		$v_{refracted}$
ПВ		shotpoint
$p^к$		p^c
$p^{ос}$		p^{sed}

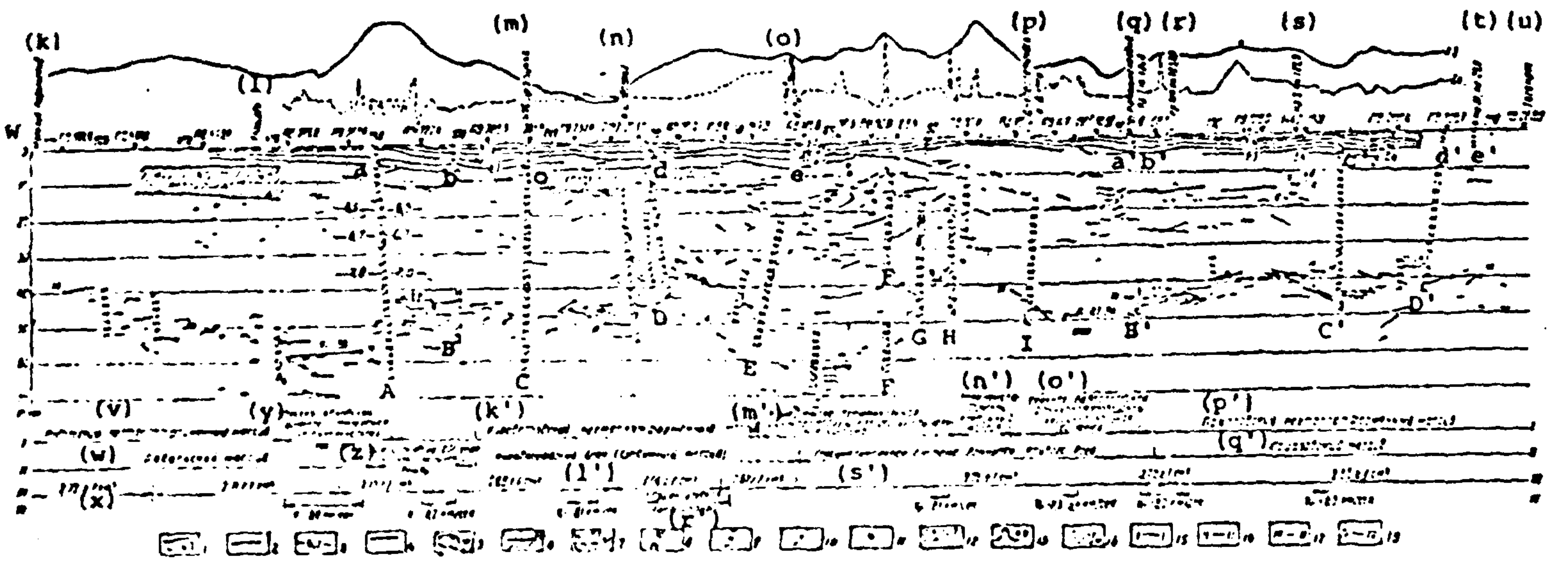

Figure 14. 1 = refracting horizons with values of boundary velocity (v_b, km/sec); 2 = reflecting areas; 3 = lines of isovelocities in the crystalline layer (km/sec); 4 = extended reflecting horizons in the crystalline layer; 5 = reduced-velocity (km/sec) layer in the crystalline layer; 6 = reflecting Mohos; 7 = refracting Mohos with values of boundary velocity (km/sec); 8 = deep and other major fractures according to DSS data (A = Tal'noe-Mironovka, B = Bug-Mironovka, C = Zvenigorodka-Annovka, D = Kirovograd, E = Krivoi Rog-Kremenchug, F = Vzikhovtsevskii, G = Krinichki, H = Surskii, I = Dnepropetrovsk, B = Orekhov-Pavlograd, C = Maniul'skii, E = Kal'mius); 9 = fractures according to geological data (a_0 = Bug, a = Tal'noe-Mironovka, b = Bug-Mironovka, c = Zvenigorodka-Annovka fracture zone, d = Kirovograd fracture zone, e = Krivoi Rog-Kremenchug, a = Devladovskii, b = Orekhov-Pavlograd, c = Maniul'skii, d = Krivoi Rog-Pavlovsk, e = Kal'mius, g = Elanchikskii); 10 = secondary dislocations; 11 = diffraction points;

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Figure 14 continued. 12 = shotpoints; 13 = curve of Δg; 14 = curve of Z_a; 15 = I-I-tectonic zones according to DSS data; 16 = II-II-tectonic zones according to geological data; 17 = III-III-areas with identical density of surface rocks; 18 = IV-IV-segments of the Moho for which the values of boundary velocities have been determined. k = Mogilev-Podol'skii; l = Bershad'; m = Novoukrainka; n = Kirovograd; o = Zheltye vody; p = Dnepropetrovsk/Dnieper River; q = Novonikolaevka, profile I, station 124.0; r = profile XIII, station 123.8; s = profile X, station 122.0; t = profile X, station 25.0; u = Taganrog; v = Podol'sk protoplatform mass; w = Podol'sk massif; x = g/cm^3; y = Odessa-Yablovka Early Proterozoic geosynclinal system; z = Belotserkovski Odessa geosynclinal branch; k' = Kirovograd protoplatform mass; l' = Kirovograd block (median mass); m' = Krivoi Rog-Kremenchug Early Proterozoic geosynclinal system; n' = Zaporozh'e-Sumy median mass; o' = Orekhovo-Pavlograd Early Proterozoic geosynclinal system; p' = Azov protoplatform mass; q' = Azov massif; r' = Ingul geosyncline; s' = geosynclinal system of Bol'shoi Krivoi Rog. (Taken from Sollogub, Chekunov, Tripol'skii, Kalyuzhnaya, and Gontovaya, 1978.)

longitudinally from Taganrog in the east to Mogilev Podol'skii in the west. The first seismic boundary to be traced occurs at a depth of 8 to 20 km. It was previously believed that this boundary was the Conrad but they believe after more detailed study that this boundary is located within the granitic layer. They do not interpret any of the boundaries in this profile to be the Conrad. This boundary is at a depth of 20 km toward the east near Krivoi Rog-Kremenchug and at a depth of 8 to 10 km in the west near Pobuzh'e. Sollogub, et al. (1978) believe that this uplifting in the west is due to a region of charnockite complex. This complex is thought to be made up of granitized basic rocks which formed deeper in the crust or in the upper mantle. The charnockite layer has a total thickness of 5 km and is characterized by higher density material (2.72 gm/cc) and higher velocities (V_p = 6.1-6.3 km/sec). These complexes are found in the region of the Podol'sk block (indicated by W in Figure 13) above a reduced velocity layer (V_p = 6 km/sec) which occurs at a depth of 5-14 km. The Moho in this profile varies between 30 to 60 km. The large variation of the Moho is deemed to be an important discovery because it was previously believed that shields had a more uniform crustal thickness. Figure 13 illustrates that areas with an uplifted and lowered Moho are generally divided by major faults. When the Moho is at 49 km depth, Pn values are 8.1 to 8.2 km/sec and at 60 km depth, Pn values are 8.6 km/sec.

Sollogub, et al. (1978) publish another profile (Figure 15) which passes through the Korosten Pluton located in the northwestern part of the shield. This pluton is composed of ultrabasic rock. These rocks are found predominantly at the surface and have a P velocity of 6.6-6.7 km/sec. They have identified a refracting boundary with a P velocity of 6.9 km/sec at a depth of approximately 4 km. With the use of both seismic and gravity data they suggest that this indicates that there are alternating layers of high and low velocity due to the presence of basic intrusions.

Pavlenkova (1969) has presented evidence for two low velocity zones within the crust. The first layer, depth range 8-12 km, is characterized by a velocity of 5.8 5.9 km/sec. The second is at a depth of 16-30 km and has a velocity of 6.0-6.1 km/sec.

BALTIC SHIELD

The Baltic Shield is to the northwest of the Russian platform. The crust in this province is a blocklike structure, with each block interpreted as an independent structure of the same tectono-volcanic cycle. As a rule, blocks are bounded by faults of different depths. The marginal parts of the block may be involved in subsequent younger tectonic movements. Where this occurs, the boundaries are usually indistinct. Proterozoic structures are found such

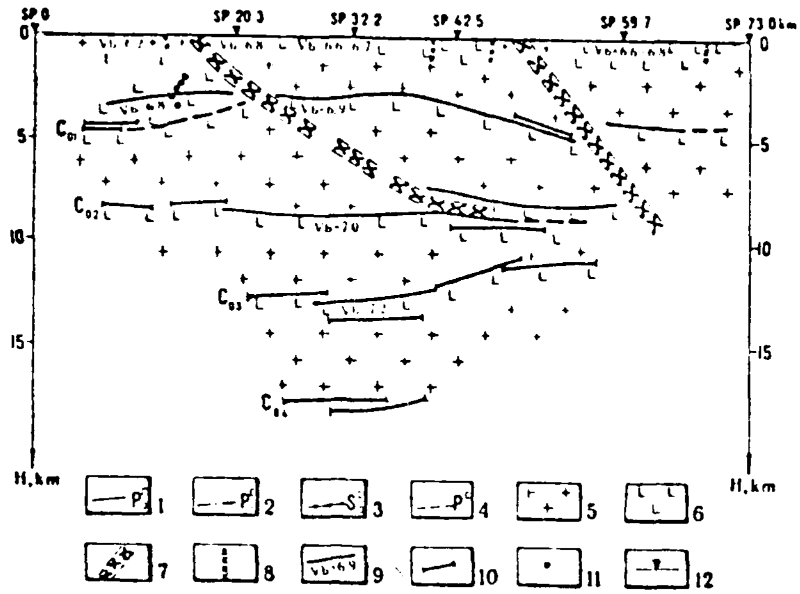

Figure 15. System of travel-time curves and crustal cross-section along profile 13 located in the area of the Korosten Pluton (Ukrainian Shield). Legend: 5 = granite-gneiss and migmatites of the Kirowograd-Zhytomir series; 6 = gabbro-labradorites of the Korosten intrusive series; 7 = deep fault zones; 8 = minor faults; 9 = refractors, boundary velocity V_b given in km/sec; 10 = reflectors within the consolidated crust; 11 = diffraction points; 12 = shotpoints. (Modified from Sollogub, Litvinenko, Chekunov, Ankudinov, Ivanov, Kalyuzhnaya, Kokorina, and Tripolsky, 1973.)

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as troughs, graben-type synclines, fault monoclines as well as complex Archean synclines and anticlines. The Baltic Shield, similar to the Ukrainian shield, consists of crystalline and highly metamorphic varieties of rocks such as granitoids, gneisses migmatites, and granites.

Litvinenko, et al. (1978) have identified two types of seismic boundaries: inclined boundaries, which are often steeply dipping, and gentle sloping boundaries, which are near horizontal. Inclined boundaries were traced in the upper 10-15 km of the crust in large regions of the shield. These boundaries are connected with complex, heavily dislocated fold structures, and indicate that the major structural zone charted encompasses at least one-third of the thickness of the crust. For the entire eastern part of the shield, all inclined boundaries dip in the direction of White Sea. Sollogub, et al. (1973) publish an upper part of a profile studied by Litvinenko et al. (1970) which appears to correspond to one of the profiles Litvinenko, et al. (1978) discuss. In this profile (Figure 16), the White Sea is towards the southwest. Deeper than this inclined boundary, all subsequent boundaries are subhorizontal. The Moho is an example of the gentle sloping boundary. The gentle boundaries are associated with transition layers characterized by large velocity gradients or packets of thin layers with variable parameters.

The Baltic Shield has a crustal thickness ranging from 30-43 km with a mean value of 35 km (Sollogub, et al.,

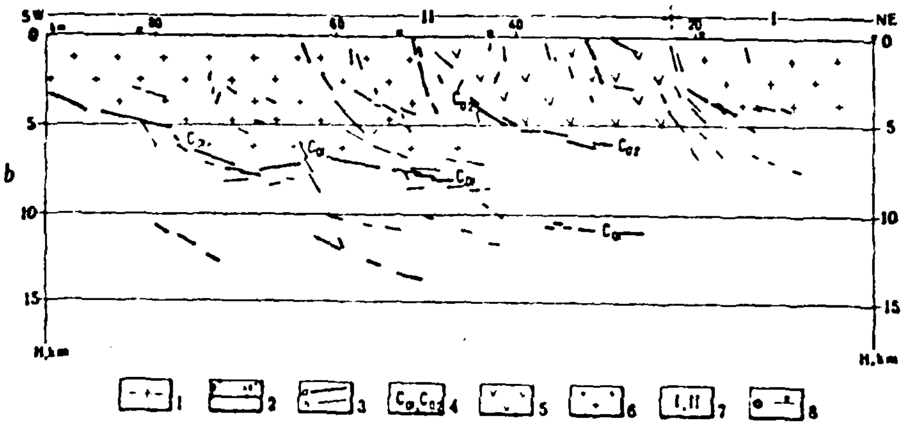

Figure 16. Seismic profile lines along the northern half of profile VI (Baltic Shield). Legend: 3 = reflectors corresponding to (a) reference waves and (b) other waves; 4 = index labels of some reference boundaries; 5 = Karelides (effusive-sedimentary series of the Vetrenny belt structure); 6 = granite-gneiss (Byelomorides, etc.); 7 = Tectonic zones: I = Byelomorides, II = Karelides (including the Vetrenny belt structure); 8 = shotpoints in plan (a) and in cross-section (b). (Modified from Sollogub, Litvinenko, Chekunov, Ankudinov, Ivanov, Kalyuzhnaya, Kokorina, and Tripolsky, 1973.)

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1973). The principal boundary is the Moho with an average Pn velocity of 8.1-8.2 km/sec. The Baltic Shield has a smaller crustal thickness than the Ukrainian Shield, suggesting a longer period of uplift which has resulted in a deeper erosion of the crust.

Rodriquez (1969) reports the results of the Kem-Ukhta profile which resolves five velocity layers. The boundaries of these layers occur at 5, 10, 16, 25, and 38 km. The P wave velocities for waves traveling along these boundaries are 6.4, 6.6, 6.75, 6.9 and 8.1 km/sec respectively. The crust along this profile ranged from 35 to 40 km so that the Moho corresponds to the 38 km boundary with an associated Pn velocity of 8.1 km/sec.

Vinnik and Ryaboy (1980) propose a low velocity zone in the uppermost 20-30 km of the mantle.

RUSSIAN CENTRAL ASIA

The Russian Central Asia region is located to the south of Kazakh. This region is noted for its high seismicity and its thick crust due to the increased thickness of the granitic layer. The main units that comprise this tectonic region are Garm, the Pamirs, Tien Shan, and Altai-Sayan mountains.

The western most part of this region is Garm which is the second most seismically active region in the USSR.

Earthquakes are found to occur as deep as 250 km. Ritsema (1966) reviews many fault plane solutions, finding that the horizontal stresses are compressional in both the crust and mantle. However, in deep earthquakes (150-200 km), the most predominant motion is thrust faulting. For shallow events, he notes that the fault plane mechanisms are in close agreement with fault lines on the surface. Figure 17 was published by Ritsema (1966) and shows the average fault plane solutions of both deep and shallow earthquakes. The dashed line and s notation represents the solution for the shallower events while the solid line and d rotation represents the solution for the deep earthquakes.

The Pamirs, the region east of Garm, was believed to have first developed as a miogeosyncline in the Early Carboniferous. At the end of the Jurrasic the region changed from geosynclinal conditions to geoanticlinal conditions. This tectonic change was accompanied by folding, intense Alpine metamorphism and granitic magmatism (Dufour, 1972). This region consists of a high plateau of folded Cenozoic sediments. There are negative Bouger anomalies as large as -450 mgals found in the Northern Pamirs. Kosminskaya, et al. (1958) believes they are associated with large crustal thicknesses.

This region is also noted for its high seismicity. Most earthquakes are generally confined to the crust and occur at a depth of less than 70 km. The focal zone runs parallel to the east-west trend of the Pamir mountains. The

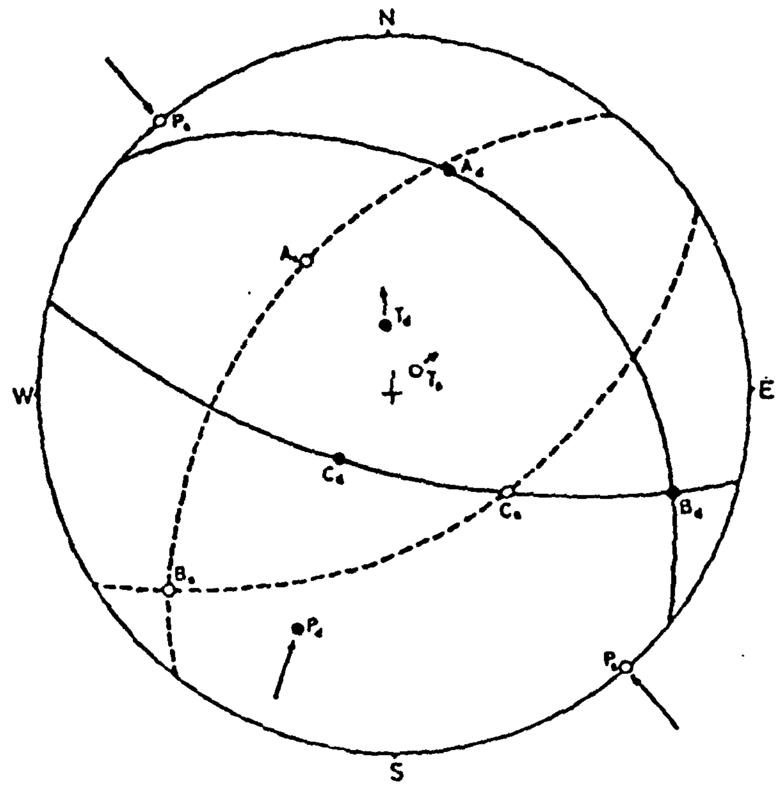

Figure 17. The average fault-plane solutions of deep and of shallow Hindu Kush earthquakes. (Taken from Ritsema, 1966.)

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predominant focal mechanisms found in this region are thrust faults and left lateral strike slip faults (Molnar, et al., 1973). These events, as well as all events in all of Central Asia, are believed to be a result of the ongoing Indian Eurasian collision (Molnar, et al., 1973; Molnar and Tapponier, 1975).

Patton's (1978) study of source and propagation effects of Rayleigh waves from Central Asian earthquakes uses the Pamirs as a reference point. The earth model used is shown in Table 1. It was derived from results of DSS studies done by Kosminskaya, et al. (1964) and Belyaevsky, et al. (1973). Patton reports that Kosminskaya, et al. (1964) found the crust near his reference point to be composed of two 30 km thick layers. The upper layer has a P velocity of 5.5 km/sec while the lower layer has a P velocity of 6.5 km/sec. Belyaevsky, et al. (1973) found crustal thicknesses as great as 65 to 70 km under the Pamir mountains just south of his reference point. Patton placed a 4 km sedimentary layer with a P wave velocity of 4.4 km/sec above the granitic and basaltic layer based on results of Arkhangel'skaya, et al. (1969), Molnar, et al. (1973), and Chen and Molnar (1975). The upper mantle was modeled after the Gutenberg earth model.

Vol'vovskii and Vol'vovskii (1978) published three cross sections taken along the Pamir DSS profile. All of these profiles show very consistent features. (Figure 18) is an east-west 300 km cross section. In the west, the profile starts slightly to the west of Mount Kharenski and

TABLE 1. LAYER PARAMETERS OF THE PAMIR EARTH MODEL

Depth, km	ρ, g/cm^3	α, km/sec	β, km/sec
0-4	2.41	4.41	2.55
4-30	2.66	5.50	3.18
30-60	2.90	6.50	3.76
60-80	3.36	8.10	4.51
80-90	3.37	8.07	4.46
90-100	3.38	8.02	4.41
100-125	3.39	7.93	4.37
125-150	3.41	7.85	4.35
150-175	3.43	7.89	4.36
175-200	3.46	7.98	4.38
200-225	3.48	8.10	4.42
225-250	3.50	8.21	4.46
250-300	3.53	8.38	4.54
300-350	3.58	8.62	4.68
350-400	3.62	8.87	4.85
400-450	3.69	9.15	5.04
450-500	3.82	9.45	5.21
500-600	4.01	9.88	5.45
600-700	4.21	10.30	5.76
700-800	4.40	10.71	6.03
800-900	4.56	11.10	6.23
900-1000	4.63	11.35	6.32

(From Patton, 1978.)

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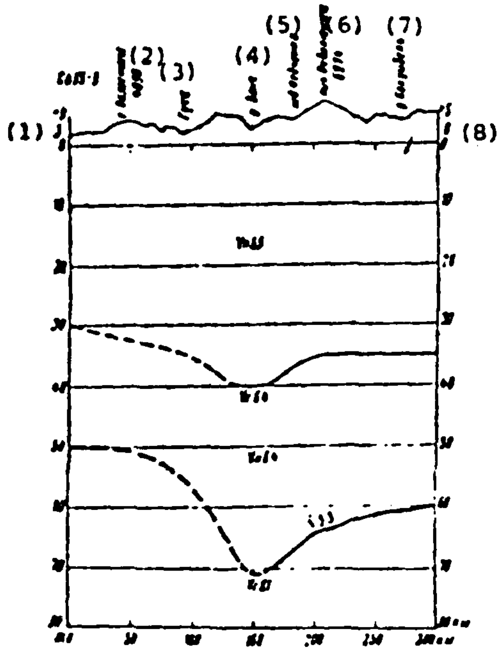

Figure 18. Seismic section of crust along Pamir III DSS profile (CA55-9). DSS point soundings (CMRW). Performed by IEP of USSR AS (1955). Authors: G. A. Gamburtsev, L. E. Aronov, P. S. Veitsman, V. A. Koroleva, I. P. Kosminskaya, G. G. Mikhota, Yu. V. Tulina, et al. (60). 1 = W; 2 = Mount Kharenshi 4090 (meters); 3 = Gucha; 4 = Vanch River; 5 = Fedchenko Glacier; 6 = Revolution Peak 6974 (meters); 7 = Kokuibel'; 8 = E. (Taken from Vol'vovskii and Vol'vovskii, 1978.)

ends to the east at Kohurbel'. The uppermost layer has a thickness of 30 to 40 km with a P wave velocity of 5.5 km/sec. The second layer has a thickness of 20 to 30 km with a P velocity of 6.4 km/sec. The depth to the Moho varies from 50 to 70 km and has a Pn velocity of 8.1 km/sec.

Tien Shan lies to the northwest of the Pamirs and is also associated with high crustal seismic activity. Molnar and Tapponier (1975) find both thrust and strike slip events in this region. However, thrust faulting is predominate.

Zunnonov, et al. (1974) review the results of the Farab-Tamdybulah DSS profile and combine this data with gravity, magnetics, and field geology to derive a model for southern and middle Tien Shan (Figure 19). The sedimentary layer varies between 0 and 7 km and has P velocities of 1.8 to 3.2 km/sec. The granitic layer is made up of bodies of basic to ultrabasic rocks, granitic bodies, Late Paleozoic granitic bodies and an Archean to Lower Proterozoic crystalline sequence. P velocities associated with each of these rock types range from 5.9 to 6.0 km/sec, 5.1 to 5.7 km/sec, 5.1 to 5.7 km/sec and 5.9 to 6.1 km/sec respectively. This entire layer appears to have a crustal thickness of 10 to 11 km. The diorite layer varies in thickness from 0 to 10 km and has a mean velocity of 5.7 to 5.8 km/sec. Within this layer there are layered segments that have velocities of 6.1 to 6.4 km/sec which correspond well with rocks of diorite composition. The basaltic layer is 17 to 25 km thick and has a P velocity of 6.6 to 6.9 km/sec which suggests that

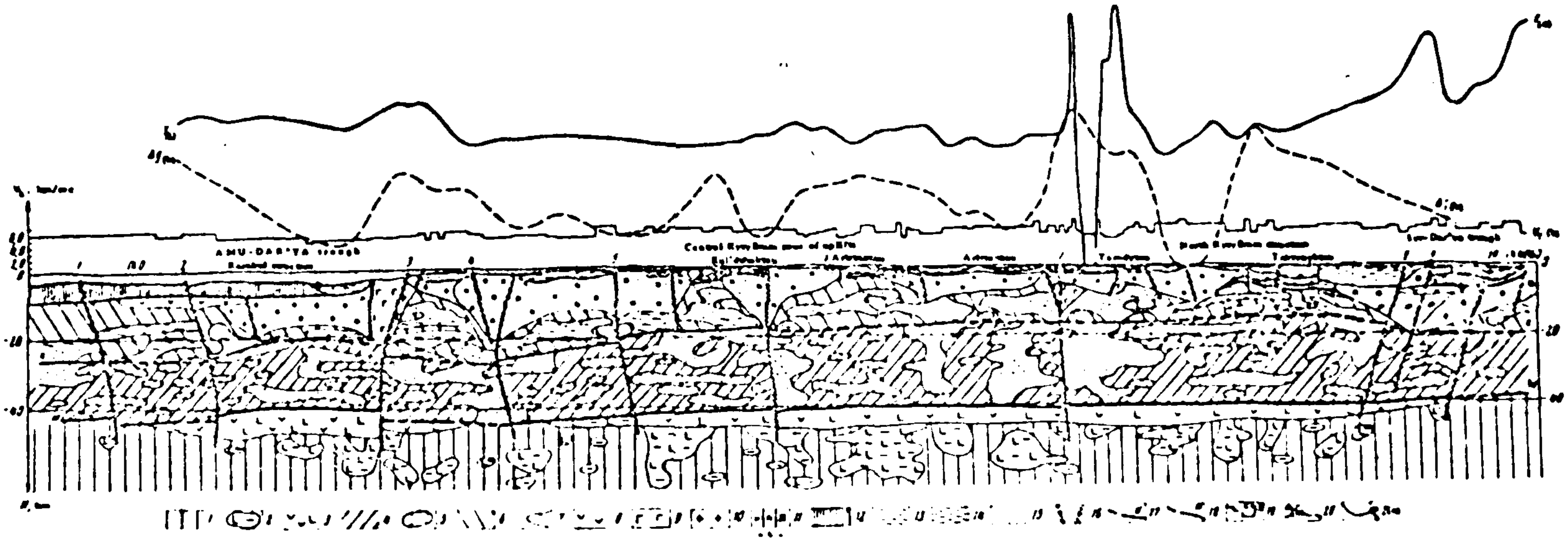

Figure 19. Geological and geophysical model of the crust and upper mantle along the Farab-Tamdybulak DSS profile. Upper mantle: 1) massive segments; 2) layered segments; 3) layer transitional from the crust to the mantle. "Basalt" layer: 4) massive segments; 5) layered segments with V_f = 6.6-6.9 km/sec. "Diorite" layer: 6) massive segments; 7) layered segments with V_f = 6.1-6.4 km/sec; 8) layer of basic rocks (metabasalts) with surface veolcity V_b = 6.5-6.8 km/sec. "Granite" layer: 9) bodies of basic to ultrabasic rocks with boundary velocity V_b = 5.9-6.0 km/sec; 10) granitic bodies presumably pre-Riphean, with $V_b \cong$ 5.1-5.7 km/sec; 11) Late Paleozoic granitic bodies (a, geosynclinal; b, teleorogenic;

Figure 19 continued. c, volcano-plutonic granitic rocks), V_b = 5.1-5.7 km/sec; 12) Archean (?)-Lower Proterozoic crystalline sequence, V_b = 5.9-6.1 km/sec. "Sedimentary" layer: 13) Riphean to Vendian terrigenous rocks, V_b = 4.8-5.8 km/sec; 14) Paleozoic volcanic-sedimentary rocks, V_b = 4.1-6.6 km/sec; 15) Meso-Cenozoic sedimentary mantle with mean velocity V = 1.8-3.2 km/sec; 16) faults; 17) K-surface; 18) M-surface; 19) graph of boundary velocity corresponding to basement surface; 20) curve of gravity anomalies; 21) curve of magnetic anomalies. (Taken from Zunnonov, Akhmedzhanov, Borisov, and Ergeshev, 1974.)

this rock consists of gabbros. The total crustal thickness for this section ranges from 38 to 45 km.

The Altai-Sayan mountain region lies to the northeast of Tien Shan. Masarskii, et al. (1976) discuss the tectonics of the region. In summary, the most common rock limits are Paleozoic sedimentary and igneous formations as well as PreCambrian metamorphic outcrops. This region developed as a geosyncline which experienced folding from the Proterozic to the end of the Paleozoic. The Kuznetsk-Altai fault zone is located to the southwest of the Eastern Sayan Range. This fault divides this region into subregions which differ in their structures and in their age of folding. The most prominent features are the Altai uplift, the Eastern Sayan Khangai uplift, the Khakass-Mongolian depression and the Zaisan-Dzungarian depression.

Like the rest of Soviet Central Asia, the Altai-Sayan region is seismically active. However, due to its isolation it has been poorly studied. More recently, temporary seismic stations have been put into operation and are improving the Soviet's data base (Masarskii, et al., 1976). This region lies just to the northwest of Mongolian Altai which has been the site of several large earthquakes. The focal mechanisms of both 1905 ($M_S = 7.9$ and $M_S \cong 8.25$) suggest that they were pure strike slip (Okal, 1977) and the mechanism of the 1957 ($M_S = 8.0$) suggests a left lateral strike slip with a component of thrust (Okal, 1976).

The average deep seismic sounding model for Soviet Central Asia has a sedimentary layer of approximately 4 km with a P velocity of 4.4 km/sec. The granitic layer has a thickness of 28 km with an average P velocity reported to be 5.5 km/sec. The basaltic layer has an average thickness of 30 km with a P velocity of 6.5 km/sec (Vol'vovskii and Vol'vovskii, 1978). However, data from recent Russian translations indicate a low velocity layer in the crust for both arm (Chepkunas, 1971) and Tien Shan (Nersesov et al., 1970a). The average thickness of this layer is 12 km and is located at a depth of 14 km. P and S wave velocities are 5.5-5.7 km/sec and 3.2-3.4 km/sec respectively. Nersesov, et al. (1970b) state that the layer above this low velocity zone has P and S velocities that are 0.4-0.5 and 0.25-0.3 km/sec higher than those found in the low velocity layer.

Alekseev, et al. (1973) summarize a study done by Lukk, et al. (1970) where a low velocity zone is found in the upper mantle. The Pn velocity is 8.1 km/sec. P velocities increase steadily to 8.6 km/sec at a depth of 75 km below the Moho. At a depth of approximately 135-185 km, P velocities decrease to 8.1 km/sec. Deeper than this layer, velocities increase to 8.6 km/sec and continue to have a positive gradient.

According to Antonova, et al. (1979) Lg waves propagate in Central Asia north of latitude 35. The Tibetan massif is a sharp boundary for the disappearance of Lg. Weaker boundaries exist along the Hindu Kush Karakorum arc and Kopetdag foothill depression. Lg is attenuated whenever its path crosses Parmir-Hindu Kush and Tien Shan. Ruzaikin, et al. (1977) find that although Lg has weaker arrivals for paths across Tien Shan, the waves still have a high frequency content and their amplitudes are large. This requires a high crustal Q in the Tien Shan region.

CRIMEA-CAUCASUS

Crimea-Caucasus region is located to the southeast of the Ukrainian shield and includes the Crimean Mountains, the Caucasus Mountains, the Carpathian Mountains, the Black and Caspian Seas. This is a region of alpine folding that formed at the turn of the Tertiary and during the Quaternary. This region is characterized by significant fluctuations in the thickness of the sedimentary layer as well as the consolidated strata. The crustal thickness ranges from 18 km in the Black Sea to greater than 55 km in the Caucasus. Thin crust occurs when the sedimentary layer increases to 15-20 km and lies directly on thin basaltic layers. A thicker crust occurs when the basaltic layer thickens. Where this occurs, the velocity in the lower part of this basaltic layer increases to 7.5 km/sec, possibly indicating a basalt-eclogite composition. The crust in this region is broken up into different blocks by deep faults. Each block has a slightly different geologic history.

This region is marked by zones of high seismic acticity which usually occur in the areas of large variation in crustal thickness (Belyaevskii, et al., 1972). To the north of the Black Sea there is an earthquake zone which dips at an angle of 60° beneath Crimea. This focal zone is believed to be related to a fracture that penetrates the crust down to a depth of 40 km. Seismic activity also occurs in the middle of the Caspian Sea when the crust changes from a continental crust into a transitional crust. This entire region has experienced uplifting due to the Alpine orogeny. In general, the present seismic activity of this zone increases in regions where the crustal blocks have greatly subsided.

The Carpathian fold region is a region of highlands. Sollogub, et al. (1973a) report on the finding of a DSS profile. They conclude that the depth to the Moho is approximately 30 km under the Inner Carpathians, while the depth to the Moho increases under the mountain structures but never surpasses 45 to 48 km. They suggest that this thickening is caused by the superposition of two different age mountain roots. The lower root formed from the submeridional Early Proterozoic mountain complex while the upper root formed from the northwestern Alpine mountains. The Peripieninian deep fault separates the Outer and Inner Carpathians. This fault has a total length of 550 km and extends from Vienna through the Carpathians (Poland, Czechoslovakia, and the USSR) into Romania. Belyaevskii, et al. (1972) reports that the Carpathian fold system is characterized by a deep basement (7 to 8 km) composed of primarily Precambrian gneiss and schist. The Moho in this region can be as deep at 55 km. In the axial zone, the depth to the Moho does not generally exceed 46-48 km.

In the Crimea, folding occurred in the Jurassic and Cretaceous and was followed by uplift and faulting in the late Tertiary and Quaternary. Along the southern coast of Crimea, there is present-day movement along the normal faults. Positive gravity anomalies associated with Crimea are probably due to the presence of a thin granitic layer (12-15 km). Neprochnov, et al. (1970) published a DSS profile which crosses part of Crimea (Figure 20). Because Crimea is surrounded on three sides by the Black Sea, most sounding done in this region seems to concentrate primarily on the Black Sea. In this profile (Figure 20), the sedimentary layer is absent, the granitic layer has a thickness of 13 to 17 km with P velocities between 6 to 6.3 km/sec. The basaltic layer has a thickness of 17 to 22 km with P velocities between 6.6 to 7.0 km/sec. Piwinskii (1979) summarizes deep seismic sounding findings which indicate a flat Moho with crustal thickness between 39 and 41 km.

The Caucasus Mountains have the thickest crust in the Alpine regio. ›nging between 35-57 km. The thickest crust is found under the eastern part where the sediment accumulation in the Mesozoic was most intense (Belyaevskii,

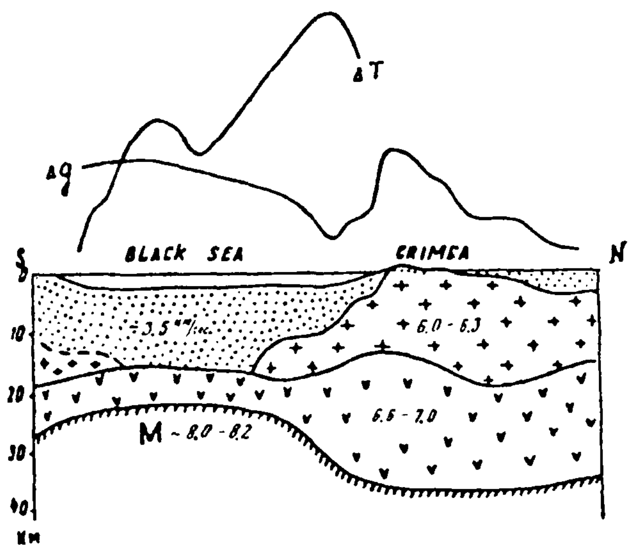

Figure 20. A cross section of the earth's crust in the central part of the Black Sea (Profile 17 in Fig. 23) and Crimea which borders on the Sea. (Taken from Neprochnov, Kosminskaya and Molovitsky, 1970.)

et al., 1972). The surface of the Moho exhibits great relief and dips below the Caucasus Mountains indicating the presence of a root zone. Seismicity, in general, follows the trend of the mountains (Nowroozi, 1971) and occurs in the crust. Earthquakes in the extension of this zone into the Caspian sea are subcrustal, depth range 50-150 km. There is both thrust and strike slip events, however, thrust faulting predominates.

Belyaevskii, et al. (1972) compiles an average crustal structure for the Caucasus Mountains. The sedimentary zone is absent. The granitic layer has a thickness of 20 km with P velocities of 5.6 to 6.0 km/sec. The basaltic layer is 35 km thick and P velocities in this layer are between 6.9 to 7.2 km/sec. The total crustal thickness is 55 km with a average P wave velocity in the consolidated crust of 6 km/sec. The Pn velocity in this region is 8.1-8.2 km/sec. Vol'vovskii (1978) reports a similar profile for the Caucasian meganticlinorium. The granitic layer is 20 km thick with a P velocity of 5.6 km/sec. The basaltic layer is 35 km thick with a P velocity of 6.9 km/sec. The average velocity in the consolidated crust is 6.4 km/sec and Pn velocities range between 8.1 to 8.2 km/sec.

Kosminskaya and Pavlenkova (1979) publish a schematic crustal cross section along the profile of the Kura depression which connects the Black and Caspian Seas (Figure 21). They believe that the Kura depression is an evolutionary link in the transformation of continental crust

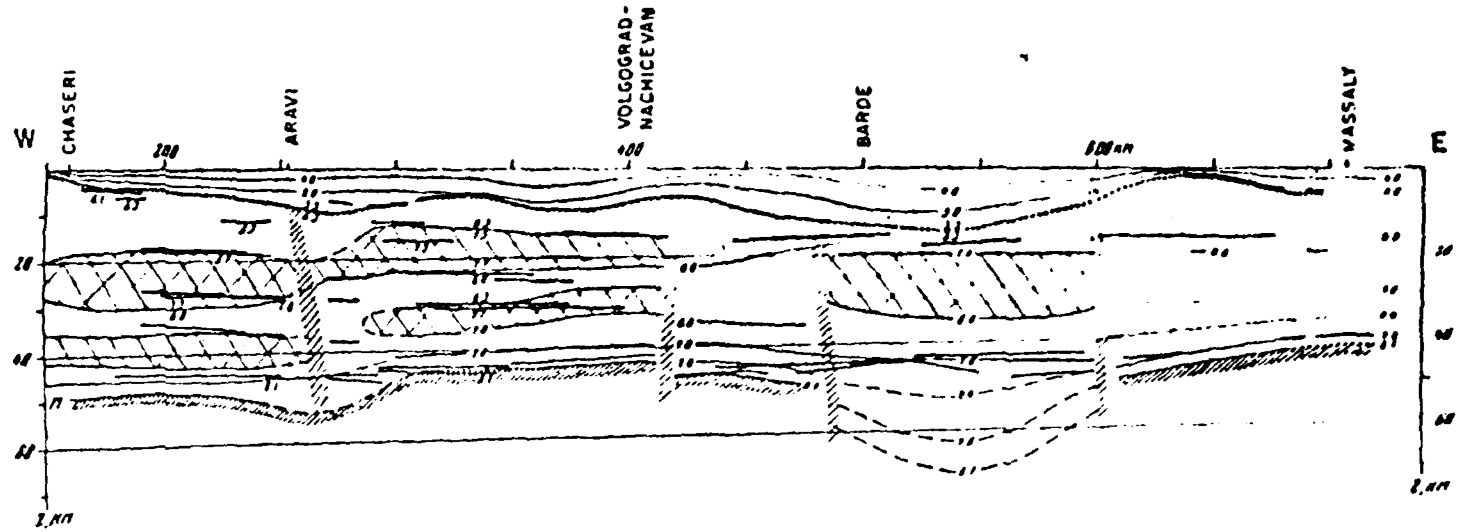

Figure 21. Seismic cross-section of the Earth's crust of the Kura depression (Caucasus). Same notations as Fig. 3. Bodies of increased velocity are shaded. (Taken from Kosminskaya and Pavlenkova, 1979.)

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into suboceanic. This depression is 40 km deep and is typical continental crust, however, there are high velocity layers inside the layers with P velocities of 6.8 to 7.5 km/sec. This rise in velocity makes the velocities in the depression close to velocities typically found in island seas.

Neprochnov, et al. (1970) summarize the deep seismic sounding findings for the Caspian and Black Seas. They both resemble small oceans, having a suboceanic crust. They are reported to have a low average seismic P velocity ranging from 3.0-3.5 km/sec. Crustal thickness vary, the average crustal thickness in the Caspian Sea is 40-45 im and is 25 km in the Black Sea. In the Caspian Sea, there is a thicker sediment accumulation and sediments here are folded, unlike the Black Sea where they are relatively horizontal. Negative Bouger anomalies are associated with the folded sediments of the Caspian Sea and positive anomalies are associated with the Black Sea. Epicenters in the Caspian Sea are located on the eastern coast near Kranovodsk and there are no recorded quakes in the deep part of the sea. Epicenters in the Black Sea are situated on the continental slope near the Crimean coast and similarly there are no quakes in the deepest part of the Black Sea. An important observation is that Lg waves do not propagate through the "graniteless" areas in the Black and Caspian Seas.

Neprochnov, et al. (1970) published an extremely useful article comparing the structure of the crust and upper mantle of the Black and Caspian Seas. Their figures include maps illustrating the depth to the Moho, depth of the sedimentary layer, depth of the granitic layer, and gravity and magnetic anomaly maps for the Black Sea (Figures 22-27). Figure 20 also shows a cross section of the crust in the Black Sea. The water depth in the Black Sea can reach as deep as 2 km in the central part of the sea. The sedimentary layer can reach as deep as 15 km with a P velocity of approximately 3.5 km/sec. The granitic layer is absent under the deepest part of the Black Sea indicating the presence of suboceanic crust. When the granitic layer is present, its thickness appears to range between 2 to 10 km and associated P velocities are 6.0-6.3 km/sec. The basaltic layer has a maximum thickness of less than 10 km. P velocities associated with this layer range between 6.6 to 7 km/sec. The Moho is found at a depth of approximately 25 km with a Pn velocity of 8 to 8.2 km/sec.

The entire Crimean-Caucausus province is very diverse. Average parameters in the crustal layers are summarized in Vol'vovskii (1978) for the mountainous regions indicating that the average sedimentary layer is 8 km thick with a mean P wave velocity of 4.0 km/sec. The average granitic layer is 15 km thick with an average velocity of 6.1 km/sec. The average basaltic layer is 27 km thick with a velocity of 6.8 km/sec. The average crustal thickness is 50 km with a Pn velocity of 8.2 km/sec.

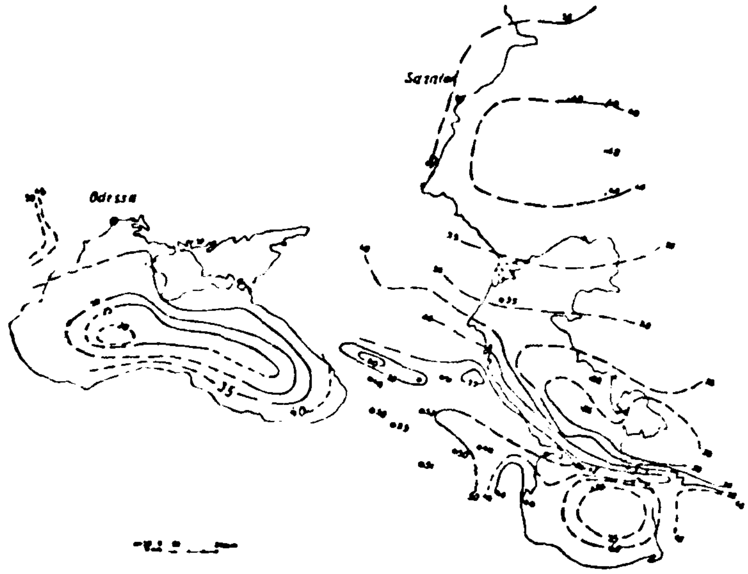

Figure 22. A map illustrating the depth of the Mohorovicic discontinuity in the region of the Black and Caspian Seas. (Taken from Neprochnov, Kosminskaya, and Molovitsky, 1970.)

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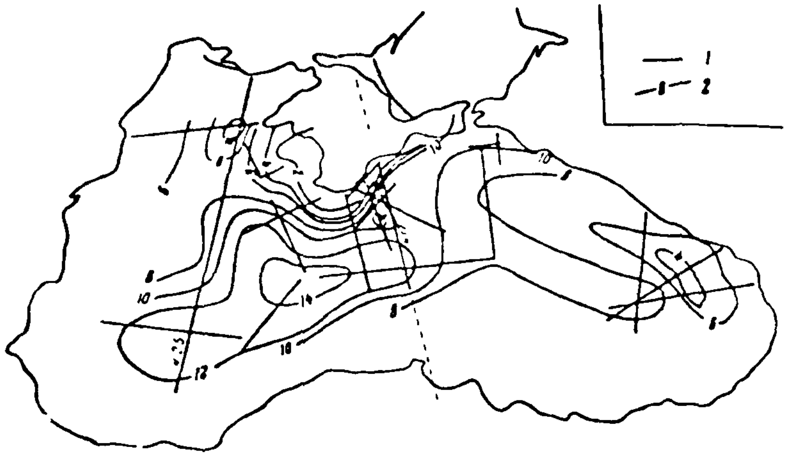

Figure 23. An isopach map illustrating the thickness of the sedimentary layers of the Black Sea Basin. 1 = DSS profiles; 2 = thickness in km. (Modified from Neprochnov, Kosminskaya and Molovitsky, 1970.)

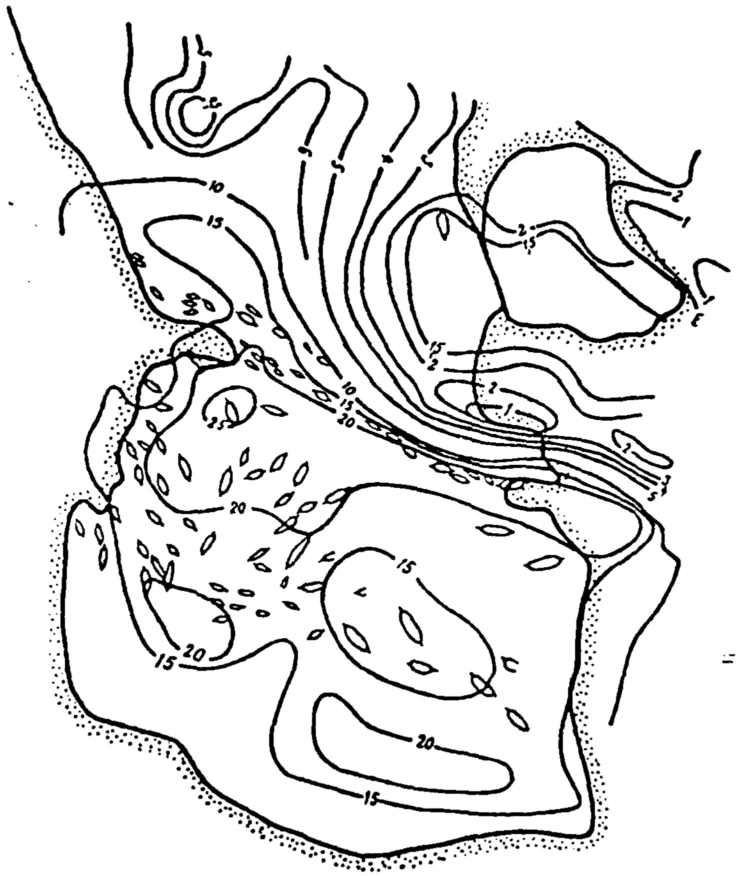

Figure 24. An isopach map illustrating the thickness of the sedimentary layer of the southern part of the Caspian Sea. (Modified from Neprochnov, Kosminskaya, and Molovitsky, 1970.)

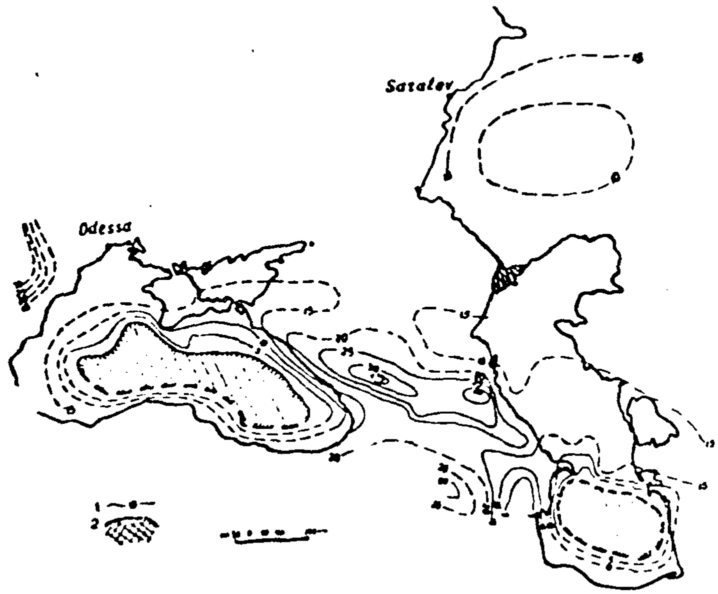

Figure 25. An isopach map showing the thickness of the "granitic" layer of the Black and Caspian Seas. 1 = thickness in km; 2 = areas without "granitic" layer. (Taken from Neprochnov, Kosminskaya, and Molovitsky, 1970.)

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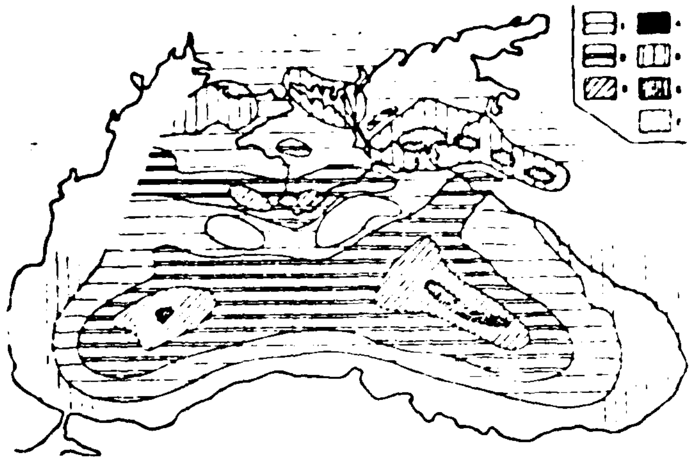

Figure 26. A Bouger anomoly map for the Black Sea. 1 = the high level anomalies; 2 = regional maximum; 3 = intensive maximum; 4 = peak of maximum; 5 = regional minimum; 6 = intensive minimum; 7 = relative minimum. (Modified from Neprochnov, Kosminskaya, and Molovitsky, 1970.)

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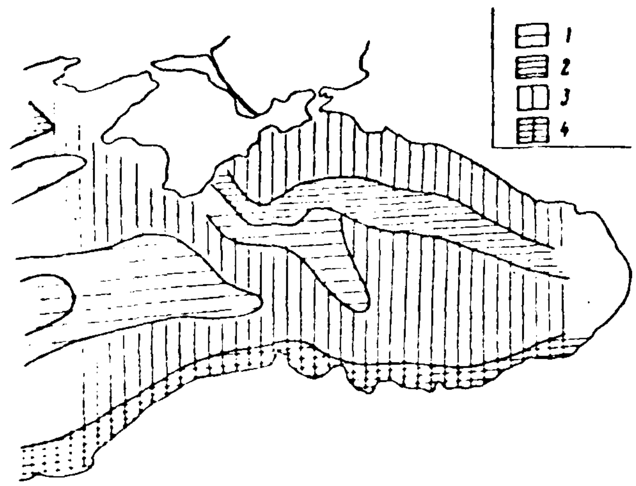

Figure 27. A map of the magnetic anomalies of the Black Sea. 1 = positive anomalies; 2 = intense positive anomalies; 3 = negative anomalies; and 4 = the interchange of the intensive positive and negative anomalies. (Taken from Neprochnov, Kosminskaya, and Molovitsky, 1970.)

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Similarly, the Black Sea has an average crustal thickness of 25 km. The sedimentary layer has an average thickness of 10 km. The average P velocity of this layer is reported to be 3.5-3.8 km/sec. The basaltic layer has an average thickness of 13 km with a P wave velocity of 6.4-6.8 km/sec. The Pn velocity is 8.0 km/sec. The sedimentary layer in the Caspian Sea area is 20 km thick with an average reported P wave velocity of 3.4-3.4 km/sec. The basaltic layer is approximately 23 km thick with a velocity of 6.6 km/sec. Pn velocities in the basin average 8.0 km/sec.

WESTERN SIBERIAN PLATFORM

The Western Siberian Platform is located to the east of the Urals and to the northeast of Kazakh. Alverson, et al. (1969) summarize the geology, tectonics, and structure. They believe that the platform has been generally stable since the Paleozoic. The margins of the platform have undergone geosynclinal deposition and orogeny in north-trending belts, with Riphean folding in the east, early Proterzoic folding in the south, and late Paleozoic folding in the west and the north. For the most part, the basement is not exposed. It is believed that the center of the platform is composed of possibly Pre-Cambrian gneiss, the eastern part of low grade Riphean schist, and the southern and western part of weakly metamorphosed Paleozoic sediments and volcanies. Triassic sandstone and basalt as thick as 500m are found near the eastern flank of the Urals. Lower

Cretaceous clastics which are coal-bearing are found to the south and can be as thick as 500-1500 meters. Most of the platform is covered by a Jurassic clastic sequence which ranges from 200-600m. The general characteristics and tectonics of the Western Siberian Platform are not very well documented in the literature. Refererences on the whole are fairly sparse in comparison with other regions.

Patton (1978), in his thesis, summarizes the results of Fotiadi and Ladynin (1974). Covering seismic data for the Siberian Platform and the Far Northeast, Fotiadi and Ladynin constructed a contour map of Moho thicknesses. They find that the Moho is 40-45 km thick under the Western Siberian platform. This region is sandwiched between areas of thinner crust, 35-45 km under the southern region the crust thickens to 45-50 km east of Lake Balkhash (in Kazakh province).

Knopoff (1972, 1977) finds that the properties of the mantle of the Siberian platform are highly consistent with those of the Baltic and Siberian shields and with ancient shields observed worldwide.

Vol'vovskii (1978) summarizes the findings of deep seismic sounding in the Western Siberian platform. He reports that the total crust is an average of 38 km thick and has an average crustal velocity of 6.5 km/sec. The crust has three layers. The sedimentary layer which is 3 km thick has an average P wave velocity of 4.2 km/sec. The granitic layer is 16 km thick with a P velocity ranging from

6.2-6.4 km/sec. The basaltic layer is 19 km thick with a P velocity ranging from 6.8-7.1 km/sec. Pn velocities are reported to range from 8.0-8.1 km/sec. He also states that the Western Siberian platform has the thinnest crust of all ancient and young cratons. The basaltic layer over the entire platform predominates slightly over the thickness of the granitic layer with the average granitic/basaltic ratio ranging between .7 and .8. The clearest exception is found in the Khanty-Mansusk depression where the granitic layer is thicker than the basaltic layer with a granitic/ basaltic ratio of 1.4.

Pavlenkova, (1979) also summarizes DDS observations done by pointwise observation (Figure 28). He finds that the average crust ranges from 40-42 km. The sedimentary layer is 3 km with a reported P velocity of 5.5 km/sec. The granitic layer is 22 km thick with a P velocity of 6.5 km/ sec. The basaltic layer is 15 km thick with a P velocity of 7.0 km/sec. He states that the average Pn velocity is 7.9 km/sec as taken from Puzyrev and Krylov (1971).

Puzyrev, et al. (1964) published a profile along Khanty-Mansusk to Ust'Tym (Figure 29). The topmost layer in this profile corresponds to the sediments and has a thickness of approximately 3 to 4 km. The P velocity associated with this layer is 2.6 km/sec. The next layer is discontinuous and has a thickness of approximately 2 km with a P velocity of 5.2 to 6.0 km/sec. The granitic layer has a thickness of 10 to 20 km and has an average velocity of 6.4

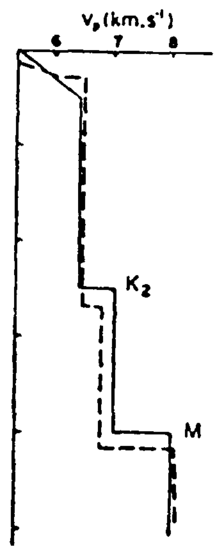

Figure 28. The variation in longitudinal velocity with depth in the West Siberian platform. (Modified from Pavlenkova, 1979.)

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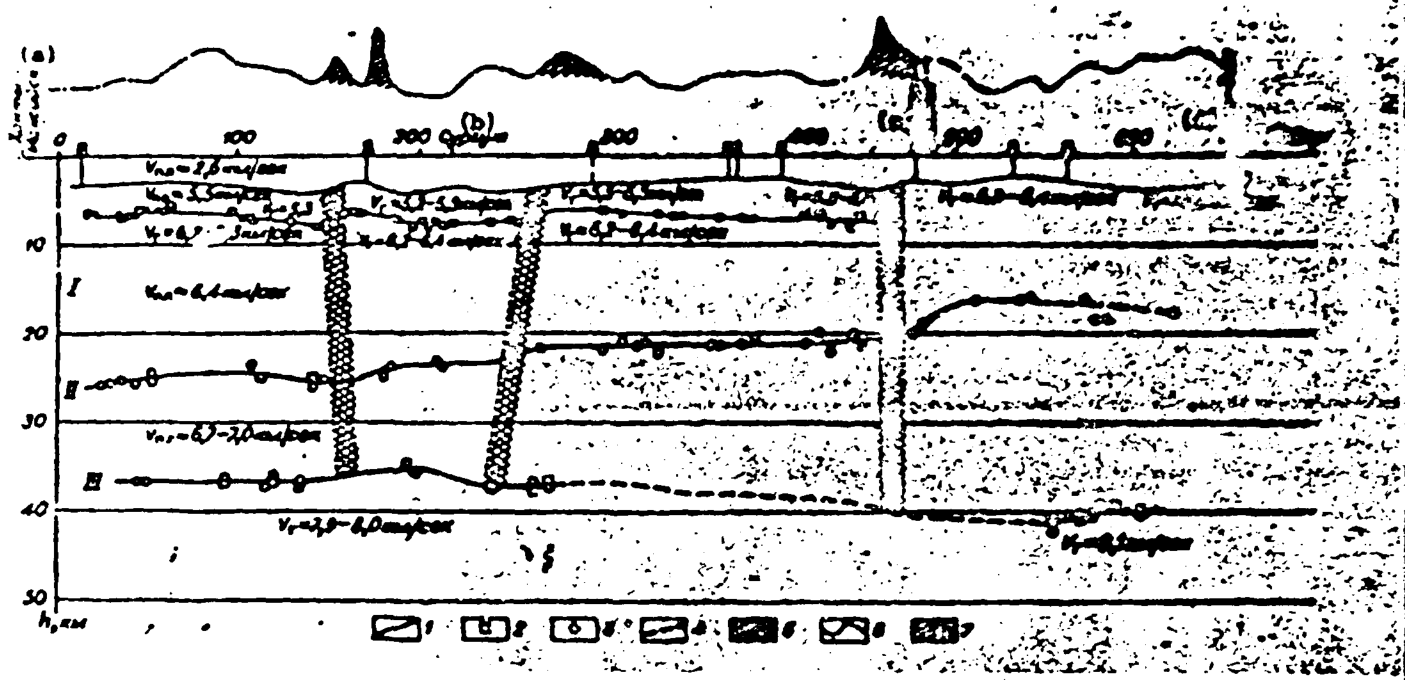

Figure 29. Crustal section according to data of point seismic observations. 1 = seismic boundaries; ϕ = surface of basement; I, II = horizons within the crust, III = Moho; 2 = depths according to refracted waves; 3 = depths according to data on reflected waves; 4 = sections of boundaries constructed with allowance for gravitational data; 5 = presumed deep fracture zones; 6 = plot of ΔT_a; anomalies reaching into linearly extended zones. a = Khanty-Mansiisk; b = Surgut; c = Aleksandrovskoe; d = Ust'-Tym. Read v_{nn} as v_{layer} and v_r as $v_{boundary}$ (km/sec). (Taken from Puzyerev, Kondrashov, Krylov, and Potaplev, 1978.)

km/sec. The basaltic layer has a thickness of 10 to 22 km with a P wave velocity of 6.7 to 7.0 km/sec. The crustal thickness in this region varies from about 35 to 40 km and associated Pn velocities range from 7.9 to 8.1 km/sec.

Finally, Piwinskii (1979) summarizes the West Siberian platform with the following conclusions. The crust is crudely layered and its thickness ranges from 34-47 km. There are several deep fracture systems that penetrate both the crust and upper mantle. The Moho is flat or exhibits only mild relief with Pn velocities ranging from 7.9-8.2 km/sec.

SIBERIAN PLATFORM

The Siberian Platform is a massive province which lies east of the West Siberian Platform and west of the Pacific Transitional Zone. The Siberian Platform consists of several subregions. Alverson, et al. (1969) synthesize most of the geology and tectonics of this region. Most of the geologic review of this platform will be from their synthesis, other references will be interjected.

The Central Siberian Platform is an immense block which has been generally stable since the Proterozoic and at its western margin since the Riphean orogeny. The basement was formed predominantly by folding and metamorphism of Archean and Proterozoic foldbelts and by accretion of Riphean foldbelts.

The Anabar Shield is an Archeozoic structure which consists of a complex system of folds, intensely compressed and often isoclinal (Nalivkin, 1960). Alverson, et al. (1962) report that basement is exposed and is generally composed of Archean gneiss, granulite, granite, and anorthosite intrusions.

According to Nalivkin (1960), the Aldan Shield is upper Proterozoic platform structure. It has many simple large folds with definite strike as well as some breaks and second order folds. Metamorphism in the shield is weak due to folding. Solonenko (1979) reports that the shield is between 2.64 and 2.34 billion years old. There are many large faults near the Stanovoy structural suture which extends hundreds of kilometers in an east-west direction. Additionally, there are large amounts of basite and ultrabasite intrusions.

The Vilyuy Basin and Angara-Lena Trough formed in the south at the end of the early Cambrian when intense folding ended geosynclinal activity.

In the Carboniferous and Permian, the northwest Tunguska Trap Field subsided and received continental coal-bearing deposits. Extensive trap fields were formed by the time of the Triassic due to intensive fracturing and injection of basic magma. The Tunguska Trap Field is underlain by Upper Permian and Lower Triassic tuff, and tuffaceous sandstone interbedded with sandstone and shale which is approximately 300-500 meters thick. Additionally, this area has been injected by many diabase intrusions.

To the east of the Central Siberian Platform is the Verkhoyansk and Chaun-Chukotsk Foldbelt. This area is composed of Paleozoic and Mesozoic geosynclines. Folding began in the Jurassic and ended in the Early Cretaceous at the Okhotsk-Chuhotsk volcanic area. The basement in this area is composed primarily of strongly metamorphosed Pre-Riphean schist, quartzite and marble. Late Cretaceous rhyolites and related volcanic rocks 1.5-2.5 kms thick are found on top of folded geosynclinal rocks. Kochetkov (1976) reports that the Central Siberian platform is separated from this folded region by extended deep faults. Additionally, this contact is characterized by young folded rocks on the platform boundary indicating movements expressed by the assymmetry of the folds.

Kochetkov (1976) reports that this region is seismic whereas the platform is nearly aseismic. There are many deep faults situated within folded regions of Stanovik-Dzhugdehur and in the marginal parts of the Aldan Shield. There has been repeated movement along these faults forming folds of several orders, ancient uplifts and sunken blocks bounded by deep faults.

To the north is the Kolyma-Omolon stable block which has been predominantly a platform region since early Proterozoic. An uplift occurred in the Mesozoic followed by a period of faulting and volcanism. In the west half of the block is about one to three kilometers of Ordovician and Silurian clastic and carbonate rocks overlain by one to two kilometers of Devonian acidic and intermediate lavas and tuff with some interbedded continental clastic rocks. In the east, the basement is overlain directly by upper Devonian volcanic sequence one to three kilometers thick and a lower carboniferous clastic-carbonate sequency as much as 1 km thick.

Piwinskii (1979) summarizes the findings of DSS in the Siberian Platform. In the vicinity of Norilsk, the crust is crudely layered and has a thickness ranging from 35 to 40 km. Near the Aldan Shield, there is also crude layering with crustal thicknesses ranging from 40 to 47 km. In both of these regions there are no deep fracture systems penetrating into the upper mantle. The crust in the vicinity of the Irkutsk amphitheater and Yakutsk have similar properties. The crust is crudely layered with thicknesses ranging from 33 to 46 km. The surface of the Moho in both regions is almost flat, exhibiting little relief. Additionally, deep fractures penetrate down to the upper mantle which result in a block-like structure. In the region of the Tunguss Syncline and in the northeastern folded regions the crust is slightly thinner with thicknesses of 29 to 39 km. Several deep fractures also occur in these regions. Several fractures penetrate as deep as the upper mantle in the Tunguss Syncline while only one fracture penetrates into the upper mantle in the northeastern folded region.

Vol'vovskii (1978) summarizes the average P velocities derived from DSS data. In the Tunguss syncline the velocities are as follows: 3.2 km/sec, 6.2 km/sec, and 6.9 km/sec for the sedimentary, granitic, and basaltic layers respectively. In the Irkutsk amphitheater they are: 5.1 km/sec, 6.1 km/sec, and 6.8 km/sec respectively. In the Aldan Shield they are: 3.2 km/sec, 5.8 km/sec, and 6.8 km/sec respectively.

Puzyrev, et al. (1973) report on a DSS profile in the Siberian Platform near the Baikal Rift Zone (Figure 30). The sedimentary layer is approximately 3 km thick with a P velocity of 5.1 km/sec. The granitic layer is 14 km thick with a P velocity of 6 km/sec. The basaltic layer is approximately 20 km thick with an average P velocity of 6.4 km/sec. The Pn velocity is reported to be 8.1 km/sec.

BAIKAL RIFT ZONE

The Baikal Rift Zone is located to the south of the Siberian Platform. Solonenko (1978) believes that it is a branch of the Central Asiatic seismic belt. In the east near the southern part of the Aldan shield it forks and forms two individual branches. The Dzhugdzhur branch extends toward the Sea of Okhotsk and the Verkhoyansk branch swings northwest and stretches toward the Arctic Ocean rift system. The most outstanding features of this province are the rift systems and a low velocity upper mantle.

Solenenko (1978) and Logatchev and Florensov (1978) discuss the evolutionary stages of the Baikal Rift development. Logatchev and Florensov (1978) break this region's

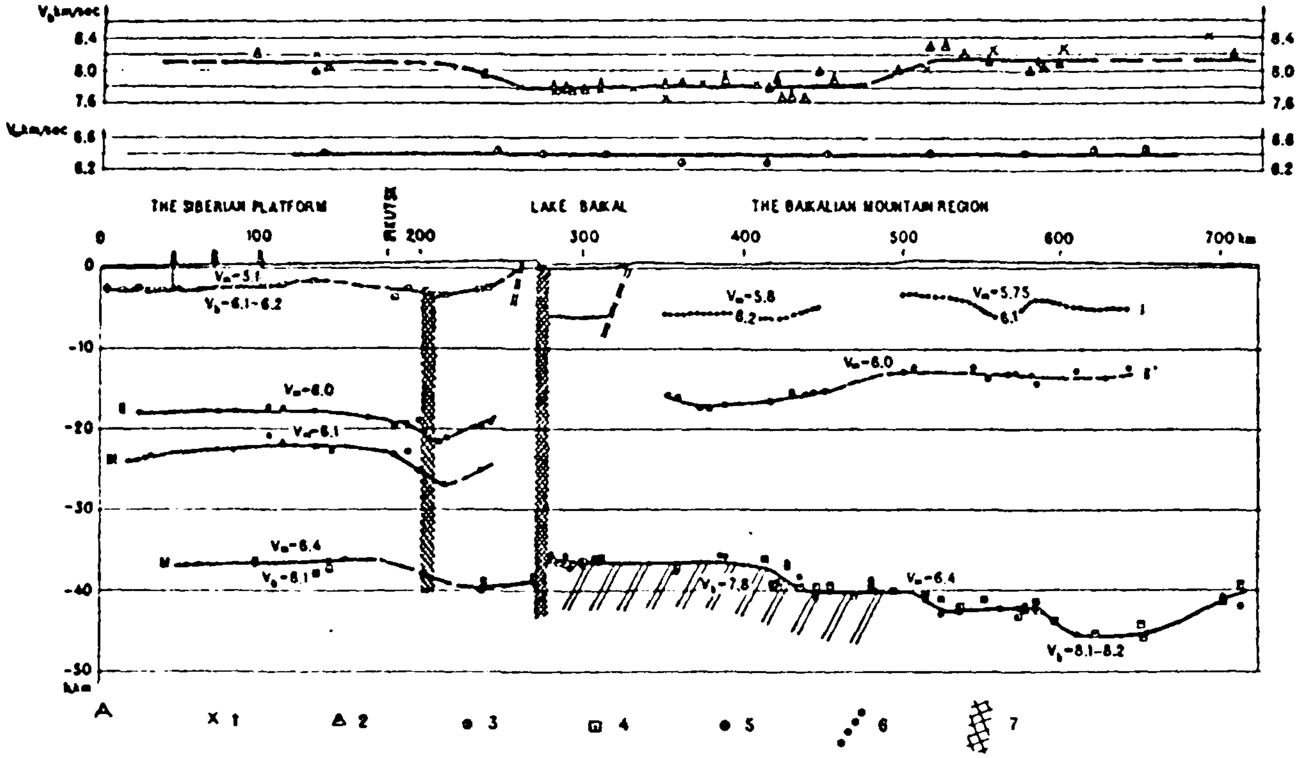

Figure 30. Seismic cross-sections of the crust and uppermost mantle (bottom) and velocity graphs (top) for profile I. I = boundary velocity below the M-discontinuity from refraction data; 2 = same as I from reflection and refraction data; 3 = average velocity in the crust from reflection data; 4 = depths determined from refraction data; 5 = same as 4 from reflection and refraction data; 6 = isolines of layer velocities (in km/sec) from diving (continuously refracted) waves; 7 = assumed zones of deep fractures; V_b, V_m = boundary and average velocity in km/sec; M = Moho discontinuity; Φ = basement surface of the Siberian platform (near coordinate origin o/o in A); II, III = boundaries within the crust. (Taken from Puzyrev et al. 1973.)

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evolution into two stages but stress that no other continental rift system possesses as large a number of young rift depressions at different contemperaneous evolutionary stages. The first stage of development is marked by weak or moderate tectonic movements and mostly slow plastic deformations of the basement. The rift zone morphology was determined by vast but shallow proto-rift basins surrounded by subdued lands and volcanic plateaus. Lacustrine and river sediments such as clay, silt, sand, tuff, limestone, marl and diatomite accumulated in the slowly subsiding basins. At this stage, the usual thickness of sedimentation is 1,000 to 4,000 meters.

The second stage of development is marked by the domination of brittle deformation with displacements along large normal and thrust faults. The uplift continued during the Pleistocene when the highest areas were covered by glaciers. The proto-rift basins deepened into symmetric or one-sided grabens. During this stage, especially in the Quaternary, extensional faulting of the crust in the Baikal-Stano part of the zone resulted in the formation of new and shallow rift valleys. In the second stage, the sedimentary thickness is between 1,000 and 1,200 meters but the sediments are of coarser composition consisting primarily of sandy sediments deposited in lakes and wide piedmont fans. Early in the Pleistocene, the individual deep lakes joined together forming Lake Baikal.

Solonenko (1968) views the rift development following the succession from incipient to embryonic to mature to aborted depressions. Incipient depressions are graben sinks which are superimposed on uplifted terrain. Some of these depressions formed during the late Pleistocene, but most developed during the Holocene. They are typically 0.6-12 km long, tens of meters to 800 meters wide, and tens of meters to 1100 m deep. Incipient depressions are found only where paleoseismic indicators show that there have been earthquakes with magnitudes larger than 7.75. Presently, numerous earthquakes have been located in these depressions wth their foci 25 to 30 km deep. Incipient depressions are also usually confined to the most uplifted sectors of arch-block, arch-fault and horst structures.

Embryonic depressions formed since the Pliocene with a typical sediment thickness of 300 to 400 meters. There are chains of embryonic depressions along the eastern branch of the rift zone. They are usually less than 300 km long and are between 5 and 6 km wide. Faulting can occur along either boundary. Large earthquakes are generated beyond the visible area of these depressions and can occur to depths of 40 km. These structures are subsiding and growing laterally at what is believed to be at the expense of the mountain structures. This is illustrated by the June 27, 1957 Muya earthquake (M = 7.9, h = 22 km) when the Namarket embryonic depression subsided 5 to 6 meters as well as shifting westward.

Mature depressions range in size from tens of kilometers to 670 km long, from 10 to 70 km wide, and from 2 to 7 km deep, occasionally reaching as deep as 8 to 8.5 km. The Baikal depression is widening; during the 1862 magnitude 7 earthquake, a crustal block approximately 260 km^2 subsided in the epicentral zone which resulted in the formation of the "Proval" Gulf (203 km^2). During the Central Baikal earthquake of 1959 (M = 6.8), Lake Baikal subsided by another 10-15 meters.

Aborted depressions are morphologically similar to embryonic ones. Some of them began forming after the neighboring large depressions but for one reason or another their development has stopped.

In the Baikal Rift Zone the most reliable indication of active rifting comes from high seismic activity of extensional type. This results from crustal fracturing caused by tensional forces acting perpendicular to the strike. Gravity anomalies suggest that the crust under the larger depressions is thinned compared with the surrounding ridges (Zorin, 1971). There is also a difference in crustal thickness in this region. The crust is 34-35 km thick under the deeper part of the Baikal depression but is as thick as 42 to 46 km under adjacent regions (Puzyrev et al., 1974).

Zorin and Rogozhina (1978) have a theory for the mechanism of the rifting. Zorin, et al. (1975) reported that high heat flow coincides spatially with the rift depressions. There are three possibilities suggested to explain this observation. The first is that the crust under the rift zone must be more heated and therefore more susceptible to plastic deformation and necking under an applied extensional stress. Secondly, the rift depressions are probably located in segments of hotter crust. Finally, mantle material might be rising along zones of deep faulting (Zorin, et al., 1975). The next part of their theory is that the rift depressions begin with deep faulting. When there is a separation occurring across these faults, rising mantle material heals the suture and heats the adjacdent crustal rocks which then deform plastically. After a period of cooling, new faults are formed and then this entire process is repeated. There is no basaltic volcanism in Baikal-type depressions except Tunka. Additionally, there are weak positive gravity anomalies found right over rift depressions even when corrections are made for sediments and variable crustal thickness. Zorin and Rogazhina (1978) believe that this is due to a relatively dense asthenosphere. Finally, they believe that a rift zone can only be formed where the anomalous low velocity mantle material has penetrated through the normal asthenospheric layer causing heating and thinning of the lithosphere.

Puzyrev, et al. (1978) compiled both explosion and earthquake seismology data to characterize the upper mantle. Included is their Moho map (Figure 31). One purpose of this map is to show that the central part of the rift zone has a highly variable crustal thickness compared with neighboring

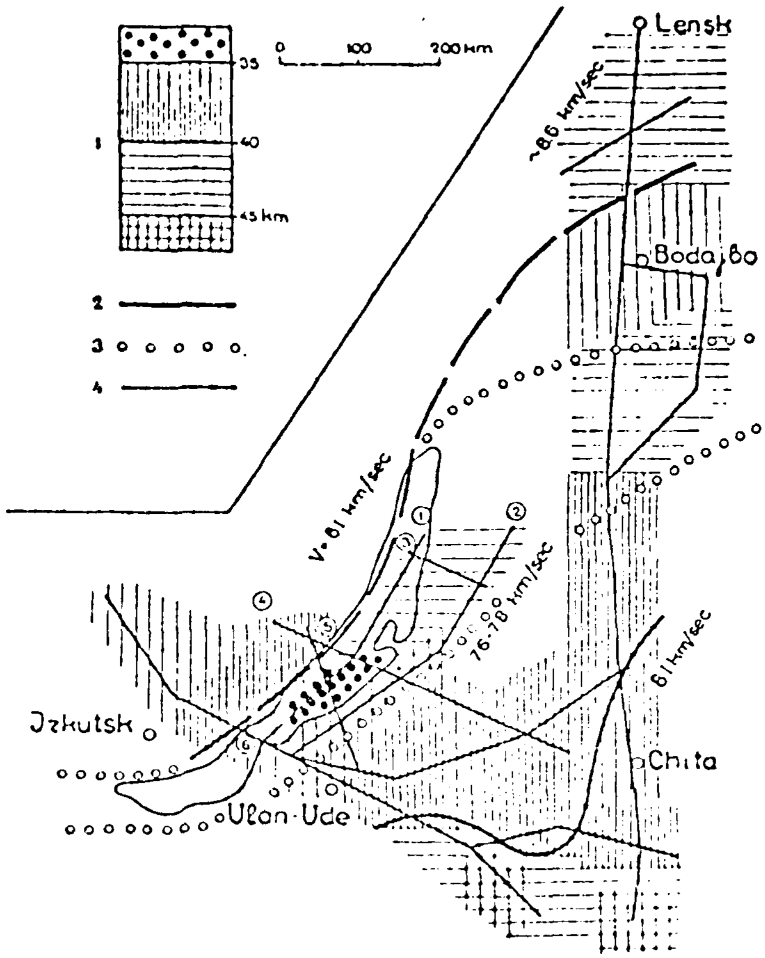

Figure 31. Schematic diagram of the upper mantle structure in the Baikal region. 1 = depth scale to the mantle surface; 2 = limits of the region with anomalously low velocity (upper surface); 3 = limits of the rift zone from geological data; 4 = DSS profiles. (Taken from Puzyrev, et al., 1978.)

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regions which are less tectonically active. In the rift zone depths to the Moho vary from 34 to 48 km. Nearby in the Siberian Platform and in Zabaikalye the crust varies in thickness from 37 to 39 km and 39 to 42 km respectively.

This figure also highlights the variation of the crustal thickness within the rift zone. In the northern part of this zone the depth to the Moho is relatively constant with the crustal thickness ranging between 42 and 44 km. This occurs under the eastern part of Baikal, under the Barguzin depression, and under the Barguzin range. To the south, the crustal thickness varies from 35 to 44 km. Puzyrev, et al. (1978) believe that this variation is due to a peculiar combination of a root and a superimposed antiroot. Similarly, this is also found in two parts of the southern Baikal sub-basin near Olkhon Island and the Sele..ga River delta. Along the Chita-Lensk profile of the Muya depression the maximum depth of the Moho is 43 km.

Puzyrev, et al. (1978) use this figure to map out the region of the anomalous upper mantle which has an area of approximately 200,000 km^2. They report that the upper mantle in this zone is formed by a layer with an average thickness of 17 km with an anomalously low P velocity of 7.6-7.8 km/sec. Below this low velocity layer, normal mantle with P velocities ranging between 8-8.1 km/sec is found for a layer that is 25-30 km thick. Below this normal layer, another low velocity is found which extends from a depth of approximately 80 km to a depth of about 150 km. P wave velocities in this low velocity zone range from approximately 7.6-7.8 km/sec. Outside of this area, Pn velocities are normal (8.1-8.2 km/sec), and increase to 8.6 km/sec in the Lensk region. As also pointed out in Figure 31 the area of this anomalous mantle is 2-3 times wider than the rift zone as defined from the surface geology.

Additionally, Puzyrev, et al. (1978) compare results of seismic studies with data on other continental rifts such as the Basin and Range, the East African Rift System, and the northern part of the Rhine graben (Figure 32). Intracrustal low-velocity layers appear to typify all of these regions except the East African Rift system. In the Baikal Rift Zone this layer is found at a depth of approximately 8 km and extends to a depth of 15 km. P velocities in this layer are approximately 6.2 km/sec. P velocities are normal both above and below this layer with an average velocity of 6.2 km/sec and 6.6 km/sec respectively. Pn travel-time curves are also generally similar for all of these regions. This thickness of the low velocity layer in the upper mantle averages from 15 to 30 km in these regions. The basic difference between the Baikal Rift Zone and the other continental rift zones is that the low velocity upper mantle layer is relatively thin.

Sherman (1978) classifies faults in this region into three major groups. Figure 33 from Sherman (1978) is a schematic map of the faults in the rift zone. Major faults are longer than 80 km long which is approximately two times

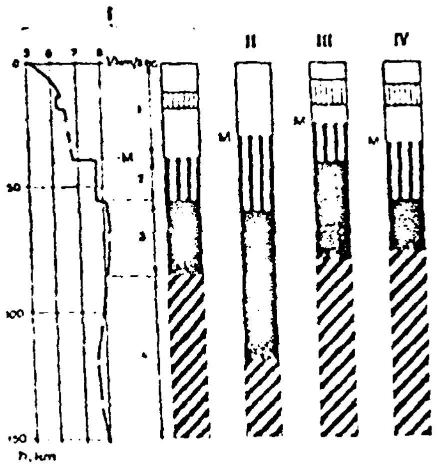

Figure 32. Columns of P wave velocities for continental rift zones: I = the Baikal zone; II = northern part of the East African zone; III = northern part of the Rhine graben; IV = North American Basin and Range Province. 1 = the crust (the dashed portion is an interval with a low P wave velocity); 2 = upper mantle layer with anomalous low velocity (7.7 km/sec); 3 = mantle with normal velocity (8.0-8/2 km/sec); 4 = low velocity zone; M = Moho discontinuity. (Taken from Puzyrev, et al., 1978.)

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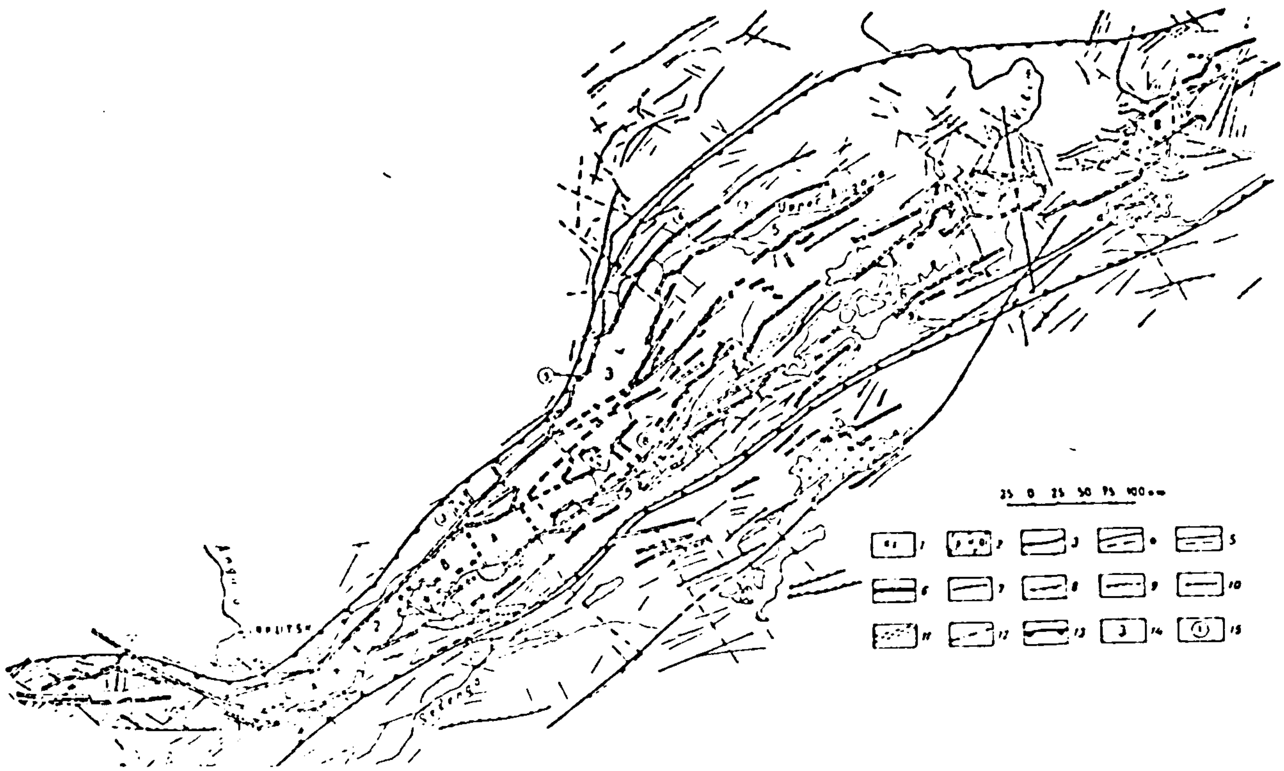

Figure 33. Schematic map of faults in the Baikal rift zone. Legend: 1 = Cenozoic sedimentary formations; 2 = Cenozoic basalts; 3 = deep and major faults; 4 = regional faults; 5 = local faults; 6 = faults rejuvenated in the Cenozoic, and Cenozoic faults proper; 7 = normal faults; 8 = oblique-slip faults; 9 = thrusts and overthrusts; 10 = tear faults; 11 = zone of intensely fractured rocks; 12 = faults distinguished from geophysical data, but not yet verified by geological mapping; 13 = the rift zone boundary; 14 = major depressions of the rift zone: 1-Tunka, 2-South Baikal, 3-North Baikal, 4-Barguzin, 5-Upper Angara (Verkhnya Angara), 6-Ysipa-Baunt, 7-Lower Muya, 8-Chara, 9-Tokka; 15 = faults referred to in this paper: (1) = Main Sayan, (2) = Tunka, (3) = Primorye, (4)= Sarma, (5) = Yelokhin, (6) = Kitchera, (7) = Upper Angara (Verkhnya Angara), (8) = Barguzin, (9) = Tsipa-Baunt; (10) = South Muya, (11) = Kodar fault system, (12) = Udokan fault system. (Taken from Sherman, 1978.)

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the mean thickness of the crust in this zone. There are six major fault zones in this region with the largest fault zone being the Main Sayan Fault (approximately 1000 km long). All major faults, which were rejuvenated in the Cenozoic, have a strike-slip component. This strike-slip component is not parallel to the northeasterly strike of the rift zone.

Regional faults range in length from 30 to 80 km. Normal faults are the most numerous in this group, however, oblique-slip faults are also important members of this group. Local faults are only a few hundred meters to several kilometers long.

The Baikal Rift Zone is a fairly active seismic zone. Golenetsky and Misharina (1978) state that the largest earthquakes (M>8) can be expected to occur within the entire region ($1.5x10^6 km^2$) at a rate of one in 150 years. Recurrence rates for earthquakes with magnitudes 7-8 are expected once in every fifty years and events (M>6) are expected once in every 15 years. The earthqukes are believed to be associated with rifting processes. Many large events are located in Northern Mongolia and appear to be much rarer in Zabaikalye. Golenetsky and Misharina (1978) believe that the seismically active area of northern Mongolia is spreading into South Zabaikalye. In the last 250 years, twenty large earthquakes (M>6.5, some reaching 7.5) have been recorded in the Baikal Rift Zone. The epicenters are usually concentrated into linear belts which outline aseismic or weakly seismic crustal blocks. Most of the earthquakes in these zones are oriented along the strike of the main rift structures.

Earthquakes occur in this region as individual shocks (including the aftershock sequence) or in swarms (Baraguzin area). Golenetsky and Misharina (1978) believe that the swarms occur in regions that have been previously seismically active. These swarms are of various durations; some lasting from a few days to others lasting over a period of several years. Additionally, smaller earthquakes are believed to be located primarily in the upper part of the crust.

Golenetsky and Misharina (1978) also report that there is a regional trend in the orientation of the stress axes of Pribaikal earthquakes with magnitudes larger than 4. These mechanisms show horizontal tension acting mainly perpendicular to the strike of the surface structures. There has also been a study of earthquakes with magnitudes smaller than 4. The stress released by these earthquakes are controlled by local geological conditions (Misharina, et al., 1975).

In the central part of the rift zone which includes Lake Baikal and extends northeast along the basin-and-range system of the Victim River, rift-type stress fields prevail. The compressional axes in the earthquake foci are near-vertical and tensional axes are near-horizontal and approximately perpendicular to the strike of the surface structures (Golenetsky and Misharina, 1978). Normal faulting in this region is predominant, however, there are local variations of the stressfield. At the end of the rifts the stresses are inconsistent. To the southwest, the foci are like those found near the central part of the rift system. To the northeast the opposite stress pattern is dominant (i.e., compressional axes near-horizontal and parallel to the structural strike).

There have been many DSS studies in this region since 1968. This section will summarize some of the major findings. The average crustal velocity in this region has been reported to be 6.4 km/sec (Puzyrev, et al., 1973, Vol'vovskii (1978), Puzyrev, et al., 1978).

Puzyrev, et al. (1978) published a cross section that traverses the major tectonic structures in this region. This profile (Figure 30) crosses the southern part of the Siberian platform, the Baikal rift zone and the exposed folded regions of Baikalian, Caledonian, and Hercynian age. In the Siberian platform there are two reflecting boundaries. The first one is at a depth of 18-21 km and the second at a depth of 23-27 km. The average velocities down to these discontinuities are 6.0 km/sec and 6.1 km/sec respectively. To the east, there is a 70 km wide crustal block that comprises the transitional zone between the Siberian platform and Lake Baikal. The crust in this zone is slightly thicker. There are two reflecting boundaries found in his crustal block that rise towards Lake Baikal. To the east is Lake Baikal which is bounded by a deep fracture zone. The Moho rises from 39 km in the Siberian platform to 36 km under this lake. Pn velocities beneath the lake are 7.8 km/sec. To the southeast is the Baikalian mountains. This was a reflecting boundary found at a depth of 16 to 17 km/sec. Above this boundary P velocities are reported to be 6.0 km/sec. Further along the profile, the depth of the Moho increases to 46 km and Pn velocities rise to 8.1 to 8.2 km/sec.

Vol'vovskii (1978) gives average crustal structures for some areas in this region. In the Enisei meganticlinorium the granite layer has an average P velocity of 6 km/sec, the basaltic layer has an average velocity of 6.8 km/sec, and the consolidated crust has an average velocity of 6.4 km/sec. In the areas of Baikal folding, the average crustal thickness is 42 km. There is no sedimentary layer. The granitic layer is 18 km with a velocity of 6.0 km/sec while the basaltic layer is 24 km with a velocity of 7.8 km/sec. The Baikal Depression has a total crustal thickness of 36 km. The water layer is 2 km, the sedimentary layer is 4 km thick with a velocity of 5.3 km/sec, the granitic layer is 11 km thick with a velocity of 6.3 km/sec, and the basaltic layer is 19 km thick with a velocity of 6.7 km/sec. The Pn velocity under Lake Baikal is reported to be 7.7 km/sec.

Piwinskii (1979) summarizes the DSS findings in the following way. The crustal thickness is reported to be approximately 35 km beneath Lake Baikal but increases to 40-50 km in the Central Siberian Platform northwest of

Irkutsk. There are several deep fracture zones that penetrate the earth's crust and upper mantle with some going as deep as 120 km. These fracture zones separate the Baikal Rift Zone from the Central Siberian Platform. Piwinskii reports that the surface of the Moho is undulatory in this region. Pn velocities are reported to range from 7.6-7.8 km/sec under Lake Baikal. The majority of the hypocenters in this region range in depth from 20 to 30 km.

PACIFIC TRANSITIONAL ZONE

The Pacific Transitional Zone is a region of high seismicity which is located to the east of the Siberian Platform and consists of Kamchatka, the Kurile Islands, Sakhalin, and the Sea of Okhotsk. During the Cretaceous this province was a geosyncline. During the transition from the Upper Cretaceous-Tertiary the easternmost part of this region was uplifted. In the Olegocene this uplift was complicated by a system of northwesterly trending deep faults. This resulted in individual zones of uplift and downwarp which shaped the mid-Kamchatka trough, the Eastern Kamchatka Range and the Western and Eastern Kamchatka foredeeps (Fedotov, et al., 1976). The Kurile-Kamchatka volcanic arc and trench, which is the easternmost part of the province, began developing in the late Tertiary. Tuyezov, et al.(1968) believe that the westernmost border of this geosynclinal region coincides with the north and northwest limits of the Yuzhno-Okhotsh depression and with the east

Kamchatka anticlinorium. The westernmost part of the Pacific Transitional zone is a folded region which includes Primor'e, Sakhalin, Okhotsk Volcanic Region and western Kamchatka. The folding ended by the end of the Tertiary.

The Pacific Transitional Zone is characterized by a highly variable crustal thickness ranging from 8-43 km. There are four types of crust found in this region; continental, subcontinental, suboceanic, and oceanic. These crustal structures differ from each other with regard to the depth of the Moho and the number of crustal layers. There is a general trend of crustal thinning in the direction of the ocean. The broad boundaries for the different crustal types are listed below, however, there are exceptions to this division. According the Beliayevsky, et al. (1968), the Ussieri-Aradersky uplift limits the area of the continental crust in the east and the Kamchatka-Kurilshaya depression separates the oceanic crust in the west. In between these crustal types, there are transitional crusts. Subcontinental crust is found in the southern part of the island arc and suboceanic crust is found in the Sea of Okhotsk.

The geosynclinal region is characterized by higher seismicity and volcanism than the folded region. All four crustal types are found here (Figure 34). The region east of the Kuril Trench is a region of oceanic crust. The sedimentary layer is 1.-1.5 km thick with an average P velocity of 1.8-2 km/sec. The basaltic layer is 4-9 km thick

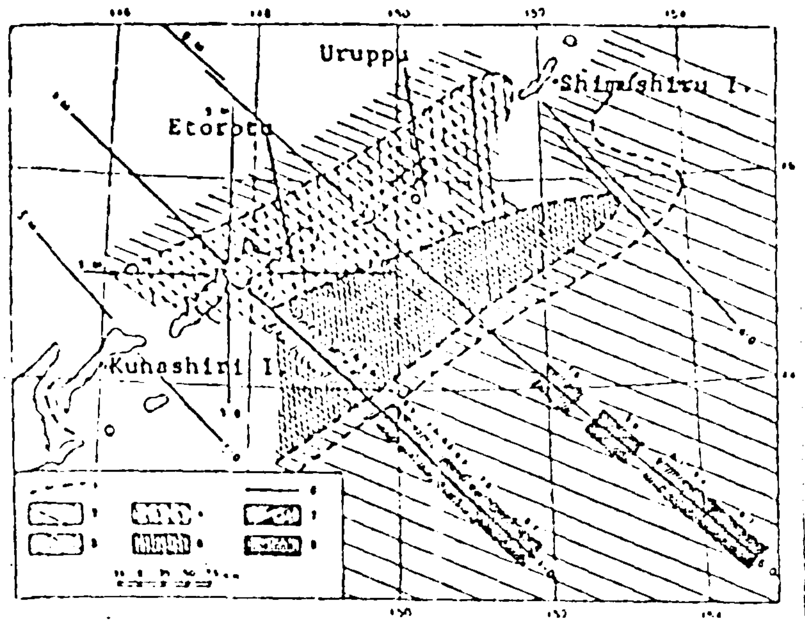

Figure 34. Location of 1957-1958 profiles in the Southern and Central Kurile Islands and zoning in accordance with types of crust in the area. 1 = approximate location of boundaries of regions with different types of crust; 2 = area with oceanic crust; 3 = suboceanic crust; 4 = subcontinental crust; 5 = continental crust; 6 = DSS profiles; 7 = areas characterized by normal values of Mohorovicic discontinuity velocities; 8 = same as 7, with above normal velocities. (Modified from Gal'perin and Kosminskaya, 1964.)

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with an average P velocity of 6.4-6.6 km/sec. Pn values alternate in this region between normal values of 7.8-8.0 km/sec and above normal values of 8.7-8.9 km/sec.

The southern part of the island arc which includes Kunaskiri, Shikotan, Etorofu and Urupper Islands and the adjacent shelf zone has subcontinental crust. The sedimentary layer is thicker than the sedimentary section in both oceanic and suboceanic crust. However, the basaltic layer (P = 6.3 km/sec) is different than either oceanic or suboceanic basaltic layers. The velocity is intermediate between a normal granite layer (V_P = 5.5-6.0 km/sec) and a normal basaltic layer (V_P = 6.6-6.8 km/sec). Where the continental shelf changes to the slope of the trench and the velocity in the basaltic layer increased to its normal value, a thin layer is found with a P velocity similar to a granite layer (5 km/sec). Additionally, this layer is found within the islands. In this region, Pn velocities are below normal and never exceed 7.5 km/sec. In summary, the average thickness of subcontinental crust is 20 km including a 4 km sedimentary layer and a 16 km layer consisting of material intermediate between granite and basalt.

There is continental crust found along the western flank of the trench characterized by a Pn velocity of 7.8-8.0 km/sec. The crust in this region reaches a maximum depth of 36 km and consists primarily of basalt. The unconsolidated sedimentary layer has an average P wave velocity of 2.8 km/ sec. The intermediate layer which is probably of volcanic origin has an average P wave velocity of 5 km/sec. This layer is not continuous over the entire region. It sppears in patches, for example, it is found near the Vityaz ridge where it has a thickness of 7 km.

The Yuzhno-Okhotska depression has suboceanic crust. There are only two crustal layers. The sedimentary layer is thicker than the oceanic sedimentary layers. The basaltic layer is as thick as the oceanic basaltic layer.

Chapman and Solomon (1976) summarize the tectonics of the North American-Eurasian Plate boundary in this region. In the oceanic regions, the plate boundary is defined by a narrow seismic belt possibly as small as 10 km in width. At the Eurasian continental margin the seismic belt widens to 300 km. Additionally, there is a broad seismic zone which extends from the Laptev Sea across the northeastern USSR to the northern Sea of Okhotsk. This zone is 600 km wide at its maximum width and includes both large and small earthquakes.

In Kamchatka, most faults are parallel to the Kurile Trench. Earthquakes associated with these faults are believed to be related to the subduction of the Pacific Plate. The Kronohi-Krutogorova fault zone is the only major fault system that trends in an east-west direction. In the Kronoki peninsula in east Kamchatka, the faults are right lateral with a maximum offset of 20-25 km. In the western portion of this fault zone the primary motion is left lateral.

The Kurile Trench is one of the most seismically active areas in the world and accounts for 80% of the seismicity in the USSR. Earthquakes are found as deep at 650 km.

Veith (1974) relocated earthquakes in the Kurile Trench as well as studying their focal mechanisms. The velocity model that he derived is shown in Figure 35. The velocities in the slab are found to be considerably higher than velocities at the same depth outside of the slab. There are five types of mechanisms (Figure 36). At all depths, transverse faulting occurs within the underthrusting Pacific Plate. Twenty percent of all earthquakes and one-third of all events deeper than 70 km are of this type. This mechanism allows for both the differential rate of convergence and the change in the dip of the plate along the arc. The second type of mechanism is shallow normal faulting which usually occurs on the oceanic side of the trench. The third type is thrust faulting which occurs along a narrow zone between the two plates down to a depth of 50 km. There is a region of low seismicity between 50 and 100 km as the source mechanism changes. The fourth mechanism occurs below 70 km in a narrow zone when the plate is in down dip compression. Finally, the fifth is down dip tension which occurs in a 30 km zone below the compressional zone between 70 and 200 km. Fedotov (1962) states that the majority of the seismicity occurs between 0 and 20 km. At a depth of 125 km, the activity falls to 10% of the activity between 0 and 20 km. At a depth of 250 km, the activity falls to 1% of the activity between 0 and 20 km.

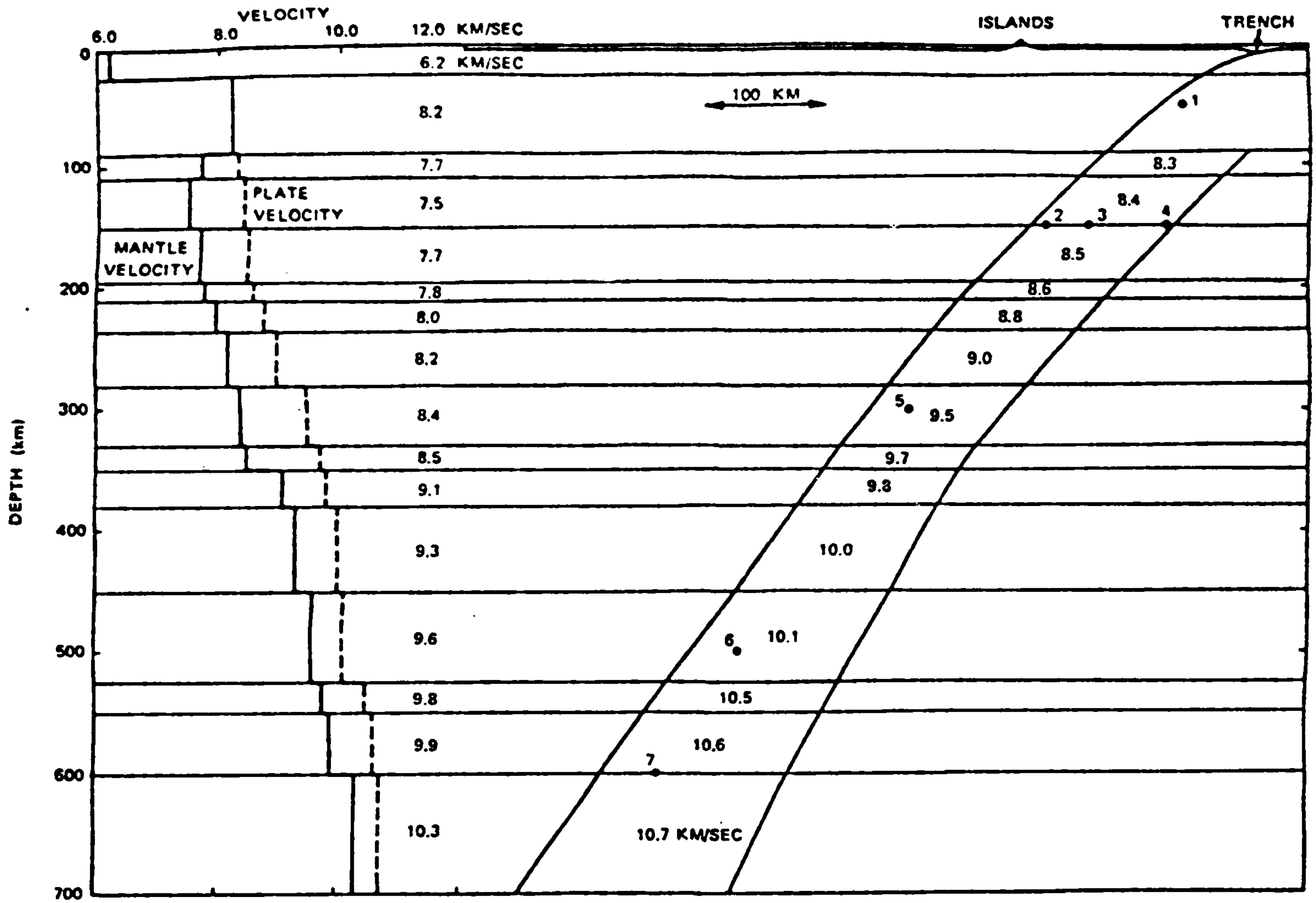

Figure 35. Velocity model for Kurile Islands. (Taken from Veith, 1974.)

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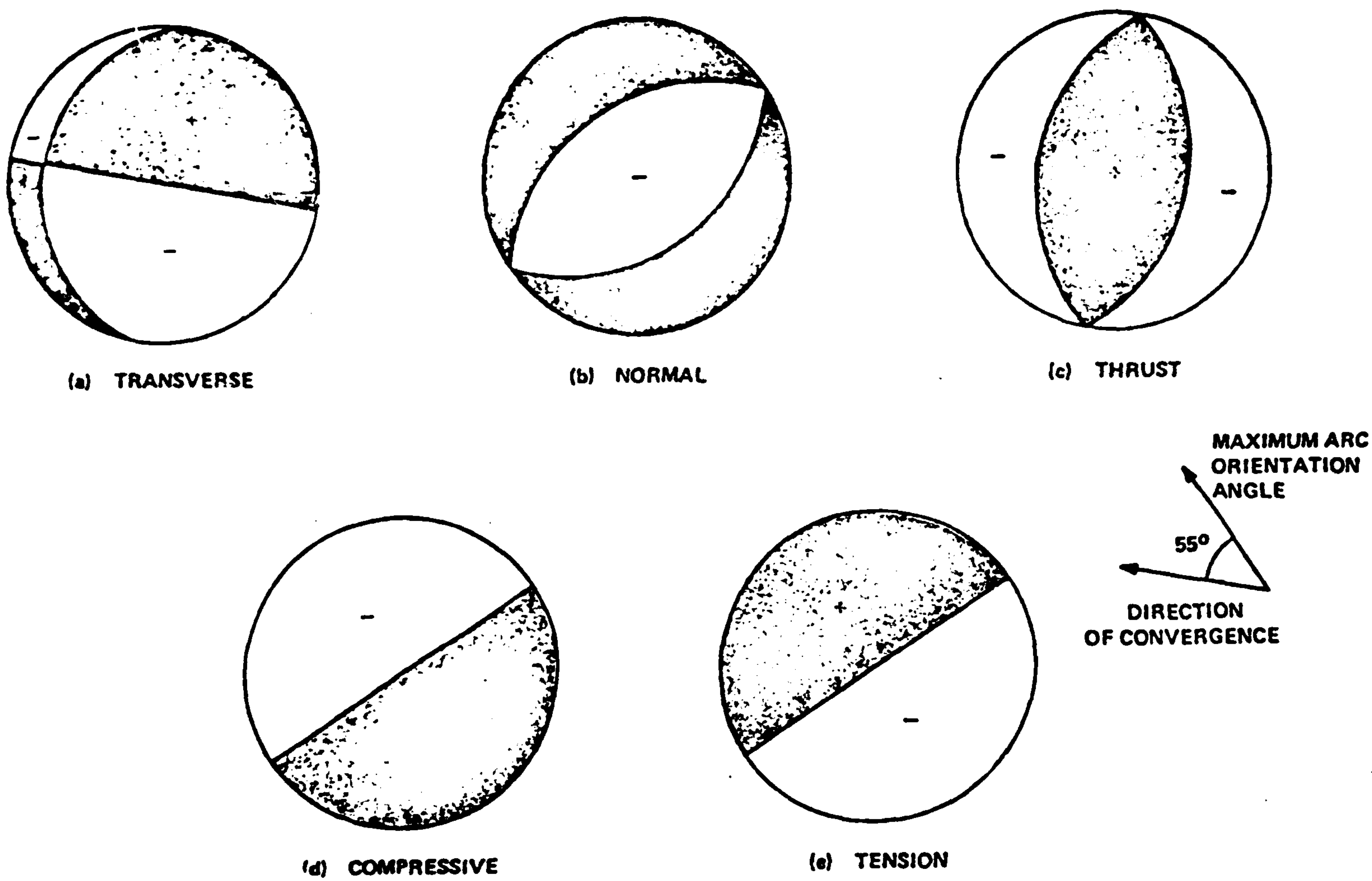

Figure 36. Lower hemisphere projections of the focal sphere for observed Kurile source mechanism. (Modified from Veith, 1974.)

Fedotov, et al. (1976) summarizes detailed seismological investigations of the South Kurile Islands. Seismic wave velocities under the islands are lower than usual at the crust-mantle boundary. The zone starts at 20 km and extends to a depth of 100 km. Pn velocities range between 7.5-7.6 km/ sec. In contrast Pn velocities under the Sea of Okhotsk range between 8.0-8.2 km/sec and Pn velocities larger than 9.0 km/sec are found under the ocean beyond the trench. In this mantle low velocity zone (P = 7.6- 7.7 km/sec) there is no wave guide. Data also suggest an increased absorption of seismic waves in the upper mantle at depth of 60 to 110 km, with maximum absorption occurring between 80-90 km. It is believed that this layer of high absorption is associated with partial melting.

Khadin (1976) divided the focal zone into four depth ranges: 0 to 20 km, 40 to 100 km, 110 to 150 km, and 160 to 250 km. For each of these zones, he calculated the mean Q . They were 220, 190, 200, and 270 respectively.

The folded region is characterized by large positive Bouger anomalies (rarely exceeding 100 mgals). The seismic activity, on the whole, in the folded region is lower than in the geosynclinal region but has regions of high seismicity. Sakhalin is a region of high seismicity. Primori'e and Okhotsk Sea were believed to be regions of no seismicity (Tuyezov, et al., 1968). However, recently with the installation of more seismometers, earthquakes with magnitudes of 4 or less have been found in the Okhotsk Basin (Chapman and Solomon, 1976).

The folded region has continental or suboceanic crust. The only region with suboceanic crust is the Sea of Okhotsk. Continental crust is found everywhere else and is characterized by crust with an average thickness of 30 km. Additionally, there is a granitic layer present with a maximum thickness of 7 km which is probably of volcanic origin (Gal'perin, et al., 1964; Tulma, 1969).

There have been several deep seismic sounding investigations of the Pacific Transitional Zone with the majority of the studies done in 1957-1958 and 1963-1964. They indicate that this region is complex and has a variety of different crustal structures.

The Sea of Okhotsk is a region of suboceanic crust, however, the North Okhotsk Basin resembles continental crust (Beliayevsky, et al., 1969). According to Rodnikov (1973), the sedimentary cover on the floor of the sea is comparitively thin and consists primarily of unconsolidated sediments. In the South Okhotsk Basin, there is a denser sedimentary layer of Cretaceous age beneath the bottom of the sedimentary layer.

The granitic layer thins toward the ocean until it vanishes in the South part of the Sea of Okhotsk (Rodnikov, 1973 and Piwinskii, 1979). Piwinskii (1979) claims that the granitic is also absent in the northcentral region while Rodnikov (1973) reports that the granitic layer exists here with P velocities exceeding 6 km/sec.

Beliayevsky et al. (1968) also report the existence of a granitic layer but with P velocities of 5.6-.6.00 km/sec. The basaltic layer has varying thicknesses. It has a minimum thickness of 57 km in the southern part of the sea where it makes up the majority of the crust and a maximum thickness of 20 km under the Sea of Okhotsk close to the margin of the Asian Continent (Rodnikov, 1973). In the thicker regions the P velocity is believed to range from 6.4-6.7 km/sec.

Including the water layer, the depth of the Moho varies from approximately 12 km to 30 km (Piwinskii, 1979; Zverev and Tulena, 1973). Vol'vovskii (1978) reports the following for the South Okhotsk basin. The water layer is 3 km, the sedimentary layer is 5.5 km and the basaltic layer is 3.5 km. Average P wave velocities are 3.5 km/sec in the sedimentary layer and 6.6 km/sec in the basaltic layer. Pn velocities are normal in the South Okhotsk Basin averaging 8.0 km/sec. Beliayevsky et al. (1968) also summarizes DSS findings for the Sea of Okhotsk. For the South Okhotsk Basin, P wave velocities are as follows: 2.4-3.0 km/sec in the sedimentary layer and 6.5-6.7 km/sec in the basaltic layer. The average crustal velocity is 6.6 km/sec and the average Pn velocity is 7.9-8.0 km/sec. In the northern part of the sea, the P wave velocities are as follows: the sedimentary layer is between 2.3 and 2.8 km/sec, the granitic layer is between 5.6-6.0 km/sec, and the basaltic layer is between 6.5-6.7 km/sec. The average for the consolidated crust is 6.2 km/sec and the mean Pn velocity is 8.0 km/sec.

Finally, Rodnikov (1973) states that most Russian scientists regard the nort and central part of the Sea of Okhotsk as an eastern extension of the Siberian Platform. The evidence for this comes from gravity and magnetic data, a constant crustal thickness of 25-30 km, and the parallelism of seismic interfaces (the surface of the consolidated crust follows the relief of the Moho).

Piwinskii (1979) in his summary of DSS in this region reports that the depth to the Moho varies between 8 and 26 km. Rodnikov (1973) reports that when the granitic layer is observed it is found at a depth of 45 km. It is usually 6-7 km thick under the major ridge and reaches a thickness of 5-6 km under the minor ridge of the arc. Vol'vovskii (1978) finds that the average cross section for the Kuril-Kamchatka trench has a 14.5 km crust. There is a water layer with an average depth of 3.5 km. The sedimentary layer is .5 km thick with an average P velocity of 2.4 km/sec. A granitic layer is absent. The basaltic layer has an average thickness of 14 km with a P velocity of 6.6 km/sec. The average Pn velocity was reported to be 8.0 km/sec.

Piwinskii (1979) reports the following conclusions about the crust in Kamchatka. The crustal thickness varies from 30-42 km but is thickest in central Kamchatka. The crust thins to the east and the west. There are three layers including a sedimentary-volcanoclastic sequence, a granite-metamorphic complex, and a basaltic sequence. Additionally, several deep fractures penetrate the crust and upper mantle.

Fedotov (1968) reports Pn velociteies for three regions in Kamchatka. Under the East Kamchatka mountain range the Pn velocity is 7.7 km/sec, under the active volcanit belt Pn is 7.2 km/sec, and near the eastern shore Pn is 7.9 km/sec.

Kuzin (1973) studied both P and S wave velocities in the upper mantle to the east of Kamchatka. In continental blocks, from 30 to 100 km, V_P ranged between 7.5 and 8.1 km/sec. Deeper than 100 km, V_P ranged between 7.9-8.1 km/sec. Similarly V_S ranged between 4.4-4.6 km/sec and 4.5-4.6 km/sec, respectively. For an oceanic block, V_P ranged between 4.5-4.9 km/sec and 4.5-4.6 km/sec.

Sakhalin is a region of continental crust. Gainanov, et al. (1968) report that beneath Sakhalin the depth to the Moho reaches 32 km in Sakhalin compared to 12 km to the east and 25 km to the west of the island. There are four layers that exist within the crust with average velocities of 4 km/sec, 5 km/sec, 6.1 km/sec, and 7.4 km/sec.

Rodnikov (1973) reports that the granitic layer in Sakhalin is usually thinner than 15 km. The upper part of the layer has P wave velocities ranging from 5.1-5.8 km/sec and is composed of igneous-sedimentary rocks which have undergone partial metamorphis to green schists. The bottom part of the layer has P velocities ranging from 6.0-6.4 km/sec and consists of gneisses, granites, and schists.

Beliayevsky, et al. (1968) reports the following average P wave velociteis for the three crustal layers: 2.4-3.0 km/sec, 5.8-6.0 km/sec and 6.7 km/sec. The average Pn velocity was reported to be 8.0 km/sec.

Finally, Vol'vovskii (1978) reports the average crust thickness for regions of Cenozoic folding is 28 km. This is considered to be the average for both Kamchatka and Sakhalin. The sedimentary layer averages 4 km with a P velocity of 2.5 km/sec. The granitic layer has an average thickness of 10 km with an average P velocity of 6 km/sec. The basaltic layer is 14 km thick with an average P velocity of 6.8 km/sec. The average Pn velocity is 7.9 km/sec.

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