DIGITAL DATABASE OF DEEP SEISMIC SOUNDING PROFILES IN NORTHERN EURASIA

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ABSTRACT

In several years of cooperation with the various successors of the Special Geophysical Expedition (Moscow, Russia) we produced a digital data set of seismic records from the unique program of ultra-long-range deep seismic sounding (DSS) profiling conducted in the former Soviet Union from the early 1970s through late 1980s. The program was unique in using peaceful nuclear explosions (PNEs) recorded along 3000-4000-km long, reversed, three-component seismic profiles. Each profile recorded one to four PNEs and several dozen chemical explosions at the same receiver locations. Long listening times of up to ~600 sec after the first arrivals allowed recording of the secondary phases (*S*, *Lg*, *Pg*, *Rg*) critical for nuclear test monitoring. The energies of the PNEs ($m_b \approx 5$) were sufficient for reliable recordings beyond 3000 km, which included consistent reflections from the mantle transition zone and several reflections from the core-mantle boundary. Chemical explosions of 5-12 tons yielded clear reflections from ~100-km depths and were recorded to 300-600-km distances.

The digitization efforts have resulted in 22 PNEs and several hundred chemical explosions now available through the Incorporated Research Institutions for Seismology (IRIS) data center. To date, complete sets of records from projects AGATE, BAZALT, BATHOLITH-1 and 2, CRATON, KIMBERLITE, RIFT, RUBY-1 and 2, and QUARTZ and SPAT were delivered in long-record Society for Exploration Geophysics (SEG-Y) standard format. For seamless data exchange with the test monitoring researchers, we have also incorporated the waveforms and ancillary data into the National Nuclear Security Administration (NNSA) database schema. Only three additional projects (BITUM, PRICASPIY, and PNE SPAT) recoverable from field magnetic tapes remain not included in the DSS PNE database.

Long-range DSS data sets provide nearly the only dense three-component recordings of regional phases in the aseismic regions of Northern Eurasia. PNE data sets cover the intermediate distance ranges (~0-3200 km) and bridge the gap between controlled-source and earthquake seismology. Dense, linear, and reversed systems of DSS observations lead to unusually detailed models of the crust and uppermost mantle over 4000-km long geotraverses. Our final objective is to combine these models in an unusually well-constrained, detailed, interactive three-dimensional (3-D) structural model of Northern Eurasia. The model can also be integrated with empirical phase calibration information, thereby leading to a unified calibration model of the region.

OBJECTIVES

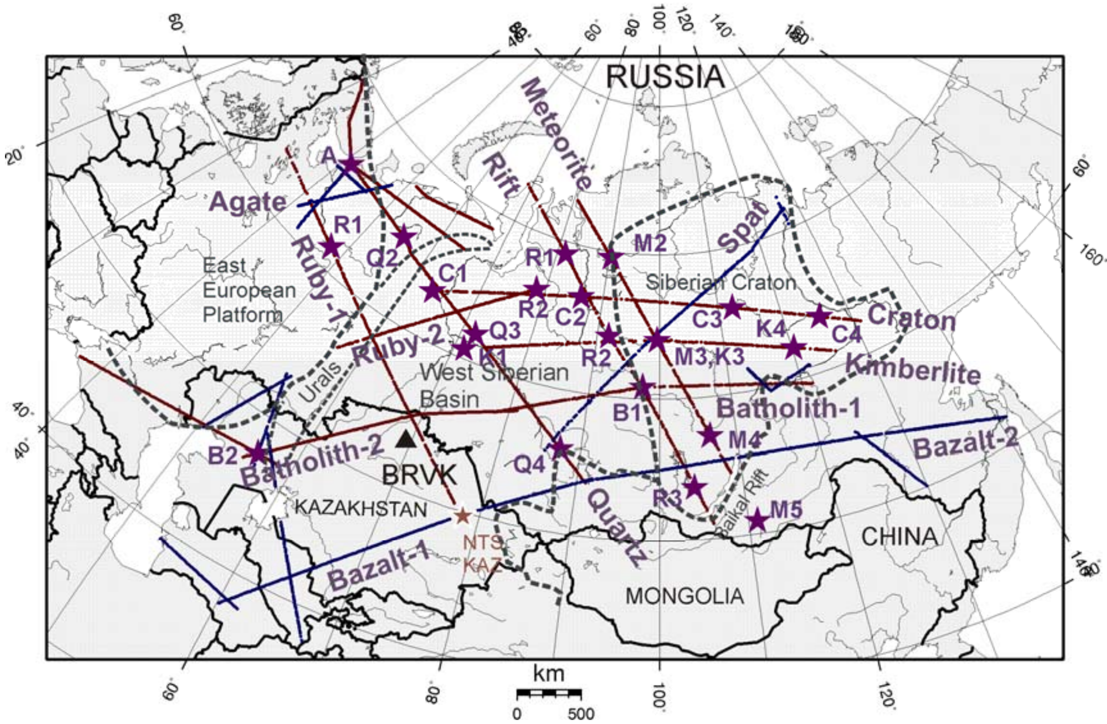

Figure 1. Twelve DSS PNE projects delivered to the public domain as a result of this project (blue labels). The PNEs (large stars) are labeled using the first letters of the corresponding profiles names and PNE number (for example, Q2 stands for PNE QUARTZ-2. PNE AGATE is shown without a number). Sultanov et al. (1999) reported the coordinates and other parameters of the PNEs used in these profiles. Colored triangles in the profiles represent the recording stations. Typically, 30-50 chemical explosions were also recorded in each profile. Major tectonic units are indicated. The Semipalatinsk nuclear test site is indicated (NTS KAZ), and the Borovoye IMS station is also shown (BRVK).

Note the extent of systematic, continuous profiling, with PNEs (labeled stars) detonated at the intersections of a two-dimensional (2-D) grid and recorded in two, and often in four, directions.

The objective of this research was to create digital copies of seismic records from most of DSS data sets preserved to date and to make them available for monitoring and broader seismological studies. This task was approached through long-term cooperation between the University of Wyoming (UW) seismology group and Center for Regional Geophysical and Geoecological Studies (GEON Center), Moscow (a division of Spetzgeofisika at the time of data acquisition, now a division of Vniigeopfisika). In this cooperation, the records were digitized at GEON, who also provided tables of channel amplifications and other information. We performed the consultations with GEON, as well as the data transfer, all the primary data reduction, reformatting, and quality control. The digital records were later submitted to IRIS and incorporated into its global on-line databases.

Twelve DSS PNE projects were selected for this work as the most important and most recent (Figure 1, west to east): AGATE, BATHOLITH-2, RUBY-1 and 2, BAZALT-1, QUARTZ, CRATON, KIMBERLITE, RIFT, METEORITE, BATHOLITH-1, and BAZALT-2. Later in the project, it became apparent that the chemical-explosion recordings from project METEORITE suffered too many data gaps, and the chemical explosion part of data set SPAT was obtained in replacement of the obligations of this project.

This report is a shortened version of the final project report submitted to the Air Force Research Laboratory (AFRL) in June. In the following section, we give a brief summary of the DSS program in the former Soviet Union, followed by a summary of the data sets and data deliveries. In *Conclusions and Recommendations*, we recap the importance of the DSS data preservation work and also describe its perspectives.

RESEARCH ACCOMPLISHED

The Deep Seismic Sounding Program in the Former USSR and Recent Studies of its Data

The DSS program carried out by Soviet scientists from the 1960s to 1990s remains a unique source of seismic data sets, allowing a detailed study of the seismic structure of the upper mantle. Long-range seismic refraction/reflection profiles covered nearly the entire territory of the former USSR, amounting to about 1/6 of the whole continental lithosphere (Figure 1). This unique network of geophysical profiles with an overall length of 150,000 km utilized nearly 60 PNEs specially designed and set up for seismic purposes, along with hundreds of powerful chemical explosions (Figure 1). The power of explosions ranged from tens of kilograms to 4,000-15,000 kg for the chemical explosions (Solodilov, 1997; Egorkin et al., 1991; Kozlovsky, 1990) and to 7-20 kiloton for nuclear explosions (Fujita, 1995; Sultanov et al., 1999).

Large chemical explosions and PNEs were recorded by densely spaced (10-15 km), 3-component, short-period (1-2 Hz) portable analog recording systems. The recording ranges of the PNEs exceeded 3200 km, allowing observations of seismic phases diving down to 800 km into the mantle (Egorkin and Pavlenkova, 1981; Ryaboy, 1989; Kozlovsky, 1990).

Acquisition of DSS data sets was among the principal scientific priorities of the Soviet government. A special institution—the Special Regional Geophysical Expedition, or Spetzgeofisika, later known as the Center GEON (the Center for Regional Geophysical and Geoecological Research, and now a division of VniiGeofisika)—was established for this purpose. A comparable project using nearly 60 nuclear explosions and helicopter support across thousands of kilometers of extremely difficult sub-Arctic terrain would have cost billions of dollars in a Western economy. It is very unlikely that a seismological project of a similar scale will be undertaken in the near future (Fuchs and Wenzel, 1997). For these reasons alone, the preservation and the maximum use of the DSS data constituted one of the priorities in today's seismology. Since all of the recordings were performed on magnetic tape in analogue format, the danger of the loss of this invaluable data set was great. The seismological group lead by Professor Scott Smithson of the University of Wyoming was the first to start the cooperation with the GEON Center in Moscow to digitize the records from nuclear and chemical explosions from the profile QUARTZ to their full length. Also, the Geophysical Institute of Karlsruhe University and the GeoForschungsZentrum at Potsdam started a joint program with GEON to digitize data from other profiles (Fuchs and Wenzel, 1997).

The most important reason for applying every effort to the analysis of DSS data is that these data cover the intermediate range and provide the link between traditional wide-angle and regional and teleseismic seismology. The energy of the sources and the depths and distance coverage of 3-component recordings is far beyond the limits of any other branch of controlled-source seismology, whereas the linear geometry and density of the profiles is still far above the level provided by seismological networks. DSS interpretations provide practically the only source of information for high-resolution imaging of the upper mantle and are a major resource for demonstrating its profound heterogeneity. Most importantly, in most of the DSS profiles along with the PNE records, a very comprehensive crustal data set using large chemical explosions was acquired, providing images of the crust that are sufficiently detailed to allow a robust inversion for the deeper mantle structures.

DSS data are unique in the length of continuous profiling, in the strength of the explosions used, in the number of source points (the combination of nuclear and chemical shots along the whole profiles), and in the recording in two to four directions from each source point (Figure 1). Dense station spacing and known positions of the explosions allow us to resolve the velocity and attenuation structure of the upper mantle in unprecedented detail when compared with earthquake data.

Earlier publications in English of some of the DSS results obtained using various data processing techniques, including non-linear velocity filtering and travel time analysis, include Belyaevsky et al. (1976), Kats et al. (1978), Vinnik et al. (1978), Yegorkin et al. (1978), Yegorkin et al. (1979), Yegorkin and Yegorkina (1980), Vinnik and Yegorkin (1981), Yegorkin and Pavlenkova (1981), Yegorkin et al. (1981), Fuchs and Vinnik (1982), Pavlenkova and Yegorkin (1983), Koshubin et al. (1984), Burmakov et al. (1986, 1987), Alekseev et al. (1988), Egorkin and Sumerina (1988), Egorkin and Zyuganov (1988), Galdin et al. (1989), Ryaboy (1989), Egorkin and Mikhaltsev (1990), Yegorkin et al. (1991), Benz et al. (1992), Yegorkin (1992), Yegorkin et al. (1992). More recently, Schueller et al. (1997) used a travel-time, refraction-reflection tomography to invert for the *P*-wave velocity structure of the northwestern part of the profile QUARTZ; Ryberg et al. (1996) presented a 2-D interpretation based solely on the first arrivals from QUARTZ PNEs; Lorentz et al. (1997) applied tomographic inversion to the mantle arrivals from

QUARTZ PNEs; and Ryberg et al. (1998) stacked all available DSS records to derive a "generalized" one-dimensional (1-D) regional velocity model of Northern Eurasia. Mechie et al. (1997) compared the observations of the asthenospheric low-velocity zones (LVZ) in a number of DSS profiles. The progress in the understanding the heterogeneity of the upper mantle structure through controlled-source and passive seismology was summarized in the 1997 EUROPROBE conference (Fuchs, 1997). Recent work focused on integration of the results into 3-D pictures of the lithosphere analysis of the Siberian profiles and analysis of mantle and crustal scattering, receiver Functions, and coda properties (e.g., Ryberg et al., 1995; Morozov et al., 1998a; Morozov and Smithson, 2000; Morozov, 2001; Nielsen and Thybo, 2003). Several longer-offset PNEs (BATHOLITH-2, CRATON-1, QUARTZ-4; Figure 1) produced reflections from the core-mantle boundary.

Two fundamental general conclusions were drawn from DSS studies. First, a number of 1-D mantle models derived for the Northern Eurasia (Mechie et al., 1993; Priestley et al., 1994; Pavlenkova, 1996) exhibit a prominent LVZ below at about 200 km depth and probably reduced velocity contrast at the 660-km boundary compared to the iasp91 model (Ryberg et al., 1998). There is no general agreement about the sharpness of the mantle transition zone discontinuities, which is critical to understanding their cause in terms of mantle mineralogy and composition. Mechie et al. (1993) and Ryberg et al. (1998) modeled the 410-km discontinuity as a sharp transition consistent with the iasp1 model, but Priestley et al. (1994) argued that the 410-km discontinuity may actually be a 35-km thick transition zone.

Another important result of the DSS studies is the demonstration of a strongly heterogeneous, 2-D structure of the uppermost mantle within the regional scale and down to at least 400 km (Mechie et al., 1993; Priestley et al., 1994; Ryberg et al. 1995; Morozova et al., 1997). This heterogeneity manifests itself in the velocity and attenuation structure (Morozov et al., 1998b), as well as in the properties of regional and global mantle boundaries (Pavlenkova, 1996; Morozova et al., 1999). The variability of the uppermost mantle partly limits the significance of 1-D regional models and partly minimizes some of the controversies in interpretations; on the other hand, this variability demands (at least) 2-D interpretations, of which very few exist at the regional scale.

In the context of nuclear test monitoring research, our group at UW, and currently at the University of Saskatchewan, emphasized a variety of empirical mapping approaches. The following models were devalued in recent years from integrated interpretations of multiple profiles. These results were principally due to the DSS PNE data becoming available through the present project:

1) An empirical 3-D first-arrival travel-time model (Morozov et al., 2005) suitable for generation of reference Source-Specific Station Correction surfaces;

2) Phase amplitude ratio maps, including quantitative correlations with crustal properties (Li et al., 2007);

3) An empirical *Lg Q* model (Li et al., submitted to BSSA). As above, significant correlations with parameters of crustal structures were found, such as correlations of *Lg Q* variations with the presence of sedimentary basins and Moho depth gradients;

4) *P* and *Lg* coda *Q* models (Morozov et al., submitted to BSSA, a and b). Notably, in these studies, we propose a different description of frequency-dependent coda *Q* that is physically consistent, results in stable and transportable estimates, allows a direct correlation to the *Lg Q* studies above, and correlates well with regional tectonics;

5) Corner-frequency and magnitude-yield analysis of the PNEs (Li et al, in preparation for BSSA).

Digitization of the DSS PNE Profile Records

DSS data were recorded using specially designed three-component seismographs "Taiga" (the name means the Russian sub-Arctic coniferous forest) and "Cherepakha" (Turtle) that were specially designed for the program. The systems equipped with NSP-1 geophones (Figure 2) were deployed by helicopters at a nominal spacing of 10-15 km along the whole length of each profile and radio-controlled to simultaneously record the waves at distances of up to 1500-3000 km. Designed for 7 to 10 days of continuous recording of the ground motion velocity, the stations operated at 0.5-20 Hz frequencies within a dynamic range of 70 dB (Figure 3; Ryaboy, 1989).

Figure 2. Playback and digitizing system for CHEREPAKHA seismographs (GEON Center, Moscow, 2004).

From the early 1990s, GEON went through a number of turbulent reorganizations, lack of funding, retirements of the key personnel, and disputes about its building in downtown Moscow. All this certainly did not improve preservation of the historic Soviet-era PNE data sets (Figure 4). Fortunately, principally owing to the present project, GEON specialists had been able to survive this period and continue recovering and digitizing the data sets (Figure 2)

While preprocessing the PNE data, we encountered a number of difficult processing problems that were related to the unusual parameters and format of the records. In order to tackle these basic data manipulation tasks, we wrote a suite of tools for the CogniSeis® DISCO seismic processing system, which was the main seismic processing system running on the dedicated VAX 11/785 in the University of Wyoming Reflection Seismology group until 1997. Later, these tools were incorporated into a new processing system called SIA (http://seiswev.usask.ca/SIA), whose further development was in fact largely inspired by the needs of the DSS data projects.

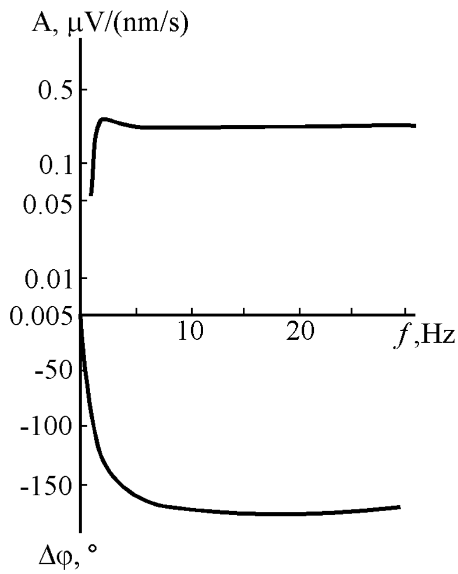

Figure 3. Amplitude and phase responses of "Taiga" recorders with NSP-1 seismometers used in DSS PNE recordings (after Ryaboy, 1989).

Figure 4. PNE analog magnetic tape data storage at the GEON Center (2004).

The PNE data sets were digitized from 1994-2005 at the GEON Center in Moscow. Digitization was performed to the full length of the analog records varying from about 100 sec for near-shot receivers to over 600 sec in far-offset PNE records. During the early stages of digitization, the digitizing equipment and software were not able to handle such long records, and so the records were split into several segments with 20-25 sec overlaps. Another complication of the initial data reduction was the shipment of the records to the University of Wyoming in four different Russian formats, none of which the existing software could read. The time starts, coordinates, gain factors, and other parameters of the records were provided in the form of hardcopy tables that we checked and loaded manually.

After the resulting records were delivered to UW, the parts of the records were concatenated using a cross-correlation technique that allowed locating the exact time starts of the record segments. At the same time, however, DISCO (a commercial seismic processing system designed for 2-D common midpoint [CMP] exploration data processing) was not able to handle the long (up to 30,000 samples per record) DSS records, and an interface had to be developed to allow splitting the records into smaller segments while allowing the processor to manipulate the long data traces in their integrity. These complications mostly affected the QUARTZ records; other data sets were provided by GEON in custom DSS formats.

Having loaded the data into DISCO, and later into SIA, we performed a tedious data editing procedure. This step involved plotting and inspecting all data records and selecting the channels with the best dynamic parameters. Typically, the DSS data were recorded into 6 channels at each recording point at 2 different gain levels. This allowed selection of the channels that were not overloaded and had better signal/noise ratios. This procedure was performed using manual editing, which took considerable time.

Many of the processing steps included in the data analysis required 3-component data. However, all three components of the recorded wavefield were not available for all stations; occasionally, some channels were missing. Given virtually no support for multicomponent data manipulation offered by the DISCO system, this irregularity (which is typical for wide-angle multicomponent data sets) of the data also caused a substantial difficulty for advanced signal analysis. This difficulty was overcome by the development of a series of special computer codes.

After the VAX 11/785 was taken out of operation in early 1997, all the tools for DSS data processing were transferred to the new seismic processing system recently developed at the UW seismology lab. This allowed us to efficiently handle DSS data and to add high performance of new UNIX-based computers (SGI Power Challenge L, SGI Indigo, Sun Sparc, and HP workstations), more versatile data analysis, color PostScript and interactive plotting programs and an interface to PROMAX, to many Seismic UNIX programs, and currently 3-D visualization.

As a result of these efforts, the PNE data sets shown in Figure 1 were digitized, edited, and formatted in long-record (Program for the Array Seismic Studies of the Continental Lithosphere—PASSCAL—extension) SEG-Y formats, and delivered to IRIS for unrestricted dissemination (Table 1). We have also created tools for exporting the data sets in CSS3.0 or NNSA-schema databases. Upon a request, these data sets may be available in this format from our FTP site.

Table 1. Numbers of PNEs and chemical shots and final data delivery schedules

#	Data set	Acquisition year	PNEs	Chemical shots	Delivery dates to IRS and AFRL
1	QUARTZ	1984-87	3	51	12/2002
2	CRATON	19780-80	4	30	11/2002
3	KIMBERLITE	1979	3	36	11/2002, 10/2003 (chemical)
4	RIFT	1982-83	3	36	10/2003
5	RUBY-1 and 2	1988-89	2	27+26	02/2004
6	AGATE (5 profiles)	1985	1	36	06/2004
7	BATHOLITH-1 (3 profiles)	1980	1	52	12/2004
8	BATHOLITH-2 (4 profiles)	1987	1	89	12/2004
9	BAZALT-1 (3 profiles)	1989	0	88	07/2005
10	BAZALT-2 (2 profiles)	1990	0	87	07/2005
11	METEORITE*	1977	4	-*	06/2007
12	SPAT**	1981	1**	39	06/2007

*Due to loss of the original field material, chemical-shot data from project METEORITE are now deemed unrecoverable.
**Only chemical-shot records provided in replacement of METEORITE.

CONCLUSIONS AND RECOMMENDATIONS

As a result of this effort, the broad seismological and seismic monitoring communities have obtained a set of digital recordings of a large number of nuclear explosions recorded across a variety of propagation paths to distances of ~3000 km. The available PNE and chemical-explosion data sets from eleven major Russian seismic projects should make important contributions to the studies research of regional seismic phases, to seismic calibration of the region, and to helping develop transportable seismic discriminants in Northern Asia. Availability of the unique PNE recordings should foster research in nuclear test monitoring. In addition, from a broader scientific perspective, the digitized DSS recordings and models of the upper mantle could also provide ideal reference and calibration data sets for the detailed structure of the upper mantle targeted by the US Array.

Combination of the results based on the DSS PNE projects of this study (velocity; reflectivity; receiver functions; mantle attenuation; *Lg Q*, *P*- and *Lg* coda *Q*; scattering; phase amplitude ratios; and empirical first-arrival travel times) makes the area of PNE profiling one of the best-constrained seismically at short periods. This conclusion applies to both fundamental and applied (monitoring) research areas.

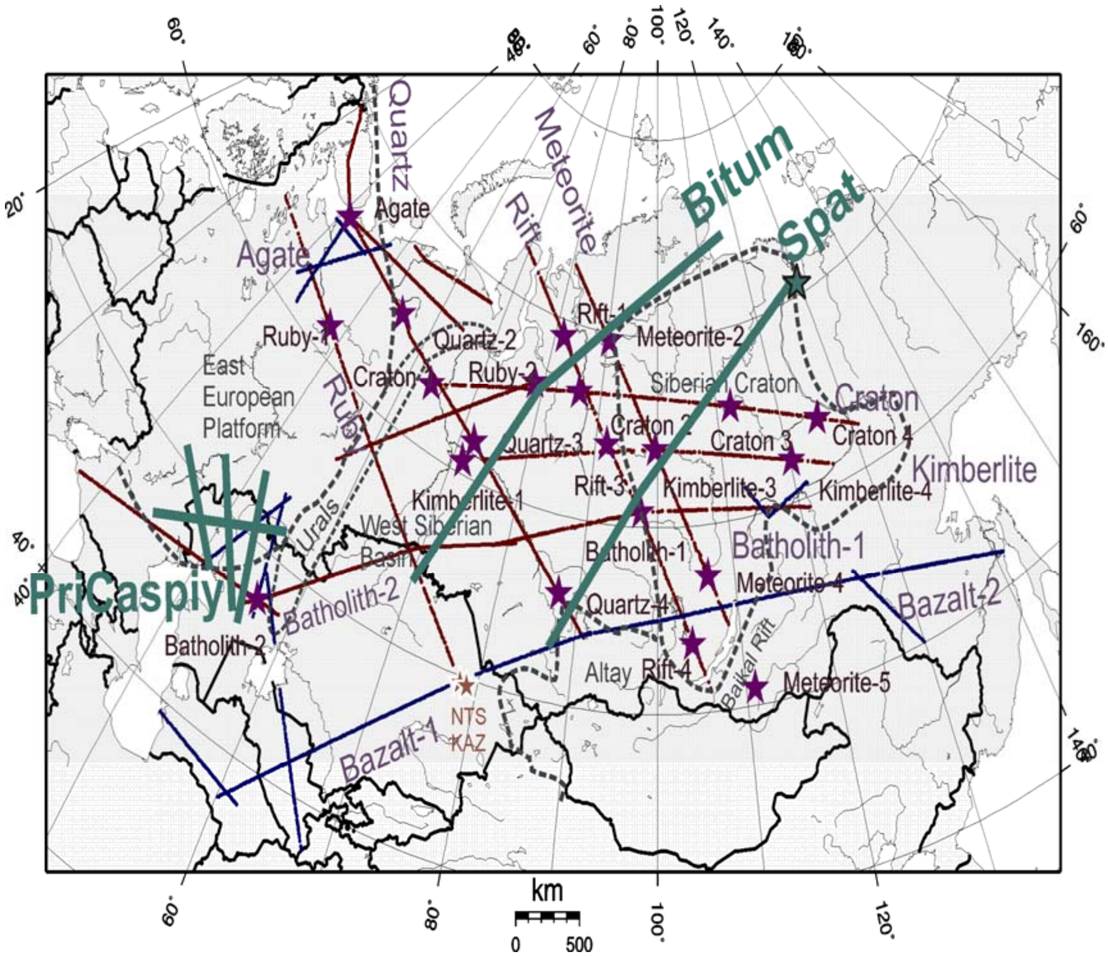

Figure 5. Map of DSS PNE profiling as in Figure 1 with the three remaining projects still available for digitization: BITUM, PRICASPIY, and SPAT (green lines). From profile SPAT, we have delivered the chemical-explosion data set as a part of the present project, and its PNE and earthquake data set still remain to be digitized.

The success of any geophysical investigation is determined by the data. In this project, we have preserved and made publicly available the complete seismic data sets from roughly 80% of the DSS PNE data that was still recoverable. Acquisition of such data, across similar distances at high latitudes, would be extremely expensive, and in the cases of PNEs, completely impossible today. Thus we strongly recommend that the remaining DSS PNE data be properly digitized and archived. The only remaining profiles that still could be digitized are SPAT (one PNE and earthquake data set), BITUM, and PRICASPIY (2 profiles; Figure 5). Digitization of these records would complete preservation of the historic DSS PNE data sets. Note that SPAT and BITUM lines are particularly important, as they cross the Siberian platform in NE-SW direction which is so far not represented in our data set (Figure 1). Multiple lines of project PRICASPIY also cover the Pre-Caspian Depression in different directions, in the vicinity of PNE BATOLITH-2 (Figure 5).

The depth of the potential analysis of the data sets is far from being exhausted. Only the QUARTZ data set has been studied thoroughly and from various standpoints and complemented by CRATON, KIMBERLITE, METEORITE, RIFT, and RUBY in only limited studies. Most of the critical (and also most tedious and difficult) work on detailed inversion of the crustal and mantle structure was done only by Russian groups (Pavlenkova and Yegorkin). Apart from QUARTZ, modern inversion techniques have been still insufficiently applied, and the very interesting fan lines from PNEs RUBY-1, RUBY-2, and AGATE have not been analyzed at all. Chemical explosion data sets are still underutilized, as well as PNEs AGATE, BATHOLITH, and SPAT. Integration of the results in a true 3-D model still remains to be performed, and this model should incorporate the various empirical attributes and be capable of numerical simulations. These are the directions in which, as we hope, the work will be continued in the future.

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