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The SHIELD'21 deep seismic experiment

V. Starostenko[1], *T. Janik*[2], *W. Czuba*[2], *P. Środa*[2], *A. Murovskaya*[1,3], *T. Yegorova*[1,3], *O. Verpakhovska*[1], *K. Kolomiyets*[1], *D. Lysynchuk*[1], *D. Wójcik*[2], *V. Omelchenko*[1], *T. Amashukeli*[1,4], *O. Legostaeva*[1], *D. Gryn*[1], *S. Chulkov*[1], *2023*

[1]S.I. Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine
[2]Institute of Geophysics of the Polish Academy of Sciences, Warsaw, Poland
[3]University of Parma, Department of Life Sciences and Environmental Sustainability, Parma, Italy
[4]GFZ German Research Centre for Geosciences, Potsdam, Germany
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The wide-angle reflection and refraction (WARR) SHIELD'21 profile carried out in 2021 crosses from SW to NE the main tectonic domains of Ukraine. The SHIELD'21 targeted the structure of the Earth's crust and upper mantle of the southwestern margin of the East European Craton with overlying Vendian-Paleozoic Volyn-Podolian Monocline and Neogene Carpathian Foredeep, Archaean and Paleoproterozoic segments of Ukrainian Shield and Late Paleozoic Dnieper-Donets Basin. The ~650 km long profile is an extension of realized in 2014 RomUkrSeis line in Romania and Ukraine from Apuseni Mountains to southwestern Ukrainian Shield. The field work performed in 2021, included the deployment of autonomous seismic stations and drilling-explosive works. A total of 264 seismic receivers were deployed (160 DATA-CUBE and 104 TEXAN stations) with the average spacing between the observation points about 2.65 km. The sampling interval for all stations was 0.01 s. Seismic energy was generated by 10 shot points with ~50 km of distance between them and total charge in all wells 5775 kg. The SHIELD'21 experiment using TEXAN and DATA-CUBE short-period seismic stations provided high-quality seismic records. The main recorded seismic waves are the refractions of *P*- and *S*-waves in sediments, basement, crust and upper-most mantle, and reflections from crustal boundaries, Moho interface and boundaries in the uppermost mantle. Correlation of travel time arrivals of seismic waves provides calculation of the velocity model for both *P*- and *S*-waves. The main objective of the SHIELD'21 project is to get new seismic data that increase our knowledge on the lithosphere structure as well as geodynamics of the oil-and-gas-bearing and ore regions of Ukraine.

Key words: WARR studies, SHIELD'21 profile, Ukraine, Ukrainian Shield, crust, upper mantle.

The regional field experiment was carried out in 2021 by the S.I. Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine and Institute of Geophysics of the Polish Academy of Sciences. The SHIELD'21 project is a controlled source wide-angle reflection and refraction (WARR) profile of ~650 km length running roughly SW-NE through the territory of Ukraine — Chernivtsi, Khmelnitsky, Vinnitsa, Zhytomyr, Kyiv, Chernihiv and Sumy regions (Fig. 1).

From SW to NE, the profile crosses the main tectonic structures, reflecting the evolution of East European Craton (EEC) lithosphere: the southwestern margin of the EEC with overlying Vendian-Paleozoic Volyn-Podolian Monocline and Neogene Carpathian Foredeep, Archean and Paleoproterozoic segments of Ukrainian Shield and Late Paleozoic Dnieper-Donets Basin [Gurskyi, Kruglov, 2004]. The SHIELD'21 profile is an extension of the previously realized RomUkrSeis line ac-

quired in 2014 and running from the Apuseni Mountains in Romania to the southwestern Ukrainian Shield [Starostenko et al., 2020].

The main objective of the SHIELD'21 project is to get new seismic data that increase our knowledge on the lithosphere structure and geodynamics of the oil-and-gas-bearing and ore regions of Ukraine on the basis of new WARR study. Coordinated with available geological and geophysical information of the region, they will create a fundamental base for the discovery of new mineral and energy resources of Ukraine.

The SHIELD'21 experiment is a continuation of the WARR studies of the Central Europe carried out within the framework of large international scientific projects. In Ukraine, such studies were performed in the regions of Carpathians, the Dnieper-Donets Basin, Crimea, the Black and Azov Seas by Ukrainian geophysical organizations in cooperation with institutions and specialists from Europe (Poland, the Netherlands, Denmark, Germany, Sweden, Finland, Belarus) and the USA [Thybo et al., 2003; Starostenko et al., 2013a,b, 2015, 2017, 2018, 2020, 2022; Janik et al., 2020, 2022]. Generalization of the experience and results of numerous geotraverses brings the new approaches to their interpretation and the interpretation itself to a higher level.

The lithosphere along the SHIELD'21 profile consists of a number of tectonic domains, which in terms of their formation age cover almost the entire history of the Earth from Archaean to Neogene time. In the southwest, the profile crosses the Forecarpathian and the Volyn-Podolian oil and gas regions. In its central part, the profile illuminates the structure of the lithosphere of the Ukrainian Shield, which is a separate metallogenic province. Precambrian rocks of the Ukrainian Shield and their weatheed uppermost crust and basement contain the vast majority of ore deposits in Ukraine. In the northeast, the profile runs through the northern part of the Dnieper Basin, being a segment of the Dnieper-Donets oil and gas region, the main source of hydrocarbons in Ukraine (Fig. 2).

The field work on SHIELD'21, performed in 2021, included the deployment of autonomous seismic stations and drilling-explosive works. Field work was carried out using the profiling system with digital short-period seismic stations TEXAN and DATA-CUBE, in close cooperation with the Institute of Geophysics of Polish Academy of Sciences.

Geodetic reconnaissance was carried out along the profile line using the Google maps and GPS devices before the beginning of data acquisition phase. Thus, the coordinates and heights of the explosion as well as observation points along the profile were determined. A total of 264 seismic stations were involved, (160 DATA-CUBE stations and 104 TEXAN stations). DATA-CUBE stations were both single-component (40 stations) and three-component (120 stations) equipped with one- and three-component geophones accordingly. Unlike single-component geophones, which are installed simply vertically, three-component geophones must be installed taking into account vertical and horizontal components orientation at the same time. All TEXAN stations were single-component ones. The average spacing between observation points was 2.65 km. The sampling interval for all stations was 0.01 s. Seismic DATA-CUBE station after the completion of the field works is shown in Fig. 3.

Shooting works. The SHIELD'21 profile is a controlled source WARR experiment, with seismic energy generated at 10 shot points (SP). «SPETSVYBUKHPROM» Ltd implemented the drilling-explosive works for all SP along the profile. The distance between the SP was about 50 km. Explosive works were carried out during night and early morning time slots to reduce the level of disturbances caused by human activity. Seismic waves, generated by explosions, penetrate the deep strata of the Earth's crust and carry information on the velocity characteristics of the rocks. In total, 120 boreholes were prepared for shooting on the territory of Ukraine within the frame of the SHIELD'21 project. The drilling depth of the bulk of the boreholes was 30 m, except SP15402 where 9 boreholes with a depth of 15 m and 2 ones with a standard depth were drilled due to difficult drilling conditions. The total charge in all boreholes was 5775 kg. The

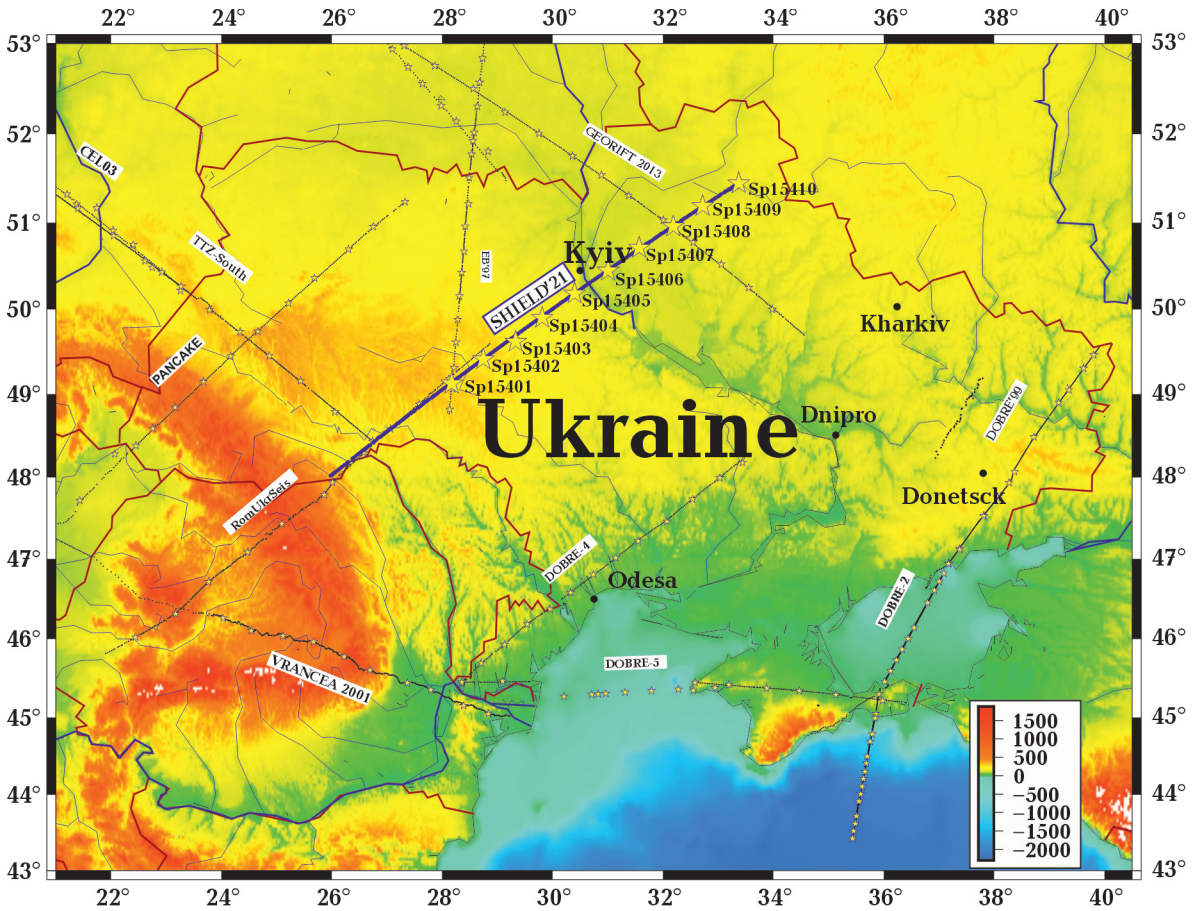

Fig. 1. Location of the SHIELD'21 and other seismic WARR profiles on the territory of Ukraine. The blue dots show the position of the seismic receivers, yellow stars indicate the position of the shot points. The color scale shows the height above the sea level and the depth of the sea in meters.

Table. Locations and other parameters of explosive sources used along the SHIELD'21 profile

Shot point number	Offset, km	Distance, km	Latitude N, deg	Longitude E, deg	Altitude, m	Time UTC, y:d:h:m:s	Charge TNT, kg	Borehole depth, m	Number of boreholes
SP15401	202.484	597.793	49.12778	28.15683	222	2021:218:01:00:23.23	600	30	12
SP15402	255.701	651.002	49.41273	28.74407	259	2021:218:02:00:12.30	325	2/30+9/15	11
SP15403	303.592	698.945	49.61942	29.32981	236	2021:217:01:30:18.75	600	30	12
SP15404	349.973	745.279	49.90049	29.81197	214	2021:217:01:00:09.98	550	30	11
SP15405	402.508	797.790	50.18387	30.39909	209	2021:215:01:59:39.44	500	30	10
SP15406	454.720	850.002	50.44875	31.00431	115	2021:215:01:00:15.93	500	30	10
SP15407	504.170	899.429	50.71069	31.56875	155	2021:214:01:30:29.53	600	30	12
SP15408	555.570	950.844	50.95694	32.18650	111	2021:214:01:00:16.34	600	30	12
SP15409	600.995	996.255	51.19028	32.71861	136	2021:212:02:37:26.58	700	30	14
SP15410	654.851	1050.117	51.44783	33.37283	121	2021:212:01:00:23.32	800	30	16

Distance — locations along the RomUkrSeis — SHIELD'21 transect, Offset — locations along the SHIELD'21 profile.

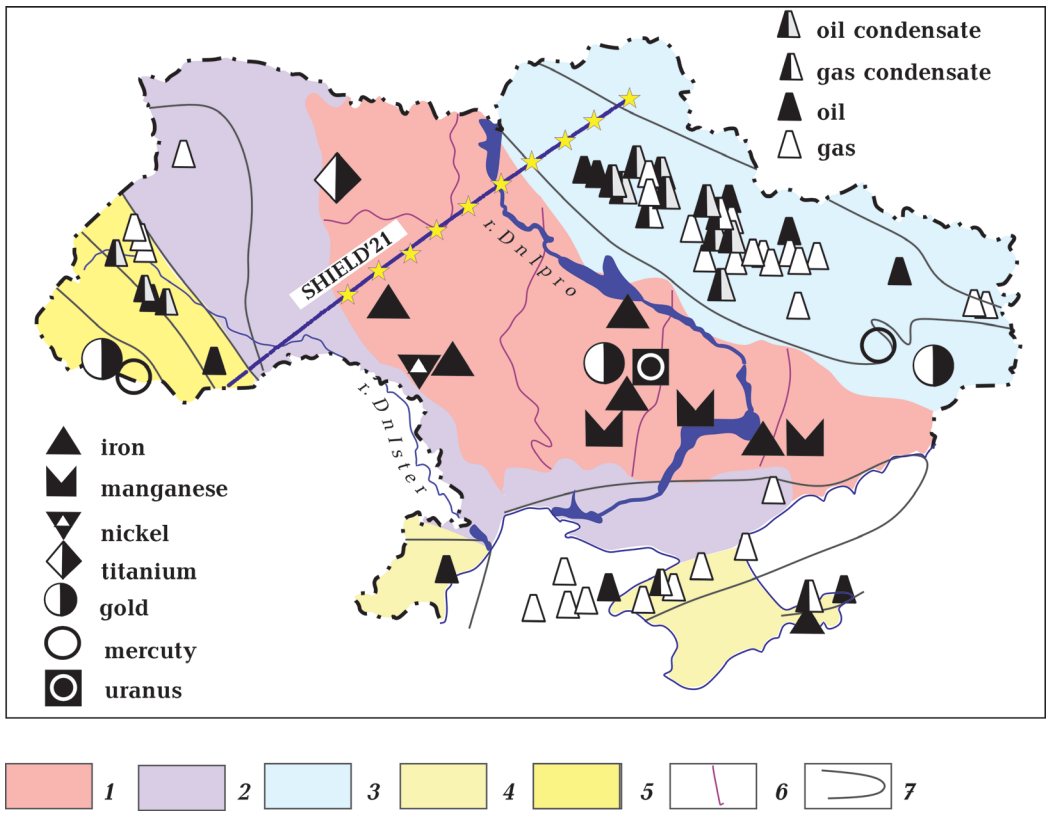

Fig. 2. The main ore and oil-and-gas-bearing provinces of Ukraine [Galetskyi, 2001]. Metallogenic provinces: *1* — Ukrainian Shield, *2* — Dniester-Black Sea, *3* — Dnieper-Donets, *4* — Crimea, *5* — Carpathians, *6* — borders of subprovinces of Ukrainian Shield, *7* — borders of oil-and-gas-bearing provinces and regions

Fig. 3. The three component DATA-CUBE and seismometer after field recording.

largest explosions were located closer to the ends of the profile. The explosions were not performed along the ~200-km-long, southwestern part of the profile due to the lack of funds. Only observations were carried out on that part of the profile. Instead, the data from RomUkrSeis profile can be used. The shooting time was recorded using the GPS and at the same time by additional seismic recorders located close to the shot points**.** Locations and other parameters of explosive sources of the SHIELD'21 experiment are shown in the Table.

Data obtained. In general, the following digital data were obtained during the field experiment: 1) records (seismograms) of DATA CUBE and TEXAN seismic stations; 2) GPS geodetic data of all the coordinates of DATA CUBE and TEXAN stations in WGS-84 format; 3) timestamps and coordinates of chemical explosions. The exact time of the explosions was recorded by electronic equipment synchronized with the GPS system.

After the field acquisition and initial data-processing seismograms have been extracted and collated into shot gathers. At the first step, during the shot gather formation for every SP, the tables of observation points and the SP coordinates have been prepared and used for seismic traces preparing in the SEGY format.

The wave field recorded by seismic stations TEXAN and DATA CUBE is shown in Fig. 4 on the example of a seismic section at the SP15407 in the central part of SHIELD'21. The obtained seismic traces provided the records of quite high quality that allow the identification of direct and refracted waves in the upper crust (P_g in first and S_g in secondary arrivals), the first arrivals of refracted *P*- and *S*-saves in the lower crust, reflected waves formed in the crust and reflections from the Moho boundary (P_mP and S_mS). The refracted *P*-wave in the upper mantle is determined to by clearly correlated in the most seismic shot gathers.

In the recorded wave field, all phases necessary for the calculation of the velocity model are observed. All seismic record sections including SP15407 (see Fig. 4) allow to correlate the phases of *P*-wave refraction in the sedimentary and deeper layers of the Earth's crust (P_{sed}, P_g and P_{ov}), as well as reflections (P_cP, from boundaries in the crust; P_mP, from the Moho discontinuity), refraction from the Moho (P_n) and reflection in the mantle (P_{mantle}).

The finite-difference refraction/reflection migration method provides additional information about the lithosphere structure along the WARR seismic profiles [Verpakhovska et al., 2018]. Since it is planned to process the data using the finite-difference refraction/reflection migration, it is necessary to determine the useful interval of the observed wave field for this. The black rectangles in Fig. 4 mark the spatial and time intervals of the observed wave field useful to form a dynamic image of the basement at the distances from 700 km to the end of the profile and the Moho discontinuity from the beginning of the profile to 680 km (see Fig. 4).

Conclusions. The SHIELD'21, a wide-angle reflection and refraction (WARR) profile of ~650 km length, running throughout the territory of Ukraine, was carried out in 2021 by the S.I. Subbotin Institute of Geophysics of the NAS of Ukraine and Institute of Geophys-

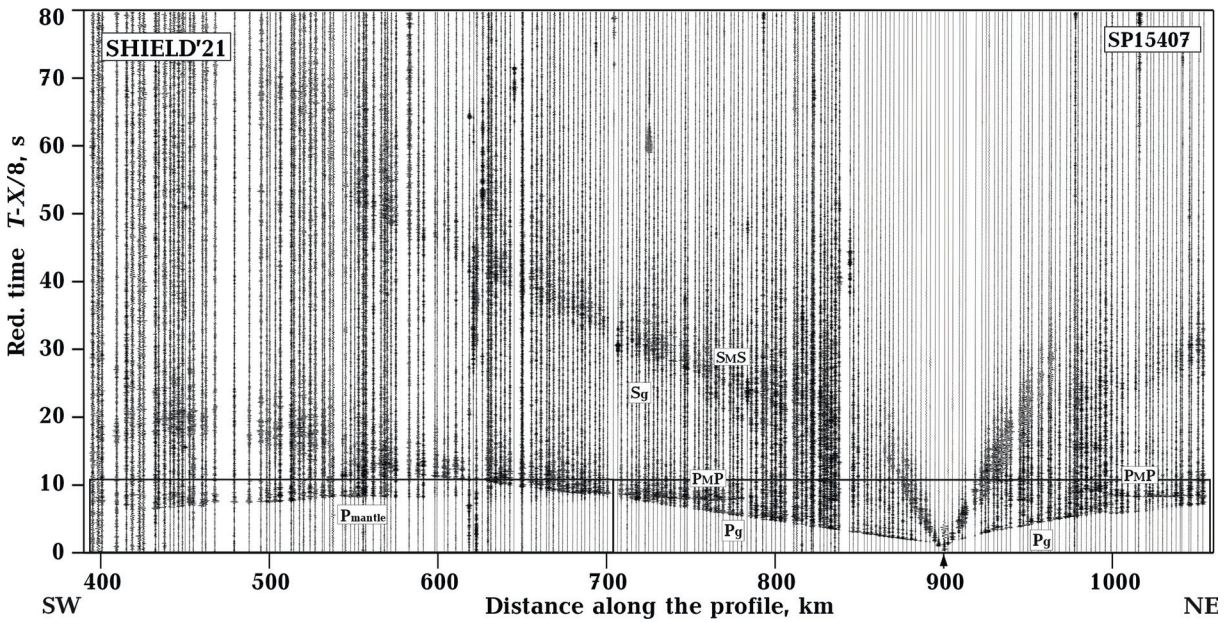

Fig. 4. Example of trace-normalized vertical-component *P*- and *S*-wave seismic record section for SP15407. A band-pass filter (2—15 Hz) and velocity reduction 8 km/s have been applied. P_g and S_g — refractions from upper crystalline crust for *P*- and *S*-waves respectively; P_mP and S_mS — reflections from Moho boundary; P_{mantle} — *P*-wave reflections in the upper mantle. Black rectangle show migration intervals.

ics PAS. From SW to NE, the profile crosses the main tectonic structures: the southwestern margin of the East European Craton with overlaying Volyn-Podolian Monocline and Carpathian Foredeep, Ukrainian Shield and Dnieper-Donets Basin. The SHIELD'21 is an extension of the RomUkrSeis line, previously realized in 2014 and extending from the Apuseni Mountains to the southwestern Ukrainian Shield [Starostenko et al., 2020].

The WARR study along the SHIELD'21 profile was conducted in the southwestern and central Ukraine to determine the structure and geodynamics of lithosphere in the main oil-and-gas-bearing and ore regions. The 264 short-period seismic stations (TEXAN and DATA CUBE) have recorded seismic waves generated at 10 shot points (SP). The seismic records of high-quality were obtained and the extraction and correlation of useful waves have been fulfilled for further velocity model calculation by ray-tracing method.

Digital processing of seismic traces and visualization of the wave field was performed; seismic data files were saved in appropriate formats; the shot gathers were prepared for every SP; velocity reduction, filtering and amplification of useful seismic waves were applied.

The obtained seismic recordings of high-quality allow to observe and correlate the main useful phases. The main branches of *P*- and *S*-wave travel time curves are recorded in most of the shot gathers. Their correlation allows to construct a velocity model for both *P*- and *S*-waves.

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Глибинний сейсмічний експеримент SHIELD'21

В. Старостенко*[1], *Т. Янік*[2], *В. Чуба*[2], *П. Срьода*[2], *А. Муровська*[1,3], *Т. Єгорова*[1,3], *О. Верпаховська*[1], *К. Коломієць*[1], *Д. Лисинчук*[1], *Д. Вуйцик*[2], *В. Омельченко*[1], *Т. Амашукелі*[1,4], *О. Легостаєва*[1], *Д. Гринь*[1], *С. Чулков*[1], *2023

[1]Інститут геофізики ім. С.І. Субботіна НАН України, Київ, Україна
[2]Інститут геофізики Польської академії наук, Варшава, Польща
[3]Університет Парми, Департамент наук про хімію,
життя та навколишнє середовище, Парма, Італія
[4]GFZ Німецький дослідницький центр геонаук, Потсдам, Німеччина

Сейсмічний профіль ГСЗ (англійський варіант — WARR) SHIELD'21, відпрацьований у 2021 р., перетинає з південного заходу на північний схід основні тектонічні структури України. Профіль спрямований на вивчення структури земної кори та верхньої мантії південно-західної окраїни Східноєвропейського кратону, яку перекривають венд-палеозойська Волино-Подільська монокліналь і неогеновий Перед-

карпатський прогин; архейського і палеопротерозойського сегментів Українського щита; пізньопалеозойської Дніпровсько-Донецької западини. Профіль SHIELD'21 (загальна довжина ~650 км) є продовженням раніше реалізованого у 2014 р. на територіях Румунії та України профілю RomUkrSeis від гір Апусени до південно-західної частини Українського щита. Дослідження WARR уздовж профілю SHIELD'21 з використанням короткоперіодичних сейсмічних станцій TEXAN і DATA-CUBE забезпечило реєстрацію сейсмічних коливань високої якості. Польові роботи, які були виконані у 2021 р., включали розгортання автономних сейсмічних станцій та проведення бурових і вибухових робіт. Усього було задіяно 264 сейсмічних приймача (160 станцій DATA-CUBE і 104 станції TEXAN), середня відстань між якими становила 2,65 км, а дискретність запису для всіх станцій складала 0,01 с. Сейсмічна енергія генерувалась у 10 пунктах вибуху з середньою відстанню між ними близько 50 км та із сумарним зарядом у всіх свердловинах 5775 кг. Основними зареєстрованими сейсмічними хвилями є заломлені *P*- і *S*-хвилі, а також відбиття від границь в осадових відкладах, фундаменті, земній корі, розділі Мохо та границь у верхній мантії. Підбір зафіксованих годографів за часом дає змогу побудувати швидкісну модель за *P*-, та *S*-хвилями. Основна мета проєкту SHIELD'21 є отримання нових сейсмічних даних, які поглиблять наші знання про структуру та геодинаміку літосфери нафтогазоносних і рудних регіонів України.

Ключові слова: дослідження WARR, профіль SHIELD'21, Україна, Український щит, літосфера.