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Наведено результати геологічних, стратиграфічних, палеонтологічних, гідрогеологічних, геофізичних та геоінформаційних досліджень викладачів та наукових співробітників геологічного факультету Київського національного університету імені Тараса Шевченка.

Для викладачів, наукових співробітників, аспірантів і студентів.

Приведены результаты геологических, стратиграфических, палеонтологических, гидрогеологических, геофизических и геоинформационных исследований преподавателей и научных сотрудников геологического факультета Киевского национального университета имени Тараса Шевченко.

Для преподавателей, научных сотрудников, аспирантов и студентов.

Visnyk deals with results of geological, stratigraphic, paleontological, hydrogeological, geophysical and geoinformational investigations carried out by lectures and scientific researches of geological faculty, Kyiv Taras Shevchenko University.

For scientists, proffessors, aspirants and students.

Відповідальний за випуск О.І. Меньшов

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MINERALOGY, GEOCHEMISTRY AND PETROGRAPHY

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ON NUMERICAL PETROPHYSICAL EVALUATION OF GRANITOIDS OF AREA NEAR THE SOUTH-UKRAINIAN NUCLEAR POWER PLANT WITH THE DETERMINATION OF THE POSSIBILITY OF USING ITS FOR THE DISPOSAL OF RADIOACTIVE WASTE

(Reviewed by the editorial board member S. Shnukov)

The most important task of modern nuclear power engineering is a safe disposal of the radioactive wastes. The various approaches have been used in developing the basic justification of choice of disposal geological environment. It was revealed that a deep repository of the radioactive wastes is suitable approach for this goal. it has substantial advantages in comparison with the surface warehousing. A carefully chosen geological environment would form a safe casing for the repository engineered barrier system, protecting it from many natural and artificial hazards. At present several developed countries have considered locating deep repositories in crystalline rock. Repository depths between about 500–1000 m are usually considered. However, a approach of deep geological repository is connected with the problem of searching of suitable geological sites and investigation a lot of characteristics of the host rock. It is thus important to consider the potential use of the special petrophysical researches in assessment studies. These petrophysical characteristics would need more in-depth analysis of the insulating properties of the host rocks.

On the basis of our researches carry out the simulation of some petrophysical characteristics and permeability of the leading petrotypes of Ingulsk and Dniester-Buh megablocks of Ukrainian Shield by statistical techniques, including correlation and factors analyses. It gave a possibility to implement of numerical classification of the all researched objects (totally 27 petrotypes). Results of analyses are also used to make predictions about the function indicators as a tool for selection of the host rocks. Finally only Oleksandrivs'k enderbites and Kirovohrad granites were chosen as the most acceptable natural objects for the radioactive wastes disposal. Also Oleksandrivsk enderbites are not far to SUNPP that means low transport costs and environmental safety. Kirovohrad granites should be chosen as the host rocks as to creation of underground laboratory of priority comprehensive researches of insulation properties of geological environmental.

Problem statement. The long-standing question of modern nuclear power engineering is the problem of the safe radioactive wastes (RAW) disposal. It is important to accelerate studies of the search for a repository site. This development are based on knowledge and understanding of the insulating properties and involved processes and has to includes directed investigations of the host rocks of prospective disposal sites. Very promising of the natural objects are hard poor-porous rocks. Respectively, it is mainly concerned with crystalline rocks and its geomechanical and hydraulic properties, also mineralogy and geochemistry.

Ukraine has 15 working nuclear power plants and has produced large amounts of radioactive wastes that have to be managed. However, at present Ukraine hasn't a respective deep repository that satisfy a modern demand. To achieve this goal need to apply the different disposal strategies based on nature of the wastes, the available host rocks and the associated engineering and scientific researches. An one side these researches, the wide petrophysical evaluation of the crystalline rocks in the near-field of South Ukrainian Nuclear Power Plant (SUNPP) are described this paper. As a result these investigations will be determined the additional sites for RAW disposal and operational capability of the host rocks are obtained.

Analysis of recent researches. There are three main types of the host rock are currently under investigation: 1) hardrocks (granites, granodyorites and other hard crystalline rocks); 2) sedimentary rocks (clays and marles); 3) chemical deposit (rock salt). It was found that the most favorable natural objects for disposal of radioactive wastes are crystalline rocks. Granite rocks are under investigation in Sweden, Finland, Czech Republic, Spain, Switzerland and other countries. Repository depths between about 500–1000 m are usually considered. In Ukraine, most recent developments of disposal concept attracted to granite massifs as the host rocks. A wide range of the host geological formations has been considered for deep repositories within the bounds of the Exclusion Zone of Chernobyl Nuclear Power Plant and on the adjacent areas [2, 3, 5]. Similar geological formations are also occur near SUNPP but its still have a low level of proper investigations. Overall petrophysical researches of the host rocks are carried out relatively recently – in conjunction with associated disposal programmes (by Swedish scientists since 2002 [6]).

It should be noted that development planning of SUNPP weren't developed to account for all possible hazards connected with the functioning of the Tashlitsk hydropower complex [1]. The main natural hazard is geodynamic tension of Pervomaisky Fault – a part of spread fractured Holovaniv Suture Zone, where SUNPP is actually located. Additionally, Holovaniv Suture Zone is a border between Ingulsk and Dniester-Buh megablocks of Ukrainian Shield where tectonically-induced fractures and faults may be superimposed upon this unstable system. In this regard, disappointing forecast concerning the possibility of natural seismic events at the center of Pervomaisky Fault with 5–6 or more times is expressed. It is clear that development of multyconceptual models of the deep geologic repository may proceed only on the basis of a good understanding of such unpredictable natural disasters and careful searching of new sites for RAW disposal.

Work objective. Our investigations will focus on the study of the physical properties of granitoids of two large megablocks of Ukrainian Shield. Granitoids of Kirovohrad complex of Ingulsk megablock are positioned on genetic connection with of uranium deposits. As is well known, such operating excavations of U-deposits are most favorable for disposal of RAW in future, and for the creation of underground laboratory studies of the flow properties of radioactive elements and the insulating characteristics of the host rocks already today.

From the above material, it is seen that a basic subject of the present invention is to provide a selection of the most favorable sites within geological boundaries based on a database of physical characteristics of leading petrotypes of granitoids rocks. Database of investigated granitoids rocks are collected and processed in research Sector of Physic-chemical studies of rocks of Geological Faculty of Taras Schevchenko National University of Kyiv. The main goals these researches are to expand a quantity of the suitable sites for RAW repository, providing the comprehensive physical and technical characteristics of massifs and improving geological criteria set for the host rocks of RAW repository.

Summary of main material. In addition to a description of geochemical and geological characteristics of geological disposal system, the input data that are generally required by petrophysical models include: rock porosity (total porosity P_t and effective porosity P_{ef}), density (bulk density σ_0), elastic properties (compressional V_p and shear seismic waves V_s), radioactivity (R_t), heat conductivity (λ) and permeability (η). The permeability is determined by quality terms of fracturing. Generally speaking, permeability embraces a wide spectrum of physical and structural characteristics of geological environmental that controlling the migration of constituents in the porewater, fluid flow and mass transport. As known, the migration of radionuclides through undisturbed saturated porous rocks or fractures and fracture zones depend on the degree of water saturation, the temperature and the permeability of the host rock. Because we observe strong correlations of a value of the permeability with total and effective porosities, elastic properties (and its anisotropies) and total radioactivity. Thermal conductivity, perhaps due to the influence of metasomatic processes, is not strong correlated with any petrophysical parameters. It was also proposed that during the preliminary stages of estimation, try to use the value of the ratio $(V_p+V_s)/P_{ef}$ and coefficients of anisotropies of seismic waves. Continuing investigation on early listed physical characteristics has led to a more sophisticated understanding of nature of permeability in barrier zones of the repository.

Having a considerable amount of analytical material, emphasis is given to the most useful aspects of quantitative applications for disposal model development and testing (mathematical research methods: cluster, correlation analyses and principal components method).

Clasterization on the base of positive correlation coefficients of granitoids rocks used in developing model that includes 4 main rock groups (Figure 1):

1) Bokov'ian and Novoukrainsk charnokites; Novoprazhsky, Orehiv and Vozsiyatsk leucogranites; Kam'iansk, Huriv tonalites, Adzhamsk granodiorites; Ingulets plagiogneisses; Oleksandrivsk enderbites;

2) Bokov'ian quartz diorites, Ivaniv quartz monzonite, Zhezheliv, Khrystoforiv, Kam'iansk granodiorites, Bokov'ian, Mytrofaniv, Novolazariv granites, Ingulets plagiogranites;

3) Krupsky quartz syenites, Ruskopolyansk granosyenites, Bobrynets, Nadiiv, Dolyniv, Krupsk granites;

4) Kirovohrad and Novoukrainsk granites.

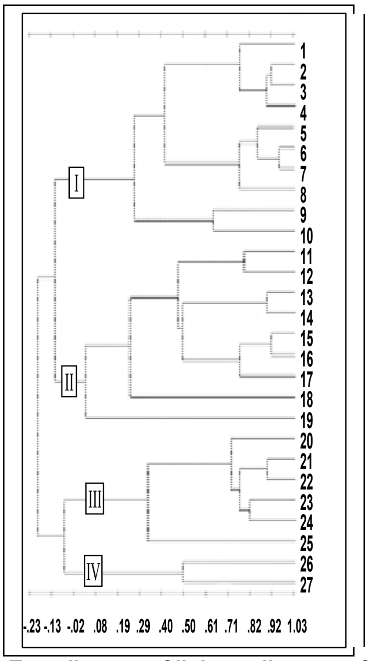

Figure 1 Tree diagram of linkage distance of leading petrotypes of Ingulsk and Dniester-Buh megablocks of Ukrainian Shield

Notes: 1. I, II, III, IV – rock groups with positive values of correlation coefficients. 2. Leading petrotypes of granitoid rocks: 1, 5 – Bokov'ian and Novoukrainsk charnockites; 2, 8, 9 – Novoprazhsky, Orehiv, Vozsiyatsk leucogranites; 3, 4 – Kam'iansk, Huriv tonalites; 6, 12, 18 – Adzhamsk, Zhezheliv, Kam'iansk granodiorites; 7 – Oleksandrivsk enderbites; 10 – Ingulets plagiogranit-gneiss; 11 – Bokov'ian quartz diorite; 13 – Ivaniv quartz monzonite; 14 – Ingulets plagiogranite; 16, 17, 19, 21 – 24, 26, 27 – Bokov'ian, Mytrofaniv, Novolazarev, Dolyn, Krupsk, Kirovohrad, Novoukrainsk granites; 20 – Ruskopolyansk granosyenites; 25 – Krupsk quartz syenites

Figure 2 shows the factor diagram constructed with two large factors (F_1 and F_2) which cumulated 69% of total variance. Also on this chart is displayed the points of representing rock groups (I, II, III, IV). On the right part of factor diagram there are fields of points of rock groups II and IV. In terms of presenting assessments these granitoids are the least reliable natural objects for safe disposal. A degree of their availability decreases in the direction of the axis F_1. It should be noted that the significant positive factor loadings, connected with F_1, corresponded with P_{ef}, AVp while significant negative loadings with V_p and V_s. This means that searching of sites for safe RAW disposal should be limited to the areas where petrotypes from groups I and III are occurred. First of all, Adzhamsk granodiorites and Oleksandrivsk enderbites may be defined as petrotypes that are suitable for creation of primary RAW disposal at depths of their location. The other petrotypes of the mentioned groups should be classified as backup option.

Discrimination of rocks according to their total radioactivity, A_{Vs} and P_t is observed along the axis F_2 where the petrophysical parameters have the significant positive factor loadings. In particular, Ruskopoliansk granosyenites and Kirovohrad granites are maximally differentiated with radioactivity. It has also been found that Kirovohrad granites may become attractive for us since uranium deposits are genetically related to massifs of "Kirovohrad type" granites. According to the recommendations of M.P.Laverov et al. [4], some the underground openings, boreholes and shafts have been worked out in U-bearing rocks, would be to use for studying the insulating properties of the host rocks.

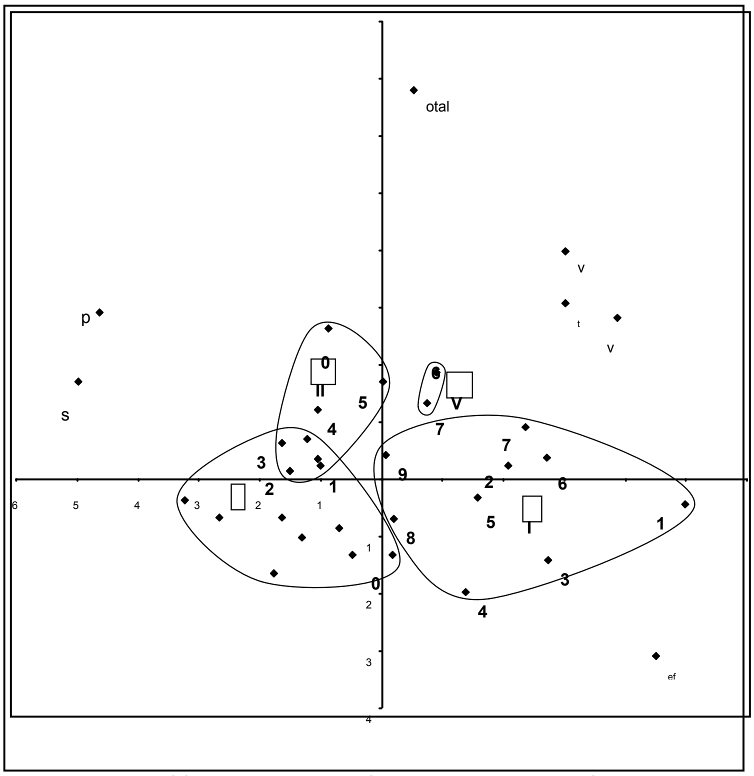

Figure 2. Factor diagram of figurative points of leading petrotypes of granitoid rocks of Ingulsk and Dniester-Bug of megablocks together with their petrophysical parameters in plot of factors $F_1 – F_2$.
Notes: 1. I, II, III, IV – rock groups outlined by results of cluster analysis.
2. Petrotypes according to their numbers, refer to Figure 1

Conclusions. All of the above 27 analyzed petrotypes of Ingulsk and Dniester-Buh megablocks of Ukrainian Shield have been reviewed with geostatistical simulation. Only 2 petrotypes (Oleksandrivsk enderbites and Kirovohrad granites) will be used to provide the proper ranges of physical properties desired for RAW disposal. Oleksandrivsk enderbites could be used as the host rocks because of are not far to SUNPP that means low transport costs and environmental safety. In addition, Kirovohrad granites should be chosen to creation of underground laboratory of comprehensive priority researches of insulation properties of the host rocks.

It should be noted that value of permeability has comprehensive nature so relevance analysis of leading petrotypes of granitoids rocks with only one characteristic of permeability is not appropriative. In particular, it is recommended to use numerical values of all proper characteristics of the host rocks as the basis of their petrophysical evaluation. Also that allowed to introduce the approach of "reference petrotype" and then respectively to classify granitoids with "conditionally suitable" and "conditionally unsuitable" categories. How it was done for granitoids of Volyn megablock of Ukrainian Shield [3]. In essence, granitoids of Ingulsk and Dniester-Buh megablocks of Ukrainian Shield should be wide investigated with the predetermined aim of developing or testing concept for repository safety in the future.

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РЕЧОВИННО-ПЕТРОФІЗИЧНА ОЦІНКА ГРАНІТОЇДІВ РАЙОНУ ПІВДЕННОУКРАЇНСЬКОЇ АТОМНОЇ ЕЛЕКТРОСТАНЦІЇ З ВИЗНАЧЕННЯМ ЇХ ПРИДАТНОСТІ ДЛЯ СТВОРЕННЯ СХОВИЩ РАДІОАКТИВНИХ ВІДХОДІВ

Однією із важливих задач сучасної ядерної енергетики є вирішення проблеми безпечної утилізації радіоактивних відходів (РАВ) працюючих блоків атомних електростанції (АЕС). Загальноприйнятною світовою практикою поводження із радіоактивними відходами є їх захоронення в спеціально обладнаних інженерних спорудах, серед яких підземний варіант сховищ РАВ має ряд суттєвих переваг у порівнянні з їх наземним складуванням. Але при виборі майданчика підземного сховища РАВ постає проблема обмеженого петрофонду придатного для використання в якості депозитарію з точки зору їх інженерної і екологічної безпеки. Все це спонукає дослідників до прискореного визначення альтернативних ділянок, придатних для нетривалого підземного захоронення РАВ в районі діючих АЕС. Зрозуміло, що правильний вибір майданчика сховища повинен враховувати велику кількість інженерно-геологічних критеріїв висунутих до вмісних порід депозитарію. Причому ваговою властивістю, що контролює тепломасоперенос в гірському середовищі є величина і характер проникності гірських порід.

Спеціальні петрофізичні дослідження показали досить обмежене коло характеристик, які дають змогу коректно оцінювати параметр ефективної проникності гірських порід. Серед них відзначимо емнісні, пружні і, певною мірою, радіоактивні параметри. В основі даного дослідження лягло положення про петрофізичне моделювання засобами математичної статистики провідних петротипів двох мегаблоків Українського щита (Дністровсько-Бузького і Інгульського) для оцінки їх ефективної проникності. Враховуючи значний обсяг аналітичних даних приймався комплексний характер оцінювання проникності зв'язаної системою множинних кореляційних навантажень із іншими вимірювальними характеристиками порід. Для їх систематизації і аналізу були використані кластер-аналіз і метод головних компонент у режимі кореляційної матриці. Це дало змогу класифікувати об'єкти досліджень і виконати операції оптимізації і вибору найбільш придатних геологічних об'єктів. За отриманими результатами серед 27 досліджених петротипів гранітоїдів придатними для утилізації РАВ за петрофізичними ознаками виявилися ендербіти олександрівські та граніти кіровоградські. Окрім величин ефективної проникності, перші з них можуть бути привабливими, з точки зору фізико-механічних властивостей і територіальної близькості до Південноукраїнської АЕС, тобто найменш затратні та екологічно безпечні з точки зору транспортування РАВ. Інший петротип (граніти кіровоградські) виявився оптимальним не тільки в якості репозитарію РАВ, але і для створення підземних лабораторій комплексних досліджень ізоляційних властивостей вмісних порід. Як свідчить французький досвід (передової атомноенергетичної країни світу) подібні лабораторії можуть бути використані для оцінювання кристалічних масивів з метою тимчасового і тривалого (консервуючого) зберігання небезпечних радіоактивних відходів.

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ВЕЩЕСТВЕННО-ПЕТРОФИЗИЧЕСКАЯ ОЦЕНКА ГРАНИТОИДОВ РАЙОНА ЮЖНОУКРАИНСКОЙ АТОМНОЙ ЭЛЕКТРОСТАНЦИИ С ОПРЕДЕЛЕНИЕМ ИХ ВОЗМОЖНОГО ИСПОЛЬЗОВАНИЯ ДЛЯ СОЗДАНИЯ ХРАНИЛИЩ РАДИОАКТИВНЫХ ОТХОДОВ

Одной из важных задач современной ядерной энергетики является проблема безопасной утилизации радиоактивных отходов (РАВ) работающих блоков атомных электростанции (АЭС). Общепризнанной мировой практикой поведения с РАВ является их захоронение в специально оборудованных инженерных сооружениях, среди которых подземный вариант хранилищ РАВ имеет ряд существенных преимуществ в сравнении с их наземным складированием. Но при выборе площадки подземного хранилища РАВ возникает проблема ограниченного петрофонда пригодного для использования в качестве репозитария РАВ с точки зрения их инженерной и экологической безопасности. Все это побуждает исследователей к ускоренному определению альтернативных участков, пригодных для непродолжительного подземного захоронения РАВ в районе действующих АЭС. Понятно, что корректный выбор площадки хранилища должен учитывать большое количество инженерно-геологических критериев к вмещающим породам репозитария. Причем значимым свойством контролирующим тепломассоперенос в горной среде является величина и характер проницаемости горных пород.

Специальные петрофизические исследования показали достаточно ограниченный набор характеристик корректно оценивающих параметр эффективной проницаемости горных пород. Среди них отметим емкостные, упругие и, в известной мере, радиоактивные параметры. В основе данного исследования легло положение о петрофизическом моделировании средствами математической статистики ведущих петротипов двух мегаблоков Украинского щита (Днестровско-Бугском и Ингульском) для оценки их эффективной проницаемости. Учитывая значительный объем аналитических данных принимался комплексный характер оценивания проницаемости связанной системой множественных корреляционных нагрузок с другими измеряемыми характеристиками пород. Для их систематизации и анализа был использован кластер-анализ и метод главных компонент в режиме корреляционной матрицы. Это дало возможность классифицировать объекты исследований и выполнить операции оптимизации и выбора соответствующих геологических объектов. По полученным результатами среди 27 исследованных петротипов гранитоидов пригодными для утилизации РАВ по петрофизическим признакам определены эндербиты александровские и граниты кировоградские. Кроме величин эффективной проницаемости, первые из них могут быть привлекательными, с точки зрения их физико-механических свойств, а также территориальной близости к Южноукраинской АЭС, а это соответственно влечет меньшие затраты на транспортировку РАВ и их экологическую безопасность. Другой петротип (граниты кировоградские) оказался оптимальным не только в качестве репозитария РАВ, но и также для создания подземных лабораторий комплексных исследований изоляционных свойств содержащих пород. Как свидетельствует французский опыт (передовой атомноэнергетической страны мира) подобные лаборатории могут быть использованы для оценивания кристаллических массивов с целью временного и длительного (консервирующего) хранения опасных радиоактивных отходов.

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IDENTIFICATION OF METASOMATIC FAMILIES IN GEOBLOCKS OF UKRAINIAN SHIELD

(Reviewed by the editorial board member V. Shevchuk)

The paper is aimed to refer metasomatites of Ukrainian Shield (USh) to the specific metasomatic families (formations) using the unified system of definitions and terms and to recognize distinctive features of metasomatic rocks for the separate megablocks of the shield. Summarizing the all available data, it can be concluded that restricted list of metasomatic families are identified for the whole of USh. In particular, within USh nearsurface families are not known at all; subvolcanic families are presented in Middle-Dniprean megablock only; but families merely of hypabyssal and abyssal depth levels are shown in other megablocks. Additionally, it has been found that alkaline metasomatic families are evidently prevailing relatively to acid and magnesian-calcian families as well as almost all metasomatic rocks of USh are early or middle Proterozoic. As well it has been found that the separate megablocks of USh are characterized by the specific features of prevalence for different types of metasomatic families. It was concluded that above features of metasomatic rocks distinguish the USh from other Precambrian shields of the world. The authors emphasize that conditionality of hydrothermal-metasomatic processes with general geologic, petrogenetic and tectonic events can give a key knowledge for application of hydrothermaly altered rocks as important petrology and metallogenic indicators.

Introduction

Long since hydrothermally altered (metasomatic) rocks are making good use as significant criterion for exploration of mineral deposits. Investigation of metasomatites allows getting multifarious and often unique information concerning geologic and physicochemical conditions of ore formation. This defines an applied significance of metasomatic rocks. However, it is well known that metasomatic processes are genetically coupled with other endogenous events such as igneous, metamorphic and ultrametamorphic processes, which to a considerable degree assign composition and metallogenic specialization of metasomatites. Therefore in-depth study of hydrothermally altered rocks has a high petrology profile to analyze rock forming conditions within certain geologic unit or region.

Several approaches of hydrothermally altered rock classification were developed since beginning of 20th century [1-3 etc]. However, the concept of metasomatic families approach come as the most general and geologically based way for metasomatic systematics [4, 5]. Concept of metasomatic families ('metasomatic formations') was first proposed in 1950 decade [6,7] based on ideas of Dmitry Korzhinskii [8], and thereafter it was advanced in the Former Soviet Union and post soviet countries [9-14 etc.]. The authors [4] have summed up these efforts and generalized principal statements of family analysis for metasomatic rocks. In general the recommendations by the IUGS (International Union of Geological Sciences) Subcommission on the systematics of metamorphic rocks concerning metasomatites [5] are based on these statements.

Numerous publications including special books were dedicated to investigation of metasomatites discovered within the Ukrainian Shield (USh) [11, 12, 15-17 etc]. Still there are very restricted numbers of generalized works given up the systematics of metasomatic rocks of USh. Except publications summarizing data on specific groups of hydrothermaly altered rocks (e.g. [11,13,15]) and publications on metasomatites of separate area of USh [11,15,17], there are a few works which anyhow analyze metasomatites for USh as a whole [18, 19, 20]. It has to be noted that all above references date from1970-1980. During last decades considerable volume of new information on metasomatites of USh has been obtained. Moreover this time holistic theoretical and applied approaches of metasomatic systematics based on the family principles have been developed [4, 5].

In particular classification of metasomatic families ("formations") has been proposed in [14]. This attempt was built upon the physicochemical grounds where main class parameters were temperature and acid-base properties of hydrothermal solutions. Besides metasomatites of Siberia, Middle Asia, Ural and other regions, several metasomatic occurrences of USh have been evaluated in [14]. However geologic level of consideration was not introduced in Scherban`s systematics [14]. Vice versa in [4] geologic and petrologic family approach was applied to the only typical metasomstites of USh namely to uraniferrous sodium alkaline metasomatites.

This paper is aimed to refer metasomatites of USh to the specific metasomatic families using the unified system of definitions and terms and to recognize distinctive features of metasomatic rocks for the separate megablocks of the shield.

Main definitions and terms of metasomatic family analysis

It is of importance to fix the meaning of some principal notions as well as relationships between ones before to classify metasomatites on the ground of the family approach. The author's understanding of the terminology of the family analysis for metasomatic systematics as the system of definitions, terms and practical rules is setting out below. Most of cited notions as such are not original. They are formulated in special publications (e.g. [4, 5, 9 etc]) and widely spread in metasomatic petrology. The problem is that part of them has various meaning in different publications and others still were not directly incorporated in the metasomatic family analysis.

Understanding of metasomatic process (metasomatism) is taken in accordance with formulation [4], which defines that metasomatic transformation of the parent rock is occurred at remaining part of the rock in a solid state and with alteration of chemical composition as a result of the interaction between the rock and aqueous endogenic fluids (solution). The most characteristic feature of metasomatic products is their zonation pattern. Therefore the subject of consideration for the family analysis is only endogenic altered rocks. Product of weathering and other products of interaction between rocks and exogenic solutions are not regarded as metasomatites. Rocks formed during interaction of fluids with melts are not related to metasomstites because solid state condition fails. Furthermore, hydrothermal filling veins, which generated by direct crystallization from solution, are not metasomatites as such, whereas substitution veins, which form as a consequence of hydrothermal transformation of parent rocks, refer to metasomatic product. Nevertheless, filling vein just as substitution veins have to be the subject of family analysis because of close spatial and genetic relationships between both vein types and metasomatites.

In general the family (formation) is paragenetic association of the rocks. Thus, definition of certain family has to be based on deducing of genetic unity of the rocks involved in this family. It means that definition criteria for different genetic types of rocks (sedimentary, igneous, metamorphic etc) have to account specific origin conditions. In particular definition of metasomatic family supposes application of the notions which show properties of metasomatism as rock forming process. Within these notions the basic one is metasomatic column which represents horizontal zonation as a general property of metasomatites. It is the certain sequence of zones, consisting of metasomatic rocks (paragenesises). The complete column is formed as result of interaction between parent rock and solution (fluid) at certain conditions (temperature, pressure, chemical composition of parent rock and acted fluid) [4, 21]. It follows from this that metasomatic column is paragenetic association of rocks or metasomatic facies [9].

Metasomatic family is defined [4] as a set of metasomatic facies (columns) which were formed by alteration of rocks of different chemical composition under an action of solutions of certain petrogenetic type. This definition includes the term "solutions of certain petrogenetic type", that is complicated in practice since common genetic character of solutions does not immediately follow from data obtained by direct geologic, mineralogical and petrography methods.

Authors of this paper suggest that metasomatic family i.e. paragenetic association of rocks has to be regarded taking into account such notions as vertical zonation, metasomatic phase and metasomatic stage. Vertical zonation is a regular changing of metasomatic columns (facies) mainly caused by changing of depth and hence by appropriate changing of temperature and chemical properties of solutions during metasomatic replacement of parent rocks under action of single hydrothermal flow [9]. Then it is accepted that metasomatic phase is a period of time when replacement of parent rocks of different chemical composition depth-independently takes place under action of single hydrothermal flow. Consequently in general case vertical zonation is formed during one metasomatic phase. Metasomatic stage can include some phases, which are distinguished with conditions and chemical directivity of alteration, but they are related to single hydrothermal process. And eventually certain metasomatic family includes rocks which were formed over one metasomatic stage. In general location and geologic age do not matter for assignment of certain metasomatic family.

In Table 1 schematic presentation of metasomatic family is shown. It is apparently that metasomatic family constitutes the whole complex of rocks generated as result of single metasomatic process of certain petrogenetic type. The vertical zonation, i.e. set of metasomatic columns (facies) has been formed during prograde phase of this process. Each column differs from another owing to various chemical composition of parent rocks (1, 2, ...k), or because of different depth (h_1, h_2, h_N) and consequently varied TP conditions (PT_1, PT_2, ... PT_N). Additionally, metasomatic family includes products of connected phases. These mineral products can be formed by the way of removal and redeposition of some chemical components (e.g. SiO_2 removal and secondary quartz precipitation caused by alkaline metasomatose), or by mineral precipitation in consequence of solutions oversaturation at temperature and/or pressure decreasing (e.g. formation of secondary carbonates).

Table 1

Schematic presentation of metasomatic family

<table>
<tr><td rowspan="7">Single metasomatic process of certain petrogenetic type</td><td colspan="2" rowspan="3">Stage, phases</td><td rowspan="3">Depth</td><td rowspan="3">TP onditions</td><td colspan="5">Products of single metasomatic process</td></tr>
<tr><td>(Parent rock)$_1$</td><td>(Parent rock)$_2$</td><td>(Parent rock)$_K$</td><td rowspan="5">Metasomatic columns (facieses) which are included in vertical zonation</td><td rowspan="6">METASOMATIC FAMILY</td></tr>
<tr><td colspan="3">Metasomatic columns (facieses)</td></tr>
<tr><td rowspan="4">Stage</td><td rowspan="3">Prograde phase</td><td>h_1</td><td>PT_1</td><td>facies$_{1,1}$</td><td>facies$_{1,2}$</td><td>facies$_{1,K}$</td></tr>
<tr><td>h_2</td><td>PT_2</td><td>facies$_{2,1}$</td><td>facies$_{2,2}$</td><td>facies$_{2,K}$</td></tr>
<tr><td>h_N</td><td>PT_N</td><td>facies$_{N,1}$</td><td>facies$_{N,2}$</td><td>facies$_{N,K}$</td></tr>
<tr><td>Connected phases</td><td>$h^{\sim}$</td><td>$PT^{\sim}$</td><td colspan="4">New formed mineral associations caused by:
- removal and redeposition of chemical components;
- T and P decreasing, solution oversaturation and precipitation of chemical components</td></tr>
</table>

Family belonging criteria for metasomatic rocks

On the whole family analysis for metasomatic rocks has to be regarded as achievement of two interdependent objectives. There are substantiation of certain metasomatic family (first objective) and referring some metasomatic rocks to certain metasomatic family (second objective).

First objective expects solution of main problem of family analysis that is substantiation of paragenetic unity for rock association. This fulfillment has to be based on results of direct geologic observations and analytical studies as well as on data deducing from these direct results (mass balance calculation, analysis of paragenesises, analysis of metasomatic zonation, estimation of physico-chemical conditions, including temperature, pressure and chemical specialization of solutions). Both direct and deducing data have to be theoretically evaluated and by this way qualitative or quantitative petrogenetic model has to be developed. Therefore final result of these coupled investigations is as firstly, formulation of petrogenetic entirety for the metasomatic rocks relating to certain family and secondly, ascertainment (identification) of geologic, geochemical and petrology characteristics for the rocks of this metasomatic family. Such characteristics, in other words family belonging criteria, have to be based on results of direct observations and measurements as well as on data deducing immediately from geological and geochemical information.

Second objective of family analysis means an investigation of metasomatic rocks with the aim to ascertain the characteristics which are belonging criteria to certain metasomatic family. Taking into account the experience of family analysis [4, 9, 10, 21 etc] the principal family belonging criteria are presented by results of:

a) direct geologic observations (morphology and geologic location of metasomatic bodies, spatial and time relationship of metasomatites with tectonic structures, igneous complexes and rock sequences of different origin etc).

b) mineralogical studies and geochemical measurements (mineral associations, macro and trace element composition of rocks and minerals)

c) formalized geochemical and petrology processing of direct mineralogical and analytical data (typical mineral paragenesises and metasomatic columns, metallogenic and geochemical specialization, chemical feature of solutions, estimates of temperature and pressure).

The most useful method for derivation of the last group of data is analysis of metasomatic zonation.

Identification of metasomatic families for Ukrainian Shield

The identification of metasomatic families was carried out on the base of family systematics presented in [4]. The metasomatic families of this classification are divided among three groups: acid, alkaline and magnesian-calcian. For each family the principal characteristics are given including geochemical and petrologic ones. There are following geochemical characteristics in [4]: typical paragenesises of inner zones in metasomatic columns, metallogenic specialization and mineral associations of connected metasomatites. Petrology characteristics include depth level of origin and relationship between metasomatic and igneous rocks. Moreover an essence of paragenetic unity of rocks for most metasomatic families is formulated as well as geologic examples, descriptions of metasomatic columns and other typical characteristics are given in [4]. "Depth levels" have to be considered as generalized characteristics of thermobaric conditions. They are [4]: nearsurface (NS), subvolcanic (SV), hypabyssal (HA) and abyssal (AB) depth levels. To refer the metasomatites of USh to certain family, available data (see tables 2,3) were compared with family formulations and descriptions by [4]. The identification of metasomatic families has been worked out for separate megablocks of USh: Volyn (V), Dnister-Boug (DB), Ros-Tykych (RT), Kirovograd (K), Middle-Dniprean (MD), Azovian (A). The boundaries between the megablocks were taken from [22].

The results of family identification are presented in Table 2. Having a single meaning metasomatic families are marked by "+". The sigh "?" denotes that there are not sufficient information in accessible data sources for confident referring of the metasomatic rocks to the given family. The albite-aegirine family (family of alkaline sodium metasomatites) has been established for K and V megablocks of USh, however in K megablock this family is represented by uraniferrous metasomatites (marked as "+") and within V megablock uranium ores were not discovered in these metasomatic rocks (marked as "{+}"). For comparison and family identification, besides the publications pointed out in the Table 2, a lot of other data sources were used. In most cases they are cited in publications indicated by "*".

Other metasomatic families of Ukrainian Shield

There are above (Table 2) metasomatic families of USh which appeared in the classification [4]. However despite of this, at least two else families within USh can be substantiated on the base of available information – subvolcanic quartz-carbonate (SQC) family and hematite-calcite-chlorite-orthoclase (HCCO) family. Brief description of these families follows below including general model formulations of paragenetic unity for related rock association, as well as geological, geochemical and petrology family belonging criteria.

The SQC family joins metasomatic rocks which were investigated in detail within Sura greenstone complex (MD geoblock of USh) and described mainly by Victor Monakhov and coauthors [17, 23-25 etc]. Moreover in these publications there are cited works on similar metasomatic rocks discovered in other greenstone complexes of the MD geoblock (Verkhvtsevo, Chortomlyk) as well as in greenstone complexes of Baltic, Australian and Brazilian shields. Generalizing the available data the following family model formulation is accepted: the SQC family includes mesothermal metasomatic rocks which were formed within Precambrian greenstone complexes as result of post magmatic hydrothermal process related to intrusion of subvolcanic porphyritic rocks. Acted hydrothermal solutions are characterized as sodium, considerable carbonate, low acid or near neutral and reduced.

Table 2

Identification of metasomatic families in geoblocks of Ukrainian shield based on systematics [4]

Metasomatic family	Depth level				USh megablocks						Data sources
	NS	SV	HA	AB	A	MD	K	RT	DB	V	
ACID											
Propylites						+					[17*], [25]
Beresites						+					[17*], [25]
Quartz-tourmaline-chlorite family						?					[17]
Greisens					+		?		?	+	[12], [22*], [30], [31*], [32*]
Quartz-feldspar family					+?					?	[12], [31], [32]
ALKALINE											
Apogranites (albitised granites)							?			+	[12], [16], [30], [31]
Albitites within aureole of nepheline syenites					+						[11], [12]
Fenites					+						[33*]
Two feldspar family							?			+	[16], [31]
Microcline-biotite family										?	[34]
Albite-aegirine family							+			{+}	[4*], [9], [11*], [14*], [22*]
MAGNESIAN-CALCIAN											
Carbonate-chlorite family						?					[17]
Amphibole-chlorite family						?					[17]
Phlogopite family										?	[12]
Calc-skarns					+?		+?	?	+?	+	[13*]
Magnesian skarns							?	?	+?	?	[13*]

In this family depending on composition of parent rocks, two distinct groups of facie are separated. Mineral composition essentially tells one group of facies from another. For this reason formerly they were described as two individual groups of metasomatic rocks. First group of SQC metasomatites are represented by zoned aureoles formed as result of hydrothermal alteration of aluminosilicate rocks with composition from acidic to basic. In this case central parts (zones) of metasomatic columns consist mainly of albite with changeable amounts of carbonate (calcite) and quartz [23].

Second group of SQC facies includes vein-type quartz-carbonate-tremolite metasomatites, which replace mainly low thickness bodies of silica-magnesia-calcian rocks (ultrabasic rocks or quartz-carbonate veins) [24]. Zonation of vein-type metasomatites appears more or less distinctly depending on thickness and composition of parent rock [24]. Geologic position, metallogenic specialization and petrology parameters are coincided for both groups of SQC. It is usual occurrence of low thickness tremolitic metasomatites within wide aureole of essentially albitic altered rocks.

Geologic evidences for belonging of metasomatic rocks to SQC family are spatial relation to subvolcanic bodies of porphyritic rocks and especially placement within local tectonic zones in exocontact area of such bodies. Vein-shaped metasomatic bodies or zoned aureoles of thickness from several centimeters to a few meters are morphologic characteristics of SQC metasomatites. Pattern of metasomatic columns for metasomatites of this family depends essentially on composition of parent rock. Vertical zonation of SQC metasomatites is not observed [23, 24]. Inner zones of metasomatic columns are composed of distinctive mineral associations; those are albite+calcite±quartz or tremolite+calcite+quartz. There is typically that secondary mineral associations of connected metasomatic phase (ankerite+biotite+pyrite or ankerite+chlorite+pyrite or ankerite+cericite+pyrite) are locally applied to minerals of inner zones in metasomatic columns of SQC metasomatites. This secondary mineralization is accompanied with gold as well as with following metallogenic associations: Fe-As-Au ±Cu, Fe-Cu-Au, Au-Cu-Mo, Au-Ag-Bi-Te-Pb [25].

Taking into account geochemical characteristics, the SQC metasomatites are distinguished from other resembling altered rocks. In particular, aceites have another (uranium) metallogenic specialization, contain ferrian minerals and are not accompanied with ankerite-biotite(chlorite, cericite)-pyrite secondary mineralization. Uraniferrous albite-aegirine metasomatites (albitites) differ from SQC rocks in the same characteristics as well as in the presence of alkaline amphiboles and pyroxenes. Tremolitic composition of amphibole is a specific sign for SQC family in comparison with another amphibole bearing metasomatites.

The HCCO family is described in detail within Kirovograd megablock of USh [26, 27]. Generalizing the available data the following family model formulation is accepted: HCCO family includes metasomatic rocks which were formed during late Proterozoic tectonic-hydrothermal activity period within tectonic zones without certain relationship with some type of magmatism or complex of igneous rocks. HCCO alteration took place at hypabyssal and low temperature conditions by the action of potassium, essentially carbonate, alkaline and oxidized solutions.

Geologic setting of HCCO metasomatites is defined by area of fractured rocks within lengthy linear fault zones. Separate metasomatic bodies are clearly zoned, but vertical zonation on a level of mineral associations is not observed. Facial varieties of HCCO family depend merely on composition of parent rocks. The typical mineral paragenesis of inner zones in metasomatic columns of HCCO metasomatites is hematite + calcite + chlorite + orthoclase which often are supplemented with net of thin vein composed of secondary chlorite and calcite. Metallogenic specialization of this family is specifically uranium. The HCCO metasomatites are distinguished from other resembling altered rocks by geochemical characteristics. For instance, aceites contain sodium feldspar instead of orthoclase, and gumbeites besides potassium feldspar contain quartz and sulfides.

Metasomatites of USh with uncertain family belonging

Variety of metasomatic rock within USh is far from limited by the list of identified metasomatic families. There is a lot of publications on numerous occurrences of another metasomatites but a scope of information in the accessible sources keeps from substantiation of family self-dependence for some metasomatites or their belonging to certain family. The examples of metasomatites with uncertain family belonging, which were discovered within megablocks of USh and described in referred sources are given in the Table 3.

Table 3

Metasomatic rocks within megablocks of USh with uncertain family belonging

Metasomatites and metallogenic (geochemical) specialization of them		Megablocks of USh						Data sources
		A	MD	K	RT	DB	V	
ACID								
Quartz-microcline metasomatites	U, Mo, Bi, TR						+	[28]
Epidote-actinolite-quartz metasomatites	(Au,As)			+				[29]
Quartz-muscovite metasomatites	Sn, W	+		+			+	[29], [30], [32]
Quartz biotite metasomatites	Au			?		+		[22*], [35], [36*]
Quartz-feldspar metasomatites (within area of pegmatites)	Li, Nb, Ta	?		+			?	[22*],[37]
	(Mn, B)	?		+			?	[22*],[29]
ALKALINE								
Albitites	Zr	+						[38]
Aegirinites	Mo	+						[39]
MAGNESIAN-CALCIAN								
Bazavlukites			+					[40*]
Prenite metasomatites				+				[41]
Scarnoids	W	+		+	+	+	+	[13*], [29]

Conclusion

Summarizing above review, it can be concluded that restricted list of metasomatic families included in [4] are identified for Ukrainian Shield in whole. In particular, within USh nearsurface families are not known at all; subvolcanic families are presented in MD megablock only; but families merely of hypabyssal and abyssal depth levels are shown in other geoblocks.

Moreover, alkaline metasomatic families are evidently prevailing in comparison with acid and magnesian-calcian families as well as almost all metasomatic rocks of USh are early or middle Proterozoic, excluding Archean altered rocks in MD geoblock and Riphean HCCO metasomatites in K megablock. On the other hand the separate megablocks of USh are characterized by the specific features of prevalence for different types of metasomatic families. For instance the distinctive metasomatites are: hypabyssal alkaline altered rocks with zirconium, rare-earth, molybdenum and apatite mineralization within A megablock; subvolcanic acid metasomatites with golden and molybdenum mineralization for MD megablock; abyssal family of uraniferrous sodium alkaline metasomatites (albite-aegirine family) with distinctive vanadium and scandium metallogenic specialization for K megablock; hypabyssal and abyssal magnesian-calcian metasomatites for RT and DB megablocks; hypabyssal alkaline metasomatites with beryllium and tin mineralization as well as varieties of sodium alkaline metasomatites uncontained uranium ores for V geoblock.

These features of metasomatic rocks distinguish the USh from other Precambrian shields of the world that indicate on a specific geologic history of USh as a whole and the geoblocks of it in particular. The example of USh shows that conditionality of hydrothermal-metasomatic processes with general geologic, petrogenetic and tectonic events can give a key knowledge for application of hydrothermaly altered rocks as important petrology and metallogenic indicators.

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ВИЗНАЧЕННЯ МЕТАСОМАТИЧНИХ АСОЦІАЦІЙ У ГЕОБЛОКАХ УКРАЇНСЬКОГО ЩИТА

Метою даної статті є ідентифікація належності метасоматитів Українського щита (УЩ) до певних метасоматичних формацій на основі єдиної системи понять і термінів формаційного аналізу метасоматичних порід, а також встановлення специфіки проявів метасоматозу в окремих мегаблоках УЩ. На основі існуючої інформації зроблено загальний висновок про те, що для УЩ в цілому впевнено ідентифікується обмежений перелік метасоматичних формацій. Зокрема, на УЩ не ідентифіковано приповерхневі метасоматичні формації, субвулканічні представлені лише в межах Середньопридніпровського мегаблоку, а в інших регіонах УЩ розповсюджені тільки гіпабісальні і абісальні формації. Крім того, можна говорити про те, що на щиті в цілому лужні метасоматичні формації суттєво переважають над кислотними і магнезіально-кальцієвими, а у віковому відношенні практично всі метасоматити УЩ є ранньо- або середньопротерозойськими З іншого боку, окремі мегаблоки УЩ характеризуються своїми специфічними особливостями з точки зору розповсюдження окремих типів метасоматичних формацій. Встановлені закономірності відрізняють УЩ від інших докембрійських щитів. Авторами підкреслюється що, поглиблений аналіз обумовленості гідротермально-метасоматичних процесів загально геологічними, петрогенетичними і тектонічними явищами є актуальною задачею, спрямованою на удосконалення використання метасоматичних порід як ефективних петрологічних і пошукових індикаторів.

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ОПРЕДЕЛЕНИЕ МЕТАСОМАТИЧЕСКИХ АССОЦИАЦИЙ В ГЕОБЛОКАХ УКРАИНСКОГО ЩИТА

Целью данной статьи является идентификация принадлежности метасоматитов (УЩ) к определенным метасоматическим формацiям на основе единой системы понятий и терминов формационного анализа метасоматических пород, а также выяснение специфики проявления метасоматоза в отдельных мегаблоках УЩ. Общий вывод, полученный на основе имеющейся информации, состоит в том, что для УЩ в целом уверенно идентифицируется только ограниченный перечень метасоматических формаций. В частности, на УЩ не идентифицированы приповерхностные метасоматические формации, субвулканические формации представлены только в пределах Среднеприднепровского мегаблока, а в других регионах УЩ распространены только гипабиссальные и абиссальные формации. Кроме того, можно утверждать, что на щите в целом щелочные метасоматические формации существенно преобладают над кислотними и магнезиально-кальциевыми, а в возрастном отношении практически все метасоматиты УЩ являются ранне- или среднепротерозойскими. С другой стороны, отдельные мегаблоки УЩ характеризуются своими специфическими особенностями с точки зрения распространенности определенных типов метасоматических формаций. Установленные закономерности отличают УЩ от других докембрийских щитов. Авторами подчеркивается, что углубленный анализ обусловленности гидротермально-метасоматических процессов общегеологическими, петрогенетическими и тектоническими явлениями является актуальной задачей, направленной на усовершенствование использования метасоматических пород в качестве эффективных петрологических и поисковых индикаторов.

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MAGNETITE- AND ILMENITE-SERIES OF GRANITIC ROCKS AND THEIR POTENTIAL NIOBIUM AND TANTALUM MINERALIZATION WITHIN THE UKRAINIAN SHIELD

(Reviewed by the editorial board member O. Mytrohin)

The paper discusses differentiating between different types of granites that occur within the territory of the Ukrainian Shied. The classification in the article partly follows the principles formulated in the early taxonomies of granites, among which are the classifications proposed by Ishihara [11], Chappel and White [4], and a lower classification proposed by Tomurko and Shcherbakov [20]. The latter made an attempt to single out two contrasting granite varieties – apobasitic and apopelitic granites – that are commonly found within the Ukrainian Shield.

Grouping granites into different genetic types runs into difficulties due to heterogeneous origin of these formations, which results from merging parental mantle with crustal sources. Nevertheless, such classification might be used in making an accurate prediction about metallogenic specialization of different genetic types of granites. The redox state of granites formation is a major factor that can largely affect possible metal concentration in them. Based on this parameter granites can be classified into ilmenite and magnetite series of granites, which differ in geological environment of their formation [6, 11] and mineralization associated with them [1].

Within the territory of the Ukrainian Shield there can be distinguished entire provinces with distinct distribution of mostly ilmenite or magnetite series of granites that reveal different ways of ore mineralization associated with them. Columbite-tantalites are common ore minerals found within these series of granites, with niobium and tantalum being characterised by close lithofillic affinity to these formations. Within the Ukrainian Shield, columbite-tantalites were found in granites and associated rare-metal pegmatites, in some apogranitic metasomatites (greisens, quartzites, perthosites), and also in alkaline rocks of various origin. It is determined the basic features of columbite-tantalites, with Ta/Nb value, Fe/Mn ratio and presence of admixture elements to have close genetic relation to different granite series. The features of mineralization, defined to be typomorphic of ilmenite and magnetite series of granites, might be used to improve survey and exploration carried out in the Ukrainian Shield.

Introduction. A possibility to use accessory oxides (magnetite and ilmenite) was first outlined in the paper published by Ishihara in 1977 [11], in which they were determined to be mineralogical criteria for metallogenic specialisation of granitic rocks. This paper discusses distinguishing between magnetite and ilmenite series of granitic rocks that might be related, to some extent, to I- and S- types of granites according to genetic classification of Chappel and White [4], or apobasic and apopelitic varieties of granites according to lower mineralogical-geochemical classification of Tomurko and Shcherbakov [20] eleborated for different granitic complexes of the Ukrainian Shield. It is obvious that classifying granites into different genetic types, such as I (igneous), S (sedimentary), A (alkaline, anhydrous, anorogenic) ones, runs into difficulties Granitic magmas can be formed from different heterogeneous parental source (protolith), crustal or mantle one predominantly, or it can represent mixture melts of crustal and mantle origin [17]. At the same time such subdivision of granites into genetic series enables predicting the likely metallogenic specialization of granitic magmas. Among the major parameters which can essentially affect general metallogenic content of granitic complexes are the following: 1) type of granitic protolith (S, I, A – types); 2) a trend of evolution; 3) degree of fractionation; 4) redox state [1].

Background. The classifications mentioned above are interesting not only because they reveal features of metallogenic specialisation in the complexes of the Phanerozoic orogenic belts [1, 4], but they might be also used to interpret the likelihood of ore mineralization, that occurred in different felsic association and granitic complexes found in other geodynamic settings even in Precambrian structures, among which there is the Ukrainian Shield.

Within the Ukrainian Shield there might be outlined distinct regions which are characterised by the distribution of mostly ilmenite or magnetite series of granites. It is important to note, that magnetite series of granites may include some syngenetic ilmenite, while ilmenite series of granites are commonly characterized by the presence of ferric iron (Fe^{+2}) in the structure of iron arsenide (loellingite $FeAs_2$).

The presence of magnetite or ilmenite in granites can predominantly be indicative of redox state of the environment, in which these granite complexes form. According to the classification eleborated by Frost [6] there are three main conditions that can maintain magnetite in granitic rocks: 1) reduction resulting from the combustion of carbon on metasedimentary rocks melting; 2) magnetite consumption by reacting with the Fe-Mg silicates in reduced rocks; 3) magnetite consumption to make sodic pyroxenes and amphiboles in peralkaline rocks. It allows estimating potential ore mineralization that might be found in granites as well as it can help to define mineralogical-geochemical features of many ore elements which are sensitive to redox state, especially those of lithophilic affinity, with niobium and tantalum being most useful among them.

Both niobium and tantalum show close association with felsic rocks and tendency for accumulation in the latest phases of fractionated intrusive complexes. In the late stages of granite evolution and superimposition of metasomatic alterations a wide range of tantalum-niobium minerals can be formed. Because of their close chemical affinity niobium and tantalum might be found in the same minerals, where these elements isomorphically replace each other. Occurring dessiminated in rockforming minerals, Nb^{5+} and Ta^{5+} can commonly be concentrated in some accessory phases during the stages of superimposed metasomatic alterations; the latter being characterized by activity of volatile elements. Columbite $(Fe,Mn)Nb_2O_6$, pyrochlore $(Na,Ca)_2Nb_2O_6(OH,F)$, ilmenorutile $(Ti,Nb,Fe)_3O_6$, fergusonite $(Y,Th)(Nb,Ta)O_4$. are among the minerals that can concentrate tantalum and niobium. These minerals can even concentrate up to 95 % of the total content of tantalum and niobium. Concentration of Ti^{4+} in the mineralogical environment being high, there can be observed processes of dissemination of Nb^{5+} and Ta^{5+} in titanium-bearing minerals. Alkaline associations are characterized by constant prevalence of niobium over tantalum.

Ta and Nb are also widely used to interpret different kinds of trace element in the environment indicative of granite rocks formation [16], to which discriminant diagrammes plotted in Nb-Y, Ta-Y, Rb-(Y+Ta) an Rb-(Y+Nb) coordinates are common. In spite of the fact, that these descriminators are commonly used for Phanerozoic granitic complexes and felsic associations, for which plate tectonics paradigm is widely accepted, these discriminative diagrams for Precambrian complexes are also mentioned in a range of recent publications.

Our primary aim in this paper is to discuss a possibility of distinguishing between different types of granites and other felsic rocks that occur within the Ukrainian Shied. The Ukrainian Shield is considered to be a part of Sarmatia segment of East European Craton that consists of both Archean and Proterozoic domains. Some researchers believe these domains to be fragments of a single craton [12, 18], for basic facts about plate tectonics in the Precambrian time remain limited [10]. Those who keep up a plate tectonics idea consider the Ukrainian Shield to be a Proterozoic collage of discrete terrains [5, 7]. Among the Archean terrains there single out the Azov one, which is situated in the East, the Dniester-Bug and Rosinsk-Tikich terrains, highly reworked in the Palaeoproterozoic, and the Middle Dnieper granite-greenstone terrain, never affected by Proterozoic processes. Palaeoproterozoic terrains are represented by the Kirovohrad domain (Ingul), which is located in the central part of the Ukrainian Shield and the Volyn domain, which comprises the westernmost part of the Shield (Figure 1).

Niobium-tantalum mineralization was found in different domains of the Ukrainian Shield. Among Precambrian rock series with associated mineralization there are distinguished rare-metal pegmatites rich in Li, Rb, Cs, Ta, Nb, Sn, Be, some apogranitic metasomatites (greisens, quartzites, perthosites), and also various alkaline rocks. Compositional affinity of Ta-Nb minerals to basic compositional features of rock series that host this mineralization is believed to be a common feature of Ta-Nb minerals found in different rock associations.

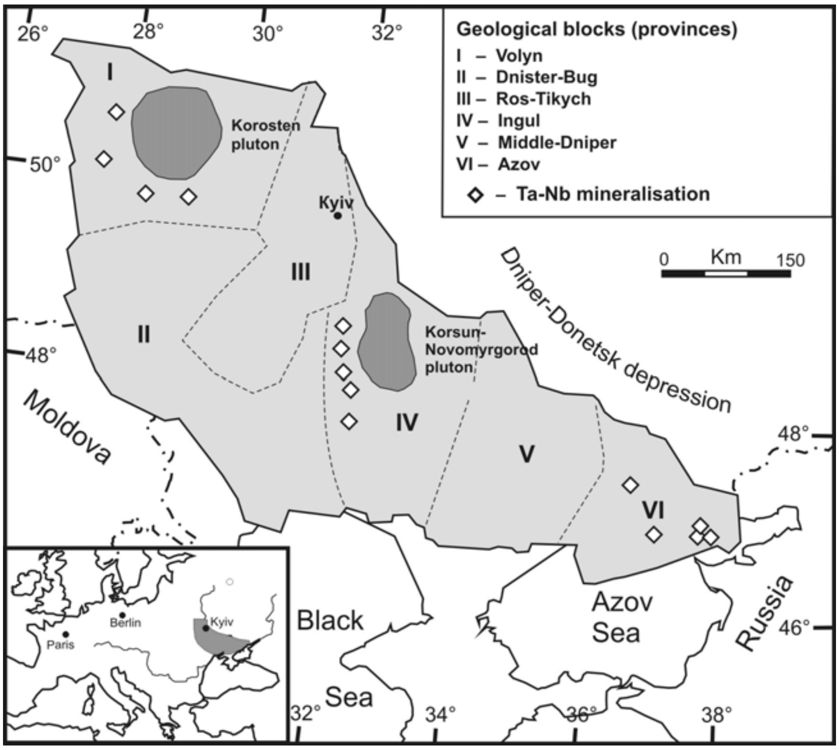

Figure 1. Schematic distribution of Ta-Nb mineralization within the Ukrainian Shield

Rare-metal pegmatites. Rare-metal pegmatites with Li, Rb, Cs and Ta-Nb mineralization were found in the Proterozoic (Volyn, Ingul) and the Archean (Azov) terrains. These rare-element pegmatites are classified as LCT type pegmatite [3]. Among the Precambrian rocks that host rare pegmatites with Ta-Nb mineralization there were distinguished metaluminous granite complexes (S-type), which are characterized by high potassic and alumina content, lack of fluorine, predominant ilmenite, as well as carbonaceous matter constancy. The age of RE pegmatites is unidentifiable because of the lack of accessory minerals commonly used as geochronometers (zircon, monacite). The age of granitic rocks that host rare-metal pegmatites is likely to be about 2.0 Ga for the Volyn and Ingul terrains and the same of 2.0 Ga (with some scientists scaling up to even the Archen age) for pegmatites of the Azov terrain.

Apogranitic metasomatites. The Nb-Ta-bearing apogranitic metasomatites of Proterozoic age were found in eastern Volyn and central Ingul terrains. They are characterized by the occurrence of large AMCG (anorthositemangerite-charnockite-granite) complexes, such as Korosten (in Volyn) and Korsun-Novomyrhorod (in Ingul) ones, with which morion, topaz- and beryl-bearing chamber pegmatites are associated, and which are classified as NYF-type pegmatites [3]. The Volyn terrain also includes metaluminuos felsic associations of Osnitsk complex (I-type) approximately dated 2.0 Ga and Perga peralkaline associations (A-type) of 1750 Ga, the latter tracing Nb-Ta mineralization. Osnitsk complex, being part of Osnitsk-Mikashevichi Orogenic Belt bordering Sarmatia from Fennoscandia [2], is thought to have predated the formation of Korosten AMCG complex. Perga complex is supposed to have appeared after the formation of Korosten NYF-type pegmatites.

Alkaline rocks. There were found about 50 massifs and occurrences of alkaline rocks and carbonatites in the central (Ingul) and eastern (Azov) terrains of the Ukrainian Shield. The only alkaline formations evident in Kirovohrad terrain turned out to be alkaline rocks and kimberlites of the Proterozoic age (2.1-1.8 Ga). The Azov terrain prevalently includes occurrences of the Proterozoic and Phanerozoic (Devonian) ages. The two main alkaline associations found in the Azov terraine were defined to be alkaline-ultrabasic (carbonatitic) and gabbro-syenitic complexes. Alkaline rocks of the eastern terrain (Azov) and the western terrain (Ingul) reveal completely different geochemical properties. Those of the Azov terrain show features of alkaline-ultrabasic associations (high contents of incompatible rare elements such as Nb, REE, Zr, Y, Sr), whereas those in the Kirovohrad terrain are characterized by low contents of Nb and Zr, and REE. This fact is interpreted to have resulted from different geodynamic settings of their origin – extensional and collisional ones, respectively. Various mineral deposits of apatite, niobium, REE, yttrium and zirconium proved to be associated with the alkaline rocks and carbonatites of the Ukrainian Shield. Most Nb and Ta of Novopoltavka economic carbonatites (Chernihivka alkaline-ultrabasic massif of the Azov terrain) were found to be concentrated in fergusonite and hatchettolite.

Application. By using optical microscopy, common chemical analysis, spectral and XRF methods there was determined chemical and mineralogical composition of granitoids and other felsic varieties of rocks. Furthermore, microprobe analysis identified some features of rock forming, ore and accessory minerals, with probes to be JXA – 5, JCXA – 733 (Institute of Geochemistry, Mineralogy and Ore Formation, NAS of Ukraine), JCXA – 8200 (Scientific and Technical Centre, NAS of Ukraine), Cameca SX – 100 (Geological Institute, Slovakian Academy of Sciences).

The study of Ta-Nb mineralization distribution within the Ukrainian Shield shows that despite inherent geochemical affinity between tantalum and niobium, these elements behave differently throughout the processes of granite complex formation, which is especially indicative of Proterozoic granite complexes. It should be emphasized that granites themselves do not commonly show high concentrations of ore minerals. Their potential economic mineralization is mostly associated with the products of late to postmagmatic alteration stages of granite system. It is these stages during which volatile components become more active followed by hydrothermal stage, during which most of the ore elements are thought to be accumulated [19]. But at the same time different pegmatites and metasomatites (greizens, secondary quartzites, perthosites) show distinctly close spatial and genetic relation to certain Proterozoic complex found in the Ukrainian Shield, which may be classified into different ilmenite or magnetite series of granites.

Within the territory of the Ukrainian Shield there can be outlined two contrasting provinces – Volyn terrain in the eastern part and Ingul terrain in the central part of the Ukrainian Shield, within which one can spatially single out fields of rare-metal granites and pegmatites that reveal typical geochemical specialization on Li, Rb, Cs, Ta, Nb, Sn, Be. These areas are characterized by mostly Proterozoic granite complexes, which distribution can be based on the features of niobium and tantalum minerals formed in contrasting redox conditions [8, 9].

In the Volyn terrain, the westernmost part of the Ukrainian Shield, the major concentrations of Nb and Ta mineralization are confined to metasomatically altered alkaline granites of Perga (A-type) and Osnitsk (I-type) complexes. Felsic rocks of these complexes are characterized by high magnetite content and that's why they may be related to magnetite series granites. Regionally, both Perga and Osnitsk granite complexes of magnetite series are related to the Osnitsk-Mikashevichi Orogenic Belt, which marks geological border between Sarmatia and Fennoscandia, the northern margin of the Ukrainian Shield. Both terrains are interpreted to have had different geological histories before 2.0 Ga and to have merged in post 2.0 Ga period of geological history [2]. It is exactly the period during which Pegra and Osnitsk granite complexes of magnetite series formed. Both granite complexes show a wide distribution of superimposed processes of metasomatic alterations (greisenization, albitization and silicification) and associated mineralization, which is confined to these metasomatites. Magnetite series granites of Perga and Osnitsk complexes are characterized by high content of fluorine and wide distribution of magnetite, with Li micas (lithionite, zynvaldite), columbites $(Fe,Mn)(Nb,Ta)_2O_6$, pyrochlore $NaCaNb_2O_6F$, Ta-cassiterite (Ta crystals in cassiterite) commonly distinguished among ore mineral associations. It was identified Ta/Nb ratio ranging from 1/10 to 1/15 and values of Fe/Mn ratio reaching 10/1, as well as complete absence of admixture elements to be the typomorphic features of columbites found in these ores.

Ingul terrain, occupying the central part of the Ukrainian Shield, is also characterized by a wide distribution of rare-metal granites, which occurrences can be spatially related to the central Kirovohrad (Ingul) orogenic belt [13]. Most granite complexes that contain Ta-Nb mineralization are related to ilmenite series granite of S-type (Yaroshevka, Polohivka, Lipniazhka complexes) with geochemical specialization on Li, Rb and Cs. These granites are characterized by high content of potassium, oversaturation in alumina and practically complete absence of fluorine. Graphite and anthraxolite that are commonly found in these ilmenite series of granites can probably testify for predominant reduction conditions of their formation.

Polohivka, Mostove, Lipniazka, North-Stankuvatka and Nadiya rare-metal deposits were determined to contain tantalum-niobium mineralization with short range of Ta/Nb values and low values of iron (FeO/MnO = 2.80-6.56). Columbites-tantalites found here are marked by heterogeneous inner structure, with different mineralogical phases to be found in a single mineral grain. These mineralogical phases are characterized by high content (weight %) of Ta_2O_5 ranging from 9.80 to 71.0, and Nb_2O_5 varying from 10.6 to 70.1 [8, 9, 13, 14]. At the same time columbite-tantalites indicate to a high content of admixure elements (weight %) with TiO_2 reaching 5.88; WO_3 – up to 3.70; SnO_2 – up to 9.20; Sc_2O_3 – up to 5.40. Some associated ore minerals, namely ilmenorutile $(Ti,Nb,Fe)_3O_6$, tapiolite $Fe(Ta,Nb)_2O_6$, microlite $(Na,Ca)_2(Ta,Nb)_2O_6(O,OH,F)$, Ta-cassiterite, nigerite are also commonly found here.

Conclusions. The basic typomorphic features of columbite-tantalite minerals, specified by Ta/Nb values, Fe/Mn ratio and admixture elements are concluded to depend on genetic granite types represented by magnetite and ilmenite series that are found in the Proterozoic complexes of the Ukrainian Shield. Magnetite series granites, which are considered to be formed in mostly oxidized environment (raised fO_2 values), are characterized by predominant niobium mineralization. At the same time ilmenite series granites, which are supposed to be formed in predominantly reducing environment, show rare-metal mineralization that is characterized by generally equal proportion of tantalum and niobium contents. This conclusion facilitates methods to optimize prospecting for potential rare metal mineralization associated with Precambrian structures within the Ukrainian Shield.

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МАГНЕТИТОВІ ТА ІЛЬМЕНІТОВІ СЕРІЇ ГРАНІТОЇДІВ ТА ОЦІНКА ЇХ ПОТЕНЦІЙНОЇ РУДОНОСНОСТІ НА НІОБІЙ І ТАНТАЛ В МЕЖАХ УКРАЇНСЬКОГО ЩИТА

У статті обговорюється можливість встановлення відмінностей між різновидами гранітів, які були сформовані в межах території Українського щита. Запропонована класифікація частково спирається на головні принципи, що були використані в деяких ранніх класифікаціях гранітів, серед яких є широко відома класифікація, яка була запропонована в роботах Ішихари [11] та Чеппела і Вайта [4], а також локальна (регіональна) класифікація, яка була запропонована в роботі Томурко та Щербакова [20]. У цій локальній класифікації була зроблена спроба навести відмінності між двома контрастними різновидами гранітів – апобазитовими та апопелітовими гранітами, які були встановлені в межах Українського Щита.

Класифікація гранітів на різні генетичні типи може стикатися з певними труднощами внаслідок гетерогенного генезису цих утворень – можливого змішування розплавів з їх батьківських мантійних та корових джерел. Але в той же час така класифікація може використовуватися для можливого прогнозу металогенічної спеціалізації різних генетичних типів гранітів. Серед параметрів, які можуть істотно вплинути на процеси накопичення металів в гранітах суттєву роль відіграють окислювально-відновні умови їх формування. На базі значень цього параметра граніти можуть бути підрозділені на два типи – граніти ільменітової та магнетитової серій, які характеризуються різними умовами їх формування [6, 11] і асоційованої мінералізації [1].

В межах території Українського Щита можливо виділити цілі провінції з відмінним розподілом переважно ільменітової або магнетитової серій гранітів. Ці граніти харатеризуються різними стилям рудної мінералізації асоційованої з ними. Тантало-ніобати знаходяться серед типових рудних мінералів, які можуть бути встановлені в тісній асоціації з цими серіями гранітів, оскільки ніобій і тантал характеризуються наявністю тісної літофільної спорідненості з цими утвореннями. На Українському Щиті тантало-ніобати були знайдені в гранітах і асоційованих з ними рідкіснометальних пегматитах, деяких апогранітних метасоматитах (грейзени, кварцити, пертозити) а також в лужних породах різного генезису.

Було встановлено, що характерні ознаки тантало-ніобатів, серед яких значення Ta/Nb, відношення Fe/Mn і присутність елементів домішок, показують близьку спорідненість з різними генетичними серіями гранітів. Ці ознаки, які були встановлені як типоморфні для ільменіт і магнетитових серій гранітів, можуть бути використані для оптимізації проведення пошуково-розвідувальних робіт на Українському Щиті.

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МАГНЕТИТОВЫЕ И ИЛЬМЕНИТОВЫЕ СЕРИИ ГРАНИТОИДОВ И ОЦЕНКА ИХ ПОТЕНЦИАЛЬНОЙ РУДОНОСНОСТИ НА НИОБИЙ И ТАНТАЛ В ПРЕДЕЛАХ УКРАИНСКОГО ЩИТА

В статье обсуждается возможность установления различия между разновидностями гранитов, сформированных в пределах территории Украинского щита. Предложенная классификация частично базируется на основных принципах, использованных в некоторых ранних классификациях гранитов, среди которых широко известная классификация предложенная в работах Ишихары [11], а также Чеппела и Вайта [4], и локальная (региональная) классификация, предложенная в работе Томурко и Щербакова [20]. В данной локальной классификация была сделала попытка провести различие между двумя контрастными разновидностями гранитов – апобазитовыми и апопелитовыми гранитам, которые были установлены в пределах Украинского Щита.

Классификация гранитов на различные генетические типы может сталкиваться с определенными трудностями из-за гетерогенного генезиса этих образований – возможного смешивания расплавов с их родительских мантийных и коровых источников. Но в то же время такая классификация может использоваться для возможного прогноза металлогенической специализации различных генетических типов гранитов. Среди параметров, которые могут существенно повлиять на накопление металлов в гранитах важную роль имеют окислительно-восстановительные условия их формирования. На базе значений этого параметра граниты могут быть подразделены на два типа – граниты ильменитовой и магнетитовой серий, которые характеризуются различными условиями образования [6, 11] и ассоциированной минерализации [1].

В пределах территории Украинского Щита можно выделить целые провинции с отличным распределением существенно ильменитов или магнетитовых серий гранитов. Эти граниты показывают различные стили рудной минерализации ассоциированной с ними. Тантало-ниобаты находяться среди типичных рудных минералов, которые могут быть установлены в тесной ассоциации с этими сериями гранитов, поскольку ниобий и тантал характеризуются наличием тесного литофильного сродства с данными образованиями. На Украинском Щите тантало-ниобаты были найдены в гранитах и ассоциированных редкометальных пегматитах, некоторых апогранитных метасоматитах (грейзены, кварциты, пертозиты) а также в щелочных породах различного генезиса.

Было установлено, что характерные признаки тантало-ниобатов, среди которых значения Ta/Nb, отношение Fe/Mn и присутствие элементов примесей, показывают близкое сродство с различными генетическими сериями гранитов. Эти признаки, установленные как типоморфные для ильменитовых и магнетитовых серий гранитов, могут быть использованы для оптимизации проведения поисково-разведочных работ на Украинском щите.

GEOPHYSICS

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CALCULATION OF SEDIMENTARY DEPOSITS ELASTIC CONSTANTS IN TRICLINIC APPROXIMATION ACCORDING TO VSP DATA

(Reviewed by the editorial board member O. Menshov)

This article attempts to define a complete component set of elastic constants tensor matrix in triclinic symmetry approximation and to evaluate the nature of seismic waves azimuthal anisotropy using field seismic surveys data. Elastic constants are determined by inverting the indicatrixes of radial and phase velocities with different polarization. Symmetry group of sedimentary strata is defined using acoustic tensor and elastic constants tensor. The basis of the standard acoustic coordinate system was the three right mutually orthogonal vectors of the acoustic tensor. Fedorov method is used for approximation of the elastic constants tensor to transversely isotropic medium, which provides not only a quantitative assessment of elastic constants matrix components but also allows us to estimate the deviation degree of real anisotropic medium elastic constants from those typical of transversely isotropic medium, the latter being the most similar to it.

Introduction

The phenomenon of seismic wave velocity anisotropy in the geological medium has long been the focus of researchers' attention. At present, the increasing interest in azimuthal seismic anisotropy is stimulated by the rapid development of three-component (3C) wide azimuth 3D seismic methods.

The existence of seismic anisotropy indicates that a real geological medium tends to possess an innate ordering of various geological and physical nature [1, 5, 6, 7, 13]. It is obvious enough that all the parameters of azimuthal seismic anisotropy are determined by the symmetry type of structural elements order in the geological medium. This follows from the Neumann-Curie's principle [1, 2, 5, 6, 8, 10, 15, 16] implying that the structural symmetry of the ordered geological medium determines the symmetry type of the elastic constants tensor. The elastic symmetry in turn limits all the azimuthal anisotropy parameters of seismic waves in ordered geological media.

Method of inversion

To solve this problem we use a modified invariant-polarization method, which determines the full components set of elastic constants matrix in the standard acoustic coordinate system while making numerical calculations by measuring the radial and phase velocities of elastic waves with different polarization. The method has been described in detail [1, 3, 5, 6, 11].

Inversion problem can be formulated as follows: to define the elastic constants of the geological medium by inverting the azimuthal dependence of the radial and phase velocities of elastic waves with different polarization specified during field seismic surveys. To solve the problem we used a nonlinear least-squares method. The objective function $\Phi(\vec{x})$ is as follows:

$$\Phi(\vec{x}) = \sum_{m=1}^{M}\left[V_m^{(e)} - V_m^{(r)}\right]^2 \quad (1)$$

where $V_m^{(e)}$, $V_m^{(r)}$ are the experimental and calculated values of velocities with different polarization (*e, r* = 1,2,3; 1 – quasi-longitudinal, 2,3 – quasi-transverse "quick " and "slow ") in the *m*-th direction measurements, $\vec{x}$ is vector of the unknown parameters with N dimensions, which includes 21 components of elastic constants matrix , density and components of the wave normal vector (if radial velocity is used). In determining components of the wave normal vector $\vec{n}$, given the conditions of their orthogonality, for numerical calculations of the radial velocity wave vector, its components were limited:

$$n_1^2 + n_2^2 + n_3^2 = 1 \quad (2)$$

Phase velocities and polarization vectors of elastic waves were derived from the Green-Christoffel equation [9]:

$$\left(\Gamma_{il} - \rho\upsilon^2\delta_{il}\right)U_l = 0, \quad (3)$$

where $\Gamma_{il} = C_{ijkl}n_j n_k$ – Christoffel tensor; υ – phase velocity; n_j – components of the wave normal vector; C_{ijkl} – tensor of elastic constants; U_l – components of elastic displacement vector; ρ – density; δ_{il} – Kronecker delta.

To determine the complete component set of tensor matrix elastic constants of sedimentary deposits in triclinic approximation, we used the results of field VSP observations, which had been held in the South Elbe region (the Caspian basin) [12] and Pierre shale data [18]. Sedimentary deposits, which have been the subject of research, are referred to the upper layers of the Lower Cretaceous. The technique of experimental seismic surveys combined observations of reflected and refracted waves on the surface and observations of direct waves in wells [12, 14, 17].

The above data show that stereo projections of all azimuthal anisotropy parameters of elastic waves (Figure 1) are strictly consistent with the symmetry type of sedimentary strata. In this case, there are certain features in the spatial behavior nature of these parameters.

It should be emphasized that obtained patterns of azimuthal anisotropy parameters distribution in sedimentary strata are in good agreement with the laboratory research of core samples by an ultrasonic pulse-phase invariant-polarization method published in a number of papers [1, 4].

Conclusions

Symmetry and a complete component set of tensor matrix elastic constants and elastic pliabilities in a standard acoustic coordinate system (Table 1) have been defined for the first time by inverting the radial velocity indicatrixes of quasi-longitudinal, "quick" and "slow" quasi-transverse waves obtained from the VSP data [12].

The elastic constants of clay strata were proved to have a planar triclinic symmetry; whereas the carbonates and shale Pierre turned out to have an axial rhombic symmetry. The value of elastic anisotropy integral coefficient is nearly 22%.

The stereo projections of seismic wave anisotropy parameters indicate that the spatial character of seismic wave azimuthal anisotropy is determined entirely by the matrix symmetry of the elastic constants tensor. There have been revealed distinct directions (longitudinal normal and acoustic axes) at different depths of clayey and calcareous shale strata.

Table 1

Elastic constants (C_{mn} , GPa – in the numerator) and elastic pliabilities S_{mn}, TPa^{-1} (in the denominator) of sedimentary deposits in working coordinate system (WCS) and standard acoustic coordinate system (SACS) calculated by seismic data inversion

Matrix indices, mn	Sand and clay deposits		Clay deposits		Carbonate deposits	
	WCS	*SACS*	*WCS*	*SACS*	*WCS*	*SACS*
11	9.15 / 280.9	9.18 / 255.2	9.16 / 238.5	8.82 / 238.2	17.79 / 86.7	17.79 / 86.7
22	10.00 / 141.1	9.41 / 233.0	10.04 / 135.5	9.57 / 175.4	14.00 / 95.7	14.00 / 95.7
33	7.34 / 438.5	7.14 / 506.7	7.28 / 379.4	7.02 / 398.0	13.85 / 134.0	13.85 / 134.0
44	0.62 / 1837.9	0.87 / 1609.1	0.71 / 1507.6	0.94 / 1330.2	3.47 / 288.2	3.47 / 288.2
55	0.98 / 1058.1	1.02 / 1004.4	0.86 / 1181.3	0.88 / 1171.8	3.41 / 293.3	3.41 / 293.3
66	1.67 / 685.3	1.76 / 700.1	1.52 / 672.0	1.81 / 656.3	2.71 / 369.0	2.71 / 369.0
12	1.99 / 53.9	2.25 / 53.8	1.90 / 41.0	2.37 / 24.0	5.00 / -2.5	5.00 / -2.5
13	6.14 / -269.3	5.92 / -245.5	5.81 / -217.4	5.55 / -197.4	9.30 / -5.7	9.30 / -5.7
23	4.01 / -125.6	4.36 / -216.5	3.95 / -109.4	4.28 / -140.9	7.00 / -4.7	7.00 / -4.7
14	0.10 / 104.4	-0.74 / 33.4	0.29 / 98.7	-0.73 / 43.9	0 / 0	0 / 0
15	0.03 / 53.2	-0.01 / -16.4	0.04 / 28.6	0.09 / -22.1	0 / 0	0 / 0
16	-0.38 / 94.0	0.29 / 48.2	0.15 / -1.9	0.79 / -35.8	0 / 0	0 / 0
24	-0.17 / 88.5	0.82 / -294.2	-0.02 / 50.4	0.56 / -138.2	0 / 0	0 / 0
25	0 / 27.7	-0.11 / -5.1	-0.14 / 37.3	0.05 / -23.8	0 / 0	0 / 0
26	0 / 32.7	-0.81 / 158.8	-0.02 / 9.1	-0.76 / 70.8	0 / 0	0 / 0
34	0.21 / -194.6	-0.47 / 272.1	0.32 / -169.0	-0.54 / 141.4	0 / 0	0 / 0
35	0.16 / -88.4	-0.06 / 30.3	0.14 / -66.6	-0.01 / 36.5	0 / 0	0 / 0
36	0.06 / -114.2	0.46 / -198.0	0.20 / -17.6	0.43 / -42.3	0 / 0	0 / 0
45	-0.05 / 166.1	0.04 / -36.3	0.02 / -10.7	0.03 / -74.9	0 / 0	0 / 0
46	-0.26 / 329.8	0.02 / -226.4	0.13 / -116.1	-0.37 / 168.6	0 / 0	0 / 0
56	-0.13 / 123.5	0.19 / -115.6	-0.05 / 46.2	0.18 / -140.8	0 / 0	0 / 0
Elastic symmetry	Planar triclinic		Planar triclinic		Axial rhombic	
A, %	21.6	21.6	21.92	21.98	13.08	13.08
Density, g/cm^3	2.300		2.193		1.986	

A – integral coefficient of elastic anisotropy

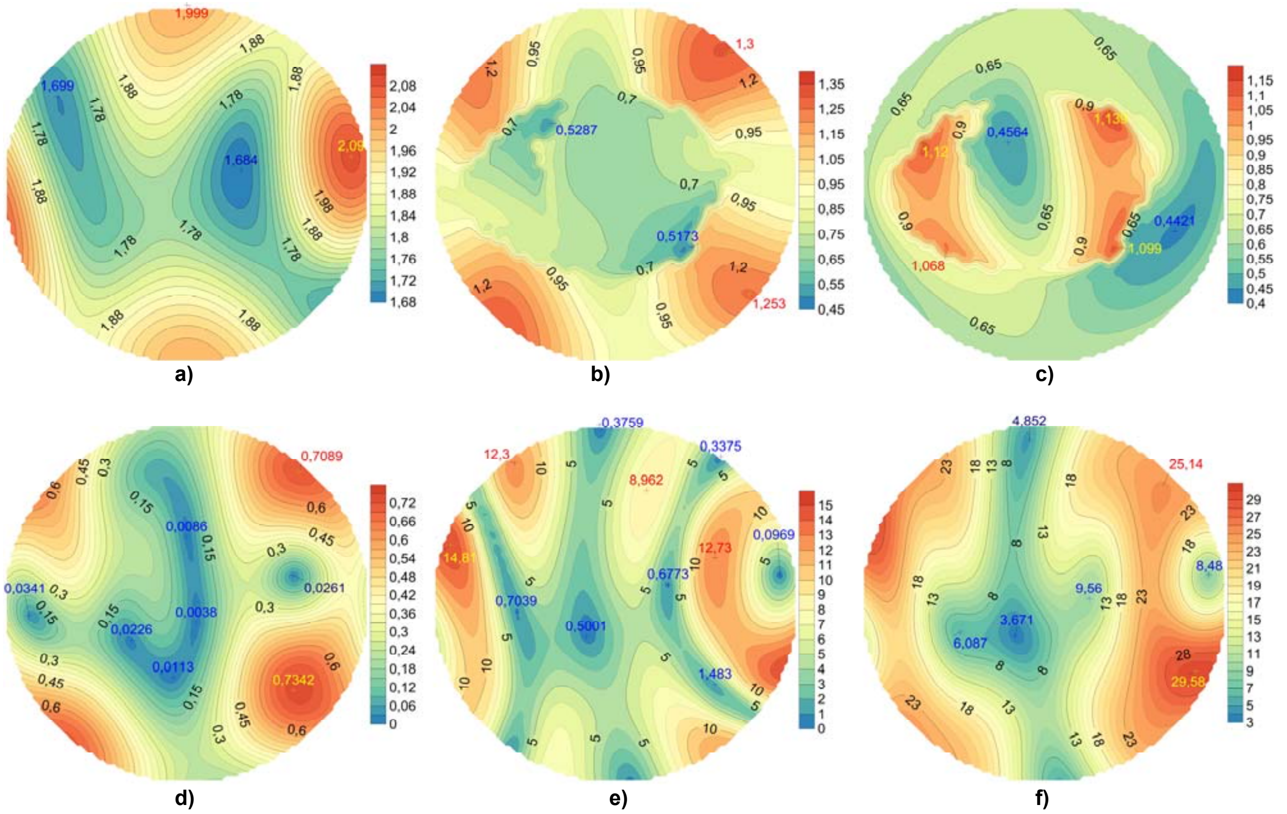

Figure 1. Stereo projections of the values distribution for sand and clay strata:
a) indicatrix of quasi-longitudinal wave, contours in km•s^{-1}; b) indicatrix of "quick" quasi-transverse wave, contours in km•s^{-1}; c) indicatrix of "slow" quasi-transverse wave, contours in km•s^{-1}; d) difference between the phase velocity values of " quick" and "slow" quasi-transverse waves, contours in km•s^{-1}; e) deviation angles of quasi-longitudinal wave elastic displacement vector from the direction of wave normal, contours in degrees; f) differential coefficient of elastic anisotropy, contours in %

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РЕЗУЛЬТАТИ ЧИСЕЛЬНИХ РОЗРАХУНКІВ ПРУЖНИХ СТАЛИХ ОСАДОВИХ ПОРІД В ТРИКЛІННОМУ НАБЛИЖЕННІ ЗА ДАНИМИ СПОСТЕРЕЖЕНЬ ВСП

В цій статті наведений приклад визначення повного набору компонент матриці тензора пружних постійних в наближенні триклінної симетрії та проведена оцінка характеру азимутальної анізотропії сейсмічних хвиль за результатами польових сейсмічних досліджень. Пружні сталі визначені шляхом інверсії індикатрис променевих або фазових швидкостей різної поляризації. Група симетрії осадової товщі визначена за допомогою акустичного тензора і тензора пружних сталих. За базис стандартної акустичної системи координат обрано праву трійку власних взаємно ортогональних векторів акустичного тензора. Для апроксимації тензора пружних постійних поперечно-ізотропним наближенням використовується метод Федорова, який забезпечує не лише кількісну оцінку компонент матриці пружних постійних, але й дозволяє оцінити ступінь відхилення пружних сталих реального анізотропного середовища від найближчого до нього поперечно-ізотропного середовища.

Вперше шляхом інверсії променевих і фазових індикатрис квазіпоздовжньої, "швидкої" та "повільної" квазіпоперечних хвиль осадової товщі, які отримані методом вертикального сейсмічного профілювання (ВСП), визначена симетрія і повний набір компонент тензорної матриці пружних сталих осадових порід. Симетрія тензорної матриці пружних сталих піщано-глинистої і глинистої товщі виявилася планальною триклінною, а карбонатної товщі та глинистого сланцю – аксіальною і планальною ромбічною. Запропонований інваріантно-поляризаційний сейсмічний метод визначення симетрії і пружних сталих відкриває нові можливості при дослідженні упорядкованого геологічного середовища методами 3D сейсморозвідки і буде сприяти суттєвому підвищенню ефективності сейсморозвідки при пошуках нафти і газу в складних геологічних умовах.

Були побудовані стерео проекції параметрів анізотропії сейсмічних хвиль, які свідчать про те, що просторовий характер азимутальної анізотропії сейсмічних хвиль повністю визначається симетрією матриці тензора пружних сталих. В глинистих і карбонатних товщах та глинистих сланцях на різних глибинах існують особливі напрямки – поздовжньої нормалі і акустичних осей.

Зроблена оцінка похибок апроксимації пружної симетрії товщ моделями поперечно-ізотропної і ромбічної симетрії. Показано, що апроксимація матриці пружних постійних триклінної симетрії більш симетричними моделями, зокрема ромбічної та поперечно-ізотропної симетрії, не лише спотворює характер азимутальної анізотропії сейсмічних хвиль, але й спричиняє значні похибки при оцінюванні азимутальної анізотропії сейсмічних швидкостей. Це може суттєво впливати на достовірність результатів 3D сейсморозвідки.

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РЕЗУЛЬТАТЫ ЧИСЛЕННЫХ РАСЧЕТОВ УПРУГИХ ПОСТОЯННЫХ ОСАДОЧНЫХ ПОРОД В ТРИКЛИННОМ ПРИБЛИЖЕНИИ ПО ДАННЫМ НАБЛЮДЕНИЙ ВСП

В этой статье приведен пример определения полного набора компонент матрицы тензора упругих постоянных в приближении триклинной симметрии и проведена оценка характера азимутальной анизотропии сейсмических волн по результатам полевых сейсмических исследований . Упругие постоянные определены путем инверсии индикатрис лучевых или фазовых скоростей различной поляризации . Группа симметрии осадочной толщи определена с помощью акустического тензора и тензора упругих постоянных. Базисом стандартной акустической системы координат выбрано правую тройку собственных взаимно ортогональных векторов акустического тензора. Для аппроксимации тензора упругих постоянных поперечно-изотропным приближением используется метод Фёдорова, который обеспечивает не только количественную оценку компонент матрицы упругих постоянных, но и позволяет оценить степень отклонения упругих постоянных реальной анизотропной среды от ближайшей к ней поперечно-изотропной среды.

Впервые путем инверсии лучевых и фазовых индикатрис квазипродольной, "быстрой" и "медленной" квазипоперечных волн осадочной толщи, полученных методом вертикального сейсмического профилирования (ВСП), определена симметрия и полный набор компонент тензорной матрицы упругих постоянных осадочных пород. Симметрия тензорной матрицы упругих постоянных песчано-глинистой и глинистой толщи оказалась планальной триклинной, а карбонатной толщи и глинистого сланца – аксиальной и планальной ромбической. Предложенный инвариантно-поляризационный сейсмический метод определения симметрии и упругих постоянных открывает новые возможности при исследовании упорядоченной геологической среды методами 3D сейсморазведки и будет способствовать существенному повышению эффективности сейсморазведки при поисках нефти и газа в сложных геологических условиях.

Были построены стерео проекции параметров анизотропии сейсмических волн, которые свидетельствуют о том, что пространственный характер азимутальной анизотропии сейсмических волн полностью определяется симметрией матрицы тензора упругих постоянных. В глинистых и карбонатных толщах и глинистых сланцах на разных глубинах существуют особые направления – продольной нормали и акустических осей.

Произведена оценка погрешностей аппроксимации упругой симметрии толщ моделями поперечно-изотропной и ромбической симметрии. Показано, что аппроксимация матрицы упругих постоянных триклинной симметрии более симметричными моделями, в частности ромбической и поперечно-изотропной симметрии, не только искажает характер азимутальной анизотропии сейсмических волн, но и влечет за собой значительные погрешности при оценке азимутальной анизотропии сейсмических скоростей. Это может существенно повлиять на достоверность результатов 3D сейсморазведки.

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ON THE ROLE OF POTENTIAL METHODS TO STUDY THE SALT AND REEF STRUCTURES IN THE DNIEPER-DONETS BASIN

(Reviewed by the editorial board member S. Vyzhva)

The article deals with some of the results of integrating geophysical methods applied in prospecting for unconventional hydrocarbon deposits under salt-stock bodies in the areas of concentration of small and low-amplitude anticlines and reef sites in the Dnieper-Donets basin (DDB).

Analysis of potential methods shows that within the DDB there are three types of salt-diapirs, which have certain characteristics in gravimetric and magnetic fields. The first and most common characteristic is the intense minima in gravity and no reflection in the magnetic field. The less common second type is stocks that outline the minimum gravity against maximum in the magnetic field. The third one, having a peculiar nature, shows both gravimetric and magnetic positive anomalies. Such a variety of manifestations of stocks in the gravimetric and magnetic fields is due, primarily, to their complex morphology.

The results of the geophysical surveys over the reef structures and the low-amplitude elevations formed over them show that they are mapped by linear, sometimes isometric, local maxima of the force of gravity of moderate intensity.

The comparison of results of previously performed studies of gravimetric and magnetic fields shows their high geologic efficiency in studying the morphology of salt stocks and identifying prospective near-stock objects when combined with seismic data and the data from exploration drilling.

Low-cost geophysical gravimetric and magnetic methods significantly reduce the cost of drilling deep exploration wells.

Introduction. Improving the efficiency of exploration for oil and gas requires further development of non-traditional methods. These activities have been conducted by various research and industrial organizations in Ukraine for many years. The theoretical basis to identify the unconventional hydrocarbons (HC) fields in the crystalline basement, under the salt-dome bodies, in the areas of concentration of small and low-amplitude anticlines and reef sites, etc are developing [2, 3, 6]. The accumulated data on exploration show that in order to reduce the exploration cost, the developments should focus on an integrated system of effective and relatively cheap non-seismic methods, while the detailed 3D seismic surveys ought to be carried out mainly at the stage of preparing objects for exploration drilling. The need for combining seismic with other geophysical methods can also be explained by the inability to obtain a sufficient geological dataset and the parameters of the oil and gas reservoir by individual methods [1, 4, 5]. A balanced combination of geophysical methods ensures effectiveness of solving inverse geophysical problems in prospecting.

The study of salt stocks. Salt domes in DDD represent the tectonic uplifts differing from the classic anticline uplifts in the presence of the salt core (Figure 1). During the penetration process of the stock, its upper part is dissolved, which often leads to the accumulation of a kind of cap. This cap consists of a poorly soluble accompanying mineral (gypsum, anhydrite) or pieces, or even large blocks, of various solid rocks trapped by salt when it moves upward.

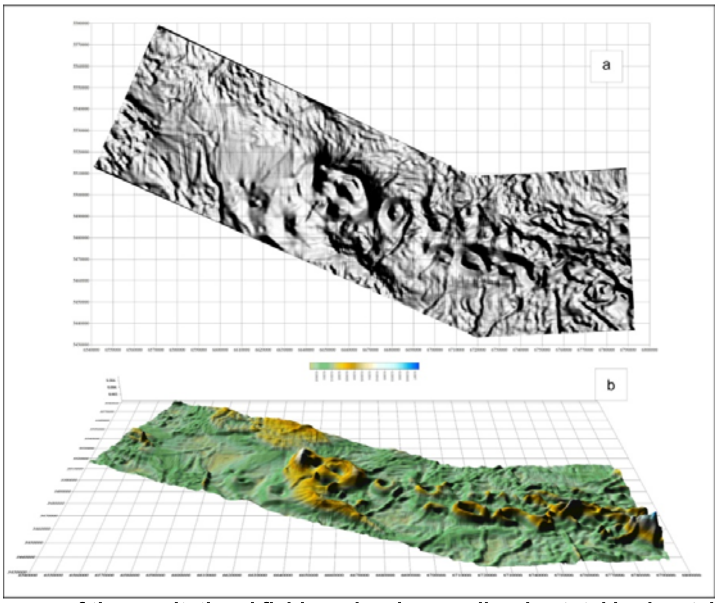

Figure 1. 3D maps of the gravitational field: a – local anomalies, b – total horizontal gradient

Analysis of the physical properties of rock salt shows that it is characterized by slightly varying low density of 2.0-2.2 g/cm3. In most cases, the DDD salt stocks of pre-Mesozoic Age break through the enclosing rocks of higher density forming the bodies with negative mass anomaly resulting in the intense minima in gravitational field. Such features are well manifested in the various transformations of the gravity field, for example, in local anomalies (Figure 1a) and in the total horizontal gradient (Figure 1b).

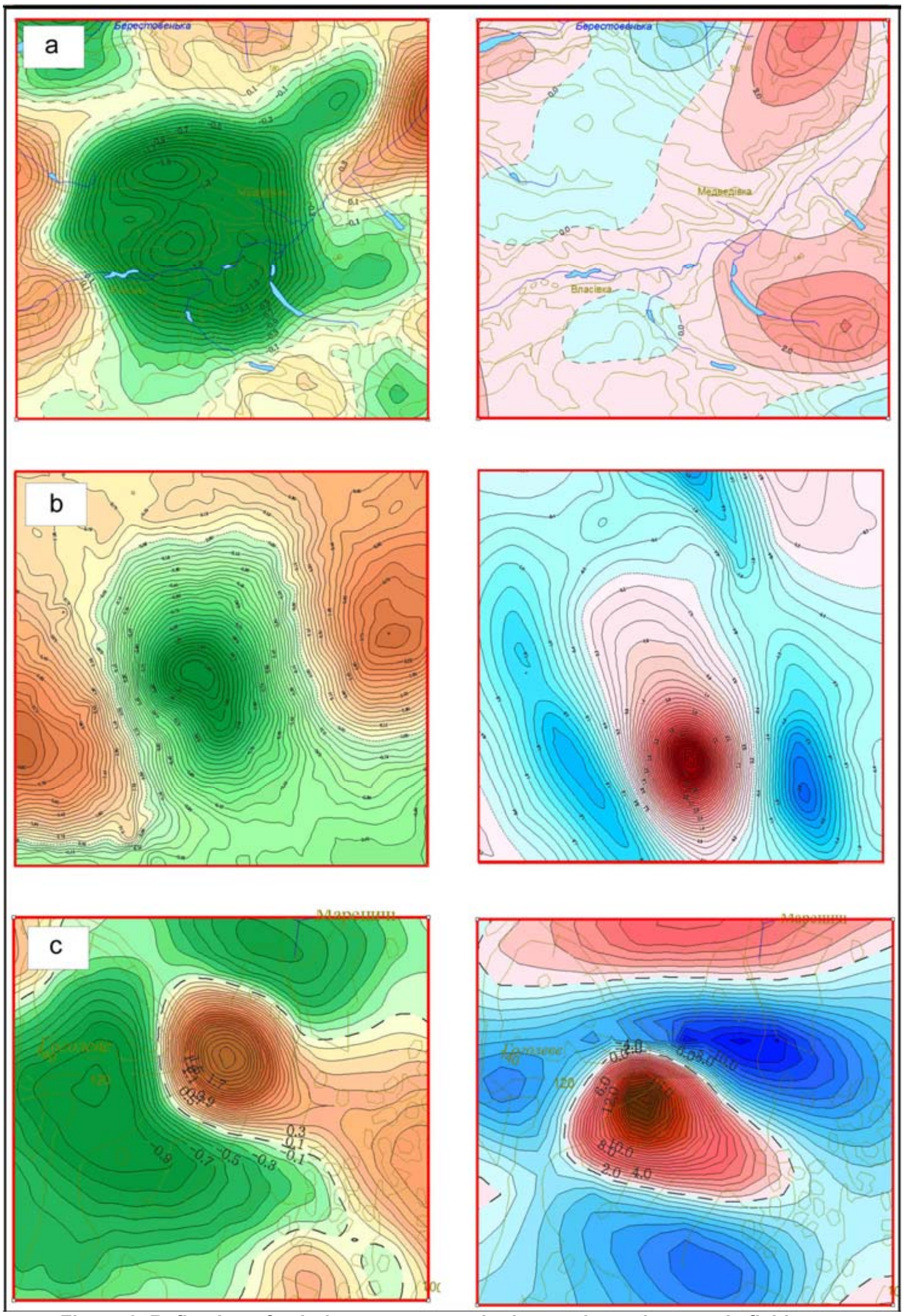

Figure 2. Reflection of salt dome structures in the gravity and magnetic fields:
a – Krestischensky stock, b – Runovschinsky stock, and c – Leykovsky stock

Salt domes in DDD are always located in groups and are characterized by columnar structure with steep and almost vertical slopes, sometimes even widening up. The height of the salt stocks is a few kilometers and can reach 6-10 km. Such salt forms are generally isometric in the cross section structures with a diameter from 1 to 8-10 km (Figure 1.2).

Salt is a weak diamagnetic rock. Therefore, big salt bodies are likely to cause negative magnetic anomalies. However, the combined effect of salt and weakly paramagnetic capturing clastic rocks does not account for their specific structure in a magnetic field. In some cases, the salt-core moving upwards captures rock blocks with significant magnetic susceptibility, which in DDD may be represented by diabases. Elevated by salt to the surface from the Devonian, diabases create magnetic anomalies with intensity of a few hundred nT which can be easily mapped in detailed surveys. It should be noted that some salt domes in DDD tend to contain large caps of dense rocks which gravitational effect being greater than that caused by the salt itself. In this case, the salt domes give maximum in gravitational field (Figure 2b).

The results of applying potential methods show that there are three types of salt-diapir identified within the DDD, with characteristics clearly seen in the gravity and magnetic fields (Figure 2). The most common ones are the intense gravity minima which are not actually observed in the magnetic field (Figure 2a).

The stocks identified with minima in gravity and maxima in the magnetic field are less common (Figure 2b). The stocks mapped by both gravity and magnetic positive anomalies are very rare (Figure 2c). This fact can possibly be explained by the presence of the Devonian volcanic rock fragments of considerable thickness in the caprocks. These volcanic rocks are characterized by high excess density compared with the surrounding sediments.

Such a variety of stock manifestations in a gravitational field is explained, first of all, by their complex morphology. It is the main factor in predicting oil and gas structures in zones near the stocks. In these zones, seismic is not always effective since it cannot accurately determine the position of the salt screen for optimal planning of exploration wells. Based on the experience in the DDD, the most correct solution of this problem can be obtained by using 2D and 3D modeling of the gravitational field. Reliability and accuracy of the obtained models depend on the quality and quantity of initial data, first of all, seismic, geological data and the degree of scrutiny of the density section [1, 4, 5]. An example is the joint high accuracy gravity and magnetic data and 3D seismic surveys in the Budyschansko-Chutovsky area in the central part of the DDD. It resulted in discovering a hydrocarbon field in the near-stock part of Runovschinsky salt dome. The results of density modeling for the Runovschinsky stock are shown in Figure 3.

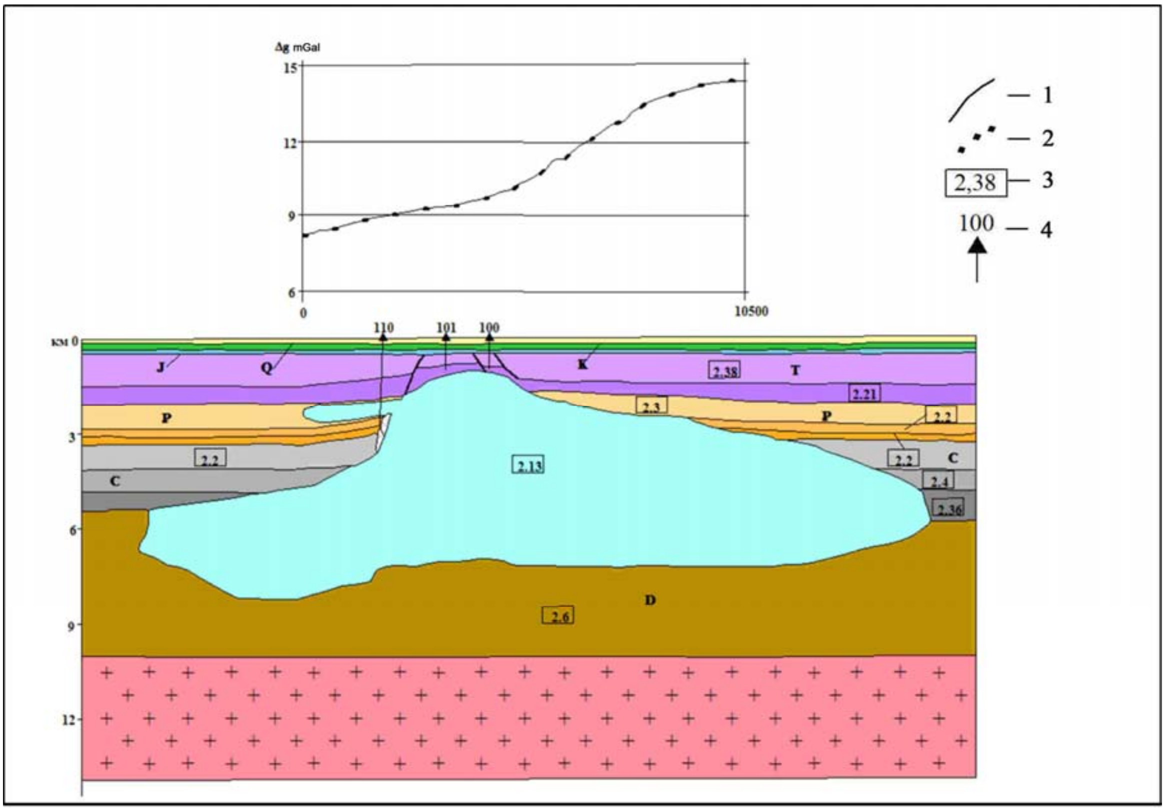

Figure 3. Density modeling of the Runovschinsky structure

As for other potential methods, it should be noted that the magnetic surveys are used as a complimentary method in the study of salt stocks to detect the presence of salt uplifts of the Devonian volcanic formations in the caprocks (the detection of their tops and thicknesses).

In the geoelectric sections, the salt stocks appear as rather high impedance heterogeneity. Resistance of a dry salt is equal or larger than 1,000 Ohm · m, while the caprock presented by carbonate-clastic rocks have resistance of 1-25 Ohms · m. The strong contrast in geoelectric properties between the stock and the caprock is the physical basis for using electrical methods to study the stock's morphology.

The authors have compared the results of previous gravimetric and electric studies with the exploration drilling and seismic data to investigate the morphology of salt stocks and allocation of near stock objects under prospecting. The comparison (Krestischenskaya, Rozpashnovskaya, Andreevskaya, Vostochno-Alekseevskaya (Figure 1), and other areas) shows high efficiency of these geological and geophysical methods.

The study of reef structures. Recently, due to the decrease in the collection of classical pericline structures, the hydrocarbon potentials are increasingly associated with the objects extensively developed in the coal formations of the northern near-edge part of the DDD and the Northern Donetsk Basin, the reef structures and the low-amplitude structures formed above them [6]. Stratigraphically, they are confined at Visean and Serpukhovian ages and possibly in the Bashkirian one.

Analysis of the density characteristics of the rocks from these stratigraphical units suggests that the Visean and Serpukhovian carbonate rocks have a slight excess of density compared to their caprock mudstone and siltstone. In the Bashkirian deposits, the density excess of carbonate rocks still further increases.

Therefore, in the gravitational field, they are mapped by linear, sometimes isometric, local maxima in the force of gravity of moderate intensity. A good example is the results from the Stelmahovskaya area in Lugansk region (Figure 4).

It should be noted, that nowadays, magnetic and electric exploration for reef structures in the DDD is not currently being carried out.

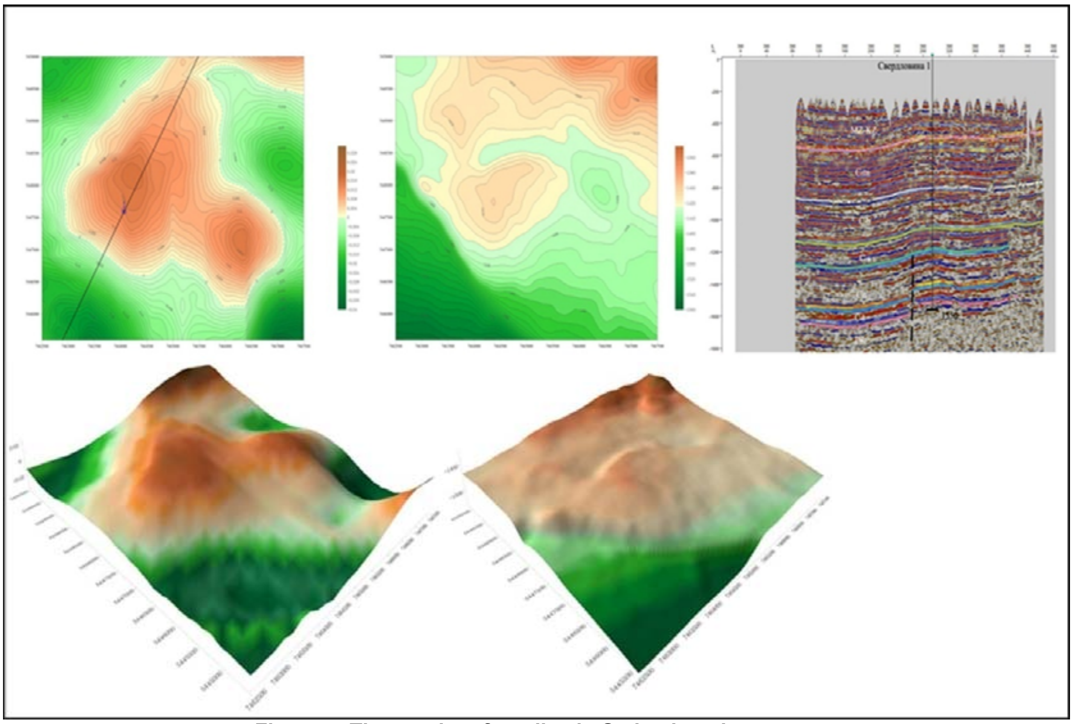

Figure 4. The results of studies in Stelmahovskaya area

Conclusions. Analysis of research data obtained with potential methods has made it possible to distinguish between three types of salt diapirs within DDB that have specific features manifested in gravimetric fields. The first and most common ones are characterized by intense gravitational minima and are not reflected in the magnetic field. The less common second ones show gravitational minima and maxima in the magnetic field. The third ones, those of a peculiar nature, are mapped with both gravimetric and magnetic positive anomalies.

Analysis of these results shows high efficiency of gravimetric methods in prospecting for unconventional oil and gas structures. Evaluation of their oil and gas prospects requires an application of joint detailed high-accuracy gravimetric and seismic surveys. Evaluation of their prospects is related to joint detailed gravimetric studies of high accuracy together with seismic. Comparing the results of the combined potential fields and wave field allows to quantify their geological efficiency. Certain difficulties in measuring their effectiveness are related to the study coursing unequally in prospecting areas, when using different methods and techniques both in the field and in the interpretation of the obtained data.

However, taking into account the complete set of results of the potential field interpretation will increase the productivity of exploration drilling. The effectiveness of these works is, in our view, evident, since the cost of gravimetric, magnetic and electric methods is much lower than the cost of deep well drilling.

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ПРО РОЛЬ ПОТЕНЦІЙНИХ МЕТОДІВ ПРИ ДОСЛІДЖЕННІ СОЛЯНИХ ТА РИФОВИХ СТРУКТУР У ДНІПРОВСЬКО-ДОНЕЦЬКІЙ ЗАПАДИНІ

У статті розглянуті деякі результати узагальнення проведених геофізичних робіт потенціальними методами при пошуках родовищ вуглеводнів нетрадиційного типу під соляно-штоковими утвореннями, в зонах концентрації малорозмірних і малоамплітудних антиклінальних і рифогенних об'єктах в Дніпровсько-Донецькій западині (ДДЗ).

Узагальнення результатів досліджень потенціальними методами показує, що в межах ДДЗ виділяється три типи соленосних діапірів, які мають характерні особливості прояву в гравімагнітних полях: перші, найбільш поширені, характеризуються інтенсивними мінімумами сили тяжіння і практично не відображаються в магнітному полі; інші, зустрічаються рідше, штоки, що відбиваються локальними мінімумами сили тяжіння, до яких приурочені максимуми магнітного поля; треті, з ексклюзивною природою, які картуються поєднаними позитивними гравітаційними і магнітними аномаліями. Така різноманітність прояву штоків в гравітаційному і магнітному полях обумовлена, передусім, їх складною морфологією

Узагальнення результатів геофізичних досліджень над рифогеними спорудами і сформованими над ними малоамплітудними підняттями показує, що в гравітаційному полі вони картуються лінійними, іноді ізометричними локальними максимумами сили тяжіння не високої інтенсивності.

Виконані авторами зіставлення результатів раніше проведених гравіметричних і магніторозвідувальних досліджень з метою вивчення морфології соляних штоків і виділення перспективних пришtokових об'єктів в комплексі з даними пошукового буріння і сейсморозвідки показало високу геологічну ефективність цих геофізичних методів.

Низька вартість геофізичних досліджень методами граві-магніторозвідки істотно знижують витрати на буріння глибоких пошуково-розвідувальних свердловин.

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О РОЛИ ПОТЕНЦИАЛЬНЫХ МЕТОДОВ ПРИ ИССЛЕДОВАНИИ СОЛЯНЫХ И РИФОВЫХ СТРУКТУР В ДНЕПРОВСКО-ДОНЕЦКОЙ ВПАДИНЕ

В статье рассмотрены некоторые результаты обобщения проведенных геофизических работ потенциальными методами при поисках месторождений углеводородов нетрадиционного типа под соляно-штоковыми образованиями, в зонах концентрации малоразмерных и малоамплитудных антиклинальных и рифогенных объектах в Днепровско-Донецкой впадине.

Обобщение результатов исследований потенциальными методами показывает, что в пределах ДДВ выделяется три типа соленосных диапиров, которые имеют характерные особенности проявления в гравимагнитных полях: первые, наиболее распространенные, характеризуются интенсивными минимумами силы тяжести и практически не отражаются в магнитном поле; вторые, встречаются реже, штоки отражающиеся минимумами силы тяжести к которым приурочены максимумы магнитного поля; третьи, с эксклюзивной природой, которые картируются совмещенными положительными гравитационными и магнитными аномалиями. Такое разнообразие проявления штоков в гравитационном и магнитном полях обусловлено, прежде всего, их сложной морфологией

Обобщение результатов геофизических исследований над рифогенными сооружениями и сформированными над ними малоамплитудными поднятиями показывает, что в гравитационном поле они картируются линейными, иногда изометричными локальными максимумами силы тяжести не высокой интенсивности.

Выполненные авторами сопоставления результатов ранее проведенных гравиметрических и магниторазведочных исследований с целью изучения морфологии соляных штоков и выделения перспективных приштоковых объектов в комплексе с данными поискового бурения и сейсморазведки показало высокую геологическую эффективность этих геофизических методов.

Низкая стоимость геофизических исследований методами грави-магниторазведки существенно снижают затраты на бурение глубоких поисково-разведочных скважин.

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MAGNETIC SUSCEPTIBILITY AND HEAVY METALS SOIL ACCUMULATION IN UKRAINIAN URBAN AREAS

(Reviewed by the editorial board member P. Pereira)

Soil pollution is an aspect of environmental magnetism research. The main objects are heavy metals and other chemical compounds. They pollute the environment and are dangerous for human life.

Purpose. The magnetic properties of polluted soils investigation for different technogenic sources and impact on the territory.

Methodology. The field stage work includes ecological and soil research, measuring the volume magnetic susceptibility with field kappameters. Laboratory studies include measuring mass-specific magnetic susceptibility with kappameters AGICO, MS-2, magnetization measurements, measuring magnetic parameters of the hysteresis loop with rock generator and special magnetometer equipment, determination of elemental composition, and electron magnetic microscopy.

Findings. Magnetic susceptibility of polluted soils ("urbanozems") increases in the upper humus horizons (A). New magnetic particles (PM particles) tend to form during high-temperature processes. There was found a high correlation between magnetic susceptibility and the lead, zinc, and copper content in the polluted soils.

Originality. A correlation between magnetic susceptibility and soil pollutants has been described. Heavy metals often stick to the surface of ferromagnetic materials and penetrate the structure of the crystal lattice under high-technology processes, with these compounds accumulating in soils.

Practical value. Further research into soil magnetism informative value is associated with the development of an optimal soil mapping technology in urban areas. Environmental magnetic investigation is a low-cost and high-performance technology to assess the technogenic and anthropogenic impact on the environment.

Introduction

Economic power and global sociopolitical influence of modern countries are associated with developed industries. Large cities have strong impacts on the surrounding environment. Powerful megalopolises are often centers of heavy industry. They are formed within extractive or processing industrial areas and centers of geopolitical activities. Hence the necessity to conduct environmental research in these centers.

More than a half of the world's population lives in urban agglomerations. In industrially developed countries, this share is as high as 75%. In Eastern Europe, Ukraine and Moldova are at the higher end of the urbanization spectrum.

Vyzhva and Zhukov [15] mark dangerous pollution levels, with special attention being paid to the capital of Ukraine. There is high atmospheric concentration of nitrogen dioxide, lead, sulphuretted hydrogen and dust. This results from harmful emissions from the city traffic. Reva et al. [12] observed a threat of radiation, geochemical and oil pollution impacts on the environment. They propose using ecogeophysical methods based on electrical geophysical investigation of soils.

It is important to understand the mechanism of biosphere changes and functions to improve the city environment. These changes are caused by the processes of industrialization, overpopulation, environmental pollution and other adverse effects of urbanization [9].

Geophysics is an effective instrument for ecological research. Investigations into environmental magnetism are very convenient and informative methods by Evans and Heller [5], Jelenska et al. [7], who analyze soils, polluted areas, lines and sources of pollution.

The magnetic method is a high-quality indicator of the soil pollution levels. Soil magnetism can identify different sources of pollution, toxic waste accumulation, poisonous gas, active materials, pesticides, organic and inorganic toxic compounds, as well as adverse chemical processes in soils. These sources of pollution are accumulated on the soil surface, which, in turn, produces negative effects on groundwater resources. Distribution of heavy metals in soils is determined by the location of the pollution sources, wind distribution, geochemical factors and geomorphology. The magnetic anomalies and the highest accumulation levels of magnetoactive materials tend to occur in topsoil horizons [3, 14].

Soil magnetic measurements show good results in detecting and mapping different sources of urban pollution, such as the burning of fuels, iron and steel industries, coal power stations, vehicle emissions. Good results were obtained in the United Kingdom by Blundell et al. [2], in Czech Republic by Fialova et al. [6], Petrovsky et al. [11], in Germany by Blaha et al. [1]. Another source of magnetic susceptibility anomalies in soils is superparamagnetic grains of non-atmospheric origin, according to Blundell et al. [2], Mullins [10].

Liu et al. [8] used magnetic measurements and heavy metal analyses of street dust as a means of determining pollution levels. Wang et al. [16] concluded that magnetic minerals in street dust samples are PSD range magnetite in high concentration.

Materials and methods

Figure 1 presents a map of pollution levels in Ukraine. The highest urbanization areas correspond to the areas with highest pollution levels. These are: Kyiv, Donetsk, Dnipropetrovsk, Zaporizhia and the South of Ukraine. The situation is better in Western Ukraine, these territories being moderately polluted. Black rings on the map in Fig 1 indicate the areas under investigation.

Urban geophysics is a part of environmental geophysics which deals with the ecological situation in big industrial cities and megalopolises. Urban geophysics investigates the spatial distribution of dangerous chemical compounds and pollution sources. Geophysical methods (soil science and geochemistry, electrometry and others) were used to study the effects of physical and chemical fields on urban and natural areas.

The Ecological system of megalopolis and natural areas has four basic components: air, water, soil, and vegetation. Soils play an important role in vital human activities within cities. There have been very important findings on atmospheric pollution, vegetation, soils, and water containing heavy metals and hydrocarbons. The magnetic properties of soils are the best studied. Among other objects of magnetic investigations are tree barks, leaves and other biota. These are transmitters of the anomalous ecological state, in which pollutants can be accumulated for a long period of time. Snow is an object of research, too. Air pollution investigation is of great importance because many pollutants are concentrated in the atmosphere. The direct study of the magnetic properties of air samples were performed by Spassov et al. [13] for a fast quantification of urban pollution sources in atmospheric particulate matter. The PM10 samples were collected on fibre-glass filters using a high-volume air sampler.

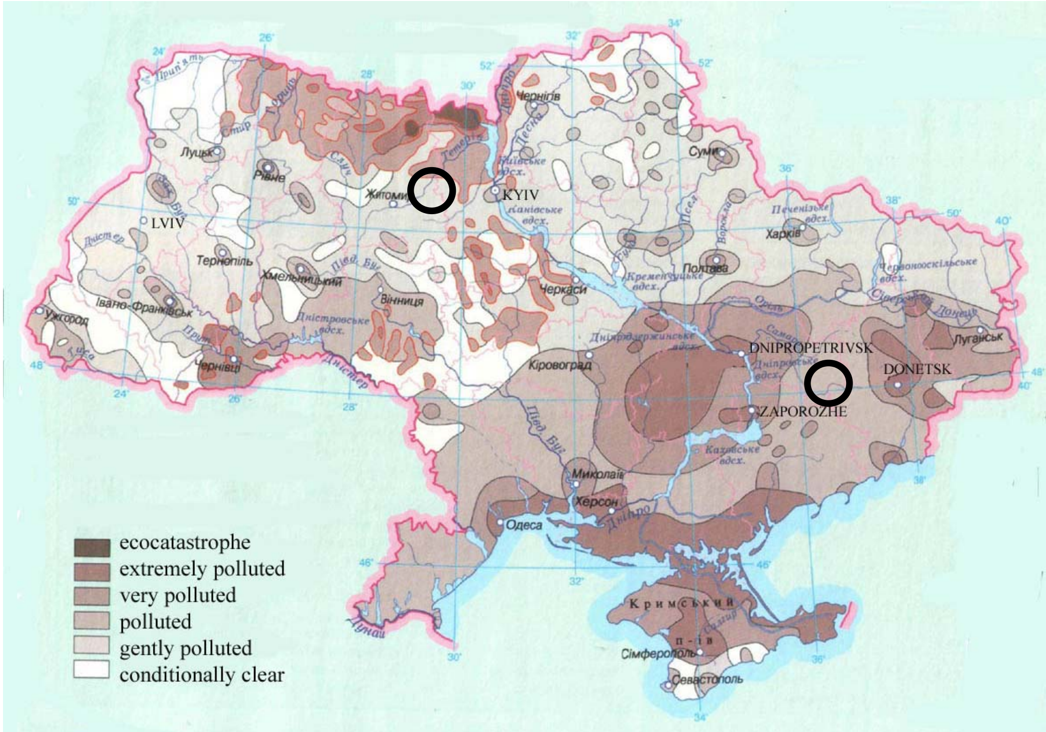

Figure 1. Map of pollution levels on the territory of Ukraine. The rings indicate the areas under study

City soils are not soils in their original meaning. Soils are unpolluted under city conditions only within forest and park areas. The specific type of soil is named urbanozem [4] (urbanosoil or anthroposols). Urbanozem is a genetically independent type of soil. It has both the natural soil and anthropogenic properties. Urban soils profile *increases* often resulting from anthropogenic accumulation of different materials. These include both household refuse and industrial waste. There are urban anthropogenic compounds in the structure of the soil. High vertical and horizontal zoning, series of buried historical, archaeological and soil layers occur in urbanozems.

In order to investigate urban soils, Kyiv was divided into a few key areas. 120 samples were taken to analyze magnetic susceptibility of the soils and the heavy metals content. Donetsk is the main city of the Donetsky coal-field, which is the driving force behind the industrial development of the city. Its population is about 1 million people. The values of the magnetic susceptibility of the urbanozem soils in different districts of Donetsk were obtained for 50 samples.

To measure magnetic susceptibility, we used the Bartington MS2 and AGICO Kappabridge.

Results and discussion

Research into soils of the capital of Ukraine (Kyiv) and the main industrial center of Ukraine (Donetsk) shows a close correlation between magnetic susceptibility of soils, heavy metals concentrations, and the sampling area. The distribution of the urbanozem soils magnetic susceptibility in different districts of Donetsk is presented in Table 1.

Figure 2 presents the distribution histogram of average magnetic susceptibility values for Donetsk region.

Table 1

The distribution of magnetic susceptibility of the urbanozem soils in different districts of Donetsk

№	District	Street	MS*10^{-9} m^3/kg
1	Kirovskiy	Fruktovaya	1934
2	Leninskiy	Leninskaya	3303
3	Leninskiy	Pintera	607
4	Proletarskiy	Razdolnaya	1063
5	Voroshilovskiy	Komsomolskiy Ave.	1173
6	Voroshilovskiy	Teatralniy Ave.	2531
7	Kalininskiy	Vladichanskogo	2078
8	Kievskiy	Universitetskaya	1694
9	Kuibishevskiy	Yugoslavskaya	7755
10	Budenovskiy	Zasulich	652
11	Kievskiy	Prosp. Kievskiy	2071

The registered values of magnetic susceptibility on the territory of Donetsk are between 2 and 50 times higher than those observed for natural soil types. The lowest magnetic susceptibility (MS=600-700*10^{-9} m^3/kg) was registered in Leninskiy and Budenovskiy districts of Donetsk. The most probable values of magnetic susceptibility (MS=1000-3000*10^{-9} m^3/kg) are in Kirovskiy, Voroshilovskiy, Kalininskiy, and Kievskiy districts of Donetsk. The highest values of magnetic susceptibility registered on the territory of Donetsk were in Leninskiy and Kuibishevskiy (Yugoslavskaya Street) districts. And the most considerable anomalies were found in the chemical plant zone (MS=7000-8000*10^{-9} m^3/kg).

The average values of magnetic susceptibility for the soils of different districts of Donetsk ranged between 1000-3000*10^{-9} m^3/kg. This is 2 to 6 times higher than in non-polluted soils. The soil samples with magnetic susceptibility of up to 6000*10^{-9} m^3/kg were collected in Kuibishevskiy (Yugoslavskaya Street) district. The left asymmetry was composed with the samples from Leninskiy and Budenovskiy districts of Donetsk. The magnetic susceptibility is 600-700*10^{-9} m^3/kg.

The correlation coefficients between magnetic susceptibility and heavy metals content in Kyiv urbanozems are presented in Table 2. The investigations were conducted in 5 zones of Kyiv with different levels of anthropogenic and technogenic impact.The highest correlation coefficients were between magnetic susceptibility and Zn, magnetic susceptibility and Pb, lower for Cu. An increase in MS values accounts for the growth of Pb, Cu and Zn concentrations in soils.

For example, the correlation between Ln MS and LN Pb for Kyiv Koncha-Zaspa area is presented in Fig.3. The correlation coefficient value is 0.9, this being the highest among the statistical samples.

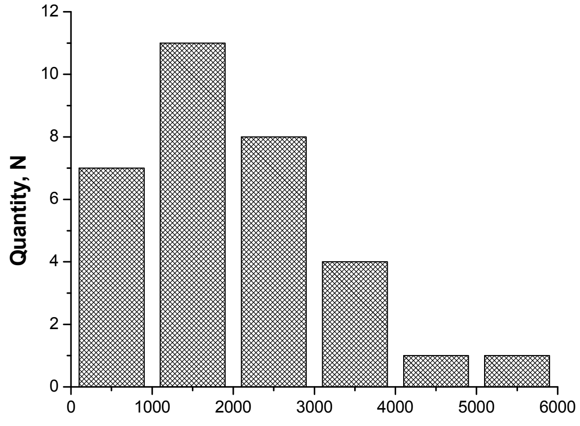

Figure 2. The distribution histogram of average magnetic susceptibility values for the soils of Donetsk districts

Table 2

The correlation coefficients between magnetic susceptibility and heavy metals content in Kyiv soils

Area	*Heavy metals*		
	Cu	**Zn**	**Pb**
Koncha-Zaspa	0.5	0.9	0.9
Kiyv-Dniprovskiy	0.8	0.7	0.8
Darnitsa	0.3	0.9	0.4
Svatoshino-Pusha-Vodytsa	0.8	0.6	0.6
Golosievo	0.5	0.9	0.9

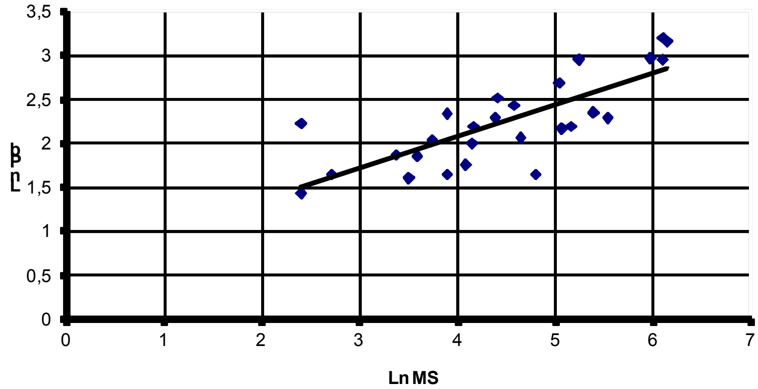

Figure 3.The regression between Ln MS and LN Pb for Koncha-Zaspa area, Kyiv

The positive correlation can be explained in terms of the single factor causing an increase in both parameters. A good example would be alphitite, which accumulates heavy metals and magnetic materials. According to Spassov et al. [13], some heavy metals are readily absorbed into the surface of iron oxides. Heavy metals have a high affinity towards iron oxides. They tend to occur as particulate matter smaller than 10 μm (PM10) or may penetrate their crystal lattice under high-temperature technological processes (fly ash).

Conclusions

The registered values of magnetic susceptibility on the territory of Donetsk were 2-50 times higher than those for natural soil types.

1. For the territory of Kyiv, the highest correlation coefficients were between magnetic susceptibility and Zn, magnetic susceptibility and Pb, lower for Cu. An increase in MS values accounts for the growth of Pb, Cu and Zn concentrations in soils.

2. Positive correlation between magnetic susceptibility and heavy metals content can be put down to the presence of particulate matter smaller than 10 μm (PM10) which may penetrate the crystal lattice under high-temperature technological processes.

3. We have emphasized the necessity for urban geophysical investigations on the territory of big industrial cities and megalopolises, with Ukrainian cities examples used as an illustration. The magnetic properties of city soils – urbanozems, snow and air – correlate with industrial dust, heavy metals and other city pollutants. The magnetic method has proved to be appropriate, low-cost and quick for this type of investigation.

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МАГНІТНА СПРИЙНЯТЛИВІСТЬ ТА НАКОПИЧЕННЯ ВАЖКИХ МЕТАЛІВ У ГРУНТАХ УРБАНІЗОВАНИХ ТЕРИТОРІЙ УКРАЇНИ

Дослідження забруднення ґрунтових покривів є частиною вивчення магнетизму навколишнього середовища. Основними об'єктами досліджень є важкі метали у ґрунтах та їх хімічний склад. Відповідні небезпечні речовини накопичуються у ґрунтах та водночас є небезпечними для життєдіяльності людини.

Мета. Дослідження магнітних властивостей забруднених грунтів при різних техногенних джерелах впливу на навколишнє середовище.

Методика. Польовий етап робіт включає еколого-ґрунтознавчі роботи, вимірювання об'ємної магнітної сприйнятливості польовими капаметрами, відбір зразків ґрунтів. Лабораторні дослідження складаються з вимірювання питомої магнітної сприйнятливості лабораторними капаметрами типу AGICO, MS2, вимірювання намагніченості, магнітної жорсткості, параметрів петлі гістерезису за допомогою рок-генератора і спеціальної магнітометричної апаратури, визначення елементного складу, електронна магнітна мікроскопія. Останнім етапом виступає комплексний аналіз та інтерпретація отриманої інформації.

Результати. Наведено результати вивчення магнітних властивостей забруднених ґрунтів території Києва та Донецька. Виявлено, що магнітна сприйнятливість заражених ґрунтових покривів – урбаноземів, може підвищуватися у багато разів у верхніх гумусних горизонтах. Вивчення магнітної мінералогії показує, що в процесі високотемпературних реакцій відбувається формування нових магнітних частинок величиною до 10 мкм (PM частинки). Відзначені високі коефіцієнти кореляції між магнітною сприйнятливістю і вмістом в заражених ґрунтах свинцю, цинку, міді.

Наукова новизна. Встановлено зв'язок між магнітною сприйнятливістю і техногенним навантаженням на урбанізовані території України. Важкі метали часто приклеюються до поверхні феромагнетиків, потрапляють до структури їх кристалічної решітки в процесі високотемпературних техногенних процесів, а потім ці сполуки накопичуються у ґрунтах.

Практична значимість. Наступні дослідження інформативності магнетизму ґрунтів в екології пов'язуються з розробкою оптимальної технології картування ґрунтових покривів урбанізованих територій магнітними методами. Екомагнітне дослідження є експресною, дешевою і високоефективною технологією оцінки техногенного впливу на навколишнє середовище.

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МАГНИТНАЯ ВОСПРИИМЧИВОСТЬ И НАКОПЛЕНИЕ ТЯЖЕЛЫХ МЕТАЛЛОВ В ПОЧВАХ УРБАНИЗИРОВАННЫХ ТЕРРИТОРИЯ УКРАИНЫ

Исследование загрязнения почвенных покровов является часть магнетизма окружающей среды. Основными объектами, которые загрязняют окружающую среду и при этом опасны для жизни человека, а также фиксируются магнитными методами, выступают тяжелые металлы и некоторые другие химические соединения.

Цель. Изучение магнитных свойств почв загрязненных вследствие техногенного влияния на территорию различных источников.

Методика. Полевой этап работ включает эколого-почвоведческие работы, измерение объемной магнитной восприимчивости полевыми капаметрами, отбор образцов почв. Лабораторные исследования состоят из измерения удельной магнитной восприимчивости лабораторными капаметрами типа AGICO, MS-2, измерения намагниченностей, магнитной жесткости, параметров петли гистерезиса с помощью рок-генератора и специальной магнитометрической аппаратуры, определение элементного состава, электронная магнитная микроскопия. Последним этапом выступает комплексный анализ и интерпретация полученной информации.

Результаты. Приведены результаты изучения магнитных свойств загрязненных почв Киева и Донецка. Выявлено, что магнитная восприимчивость зараженных почвенных покровов – урбаноземов, может повышаться во много раз в верхних гумусных горизонтах. Изучение магнитной минералогии показывает, что в процессе высокотемпературных реакций происходит формирования новых магнитных частиц величиной до 10 мкм (PM частицы). Отмечены высокие коэффициенты корреляции между магнитной восприимчивостью и содержанием в зараженных почвах свинца, цинка, меди.

Научная новизна. Установлена связь между магнитной восприимчивостью и техногенной нагрузкой на урбанизированные территории Украины. Тяжелые металлы часто приклеиваются к поверхности ферромагнетиков, попадают в структуру их кристаллической решетки в процессе высокотемпературных техногенных процессов, а затем эти соединения накапливаются в почвах.

Практическая значимость. Последующие исследования информативности магнетизма почв в экологии связываются с разработкой оптимальной технологии картирования почвенных покровов урбанизированных территорий магнитными методами. Экомагнитные исследования являются экспрессной, дешевой и высокоэффективной технологией оценки техногенного влияния на окружающую среду.

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MODEL OF SEISMIC VELOCITY DISTRIBUTION FOR COMPLETE COMPLEX OF PROCESSING AND INTERPRETATION OF SEISMIC DATA IN DNIEPER-DONETS BASIN

(Reviewed by the editorial board member G. Prodaivoda)

Advanced understanding of geological structure of petroleum fields remains one of the main drivers of successful exploration and production. Due to limitations of seismic method we can acquire data only in time domain, while other data, like petrophysical or geological, are acquired in depth. Combining these main data sources in a single exploration project remains one of the main task of exploration geologist since it allows avoiding mistakes in depth estimation of prospects, and thus correct estimations for drilling.

The key for correlations between time and depth domain is vertical seismic profiling (VSP), which allows estimation of seismic waves' travel time with depth. Basically, so far this is the only direct measurement of time-depth relationship in petroleum fields. Correct processing and interpretation of this data will lead to correct interpretation and prospect evaluation.

In the paper VSP data processing workflow is being proposed. Calculation methods of interval, average and layer velocities and statistical methods to crosscheck obtained results are suggested. Statistical analysis allows avoiding subjective mistakes, and though in some situations might require later manual corrections for geological factors, nevertheless it allows to guarantee quality of the data and introduces unique approach to its interpretation.

Obtained seismic velocities later were incorporated in seismic data processing graph and an optimal graph for processing seismic data using VSP velocities is introduced. Applying well velocity data allows us to properly estimate velocity models for depth migration and to avoid uncertainties related to velocity estimation.

Seismic images, obtained after processing, were used for seismic interpretation, which helped to specify geological structure of the prospects in the cutoff part of the Dnieper-Donets Basin. Modern software and interpretation methods of seismic data allow significant improving of mapping accuracy and tracing tectonic faults.

Introduction. Advanced understanding of geological structure of the fields of Dnieper-Donets Basin is one of the most important steps in modern geological exploration hence it allows increasing of oil and gas resources and reserves. In return, this challenge became unreachable without precise processing of acquired seismic data and detailed understanding of velocity model prior migration.

Significant amount of geological and geophysical studies were held at the area of interest, including electrometric, magnetic, gravity and seismic surveys. Wildcat, parametric, and some production wells are drilled.

Acquiring of these data allowed creating acceptable geological model of the area. Nevertheless, the most important issue related to depth conversion cannot be solved correctly solely by little amount of velocity data from certain fields, also we cannot rely completely on velocity models created based on velocity spectra analysis prior migration. Though such velocity cubes might be used later for depth conversion relatively easily using well-known Dix equation, we should take into account possible mistakes that might be introduced during velocity spectrum analysis. Thus, 5% mistake in velocity estimated from velocity spectra can result in about 20% mistake in interval velocities calculated via Dix equation. This is why using borehole seismic data is a crucial step for accurate depth models of petroleum prospects and leads.

Since most of well seismic data had being acquired in different time by different tools and processed by different methodologies, it was important to develop a methodology allowing processing and interpretation of the data and bringing it to one standard. Later these data, from more than 300 wells, were used to create interval, average and layer velocity models for central part of Dnieper-Donets Basin, helping to understand velocity distribution in the region based not only on onshore seismic, but on the well data.

These velocity data were introduced into processing workflow, allowing us to use additional information for velocity modeling and thus obtaining seismic images of higher quality and more accurate distribution of reflectors. And obviously, their correlation with geological strata.

A workflow to enhance processing graph using velocity model acquired from VSP data at the whole central part of DDB is being proposed in the paper.

Significant amount of geologic and geophysical surveys were held at the area of interest, including electric, magnetics, gravity and seismic surveys. Wildcat, parametric, and production wells are drilled.

Most of the fields at the area are linked to non-anticline traps – tectonic blocks with monoclines.

The processing was performed in a wide frequency range with preservation of kinematic and dynamic characteristics of the seismic record.

All processing consisted of three main steps:

1. Time processing of seismograms.
2. Prestack time migration.
3. Processing of the 3D volume.

The first and third stages of processing were performed in the Echos software package. The second stage was performed in GeoDepth.

Along with loading seismic profiles in geologic database of the project, well log data was entered – coordinates of wells in the area of study, stratigraphy markers, their depth marks, VSP data, acoustic and radioactive logs, well deviations and others.

Results of interpretation of seismic images build using suggested processing graph allowed obtaining much more detailed geological structure, with more accurate depth correlation of the strata. Correct understanding of depth relations can foster petroleum production from the field and will be essential for well planning.

Methodology of VSP data interpretation. Collection and analysis of wellbore seismic data, mainly results of VSP research was the first step in preparation data for velocity modeling. Authors have collected the data from more than 300 wells. Most of these wells are located at the area of research, while some wells are located outside the area, but in "immediate" vicinity. These wells were incorporated into model in order to control extrapolation process at the borders of the research area.

About 5% of these data were not conditional – it was not possible neither to re-interpret the data, nor even understand the readings. Therefore, we made conclusion that such oil fields may be considered as the ones without well velocity data.

Since all the VSP surveys were conducted in different time by different methodologies, we have decided to re-interpret the data – in order to bring it to one standard.

In order to have all the VSP interpretation results we have developed following workflow:

- at the first stage vertical time travel curves were referenced to absolute depth level (sea level) and correction of an a priori mistakes was made.
- at the second stage corrected time travel curve was recalculated in the time travel curve with constant increment. If input time travel curve was reordered with a step of 20 meters and more, step of an output curve was set to 20 meters. If input time travel curve was reordered with increment of 10-15 meters and more, increment in the output curve was set to 10 meters.
- at the third stage obtained data was transferred in digital and graphical form for further processing.

A section of vertical time travel curve with location of reading points is presented at Figure 1. Figure 2 shows time travel curve with reading points (A) and interval velocities calculated in the well. Red arrow indicates a layer with anomalously high velocities, which corresponds to one reading point at the time travel curve and most likely is a result of measurement mistake.

Average and interval velocities based on VSP data were calculated according to the following workflow:

$$Vp\_av = \frac{H}{Tp}, \quad (1)$$

were V_{p_av} – average velocity for primary wave, H – vertical depth from the reference datum, T_p – wave transit time.

For interval velocity:

$$V\,\text{int} = \frac{\Delta H}{\Delta Tp}, \quad (2)$$

were V_{int} – interval velocity of primary wave, ΔH – depth differential, ΔT_p – primary wave transit time.

Figure 3 presents an example of layer velocity modeling.

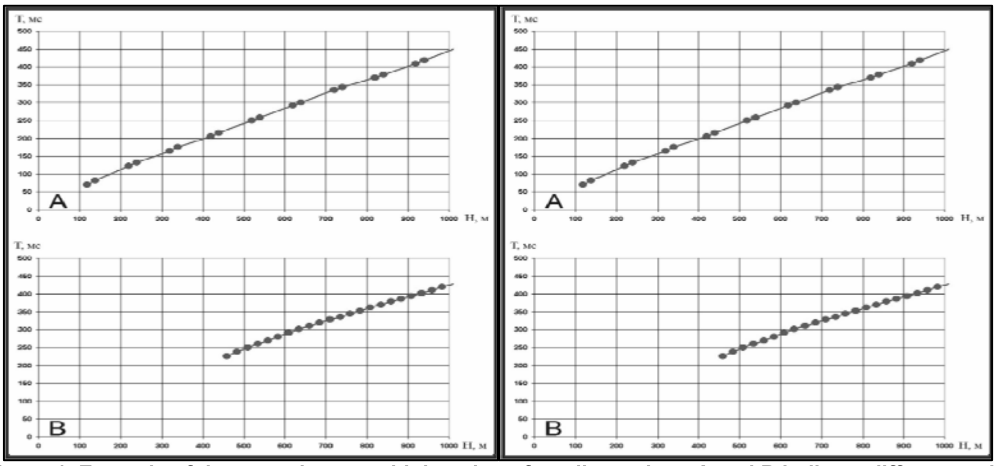

Figure 1. Example of time travel curve with location of reading points. A and B indicate different wells

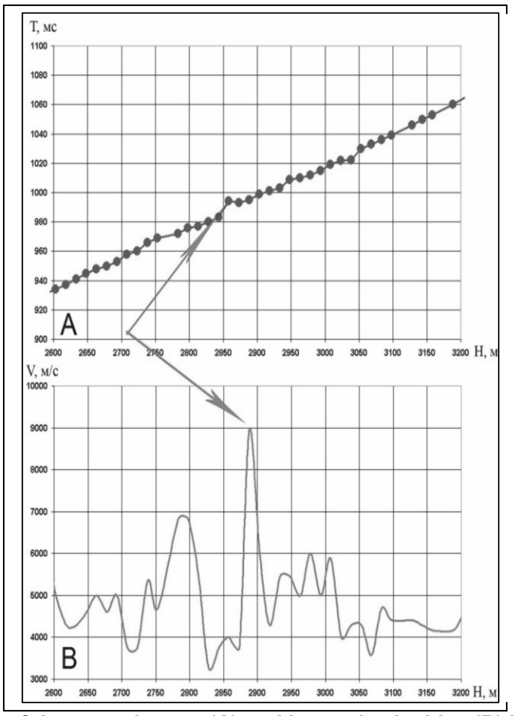

Figure 2. Example of time travel curve (A) and interval velocities (B) before corrections. Arrows indicate errors of the first arrival readings

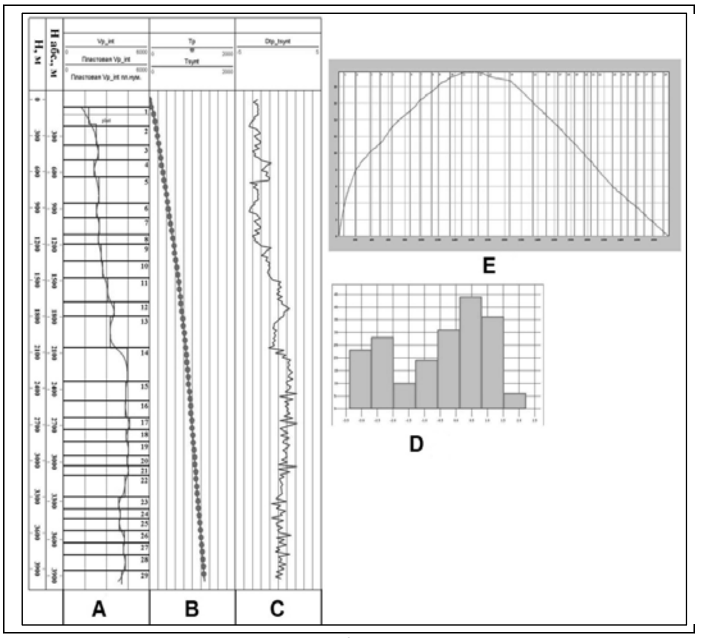

Figure 3. An example of layer velocity modeling.
A – interval and layer velocities, B – forward modeling – calculation of vertical time travel curve, which is later compared to real time travel curve (B, C). E – correction of the model with reduced time travel curve, D – statistical control of the data

Calculation of layer velocity based on traditional methods (choosing breakpoints of time travel curve) is the most subjective and open to errors since interpreter's point of view is the main criteria in this approach. At the other hand, suggested methodology allows calculating layer velocities automatically, reducing human factor.

To calculate layer velocities authors have used not time travel curves, but interval velocities. Based on common petrophysical algorithms [2, 3] these data were converted into layers and layer velocities were calculated based on the equation (3):

$$Vp = \frac{\Delta H}{\Delta Tp}, \quad (3)$$

were V_p – layer velocity, ΔH – thickness of the layer, ΔT_p – wave transit time in the layer.

Calculated layer velocities were used for forward geophysical modeling – calculation of time travel curves, which were compared to recorded ones. If qualitatively both curves matched, the process was finished. If qualitatively curves did not match – model was corrected solving inverse problem of reduced time travel curve with additional quality control, both visual and statistical.

Optimal graph of seismic data processing

1. Reading of field seismic data in SEG-Y format and recording them on magnetic disk of the workstation.
2. Formation, linking and verification of the array of source points and receiver points positions for further development of the project database in the processing system ProMAX 3D, obtaining position schemes of the source and receiving points.
3. Binning points of CDP. Obtaining multiplicity distribution in the area of interest.
4. Entering parametric information required for the system processing ProMAX 3D in the headers lines.
5. Quality control of assigned geometry by visual control of seismogram first entries in the records.
6. Calculation of static corrections using data of explosive seismic investigations CDP method of previous surveys and SRM data.
7. Formation of tables of static corrections for source and receiving points and entering them into project database.
8. Editing of input seismographic records. Making changes to the tables of the database.
9. Calculating of an a priori 3D cube.
10. Analysis of seismic characteristics of the input data.
11. Selecting parameters and restoring the values of the amplitudes.
12. Attenuation of sound waves.
13. Testing of the parameters and performance of FK filtering by source points.
14. Testing of parameters and deconvolution of input data.
15. Calculating of control 3D cube after FK filtering and deconvolution.
16. The first cycle analysis of stacked 3D velocity grid by 2.5 by 2.5 km.
17. The first cycle of the automatic 3D static corrections and editing of results.
18. Calculating of the control 3D cube using the first cycle static and kinematic corrections.
19. Weakening of multiple waves of seismographic records.
20. The second cycle of velocity stacking on the 1.25 x1, 25 km grid.
21. The second cycle of the automatic 3D static corrections.
22. Calculating control 3D cube using second cycle of static and kinematic corrections.
23. DMO-transformation in the high-speed analysis points.
24. Adjustment of velocity stacking using data corrected by DMO.
25. DMO transformation.
26. Zero-phase deconvolution of stacked data.
27. Weakening of incoherent noise.
28. Building of the velocity model for 3D time migration.
29. Time 3D migration of the stacked data.

Data interpretation. Reinterpretation of 3D seismic data and formation properties at the Southern border of Dnieper-Donets Basin led to revealing new aspect of geological structure of the area, determine areas of petroleum leads and re-estimate formation properties of key productive horizons.

Interpretation workflow

Today, when new technologies and equipment are developed, both for seismic data acquisition and its processing and interpretation, it has become possible further research of Southern part of Dnieper-Donets Basin border. Interpretation was carried out on 20 seismic profiles, which forms fairly uniform grid. For alignment of wells two profiles of past years – 19-43-81 and 70-43-90 were used. After processing of seismic data, and also reprocessing of profiles from previous years, in the ProMAX system, all materials were loaded into the database of "Integral Plus" interpretation package. The seismic reference datum of profiles is 150 m.

For tying seismic boundaries with geological data at all deep drilling wells, as well as to determine the characteristics of the complex nature reflectors, seismic modelling was carried out.

For convolution of impulse traces 23 Hz Ricker wavelet was used, determined from seismic profiles 77-2-02. Calculations of synthetic traces were performed based on an acoustic borehole logging and generalized velocity curves. Results of seismic modelling showed that the lower and upper borders of Visean formations correspond to an acoustically hard surface. Stratigraphic boundaries coincide with the top of seismic vibrations' wavetrain. This conclusion is also confirmed by comparing calculated seismic traces with the real wave field.

Conclusions. Modern software and interpretation methods of seismic data allow significant improving of mapping accuracy and tracing tectonic faults. Application of new techniques for the interpretation of data makes it possible to create 3D geological models, defining distribution of zones with better reservoir properties, predict values of porosity and zones of lithological substitutions. Using algorithms of seismic facies analysis allows much more reliable establishment of lithological substitution zones and estimate distribution of formations with similar porosity and permeability properties. As a result of seismic studies the geological structure of southern border of Dnieper-Donets Basin was clarified.

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ВИКОРИСТАННЯ МОДЕЛІ РОЗПОДІЛУ ШВИДКОСТЕЙ СЕЙСМІЧНИХ ХВИЛЬ ПРИ ПОВНОМУ КОМПЛЕКСІ ОБРОБКИ ТА ІНТЕРПРЕТАЦІЇ СЕЙСМІЧНОЇ ІНФОРМАЦІЇ НА ПРИКЛАДІ ПЛОЩ ДНІПРОВСЬКО-ДОНЕЦЬКОЇ ЗАПАДИНИ

Комплексне уявлення про геологічну будову родовищ нафти та газу є основним інструментом, що забезпечує успішну розвідку родовища та видобування корисних копалин. Відомим обмеженням сейсморозвідки є те, що отримані дані знаходяться в часовій області, в той час як більшість інших методів, таких як геофізичні дослідження свердловин чи петрофізика, мають глибинну розмірність. Інтеграція цих типів даних в єдиному геологорозвідувальному проекті є однією з першочергових задач геофізика-інтерпретатора оскільки дозволяє уникнути помилок у визначенні глибин родовища та прогнозах при бурінні.

Основним інструментом при кореляції часових та глибинних даних є результати вертикального сейсмічного профілювання, що дозволяють оцінити час проходження сейсмічних хвиль з глибиною. Коректна обробка та інтерпретація цих даних є ключовою для коректної інтерпретації сейсмічних даних та побудови геологічних моделей.

В даній роботі автори пропонують методику обробки даних вертикального сейсмічного профілювання, розрахунку інтервальних, середніх та пластових швидкостей. Для контролю якості отриманих результатів було використано статистичні методи. Статистичний аналіз дозволяє уникнути суб'єктивних помилок інтерпретатора, хоча, безперечно, в подальшому може знадобитись коректування отриманих результатів з врахуванням наявних геологічних умов.

Розраховані швидкості сейсмічних хвиль були використані для розробки оптимального графу обробки сейсмічних даних. Використання свердловинних даних дозволяє створити більш точну швидкісну модель для глибинної міграції та уникнути невизначеностей в оцінці швидкостей.

Сейсмічні зображення, отримані в результаті обробки та міграції, були використані при інтерпретації та дозволили уточнити геологічну структуру родовищ прибортової частини Дніпровсько-Донецької западини. Сучасне програмне забезпечення та методи інтерпретації сейсмічних даних дозволяють значно підвищити точність картування та коректність визначення тектонічних порушень.

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ИСПОЛЬЗОВАНИЕ МОДЕЛИ РАСПРЕДЕЛЕНИЯ СКОРОСТЕЙ СЕЙСМИЧЕСКИХ ВОЛН ПРИ ПОЛНОМ КОМПЛЕКСЕ ОБРАБОТКИ И ИНТЕРПРЕТАЦИИ СЕЙСМИЧЕСКОЙ ИНФОРМАЦИИ НА ПРИМЕРЕ ПЛОЩАДЕЙ ДНЕПРОВСКО-ДОНЕЦКОЙ ВПАДИНЫ

Комплексное понимание геологического строения месторождений нефти и газа является основным инструментом обеспечивающим успешную разведку месторождения и добычу полезных ископаемых. Известным ограничением сейсморазведки является то, что полученные данные находятся во временной области, в то время как большинство других методов, таких как геофизические исследования скважин или петрофизика, имеют глубинную размерность. Интеграция этих типов данных в едином геологоразведочном проекте является одной из первоочередных задач геофизика-интерпретатора поскольку позволяет избежать ошибок в определении глубин месторождения и прогнозах при бурении.

Основным инструментом при корреляции временных и глубинных данных являются результаты вертикального сейсмического профилирования, которые позволяют оценить время прохождения сейсмических волн с глубиной. Корректная обработка и интерпретация этих данных является ключевой для корректной интерпретации сейсмических данных и построения геологической модели.

В данной работе авторы предлагают методику обработки данных вертикального сейсмического профилирования, расчета интервальных, средних и пластовых скоростей. Для контроля качества полученных результатов были использованы статистические методы. Статистический анализ позволяет избежать субъективных ошибок интерпретатора, хотя безусловно в дальнейшем может потребоваться корректировка полученных данных с учетом наявных геологических условий.

Рассчитанные скорости сейсмических волн были использованы для разработки оптимального графа обработки сейсмических данных. Использование скважинных данных позволяет создать более точную скоростную модель для глубинной миграции и избежать неопределенностей в оценке скоростей.

Сейсмические изображения, полученные в результате обработки и миграции, были использованы при интерпретации и помогли уточнить геологическую структуру месторождений прибортовой части Днепровско-Донецкой впадины. Современное программное обеспечение и методы интерпретации сейсмических данный позволяют значительно повысить точность картирования и корректность определения тектонических нарушений.

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DETERMINING THE FOCAL MECHANISM OF AN EARTHQUAKE IN THE TRANSCARPATHIAN REGION OF UKRAINE

(Reviewed by the editorial board member G. Prodaivoda)

In the paper, the theory of seismic wave propagation in anisotropic media is presented, with the use of the matrix method when determining the mechanisms of local earthquakes. These issues are of importance in seismic studies in the Carpathian region where the number of seismic stations is insufficient.

The work is aimed at the development of a methodology for calculating displacements on the surface of anisotropic medium and determining the mechanisms of local earthquakes with the use of the graphic method. The purpose of the graphic method consists in making it possible to use seismic records at the stations with indistinct polarities of first P-wave motions. The ratio between the amplitudes of direct P- and S-waves is used as an auxiliary parameter.

The research results are illustrated with examples of using the records of 04.04.2013 event near Nyzhnye Selyshche (φ=48,1977, λ=23,4663, h=1,73 km, M_L=2). Comparative analysis is carried out of seismograms calculated with the matrix method and those recorded at a seismic station, which confirms the effectiveness of the methodology for determining the seismic source parameters. Based on the graphic method, spectral and geometric parameters of the seismic source have been obtained: seismic moment, radius of shear dislocation, slip area, mean fault slip, stress drop, energy and magnitude.

Scientific novelty of the work consists in developing a method of calculating the displacement field in anisotropic media with the use of the matrix method and in amending the graphic method so as to ensure determining the mechanisms of local earthquakes in the Carpathian region where the number of seismic stations is limited.

Practical application of the work is in determining the source parameters of local earthquakes, based on the developed approaches, which is of crucial importance in local seismological studies.

The version of the matrix method developed in this work for calculating seismic wave propagation in anisotropic media can be used for determining the tensor of seismic moment with the number of seismic stations being limited.

Introduction

Determining earthquake focal mechanisms in the Transcarpathian region of Ukraine is one of the most topical issues in local seismological investigations. As the level of local seismic activity is low, the number of reliable polarities of first motions at local seismic stations is very often insufficient to determine the mechanism in a traditional way, which necessitates the development of alternative methods and improvement of the traditional ones.

An approach is often used where nodal planes are plotted on a lower-hemisphere stereographic projection to best fit the polarities of first arrivals of *P* waves at the stations, the location of a station polarity on the projection depending on the station azimuth and take-off angle of the ray of first arrival connecting the source and the station.

These focal mechanisms are determined using a method that attempts to find the best fit to the direction of *P*-wave first motions observed at each station. For a double-couple source mechanism (or only shear motion on the fault plane), the compression first motions should lie only in the quadrant containing the tension axis, and the dilatation first motions should lie only in the quadrant containing the pressure axis. Accuracy of the focal mechanism solution depends on the input data: velocity model and coordinate of the hypocenter (they determine the take-off angle), quality of seismic records and sign inversion on the seismometer, so that "up" is "down" (they determine the entry wave character).

But sometimes there is not enough information about the first arrivals of *P* waves. Both information about fuzzy arrivals of *P*-waves (which can mean proximity to the nodal plane) and the value logarithm of the amplitude ratio of *S*-wave and *P*-wave amplitude at each station is important for the distribution of compression and tension by nodal lines in the quadrants.

However, it is appropriate to develop other methods for determining the parameters of an earthquake source. One of these methods is based on the expressions for displacement field on free surface of an anisotropic medium and spectra of real records from stations that recorded these events.

Using the Thomson – Haskell matrix method of constructing wave fields on the free surface is also feasible. A method has been developed here for mathematical modeling of elastic waves in medium consisting of homogeneous anisotropic layers with parallel boundaries.

At the boundaries between the layers, the condition of the hard contact is performed. A free surface is free of stress. Wave source is located inside an anisotropic layer at a certain depth $z=z_s$. The radiation condition is also fulfilled (the wave of the lower half space (n+1) does not return).

The solution is shown here for the direct problem when a point source represented by a randomly oriented force on an arbitrary boundary of a layered anisotropic medium is preset. A "wave propagator" is introduced in order to present the theory of the matrix propagator in a homogeneous anisotropic medium. The basic expressions for the stress-displacement field with using the matrix propagator and the radiation condition are obtained. In fact, the direct problem is reduced to the determination of the propagator $P(z,z_0)$.

To determine the earthquake source parameters, we use the spectra of real records and the basic expressions for the stress-displacement field with the matrix propagator.

Matrix method. Direct problem

We assume the usual linear relationship between stress τ_{ij} and strain e_{kl}

$$\tau_{ij} = c_{ijkl} \cdot e_{kl} = c_{ijkl} \frac{\partial u_l}{\partial x_k} \qquad (1)$$

where $\vec{u} = (u_x, u_y, u_z)^T$ is displacement vector.

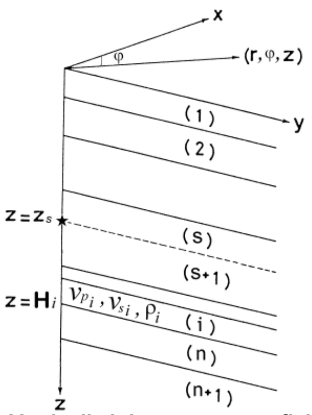

Figure 1. Vertically inhomogeneous field model

The equation of motion for an elastic homogeneous anisotropic medium, in the absence of body forces, is [*Fryer et al,* 1984]

$$\rho \frac{\partial^2 u_i}{\partial t^2} = c_{ijkl} \frac{\partial^2 u_l}{\partial x_i \partial x_k}, \qquad (2)$$

where ρ is the uniform mass density, and c_{ijkl} are the elements of the uniform elastic coefficient tensor which satisfy the symmetry conditions

$$c_{ijkl} = c_{jikl} = c_{ijlk} = c_{klij},$$

so that only 21 independent constants are involved. The suffixes can take the values 1, 2, or 3, and the summation convention for repeated suffixes is assumed.

Taking the Fourier transform of (1) and (2), we obtain the matrix equation [6]

$$\frac{\partial \vec{b}}{\partial z} = j\omega A(z)\vec{b}(z), \qquad (3)$$

where $\vec{b} = \begin{pmatrix} \vec{u} \\ \vec{\tau} \end{pmatrix}$ is the vector of displacements and scaled tractions, $\vec{\tau} = -\frac{1}{j\omega}(\tau_{xz}, \tau_{yz}, \tau_{zz})^T$. With the definition of $\vec{b}$ the system matrix A has the structure:

$$A = \begin{pmatrix} T & C \\ S & T^T \end{pmatrix};$$

where T, S and C are 3×3 sub matrices, C and S are symmetric.

For any vertically stratified medium, the differential system (3) can be solved subject to specified boundary conditions to obtain the response vector b at any desired depth. If the response at depth z_0 is $\vec{b}(z_0)$, the response at depth z is

$$\vec{b}(z) = P(z, z_0)\vec{b}(z_0) \qquad (4)$$

where $P(z, z_0)$ is the stress-displacement propagator. The matrix propagator is defined as

$$P(z,z_0) = I + \int_{z_0}^{z} A(\xi_1)d\xi_1 + \int_{z_0}^{z} A(\xi_1)\int A(\xi_1)A(\xi_2)d\xi_2 d\xi_1 + \dots, \qquad (4^*)$$

where I is the 6 x 6 identity. If D is the local eigenvector matrix of A then

$$D^{-1}AD = \Lambda \qquad (5)$$

where Λ is diagonal. The diagonal elements of Λ are the eigenvalues of A which are the vertical phase slownesses $q = p_z$. In general, we may write

$$\Lambda = diag(q_P^U, q_{s_1}^U, q_{s_2}^U, q_P^D, q_{s_1}^D, q_{s_2}^D), \qquad (6)$$

where superscripts U and D denote upgoing and downgoing disturbances, the subscript P denotes quasi-P and S_1, S_2 denote the two types of quasi-S. For an isotropic medium $q^U = -q^D$, but for general anisotropy there is no such simple relationship between the vertical slownesses [9]. However, for our choice of Fourier transform and the definition of A in (3), it follows from the radiation condition that $\mathrm{Im}(q^D)>0$ and $\mathrm{Im}(q^U)<0$.

Given the eigenvector matrix D, we may define a wavevector $\vec{v}$ from the transformation

$$\vec{b} = D\vec{v}. \qquad (6)$$

As in the isotropic case the elements of $\vec{v}$ may be identified with the amplitudes of upward and downward travelling plane waves,

$$\vec{v} = [v_u, v_D]^T = [\varphi_u, \psi_u, \chi_u, \varphi_D, \psi_D, \chi_D]^T \qquad (7)$$

where φ, denotes qP amplitude and ψ, χ the two qS amplitudes. As before, U and D denote up and down.

If the elastic parameters are locally constant, then D is independent of z and substitution of (6) and (5) into (3) yields

$$D\frac{\partial \vec{v}}{\partial z} = j\omega AD\vec{v} \qquad (8)$$

with the solution

$$\vec{v}(z) = e^{j\omega\Lambda(z-z_1)} \cdot \vec{v}(z_1) = Q(z, z_1) \cdot \vec{v}(z_1) \qquad (9)$$

where z_1 is a reference depth. From (7) it is apparent that Q may be regarded as a 'wave propagator' since it is the solution to

$$\frac{\partial Q(z, z_1)}{\partial z} = j\omega\Lambda Q(z, z_1), \; Q(z_1, z_1) = I \qquad (10)$$

We note from (6) that within the uniform layer, Q has the structure [6]

$$Q(z, z_1) = \begin{pmatrix} E_u & 0 \\ 0 & E_D \end{pmatrix} \qquad (11)$$

with

$$E_u = diag\left[e^{j\omega(z-z_1)q_P^u}, e^{j\omega(z-z_1)q_{s_1}^u}, e^{j\omega(z-z_1)q_{s_2}^u}\right],$$

$$E_D = diag\left[e^{j\omega(z-z_1)q_P^D}, e^{j\omega(z-z_1)q_{s_1}^D}, e^{j\omega(z-z_1)q_{s_2}^D}\right] \qquad (12)$$

Using (6) and (9), the stress-displacement vector at any level z within the uniform medium is

$$\vec{b}(z) = DQ(z, z_1)D^{-1}\vec{b}(z_1). \qquad (13)$$

By comparison with (4), the desired propagator for the uniform interval is

$$P(z, z_1) = DQ(z, z_1)D^{-1} \qquad (14)$$

To find this propagator, it is necessary to find the eigenvalues (vertical slownesses), the eigenvector matrix D, and its inverse D^{-1}. In the isotropic case these are known analytically, so the construction of the propagator is straightforward. In the anisotropic case, analytic solutions have been found only for simple symmetries, so in general, solutions can be found numerically.

The layered anisotropic medium, which consists of n homogeneous anisotropic layers on $(n+1)$ anisotropic half space (Figure 1), is considered. The matrix propagator (4*) can be represented by a "wave propagator" in each layer for an anisotropic layered medium. The source in the form of a stress-displacement discontinuity $\vec{F} = \vec{b}_{s+1} - \vec{b}_s$ is placed on the s-boundary (Fig. 1); it is easy to write the following matrix equation, using (13-14):

$$\vec{b}_{n+1} = P_{n,s}\vec{b}_{s+1}\Big|_{z=z_s},$$

$$v_{n+1} = D_{n+1}^{-1} D_n Q_n D_n^{-1} \cdots D_{s+1} Q_{s+1} D_{s+1}^{-1} \cdot \vec{b}_{s+1}\Big|_{z=z_s},$$

$$\vec{b}_s\Big|_{z=z_s} = P_{s,s-1}P_{s-1,s-2}\cdots P_{2,1}P_{1,0}\cdot\vec{b}_0 = = D_s Q_s D_s^{-1} \cdots D_1 Q_1 D_1^{-1} \cdot \vec{b}_0,$$

$$v_{n+1} = D_n Q_n D_n^{-1} \cdots D_{s+1} Q_{s+1} D_{s+1}^{-1} \cdot (\vec{b}_s + \vec{F}) = G^{n+1,s+1} \cdot (G_{s,1}\vec{b}_0 + \vec{F}) = ,$$
$$G^{n+1,s+1} = G_{s,,1}\vec{b}_0 + G^{n+1,s+1}\cdot\vec{F} = G\vec{b}_0 + G^{n+1,s+1}\cdot\vec{F}$$

where

$$G = D_{n+1}^{-1} D_n Q_n D_n^{-1} \cdots D_{s+1} Q_{s+1} D_{s+1}^{-1} \cdots D_2^{-1} D_1 Q_1 D_1^{-1}$$

– characteristic matrix of a layered anisotropic medium.

$$\vec{v}_{n+1} = G\vec{b}_0 + G\cdot G_{s,1}^{-1}\cdot\vec{F} = G(\vec{b}_0 + G_{s,1}^{-1}\cdot\vec{F}) = G(\vec{b}_0 + \tilde{\vec{F}}), \quad (15)$$

where $\tilde{\vec{F}} = G_{s,1}^{-1}\cdot\vec{F}$, $G = G^{n+1,s+1}\cdot G_{s,1}$.

Using (15) and the radiation condition (with a half-wave (*n* +1) not returned), and also the fact that the tension on the free surface equals zero, we obtain a system of equations:

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ v_D^P \\ v_D^{S_1} \\ v_D^{S_2} \end{pmatrix} = \begin{pmatrix} G_{11} & G_{12} & G_{13} & G_{14} & G_{15} & G_{16} \\ G_{21} & G_{22} & G_{23} & G_{24} & G_{25} & G_{26} \\ G_{31} & G_{32} & G_{33} & G_{34} & G_{35} & G_{36} \\ G_{41} & G_{42} & G_{43} & G_{44} & G_{45} & G_{46} \\ G_{51} & G_{52} & G_{53} & G_{54} & G_{55} & G_{56} \\ G_{61} & G_{62} & G_{63} & G_{64} & G_{65} & G_{66} \end{pmatrix} \begin{pmatrix} u_x^{(0)} + \tilde{F}_1 \\ u_y^{(0)} + \tilde{F}_2 \\ u_z^{(0)} + \tilde{F}_3 \\ \tilde{F}_4 \\ \tilde{F}_5 \\ \tilde{F}_6 \end{pmatrix} \quad (16)$$

or

$$\begin{cases} G_{11}u_x^{(0)} + G_{12}u_y^{(0)} + G_{13}u_z^{(0)} = -(G_{11}\tilde{F}_1 + G_{12}\tilde{F}_2 + G_{13}\tilde{F}_3 + G_{14}\tilde{F}_4 + G_{15}\tilde{F}_5 + G_{16}\tilde{F}_6) \\ G_{21}u_x^{(0)} + G_{22}u_y^{(0)} + G_{23}u_z^{(0)} = -(G_{21}\tilde{F}_1 + G_{22}\tilde{F}_2 + G_{23}\tilde{F}_3 + G_{24}\tilde{F}_4 + G_{25}\tilde{F}_5 + G_{26}\tilde{F}_6) \\ G_{31}u_x^{(0)} + G_{32}u_y^{(0)} + G_{33}u_z^{(0)} = -(G_{31}\tilde{F}_1 + G_{32}\tilde{F}_2 + G_{33}\tilde{F}_3 + G_{34}\tilde{F}_4 + G_{35}\tilde{F}_5 + G_{36}\tilde{F}_6) \end{cases} \quad (17)$$

As a result, the displacement field of the free surface of the anisotropic medium is in the spectral domain as:

$$\vec{u} = \begin{pmatrix} u_x^0 \\ u_y^0 \\ u_z^0 \end{pmatrix} = (G^{13})^{-1}\cdot\vec{y} \quad (18)$$

where $G^{13} = \begin{pmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{pmatrix}$, $\vec{y} = \begin{pmatrix} a \\ b \\ c \end{pmatrix}$,

$$a = -(G_{11}\tilde{F}_1 + G_{12}\tilde{F}_2 + G_{13}\tilde{F}_3 + G_{14}\tilde{F}_4 + G_{15}\tilde{F}_5 + G_{16}\tilde{F}_6),$$
$$b = -(G_{21}\tilde{F}_1 + G_{22}\tilde{F}_2 + G_{23}\tilde{F}_3 + G_{24}\tilde{F}_4 + G_{25}\tilde{F}_5 + G_{26}\tilde{F}_6),$$
$$c = -(G_{31}\tilde{F}_1 + G_{32}\tilde{F}_2 + G_{33}\tilde{F}_3 + G_{34}\tilde{F}_4 + G_{35}\tilde{F}_5 + G_{36}\tilde{F}_6).$$

Using (18) and the three-dimensional Fourier transform, we obtain a direct problem solution for the displacement field of the free surface of an anisotropic medium in the time domain as:

$$\vec{u}(x,y,z_R,t) = = \frac{1}{8\pi^3}\iiint_{-\infty} \omega^2 \vec{u}(p_x,p_y,z_R,\omega) e^{j\omega(t-p_x x-p_y y)} dp_x dp_y d\omega,$$

where z_R – epicentral distance, p_x, p_y – horizontal slowness.

The stress-displacement discontinuity is determined via the seismic in matrix form [7]:

$$\vec{F} = \begin{pmatrix} -c_{55}^{-1}M_{xz} \\ -c_{44}^{-1}M_{yz} \\ -c_{33}^{-1}M_{zz} \\ p_x(M_{xx} - c_{13}c_{33}^{-1}M_{zz}) + p_y M_{xy} \\ p_x M_{yx} + p_y(M_{yy} - c_{23}c_{33}^{-1}M_{zz}) \\ p_x(M_{zx} - M_{xz}) + p_y(M_{zy} - M_{yz}) \end{pmatrix} \delta(z - z_z) \quad (19)$$

where M_{xx}, M_{yy}, M_{zz}, M_{xz}, M_{yz}, M_{yx}, M_{xy}, M_{zy}, M_{zx} – components of the seismic moment tensor, and c_{13}, c_{23}, c_{33}, c_{44}, c_{55} – components of the stiffness matrix.

Matrix method. Inverse problem

We can write the stress-displacement discontinuity $\vec{F}$ for weak seismic events as:

$$\vec{F} = \begin{pmatrix} F_1 \\ F_2 \\ F_3 \\ 0 \\ 0 \\ 0 \end{pmatrix}. \quad (20)$$

Using (16, 19, 20), we obtain a system of equations, which has a unique solution:

$$\begin{cases} G_{11}u_x^{(0)} + G_{12}u_y^{(0)} + G_{13}u_z^{(0)} = -(G_{11}\tilde{F}_1 + G_{12}\tilde{F}_2 + G_{13}\tilde{F}_3) \\ G_{21}u_x^{(0)} + G_{22}u_y^{(0)} + G_{23}u_z^{(0)} = -(G_{21}\tilde{F}_1 + G_{22}\tilde{F}_2 + G_{23}\tilde{F}_3) \\ G_{31}u_x^{(0)} + G_{32}u_y^{(0)} + G_{33}u_z^{(0)} = -(G_{31}\tilde{F}_1 + G_{32}\tilde{F}_2 + G_{33}\tilde{F}_3) \end{cases}. \quad (21)$$

$$\vec{F} = G_{s,1}\cdot\tilde{\vec{F}}, \quad (22)$$

where $G_{s,1}$ is the characteristic matrix of the source.

Using (21, 22), we find explicitly the stress-displacement vector $\vec{F}$. From (19) equations for the determination of the seismic moment tensor components are derived:

$$M_{xz} = M_{zx} = -F_1\cdot c_{55}$$
$$M_{yz} = M_{zy} = -F_2\cdot c_{44} \quad (23)$$
$$M_{zz} = -F_3\cdot c_{33}$$

To determine the angles of orientation of the plane of rupture (φ_s, δ, λ), we use the trigonometric system of equations which represent the known components of seismic moment tensor via the angles of orientation of the plane of rupture [1]:

$$M_{xz} = -M_0 \cdot (\cos\delta \cdot \cos\lambda \cdot \cos\phi_s + \cos 2\delta \cdot \cos\lambda \cdot \cos\phi_s)$$
$$M_{yz} = -M_0 \cdot (\cos\delta \cdot \cos\lambda \cdot \cos\phi_s - \cos 2\delta \cdot \sin\lambda \cdot \cos\phi_s)\ , \quad (24)$$
$$M_{zz} = M_0 \sin 2\delta \cdot \sin\lambda$$

where M_0 – seismic moment determined from the spectrum of seismograms. The found angles of orientation of the plane of rupture (φ_s, δ, λ) are substituted in the following equation to find the total seismic moment tensor [1]:

$$M_{xx} = -M_0 \cdot (\sin\delta \cdot \cos\lambda \cdot \sin 2\phi_s + \sin 2\delta \cdot \sin\lambda \cdot \sin^2\phi_s)$$
$$M_{xy} = M_{yx} = M_0 \cdot (\sin\delta \cdot \cos\lambda \cdot \cos 2\phi_s + \frac{1}{2}\sin 2\delta \cdot \sin\lambda \cdot \sin 2\phi_s) \ . \quad (25)$$
$$M_{yy} = M_0 \cdot (\sin\delta \cdot \cos\lambda \cdot \sin 2\phi_s - \sin 2\delta \cdot \sin\lambda \cdot \cos^2\phi_s)$$

As a result, we write the seismic moment tensor using the symmetry condition:

$$M = \begin{pmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{xy} & M_{yy} & M_{yz} \\ M_{xz} & M_{yz} & M_{zz} \end{pmatrix}. \quad (26)$$

Determining the focal mechanism by graphical method

Today, the focal mechanism solution for earthquakes in a region of low seismic activity is a topical issue. It is of crucial importance for the Transcarpathian region of Ukraine, where the number of stations is limited and seismic activity is low. It is impossible to determine a focal mechanism with software packages.

It is proposed to determine the focal mechanism by applying the traditional graphical method based on the first arrival P-waves [10] using the information about fuzzy first motion [5] and the *S*/*P* amplitude ratio [8].

To test the graphical method, an event dated 04.04.2013 21:15:14.36 is considered (φ=48.1977, λ=23.4663, h=1.73 km) near the village Nyzhnye Selyshche. This event was recorded by 9 stations (Figure 2)

Figure 2. Map of seismic stations in the Transcarpathian region and the specified location near to the epicenter of events near Nyzhnye Selyshche village

The polarities of first motion P-waves were defined from complete records seismograms taking into account the possible inversion of the sign on the *z*-component. A logarithm of the amplitude ratio S/P is calculated using data from the three components seismic records of this event at each station [8]. Input data for the azimuth and take-off angle are calculated by software packages for this event (Table 1).

Table 1

Input data for the focal mechanism solution

Stations	First arrival	Azimuth,°	Take-off angle,°	lg As/Ap
NSLU	+ Pg	269	-53	-
KORU	-Pg	260	31	0.43
MEZ	-Pg	6	31	0.084
BRIU	-Pn	295	42	0.65
TRSU	-Pn	253	42	0.57
BERU	xPn	274	42	2.64
MUKU	-Pn	297	42	0.71
UZH	-Pn	299	45	0.88
KSV	-Pn	83	45	1.05

The graphical method is used to determine the focal mechanism for this event according to the input data [10]. The data about first motion P-wave is plotted using a lower-hemisphere stereographic projection. The point-projection rays from the source to the station were applied on the stereonet. The red points are the points of compression (where the *P*-wave first motion recorded was up), the blue points are the points of dilatation (where the *P*-wave first motion recorded was down), and black points are the points of fuzzy first motion. Several averaged versions of the nodal plane locations are determined out of all the possible alternative versions for this event (Figure 3).

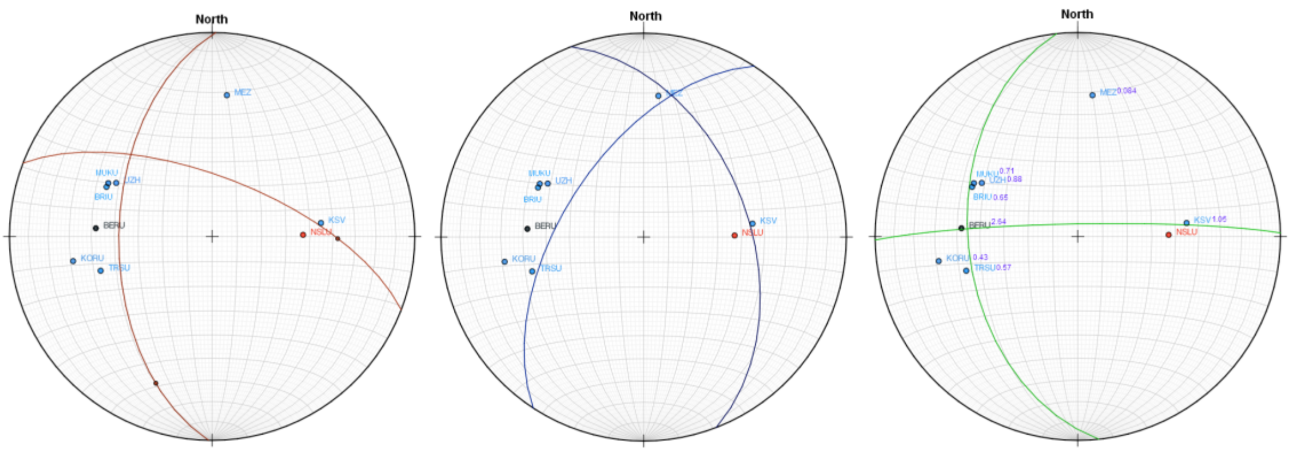

Figure 3. Averaged versions of the nodal planes locations for event 04.04.2013 21:15:14.36 (φ=48.1977, λ=23.4663, h=1.73 km) near the village Nyzhnye Selyshche

The determining criteria for the most suitable locations of the nodal planes for the 4.04.2013 earthquake were: fuzzy first motion on the station BERU, a small logarithm value of amplitude ratio S/P at the station MEZ indicates a location projection station in the middle of the quadrant, and the logarithm value of the amplitude ratio S/P at the station KSV, which is larger than 1, indicates the proximity to the nodal line. Consequently, the focal mechanism for event 04.04.2013 21:15:14.36 (φ=48.1977, λ=23.4663, h=1.73 km) near the village Nyzhnye Selyshche is represented by diagram (Figure 4) with parameters in Table 2.

Table 2

Parameters of the focal mechanism for the event 04.04.2013 21:15:14.36 (φ=48.1977, λ=23.4663, h=1.73 km) near the village Nyzhnye Selyshche

Plane1			Plane2			P		T		N	
Strike (φ_s)	Dip (δ)	Slip (λ)	Strike (φ_s)	Dip (δ)	Slip (λ)	Azm	Plunge	Azm	Plunge	Azm	Plunge
174°	45°	173°	269°	85°	45°	33°	27°	142°	34°	274°	44°

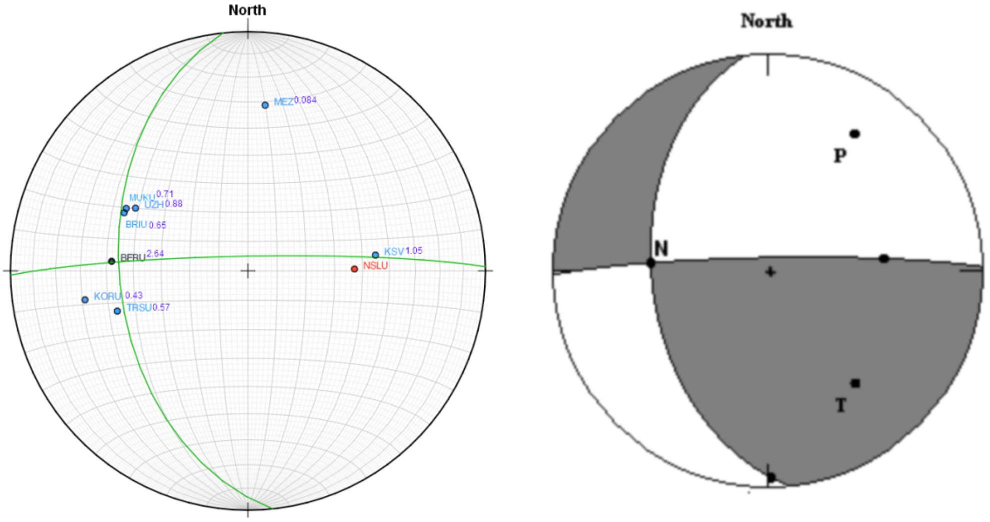

Figure 4. The focal mechanism determined by graphic method for the event04.04.2013 21:15:14.36 (φ=48.1977, λ=23.4663, h=1.73 km) near the village Nyzhnye Selyshche

Seismic moment and other spectral parameters are computed by (27-33) [2] for each station and the average values of these parameters are represented in Table 3.

The seismic moment is computed according to:

$$M_0 = 4\pi r v_p^3 \rho u_0 / (\Theta S_a), \tag{27}$$

where r – is hypocentral distance, v_p - *P*-wave velocity, ρ – density, u_0 – low-frequency level (plateau) of the displacement spectrum, *Θ* – average radiation pattern and S_a – surface amplification for *P* waves.

The radius of shear dislocation R is computed from the relationship:

$$R = \frac{3.36 v_p}{2\sqrt{3}\pi f_c}, \tag{28}$$

where f_c - is the corner frequency of the *P* wave. The size of the circular rupture plane is computed as:

$$A = \pi R^2. \tag{29}$$

The average source dislocation is according to

$$\overline{D} = M_0 / \mu A, \tag{30}$$

where the shear modulus is computed by

$$\mu = v_p^2 \rho / 3. \tag{31}$$

The stress drop, seismic energy and magnitude ML are computed according to:

$$\Delta\sigma = 7 M_0 / 16 R^3, \tag{31}$$

$$E_s = M_0 \cdot 1.6 \cdot 10^{-5}, \tag{32}$$

$$ML = (lg\, E_s - 4)/1.8. \tag{33}$$

With the seismic moment and the parameters of the focal mechanism, the moment tensor M is defined from (24, 25) [1]:

$$M = \begin{pmatrix} -11.42494 & -54.24707 & -54.15575 \\ -54.24707 & 1.96935 & 5.69199 \\ -54.15575 & 5.69199 & 9.45559 \end{pmatrix} \cdot 10^{11} \tag{34}$$

Approbation of the inverse problem

The inverse problem is solved for the event, which took place near the village Nyzhnje Selyshche.

The orientation angles of the fault plane are determined by the graphic method (φ_s = 174°, δ = 45 °, λ = 173°) and the focal mechanism is determined for the event. The seismic tensor (27) is obtained by substituting the orientation angles of the fault plane and the magnitude of seismic moment in (24, 25).

The real seismic records at station Mezhyhirya is used for the inverse problem. The earthquake source is located in the first layer. Therefore, a two-layered anisotropic model of medium (with TI symmetry) is selected, whose parameters are given in Table 4.

The orientation angles of the fault plane (φ_s = 177°, δ = 45°, λ = 175°) are obtained as a result of the inverse problem solving using spectrum of real seismic record and the velocity model (Table 4). The seismic tensor is obtained by substituting the orientation angles of the fault plane and the magnitude of seismic moment in (24, 25):

$$M = \begin{pmatrix} -5.73144 & -54.70825 & -54.57932 \\ -54.70825 & -1.03079 & 2.86038 \\ -54.57932 & 2.86038 & 6.76224 \end{pmatrix} \cdot 10^{11} \tag{35}$$

The focal mechanism is shown in Figure 4 which is based on the seismic moment tensor (35).

Table 3

Spectral parameters for the event 04.04.2013 21:15:14.36 (φ=48.1977, λ=23.4663, h=1.73 km) near the village Nyzhnye Selyshche

M_0, Nm	f_{cp}, Hz	R, m	A, m^2	$\overline{D}$, m	$\Delta\sigma$, MPa	E_s, J	ML
6.68784*10^{12}	6.81	213.191	1.4271*10^{5}	2.85*10^{-3}	0.302	1.07*10^{8}	2.22

Table 4

Velocity model for seismic station Mezhyhirya

№	c_{11}, GPa	c_{13}, GPa	c_{33}, GPa	c_{44}, GPa	c_{66}, GPa	ρ, kg/m^3	*h*, m
1	81.12	25.342	84.397	37.036	28.127	3000	2400
2	100.38	33.464	100.38	33.458	33.458	3367	6600

Table 5

Velocity model for seismic station Korolevo

№	c_{11}, GPa	c_{13}, GPa	c_{33}, GPa	c_{44}, GPa	c_{66}, GPa	ρ, kg/m^3	*h*, m
1	76.81	24.57	76.71	24.36	24,26	3000	2400
2	100.38	33.464	100.38	33.458	33,458	3367	6600

where c_{11}, c_{13}, c_{33}, c_{44}, c_{66} – components of the stiffness matrix, ρ – density, h – thickness of layer.

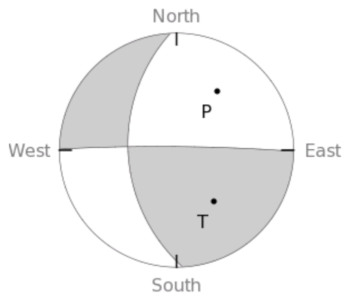

Figure 5. The focal mechanism determined by the proposed method for the event which took place near the village Nyzhnje Selyshche (φ_s = 177º, δ = 45 º, λ = 175º)

The focal mechanisms of the earthquake built by two different methods (Figure 4–5) are actually identical, which confirms the correctness and accuracy of the matrix method.

The synthetic seismograms are constructed for the earthquake's focal mechanism (Figure 5) and the velocity models (Table 4-5) to confirm the inverse problem solutions. A comparative analysis is done of synthetic seismograms and real records at the stations Mezhyhirya and Korolevo, which are filtered in the frequency range from f_0 = 0.1Hz to f_{max} = 5Hz (Figure 6-7).Synthetic seismograms are built for the obtained seismic tensor (35) and the velocity model (Table 4-5).

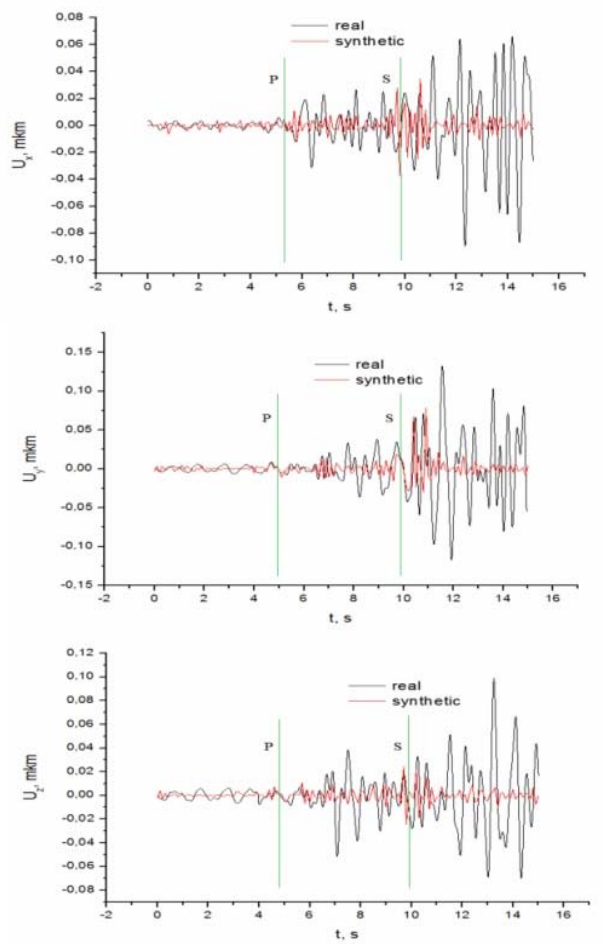

Figure 6. Comparison of synthetic seismograms with real seismic record from station Mezhyhirya

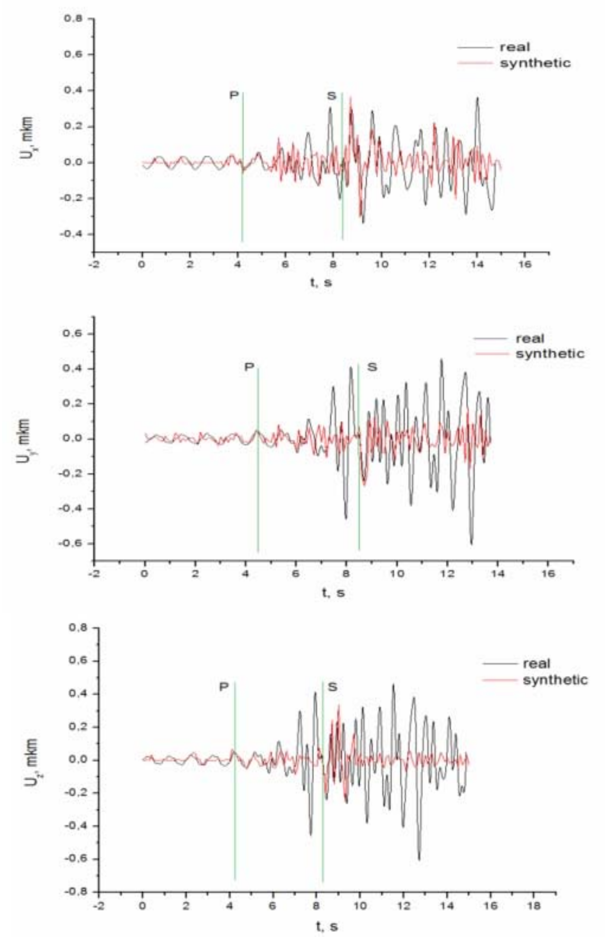

Figure 7. Comparison of synthetic seismograms with real seismic record from station Korolevo

Conclusion

Comparative analysis of waveforms confirms the feasibility of using the matrix method for solving seismology problems with earthquakes sources being distributed in time. Similarity of the focal mechanisms obtained by two different methods confirms the correctness of the solutions for this event.

More accurate results in determining the earthquake focal mechanisms are obtained when using the spectrum data from stations that are located at a smaller epicentral distance. The best results were obtained for those stations where records have a lower noise level. Choosing the velocity model is essential for determining earthquake focal mechanisms.

We can conclude that the graphical method is suitable for determining focal mechanisms for earthquakes in the Carpathian region of Ukraine.

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ВИЗНАЧЕННЯ ФОКАЛЬНОГО МЕХАНІЗМУ ЗЕМЛЕТРУСУ В ЗАКАРПАТТІ

У роботі представлено теорію поширення сейсмічних хвиль в анізотропному середовищі з використанням матричного методу Томсона-Хаскела, а також визначення механізмів вогнищ місцевих землетрусів. Такі задачі є надзвичайно актуальні для вивчення сейсмічності Закарпаття через обмежену кількість сейсмічних станцій.

Метою роботи є розроблення методики для побудови поля переміщень на вільній поверхні анізотропного середовища і визначення механізмів вогнищ місцевих землетрусів графічним методом. Суть графічного методу полягає у використанні сейсмічних записів на станціях з неточним вступом прямих Р-хвиль. Як допоміжний параметр у роботі використано відношення амплітуд прямих Р і S хвиль.

Результати запропонованих підходів показано на прикладі використання записів події 04.0.2013 р. біля с. Н. Селище (φ=48.1977; λ=23.4663; h=1.73 км, ML=2). Зокрема, представлено порівняльний аналіз сейсмограм, отриманих матричним методом із реальними записами, що підтверджує використання методики для визначення параметрів джерела. На основі графічного методу для визначення механізмів вогнищ місцевих землетрусів отримано спектральні та геометричні параметри джерела: сейсмічний момент, радіус зсувної дислокації, площу розриву, середню посувку по розриву, спад напруги, енергію та магнітуду.

Наукова новизна роботи полягає у розроблені методики визначення поля переміщень у випадку анізотропного середовища з використанням матричного методу, а також розвитку графічного методу для побудови механізмів вогнищ землетрусів Закарпаття у випадку обмеженої кількості станцій.

Практична значимість роботи полягає в тому, що на основі розроблених підходів є можливість визначення параметрів вогнищ місцевих землетрусів, що є важливим для вивчення сейсмічності регіону. Розроблена модифікація матричного методу для поширення сейсмічних хвиль в анізотропних середовищах може бути використана для визначення тензора сейсмічного моменту у випадку обмеженої кількості станцій.

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ОПРЕДЕЛЕНИЕ ФОКАЛЬНОГО МЕХАНИЗМА ЗЕМЛЕТРЯСЕНИЯ В ЗАКАРПАТЬЕ

В работе представлено теорию распространения сейсмических волн в анизотропной среде с использованием матричного метода Томсона – Хаскела, а также определения механизмов очагов местных землетрясений. Такие задачи чрезвычайно актуальны для изучения сейсмичности Закарпатья из-за ограниченного количества сейсмических станций.

Целью работы является разработка методики для построения поля перемещений на свободной поверхности анизотропной среды и определения механизмов очагов местных землетрясений графическим методом. Суть графического метода заключается в использовании сейсмических записей на станциях с неточным вступлением прямых Р-волн. Как вспомогательный параметр в работе использовано отношение амплитуд прямых Р и S волн.

Результаты предложенных подходов показано на примере использования записей события 04.0.2013 г. в районе с. Н. Селище (φ = 48.1977; λ = 23.4663; h = 1.73 км, ML = 2). В частности, представлен сравнительный анализ сейсмограмм, полученных матричным методом, с реальными записями, подтверждающий возможность использования методики для определения параметров источника. На основе графического метода для определения механизмов очагов местных землетрясений получены спектральные и геометрические параметры источника: сейсмический момент, радиус сдвиговой дислокации, площадь разрыва, среднюю подвижку по разрыву, сброс напряжения, энергию и магнитуду.

Научная новизна работы заключается в разработанной методике определения поля перемещений в случае анизотропной среды с использованием матричного метода, а также развития графического метода для построения механизмов очагов землетрясений Закарпатья в случае ограниченного количества станций.

Практическая значимость работы заключается в том, что на основе разработанных подходов является возможность определения параметров очагов местных землетрясений, что важно для изучения сейсмичности региона. Разработанная модификация матричного метода для распространения сейсмических волн в анизотропных средах может быть использована для определения тензора сейсмического момента в случае ограниченного количества станций.

MINERAL RESOURCES

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THE MORPHOLOGY AND COMPOSITION OF LIBERIA PLACER GOLD

(Reviewed by the editorial board member V. Zagnitko)

Due to civil war in Liberia, which lasted from 1989 to 2003, the geological study of the country was suspended, and became possible only after its end. That is why today, Liberia has no specific geological zoning of the gold-bearing regions. The morphology of gold of Liberia is examined very poorly, and Soviet literature paid no attention to studying this issue.

This article is devoted to the study of morphological forms of gold from different regions of the Republic of Liberia.The main objectives of the morphological analysis are to distinguish the main morphological types of gold of the country and their origin and to identify possible ways of placer formation. For achieving more accurate results, roentgenospectrographic and roentgen-fluorescent analyses were carried out. The comparative analysis of the morphological features and the fineness of gold was held in eight regions: Kolahum, Magua, Konia and Zeya in the northern part of the country, Solo and Eastern in its southern part, Soso in the western part, and Timbo in the central part of Liberia.

Different types of the gold under study were distinguished according to their morphological features which may indicate their genesis. Well-flattening of grains indicates either a large distance of the transportation of the material, or the fact that the gold has been reworked from nearby local paleoplacers. In the case of the Magua area, considering a large variety of shapes, sizes and the mineral composition of the gold grains, its gold can be of two genetic types: 1) paleoplacer gold, the closest analogue of which is Tarkva deposit in Ghana; 2) indigenous gold, related to ferruginous quartzites, where laterite crusts of weathering are developed.

As a result of the roentgenospectrographic (electron microprobe) analysis of gold from different regions, it was found that all of the analysed grains have gold content close to 100%. Due to the results of the analysis, we can affirm that all the samples, except of the sample number 142 are of typical metallic composition of gold, which represent the geochemical features of this element. Sample number 142 is distinguished by its anomalous silver content, which reaches 16.7%.

Introduction. The Republic of Liberia stretches for 500 miles along the Atlantic Ocean. The relief of the country is midlands covered with forests and a swampy tropical coast. The coastal lowland plain is slightly dissected and swampy here and there. In the hinterland, the plain rises up to 400-600 m and turns into Leone-Liberian Upland. There are also many wide but short rivers (the Mano, the Loffa, and the St.Paul). The climate is tropical, hot, and humid.

The geology of Liberia is determined by its location on two large geological structures:

- early Precambrian Leone-Liberian massif (the Leo-Man shield), which occupies most of the country;
- late Precambrian mobile belt Rockelides, separated from the massif by a large thrust and located along the coast.

Among Archean granite-gneisses of the Leone-Liberian massif, the residues of greenstone belts are preserved. They are metasedimentary and metavolcanic formations such as quartz-mica and quartz-mica-graphite shales, ferruginous quartzites, amphibolites and itabirites (Nimba and Simandu series).

Early Proterozoic metamorphic formation (Birrim series) is composed of shales, quartzites, metaeffusives of mafic, intermediate, and more rarely felsic composition, manganeseferous phyllites, gondites, transected by Eburnean granites. More recent formations involve Permian-Triassic and Jurassic trappean sills and dikes, and small kimberlite bodies. Laterites and alluvial deposits are of the Quaternary age.

The territory of the country was greatly influenced by the periods of tectonic-magmatic activation that accompanied the formation of the West African craton:

- Cratonization stage (3,5 – 2,6 Ga)
- Before Eburnean stage 2,5 – 2,3 (Ga)
- Eburnean stage 2,2 – 1,8 (Ga)
- Meso-Cenozoic stage 300 – 50 (Ma)

Exactly during the Eburnean stage, the accumulation of gold-bearing conglomerates of Tarkwa series (Ghana) took place, and the main gold-quartz and gold-sulfide deposits of this craton were formed. Besides, a significant impact on the geological structure of Liberia was made by the Phanerozoic epochs of tectono-magmatic activation associated with the formation of the Atlantic. This activation facilitated the formation of a large number of Mesozoic and Cenozoic dykes.

Natural and geographical conditions and the geological structure of Liberia define the main directions of industry development, which is poorly developed and has basically raw-product orientation. Among mineral resources, the country is rich only in high-quality iron ores in explored reserves of which Liberia takes one of the first places in Africa. They are usually associated with ferruginous quartzites of supracrustal Archean complexes (Bea Mountain, Wologisi). In the country, there are also deposits of manganese, barite, gold, diamonds, and cyanite. Liberian diamonds are mined from alluvial and eluvial placers. Most of the gold deposits of Liberia are also related to alluvial deposits; however, in the east of the country, auriferous quartz lodes were found too.

State of the problem. During the period of civil war in Liberia, which lasted from 1989 to 2003, the geological study of the country was suspended, and became possible only after its end. That is why today Liberia has no specific geological zoning of the gold-bearing regions. Its production is mostly carried out by manual methods.

The morphology of gold of Liberia is examined very poorly. Soviet literature paid no attention to studying this issue; although, there are some sources which represent general characteristic of the gold mining sector in Liberia [3].

Setting of the problem. The main objectives of morphological analysis are to distinguish the main morphological types of gold of the country and their origin and to identify possible ways of placer formation. For achieving more accurate results, roentgenospectrographic and roentgenfluorescent analyses were carried out.

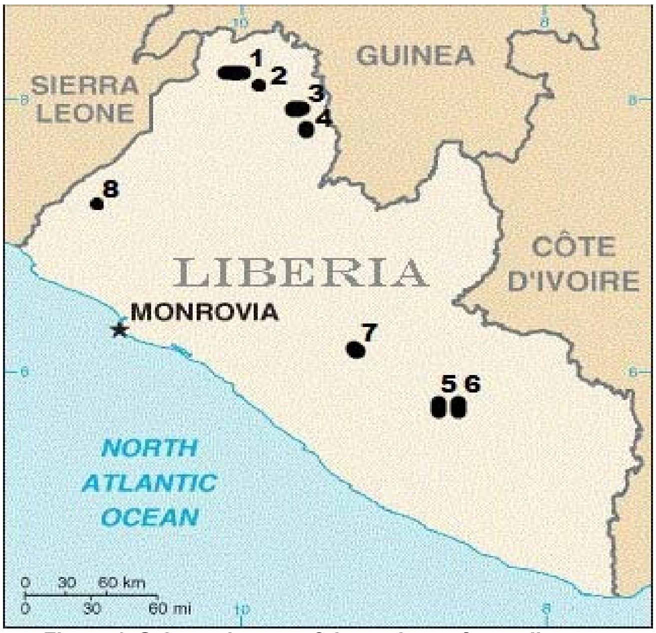

Figure 1. Schematic map of the regions of sampling:
1 – Kolahun, 2 – Magua, 3 – Konia, 4 – Zeya, 5 – Solo, 6 – Eastern, 7 – Timbo, 8 – Soso Camp

Morphological analysis of gold. The comparative analysis of the morphological features and the fineness of gold was held in eight regions: Kolahum, Magua, Konia and Zeya in the northern part of the country, Solo and Eastern in its southern part, Soso in the western part, and Timbo in the central part of Liberia (Figure 1).

The Kolahun area (775 km^2) is situated in the northwestern part of the Republic of Liberia. The geological structure of the area is predominated by Archaean granites and gneiss-granites (geochronological dating is 2580-2770 million years) with their significant feature of granite-gneiss cupolas. They are transected by diabase dykes, mainly of sublatitudinal, more rarely of submeridian and north-west directions, that reflects the features of fault tectonics of the area. Among faultings, submeridional and north-east shear zones as well as sublatitudinal fault systems and disjoining structures (fracture systems) are prevailing.

Gold grains from Kolahun samples are characterised by a round flat shape, indicating an intense mechanical wear. The grains have glitter and golden yellow colour, which may indicate a high fineness of gold. There are only two available samples with signs of gold from this region, one in each, that's why their exact origin is difficult to determine (Table 1).

The perspective area of Magua is located in the southeast framing of the Kolahun area. The flat part of the territory is composed of Archean leucocratic gneisses, including lens-shaped amphibolite bodies and quartz-muscovite shales. The mountainous part of the area is predominately composed of quartz-muscovite and quartz-amphibole shales, up to phyllites, which contain horizons and lenses of quartz conglomerates.

Table 1

General table of linear characteristics of gold samples by areas

Area	Number of samples with gold	Number of gold grains in the area	Measured results								
			length (μm)			width (μm)			elongation		
			min	max	av.	min	max	av.	min	max	av.
Kolahun	2	2	272	340	306	170	272	221	1,25	1,6	1,43
Magua	17	314	68	1598	359	34	884	230	1	5	1,61
Konia	2	19	204	1054	478	136	578	311	1,08	2,58	1,55
Zeya	3	104	136	1190	449	102	1190	279	1	3,78	1,66
Solo	9	464	102	1394	341	68	918	207	1	8	1,71
Timbo	5	324	102	2040	428	34	1224	268	1	4,67	1,66
Soso Camp	4	213	68	884	274	34	510	181	1	5	1,63
Total	42	1440	68	2040	364	34	1224	228	1	8	1,66

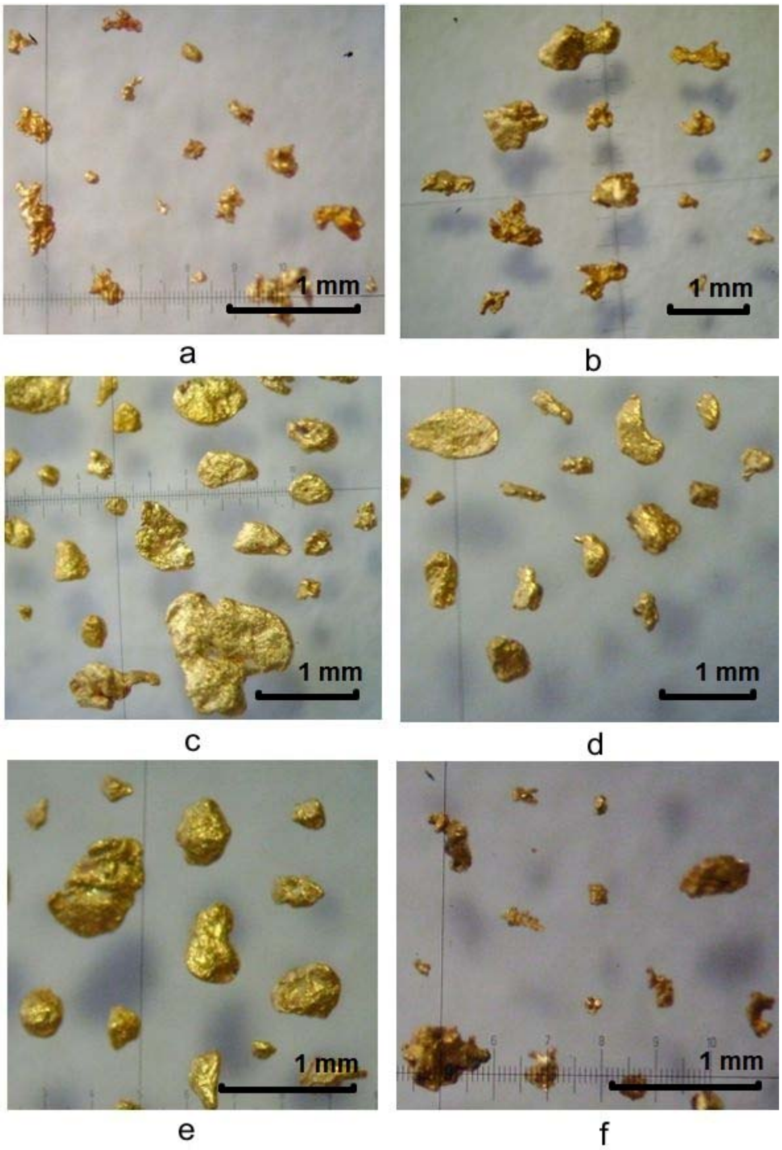

Figure 2. Photo of gold grains from different regions of Liberia:
a – Magua, b – Konia, c – Zeya, d – Solo, e – Timbo, f – Soso Camp

The gold from the region of Magua is characterized by the presence of irregular in shape and discoid grains; they have a smooth or commonly folded surface, usually with incurved protrusions and traces of mechanical wearing. The colour of grains is generally golden yellow, and the shine is bright. Extremely interesting is the sample number 142, which contains gold grains of two various types of morphology which may have different origin (Figure 2, a). The first, well-flattened type of grains, most likely was transported in a fluvial environment, and the second type, with a rough surface and various protrusions, was formed in situ from a nearby primary source.

The perspective area of Konia is located in the north-western part of Liberia. The region is composed of monotonous granites and gneisses. In a dump of developments and in deluvium, light grey and grey banded migmatites prevail; also there occur fragments of quartz, dark-green-grey amphibolites, and crystal slates.

The gold from the region of Konia is irregular in shape with a commonly folded surface and smoothed grain outlines (Figure 2, b). The colour of grains is golden yellow with a bright shine, which also indicates a high fineness. The linear dimensions of gold grains from this region are above average taken in all regions of research.

The area of Zeya is located in the river basin of the same name, 10 km to the south of Konia's frame, so it has a similar geological structure. Gold grains from this region usually have a commonly folded discoid and leaf shape (Figure 2, c). Their shape indicates that the distance of transportation was not very long, which suggests the presence of indigenous sources close to the alluvial placers. The grains are golden yellow. Compared to the gold of the Magua area, it is characterized by a wide variety of shapes and sizes and, in particular, by the presence of large fractions of grains that highly exceed the size of the gold of the Magua area.

The Solo (902 km^2) and Eastern (803 km^2) areas are located in the south-eastern part of the Republic of Liberia. Geologically, the area is located in the block, composed of Paleoproterozoic sediments, comparable with a series of West African Birrim, favourable for gold mineralization. These deposits occur in the north-western part of the Solo area, where they create a block of 36 x 8 km, extended to the north-east. There are complexes of the rocks favourable for gold mineralization, such as shales, including black shales, and geological structures, namely a combination of fault structures of north-east and north-west directions. The rest of the territory mostly consists of gneisses intersected by diorite intrusions. Also, in the central part of the Eastern area, there is a number of amphibolite bodies elongated in a north-east direction.

In the samples from these regions, there are both irregular in shape and spherical grains with smoothed grain outlines and a smooth surface (Figure 2, d). The colour of grains is generally golden yellow, which may indicate a high fineness of gold. The linear dimensions of gold grains from the Solo and Eastern regions are below average taken in all regions of research (274 versus 296 microns).

The area of Timbo is located in the central part of Liberia in the Timbo river basin. In the samples from this region, there are irregular in shape and discoid grains with a commonly folded surface (Figure 2, e). The grains are golden yellow, the linear dimensions of them are above average taken in all regions of research (348 versus 296 microns).

The perspective area of Soso Camp is located in the western part of the Republic of Liberia, near the eponymous village. Gold is already mined there by intensive artisanal workings in the crust of weathering. The crusts of weathering are developed along the series of alternation of leucocratic and melanocratic gneisses with blocks of more acidic rocks, possibly granites. In the crust of weathering, there are also impregnations of amphibolite shales sized up to 5-6 m, along which the manganese oxides and fragments of quartz deposits are being developed.

The gold grains from the Soso Camp area are commonly irregular in shape with folded outlines; they also tend to be smaller in size (Figure 2, f). All this indicates that the gold has been transported from not far away, in other words, it was formed in situ during the formation of the crust of weathering on the basement rocks. The colour of gold grains has a brown tint, which may indicate the presence of admixtures of other metals and a low fineness of gold.

Roentgenospectrographic analysis. As a result of the roentgenospectrographic (electron microprobe) analysis of gold from different regions, it was found that all of the analysed grains have gold content close to 100%. In other words, all gold samples have high levels of gold fineness. The only exception is the grain from sample number 142, which was collected near the village of Kpadamey (the Magua area). It has a high silver content, about 45%. After this analysis, it was decided to conduct an additional roentgenospectrographic analysis of three more gold grains from this region. One was selected from number 139, also taken from the alluvial-diluvial placers near the village of Kpadamey. Morphologically, it is highly flattened. The electron microprobe analysis showed the presence of a significant admixture of silver, about 10%. The other two gold grains were taken from the same sample number 142. However, unlike the previous case, there have been selected the instances of a well-flattened type. According to the microprobe analysis, they both are almost 100% composed of gold, with no meaningful content of silver.

It confirms a guess that was made after the morphological analysis: a well-flattened type of grains was transported from remote regions or reworked from local paleoplacers, while the other type of grains with elongations in several ways and protrusions was formed in situ.

Roentgen-fluorescent analysis. Six samples were given to the laboratory to conduct the research (Table 2).

Table 2

The results of the roentgen-fluorescent analysis

Area	Sample №	Ag (%)	Cu (%)	Zn (%)	Au (%)	Total (%)
Magua	32	3,27	1,08	0,22	95,42	100,00
Magua	142	16,70	15,68	3,87	63,75	100,00
Konia	204-1	1,74	3,31	0,56	94,40	100,00
Zeya	121	2,15	0,43	0,09	97,32	100,00
Solo	1004	2,39	0,20	0,06	97,34	100,00
Soso Camp	77	1,98	2,42	0,06	95,53	100,00

Due to the results of the analysis, we can affirm that all the samples, except of the sample number 142 are of typical metallic composition of gold, which represent the geochemical features of this element. Anomalous silver content was observed in sample number 142; it is up to 16.7%. This outcome confirms the results of the electron microprobe studies and the morphological analysis in the following way: taking into consideration the fact that in the sample there are gold grains with a high and low fineness (based on the electron microprobe analysis), and also knowing that the vast majority of gold grains are of low fineness (based on morphological analysis), we can therefore state the fact that the obtained silver content is just the result of the mixture of gold grains with different fineness.

An interesting result of this analysis is also an abnormally high content of zinc in the sample number 142. The presence of zinc may be associated with some rock-forming minerals, from which this gold placer was formed. To confirm this hypothesis, there has to be carried out a detailed study of the bedrock of this region which could produce the placer gold of the Magua area.

Conclusions. As a result of the research, there can be presented a range of morphological features of the gold under study which may indicate its genesis. Well-flattening of grains indicates either a large distance of the transportation of the material, or the fact that the gold has been reworked from nearby local paleoplacers. In the case of the Magua area, considering a large variety of shapes, sizes and the mineral composition of the gold grains, its gold can be of two genetic types: 1) paleoplacer gold, the closest analogue of which is Tarkva deposit in Ghana; 2) indigenous gold, related to ferruginous quartzites, where laterite crusts of weathering are developed.

The Zeya area is related to the south-eastern part of the belt of rocks which are similar in composition to those associated with Magua mineralization. They are shales, quartzites, amphibolites, and ferruginous quartzites. Considering a relative similarity in morphological characteristics of the gold grains and the proximity of their geographical location, the gold of the Kohalun area may have the same genesis as the Magua gold. The gold from the Konia region is not well-flattened and has a commonly folded surface; it may indicate that the distance of its transportation was very short.

At the Solo area, as a result of geological studies, there were found the complexes of the rocks favourable for gold mineralization. They are shales, including black shales and geological structures, namely a combination of fault structures of north-east and north-west directions. Most likely, the auriferity of the Solo area is associated with these conditions.

The gold grains from the Timbo area are mainly irregular in shape with a commonly folded surface. This may indicate a relatively short distance of transportation. It is likely that the gold placers are associated with alluvial-diluvial sediments of small streams or granitoids' crusts of weathering.

The gold from the Soso Camp area, according to the morphological analysis and geological studies, could be accumulated during the formation of the crust of weathering on the basement rocks, among which their felsic varieties were prevailing.

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МОРФОЛОГІЯ ТА СКЛАД ЗОЛОТА РОЗСИПНИХ РОДОВИЩ ЛІБЕРІЇ

У зв'язку з періодом громадянської війни, яка тривала в Ліберії з 1989 по 2003 рік, геологічне вивчення країни було призупинене, і стало можливим тільки після її закінчення. Саме тому до сьогодні територія Ліберії не має чіткого геологічного районування золотоносних регіонів. Морфологія золота Ліберії вивчена дуже слабко. У вітчизняній літературі вивченню цього питання увага не приділялась.

Стаття присвячена дослідженню морфологічних форм золота з різних регіонів республіки Ліберія. Основними цілями проведеного морфологічного аналізу було виділення основних морфологічних типів золота країни та їх генезису, а також визначення можливих шляхів формування розсипів. Для досягнення більш точних результатів було також проведено мікрозондовий та рентгенофлуоресцентний аналізи. Порівняльний аналіз морфологічних особливостей та пробності золота проводився по восьми регіонам досліджень: Колахун, Магуа, Конія та Зея в північній частині, Соло і Східна – в південній частині, західній (Сосо) і центральній (Тімбо) частинах Ліберії.

Різне за типом золото, що досліджувалось, було класифіковане за його морфологічними особливостями, що могли також вказувати на його генезис. Добра окатаність зерен вказує або на значну відстань переносу матеріалу, або на те, що золото було перевідкладене із палеорозсипищ. У випадку регіону Магуа, враховуючи велику різноманітність форм, розмірів та речовинного складу золотин, дане золото може мати два генетичні типи: 1) палеорозсипне, найближчим аналогом якого є родовище Тарква в Гані; 2) корінне, приурочене до залізистих кварцитів, на яких розвиваються латеритні кори вивітрювання.

В результаті проведеного рентгеноспектрального (мікрозондового) аналізу золотин з різних регіонів було визначено, що всі аналізовані зерна мають у своєму складі вміст золота близький до 100%. За результатами проведеного аналізу можна засвідчити, що усі проби, окрім проби №142 мають типовий металічний склад золота, який характерний для геохімічних особливостей даного елементу. У пробі №142 відмічається аномальний вміст срібла, який становить аж 16,7%.

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МОРФОЛОГИЯ И СОСТАВ ЗОЛОТА РОССЫПНЫХ МЕСТОРОЖДЕНИЙ ЛИБЕРИИ

В связи с периодом гражданской войны, которая длилась в Либерии с 1989 по 2003 год, геологическое изучение страны было приостановлено, и стало возможным только после её окончания. Именно поэтому до сих пор территория Либерии не имеет четкого геологического районирования золотоносных регионов. Морфология золота Либерии изучена очень слабо. В отечественной литературе изучению этого вопроса внимание не уделялось.

Статья посвящена изучению морфологических форм золота из разных регионов республики Либерия. Основными целями проведённого морфологического анализа было выделение основных морфологических типов золота страны и их генезиса, а также определение возможных путей формирования россыпей. Для достижения более точных результатов было также проведено микрозондовый и рентгенофлуоресцентный анализы. Сравнительный анализ морфологических особенностей, а также пробности золота был проведён по восьми регионам исследований: Колахун, Магуа, Кония и Зея в северной части, Соло и Восточная – в южной части, западной (Сосо) и центральной (Тимбо) частях Либерии.

Разное по типу золото, что исследовалось, было классифицировано по его морфологическим особенностям, что могли также указывать на его генезис. Большая степень окатанности зёрен указывает или на значительное расстояние переноса материала, или на то, что золото было переотложено из палеороссыпей. В случае региона Магуа, учитывая большое разнообразие форм, размеров и вещественного состава золотин, это золото может иметь два генетические типы: 1) палеороссыпное, ближайшим аналогом которого является месторождение Тарква в Гане; 2) коренное, приуроченное к железистым кварцитам, на которых развиваются латеритные коры выветривания.

В результате проведённого рентгеноспектрального (микрозондового) анализа золотин с разных регионов было определено, что все рассматриваемые зёрна имеют в своём составе содержание золота близкое к 100%. По результатам проведённого анализа можно говорить, что все пробы, кроме пробы №142 имеют типичный металлический состав золота, который характерен для геохимических особенностей данного элемента. В пробе №142 отмечается аномальное содержание серебра, которое составляет вплоть до 16,7%.

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ECONOMIC EFFICIENCY OF FAST WELL DRILLING IN DONBASS

(Reviewed by the editorial board member V. Mykhailov)

The main purpose of this paper is to study the optimal conditions for rational degassing during gas-hazardous mines operation and cost-effectiveness to ensure safe operation, to increase coal production and to use the produced gas commercially.

The work methodology is complex and combines mining-technological and economic components. The first step was to analyze the results of the project degassing, which was held directly in the field CG "Pokrovske", and define the main parameters affecting the efficiency of degassing. The parameters of drilling conducted on CG "Pokrovske" in 2012 were generalized. The next step was to establish a correlation between the parameters of drilling speed and lava promotion. The data on real drilling performance achieved in the implementation of degassing project showed that the average drilling speed was now about 100 m per day against the previous years' average of 500 m per month. The formulas for determining annuity from the drilling organization operations are given. The final stage of the research was to determine the optimum drilling performance for degassing at an economically favorable, rational expediency and efficiency level.

The obtained results revealed that the main parameters affecting the efficiency of degassing are drilling speed, optimization of degasification wells construction, as well as calculation of the effective well spacing and timing of their preparation for the lavas approach. It has been found out that the main factors to achieve efficiency of operation include cutting down on wages of the workers engaged in servicing rigs, due to drilling speeds, and decreasing investments into the construction of wells. Emphasis is laid on the need for integrated development of the existing fields, which combines degassing with coal mining.

Scientific novelty of the paper is in the development of formulas for calculating the drilling organization's annual income depending on drilling speed characteristics. Fast drilling technology offers clear advantages as compared to the conventional one.

The practical application of the paper is in determining the optimum speed and drilling conditions that ensure cost-effective degassing. The theoretical assumptions were confirmed by the results obtained from using the fast drilling operation technology developed by "Donetsksteel".

Problem definition and its relationship with important scientific and practical tasks.

Being under the influence of the gas factor, leading domestic mines have reached the limit of their output capacity. They need non-trivial solutions for safe and high efficiency coal mining operations. The preliminary degassing which is of preferential extensive use in the United States, Canada, Australia, China and other countries could be a solution; but about 10 years are required for 50-percent reduction in gas emissions; Ukrainian enterprises do not have so much time for that. That is why they are forced to find a combination of space and time performing coal mining operations and drilling, namely, to use wells drilled from the surface for degassing purposes. General mine ventilation ensures degassing of about 55% of the daily emissions in highly productive longwalls; this type of ventilation is followed by degassing by wells drilled from the development workings (25%), and finally, degassing by wells drilled from the surface (up to 20%).

Analysis of recent research and publications.

Conducted in recent years, research and its analysis in publications [1, 2, 3] are increasingly presenting arguments regarding the need for effective concomitant degassing. The conventional methods for underground degassing by drilling wells from excavations cannot provide the necessary safety conditions for gas factor in gas-hazardous mines. Equipping the mines with a modern coal-mining complex will increase labor productivity. Designed degassing pipes system, especially in old mines, are limited by bandwidth. It is necessary to create additional degassing systems that could provide the necessary working conditions in the mines and contribute to the rational use of the extracted gas. The solution to this problem could be drilling degasification wells from the surface, the advance of lava with forgery and gravitational unloading are an additional way to underground extraction of gas from the coal-rock block. Degasification wells drilling should be conducted with the greatest possible speed.

Aspects of the problem to be solved.

Despite the fact that the method of degassing by wells drilled from the surface is the third in the row of the methods used for further development of Ukrainian mines, it is a crucial one, as all other resources have already been mobilized.

Degassing by wells from the surface requires drilling of a great number of wells. It has a direct impact on the economic aspect of coal mining. However, the focus had primarily been on the technical side [1, 2, 3]. Therefore, to improve the efficiency of coal mining in Ukraine, in this paper we set the goal to determine a rational scope of application of wells drilled from the surface.

Purpose of the article. The main purpose of this paper is to study the optimal conditions for rational degassing during gas-hazardous mines operation and cost-effectiveness to ensure safe operation, to increase coal production and to use the produced gas commercially.

The main research material.

Degassing efficiency depends on the well spacing density and the time factor. A proper combination of coal mining and well drilling operations is an important requirement: by the time of well completion, projection of well bottom on mined seam is to be at a distance of not less than 30 m ahead of the production face.

Thus, time provided for drilling and completion of a well shall satisfy the inequality:

$$T_{D1} \le (L_1 - l_i) / m_{LW} , \qquad (1)$$

where T_{D1} – time of well drilling that is allowed by conditions of degassing technology, days; L_1 – spacing between wells within a single extraction panel, m; l_1 – minimum distance from the advancing face to the projection of well on the degassed seam at the time of well completion, m; m_{LW} – average daily advance of production face, m/day.

In order to stay within the stipulated time, commercial drilling speed is to be at least:

$$S_{1C} \geq nh_i / T_{D1c}\,, \tag{2}$$

where S_{1c} – commercial drilling speed for a well, m/day; n – number of degassing wells that are to be constructed according to the plans by one drilling rig for the time T_{D1}; h_i – depth of i-th degassing well, m.

$$h_i = H_i - h_2\,, \tag{3}$$

where H_i – depth of occurrence of the seam where degassing is performed, m; h_2 – project distance from the well shoe to the roof of the longwall, m.

The following parameters of well construction were taken as optimum ones for Project of Degassing that is being implemented in "Pokrovskoye" mine: L_1=300 m; l_1=30 m; h_2=15 m. If a degassed seam occurs at a depth of 800 m, the depth of the well is to be 785 m.

When average daily advance of a longwall is 7m (as it is in fact in case of mines characterized by high output capacity), for the construction of such a well not more than $\frac{300-30}{7} = 39\ days$ are to be spent.

In the project of degassing that was developed for "Pokrovskoye" mine by a specialized organization "Donbassgeologiya", use of the Canadian drilling rig produced by National Oilwell Varco (Dreco) was assumed; while construction of wells from the surface was considered as rig-down and rig-up operations with a duration of 12 days and the actual drilling. Standard well drilling speed for a depth of 674 m was 40.5 days; 724 m – 43.5 days; 800 m – 48 days (drilling speed – 500 m per month per one drilling rig). Thus, in view of rig-down and rig-up operations for the well with a depth of 800 m, 60 days were required. It conditioned commercial speed of well construction of 13.3 m/day.

Drilling speed required under condition (2) is to be not less than 22 m/day. This means that the investment project for the creation and operation of the drilling organization, specialized in the construction of degassing wells drilled from the surface, would require more drilling rig complexes, and in case of simultaneous operation of several longwalls, a number of drilling rigs would be increased in proportion to the number of concurrent mined panels. And it's not just arithmetic addition of pieces of equipment – significant increase in investment and operating costs is observed. Up-to-date drilling complexes are expensive ones (drilling rig produced by Dreco costs $ 9.7 million USD), each drilling rig is serviced by a separate crew, each drilling rig requires maintenance, including transportation from place to place, etc.

In order for the investment project for the foundation and operation of the drilling organization to be break-even, cash flow CF_t from its implementation represented in the form of annuity is to meet the following condition [1]:

$$CF_t \geq \frac{Inv}{\sum_{1}^{T} \frac{1}{(1+m_1)^t}}\,, \tag{4}$$

where CF_t – annual cash flow (annuity) from the activity of drilling organization, mln UAH; INV – cumulative amount of investments, mln UAH; m_1 – cost of capital, fraction unit; t – current year of project implementation; T – duration of the investment project.

The break-even condition (4) shows the amount of the annual cash flow that turns a net present value (*NPV*) under the project to zero for a given volume of investments and rate of capital cost. Condition *NPV*=0 gives very informative indicators for an investor – with their help, even roughly, the economic prospects of the project, its feasibility and, finally, efficiency can be estimated.

In 2012, in "Pokrovskoye" mine as a result of progressive fast drilling operations performed by one Ultra Single 150 drilling rig on three production panels, 36 degassing wells were drilled for 301 machine-days. According to the initial project, based on the traditional drilling technologies, 6 drilling rig complexes of Dreco type would have been involved to serve three longwalls. Individual parameters of drilling operations were summarized in the table.

Annual cash flow on break-even condition of the project was calculated based on 20 years of operation of drilling complexes and the rate of 12% per annum.

Table 1

Actual and Estimated Indicators of Drilling Operations

Indicator	Measurement Unit	Value
Wells constructed in 2012	pcs	36
Average duration of well construction	days	8±2
Deductions for salary payment for drill site	thous. UAH/day	18.5
Costs excluding depreciation when using one Ultra Single 150 drilling rig	mln UAH/well	1.0±0.1
Wage and salaries fund for drill site when using one Ultra Single 150 drilling rig	mln UAH/year	5.5
Wage and salaries fund for drill site when using six Dreco drilling rigs	mln UAH/year	32.9
Total costs when using one Ultra Single 150 drilling rig	mln UAH/year	37.3
Total costs when using six Dreco drilling rigs	mln UAH/year	64.7
Unit costs excluding depreciation when using six Dreco drilling rigs	mln UAH/well	1.8
Investments when using one Ultra Single 150 drilling rig	mln UAH	192
Investments when using six Dreco drilling rigs	mln UAH	466
Annual cash flow on break-even condition of the project when using one Ultra Single 150 drilling rig	mln UAH	26
Annual cash flow on break-even condition of the project when using six Dreco drilling rigs	mln UAH	62

When comparing the projects, design identity of wells was assumed; increase in costs of maintenance of drilling complexes in case of their greater amount etc. was not taken into account. As major factors in achieving economic efficiency, only savings on salaries of personnel directly engaged in drilling rigs maintenance, and reduction in amount of investments due to reducing the time of a well construction.

The value of the annual income of the drilling organization on break-even condition of the investment project (taking into account appropriate annuity of cash flow) is to satisfy the following condition:

$$G \geq CF_t + C_{dr}\,, \tag{5}$$

where G – average amount of annual income of drilling organization, mln UAH; C_{dr} – cost of the construction of wells drilled from the surface without depreciation deductions, mln UAH.

Conclusions. In the case of fast drilling technologies, the above mentioned 36 wells constructed for "Pokrovskoye" mine would have cost for coal production enterprise more than 62 mln UAH taking into account the requirement to ensure break-even condition of the project; in case of conventional drilling technologies – more than 127 mln UAH.

In the past, artillery-type weapons were cast with the Latin inscription "Ultima ratio regum", which had the following meaning: "The final argument of kings". For owners of the leading Ukrainian mines such a "final argument" is degassing wells drilled from the surface. But, according to the assessment performed by the Institute of

Industrial Economics of National Academy of Sciences of Ukraine, the basic project is not economic. Degassing of Coal and Gas Deposits by wells drilled from the surface can be economic providing the commercial drilling speed exceeds 22 m/day and enables using one drilling complex.

While acknowledging the importance and effectiveness of the process of preliminary degassing by wells drilled from the surface, it should be recognized that degassing combined with mining operations will be of immediate interest to the existing mines for at least another 15-20 years. It determines the topicality and value for the domestic coal industry of the progressive fast drilling operations technology developed by "Donetsksteel".

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ЕКОНОМІЧНА ЕФЕКТИВНІСТЬ ШВИДКІСНОГО БУРІННЯ СВЕРДЛОВИН В УМОВАХ ДОНБАСУ

Головною метою даної роботи є дослідження оптимальних умов раціонального проведення дегазаційних робіт при експлуатації газонебезпечних шахт та їх економічної ефективності для дотримання безпеки робіт, нарощування видобутку вугілля та використання вилученого газу у господарчих цілях.

Методика робіт є комплексною та поєднує гірничо-технологічну та економічну складові. Першим етапом був аналіз результатів проекту дегазації, проведеного безпосередньо на родовищі ШУ "Покровське" та визначення головних параметрів, що мали вплив на результативність дегазаційних робіт. Узагальнено параметри бурових робіт, що були проведені на ШУ "Покровське" у 2012 році. Наступним кроком було встановлення взаємозв'язку між параметрами буріння свердловини та швидкістю посування лави. На прикладі реальних показників буріння, які досягнуті при реалізації дегазаційного проекту, розрахована середня швидкість буріння, яка складає біля 100 м/добу при середніх показниках минулих років 500 м/місяць. Наведено розрахункові формули для визначення щорічного грошового потоку від діяльності бурової організації. Кінцевою стадією у роботі було визначення оптимальних показників буріння для проведення дегазаційних робіт на економічно вигідному, раціонально-доцільному та ефективному рівні.

Отримані результати дозволили встановити, що основними параметрами, що впливають на результативність дегазації, є швидкість буріння, оптимізація конструкції дегазаційних свердловини, а також розрахунок ефективних відстаней між свердловинами та визначення часу їх підготовки до підходу лав. Визначено, що основними факторами для досягнення ефективності робіт є економія на заробітних платах робітників, що зайняті на обслуговуванні бурових установок, за рахунок швидкостей буріння та скорочення обсягу інвестицій для будівництва свердловини. Підкреслено необхідність комплексного освоєння існуючих родовищ, що поєднує проведення дегазації з видобутком вугілля.

Наукова новизна роботи полягає у виведенні формули для розрахунку річного прибутку бурової організації у залежності від швидкісних характеристик проведення бурових робіт. Встановлено переваги технологій швидкого буріння свердловин у порівнянні з традиційними.

Практична значимість роботи полягає у визначенні оптимальної швидкості та умов буріння, за яких проведення дегазації є доцільним та економічно вигідним. Висновки підтверджені результатами, отриманими при використанні на практиці технології швидкісного буріння, розробленої ПрАТ "Донецьксталь".

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ЭКОНОМИЧЕСКАЯ ЭФФЕКТИВНОСТЬ СКОРОСТНОГО БУРЕНИЯ СКВАЖИН В УСЛОВИЯХ ДОНБАССА

Главной целью данной работы является исследование оптимальных условий рационального проведения дегазационных работ при эксплуатации газоопасных шахт и их экономической эффективности для обеспечения безопасности работ, наращивания добычи угля и использования добытого газа в хозяйственных целях.

Методика работ является комплексной и объединяет горно-технологическую и экономическую составляющие. Первым этапом был анализ результатов проекта дегазации, который проведен непосредственно на месторождении ШУ "Покровское" и определение главных параметров, влияющих на результативность дегазационных работ. Обобщенны параметры буровых работ, проведенных на ШУ "Покровское" в 2012 году. Следующим шагом было установление взаимосвязи между параметрами бурения скважины и скоростью продвижения лавы. На примере реальных показателей бурения, достигнутых при реализации дегазационного проекта, рассчитана средняя скорость бурения, которая составляет около 100 м/сутки при средних показателях прошлых лет 500 м/месяц. Приведены расчетные формулы для определения ежегодного денежного потока от деятельности буровой организации. Конечной стадией в работе было определение оптимальных показателей бурения для проведения дегазационных работ на экономически выгодном, рационально-целесообразном и эффективном уровне.

Полученные результаты позволили установить, что основными параметрами, влияющими на результативность дегазации, являются скорость бурения, оптимизация конструкции дегазационных скважин, а также расчет эффективных расстояний между скважинами и определение времени их подготовки к подходу лав. Определено, что основными факторами для достижения эффективности работ является экономия на заработных платах рабочих, занятых на обслуживании буровых установок, за счет скоростей бурения и сокращение объема инвестиций для строительства скважины. Подчеркнута необходимость комплексного освоения существующих месторождений, сочетающего проведение дегазации с добычей угля.

Научная новизна работы заключается в выведении формулы для расчета годовой прибыли буровой организации в зависимости от скоростных характеристик проведения буровых работ. Установлены преимущества технологий быстрого бурения скважин по сравнению с традиционными.

Практическая значимость работы заключается в определении оптимальной скорости и условий бурения, при которых проведение дегазации целесообразно и экономически выгодно. Выводы подтверждены результатами, полученными при использовании на практике технологии скоростного бурения, разработанной ЗАО "Донецксталь".

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STRESS AND STRAIN ANALYSIS DURING THE SLEME TUNNEL EXCAVATION

(Reviewed by the editorial board member B. Maslov)

A stress and strain analysis by Finite Element Method (FEM) has been carried out during the portal section excavation for the Sleme Tunnel right tube.

A comparison has been made of 2D and 3D model results with on-site measurement results for tunnel convergence and ground surface settlement. Multistage excavations with pipe roof support of the working face were modelled.

The calculation model has shown that safe and cost-efficient excavation technology had been applied in the case under consideration.

Introduction

A tunnel excavation requires detailed consideration based on geotechnical and geophysical investigation results, excavation method, supporting method, geotechnical measurements inside a tunnel, land surveying of the ground surface, and an impact of the tunnel excavation on structures in urban areas. Development of traffic networks entails excavation of tunnels in geologically unfavourable conditions. Due to large radii and relatively small ascents and gradients of the road and railroad routes which cannot follow the ground configuration, it is necessary to drive tunnels even in weak rocks. Tunnel is a civil structure built in unknown material, unlike concrete, wooden or steel structures where the material is known in advance. Tunnels are also built in urban areas, with low overburden, which makes the construction still more complex.

Theoretically, excavations under low overburden are those with the overburden height H being less than the tunnel diameter D (H<D).

When a tunnel is excavated with low overburden in weak and loose rocks, the possibility of working face caving-in increases, thus additional measures need to be taken including supporting and multistage excavation.

Excavations when height H = D are made with particular caution and careful selection of technology, which calls for wide experience. Designers tend to avoid portal zone excavation, which requires high portal cutting or side cut. This approach is easily applied outside urban areas, but when the works are carried out in urban areas there is often no alternative.

For road tunnels with two lanes (width D), the New Austrian Tunnelling Method (NATM) defines height H $\leq$ 2D with low overburden, and this approach has been accepted in construction practice. Width D $\approx$10 m is adopted for typical cross-section of a road tunnel in Croatia. Figure 1 shows heights of overburden H = D = 10 m and H = 2D = 20 m.

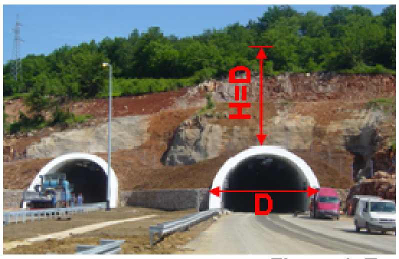

Figure 1. Tunnel portals [3]

The NATM method can be tailored to frequent changes in geological and geotechnical conditions at the working face when the neighbouring geological formation is integrated with the ring-shaped support structure which, to put it simply, means that the rock itself is made a part of the support structure. The majority of time-related processes of stress redistribution happen in the bearing rock mass arch, a zone around the tunnel opening. The term "rock mass arch activation" means activities undertaken to maintain and/or increase the rock bearing capacity and use it to favourably affect the development of the induced stress state, since the tunnel boring changes the in-situ stress state σ_v^o and σ_h^o into a considerably less favourable induced stress state σ_v and σ_h.

Unlike mechanical excavation of an entire profile in favourable geological formations, boring in rock mass with frequently changing geological and geotechnical conditions along the tunnel line requires that a multistage excavation method be used. Profile development using a multistage excavation method is applied when the excavation with low overburden is carried out in urban areas, weak rocks/soil, fault zones, and when excavation is carried out for underground rooms with larger cross-sections. A multistage excavation is usually carried out in three stages: top heading (Stage I.) – bench (Stage II.) – invert (Stage III.). The distance between the stages depends on geological conditions at the working face. In weak rocks/soil, the bench and invert are excavated in intervals exceeding one tunnel diameter D, in order to quickly close the support ring and reach the new state of balance preventing occurrence of larger convergences.

The majority of theoretical research is into the tunnel excavation with low overburden focus on excavation using the Tunnel Boring Machines (TBM) in urban areas. The reason is a possibility of forecasting ground settlement as the most frequently encountered side effect of tunnelling within urban areas. This topic is particularly interesting for development and use of the TBMs with large diameters, which thus indirectly influences the direction in which the research goes. However, in excavation of shorter tunnels, frequent changes of tunnel cross-section and surface areas and side passages, the TBM is still much more expensive than excavation using the NATM.

Authors writing about the NATM focus on the cases of low overburden and use of NATM in weak rock mass and urban areas, when NATM is used instead of the TBM. The Croatian authors have also published works [10, 16] describing examples of tunnel construction (design and construction). Some authors analyse incidents occurring during excavation of tunnels with low overburden using the NATM, which are frequently due to insufficient knowledge of the method [1].

The highest risk encountered when excavating in weak rocks with low overburden is ground surface settlement, since consequences might sometimes be grave (Figure 2), even disastrous, causing human casualties. Therefore, the excavation methods chosen need to ensure security of work performance and minimum settlement, which depends on geological and geotechnical characteristics of the rock mass, tunnel cross-section and excavation technology.

London (2002) Munich (1994)

Figure 2. Ground surface caving-in during tunnel excavation in urban areas [1]

High standards of the work carried out along the tunnel line minimize the risks during excavation. However, caving-in happens during the tunnel excavation and accidents in tunnelling practice cannot always be avoided.

A condition analysis needs to be made of endangered structures along the tunnel line which might respond to an underground excavation before the tunnel excavation starts.

In damage classification, it is necessary to differentiate between the damage on load-bearing parts of the structure which could ultimately cause collapse of the structure or a part thereof and the damage on secondary structural members.

Ground surface settlement surveying (levelling, GPS – Geodetic Positioning System) is carried out during the tunnel excavation, and optical 3D measurements are carried out in the tunnel including measurements of excavation outline benchmark displacement (profile convergence).

Ground settlement caused by tunnel excavation at a certain distance gradually increases closer to the working face. To mitigate settlements and stabilise the excavation, it is necessary to improve the rock mass during the excavation process by grouting, pipe roof installation, soil freezing or core reinforcement by fibreglass pipes [12]. This paper discusses use of pipe roof for reinforcement [7].

Figure 3. Excavation protection with paling [3]

The pipe roof method is a modern version of paling (steel rods and breakdown sheets, Figure 3), an old mining method of working face protection against material falling in and easier installation of the support system members during the rock mass excavation.

A pipe roof method (Figure 4) is a technique where grout-mix filled perforated steel pipes are embedded along the tunnel outline in the excavation progress direction, which creates a grouted zone as a protective arch under which the excavation is carried out [11, 13]. An actual pipe roof installation effect could only be evaluated by back analysis once the geotechnical measurements have been completed, since it depends on the rock type, number of installed pipes, diameter of rock bolt walls and excavation method.

Figure 4. Pipe roof installation [3]

Land Surveying Results

The Sleme Tunnel is situated at the Vrata – Delnice section of the Rijeka– Zagreb Highway. The 835 m long left tube was finished in 1995, and the 858 m long right tube in 2008. The right tube portal excavation was based on the known geology and using the pipe roof support.

The tunnel line passes through the Lower Jurassic carbonate sediments – liassic limestone with dolomite interlayers. The limestones are light to dark grey, often recrystallised, fossil contents are encountered with rarely, typically in about 0.50 m layers fissured and fractured due to subsequent tectonic activity and occasionally hardly noticed. The limestones are highly kartstified in the surface zone, with large crack aperture, and kartstification of deposits confirmed during the tunnelling. The crack filling material consists of high plasticity clay and calcite up to 5 mm. The clay is also encountered in form of clusters, lenses and interlayers. The surface is mostly covered with fine detritus and clays-sandy material. The rock mass is heterogeneous and it consists of clay, sand and loose karst rocks.

The area in which the Sleme Tunnel was built is tectonically highly fractured and it belongs to the geotectonic unit of Dinaric carbonate platform. Generally, the area is characterized by variable discontinuity orientations on a relatively small space, which is an indication of its being exceptionally tectonically fractured, as was actually confirmed during boring of both tunnel tubes.

The measurements were carried out in the west portal. Because the entire section was at risk of the working face caving in, a pipe roof was installed consisting of ϕ114.3/6.3, 15.0 m long steel pipes filled with cement grout mix as a reinforcement of the top heading arch.

The excavation outline displacements were measured with optical 3D method in three benchmarks: in benchmark 1 in the u top heading apex, and in benchmarks 2 and 3 in the bench sides (Figures 5 and 6).

Figure 5. The Sleme Tunnel portal with marked positions of the right tube measuring points 1, 2, 3, R1 and R2

Settlement was measured using optical methods. Two benchmarks were set at the chainage 34+961.50 of the west portal, 10 m from the excavation start point. The benchmark installed in the tunnel axis is R2, and the benchmark R1 is placed 8.50 m left from the tunnel axis. Positions of benchmarks R1 and R2 are marked in Figures 5 and 6. The measurement results are given in Table 1.

Table 1

Measurement results for profile convergence and settlements during the Sleme Tunnel right tube excavation

Chainage	Overburden (m)	Measurement of	Vertical displacement u_y(mm)	Transverse displacement u_x(mm)	Longitudinal displacement u_z(mm)
34+962.50*	8.5	convergence	-12	3	8
34+975.00*	11.0	convergence	-5	7	3
34+985.00	17.0	convergence	-4	5	3
34+996.00*	21.0	convergence	-2	3	3
34+961.50	8.0	settlement	-17		

* Numerical calculations for 10 m and 20 m high overburden

For comparison, the largest measured horizontal (transverse) displacement of the left tube at a 25 m distance from the entrance [8], in identical rock mass, was 20.42 mm, which is considerably more than the displacement in the right tube (3–7 mm). A lot of problems were encountered during the left tube excavation work, and a top heading arch was reinforced using the paling (Figure 3). Minor convergences in the right tube are caused by installation of the pipe roof.

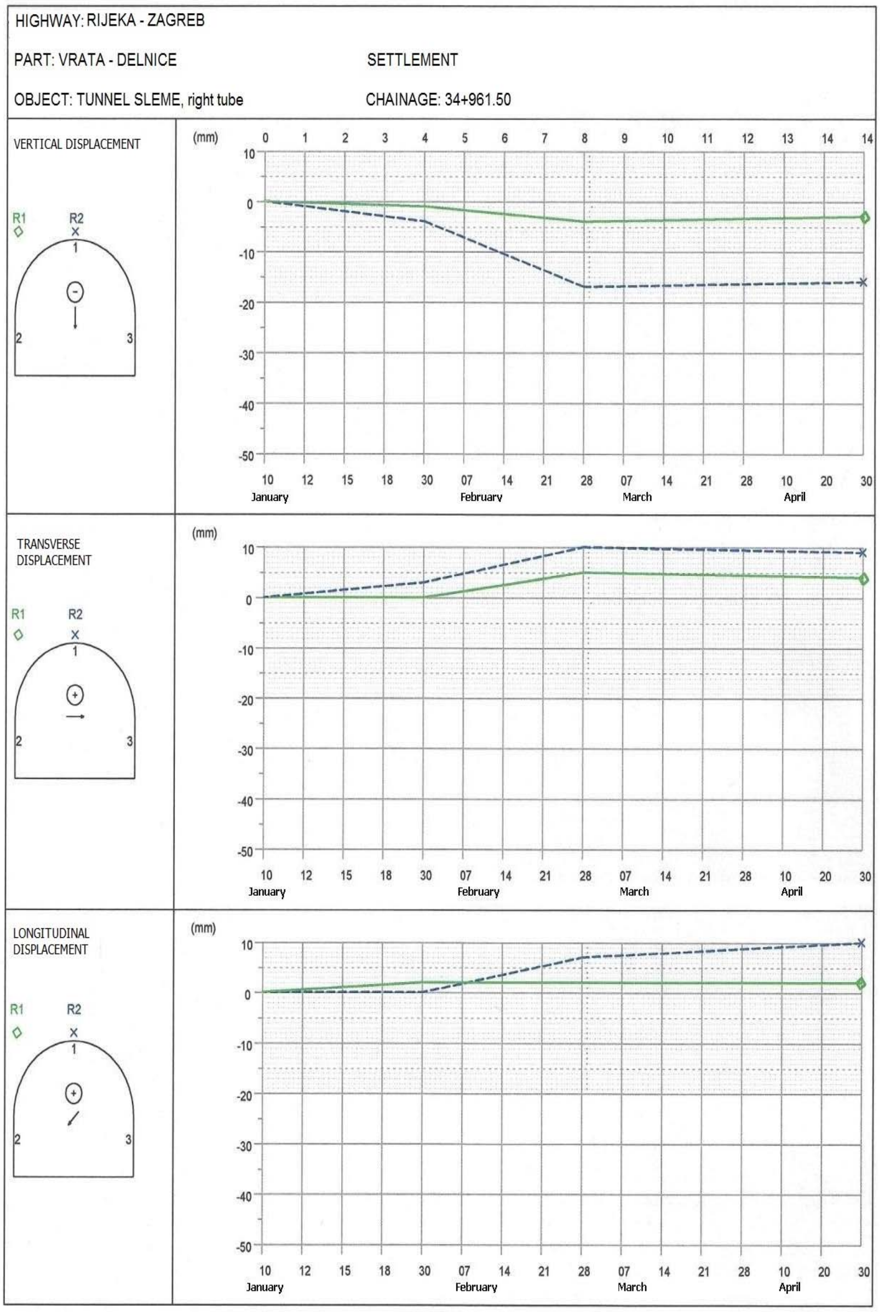

Figure 6. Settlements measured at chainage 34+961.50

3. Excavation Numerical Modelling

An important role in selecting an excavation method is played by numerical modelling of excavation in rock mass based on geotechnical data for the constructed tunnels. [2]. Some of the problems encountered in numerical modelling of weak rocks are described in the paper [6]. Numerical analysis, together with geotechnical measurements, ensures safer and more cost-efficient design of tunnels and other underground structures [10]. Actual mechanical properties of a rock mass are very hard to determine [9] and even the best field investigations could render incomplete data. The tunnel construction is faced with a problem of considerably varying physical and mechanical characteristics of the rock mass, which results in sudden changes in geological conditions that have a major impact on the tunnel excavation. Stress variations within the rock mass/soil quite often result in working face caving in when reactive pressure with which the primary support acts on the rock mass is not sufficient. The lower overburden causes less favourable stress state due to the heterogeneous nature of the rock mass, lower self-supporting capacity and surface impacts (water courses, structure load acting on the surface, dynamic load of roads).

The stress and strain analysis with the FEM method uses the following software: Sage Crisp 4 for 2D models [15] and Plaxis 3D Tunnel for 3D models [14].

Calculations were made for 10 and 20 m high overburden, for three-stage excavation without the pipe roof (Case a), three-stage excavation with pipe roof in top heading arch – design concept (Case b), and two-stage excavation (top heading+bench, invert) with use of pipe roof and 2 m invert excavation stage (Case c). Ultimately, the two-stage excavation with reinforced pipe roof and 4 m invert excavation stage (Case d) was carried out.

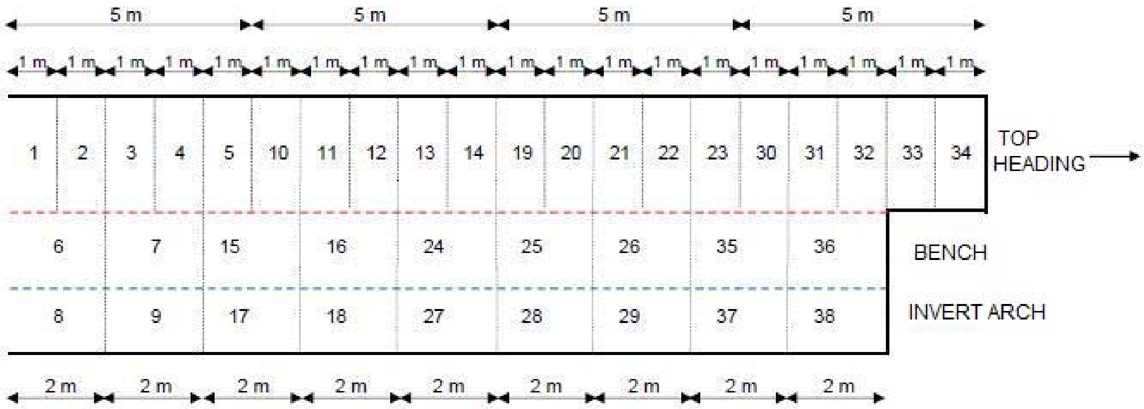

Figure 7. Three-stage profile excavation for 3D calculation

The computational model of three-stage excavation using NATM method – top heading, bench, invert consists of six phases (Figure 7):

1. Top heading excavation
2. Shotcrete placement into the top heading
3. Bench excavation
4. Shotcrete placement into the bench
5. Invert excavation (excavation stage 2 m)
6. Shotcrete placement into the invert.

First, the top heading excavation and supporting with shotcrete on a 5 m long section were simulated, with 1 m cycle step (excavation and support). Then, excavation and shotcrete supporting of the bench on a 4 m long section was simulated. The cycle step was 2 m. Next, the excavation and shotcrete supporting of the invert on a 4 m long section was simulated, with 2 m cycle step. A new top heading, bench and invert excavation cycle followed until the top heading length reached 20 m, and bench and invert length 18 m. The total number of excavation cycles was 38, and the total number of 3D calculation stages 76. A model was created for a half of the cross-section excavation, since the tunnel cross-section is symmetrical related to the axis (Figure 8).

Since 3D calculation can show results for several cross-sections with co-ordinates corresponding to the excavation stages, the cross-sections z = 0 (initial plane) are shown which present the calculation in the excavated and supported part of the tunnel located 20 m from the working face (z = –20 m). Figure 8 shows position of these planes.

The computational model of two-stage excavation using the pipe roof consists of four phases (Figure 9):

1. Top heading and bench excavation
2. Shotcrete placement into the top heading and bench
3. Invert excavation (excavation stage 4 m)
4. Shotcrete placement into the invert.

A 15-node wedge finite element mesh was used for 3D model, while triangular and square finite elements were used for 2D model. In order to eliminate impact of boundary conditions, width of the coverage area selected for calculations is four times tunnel opening to the left and right from the tunnel axis. In the tunnel axis direction (longitudinal direction), the coverage area width in 3D analysis was 50 m.

The adopted physical and mechanical characteristics of the portal zone rock mass [4, 5], pipe roof and primary support are given in Table 2. The Mohr–Coulomb elastic–ideally plastic model was selected for the rock mass, and an isotropic- elastic model for the primary support.

The pipe roof consists of 29 steel pipes, ϕ114.3/6.3, 15 m long, filled with cement grout mix. The shotcrete thickness is 20 cm, and rock mass reinforcement using pipe roof in the top heading arch is 50 cm, which approximately corresponds to the as-built situation. Since there is no general rule for calculation of the pipe roof reinforcement, an approximate method was used to calculate modulus of elasticity acc. to [6], Table 3, where the weak rock mass was replaced with a system comprising steel pipes + grout mix. Bulk density of the zone reinforced in this way is 19.2 kN/m^3.

The calculation results are tabulated and shown in a diagram (stresses, vertical displacements, ground settlements). Figure 10 shows the pipe roof reinforcement for two-stage excavation of the whole profile (2D calculation), effective vertical stresses (a) and vertical displacements (b) for a 10 m overburden.

The 2D calculation results, i.e. ground surface vertical displacements – settlements with 10 m high overburden after excavation of all stages, are shown in Figure 11.

The 3D calculation results of the ground surface settlement with visible effect of the excavation pipe roof reinforcement are given in Figure 12.

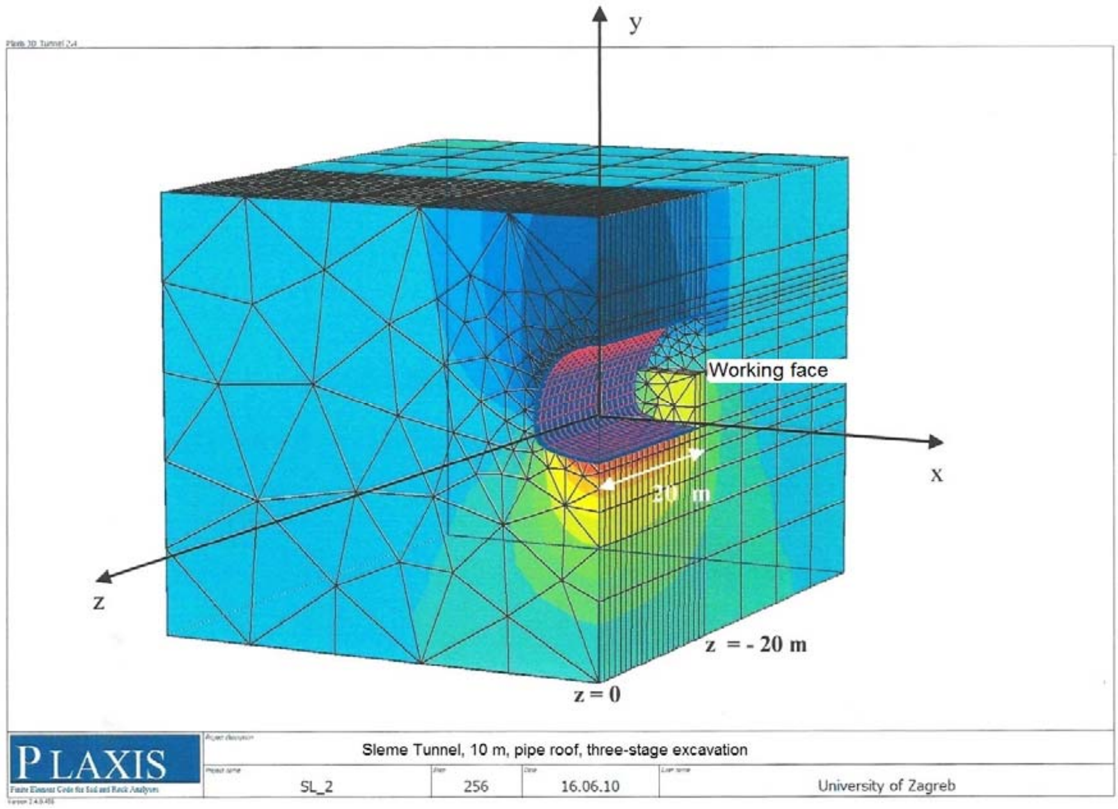

Figure 8. Position of plane z = 0 (excavation of whole profile) and z = –20 m (working face)

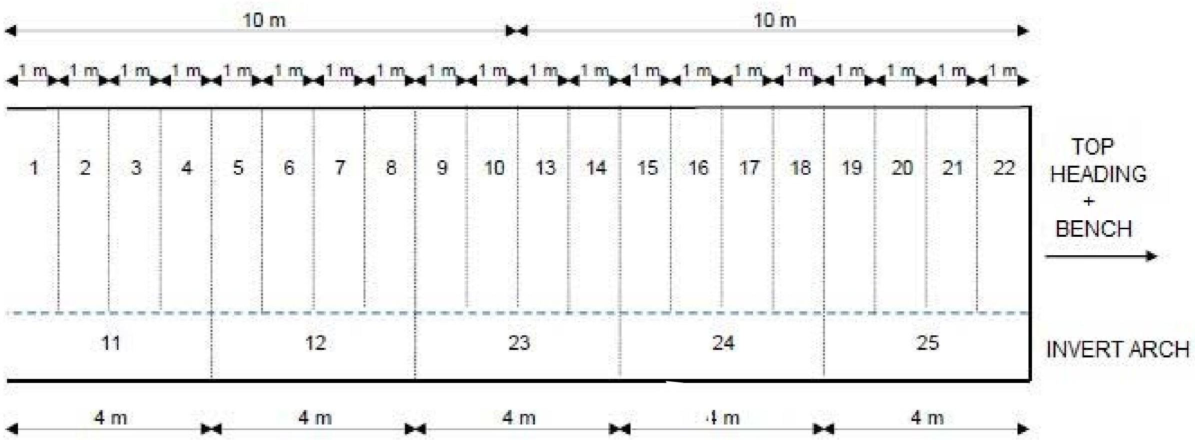

Figure 9. Two-stage profile excavation for 3D calculation

Table 2

Physical and mechanical characteristics of the rock mass, pipe roof and primary support

	Rock mass – Portal zone	Pipe roof – reinforced rock mass	Primary support – shotcrete
Modulus of elasticity E (MPa)	300	19,900	3,000
Poisson coefficient ν (-)	0.25	0.25	0.20
Bulk density ρ (kN/m^3)	26.5	19.2	25.0
Angle of internal friction φ (°)	28	-	-
Cohesion c (kPa)	40	-	-

Table 3

Calculation of the modulus of elasticity of the pipe roof reinforcement

Element	Surface area (m^2)	Modulus of elasticity (MPa)	Product
	a	b	a · b
Pipes	0.06	210 E+03	12.60 E+06
Grout mix	5.94	18 E+03	106.92 E+06
Sum:	6.00		119.52 E+06
Modulus of elasticity of rock reinforcement with pipe roof	mass	19,900	

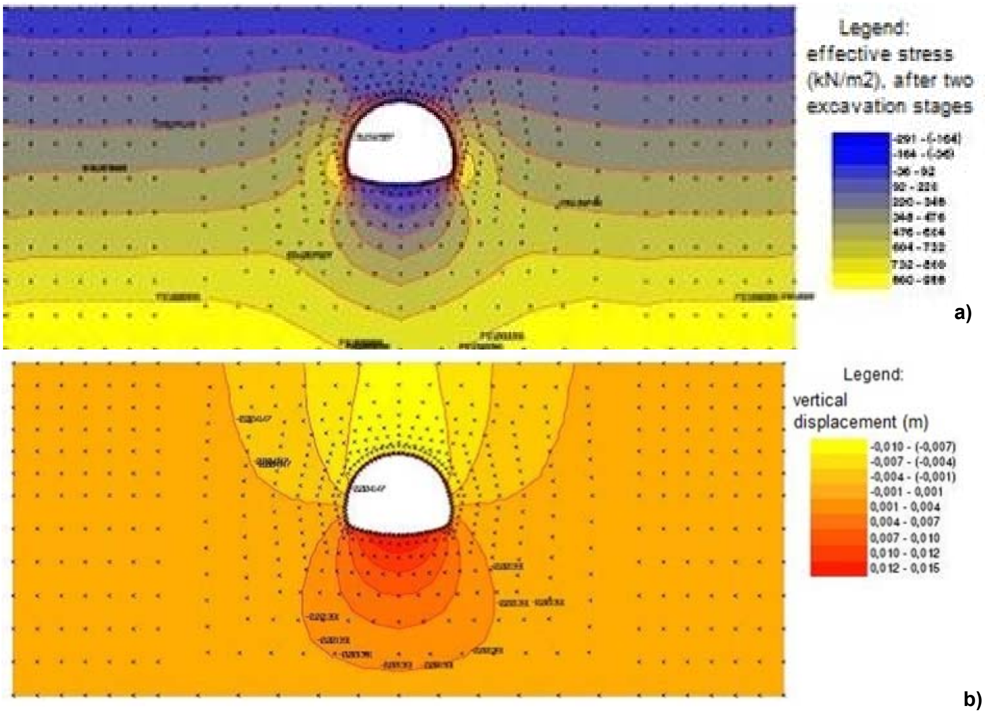

Figure 10. Two-stage excavation with pipe roof reinforcement, 10 m overburden:
a) effective stress, b) vertical displacement

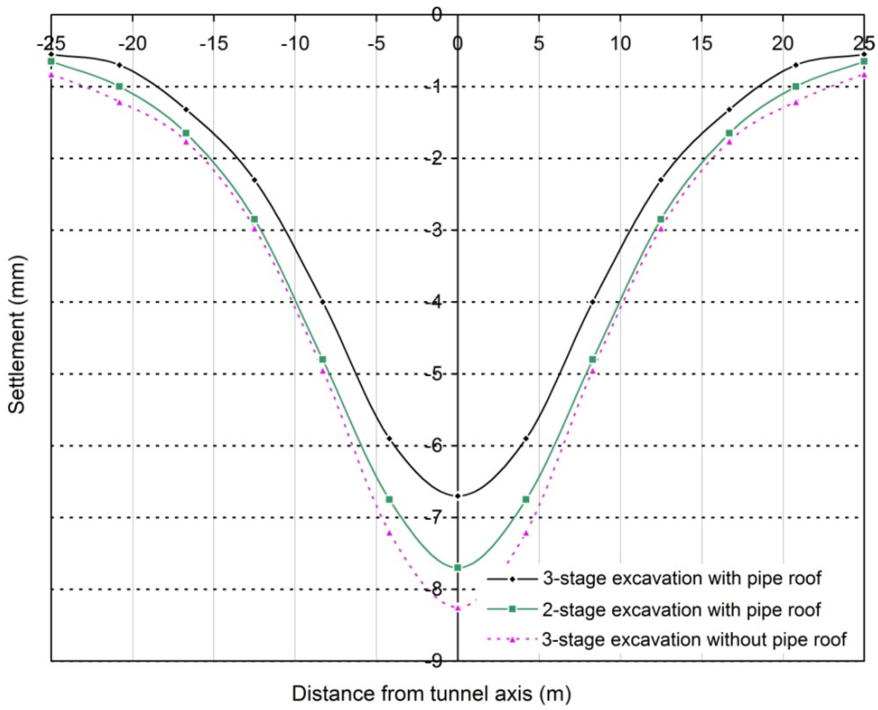

Figure 11. Ground surface settlement after excavation of all stages, 2D calculation

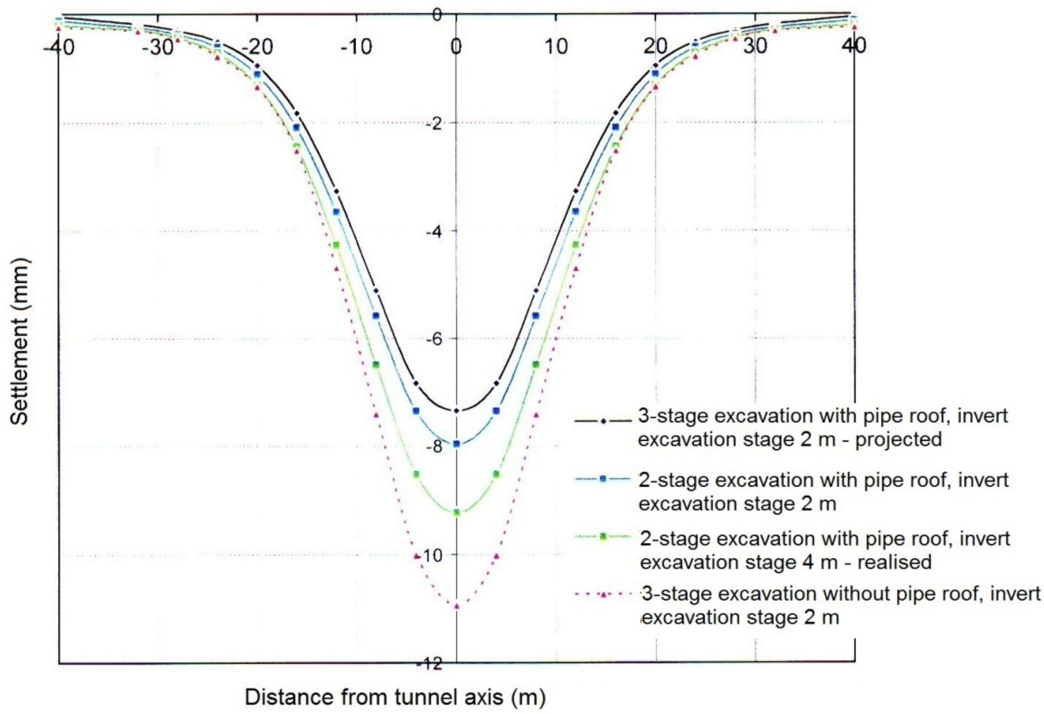

Figure 12. Ground surface settlement after excavation of all stages, 3D calculation

Use of pipe roof mitigates convergences in the tunnel and settlements. In real conditions, impact of the underground opening on the settlement equals radius of plastification of the rock material which depends on equivalent radius of the opening. With increase in overburden, the pipe roof effect on the settlement decreases, so when the overburden is higher, the pipe roof acts so that it reduces convergences in the top heading.

Values of vertical displacements of the top heading apex and ground surface after whole profile excavation (*20 m from the working face in plane z = 0) obtained by calculations are given in Table 4. Calculation results are given for 3-stage excavation (top heading, bench, invert) using NATM method: without pipe roof (Case a) and with pipe roof reinforcement (Case b, Figure 7 – design concept); and for 2-stage excavation (top heading + bench, invert) with pipe roof and 2 m invert excavation stage (Case c) and 4 m (Case d, Figure 9 – construction).

Table 4

Vertical displacements u_y in characteristic points

Overburden 10 m	**Calculation**	**Vertical displacements u_y (mm)**			
		No pipe roof	**Pipe roof**		
		3-stage	**3-stage**	**2-stage**	**2-stage**
Point		Case a	Case b	Case c	Case d
Ground surface	2D	- 7.5	- 6.7	- 7.7	
Top heading apex	2D	- 11.2	- 8.6	-9.7	
				Invert excavation stage 2 m	Invert excavation stage 4 m
Ground surface	3D*	- 8.5	- 7.3	- 7.9	-9.2
Top heading apex	3D*	- 11.9	- 9.4	- 10.0	- 11.4
Overburden 20 m					
Ground surface	2D	- 9.0	- 7.8	- 9.7	
Top heading apex	2D	-19.2	- 13.7	- 16.0	
				Invert excavation stage 2 m	Invert excavation stage 4 m
Ground surface	3D*	- 9.5	- 8.7	- 9.0	-9.9
Top heading apex	3D*	- 18.8	- 15.6	- 15.7.0	-17.0

(* displacement for z = 0; 20 m from working face)

Difference in total vertical displacements for two-stage excavation with 2 m and 4 m invert excavation stage is 1.3 mm for settlement, and 1.4 mm in the top heading apex. The measurement and calculation results show that an optimum invert excavation stage for the contractor would be 4 m. Also, the shorter invert excavation stage results in less intensive overall convergence.

In addition to vertical displacement u_y and excavation cross-section convergences u_x, the 3D stress and strain analysis calculates displacements in working face u_z (pre-convergence, Figure 13) which are particularly important for excavation in weak rock/soil since they ensure timely response. Provided ther are continuous geotechnical measurements, and sufficiently small strains, a multistage excavation could be done in a smaller number of stages.

Results of 2D and 3D numerical calculations are compared with the results of measurements at chainages 34+962.50 and 34+975.00 for 10 m high overburden and actual two-stage excavation with pipe roof and 4 m invert excavation stage (Table 5.).

The results of 3D calculation for 10 m high overburden correspond very well with measured convergences. The difference in vertical displacements u_y is -0.6 mm, and difference in transverse u_x and longitudinal u_z direction is only 2 mm, which is negligible.

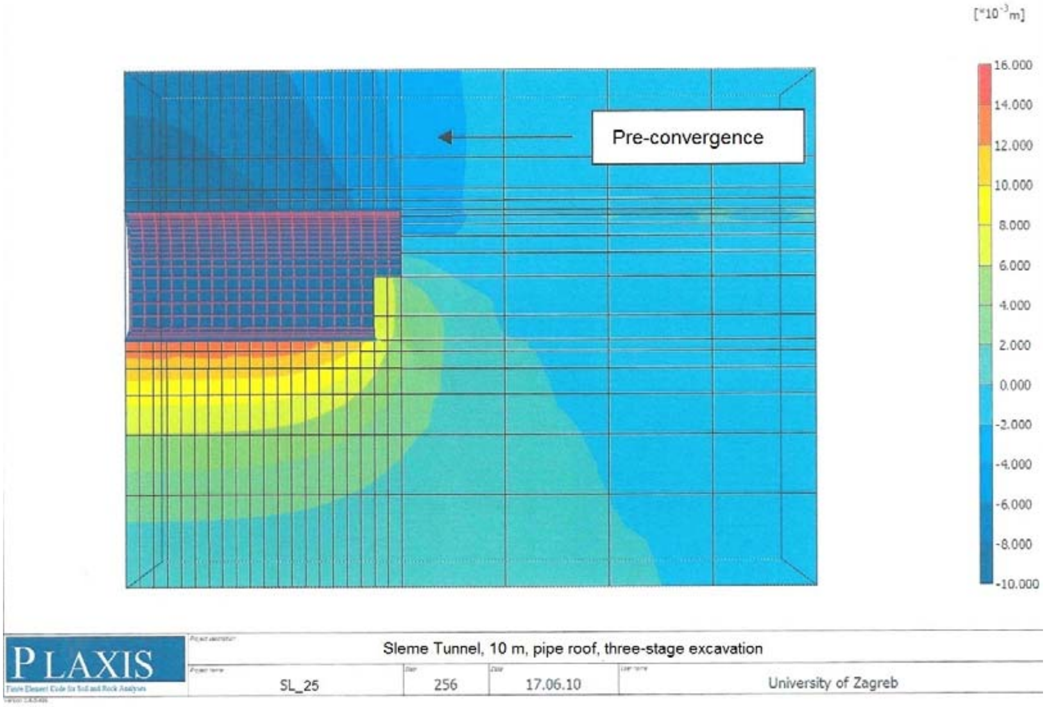

Figure 13. Vertical displacements u_y in longitudinal section, overburden height 10 m, pipe roof

Table 5

Comparison of measurement results and calculated displacements

Overburden 10 m	Vertical displacement u_y (mm)	Transverse displacement u_x (mm)	Longitudinal displacement u_z (mm)
Measured	-12.0(100%)	7.0 (100%)	8.0 (100%)
2D	-9.7 (81%)	-	-
3D	-11.4 (95%)	9.0 (128%)	10.0 (125%)

With such convergences (maximum 12 mm), a 0.20 m thick support system is sufficiently yielding not to cause the support failure, which complies with the NATM principles. The same applies to 20 m high overburden. The highest calculated convergence in a tunnel for two-stage excavation is 17 mm, which is in good correspondence with measured convergences. Displacement calculations and measurements indicate that it is possible to make a more cost-efficient tunnel excavation under the pipe roof protection in a smaller number of stages, i.e. in two instead of three design stages, which is a common approach to excavation of portal sections in weak and weathered rocks.

Conclusions

Excavation of a tunnel with low overburden is a complex design 3D problem. In such conditions, the rock mass is very heterogeneous and has variable physical and mechanical characteristics, it is prone to surface impacts and thus potentially unstable. The practice shows that even when the rock mass is well investigated, it is still not always possible to forecast all the geological "pitfalls" of the underground. Sudden and unpredicted changes in rock mass characteristics could, in worst case scenario, cause tunnel caving in and damage to the structures on the surface.

Numerical modelling enables predicting of rock mass reaction to the tunnel profile excavation. An advantage of the 3D FEM analysis is that it makes possible not only modelling of an excavation by stages, but also by change in excavation stage length in a particular phase (top heading, bench or invert). The excavation stage is commonly determined empirically, according to some of the engineering rock mass classifications or by in situ variation of excavation stage with permanent geotechnical measurements. Based on its long-term experience, contractor had decided not to carry out the three-stage excavation but rather to make a joint excavation of the top heading and bench during the first stage and to carry out the invert excavation subsequently (second stage). The 3D calculation has confirmed that the excavation stage of 4.0 m for the invert (the envisaged stage was 2.0 m) is a boundary stage where strains are such that they do not cause tunnel caving in. An analysis of an optimum stage for excavation progress shows that there are cases when the stages in certain phases can be longer than designed. A contractor has to decide whether to assume certain geotechnical risks. An increase in an excavation stage shortens the construction time and reduces the project costs. Quality forecasts are possible only with numerical simulations of the 3D model of the tunnel excavation, along with experience, intuition and field measurements. This approach results not only in project cost reduction but also in improvement of work performance safety.

Data on geotechnical measurements, which are usually kept unused on the archives, need to be used in the stress and strain analysis so that the empirical knowledge could be complemented with the results of numerical calculations. The analysis is intended to determine the degree to which the numerical calculation results correspond with the field measurement results. The back analysis of the as-built status of the tunnel is particularly important for verification of design parameters and excavation method.

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АНАЛІЗ СТРЕССУ ТА ДЕФОРМАЦІЙ ПІД ЧАС РОЗКОПОК ТУНЕЛЮ СЛЕМЕ

Проведено аналіз стресу і деформації методом скінченних елементів (МСЕ) під час розкопок розділу портал на правій трубі тунелю Слеме.

Порівняльний аналіз виконано на основі 2D і 3D моделювання з результатами вимірювань на місцевості для конвергенції тунелю і поверхні наземних будов. Багатоступінчасті розкопки з підтримкою труби на даху робочої поверхні були змодельовані.

Розрахункова модель показала, що безпечна і економічно ефективна технологія розкопки були застосовані в розглянутому випадку.

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АНАЛИЗ СТРЕССА И ДЕФОРМАЦИЙ ПРИ РАСКОПКАХ ТОННЕЛЯ СЛЕМЕ

Проведен анализ стресса и деформации методом конечных элементов (МКЭ) при раскопках раздела портал на правой трубе тоннеля Слеме.

Сравнительный анализ выполнен на основе 2D и 3D моделирования с результатами измерений на местности для конвергенции тоннеля и поверхности наземных строений. Многоступенчатые раскопки с поддержкой трубы на крыше рабочей поверхности были смоделированы.

Расчетная модель показала, что безопасная и экономически эффективная технология раскопки были применены в рассматриваемом случае.

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ECOLOGICAL AND GEOLOGICAL INVESTIGATION OF THE MINE INDUSTRIAL REGIONS IN LUHANSK DISTRICT IN CONNECTION WITH COAL-MINING INDUSTRY'S RESTRUCTURING

(Reviewed by the editorial board member M. Korjnev)

***Goal.** A range of problems arisen in the process of coal-mining industry's restructuring in Luhansk district is analyzed.*

***Methodology.** Main factors determining the possibility of unfavorable and dangerous processes related to the closure of coal mines are described and analyzed.*

The new data of the concentration of heavy metals and toxins in waters, soil, coal waste and rock dumps in industrial areas of closed mines in Luhansk district are obtained. In order to define the pollution level by several elements, a total index of concentration (TIC) has been applied. This index characterizes the overall geochemical load produced by all chemical elements with abnormal level of concentration.

***Research results.** The data processing of lithographic sampling in Luhansk region has helped to define five large and more than 40 smaller areas of anthropogenic pollution. Within the main industrial areas, the more intensely polluted sites (2-32 km^2) were revealed. They are related to some plants or industrial units. TIC here is 16-50, and in some sites it reaches 150.*

***Topicality.** It is revealed that the most contrasting (TIC 8 – 126) and extensive (410 km^2) anthropogenic area is located in Almazno-Mar`yvsk mine industrial region and stretches over 48 km in the northwest direction from the town of Perevalsk to the town of Zolotoye. Typical contaminants for this region are arsenic, lead, fluorine, mercury, barium, manganese. Within the region, large areas (15-25 km^2) with the maximum (TIC 16-77) pollution level of land were revealed. They are limited to industrial and intended for building landscapes of the towns of Alchevsk, Bryanka, and Stahanov. More local (1-4 km^2) but nevertheless more contrasting (TIC 16-126) abnormalities related to contamination are recorded near the coil mining plants of the towns of Teplohorsk, Zolotoye, and Horskoye.*

***Conclusion.** The main pollutants of soils and bed deposits are revealed, they are the following: arsenic, lead, fluorine, mercury, phosphorus, zinc, and barium. Cadmium, thallium, antimony, manganese, lithium, copper and chromium are also found. In order to determine the level of land pollution by several elements, the total index of concentration was used. The specific features related to the occurrence of some microelements in industrial waste of Donbas are described, their probable sources and possible ways of use are suggested.*

Introduction. In the regions of coal industry development extremely unfavorable ecological circumstances have emerged. Anthropogenic changes in the geological environment that covers the area of more than 15000 km^2 within the limits of Donetsk, Luhansk and Dnepropetrovsk prove this fact. The situation took a dangerous turn due to the consecutive implementation of the program of removing from service unprofitable mines, chiefly by applying a method of "wet" conservation.

It is revealed that the main factors that precondition the unprofitable and dangerous processes associated with the closure of mines are the following:

- a fault-block structure of rock masses with a wavelike translation of blocks;
- monoclinique bedding of multilayer, lithologically heterogeneous and irregularly weathered mass of coal deposits;
- disturbance of the stressed state of rock masses in underworked areas, including the areas of abandoned shallow workings;
- a wide spread occurrence of fill-up grounds (rock dumps, dumps of domestic and industrial wastes);
- a large number of hydraulic engineering structures (tailing dumps, sludge dumps, settling basins, etc.);
- occurrence of soluble rocks and rocks that change their properties when soaked and rehydrated;
- imposition of depression cones in the areas related to mines;
- changes in chemical composition of surface and underground waters as a result of mines operation [1,2].

Taking into account the above listed, it is possible to suggest that Donbas represents a disturbed and very sensitive to exposure anthropogenic structure. The change in the state of the rock mass in the context of removal of mines from service will keep its magnitude but there will be the emergence and development of the whole complex of phenomena and processes quite undesirable in terms of ecological and geological safety. Among the particularly dangerous processes are the following:

- underflooding of territory and submersion of underground structures;
- rehydratation of soils, change of their physical and mechanical properties, activation of such processes as subsidence and hydration of ground base under various buildings, weakening of structure bonds in grounds that will induce the development of exogenic geological processes (sliding of slopes, ravines, etc.);
- activation of suffusion and erosion processes, irregular subsidence of the surface and, as a result, the deformation of buildings and structures;
- a hydrodynamic impact on the soil masses and buildings;
- intensification of gas release and gas accumulation in underground structures, cellars and basements, which is closely related to the issues of social safety;
- activation of underground water movement in the direction of operating mines, changes in the surface run-off;
- change in chemical composition of underground water, including the water of small artesian basins used for domestic and industrial water supply;
- increased corrosivity of groundwater and relevant processes of deterioration of metal, concrete and reinforced concrete structures.

The removal of mines from service affords ground to consider ecological and hydrogeological factors and wastes accumulated during the long-term mining (for instance, waste dumps, slurry sumps and wastes of coal dressing placed on industrial areas) as a source of important influence on ecological and geological characteristics of natural and anthropogenic systems. It is known that in Stakhanov mining industry region there is approximately a hundred of waste dumps; these waste dumps are the sources of air pollution. Moreover, they have a negative effect on the surface run-off, soil cover, and underground waters. Therefore, the new data acquisition on the concentration of heavy metals and toxic components in waste dumps will improve the ecology of the area. Hence, the research on the effect waste dumps and waste coal have on the environment is extremely topical [3,4].

Goal. *The goal of investigation* is to reveal a mechanism of toxic and "small" elements distribution both in the rocks containing coals and the waste produced by coil industry plants. This will help to solve ecological and geochemical problems concerning further storage or use of products coming from coal conversion.

Methodology. In order to realize these goals, it is necessary to solve the following tasks:

- to study the geological structure and hydrogeological conditions within the locations of industrial enterprises;
- to study the special aspects of the waste storage;
- to carry out an investigation of potentially dangerous objects of industrial plants: industrial area, waste dumps, production waste, refuse dumps, mine water settling basins, slime tanks, etc.;
- to define and map investigated anomalies.

Anthropogenic anomalies are characterized by a complex of elements-impurities, therefore, in order to estimate a level of land pollution by several elements, a total index of concentration is used (TIC). This index characterizes the geochemical load produced by all chemical elements with abnormal content. According to the standards GOST 17.4.02-83 "Classification of chemical substances for land pollution control", 24 elements of 1-st, 2-nd and 3-d classes of danger were defined.

In some samples only selective components were determined. In order to define the TIC, the value of their concentration was taken on the basis of related samples or, otherwise, baseline value was used. This applies primarily to arsenic [5].

Research results. In the result of data processing of lithographic sampling in the limits of Luhansk region five large and more than 40 local polluted areas were revealed. Within the main anthropogenic site, the more intensely contaminated plots (2-32 km^2) were determined. All of them are related to some plants or industrial units. TIC here is 16-50, and in some plots it reaches 150.

It is found that configuration of anthropogenic anomalies is very complicated and preconditioned by irregular distribution of pollution sources (mines, plants, industrial dumps). Besides, complex air flows in urban area also add to the problem. The main impurities of subsoil are: arsenic, lead, fluorine, phosphorus, mercury, zinc, and barium; while cadmium, antimony, molybdenum, chromium, manganese, copper, lithium, and thallium are of less importance.

The determination of natural geochemical background plays a key part in defining the intensity of anthropogenic pollution of subsoil. The assessment of geochemical background was carried out on the basis of characteristical samples in the areas located far away from a source of pollution. Local background was defined for each of the three sites, as well as for the whole investigated area. The coefficient of variation characterizing the diversity of background content ranges from 12 to 67.

Comparative characteristic of local background values shows the certain (6-30%) increase in the content of lead, phosphorus, cobalt from the west to the east. Higher concentration of magnesium, chromium, barium, lithium was found in the central part of the investigated area.

It was revealed that geochemical background in the south of Luhansk region practically doesn't differ from clarkes and regional geochemical background of the soils in Donetsk region [3,4].

Selected samples (n=1797) helped to define mean contents of chemical elements. All the elements except vanadium and niobium showed an increase in mean contents in relation to background concentration.

Topicality. It is revealed that the more contrasting (TIC 8 – 126) and extensive (410 km^2) anthropogenic site is located in Almazno-Mar`yvsk mine industrial region. It stretches over 48 km in the northwest direction from the town of Perevalsk to the town of Zolotoye. Arsenic, lead, fluorine, mercury, barium, manganese are typical contaminants for this region. Within the site large plots (15-25 km^2) with maximum (TIC 16-77) subsoil pollution were detected. They are limited to industrial and intended for building landscapes of the towns of Alchevsk, Bryanka, and Stahanov. More local (1-4 km^2) but nevertheless more contrasting (TIC 16-126) abnormalities related to contamination are recorded near the coal mining plants of the towns of Teplohorsk, Zolotoye, and Horskoye.

A close connection between maximum concentration of elements and industrial and urbanized landscapes is particularly noticeable in a geological profile Zoinsk-Mikhaylovka that runs across the town of Alchevsk. Here one can detect positive abnormalities of lead, barium, manganese, chromium, copper and negative abnormalities of phosphorus and vanadium, and the latter two are not characteristic for industrial landscapes.

The revealed anthropogenic site comes second in terms of size and pollution level. It is a location (5 km wide and 80 km long) of sublatitudinal extension within the limits of Bokovo-Khrustalny and Dolzhano-Rovenetsky mining regions. Here arsenic, lead, mercury, barium, and molybdenum have the most profound effect on the structure of contamination. Maximal contamination level (TIC 16-149) is recorded on the territory of industrial and urbanized landscapes of the towns of Vakhrushevo, Krasnyi Lukh, Antratzit, Sverdlovsk, Chervonopartizansk, and a village Dzerzhinsky.

Peculiarities of chemical elements distribution in the direction Krasniy Luch-Rovenki, Sverdlovsk-Krasnodon allow to associate their maximal concentration with urban agglomeration and certain plants (a mine "Centrosoyuz", a plant "Titan", Krasnidon industrial and domestic waste).

Characteristic feature of anthropogenic site (TIC 8-120), which was found in the area subjected to the influence of enterprises of Luhansk (80 km^2), is the presence of such elements as cadmium, antimony, lead, zinc which are the main land pollutants.

Besides, large anthropogenic sites of pollution (100-120 km^2) were detected near the towns of Lisichansk and Krasnodon.

Waste dumps and waste coal may be used as a secondary source of natural resources and building material, for instance, as back filling in road construction. This will guarantee the complex effective use of coal dumps and lead to the improvement of ecological situation in coal mining regions.

Taking into account a range of modern ecological problems in coal regions, the view on rock dumps as mere recultivation objects seems to be somewhat narrow. According to the results of geological exploration, the majority of mining waste should be considered as prospective deposits of ferrous, non-ferrous and rare-earth metals [4,6].

Available operational experience in processing such anthropogenic deposits shows that the better they are explored, the more valuable they may become .

Conclusions. Special features of geological structure and hydrogeologic conditions of investigated territories are studied. It is defined that mining enterprises are the main sources of pollution of land, bed deposits, surface and underground waters. Environmental pollution by harmful and toxic elements has integrated nature due to a vast variety of sources of pollution, specific features of migration and accumulation.

The main pollutants of soils and bed deposits are explored, and they are the following: arsenic, lead, fluorine, mercury, phosphorus, zinc, barium. Cadmium, thallium, antimony, manganese, lithium, copper and chromium also occur. Dangerous concentrations of these elements are found on industrial sites of coal mining enterprises and coking plants, where the total index of pollution ranges from 16 to 32 units, and in some enterprises it reaches 130 units.

Implementation of a complex approach to a coal-mining industry's restructuring requires a change of attitude to rock dumps, their estimation as a raw stock and adoption of new management solutions concerning their diversified usage, particularly on the state level.

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ЕКОЛОГО-ГЕОЛОГІЧНІ ДОСЛІДЖЕННЯ ГІРНИЧОПРОМИСЛОВИХ РАЙОНІВ ЛУГАНСЬКОЇ ОБЛАСТІ В ЗВ'ЯЗКУ З РЕСТРУКТУРИЗАЦІЄЮ ВУГІЛЬНОЇ ПРОМИСЛОВОСТІ

***Мета.** Проаналізовано комплекс проблем що виникли при реструктуризації вугільної промисловості Луганської області.*

***Методика.** Описано та систематизовано основні фактори які визначають можливість виникнення несприятливих і небезпечних процесів при закритті вугільних шахт.*

Отримані нові дані за вмістом важких металів і токсичних компонентів у ґрунтах, відходах вуглезбагачення і породних відвалах на проммайданчиках ліквідованих шахт Луганської області. Для визначення величини забруднення ґрунтів кількома елементами застосований сумарний показник концентрації (СПК). Характеризує він загальну геохімічну навантаження, створювану усіма хімічними елементами з аномальними змістами.

***Результати.** У результаті обробки даних літохімічного опробування території Луганської області виявлено п'ять великих площинних техногенних ореолів забруднення і більше 40 локальних. Всередині основних техногенних ореолів виділяються ділянки (2-32 км^2) з більш інтенсивним забрудненням ґрунтів. Вони приурочені до окремих підприємств або промислових вузлів. СПК тут 16-50, а в окремих місцях досягає 150.*

***Наукова новизна.** Визначено, що найбільш контрастний (СПК 8 – 126) і великий (410 км^2) техногенний ореол розташований в Алмазно-Мар'ївському гірничопромисловому районі і простягається на 48 км в ПЗ напрямку від м. Перевальськ до м. Золоте. Характерними забруднювачами для нього є миш'як, свинець, фтор, ртуть, барій, марганець. Усередині ореолу виявлені великі (15 25 км^2) ділянки з максимальним (СПК 16 – 77) забрудненням почвогрунтів. Приурочені вони до промислово-селитебних ландшафтів міст Алчевськ, Брянка, Стаханів. Більш локальні (1-4 км^2) , але контрастні (СПК 16 – 126) аномалії з забрудненням ґрунтів відзначені поблизу вугледобувних підприємств рр. Теплогірськ, Золоте, Гірське.*

***Практичне значення.** Виявлено основні елементи – забруднювачі почвогрунтов і донних відкладень , ними є: миш'як, свинець, фтор, ртуть, фосфор, цинк, барій. Зустрічаються кадмій, талій, сурма, марганець, літій, мідь і хром. Описано особливості поширення деяких мікроелементів в промислових відходах Донбасу, наведені можливі джерела їх надходження і варіанти використання.*

***Ключові слова.** Вугільна промисловість, еколого-геологічні дослідження, грунти, підземні води, забруднення, сумарний показник концентрації (СПК), Луганська область.*

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ЭКОЛОГО-ГЕОЛОГИЧЕСКИЕ ИССЛЕДОВАНИЯ ГОРНОПРОМЫШЛЕННЫХ РАЙОНОВ ЛУГАНСКОЙ ОБЛАСТИ В СВЯЗИ С РЕСТРУКТУРИЗАЦИЕЙ УГОЛЬНОЙ ОТРЯСЛИ

***Цель.** Проанализирован комплекс проблем возникших при реструктуризации угольной промышленности Луганской области.*

***Методика.** Описаны и систематизированы основные факторы определяющие возможность возникновения неблагоприятных и опасных процессов при закрытии угольных шахт.*

Получены новые данные по содержанию тяжелых металлов и токсичных компонентов в грунтах, отходах углеобогащения и породных отвалах на промплощадках ликвидированных шахт Луганской области. Для определения величины загрязнения грунтов несколькими элементами применен суммарный показатель концентрации (СПК). Характеризует он общую геохимическую нагрузку, создаваемую всеми химическими элементами с аномальными содержаниями.

***Результаты.** В результате обработки данных литохимического опробования территории Луганской области выявлено пять крупных площадных техногенных ореолов загрязнения и более 40 локальных. Внутри основных техногенных ореолов выделяются участки (2-32 км^2) с более интенсивным загрязнением почв. Они приурочены к отдельным предприятиям или промышленным узлам. СПК здесь 16-50, а в отдельных местах достигает 150.*

***Научная новизна.** Определено, что наиболее контрастный (СПК 8-126) и обширный (410 км^2) техногенный ореол расположен в Алмазно-Марьевском горнопромышленном районе и простирается на 48 км в СЗ направлении от г. Перевальск до г. Золотое. Характерными загрязнителями для него являются мышьяк, свинец, фтор, ртуть, барий, марганец. Внутри ореола выявлены крупные (15–25 км^2) участки с максимальным (СПК 16-77) загрязнением почвогрунтов. Приурочены они к промышленно-селитебным ландшафтам городов Алчевск, Брянка, Стаханов. Более локальные (1–4 км^2), но контрастные (СПК 16-126) аномалии с загрязнением почв отмечены вблизи угледобывающих предприятий гг. Теплогорск, Золотое, Горское.*

***Практическое значение.** Выявлены основные элементы-загрязнители почвогрунтов и донных отложений, ими являются: мышьяк, свинец, фтор, ртуть, фосфор, цинк, барий. Встречаются кадмий, таллий, сурьма, марганец, литий, медь и хром. Описаны особенности распространения некоторых микроэлементов в промышленных отходах Донбасса, приведены возможные источники их поступления и варианты использования.*

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PECULIARITIES OF DEGRADATION IN LOESS SOILS' DEFORMATION AND STRENGTH PROPERTIES ON THE EXAMPLE OF DNIPROPETROVSK CITY

(Reviewed by the editorial board member B. Maslov)

Presentation of mathematical modeling results for the deformation and strength properties degradation process using the group method of data handling. Testing of this method had been applied to longitudinal data on the variability of the properties of the geological environment as an element of regional level natural – technogenic system.

Research Objective: to establish the peculiarities of massif degradation on the example of the longitudinal data research on periglacial formation soils' properties using methods of stochastic and inductive modeling.

Solution methods and software: stochastic modeling performed with methods of correlation and multiple regression analysis; inductive modeling – with group method of data handling. Software: STATIST (O. Honchar DNU), trial version of STATISTICA, customized program by Koryashkina L.S. (Candidate of physical-mathematical sciences, Associate Professor at O. Honchar DNU)

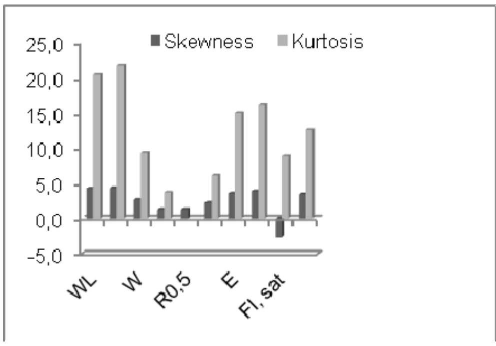
Results. These peculiarities indicate that there is subordination between subsidence properties degradation and changes in aggregate content: this confirms the A.K. Larionov's theory about consecutive destruction of rock's aggregate system and decrease in coagulation-dispersion type connections as a result of increase of water film thickness during subsiding.

Scientific innovation. Methods of inductive mathematical modeling applied to the description of change pattern in loess soils' exposed to technogenesis allows to objectively establish factorial variables whose changes affect the intensity of the process. Coordinates, soils' physical properties indicators were set as the factor variables. The evaluation of technogenic impact intensity is not performed, which greatly simplifies the solution.

Practical significance. Inductive Modeling will enable more accurate predictions of strain.

Presentation of the basic research results. Peculiarities of the loess soils' deformation and strength properties have been the subject of scientific research for a long time (Krokos V.I., Abelev Yu.M., Larionov A.K., Lysenko M.G.). The nature of subsidence as a physical-chemical process is explained from the view point of theories by Denisov N.Ya., Sergeev E.M. and Minervin A.V. Subsidence change patterns as a result of properties change in rocks exposed to technogenic factors are researched insufficiently and represent a current scientific problem. A lot of attention is drawn to the problems of subsidence properties degradation in soils massifs' exposed to technogenesis [1, 4, 5].

There is a shortage of works dedicated to the change patterns of loess-type and loess soils exposed to the simultaneous influence of high intensity transient physical fields, for instance, in cities. To study the real processes in subsiding soils' composition changes, conditions and properties under their exposure to complex factors' impact one needs to research longitudinal data series. Such sampling is time-consuming. In some cases it is very difficult to restore the data about technogenic impact intensity. Methods of permeability experimental modeling, consolidation in the process of argillaceous soils formation are in the stage of development [6]. Special attention is dedicated to the study of the relationship between the soils' structural-textural features and development of hazardous and unfavorable processes [7, 8]. The study of soils' deformational behavior as a result of microstructure peculiarities – is one of the trends which has been both traditional and fast growing in recent years [9, 10, 11]. Physical experimental modeling methods contribute to the solution of forecasting problems on condition that mechanical similarity criteria are strictly adhered to. Due to the development of the nonlinear dynamics methods, the theory of dynamic systems [12] and their application in tackling practical tasks in geology there is a need to change modeling methods used for engineering-geological processes forecasting.



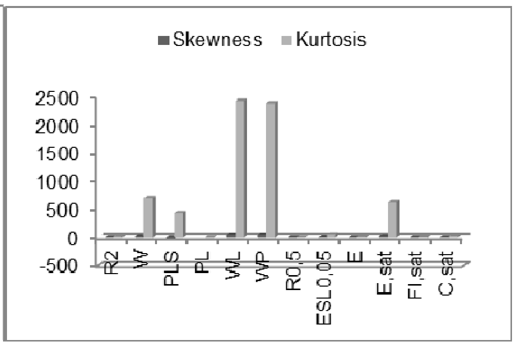


Figure 1. Skewness of average values (in a year) (a) and particular values of periglacial formation properties' indicators (b)

Methods of inductive mathematical modeling allow to solve a wider array of tasks in massif's condition evaluation. To characterize the periglacial formation properties, the total number of 3,104 monoliths was selected from the aeration zone. The foundation is comprised of the standard measurements of the properties' engineering-geological indicators – materials of State Enterprise "UkrGIINTIZ, OSC "DneproGiprotrans", "Ukrjuzhgeologija" that were included into the common database (1956-2007 years).Stochastic analysis of average values (by the measurement year) and particular values showed that data skewness and kurtosis in the second case is several time higher (Figure 1).

The rank correlation of year's average values showed that linear correlation with indicator's measurement year was discovered for fraction composition 0.25-0.1 mm (rank correlation coefficient r equals = 0.42); the negative correlation – for deformation module and specific cohesion (r =-0.57; -0.72 respectively). The correlation was not confirmed by regression. The particular values' rank correlation showed that indicators have a sense of the spatial variable, there is correlation of values with the sampling depth z.Thus, the rank correlation coefficient for soil density ρ with sampling depth z equals 0.57, natural humidity w 0.21 and deformation module E 0.61.

Positive correlation with sampling year t was discovered for the following indicators: content of particles bigger than 2 mm with natural humidity w. per unit, (r=0.288). Positive correlation with sampling year t was discovered for absolute deformation value in case of compression testing of naturally humid soil at the stage of normal compression 0.15 mPa (r=0.43), the internal friction angle Fi (r=0.66). Negative correlation with sampling year t was discovered for values distribution of specific cohesion c, mPa, (r=-0.697), deformation module E, mPa, (r=-0.25). Rank correlation values between the indicators are not high (Table 1).

Table 1

Correlation matrix for periglacial formation properties' indicators (particular values)

	WL	*WP*	*W*	*PLS*	*PL*	*R 0,1*	*DEF0,15*	*ESAT*	*FI*	*C*
WL	1.00	0.49	0.36	0.47	0.19	-0.14	0.10	-0.12	-0.40	0.48
WP		1.00	0.36	0.14	0.11	0.09	0.33		0.24	
W			1.00	0.18	0.53	0.26	0.38		-0.16	0.16
PLS				1.00	0.14	0.11	0.12	-0.12		
PL					1.00	0.16	-0.33	0.49		0.30
R0,1						1.00	0.32		0.62	-0.42
DEF0,15							1.00	-0.30	-0.22	-0.23
E, sat								1.00	0.29	0.32
FI									1.00	-0.64
C										1.00

Notes to Table. 1-5: 1. Only meaningful values of rank correlation coefficient are presented. 2. Empty cells mean the absence of meaningful values of rank correlation coefficient. 3. WL, wl, WP,wp – plasticity limits, per unit; W,w – natural humidity, per unit; ρs – soil particles' density, gr/cm3; PL, ρ- soli density, gr/cm3; R 0,1 – fraction particle content 0,25-0,1 мм; DEF0,15 – absolute deformation during naturally humid soil compression test at the level 0,15 mPa; E, sat – deformation module in water saturated condition, mPa; FI – internal friction angle, degree; C,c – specific cohesion, mPa. 4. Symmetrical matrix elements are not displayed.

Multiple regression of indicators properties' particular values in the inhomogeneous sample showed that correlation models are standard in the set of the dependent and independent variables irrespective of the multi – colinearity signs (Table 2).

The multiple regression analysis method requires adherence to strict conditions regarding the homogeneity of selective distribution; these conditions can not be fulfilled in this case. To find the optimal model of correlation between the indicators of subsidence, deformation and strength properties, group method of argument handling was used[4]. Standard, most often measured indicators were chosen as variables characterizing the inner properties of the formation. Testing numerous possible variants allowed us to define the optimal fraction of particle size content that determines the values of relative subsidence. On the compression level approximately equal to the common urban one, particle size content is not a factor for subsidence degradation due to the fact that fraction content is used as a nonlinear component in the model which does not include time as a factor variable.

In the compression interval 0.05–0.1 mPa, with the linear variable t the coefficient is high, the fraction interval for which the time changes act as the subsidence factor is bigger. Fraction content changes in time act as subsidence factor on the compression levels which correspond to extra load (0.3 mPa), for fraction content 0.5-0.25 mm. It is possible to find correlation between changes in certain fractions content, pressure and micro aggregates' size (Table 3).

Table 2

Regression model for particular values of loess formation (particular values)

The dependent variable	Regression Model	Model's parameter AR^2
PL	ρ=0,0008year+0,01z+0,0267w	0,992
WL	WL=0,103*ρ_s	0,97

Table 3

Coefficients for models' factor variables in loess type loams' subsidence

Compression mPa	Fraction, R, mm	Coefficients for variables' linear elements						
		Year, t	*WL,*	*WP*	*W*	*PLS*	*PL*	*R*
	0.25-0.1		0.0015	+				+
	0.05-0.01	0.0011				+	0.0017	
0.05	0.01-0.005	+	0.01		0.005	+	+	
	1.0-0.5				+	+		0.107
	0.5-0.25		+	256.42	91.836	0.005	1.173	1.807
	0.25-0.1	+	+			0.0055	-0.048	-0.028
	0.1-0.05	0.867	24.604	+	0.135	0.0317	-0.016	0.986
0.1	0.05-0.01	+		-0.053		+	0.0025	+
	1.0-0.5			+	0.177	+	0.001	0.0057
	0.5-0.25	+		0.07	-0.831	0.004	+	0.002
0.3	0.25-0.1		0.03	0.006	0.378		0.006	

Notes to Table 3-6: (+) – the variable is included as a factor one, as non-linear element: an empty cell means that variable is not included as a factor one. R – content of a fraction in the range 0.25-0.1; 0.1-0.05; 0.05-0.01; 0.01-0.005 mm

Results analysis shows: the higher the compression, the bigger is the aggregates' size whose changes in time act as a factor in subsidence properties' degradation. Linear relation between functional and factor variables is due to the controlling impact of the destruction process. In the loads' interval 0.05-0.1 MPa which are nearly equal to structural strength, accumulation takes place – slight increase in fraction content 0.25-0.1 mm, because the increase signs of relative subsidence (in the process of degradation) and fraction content are not identical. The reason for that is the destruction of big aggregates sized 0.5-0.25 mm and of the fraction sized 0.1-0.05 mm, this is indicated by the sign "+" or " –" in front of the coefficient. At the compression level of 0.3 MPa takes place the destruction of sand aggregates sized 0.5-0.25 mm. Coefficient analysis at linear factor variable "fraction content" indicates, that linear relation between relative subsidence coefficient and fraction content predominates at compression level 0.05–0.1 MPa. This level is nearly equal to structural strength limit. With linear variables at other compression levels coefficients are lower or non-existent. Linear relation between fraction content and subsidence degradation appears in the dispersion range from 1 to 0.05 mm, which corresponds to the sizes of macro- and microaggregates in loesses [2, p. 146]. Non-linear relation of increase appears in fraction 0.05-0.01 mm and subsidence degradation. These peculiarities indicate hat there is subordination between subsidence properties degradation and changes in aggregate content: this confirms the A.K. Larionov's theory about consecutive destruction of rock's aggregate system and decrease in coagulation-dispersion type connections as a result of increase of water film thickness during subsiding [2, p. 225]. Fraction content 0.1-0.25 mm has the biggest impact on the values of plasticity's lower limit, natural humidity and density.

All the functional variables – deformation properties indicators have the spatial pattern (Table 4). Correlation between time and physical properties is more evident in the models created for the undisturbed condition.

Values of the internal friction angle increase in time, module's values – decrease. Increase in internal friction angle values and the deformation module with depth reflects the relationship between values in their natural condition and the changes due to technogenic impact.In some cases values' decrease (increase) in time does not negate relationship with the sampling depth; this affects the results of the regressive analysis: models for properties regression and the coordinate have not been received. Deformation and strength properties' change in time are connected with changes of medium's dispersion, they reflect degradation's direction and intensity.

Table 4

Coefficients at linear elements of models' factor variables for the physical-mechanical indicators of loess loams' properties

Variable	Factor variable (upper line) and their values (lower line)						
	z	*t*	*WL*	*WP*	*W*	*PLS*	*PL*
E	0.863	-0.543	0.226	-12.05	11.577	-0.832	-
	t	*z*	*WL*	*WP*	*W*	*PLS*	*PL*
Fi	-	0.781	-7.316	-	56.953	0.101	14.639
	z	*t*	*year*	*WL*	*WP*	*W*	*PLS*
E, sat	0.705	+	0.001	-	0.358	4.654	-0.035

Notes to table 4-6: (+) – the variable is a factor one, the relation is non-linear; (-) – the variable is not a factor one; 0.705 – coefficient of the linear polynomial element of *ai Xi* type, where *a* – is a coefficient at factor variable; *X* – factor variable, year – indicator's measurement year

Table 5

Coefficients at linear factor variables in models of paleosoil horizons' relative subsidence

Compression MPa	Fraction R	Coefficients at linear factor variables t. year						
	R	t. year	z	WL	W	PLS	PL	R
0.05	0.01-0.005		+	0.069			0.006	+
	менее 0.005		+	-0.119		+	-0.004	+
0.1	1-0.5	+	+		0.13	0.0016	0.0018	
	0.5-0.25	+	+		0.13	0.0016	0.0018	
	0.25-0.1			+	+		-0.009	-0.011
	0.01-0.005			+	-0.018		+	0.001
	менее 0.005		0.217	0.289		+	0.055	-0.001
0.15	0.25-0.1				+	+	-0.106	
	0.1-0.05				+	+	-0.106	
0.2	0.01-0.005				-0.693	+	0.001	+
	менее 0.005				-0.693	+	0.001	+
0.3	0.5-0.25		+		17215	56.86	+	0.031
	Менее 0.005	0.071	+	+	+	0.069	0.0197	+

Table 6

Coefficients of linear factor variables in models of paleosoil horizons' physical-mechanical properties

Variable	Coordinates		Physical properties indicators				
	t	***z***	***WL***	***WP***	***W***	***PLS***	***PL***
C		-0.085	5.046	-1.063	-0.097	+	-0.398
C. sat				1.111	-1.694	-8.26	0.9
E	0.0048			24.528	-1.194	-0.192	1.676
E. sat	+	0.94		80.57	-26.71	0.104	
Fs. sat	+	+	-126.23	67.23	270.17	1.111	

Notes: Fs – internal friction angle, degree, complete water saturation condition

Result analysis of paleosoil horizons' changes study shows that soil density is a linear factor variable, while soil particles density is non-linear in the majority of models (Table 5). Linear relation between the sandy and silt fractions' content and subsidence degradation is discovered in the compression interval 0.05-0.1 MPa; this points out to the relationship change between the compressions' interval in which aggregates' destruction is a factor for subsidence degradation. Linear relation between clay fraction content changes in time appears only at the level of 0.3 mPa, in all other cases linear relation is poorly defined or absent. Subsidence models' spatial pattern is confirmed at the initial compression levels. In this model selection factions act as factor variables. Coefficient values are smaller than in loess-like loams' models. In paleosoil horizons microaggregate content changes are less defined than in loess-like loams.

Linear connections with measurement year are confirmed only for the deformation module values (Table 6), the tendency does not correspond to mechanical properties indicators' changes for subsiding loess-like loams. In the process of subsidence degradation in paleosoil horizons fine sand aggregates' and fine clay aggregates' accumulation is accompanied by a decrease in the fraction content 0.01- 0.005 mm.

Conclusions:

* For loess-like loams and paleosoil horizons the aggregate composition changes in the process of subsidence

degradation are characterized by different trends, which leads to the decrease in massif's anisotropy.

* Indicators of loess-like loams deformation properties do not lose the character of spatial variables. The internal friction angle values increase in time, while module values – decrease; but with depth – they increase.

* For loess-like loams, deformation and strength properties' changes in time are connected with the medium's dispersion changes which reflect direction and intensity of degradation.

* Result analysis of paleosoil horizons' changes study indicates that soil particles' density is present as non-linear factor variable in the majority of models.

* Compression intervals in which aggregates destruction is a subsidence degradation factor depends on the type of soil, because for loess-like loams and paleosoil horizons the difference in coefficients at linear factor variable "fraction content" is one order of magnitude or more. Microaggregate content changes in paleosoil horizons are less defined, than in loess-like loams.

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ОСОБЛИВОСТІ ДЕГРАДАЦІЇ ДЕФОРМАЦІЙНИХ ТА МІЦНІСНИХ ВЛАСТИВОСТЕЙ ЛЕСОВИДНИХ ГРУНТІВ НА ПРИКЛАДІ м. ДНІПРОПЕТРОВСЬКА

Наведено результати математичного моделювання деформаційних і міцнісних властивостей в процесі деградації з використанням методу групового обліку аргументів. Цей метод був застосований для опису мінливості властивостей геологічного середовища як елемента природно – техногенної системи регіонального рівня.

Мета дослідження: встановити особливості деградації масиву на прикладі тривалого дослідження даних про властивості перигляціальних ґрунтів з використанням методів стохастичного та індуктивного моделювання. Методи рішення і програмне забезпечення: стохастичне моделювання виконано методами кореляційно – регресійного множинного аналізу; індуктивне моделювання – методом групового урахування аргументів. Програмне забезпечення: STATIST (ДНУ ім. О. Гончара), STATISTICA (trial – версія), авторська програма (канд. фіз.-мат. наук, доцент ДНУ ім. О. Гончара Л.С. Коряшкіна). Результати підтверджують підпорядкованість деградації властивостей і змін агрегатного склад, що підтверджує теорію А.К. Ларіонова про послідовне руйнуванні агрегативної системи породи і зменшенні зв'язків коагуляційно – діспергаційного типу в результаті збільшення товщини водних плівок при осіданні [2, с. 225]. Наукова новизна. Методи індуктивного математичного моделювання застосовуються для опису зміни властивостей лесових ' ґрунтів , що піддаються техногенезу, дозволяє об'єктивно встановити факторіал змінних , зміна яких впливає на інтенсивність процесу. Координати, фізичні показники властивостей були обрані факторними змінними. Оцінка інтенсивності техногенного впливу не виконується, що значно спрощує вирішення. Практичне значення. Індуктивне моделювання дозволить виконувати більш точні прогнози деформації.

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ОСОБЕННОСТИ ДЕГРАДАЦИИ ДЕФОРМАЦИОННЫХ И ПРОЧНОСТНЫХ СВОЙСТВ ЛЕССОВИДНЫХ ГРУНТОВ НА ПРИМЕРЕ г. ДНЕПРОПЕТРОВСКА

Приведены результаты математического моделирования деформационных и прочностных свойств в процессе деградации с использованием группового метода учета аргументов. Этот метод был применен для описания изменчивости свойств геологической среды как элемента природно – техногенной системы регионального уровня.

Цель исследования: установить особенности деградации массива на примере длительного исследования данных о свойствах перигляциальных грунтов с использованием методов стохастического и индуктивного моделирования. Методы решения и программное обеспечение: стохастическое моделирование выполнено методами корреляционно-регрессионного множественного анализа; индуктивное моделирование – методом группового учета аргументов. Программное обеспечение: STATIST (ДНУ им. О. Гончара), STATISTICA (trial – версия), авторская программа (канд. физ.-мат. наук, доцент ДНУ им. О. Гончара, Л.С. Коряшкина). Результаты указывают на соподчиненность деградации просадочных свойств и изменений агрегатного состава, что подтверждает теорию А.К. Ларионова о последовательном разрушении агрегативной системы породы и уменьшении связей коагуляционно-диспергационного типа в результате увеличения толщины водных пленок при просадке [2, с. 225]. Научная новизна. Методы индуктивного математического моделирования применяются для описания изменения свойств лессовых 'грунтов, подвергающихся техногенезу, что позволяет объективно установить факторные переменные, изменение которых влияет на интенсивность процесса. Оценка интенсивности техногенного воздействия не выполняется, что значительно упрощает решение. Практическое значение: индуктивное моделирование позволит выполнять более точные прогнозы деформации просадки.

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POTABLE CENOMANIAN-CALLOVIAN GROUNDWATER COMPLEX CHEMICAL COMPOSITION CHANGES DYNAMICS IN KYIV AS A RESULT OF LONG-TERM EXPLOITATION

(Reviewed by the editorial board member M. Korjnev)

Purpose. Potable ground water chemical composition and quality class changes tendencies of Cenomanian-Callovian groundwater complex in Kyiv as a result of long-term exploitation were revealed. For this purpose mathematical-statistical methods and GIS-technologies were used.

Methodology. In the research systemic, mathematical-statistical, geoinformational approaches, typification method and descriptive procedure were used. For mathematical and statistical processing Microsoft Excel, Statistica, Attestat software packages were chosen; for cartographic schemes construction and for spatial analysis and modelling in GIS Corel Draw, MapInfo Professional and ArcView programs were used.

Findings. Kyiv potable ground water chemical composition and quality class changes investigation methodology on the basis of combined mathematical-statistical methods and geoinformatics technologies were developed. Non-parametric statistics method (Mann-Witney criterion), used for hydrogeochemistry data analysis, description and substantiation are given. Kyiv territory typification, based on geomorphology characteristic, was done; the most vulnerable to contamination city zones were defined.

Originality. For the first time general tendency of Cenomanian-Callovian groundwater complex deterioration was revealed in Kyiv; it was determined that city potable groundwater chemical composition basic components changes of observable groundwater complex have irregular space character and depend on exploitation intension and geo-hydrogeological and geomorphological territory district structure. Also for the first time Kyiv territory typification, based on Cenomanian-Callovian potable ground water chemical composition basic components and quality class changes, was implemented; deterioration tendencies were determined.

Practical value. Practical application of determined Cenomanian-Callovian complex potable ground water chemical composition and quality class changes tendencies in Kyiv will allow to prevent further ground water deterioration with the help of exploitation system optimization. Obtained results have the potential to become the basis for the potable ground water chemical composition monitoring system development in Kyiv; methodological approaches and techniques can be used for urbanized territories ground water study.

Introduction. Nowadays Kyiv population potable water supply is provided both at the expense of surface water (75,9 % of city supply general balance) and groundwater (24,1 %) [5]. Since surface waters are polluted and need considerable preliminary water preparation for potable quality assurance, strategically important potable water source is groundwater. From this point of view within the bounds of Kyiv important groundwater sourses are groundwater complex in sediments of the middle and the upper Jurassic Ivanytska formation and the lower and the upper Cretaceous Zagoryvska, Zhuravynska, Burimska formation (next – Cenomanian-Callovian groundwater complex) and aquifer in sediments of the middle Jurassic Bayos layer Orelska formation.

During long-term exploitation (more than 100 years), significant changes of active water exchange zone hydrodynamic conditions appeared. Also these changes are detected in the above mentioned groundwater complex and aquifer [2, 4]. This potentially should have an effect on groundwater chemical composition. However, modern water quality observation system is exceptionally factographic (MPC accordance periodical dotted control) and doesn't provide spatio-temporal estimation of groundwater chemical composition changes, the same way as deterioration forecasting.

In this connection the necessity of research to reveal potable Cenomanian-Callovian groundwater complex chemical composition and quality changes tendencies, based on modern native and european requirements, appeared.

Methodology. Systemic, mathematical-statistical, geoinformational approaches, typification method and descriptive procedure were used in research. For mathematical and statistical processing Microsoft Excel, Statistica, Attestat software packages were chosen; for cartographic schemes construction and for spatial analysis and modelling in GIS Corel Draw, MapInfo Professional and ArcView programs were used.

Accumulated during decades data about chemical composition of Cenomanian-Callovian groundwater complex are disordered on area and in time. For the purpose to generalizate this data in the view of spatio-temporal estimation of water quality changes, the author has created geoinformational database model with the help of MapInfo Professional software (scale 1:10000, projection GK, zone 6, Pulkovo 1942). The attributive table architecture, containing Cenomanian-Callovian groundwater complex chemical composition and bacteriological quality factors on separate wells, has been designed. The table contains both modern and archival data. Today geoinformational database model supports information on 298 wells.

Given data have been analyzed by using the demands of National Standard of Ukraine "Sources of centrical potable water-supply. Hygienic and ecological demands for water quality and withdrawal principles. ДСТУ 4808:2007" [6]. These demands are designed for the centrical potable water-supply sources and determine hygienic, ecological and technological requirements for new and present centrical water-supply sources.

It has been revealed that, during long-term exploitation, Cenomanian-Callovian groundwater complex quality has become worse in such factors as mineralization (has changed from 1 quality class to 3 class) and hardness (has changed from 3 quality class to 4 class).

For such groundwater chemical composition factors as mineralization, ammonium and oxidizability histograms have been constructed and verification of samples in accordance to normal (logarithmically normal) probability law has been done (Figure 1).

It has been revealed that different temporal samples obey different statistical laws (normal or logarithmically normal). In many cases is not possible to determine statistical law. Bimodal distribution existence for oxidizability gives the possibility to assume that this factor changes on area irregularly. At the next research stage for each factor verification of two different temporal samples (the end of the XIX – the beginning of the XX century and the beginning of the XXI century) accordance to the one universal set by means of Mann-Witney criterion has been done [1].

The following statistically significant results have been obtained. Longstanding monitoring data show that mineralization value (mean and median) in Cenomanian-

Callovian groundwater complex has practically not changed (mean 356,9 ppm and median 350 ppm at the beginning of the XXI century compared to mean 356,5 ppm and median 353,7 ppm at the end of the XIX – the beginning of the XX century). As for ammonium concentration in observable groundwater complex, its value has been stable till the 1990s, when ammonium mean value rose to 1,3 ppm and median value rose to 0,4 ppm. At the beginning of the XXI century ammonium concentration decreased to the end of the XIX century – the beginning of the XX century level. Oxidizability concentration rose in mean value in 1,38 ppm and in median value in 0,87 ppm at the groundwater complex intensive exploitation period (the 1960s-1980s). Though statistically in oxidizability today's Cenomanian-Callovian chemical composition does not differ from the end of the XIX – the beginning of the XX century, mean and median oxidizability values in the 2000s are higher than at the beginning of exploitation.

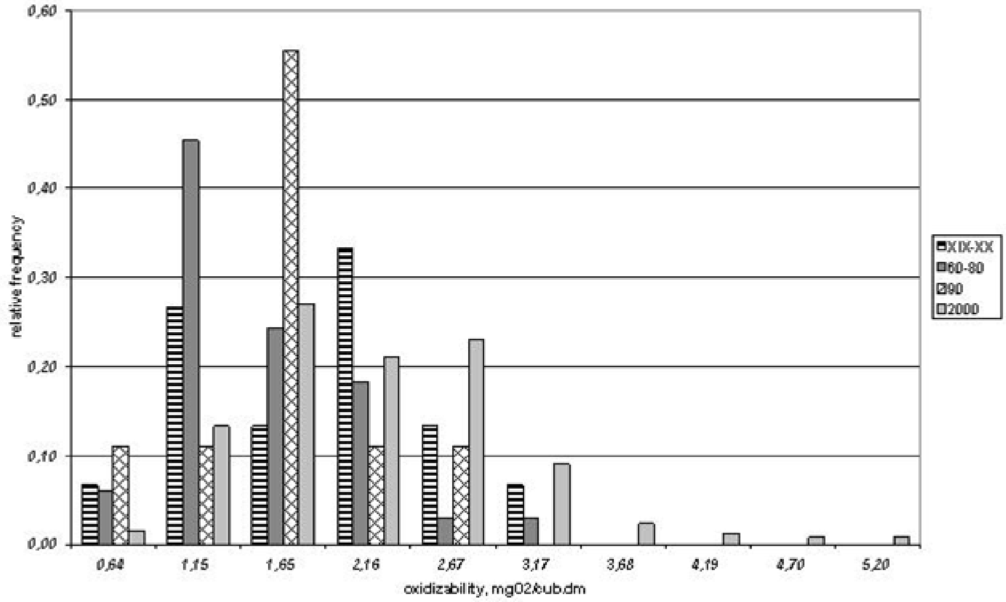

Figure 1. Oxidizability value histogram for period from the end of the XIX to the beginning of the XXI century

The author has suggested that irregularity of Cenomanian-Callovian groundwater complex chemical composition factors changes are stipulated by the territory geological-hydrogeological and geomorphological structure features and long-term groundwater complex exploitation. With the aim to check this suggestion the author has constructed five schematic geological-hydrogeological sections for the Kyiv territory districts, which geomorphologically differ from each other, on the basis of available printed and fund materials: Prydniprovska upland flat part, Prydniprovska upland loess residual outcrops, minor rivers valleys, the Dnipro river valley and the part of Prydniprovska lowland. The main aquifers and groundwater complexes hydrodynamic heads as of the middle of the XX century and of the beginning of the XXI century have been put on sections. Constructed sections testify that territory districts are characterized by difference in inter-relations of the main aquifers and groundwater complexes hydrodynamic heads. Therefore the conclusion was drawn about necessity of further research taking into account the above mentioned territory typification. For this purpose geoinformational database model in MapInfo Professional software has been amplified with respective layer which spatially reflects such typification (Figure 2).

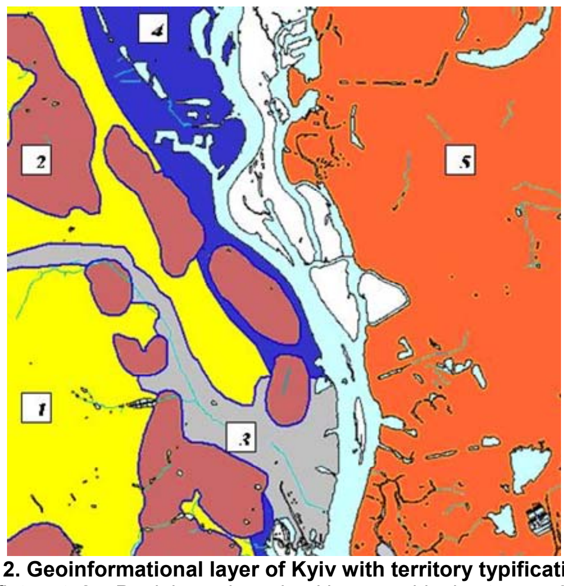

Figure 2. Geoinformational layer of Kyiv with territory typification:
1 – Prydniprovska upland flat part; 2 – Prydniprovska upland loess residual outcrops; 3 – minor rivers valleys; 4 – the Dnipro river valley; 5 – the part of Prydniprovska lowland

Groundwater chemical analyses results samples have been formed separately for each type with the aim of further mathematical-statistical treatment. By means of Statistica software using non-parametric Mann-Witney criterion verification of samples belonging to the one universal set has been done for four time periods: the end of the XIX – the beginning of the XX century, the 1960s-1980s, the 1990s, the beginning of the XXI century. Different temporal samples of selected factors have been compared both for each separate territory type and for different types [3].

It has been revealed that within the limits of Prydniprovska upland flat part and Prydniprovska upland loess residual outcrops, minor rivers valleys and the part of Prydniprovska lowland mineralization stays invariable during all the groundwater complex exploitation period. However within the limits of the Dnipro river valley mineralization has decreased since the 1990s and stays this way today.

Within the bounds of Prydniprovska upland loess residual outcrops and minor rivers valleys ammonium does not change. In Prydniprovska upland flat part and the Dnipro river valley ammonium concentration decreased in the 1960s-1980s. Next within the limits of the Dnipro river valley changes are not fixed, while in Prydniprovska upland flat part ammonium value increased in the 1990s; at the beginning of the XXI century ammonium decreased again.

Within the limits of Prydniprovska upland loess residual outcrops, the Dnipro river valley, minor rivers valleys oxidizability value increased at the groundwater complex intensive exploitation period (the 1960s-1980s) and stays this way today. However in Prydniprovska upland flat part oxidizability value remained stable before the beginning of the XXI century. Today oxidizability has decreased compared to the 1990s of the XX century.

During the research of groundwater complex chemical composition changes process between isolated territory types the following tendencies have been revealed:

1. The highest mineralization values at the end of the XIX century – the beginning of the XX century were within the limits of the Dnipro river valley (median 388,4 ppm). In mineralization the Dnipro river valley has exceeded Prydniprovska upland flat part (332 ppm), minor rivers valleys (348 ppm) and Prydniprovska upland loess residual outcrops (328 ppm). In the 1960s-1980s mineralization values in all five types became uniform and stay this way.

2. The highest oxidizability values at the end of the XIX century – the beginning of the XX century were within the limits of Prydniprovska upland loess residual outcrops (1,6 ppm) which exceeded Prydniprovska upland flat part (1,25 ppm) and minor rivers valleys (1,36 ppm). In the 1960s-1980s of the XX century oxidizability values increased in the Dnipro river valley and essentially exceeded Prydniprovska upland flat part and the part of Prydniprovska lowland. The highest oxidizability values at the beginning of the XXI century are in the part of Prydniprovska lowland (2,23 ppm) which exceed Prydniprovska upland flat part (1,84 ppm) and the Dnipro river valley (1,64 ppm).

3. At the end of the XIX century – the beginning of the XX century ammonium values were different in all the types: the lowest values were in Prydniprovska upland loess residual outcrops (0,28 ppm) and in minor rivers valleys (0,15 ppm). The highest ammonium values were in Prydniprovska upland flat part (0,36 ppm) and the Dnipro river valley (0,35 ppm). In the 1960s-1980s ammonium values in all five types became uniform and remained this way before the beginning of the XXI century. The highest ammonium values at the beginning of the XXI century are within the limits of minor rivers valleys (0,42 ppm) and in the Dnipro river valley (0,38 ppm), which exceed Prydniprovska upland flat part (0,14 ppm) and Prydniprovska upland loess residual outcrops (0,22 ppm).

Conclusions. It is possible to contend that the most vulnerable to groundwater chemical composition changes territory types are minor rivers valleys, the Dnipro river valley and the part of Prydniprovska lowland. These three types are characterized by increasing of mineralization, ammonium and oxidizability values in time. This phenomenon can be explained by the fact that the above mentioned types are geologically less protected from surface contamination. Moreover, these types are more influenced by surface water than other types. Cenomanian-Callovian groundwater complex chemical balance disturbance contemporizes with hydrodynamic conditions disturbance, determined by experts-hydrogeologists since the 1950s.

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ДИНАМІКА ЗМІН ХІМІЧНОГО СКЛАДУ ПИТНИХ ПІДЗЕМНИХ ВОД СЕНОМАН-КЕЛОВЕЙСЬКОГО ВОДОНОСНОГО КОМПЛЕКСУ НА ТЕРИТОРІЇ м. КИЄВА В УМОВАХ ТРИВАЛОЇ ЕКСПЛУАТАЦІЇ

***Мета.** Виявлення тенденцій змін хімічного складу та класу якості питних підземних вод сеноман-келовейського водоносного комплексу в межах м. Києва, викликаних тривалою експлуатацією, за допомогою математико-статистичних методів та ГІС-технологій.*

***Методика.** В роботі застосовані системний, математико-статистичний, геоінформаційний підходи до вивчення об'єкта, метод типізації та описовий метод. Для математичної і статистичної обробки були обрані пакети програм Microsoft Excel, Statistica, Attestat; для побудови картографічних схем, а також для просторового аналізу і моделювання в ГІС були застосовані програми Corel Draw, MapInfo Professional та ArcView.*

***Результати.** Розроблена методика дослідження змін хімічного складу та якості питних підземних вод м. Києва на базі спільного застосування методів математичної статистики та геоінформаційних технологій. Наведено опис та обґрунтування застосування методів непараметричної статистики (критерій Мана-Уітні), що був використаний для аналізу гідрохімічних даних. Виконана типізація території м. Києва та виділені найбільш вразливі до забруднення ділянки міста.*

***Наукова новизна.** Вперше виявлена загальна тенденція до погіршення класу якості води сеноман-келовейського водоносного комплексу в межах території м. Києва. Встановлено, що зміни основних компонентів хімічного складу питних підземних вод досліджуваного водоносного комплексу на території міста мають нерівномірний за площею характер і залежать від інтенсивності експлуатації та геолого-гідрогеологічної і геоморфологічної будови ділянки території. Також вперше була виконана типізація території м. Києва за змінами основних компонентів хімічного складу та класу якості питних підземних вод сеноман-келовейського водоносного комплексу і встановлені тенденції цих змін.*

***Практична значимість.** Практичне врахування встановлених тенденцій змін хімічного складу та класу якості питних підземних вод сеноман-келовейского водоносного комплексу в межах м. Києва дозволить запобігти подальшому погіршенню якості підземних вод шляхом оптимізації системи їх експлуатації. Отримані результати можуть слугувати основою для розробки системи моніторингу хімічного складу питних підземних вод у м. Києві, методичні підходи та прийоми можуть бути використані для вивчення підземних вод на інших урбанізованих територіях.*

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ДИНАМИКА ИЗМЕНЕНИЙ ХИМИЧЕСКОГО СОСТАВА ПИТЬЕВЫХ ПОДЗЕМНЫХ ВОД СЕНОМАН-КЕЛОВЕЙСКОГО ВОДОНОСНОГО КОМПЛЕКСА НА ТЕРРИТОРИИ г. КИЕВА В УСЛОВИЯХ ДЛИТЕЛЬНОЙ ЭКСПЛУАТАЦИИ

***Цель.** Выявление тенденций изменений химического состава и класса качества питьевых подземных вод сеноман-келловейского водоносного комплекса в пределах города Киева, вызванных длительной эксплуатацией, при помощи математико-статистических методов и ГИС-технологий.*

***Методика.** В работе использованы системный, математико-статистический, геоинформационный подходы к изучению объекта, метод типизации и описательный метод. Для математической и статистической обработки были выбраны пакеты программ Microsoft Excel, Statistica, Attestat; для построения картографических схем, а также для пространственного анализа и моделирования в ГИС были использованы программы Corel Draw, MapInfo Professional и ArcView.*

***Результаты.** Предлагается методика исследования изменений химического состава и качества питьевых подземных вод г. Киева на базе совместного применения методов математической статистики и геоинформационных технологий. Приведено описание и обоснование методов непараметрической статистики (критерий Манна-Уитни) и критерия Аббе, которые были использованы для анализа гидрохимических данных. Выполнена типизация территории г. Киева по геоморфологическому признаку и выделены наиболее уязвимые к загрязнению участки города.*

***Научная новизна.** Впервые выявлена общая тенденция к ухудшению класса качества воды сеноман-келловейского водоносного комплекса в пределах территории г. Киева и установлено, что изменения основных компонентов химического состава питьевых подземных вод исследуемого водоносного комплекса на территории города имеют неравномерный по площади характер и зависят от интенсивности эксплуатации, а также геолого-гидрогеологического и геоморфологического строения участка территории. Также впервые была выполнена типизация территории г. Киева по изменениям основных компонентов химического состава и класса качества питьевых подземных вод сеноман-келловейского водоносного комплекса и установлены тенденции этих изменений.*

***Практическая значимость.** Практический учет установленных тенденций изменений химического состава и класса качества питьевых подземных вод сеноман-келловейского водоносного комплекса в пределах г. Киева позволит предотвратить дальнейшее ухудшение качества подземных вод путем оптимизации системы их эксплуатации. Полученные результаты могут послужить основой для разработки системы мониторинга химического состава питьевых подземных вод в г. Киеве, методические подходы и приемы могут быть использованы для изучения подземных вод на урбанизированных территориях.*

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GROUNDWATER AND ITS SUSCEPTIBILITY TO CONTAMINATION IN KHERSON REGION

(Reviewed by the editorial board member O. Koshliakov)

Goal. The goal of the research is zoning of Kherson region on the basis of the upper Miocene water-bearing complex sensitivity to contamination caused by potentially dangerous types of economic activity.

Research methods. The methodical approach to determining the sensitivity of groundwater to contamination based on sensitivity index was proposed. For these purpose the index-rating, parametric methods, method of zoning and geoinformational (GIS) approach were used.

Research results. This study evaluated the sensitivity of the upper Miocene aquifer complex to contamination in Kherson region. The groundwater sensitive to pollution is mostly in the areas closest to the rivers (Dniper, Ingylets), where natural protection of groundwater is low, and in urban areas with a great number of anthropogenic objects.

Originality. For the first time, the quantitative criterion has been developed to assess anthropogenic load on the underground hydrosphere. Based on this criterion, a consistent approach to the assessment of groundwater vulnerability to pollution in the Kherson region was proposed. Such approach takes into account not only the static factors of groundwater protection, but also its dynamic component – anthropogenic loads, hydrogeodynamic conditions.

Practical application of the research. The potentially dangerous territories were allocated, in terms of pollution of the upper Miocene water-bearing complex – the main source of potable groundwater. This zoning is an important step in planning the location of monitoring, water supply wells and dangerous anthopogenic objects. The methodological approaches and techniques can be used to study groundwater in other areas.

Introduction. Groundwater is an important source of water to supply human needs. In the last few years, there has been a tendency for drinking groundwater quality to deteriorate, which resulted in increasing anthropogenic impact on the environment. The protection of groundwater quality from the impact of human activities is a high priority because:

- groundwater moves slowly through the ground and so the impact of human activities lasts for a relatively long time;
- groundwater may be difficult to clean up, even when the source of pollution is removed;
- groundwater provides baseflow to surface water systems and accordingly its quality influences the recreational value of surface water and its potential use for water supply purposes;
- unlike surface water where flow is in defined channels, groundwater is present everywhere.

The groundwater sensitivity to pollution schemes should be used by land-use planners and water resources managers for the most practical and effective means of protecting groundwater and preventing pollution. The scheme consists of two closely interlinked components: groundwater protection and potentially groundwater pollution activities.

This study presents the methodological approach to build digital map of groundwater sensitivity to pollution in Kherson region. This is because, Kherson region is one of the most problematic regions of Ukraine, from the point of view of the present state and maintains the trend of drinking groundwater quality deterioration.

Kherson region is located in the south of Ukraine, in the area of insufficient moisture. One of the major ecological problem of the region is the shortage of fresh groundwater. This problem reveals causal relationship between the irrigation practice, aquifer overexploitation and a complex of natural conditions.

The main source of drinking water is the upper Miocene (the main Neogene) water-bearing complex, widespread in Kherson region. Under the influence of natural and anthropogenic factors, the groundwater quality deteriorates over time. Thus, the regional process of increasing of the water salinity, total hardness, phenol and nitrate contamination and local pollution by Ba, Li, Se of groundwater were fixed in the years 2006-2009, during the testing of groundwater withdrawals [2].

The study has produced a map of sensitivity to pollution of the upper Miocene aquifer complex in Kherson region which will be useful to policy makers for scheduling of dangerous anthropogenic objects and new water supply wells in order to maintain the quality of drinking groundwater. It is for these reasons that the study has derived its relevance.

Methodology. Index-rating, parametric methods, method of zoning and geoinformational (GIS) approach were used in research. Schematically, the algorithm of mapping of sensitivity groundwater to pollution is illustrated in Figure 1.

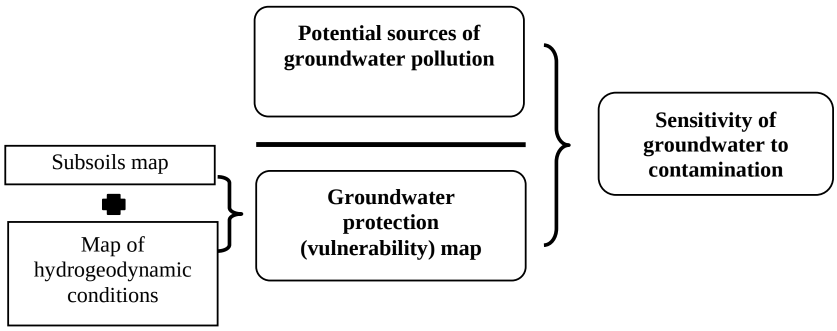

Figure 1. Conceptual framework for production a map of sensitivity groundwater to contamination

The first stage of the work is the creation of information layers maps, accompanied by attribute tables (database). The ArcView GIS package was used to digitize a groundwater protection map and other relevant themes of the study area. The following information layers were created:

1. Local potential sources of groundwater pollution (field of filtration, gas stations, sedimentation tanks, cattle

cemetery, farm, storage of fertilizers, pesticides, toxic chemicals, waste dump);

2. Natural protection map of the upper Miocene aquifer complex;

3. Hydrodynamic conditions map, with different hydrodynamic ratio of the first surface aquifer and the upper Miocene aquifer complex.

The input data for informational layers were collected from the published map – "Level of changes in forming of the main upper Miocene aquifers zoning map", scale 1:200 000 (A. Luschyk, 2010) [2].

At the second stage of the work, the index-rating method was applied. For each object in the database a quantitative assessment has been given in terms of its impact on groundwater. The degree of possible impacts of anthropogenic objects on the groundwater in these natural and man-made conditions was estimated by the hazard index – the ratio of the amount of experimentally detected toxic elements in groundwater to their theoretical predictions (by A. Luschyk, [2]). Hazard index values vary in the range of 0 to 1, respectively, anthropogenic objects, with a value of hazard index which equals one, have had the greatest negative impact on groundwater (waste dump, storage of liquid waste).

The degree of natural protection of the upper Miocene aquifer complex was estimated by the methodological approach developed by VSEGINGEO. Thus, the natural protection of groundwater depends on geological factors – composition and thickness of subsoils. In other words, the subsoils (sands, gravels, glacial tills (or boulder clays), peat, lake and alluvial silts and clays), are the single most important natural feature influencing groundwater vulnerability and groundwater contamination prevention. Groundwater is mostly at risk where the subsoils are absent or thin and, in the areas of karstic limestone, where surface streams sink underground at swallow holes. Three groundwater natural protection categories are used in the map – protected, conditionally protected and unprotected. All polygons with different degrees of natural protection of groundwater were estimated by respective points – 3 points (protected area), 2 points (conditionally protected), 1 points (unprotected). Geological factors that determine the natural protection of groundwater are constant over time.

The protection of groundwater depends on hydrogeological condition too, in particular on hydrogeodynamics of the adjacent aquifers. Hydrogeodynamics conditions determine the velocity and the direction of seepage of infiltrated water (and contaminants). But this is a variable factor of the groundwater protection. In this research the present state of the hydrogeodynamic conditions of the upper Miocene aquifer complex were analyzed. Polygons with different degrees of hydrogeodynamic conditions of the upper Miocene aquifer complex were estimated by points too – 3 points (protected area), 2 points (conditionally protected), 1 points (unprotected). The upper Miocene aquifer complex is protected in areas where the level of the surficial aquifer is located below the level of the upper Miocene. Thus, the contaminated water of the surficial aquifer can't seep into the deeper aquifers. The conditionally protected areas are where the level of the surficial aquifer is located above the level of the upper Miocene aquifer complex on 0-10 m. The unprotected areas are where the level of the surficial aquifer is located more than 10 m above the level of the upper Miocene aquifer complex. Namely, under such pressure differences the water seepage through the clay strata begins.

The parametric method was used at the third stage of research. To characterize the interaction between the groundwater and the environment pollution the sensitivity index was used, proposed by V. Goldberg in 1987 and modified by the author. According to V. Goldberg, the sensitivity index (P) is the ratio of anthropogenic load module (m) to the protection of groundwater index (S), expressed in points. Thus, the sensitivity of groundwater to contamination is directly proportional to anthropogenic impact on the underground hydrosphere and inversely proportional to the protection of groundwater [1]. Special quantitative criterion (total hazard index) was proposed by the author, to identify the anthropogenic load on the underground hydrosphere [3]. Based on total hazard index the sensitivity index was calculated according to the following equation:

$$P = \frac{\sum K_h / F}{\left(S_n + S_g\right)}, \qquad (1)$$

were P – sensitivity index; $\sum K_h$ – total hazard index (sum of hazard indexes of each local potential source of groundwater pollution, located on the unit area); F – area, km^2; S_n – natural protection of groundwater, in points; S_g – protection of groundwater that depends on hydrogeodynamic conditions, in points. For areas with similar conditions of protection of the upper Miocene aquifer complex the sensitivity index was calculated.

At the last stage of the work, the map of sensitivity of the upper Miocene aquifer complex to contamination was prepared (Figure 2) using the sensitivity index.

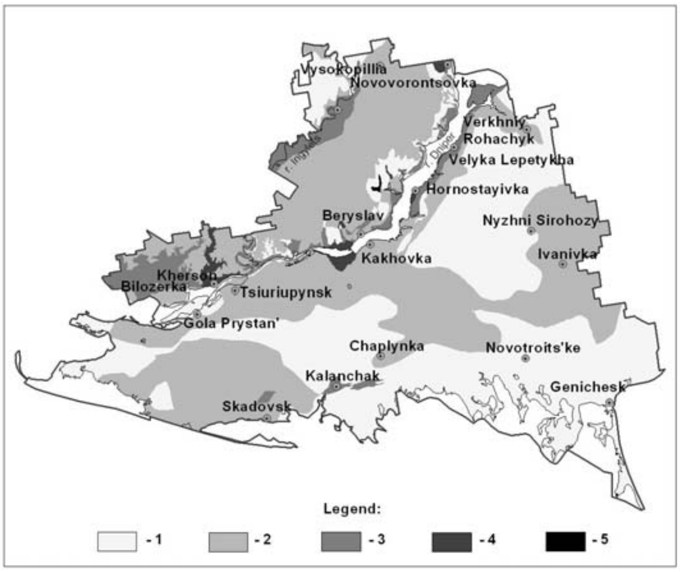

Figure 2. Scheme of sensitivity of the upper Miocene aquifer complex to contamination in Kherson region:
1 – P=0; 2 – P=0-0,01; 3 – P=0,01-0,03; 4 – P=0,03-0,08; 5 – P=0,08-0,12

The impact of anthropogenic objects on the groundwater and the other themes within the protection of groundwater were assessed using GIS overlay manipulations. As a result, five classes of groundwater sensitivity to pollution were identified in Kherson region. The method of the natural breakdown in ArcView GIS was used to separate the classes. These classes are as follows:

1. Areas marked as not susceptible to pollution (P=0);
2. Areas marked as badly susceptible to pollution (P=0-0,01);
3. Areas marked as potentially susceptible to pollution (P=0,01-0,03);
4. Areas marked as susceptible to pollution (P=0,03-0,08);
5. Areas marked as highly susceptible to pollution (P=0,08-0,12).

As presented in Figure 2, there are variations in the degree of groundwater sensitivity to pollution in Kherson region. Significant part of Kherson region has had a low degree of sensitivity of the upper Miocene aquifer complex to contamination (1, 2 classes). The groundwater sensitive to pollution is mostly in the areas closest to the rivers (Dniper, Ingylets), where natural protection of groundwater is low, and in urban areas with a great number of anthropogenic objects.

Conclusions. In this research, an algorithm for estimation sensitivity of groundwater to contamination without additional field work was proposed. Such an approach takes into account not only the static factors of groundwater protection, but also its dynamic component – anthropogenic loads, hydrogeodynamic conditions. This study emphasises the importance of a GIS database in tackling groundwater vulnerability related problems.

The scheme of sensitivity of the upper Miocene aquifer complex to contamination in Kherson region can be applied to groundwater conditions management as part of groundwater monitoring procedure, for the planning authorities to carry out their functions, and a framework to assist in decision-making on the location, nature and control of development and activities in order to protect groundwater.

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ПІДЗЕМНІ ВОДИ ТА ЇХ ЧУТЛИВІСТЬ ДО ЗАБРУДНЕННЯ У ХЕРСОНСЬКІЙ ОБЛАСТІ

Мета. Метою дослідження є районування території Херсонської області за рівнем чутливості підземних вод верхньоміоценового водоносного комплексу до забруднення, спричиненого потенційно небезпечними для підземних вод видами господарської діяльності.

Методи дослідження. Запропоновано методичний підхід до визначення рівня чутливості підземних вод до забруднення, на основі кількісного критерію – індексу чутливості. В роботі застосовувались індексно-рейтингові, параметричні, методи районування та геоінформаційний підхід.

Результати дослідження. Визначено рівень чутливості підземних вод верхньоміоценового водоносного комплексу до забруднення на території Херсонської області. Так, найбільш уразливими до забруднення є території поблизу річкових долин (Дніпро, Інгулець), де низька природна захищеність водоносного горизонту та в районах міської забудови, де розміщується велика кількість техногенних об'єктів.

Наукова новизна. Вперше запропоновано кількісний критерій для оцінки антропогенного навантаження на підземну гідросферу. На основі такого критерію, розроблено методичний підхід до оцінки чутливості підземних вод до забруднення для території Херсонській області. В даному підході враховані не лише статичні фактори захищеності підземних вод, але й її динамічна складова – антропогенне навантаження, гідрогеодинамічні умови.

Практична значимість. Виділено потенційно небезпечні території з точки зору забруднення верхньоміоценового водоносного комплексу – основного джерела питних підземних вод. Таке районування території є важливим етапом при плануванні розміщення моніторингових, водозабірних свердловин, небезпечних техногенних об'єктів. Запропоновані методичні підходи та прийоми можуть бути використані для вивчення підземних вод на інших територіях.

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ПОДЗЕМНЫЕ ВОДЫ И ИХ ЧУВСТВИТЕЛЬНОСТЬ К ЗАГРЯЗНЕНИЮ В ХЕРСОНСКОЙ ОБЛАСТИ

Цель. Целью исследования является районирование территории Херсонской области по уровню чувствительности подземных вод верхньомиоценового водоносного комплекса к загрязнению, вызванного потенциально опасными для подземных вод видами хозяйственной деятельности.

Методы исследования. Предложен методический подход к определению уровня чувствительности подземных вод к загрязнению, на основе количественного критерия – индекса чувствительности. В работе применялись индексно-рейтинговые, параметрические, методы районирования и геоинформационный подход.

Результаты исследования. Определен уровень чувствительности подземных вод верхньомиоценового водоносного комплекса к загрязнению на территории Херсонской области. Так, наиболее уязвимыми к загрязнению являются территории вблизи речных долин (Днепр, Ингулец), где низкая естественная защищенность водоносного горизонта и в районах городской застройки, где сосредоточено большое количество техногенных объектов.

Научная новизна. Впервые предложен количественный критерий для оценки антропогенной нагрузки на подземную гидросферу. На основе такого критерия, разработан методический подход к оценке чувствительности подземных вод к загрязнению для территории Херсонской области. В данном подходе учтены не только статические факторы защищенности подземных вод, но и ее динамическая составляющая – антропогенная нагрузка, гидрогеодинамические условия.

Практическая значимость. Выделены потенциально опасные территории с точки зрения загрязнения верхньомиоценового водоносного комплекса – основного источника питьевых подземных вод. Такое районирование территории является важным этапом при планировании размещения мониторинговых, водозаборных скважин, опасных техногенных объектов. Предложенные методические подходы и приемы могут быть использованы для изучения подземных вод и на других территориях.

GEOLOGICAL INFORMATICS

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MODELLING SOIL WATER REPELLENCY IN AN ABANDONED AGRICULTURAL FIELD

(Reviewed by the editorial board member O. Menshov)

Soil Water Repellency (SWR) is a natural property of soils with impacts on soil erosion, water infiltration, superficial and subsurface hydrology, nutrients leaching and plant growth.

Purpose: Study the spatial distribution and identify the most accurate interpolation method to estimate SWR in an abandoned agricultural field.

Methodology: A plot with 21 m^2 (07x03 m) was designed. Inside this plot SWR was measured in the field every 50 cm. In order to identify the most reliable map, we tested several interpolation methods, as Ordinary Kriging (KRG), Inverse Distance to a Weight (IDW) with the power of 1, 2, 3, 4 and 5, Radial Basis Function (RBF) (Inverse, Multiquadratic, Multilog, Multiquadratic, Natural Cubic Spline and Thin Plate, Spline) and, Local Polynomial, with the power of 1 and 2.

Findings: The results show that SWR was very heterogeneous, even in small distances, showing that soil hydrological properties can change very quickly in space. The spherical model was the best predictor of SWR and the most accurate interpolation method was the Multilog and the more biased the Natural Cubic Spline.

Originality: The test of several interpolation methods in SWR spatial distribution were not explored in detail, and this study represents an advance in this field.

Practical value: A better interpolation of SWR and other variables will help to have a better understanding of small scale processes in larger areas. Mapping with a better accuracy will improve models and contribute to a better prediction.

Introduction

Soil water hydrophobicity (SWR) is a natural property of soils. Among other factors, SWR depends on soil moisture, mineralogy, texture, pH, organic matter, aggregate stability, fungal and microbiological activity and plant cover. It has implications for plant growth, soil water infiltration, superficial and subsurface hydrology, soil erosion and nutrients leaching [5]. Depending on the level, SWR can also have positive impacts on soil structure and aggregate stability, carbon sequestration and protects soil from crusting [17, 1, 11].

Soil water repellency has been widely studied around the world in the most diverse climate regions [13] and environments, including forests [7, 14] grasslands, pastures [20], heathlands [35], steppes [8], sand dunes [5], golf fields [22], fire affected areas [4, 17, 21, 27] and agriculture fields [30, 32, 11, 10]. Previous studies showed that soil management in agricultural areas have important implications concerning the persistence, intensity and spatial distribution of SWR. Blanco-Canqui and Lal [2] and Roper et al. [31] observed that no-tillage soils have a higher SWR than tilled soils. The authors attributed this to the presence of soil organic matter that normally increases SWR [35].

Soil water repellency is highly variable in space and time [11, 29], even in small distances [16], imposing a challenge in mapping this small distance variation. Small scale variation modelling is important to understand large scale processes [3, 24]. Mapping small scale variations is complex due to the heterogeneous data distribution, and normally it is recommended to test several interpolation methods in order to know the less biased spatial predictor [26]. The objective of this work is testing the best interpolation method to estimate SWR in an abandoned agricultural field.

Materials and Methods

The studied area is located in an abandoned agricultural field located near Vilnius city (54 49' N, 25 22', 104 masl), Lithuania. The mean annual rainfall is 735 mm and temperature is 8.8°C. In a flat area an experimental plot with 21 m^2 (07x03 m) was designed and SWR repelency was assessed. Inside this plot, we measured SWR in the field every 50 cm, collecting a total of 105 sample points. Measurements were carried out on 28 May, 2012, after a period of 15 days without rainfall. Soil water repellency was assessed placing 5 droplets (±0.05 ml) in soil surface and measuring the water drop penetration time (WDPT) in seconds (s) [33].

Some statistical analyses were carried out: Mean (m), Standard Deviation (SD), Coefficient of Variation (CV%) Minimum (Min), 1st quantile (Q1), median (M), 3rd quantile, Maximum (Max), Skewness (SK) and Kurtosis. The spatial autocorrelation of SWR was assessed with the Moran's *I* Index, a measure similar to Pearson correlation coefficient. A value near 0 represents a random pattern, +1 a strong positive autocorrelation (clustered) and -1 a strong negative autocorrelation (dispersion) [23].

Previous to data modelling, normal distribution was tested with the Kolmogorov-Smirnov (K-S). Data normal distribution was considered at a p>0.05. This method, SK and Kur evaluate the data distribution and asymmetry that affect the interpolation methods accuracy. Previous studies show that it is desirable that data be as close as possible to normal distribution. If data is highly skewed, it may have negative impacts on the variogram modelling and interpretation [19, 23]. In this study we used the transformations, currently used in previous studies, Neperian logarithm (ln), Square root (SQR) and Box-Cox (BC), which were not powerful enough to normalize data distribution [23. 24].

The spatial patterns of SWR were analysed with an experimental omnidirectional variogram (it is assumed that SWR variability is equal in all directions) that observes the spatial continuity of SWR. The nugget effect, range, sill and nugget/sill ratio were measured. For the interested readers, details of variogram modelling can be consulted in Fu et al. [9] and Pereira et al. [24] [23]. Data interpolation tests were carried out using the most common methods, such as Ordinary Kriging (KRG), Inverse Distance to a Weight (IDW) with the power of 1, 2, 3, 4 and 5, Radial Basis Function (RBF) (Inverse, Multiquadratic, Multilog, Multiquadratic, Natural Cubic Spline and Thin Plate, Spline) and, Local Polynomial, with the power of 1 and 2. For detailed information about these methods Pereira and Ubeda [25] can be consulted. The best interpolation method was assessed with the cross validation method that compares the observed and estimated values of SWR. The cross validation was obtained by taking the value of a determinate sample point and estimating it from the remaining ones. The residuals produced were used to evaluate the accuracy of each method. The Mean Error (ME) and the Root Square Mean Error (RMSE), calculated from the residuals, were used to assess interpolation methods performance. The method with the lower RMSE was considered the best estimator. More information about these indices can be found in Pereira and Ubeda [25]. Pearson correlation coefficient was calculated between the observed and estimated values. Significant differences were considered at a p<0.05. Statistical analyses were carried out with Statistica 7.0 and interpolation methods assessment with Surfer 9.0 for windows.

Results and Discussion

Soil water repellency varied from 1 to 772 s, and had an average of 25.73. The CV% was 361.09%, showing that in this small plot SWR was extremely high variable. The results of SK show that the majority of the values were concentrated in lower values of the distribution (Positive SK) that is evidence of the presence of extreme positive outliers. Data also showed an extremely high KUR, which means that data have a peaked distribution (Table 1). The result of the Moran's *I* index was 0.026, p<0.513, suggesting that the distribution of SWR was random and no specific pattern was observed. According to the results of the K-S test, the original and transformed distributions were considered not normally distributed (p<0.05). To model the spatial distribution of SWR, we used the Ln transformed data since they were closer to normal distribution and presented the lower SK and KUR values (Table 1). This criterion was used in previous works [14, 36, 34, 23]. In this case we did not remove the outliers because it would mean loss of important information.

Table 1

Descriptive statistics of SWR and results of K-S test. Original data in seconds (s)

	m	SD	CV%	Min	Q1	M	Q3	Max	SK	KUR	K-S *p*
Original data	25.73	92.93	361.09	1	1.66	2.66	7	772	6.13	43.10	0.01
Ln	1.49	1.46	98.16	0	0.51	0.98	1.94	6.64	1.50	2.02	0.01
SQR	3.06	4.06	132.72	1	1.29	3.06	2.64	27.78	3.85	17.02	0.01
BC	4.95	3.51	71.06	2.48	3.03	4.95	5.09	22.48	2.77	8.69	0.01

Among all the tested models, the spherical was the best fitted to explain SWR spatial variability (Figure 1), as observed in previous studies [28]. The nugget effect was 1.2, the range 101 cm, the Sill, 2.22 and Nugget/Sill ratio 54.05%. The nugget effect is normally attributed to the small number of samples, small distance variance and presence of outliers [18]. In this case the nugget effect may be due to the small scale variance of SWR and to the presence of outliers, since the data that we used was not normally distributed. The spatial correlation of SWR increased with the distance until the distance of 101 cm. This suggests that spatial correlation range was higher than the sample density (50 cm), showing that the sample design was good to measure SWR variability. It is important to mention that the spatial correlation was short in the space, which confirms the random pattern identified with the Moran's *I* index. The nugget/sill ratio result suggested that the SWR has a moderate spatial dependency. According to Chien et al. (1997), ratios less than 25% show that the variable has a strong spatial dependence, between 25 and 75%, the variable has a moderate spatial dependence, and when higher than 75, the variable has a weak spatial dependence.

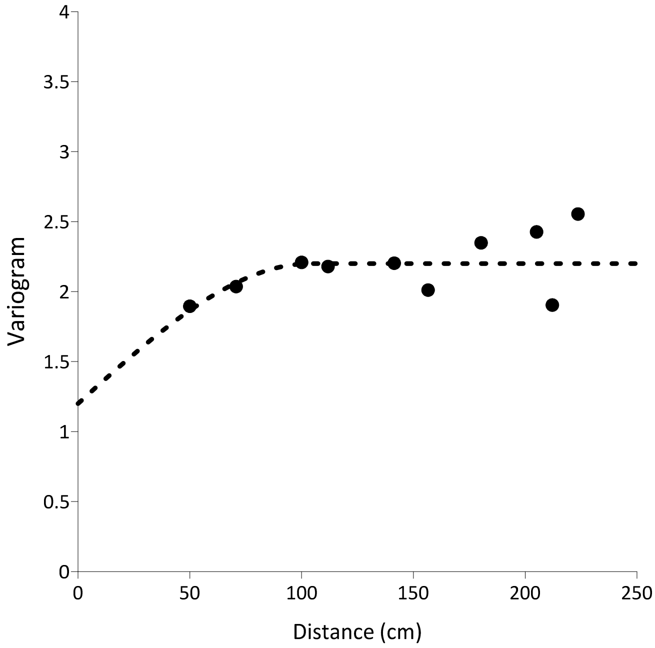

Figure 1. Omnidirectional Experimental Variogram calculated for SWR

The most accurate method to interpolate SWR was Multilog, with a RMSE of 1.353 and the less precise was Natural Cubic Spline with an RMSE of 1.686 (Table 2). The ME of all the interpolation methods were close to 0, showing that the predictions were unbiased. On average, LP 1 and 2 under-estimated the original values (negative ME). The coefficient of correlation between observed and estimated were significant in all the cases but was not strong. They range between 0.25 in IDW1 and 0.38 in Multilog (Table 2).

Table 2

Summary statistics of the accuracy of interpolation methods. Numbers in bold indicate the most accurate method and underlined, the least accurate. Correlations between observed and estimated values significant at **p<0.01 and ***p<0.001

	Type	Min	Max	ME	RMSE	Obs *vs* Est
KRG	Ordinary (Point)	-4.844	2.461	0.003	1.406	0.37***
IDW	Power (1)	-4.997	1.587	0.011	1.425	0.25**
	Power (2)	-4.702	1.733	0.013	1.377	0.32***
	Power (3)	-4.646	1.873	0.013	1.369	0.34***
	Power (4)	-4.726	2.060	0.012	1.378	0.35***
	Power (5)	-4.772	2.135	0.011	1.386	0.35***
RBF	Inverse multiquadratic	-4.685	1.871	0.001	1.379	0.37***
	Multilog	-4.798	2.188	0.003	1.353	0.38***
	Multiquadratic	-4.814	2.736	0.004	1.447	0.37***
	<u>Natural cubic spline</u>	<u>-4.558</u>	<u>4.612</u>	<u>0.013</u>	<u>1.686</u>	<u>0.36***</u>
	Thin Plate Spline	-4.738	3.754	0.007	1.552	0.36***
LP	1	-4.911	2.136	-0.026	1.392	0.28**
	2	-4.695	2.437	-0.016	1.382	0.32***

The interpolation methods tested allowed us to identify the best spatial predictor and the most precise SWR spatial distribution. The map interpolated with the best method showed that SWR was low in the northeast part of the plot, and high at northwest and in the south of the area of interest (Figure 2a). The interpolation with the less biased method showed that the distribution is more heterogeneous and no clear pattern was identified (Figure 2b). This suggests that previously to mapping any variables, it is essential to test several methods in order to have the best data interpolation, as observed in previous studies [24, 23]. The maps of the residuals produced are in the figures 2c and 2d. The interpolated map with the most accurate method residuals showed that the major errors were identified in the areas where SWR was high. This correlates the observed with the results from the SK which suggest that data were mostly concentrated in the lower values (positive SK) and few samples had high values. The cross-validation procedure, estimated them substantially lower than the original ones. The errors were high and heterogeneous in the less accurate method than in the best one, suggesting that the Natural Cubic Spline interpolation has produced high positive and negative errors. In comparison to Multilog, the values predicted by Natural Cubic Spline were very distant from the original values.

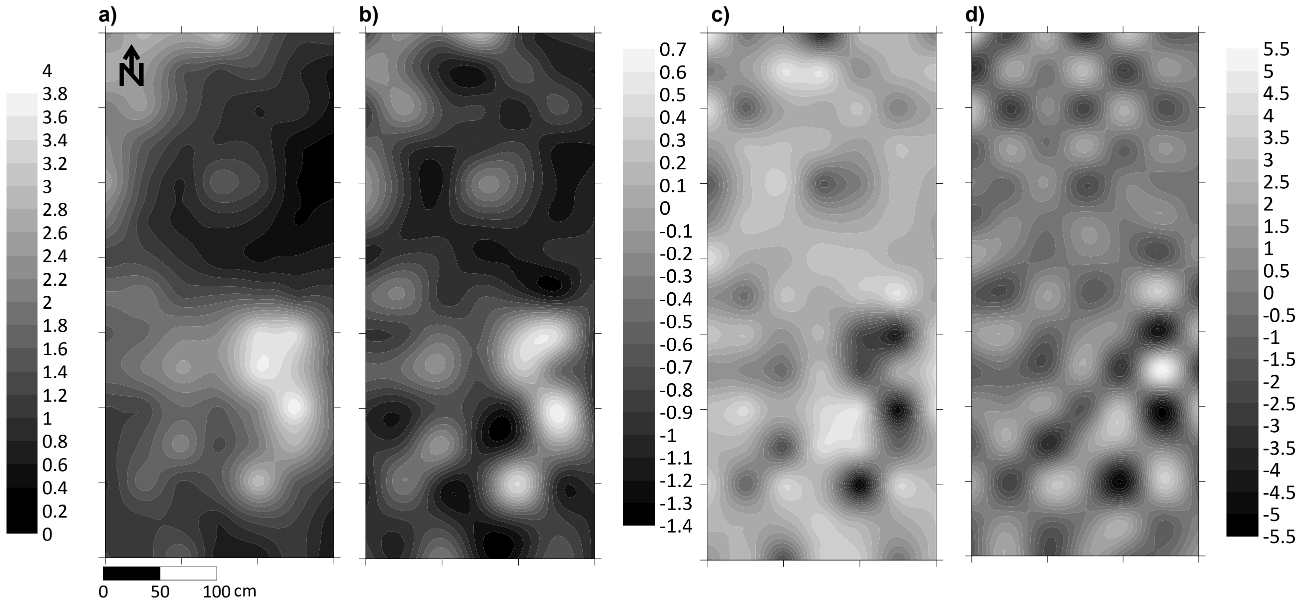

Figure 2. Soil water repellency interpolation according to the most a), less b) accurate method and the residuals obtaned from the best c) and worst d) interpolation technique

Conclusions

1. Soil water repellency was highly variable in the studied plot and had a random pattern distribution, suggesting that soil hydrological properties can be very heterogeneous at short distances.

2. The spherical was the best model to explain SWR variability. The SWR range was short, but the sample density was adequate to measure SWR spatial variability.

3. The best SWR interpolator was Multilog and the less accurate was Natural Cubic Spline. The lowest SWR was identified in the northeast and south of the plot, while highest values were observed in the south and northwest.

4. The interpolated maps with the most and least accurate method showed different spatial configurations, highlighting the need for testing several interpolation methods, previous to mapping any variables.

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МОДЕЛЮВАННЯ ГІДРОФОБНИХ ВЛАСТИВОСТЕЙ ГРУНТІВ В УМОВАХ НЕОБРОБЛЮВАНИХ СІЛЬСЬКОГОСПОДАРСЬКИХ УГІДЬ

Гідрофобність грунтів є природною властивістю, яка пов'язана з впливом ерозійних процесів, інфільтрації води, поверхневих і підземних гідрогеологічних процесів, поживних речовин, вилуговування і росту рослин.

Мета: Дослідження просторового розподілу і визначення найбільш точних методів інтерполяції для оцінки гідрофобності грунтів у межах необроблюваних сільськогосподарських угідь.

Методика: Було обрано ділянку площею 21 м^2 (7х3 м). Усередині цієї ділянки гідрофобність грунтів визначалася з кроком 50 см. З метою визначення найбільш надійної карти було протестовано кілька методів інтерполяції – звичайний крігінг, зворотня відстань до ваги з силою 1, 2, 3, 4 і 5, Радіальна базисна функція (Зворотня, мультиквадратична, мультилогарифмічна, натуральний кубічний сплайн і тонкої пластини, сплайн), Локальна поліномна з силою 1 і 2.

Результати: Отримані результати показують, що гідрофобність грунтів дуже неоднорідна, навіть на невеликих відстанях. Останнє свідчить, що гідрологічні властивості грунтів можуть змінюватися дуже швидко в просторі. Сферична модель стала найкращим передвісником гідрофобності грунтів. Крім того, найбільш точним методом інтерполяції виявлено Мультилогарифмічний метод, а найбільш обгрунтований метод кубічного сплайну.

Новизна: Дослідження декількох методів інтерполяції просторового розподілу гідрофобності грунтів не вивчалися раніше, а отже наведені матеріали несуть нову інформацію у даній сфері досліджень.

Практичне значення: Більш точна інтерполяція гідрофобності грунтів та інших показників допоможе глибше зрозуміти тонкі процеси у межах великих площ. Картування з вищою точністю поліпшить моделі та зробить вагомий внесок у прогнозування ерозії грунтів.

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МОДЕЛИРОВАНИЕ ГИДРОФОБНЫХ СВОЙСТВ ПОЧВ В УСЛОВИЯХ НЕОБРАБАТЫВАЕМЫХ СЕЛЬСКОХОЗЯЙСТВЕННЫХ ЗЕМЕЛЬ

Гидрофобность почв является естественным свойством, которое связано с влиянием эрозионных процессов, инфильтрации воды, поверхностных и подземных гидрогеологических процессов, питательных веществ, выщелачивание и роста растений.

Цель: Исследование пространственного распределения и определение наиболее точных методов интерполяции для оценки гидрофобности почв в пределах необрабатываемых сельскохозяйственных земель.

Методика: Был избран участок площадью 21 м^2 (7х3 м). Внутри этого участка гидрофобность почв определялась с шагом 50 см. С целью определения наиболее надежной карты были протестированы несколько методов интерполяции – обычный кригинг, обратнае расстояние к весу с силой 1, 2, 3, 4 и 5, Радиальная: базисная функция (Обратная, мультиквадратическая, мультилогарифмическая, натуральный кубический сплайн и тонкой пластины, сплайн), Локальный полином с силой 1 и 2.

Результаты: Полученные результаты показывают, что гидрофобность почв очень неоднородна, даже на небольших расстояниях. Последнее свидетельствует, что гидрологические свойства почвы могут меняться очень быстро в пространстве. Сферическая модель стала лучшим предвестником гидрофобности почв. Кроме того, наиболее точным методом интерполяции стал Мультилогарифмический метод, а наиболее обоснованный метод – кубического сплайна .

Новизна: Исследование нескольких методов интерполяции пространственного распределения гидрофобности почв изучалось ранее, а следовательно приведенные материалы несут новую информацию в данной сфере исследований.

Практическое значение: Более точная интерполяция гидрофобности почв и других показателей поможет глубже понять тонкие процессы в рамках больших площадей. Картирование с высокой точностью улучшит модели и сделает весомый вклад в прогнозирование эрозии почв.

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MODELLING OF STRESS-STRAIN STATE OF CRUSTAL SYSTEMS IN CONTEXT OF SPACE PROBLEM DURING THE GRANITE FORMATION

(Reviewed by the editorial board member V. Shevchuk)

The problem of granites holds a special place in geology. Research of the granite formation problem leads to a number of partial problems, among those the question of depth of the granite generation and mechanisms of provision of space for large granitoid solids are distinguished. In the problem of space the geomechanical constituent is of primary importance. The major factors forming the stress-strain state in the system of the granite formation are permanently acting mass gravitation forces, tectonic forces of inter-slabs interaction, pseudo-mass forces, forces of volumetric thermoelastic effects, phase transitions in processes of metamorphism, metasomatism, partial and complete fusion. In existing investigations of stress-strain state of crust systems the geological mediums are supposed to be quasi-homogeneous. The objective of this work is to develop the general approach to computer modeling of the behavior of geological and mechanical systems of mega-blocks range, in context of space problem during the granite formation, taking into account structure anisotropy of the system.

While the possibilities of full-size modeling of complex multifactorial magmatogene systems are limited, the possibilities of mathematical modeling are more appropriate, especially in view of the mechanical systems modeling. Verification of geological hypotheses and empirical data by constructing simple models with its further complication by means of transition to more and more complex combinations of force factors, rheological states, boundary conditions, and other factors is the most optimal. In the article the problem of stress-strain assessment of geological and mechanical system of mega-blocks range is analyzed. Assuming that the temperature of medium is known, there were obtained governing relations describing the behavior of geological and mechanical system at combined action of the gravity, non-homogeneous temperature field and power and kinematic influences imposed on the boundaries of considered system. The algorithm for solving of elastic problem is developed by means of the modified boundary element method.

The governing relations of the considered problem are obtained as well as the numerical and analytical algorithm of stress-strain assessment of the considered geological and mechanical system is developed.

Mathematical model and corresponding algorithm of the numerical calculation of stress-strain state of the considered system allow analyzing the stress-strain state of geological and mechanical system at combined action of gravity, non-homogeneous temperature field and imposed on the boundaries of considered system power and kinematic influences, taking into account structure anisotropy of the system.

Thus the method proposed herein allows investigating the nature of stresses fields, and hence to forecast geometry of potential zones of relative decompression and tension, which are the most auspicious for granite formation.

The problem of granites holds a special place in geology. From question of origin of rock of certain composition it transformed into complex problem wherein the petrological aspect is connected with structural and tectonic (dynamic and kinematic, geomechanical) and other aspects [1, 3].

Research of the granite formation problem leads to a number of partial problems, among those the question of depth of the granite formation and mechanisms of provision of space for large granitoid solids are distinguished. The question of space, occupied by the large granitoid rocks, in its turn, is connected with the tectonic position of granitoid complexes and geodynamic conditions of mass granite formation [5, 12].

In the problem of space the geomechanical constituent is of primary importance. Dimensional parameters of large granitoid solids, direct connection of the granite formation with orogeny of crystallization and deformation processes, as well as the character of structural anisotropy of granitoids indicate the complex hierarchical pattern of stress-strain state and the influence of many power factors of different origin on the cumulative stress-strain states.

Modeling of magmatogene processes and structures is a powerful tool of studies. While the possibilities of full-size modeling of complex multifactorial magmatogene systems are limited, the possibilities of mathematical modeling are more appropriate, especially in view of the mechanical systems modeling. The mathematical modeling techniques can be different, but the most optimal one is the verification of geological hypotheses and empirical data by constructing the simple models with its further complication by means of transition to more and more complicated combinations of force factors, rheological states, boundary conditions, from one-dimensional through two-dimensional toward three-dimensional etc.

The major factors causing the stress-strain state in the system of the granite formation are permanently acting mass gravitation forces, tectonic forces of inter-slabs (inter-blocks) interaction, pseudo-mass forces, forces of volumetric thermoelastic effects, phase transitions during metamorphism, metasomatism, partial and complete fusion.

Among the above mentioned factors that form the stress-strain state in the system of the granite formation, one of the most important is, undoubtfully, an anomalous heat-mass flux with key role of fluid-convective heat-mass transfer. It was ascertained that, first, fluid heat transfer provides relatively fast stabilization of heat anomalies in upper crust even without additional heat emission due to chemical transformations in fluid [4], and, second, progressive stage of development of heat anomalies is necessarily accompanied by forming of inversive stress fields (by redesignation of the principal normal stress axis) with subvertical orientation of minimal compression (expansion) axis facilitating the subvertical crust breaking within thermofluid anomaly and lifting of the daylight surface free from stresses [8, 9, 10, 11]. However, in this research of stress-strain state of crust systems there is generally accepted simplification that consists in assumption of structural isotropy of geological medium that is supposed to be quasi-homogeneous.

Let's consider more detailed physical model of geological and mechanical system of mega-blocks rank. While developing the model we rely upon models of mechanics of deformable bodies.

Let's consider the problem of determination of stress-strain state of such geological and mechanical system. Assume the medium temperature is the known function of the coordinates. Let's develop the governing relations those describe the behavior of geological and mechanical system at combined action of the gravity, non-homogeneous temperature field and power and kinematic influences imposed on the boundaries of considered system.

Let's consider the section of the depth rock mass, which elastic properties depends on temperature, that is supposed to be known function of coordinates (that can be described analytically or numerically in every point of the considered body). So, after solving the temperature problem we obtain the distribution of temperature in the considered body. Supposing that the small change of temperature induces the small changes of elastic properties of material, present the considered body as zonal-homogeneous matrix with multilayered inclusion, where the boundary of each layer is isotherm, and temperature in every point of this layer differs slightly from averaged value of temperature for this layer. Carrying out the averaging over all the points of the selected layer, we obtain averaged elastic parameters of layer – $\left\langle C^p_{ijkl}\right\rangle, \left\langle \beta^p_{ij}\right\rangle$, related to mean temperature of layer. Temperature is changed from layer to layer according to the law that is known from solution of the temperature problem, and elastic parameters of every layer are constant and equal to averaged values $\left\langle C^p_{ijkl}\right\rangle, \left\langle \beta^p_{ij}\right\rangle$. Then we can pose the elastic problem, where temperature as known function of coordinates is contained in equilibrium equations as volume forces and in boundary conditions on the edge of matrix and in the conditions of mechanical contact on the edge between adjacent layers of matrix. Duhamel-Neumann's relations

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} - \beta_{ij}T, \quad k,l,i,j = 1,2,$$

in case of orthotropic thermosensitive elastic material for the general plane stress state in Oxy plane have the following form:

$$\sigma_{11} = \frac{\left(s_{22}\varepsilon_{11} - s_{12}\varepsilon_{22}\right)}{\left(s_{11}s_{22} - s_{12}^2\right)} + \frac{\alpha_2 s_{12} - \alpha_1 s_{22}}{\left(s_{11}s_{22} - s_{12}^2\right)}T;$$

$$\sigma_{22} = \frac{\left(-s_{12}\varepsilon_{11} + s_{11}\varepsilon_{22}\right)}{\left(s_{11}s_{22} - s_{12}^2\right)} + \frac{\alpha_1 s_{12} - \alpha_2 s_{11}}{\left(s_{11}s_{22} - s_{12}^2\right)}T; \quad \sigma_{12} = \frac{2\varepsilon_{12}}{s_{66}}. \qquad (1),$$

where α_1 and α_2 – coefficients of linear expansion of orthotropic material.

Introduce the following denotations:

$$\sigma^e_{11} = \frac{\left(s_{22}\varepsilon_{11} - s_{12}\varepsilon_{22}\right)}{\left(s_{11}s_{22} - s_{12}^2\right)},$$

$$\sigma^e_{22} = \frac{\left(-s_{12}\varepsilon_{11} + s_{11}\varepsilon_{22}\right)}{\left(s_{11}s_{22} - s_{12}^2\right)}, \quad \sigma^T_{11} = \frac{\alpha_2 s_{12} - \alpha_1 s_{22}}{\left(s_{11}s_{22} - s_{12}^2\right)}T.$$

$$\sigma^e_{22} = \frac{\alpha_1 s_{12} - \alpha_2 s_{11}}{\left(s_{11}s_{22} - s_{12}^2\right)}T.$$

Then relations (1) can be represented as:

$$\sigma_{11} = \sigma^e_{11} + \sigma^T_{11}; \quad \sigma_{22} = \sigma^e_{22} + \sigma^T_{22}; \quad \sigma_{12} = \frac{2\varepsilon_{12}}{s_{66}}.$$

Elastic equilibrium equations can be reduced to the form:

$$\begin{cases} \dfrac{s^0_{22}}{s^0_{11}s^0_{22} - \left(s^0_{12}\right)^2}\dfrac{\partial^2 u_1}{\partial x_1^2} + \dfrac{1}{s^0_{66}}\dfrac{\partial^2 u_1}{\partial x_2^2} + \left(\dfrac{1}{s^0_{66}} - \dfrac{s^0_{12}}{s^0_{11}s^0_{22} - \left(s^0_{12}\right)^2}\right)\dfrac{\partial^2 u_2}{\partial x_1 \partial x_2} + X_1 + \dfrac{\partial T}{\partial x_1}\dfrac{\alpha_2 s^0_{12} - \alpha_1 s^0_{22}}{s^0_{11}s^0_{22} - \left(s^0_{12}\right)^2} = 0 \\ \dfrac{1}{s^0_{66}}\dfrac{\partial^2 u_2}{\partial x_1^2} + \dfrac{s^0_{11}}{s^0_{11}s^0_{22} - \left(s^0_{12}\right)^2}\dfrac{\partial^2 u_2}{\partial x_2^2} + \left(\dfrac{1}{s^0_{66}} - \dfrac{s^0_{12}}{s^0_{11}s^0_{22} - \left(s^0_{12}\right)^2}\right)\dfrac{\partial^2 u_1}{\partial x_1 \partial x_2} + X_2 + \dfrac{\partial T}{\partial x_2}\dfrac{\alpha_1 s^0_{12} - \alpha_2 s^0_{11}}{s^0_{11}s^0_{22} - \left(s^0_{12}\right)^2} = 0 \end{cases} \qquad (2)$$

for matrix and

$$\begin{cases} \dfrac{s^P_{22}}{s^P_{11}s^P_{22} - \left(s^P_{12}\right)^2}\dfrac{\partial^2 u_1}{\partial x_1^2} + \dfrac{1}{s^P_{66}}\dfrac{\partial^2 u_1}{\partial x_2^2} + \left(\dfrac{1}{s^P_{66}} - \dfrac{s^P_{12}}{s^P_{11}s^P_{22} - \left(s^P_{12}\right)^2}\right)\dfrac{\partial^2 u_2}{\partial x_1 \partial x_2} + X_1 + X_1^T = 0 \\ \dfrac{1}{s^P_{66}}\dfrac{\partial^2 u_2}{\partial x_1^2} + \dfrac{s^P_{11}}{s^P_{11}s^P_{22} - \left(s^P_{12}\right)^2}\dfrac{\partial^2 u_2}{\partial x_2^2} + \left(\dfrac{1}{s^P_{66}} - \dfrac{s^P_{12}}{s^P_{11}s^P_{22} - \left(s^P_{12}\right)^2}\right)\dfrac{\partial^2 u_1}{\partial x_1 \partial x_2} + X_2 + X_2^T = 0 \end{cases} \qquad (3)$$

for every inclusion.

Here $X_1^T = \frac{\partial T}{\partial x_1}\frac{\alpha_2 s_{12}^p - \alpha_1 s_{22}^p}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2}$ $X_2^T = \frac{\partial T}{\partial x_2}\frac{\alpha_1 s_{12}^p - \alpha_2 s_{11}^p}{s_{11}^P s_{22}^P - \left(s_{12}^P\right)^2}$, X_1 and X_2 are components of gravitation forces.

Boundary conditions on the edge of matrix can be written as follows:

$$\sigma_{ij}^0 n_j^0 |_{\Gamma_p^\sigma} = p_i, \; u_i^p |_{\Gamma_p^u} = \varphi_i, \; i,j=1,2, \; p=1,...,N,$$

where $\Gamma_p^\sigma \cup \Gamma_p^u = \Gamma_p$,

or via σ_{ij}^e:

$$\sigma_{11}^{e0} n_1^0 + \sigma_{12}^{e0} n_2^0 |_{\Gamma_0} = -\frac{\alpha_2 s_{12} - \alpha_1 s_{22}}{\left(s_{11}s_{22} - s_{12}^2\right)} T n_1^0,$$

$$\sigma_{11}^{e0} n_1^0 + \sigma_{12}^{e0} n_2^0 |_{\Gamma_0} = -\frac{\alpha_1 s_{12} - \alpha_2 s_{11}}{\left(s_{11}s_{22} - s_{12}^2\right)} T n_2^0.$$

Conditions of ideal mechanical contact on the edge of matrix and every inclusion, are as follows:

$$\sigma_{ij}^p n_j^p |_{\Gamma_p} = \sigma_{ij}^{p+1} n_j^{p+1} |_{\Gamma_p} \; u_i^p |_{\Gamma_p} = u_i^{p+1} |_{\Gamma_p}, \; i,j=1,2, \; p=1,...,N.$$

Multiplying both parts of each equation (2), (3) on the correspondent fundamental solutions $U_i^{k(0)}$ and $U_i^{k(p)}$, $p=1,...,N$ and integrating over domains of considered body, and each of its layers, integrating (5)-(8) by parts, making use of Ostrogradskii-Gauss formulas, we obtain Somigliano relation for matrix:

$$\chi(S)u_k^{(0)}(\xi) = \int_{S_0} X_i U_i^{k(0)} dS_0 + \int_{\Gamma_0} \sigma_{ij}^{(0)} n_j^{(0)} U_i^{k(0)} d\Gamma_0 - \int_{\Gamma_0} g_i^{k(0)} u_i d\Gamma_0 -$$

$$-\int_{\Gamma_1} \sigma_{ij}^{(0)} n_j^{(1)} U_i^{k(0)} d\Gamma_1 - \int_{\Gamma_1} g_i^{k(0)} u_i d\Gamma_1, \; \begin{cases} \chi = 1, \xi \in S_0 \\ \chi = 0, \xi \notin S_0 \end{cases}$$

and for every inclusion:

$$\chi(S)u_k^{(p)}(\xi) = \int_{\Gamma_p} \sigma_{ij} n_j U_i^{k(p)} d\Gamma_p - \int_{\Gamma_p} g_i^{k(p)} u_i d\Gamma_p + \int_{S_p} X_i U_i^{k(p)} dS_p -$$

$$-\int_{\Gamma_{p+1}} \sigma_{ij} n_j U_i^{k(p)} d\Gamma_{p+1} + \int_{\Gamma_{p+1}} g_i^{k(p)} u_i d\Gamma_{p+1}, \; \begin{cases} \chi = 1, \xi \in S_p \\ \chi = 0, \xi \notin S_p \end{cases}.$$

Here $g_i^{k(0)}(\xi, x)$ and $g_i^{k(p)}(\xi, x)$ – fundamental forces for matrix and every inclusion ($p=1,...,N$). Let's divide each of p layers on m_p additional layers. Suppose, that on the edge of each intermediate layer the temperature is constant, namely for j - th sublayer of p - th layer the following relations hold:

$$\begin{cases} T_p^j = T_p, j = 0 \\ T_p^j = T_{p+1}, j = m_p \end{cases}.$$

Then surface integral containing temperature, taking into account that temperature of every layer (zone with constant mechanical characteristics) is constant, can be written in the form

$$\int_{S_p \setminus S_{p+1}} \left(\frac{\alpha_2 s_{12} - \alpha_1 s_{22}}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2} \frac{\partial T}{\partial x_1} U_1^{k(p)} + \frac{\alpha_1 s_{12} - \alpha_2 s_{11}}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2} \frac{\partial T}{\partial x_2} U_2^{k(p)} \right) dS_p =$$

$$\frac{\alpha_2 s_{12} - \alpha_1 s_{22}}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2} \int_{S_p \setminus S_{p+1}} T U_{1,1}^{k(p)} dS_p + \frac{\alpha_1 s_{12} - \alpha_2 s_{11}}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2} \int_{S_p \setminus S_{p+1}} T U_{2,2}^{k(p)} dS_p$$

Here $T_j^* = \frac{T_p^j + T_p^{j+1}}{2}$ – mean temperature of j-th sublayer of p-th layer, Γ_p^j – j -th isotherm of p -th layer, and

$$I_j = \int_{\Gamma_p^j} U_i^{k(p)} n_i d\Gamma_p^j.$$

Let's discretize boundaries of inclusion and layers using segments as elements of discretization and work in on these segments local coordinates system. Using boundary properties of potentials of single and double layer we get the system of integral equations for defining displacements in zonal-homogeneous body. Let's carry out passage in integral representations, and direct (for every equation) the observation point step-by-step to the center of every segment of discretization. Thus we obtain the system of boundary integral equations for matrix, for every layer, and for internal inclusion. Further, unknown densities of potentials of double layer on the boundaries of inclusions can be represented as functions of two unknowns along the segments of discretization. After solving the system of boundary integral equations it allows defining all the components of displacements and stresses on all the contacting boundaries.

In the case of linear approximation the components of displacements on every segment of discretization can be written as follows:

$$u_1'^{i(p)}(x') = a_{1i}^p x_1' + a_{2i}^p x_2' + a_{3i}^p$$

$$u_2'^{i(p)}(x') = a_{4i}^p x_1' + a_{5i}^p x_2' + a_{6i}^p, \; p=1,...,N, i=1,...,M_p \quad (4)$$

Using Cauchy relations and Duhamel-Neumann's law for isotropic elastic body, we obtain correspondent relations for stresses on every segment of discretization:

$$\sigma_{11}^{i(p)}(x') = \left(\frac{s_{22}^p}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2} \right) a_{1i}^p - \left(\frac{s_{12}^p}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2} \right) a_{5i}^p + \frac{\alpha_2^p s_{12}^p - \alpha_1^p s_{22}^p}{\left(s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2\right)} T$$

$$\sigma_{22}^{i(p)}(x') = -\left(\frac{s_{12}^p}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2} \right) a_{1i}^p + \left(\frac{s_{22}^p}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2} \right) a_{5i}^p + \frac{\alpha_1^p s_{12}^p - \alpha_2^p s_{11}^p}{\left(s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2\right)} T$$

$$\sigma_{12}^{i(p)}(x') = \frac{1}{s_{66}^p}\left(a_{2i}^p + a_{4i}^p\right), \; p=0,...,N, i=1,...,M_p.$$

Note that in the case of linear approximation stress tensor components are constant on every segment of integration. Since we consider multiply-connected domain, we have to add conditions of contact interaction on the edge of each of subdomains to above conditions. In the case of ideal mechanical contact on the edge of contacting zones, these conditions, taking into account approximation (4), can be written down as follows:

$$a_{1i}^p = a_{1i}^{p+1}, a_{3i}^p = a_{3i}^{p+1}, a_{4i}^p = a_{4i}^{p+1}, a_{6i}^p = a_{6i}^{p+1}; \; \frac{1}{s_{66}^p}\left(a_{2i}^p + a_{4i}^p\right) = \frac{1}{s_{66}^{p+1}}\left(a_{2i}^{p+1} + a_{4i}^{p+1}\right);$$

$$-\left(\frac{s_{12}^p}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2} \right) a_{1i}^p + \left(\frac{s_{22}^p}{s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2} \right) a_{5i}^p - \frac{\alpha_2^p s_{12}^p - \alpha_1^p s_{22}^p}{\left(s_{11}^p s_{22}^p - \left(s_{12}^p\right)^2\right)} T =$$

$$= -\left(\frac{s_{12}^{p+1}}{s_{11}^{p+1} s_{22}^{p+1} - \left(s_{12}^{p+1}\right)^2} \right) a_{1i}^{p+1} + \left(\frac{s_{22}^{p+1}}{s_{11}^{p+1} s_{22}^{p+1} - \left(s_{12}^{p+1}\right)^2} \right) a_{5i}^{p+1} - \frac{\alpha_2^{p+1} s_{12}^{p+1} - \alpha_1^{p+1} s_{22}^{p+1}}{\left(s_{11}^{p+1} s_{22}^{p+1} - \left(s_{12}^{p+1}\right)^2\right)} T,$$

$$p = 0, \ldots N-1.$$

Thus, we obtain the system of linear algebraic equations, which is to be made closed by adding to system the equations of continuity of displacements on every segment of discretization.

Using Somigliano identity we can obtain components of displacements in internal points of considered body from obtained system of linear algebraic equations. Differentiating Somigliano identity we obtain correspondent integral representations for all the components of stress tensor in internal points:

$$\sigma_{ij}(\xi)=\int_{\Gamma_0}\mathrm{E}_{ik}^{j}(\xi,x)\,p_k(x)\,d\Gamma_0(x)-\int_{\Gamma_0}\Sigma_{ik}^{j}(\xi,x)\,u_k(x)\,d\Gamma_0+\int_{S}\mathrm{E}_{ik}^{j}(\xi,x)\,X_k(x)\,dS_0 \qquad (5)$$

Here $\mathrm{E}_{ik}^{j}(\xi,x)$ and $\Sigma_{ik}^{j}(\xi,x)$ – strains and stresses in an arbitrary point x accordingly, caused by unit concentrated force, applied in point ξ, and directed along k-th axis.

Expressions in the right part of (5) do not contain unknown values, and thus, in order to obtain expressions for displacements and stresses, it is only necessary to calculate right parts of the above expressions.

Thereby approach that was proposed in [2] and proceeded with [6], [7], can be extended to problems of the stress-strain state assessment of core systems, provided that correspondent fundamental solutions for problems of plane elasticity of anisotropic zonal-homogeneous bodies are known.

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МОДЕЛЮВАННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ КОРОВИХ СИСТЕМ В КОНТЕКСТІ ПРОБЛЕМИ ПРОСТОРУ ПІД ЧАС ГРАНІТОУТВОРЕННЯ

В геології особливе місце займає проблема гранітів. Розгляд задачі гранітоутворення призводить до ряду часткових задач, серед яких вирізняються питання глибинності гранітоутворення та механізмів забезпечення простору для крупних гранітоподібних тіл. В проблемі простору геомеханічна складова має першочергову важливість. Головні чинники, що формують напружено-деформований стан в системі гранітоутворення –постійно діючі масові гравітаційні сили, тектонічні сили міжплитної взаємодії, псевдомасові сили об'ємних термопружних ефектів, фазових перетворень в процесах метаморфізму, метасоматозу, часткового і повного плавлення. В існуючих дослідженнях напружено-деформованого стану корових систем геологічні середовища вважаються квазіоднорідними. Метою роботи є побудова загального підходу до комп'ютерного моделювання поведінки геолого-механічних систем рангу мегаблоків в контексті проблеми простору під час гранітоутворення, з врахуванням структурної анізотропії системи.

Оскільки можливості натурного моделювання складних багатофакторних магматогенних систем є обмеженими, більш доцільним є математичне моделювання, особливо в сенсі моделювання механічних систем. Найбільш оптимальним є перевірка геологічних гіпотез і емпіричних даних шляхом створення простих моделей з подальшим їх ускладненням за рахунок переходу до все більш складних комбінацій силових факторів, реологічних станів, граничних умов і т.д. В статті розглядається задача визначення напружено-деформованого стану геолого-механічної системи рангу мегаблоків. Вважаючи температуру середовища відомою, одержано визначальні співвідношення для описання поведінки геолого-механічної системи при сумісній дії на неї гравітації, неоднорідного температурного поля і заданих на границях системи силових і кінематичних впливів. Для побудови алгоритму розв'язання пружної задачі використовується модифікований метод граничних елементів.

Одержано визначальні співвідношення розглядуваної задачі, побудовано чисельно-аналітичний алгоритм визначення напружено-деформованого стану розглядуваної геолого-механічної системи.

Математична модель та відповідний алгоритм чисельного розрахунку напружено-деформованого стану розглядуваної системи дозволяють аналізувати напружено-деформований стан геолого-механічної системи при сумісній дії на неї гравітації, неоднорідного температурного поля і заданих на границях системи силових і кінематичних впливів, з врахуванням структурної анізотропію системи.

Таким чином, запропонований метод дозволяє досліджувати характер полів напружень, а отже, прогнозувати геометрію потенційних областей відносної декомпресії та розтягу, які є найбільш сприятливі для гранітоутворення.

Ключові слова: гранітоутворення, структурна анізотропія, термопружність.

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МОДЕЛИРОВАНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ КОРОВЫХ СИСТЕМ В КОНТЕКСТЕ ПРОБЛЕМЫ ПРОСТРАНСТВА ВО ВРЕМЯ ГРАНИТООБРАЗОВАНИЯ

В геологии особое место занимает проблема гранитов. Рассмотрение задачи гранитообразования приводит к ряду частных задач, среди которых выделяются вопросы глубинности гранитообразования и механизмов обеспечения пространства для крупных гранитоидных тел. В проблеме пространства геомеханическая составляющая имеет первостепенную важность. Главные факторы, формирующие напряженно-деформационное состояние в системе гранитообразования – постоянно действующие массовые гравитационные силы, тектонические силы межплитного взаимодействия, псевдомассовые силы объемных эффектов термоупругости, фазовых преобразований в процессах метаморфизма, метасоматоза, частичного и полного плавления. В существующих исследованиях напряженно-деформированного состояния коровых систем геологические среды считаются квазиоднородными. Цель работы – к компьютерному моделированию поведения геолого-механічних систем ранга мегаблоков в контексте проблемы пространства во время граитообразования, с учетом структурной анизотропии системы.

Поскольку возможности натурного моделирования сложных многофакторных магматогенных систем ограничены, более целесообразным представляется математическое моделирование,особенно в смысле моделирования механических систем. Наиболее оптимальной является проверка геологических гипотез и эмпирических данных путем создания простых моделей с последующим их усложнением за счет перехода ко все более сложным комбинациям силовых факторов, реологических состояний, граничных условий, и т.д. В статье рассматривается задача определения напряженно-деформированного состояния геолого-механической системы ранга мегаблоков. Считая температуру среды известной, получены определяющие соотношения для описания поведения геолого-механической системы при совместном воздействии на нее гравитации, неоднородного температурного поля и заданных на границах системы силовых и кинематических воздействий. Для построения алгоритма решения упругой задачи используется модифицированный метод граничных елементов.

Получены определяющие соотношения рассматриваемой задачи, построен численно-аналитический метод определения напряженно-деформированного состояния рассматриваемой геолого-механической системы.

Построенная математическая модель и соответствующий алгоритм численного расчета напряженно-деформированного состояния рассматриваемой системы позволяет анализировать напряженно-деформированное состояние геолого-механической системы совместном воздействии на нее гравитации, неоднородного температурного поля и заданных на границах системы силовых и кинематических воздействий, с учетом структурной анизотропии системы.

Таким образом, предложенный метод позволяет исследовать характер полей напряжений, а следовательно, прогнозировать геометрию потенциальных областей относительной декомпрессии и растяжения, являющиеся наиболее благоприятными для гранитообразования.

Ключевые слова: гранитообразование, структурная анизотропия, термоупругость.

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ВІСНИК

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