Geothermal waters of the Khankala deposit formation, use, forecasts

Anvar Farkhutdinov

THÈSE DE DOCTORAT

de l'Université de recherche Paris Sciences et Lettres
PSL Research University

Préparée dans le cadre d'une cotutelle entre
MINES ParisTech
et l'Université d'État de Bachkirie

Geothermal waters of the Khankala deposit: formation, use, forecasts

Les eaux géothermiques du gisement de Khankala: formation, utilisation, prévisions

Ecole doctorale n°398

Géosciences, Ressources Naturelles et Environnement

Spécialité Géosciences et Géoingénierie

COMPOSITION DU JURY :

M. Alain DUPUY
Professeur, Institut polytechnique de Bordeaux,
Président

Mme. Natalia KHARITONOVA
Professeur, Université d'État de Moscou,
Rapporteur

M. Alain GADALIA
Ingénieur, Bureau de Recherches Géologiques et Minières,
Rapporteur

M. Patrick GOBLET
Directeur de recherches, MINES ParisTech,
Examinateur

M. Sergei CHERKASOV
Directeur, Musée géologique d'État Vernadsky,
Examinateur

M. Stepan SHVARTSEV
Professeur, Université polytechnique de Tomsk,
Examinateur

M. Oleg SAVICHEV
Professeur, Université polytechnique de Tomsk,
Examinateur

Soutenue par Anvar FARKHUTDINOV
le 23.12.2016

Dirigée par **Patrick GOBLET**
et Ayfar GAREEV

Remerciements

I am grateful to École des Mines and in particular to Patrick Goblet for accepting me as a PhD student, making this work possible and enormous contribution to it. I express my sincerest appreciation to Sergey Cherkasov for providing overall support from the start till the end. I would like to thank Chantal de Fouquet for her help, advices and ideas used in this work. Thanks to Ayfar Gareev for support.

Thanks to Emmanuel Ledoux, Dominuque Bruel and Sergey Svyatovets for useful advices and comments. I am grateful to Larisa Belan and Victor Lgotin for support, to Magomed Mintsaev, Arbi Shaipov, Sharputdi Zaurbekov and Magomed Labazanov for their help and warm hospitality in Grozny. Thanks to Rifa Ibatullina, Elodie Guilgaris and Eline Malcuit for useful comments and suggestions.

I would also like to thank Françoise Nore, Trevor Cox, Ghassen Jomaa, Irina Sin, Jamal El Abbadi, Marco Campestrini for their friendship and good times passed at École des Mines. I am grateful to Ekaterina Filimonenko, Bulat Soktoev and Albina Yalaltdinova for their help.

Достық – ұлы күш. Достық қошеметпен, ал шынмен және абыроймен берік.

Я благодарен моему деду, родителям, тёте и братьям, имевшим огромное положительное влияние на протяжении всего пути. Я благодарен своей маме за поддержку в написании данной работы.

Мең нәнкә дә бер әнкәне алыштыра алмас. Кемнең әнисе юк, шуның хәле начар.

Résumé

L’introduction

L’utilisation d’énergies renouvelables connait actuellement un regain d’attention dans le monde entier. En particulier, l’exploitation d’eaux géothermales apparait comme très intéressante du fait de son faible impact écologique et de son coût. La Russie dispose d’un potentiel géothermal important, qui n’est pas utilisé à une échelle industrielle. L’une des zones les plus prometteuses est la République de Tchétchénie, qui se situe au troisième rang en Russie en termes de réserves reconnues en eaux géothermales; le secteur le plus important est le site de Khankala.

Au vu de la croissance constante des besoins en électricité et en chaleur en République de Tchéténie, il apparait justifié de mobiliser les techniques d’estimation géostatistique et de modélisation phénoménologique pour étudier l’exploitation des ressources géothermales. L’objectif de ce travail est ainsi d’identifier les caractéristiques de la ressource géothermale de Khankala et de prévoir les modifications de température entraînées par son exploitation.

Objectifs de l’étude

1. Analyser le contexte hydrogéologique de la zone sud-est du basin artésien de Ciscaucasie de l’Est ainsi que les conditions de développement des eaux géothermales.

2. Etablir une carte de distribution des températures au sein de la ressource géothermale de Khankala, ainsi qu’une carte structurale de la couche productrice principale.

3. Construire un modèle mathématique de simulation permettant de prédire l’évolution de la température durant l’exploitation de la ressource géothermale.

4. Emettre des recommandations pour l’exploitation future de la ressource de Khankala.

Chapitre 1. Les recherches en Géothermie

La classification russe désigne par eaux géothermales des eaux souterraines naturelles à une température d'au moins 20 °C. Leur usage s'est développé depuis plus d'un siècle. L'utilisation des eaux thermales comme source d'énergie a débuté dans la première moitié du XIXe siècle grâce au développement de la thermodynamique, qui a permis une utilisation efficace et directe de la chaleur de l'eau chaude et de la vapeur, et même la production d'électricité. On présente ici d'abord la situation actuelle en Russie vis-à-vis de l'utilisation des eaux géothermales, puis l'histoire de la découverte et de l'exploitation du gisement de Khankala. Le développement initial de l'énergie géothermale a commencé dans deux régions: le Kamtchatka et le Caucase du Nord. Dans le premier cas, l'eau géothermale a été utilisée pour produire de l'électricité, et dans le second pour produire de la chaleur.

A ce jour on dénombre 66 gisements potentiels d'eaux géothermales dans la Fédération de Russie. 50% seulement de cette ressource sont utilisés pour produire 1.5 millions de Gigacalories thermiques, ce qui équivaut à la combustiond'environ 300 000 tonnes de charbon [Alkhasov, 2011].

Ces gisements sont principalement situés sur le teritoire de la République de Tchétchénie, suivie par la région de Krasnodar, le Daghestan et le Kamtchatka.

Dès les années 20 au siècle dernier, une source d'eau géothermale a été découverte à l'emplacement du champ pétrolier Oktyabrsk en République tchétchène. Dans les années soixante-dix, l'Institut VNIPIgazdobycha a mené une exploration détaillée du gisement Khankala, situé à 10 kilomètres au sud-est de Grozny. Les prélèvements réguliers d'eau ont commencé en 1974, avec la mise en service de serres. Mais en 1994, du fait de la guerre sur le territoire de la République, l'exploitation du gisement Khankala a été arrêtée. En raison de ces événements tragiques, beaucoup de données sur le gisement géothermique ont été perdues et, pendant une longue période, l'eau a été utilisée et rejetée de façon primitive par la population locale [Farkhutdinov et al., 2014].

En 2013, le Grozny State Oil Institute, la compagnie ArenStroiCentr et le musée d'état de Vernadsky ont lancé, au sein du consortium "Ressources géothermiques" et avec l'accompagnement scientifique du BRGM, un projet pilote de construction d'une centrale géothermique utilisant la couche XIII, la plus prometteuse du gisement géothermique de Khankala. La capacité de l'installation est de 5.45 Gcal/heure, utilisées pour faire fonctionner un complexe de serres. La station géothermale repose sur un système en doublet, constitué d'une boucle fermée, d'un puits de production et d'un puits de réinjection.

Bien que la Russie dispose de ressources importantes et démontrées en eaux géothermales, celles-ci sont peu utilisées. L'utilisation directe des eaux thermales, la production d'électricité et les domaines connexes ne sont pas bien développés. Il n'existe aucune installation géothermale autre que le site de Khankala reposant sur un système de doublet réinjectant 100% de l'eau utilisée. Tous les autres exemples russes connus d'utilisation d'eaux géothermales dans des bassins rejettent leurs eaux soit directement en surface, soit dans des aquifères superficiels. L'installation de Khankala a été mise en service avec succès début 2016; elle est destinée à fournir une expérience précieuse et à promouvoir une nouvelle phase d'exploration et de développement des ressources géothermales dans la région.

Chapitre 2. Description physiographique, géologique et hydrogéologique de la zone d'étude

Ce chapitre décrit la situation géographique, le relief, le climat et l'hydrographie de la République tchétchène. Son territoire couvre les pentes septentrionales du Grand Caucase ainsi que les steppes et plaines environnantes. Environ 35% du territoire de la République tchétchène sont occupés par des crêtes montagneuses, des vallées et des bassins séparant les massifs montagneux. Le reste du territoire est plat, le plus souvent marqué par un relief de collines.

Ces reliefs déterminent la direction d'écoulement des eaux souterraines du réservoir de Karagan-Chokrak, depuis leur zone de recharge dans les Montagnes Noires vers le Nord-Nord-Est. Les conditions climatiques, marquées par des précipitations abondantes, ainsi qu'un réseau hydrographique dense là où les niveaux réservoirs de Karagan-Chokrak affleurent dans les Montagnes Noires, créent des conditions favorables pour l'alimentation en eau, avec le développement d'une ressource abondante au sein de ces couches. Les conditions climatiques entraînent un besoin de chauffage limité à 7 mois par an (d'octobre à avril), période durant laquelle les eaux géothermales sont utilisées pour le chauffage de serres. La situation hydrogéologique de la République de Tchétchénie est liée à sa situation au Sud-Est du Bassin artésien du Ciscaucase de l'Est.

La bonne perméabilité des niveaux du Karagan-Chokrak, un flux géothermique élevé, une lithologie et des structures tectoniques particulières, associés à la circulation hydrogéologique générale, ont permis une accumulation d'eaux géothermales au Miocène moyen dans ce bassin artésien. Les caractéristiques lithologiques du territoire – amincissement des couches productives du Karagan-Chokrak et diminutionde la teneur en argile du nord au sud et de l'est à l'ouest ont permis d'identifier les conditions hydrogéologiques les plus favorables dans le sud-est de la région. Pour cette raison, après une longue interruption dans l'utilisation des eaux géothermales dans la région, c'est le plus grand gisement de la République Tchétchène – Khankala, situé dans le sud-est de la région, qui a été choisi comme zone de développement prioritaire.

Chapitre 3. Analyse géostatistique du réservoir d'eaux géothermales de Khankala

De nos jours, alors que les eaux géothermales constituent une forme d'énergie connue depuis longtemps, de nombreux chercheurs mettent en avant la question de la "durabilité" de l'exploitation du réservoir géothermique. Les techniques d'analyse reposant sur l'approche géostatistique et la modélisation numérique, qui ont été activement mises en œuvre dans de nombreux domaines scientifiques, constituent des outils efficaces pour l'évaluation de la ressource. Nous avons fait appel à l'analyse géostatistique (Chapitre 3) et à la modélisation numérique de la réinjection d'eau (Chapitre 4) afin de proposer des règles d'exploitation de la ressource de Kankala.

Analyse géostatistique et estimation de la cote de la couche XIII

La phase initiale du travail a consisté en une collecte de données. Une carte créée en 1967 a été utilisée à cette fin. Les coordonnées et les cotes absolues sont issues de cette carte et réinterprétées en utilisant des méthodes géostatistiques. Dans ce travail, le krigeage universel a été utilisé.

La cote du toit de la couche XIII a été corrigée d'une dérive quadratique ($1\ x\ y\ x^2\ xy\ y^2$) afin de la rendre stationnaire. Le modèle de variogramme choisi est cubique avec une portée de 667 m et un seuil égal à 1084.3 m^2. Un voisinage unique est retenu en raison de la faible quantité de données. Avant l'interpolation, les paramètres sélectionnés (modèle et voisinage) sont vérifiés par validation croisée: les données brutes sont "masquées" et réestimées, puis la différence entre les données originales et obtenues est calculée. La procédure de validation croisée montre que les paramètres sélectionnés fournissent une précision suffisante, qui se traduit par un coefficient de corrélation de 0.99. La carte structurale de la couche XIII a donc été créée en utilisant ce modèle.

Ceci est illustré par le remarquable accord entre cotes prédite et mesurée à l'occasion du forage du puits de production (erreur de 9 m, pour un écart-type de krigeage de 10 m)

Analyse géostatistique et modélisation de la distribution de température dans le réservoir géothermal de Khankala

Des mesures de température dans les puits du réservoir de Khankala ainsi que des observations géologiques ont été faites en 1968 et 1988, et sont décrites dans les rapports [Shpak, 1968f; Krylov, 1988f]. Environ cent mesures ont été effectuées en tout dans quatorze puits productifs.

Les mesures de température montrent une croissance linéaire au début, puis un gradient plus faible lorsqu'on atteint les formations productives. Cela s'explique par le mécanisme de convection causé par la circulation des eaux géothermales. Pour cette raison nous avons choisi d'effectuer deux estimations reposant sur deux modèles différents.

Il a été décidé d'estimer la température à l'intérieur du réservoir en prenant le toit de la couche XIII comme base du plan de référence, puis de passer au plan de référence normal près de la surface. Les deux estimations ont enfin été combinées.

Une carte tridimensionnelle de la répartition de température au sein du réservoir géothermal de Khankala a été créée. La température de la couche XIII dans le puits de production estimée par géostatistique est égale à 96.2 °C (écart-type de krigeage – 0.5 °C), la température réelle de l'eau à la tête du puits de production est de 95 °C.

La carte du toit de la couche XIII et le modèle 3D de répartition de la température dans le réservoir géothermal de Khankala ont été créés pour la première fois en utilisant des techniques géostatistiques. Ceci permet d'identifier les domaines les plus prometteurs pour les travaux futurs. La connaissance de la température ainsi que les informations sur le débit de production permettent une évaluation préliminaire de la capacité réalisable de la centrale géothermique.

Chapitre 4. Modélisation numérique de l'exploitation de la ressource géothermale de Khankala

Une des étapes du travail, outré l'estimation géostatistique, est la simulation de la réinjection des eaux géothermales, afin d'établir des règles d'exploitation et de prédire l'évolution de la ressource. Ce travail de modélisation a été effectué en utilisant le code Metis [Goblet, 1980].

Modèle régional d'écoulement des eaux souterraines

La phase initiale du travail a consisté à créer un modèle hydrogéologique régional afin de comprendre les aspects généraux de la circulation de l'eau dans la couche XIII du gisement d'eaux géothermiques de Khankala, dans le vaste territoire de la République tchétchène. Comme la couche XIII est isolée des autres par des couches intercalaires imperméables, et du fait de la grande différence entre extensions horizontale et verticales, un modèle bidimensionnel a été adopté.

La zone de recharge du réservoir est l'affleurement des niveaux Karagan-Chokrak au sud de la Tchétchénie, au sein des montagnes Noires. Cette zone a été choisie comme limite sud de la zone modélisée. La frontière nord est la rivière Terek qui est supposée agir comme un axe de drainage régional. Le problème d'écoulement est décrit par deux lois: la loi de Darcy et la loi de conservation de masse (équation de continuité). Avant de modéliser la géométrie, les paramètres du système, les conditions initiales et les conditions aux limites ont été définies.

Ce modèle régional d'écoulement des eaux souterraines dans la couche XIII permet de calculer un débit d'eau de 0.62 m^3/s à travers la frontière.

Modélisation du doublet géothermique implanté dans la couche XIII du réservoir de Khankala

Les résultats de la modélisation régionale des écoulements souterrains ont été pris en compte dans la simulation de la réinjection du doublet sous forme d'une composante d'écoulement régional superposée à l'écoulement créé par le doublet. Les résultats de l'estimation de la température et de la carte structurale de la couche productive XIII obtenus par application des méthodes géostatistiques sont utilisés d'une part pour créer le maillage, et d'autre part pour calculer les conditions initiales du système.

Les mécanismes d'écoulement d'eau et de transport de chaleur sont couplés: à chaque pas de temps, le programme effectue une résolution alternative des équations qui les décrivent. La durée simulée est égale à 50 ans.

Différentes hypothèses ont été examinées lors de la modélisation numérique:

– Influence de la distance entre puits de production et d'injection (450, 750, 1000 m).

– Perméabilité de deux zones de failles régionales.

– Influence de l'écoulement régional.

Les résultats ont été comparés avec la solution analytique décrivant la variation de température au puits de production d'un doublet [Gringarten et Sauty, 1975]:

La suite de l'étude a consisté à simuler le comportement de récupération de la ressource de la couche productive Khankala XIII. On a supposé une durée d'exploitation de 50 ans (pour une distance entre puits de 450 m), à la suite de quoi le développement de la ressource a été arrêté.

Lorsque l'on prend en compte l'écoulement régional, la distribution initiale de température se reconstitue à 96.9% après 150 ans d'interruption de l'exploitation. En cas d'absence d'écoulement régional, le taux de récupération est de 75.7%.

Compte tenu des résultats de la modélisation numérique, il est fortement recommandé de choisir une distance entre puits d'injection et de production égale ou supérieure à 750 m. Dans ce cas, la température au puits de production ne diminue pas drastiquement après 25–30 ans, durée au bout de laquelle les équipements de puits peuvent nécessiter un remplacement. Il convient de noter qu'il est important de positionner les puits selon un axe parallèle aux deux zones de failles en plaçant l'impact du puits de production au Sud et celui du puits d'injection au Nord, de telle sorte que l'écoulement régional ralentisse l'arrivée du front froid au puits de production.

L'un des principaux avantages du gisement géothermal de Khankala est qu'il s'agit d'un système multicouches. En cas de baisse significative de la température du puits de production après une certaine période d'exploitation de la couche XIII, il est possible de forer un nouveau doublet sur le même territoire, de manière à exploiter les ressources très prometteuses des couches IV-VII, XVI ou XXII, de sorte que la station géothermique pourrait continuer à fonctionner. La ressource de la couche XIII pourrait être utilisée à nouveau après un certain temps d'interruption, compte tenu de la vitesse relativement élevée de récupération de la température. D'une manière générale, on pourrait organiser l'utilisation périodique de différentes couches pour parvenir à une utilisation durable des eaux géothermiques du réservoir de Khankala.

Chapitre 5. Recommandations pour l'exploitation de la ressource géothermique de Khankala

Un dispositif d'extraction de la chaleur par doublet est utilisé sur le réservoir géothermique de Khankala. Ce choix a été effectué après avoir étudié l'expérience internationale, en particulier française, en matière d'exploitation des eaux géothermiques. Pour cette raison, lors de l'élaboration de recommandations pour une exploitation plus poussée du gisement de Khankala, une analyse comparative avec le bassin artésien de Paris a été utilisée.

Comparés aux eaux géothermales du bassin parisien, les gisements de la République tchétchène présentent les avantages suivants:

1. Température plus élevée du fluide.

2. Faible salinité des eaux, ce qui signifie une corrosivité relativement faible.
3. Épaisseur relativement élevée de certaines couches productives.

On constate en revanche certains inconvénients:
1. De nombreuses couches productives n'ont été testées qu'en mode artésien, à des débits relativement faibles.
2. Les couches sont constituées de grès avec intercalaires et lentilles d'argile, ce qui peut nuire à l'injectivité.
3. La structure tectonique des dépôts est complexe, et affectée de zones de faille.

L'expérience réussie du développement du Bassin Artésien de Paris, depuis plus de 45 ans, permet d'anticiper les problèmes éventuels dans l'exploitation des gisements de la République tchétchène et de proposer des solutions. La création de cartes de température, de salinité, de répartition de la transmissivité, grâce à l'approche géostatistique, puis la simulation numérique de l'exploitation par modélisation mathématique, sont fortement recommandées (sous réserve de disponibilité des données) pour mieux comprendre les caractéristiques géothermiques de la République tchétchène. L'exploitation des eaux géothermiques de la République tchétchène nécessite une surveillance constante, des analyses chimiques et des mesures de la vitesse de corrosion et d'entartrage. Afin d'éviter la précipitation des bactéries, l'une des meilleures méthodes est de faire fonctionner les puits au débit le plus élevé possible. Le système multicouche du gisement d'eaux géothermiques de Khankala et la récupération relativement rapide du régime de température après arrêt de l'exploitation permettent de proposer l'installation de plusieurs doublets pour différentes couches productives, ce qui contribuera grandement à une utilisation durable.

Chapitre 6. Évaluation écologique et économique du projet de Khankala

Aspects écologiques

Le principal gaz à effet de serre émis par une station géothermique est le CO_2 (90%), dont la quantité varie considérablement (en moyenne 122 CO_2/Wh). Pour les centrales géothermiques binaires avec boucle fermée, comme celle Khankala, la quantité d'émissions de CO_2 est proche de zéro. L'utilisation des eaux géothermiques de la couche XIII sur le site de Khankala permet d'éviter l'émission de 7 000 tonnes de CO_2 pendant la saison de chauffage (7 mois), ce qui équivaut à la quantité de dioxyde de carbone émise par une chaudière gazière ayant une capacité similaire de 5.45 Gcal/heure.

En ce qui concerne les effets négatifs qui accompagnent l 'exploitation du gisement de Khankala – pollution sonore, impact paysager, impacts physiques, pollution thermique et chimique, ils peuvent être surmontés à l'aide de technologies modernes, dont l'installation d'un système de circulation en doublet.

La technologie de doublet avec réinjection des eaux géothermales utilisées, ainsi que les méthodes modernes de surveillance et de gestion environnementale, peuvent résoudre le problème des conséquences négatives de l'exploitation des ressources du gisement de Khankala. Parallèlement, l'utilisation des eaux géothermiques, qui se substituent partiellement aux énergies traditionnelles, permet d'améliorer sensiblement les conditions environnementales régionales.

Aspects économiques

La station géothermique de Khankala n'a pas d'équivalent en Russie, donc l'investissement pour sa construction est augmenté du coût de la recherche et développement (R&D). Mais à l'avenir, il sera possible de fournir des services d'ingénierie pour l'installation du système de circulation géothermique (SCG), en réutilisant les résultats de cette première expérience, ce qui pourrait avoir un impact positif sur l'efficacité du projet et le retour d'investissement.

Les coûts de production de l'énergie thermique sont: les matériaux de base et auxiliaires (y compris les inhibiteurs), l'électricité, les salaires, les déductions de la masse salariale, la dépréciation des immobilisations, la réparation et la révision, les frais d'extraction des eaux souterraines et autres. Afin d'estimer l'efficacité commerciale de l'utilisation des eaux géothermiques au SCG, des indicateurs d'attractivité des investissements du projet ont été calculés. Du point de vue de l'efficacité sociale, le développement géothermique présente d'importants avantages. Il favorise la création de nouveaux emplois au cours de l'exploration, du forage et de la construction de centrales géothermiques, ainsi que des emplois permanents avec le démarrage de l'exploitation de la centrale. Le soutien de l'Etat, y compris dans le cadre de la réglementation tarifaire, est nécessaire pour le remboursement des projets géothermiques, selon notre évaluation.

Pour la mise en œuvre de projets géothermiques en Russie, il existe un manque de cadre législatif et d'assurance spécifiques, dont notre pays n'a pas de pratique, contrairement par exemple à la France et à l'Islande, où le gouvernement a fortement soutenu le développement de ce type d'énergie de remplacement, compte tenu de sa durabilité et de son respect de l'environnement.

En cas de réussite du projet Khankala, il est possible que des travaux d'exploitation des 13 autres réservoirs de la République tchétchène soient mis en chantier, ce qui peut modifier le système local de consommation d'énergie et contribuer de manière significative à la stabilité économique de la région.

Conclusion

La Russie possède un potentiel reconnu et important de ressources en eau géothermique, mais aujourd'hui, seule une faible proportion est utilisée. Le projet Khankala est une nouvelle étape dans l'utilisation des eaux géothermiques dans le Caucase du Nord, car il est le seul exemple russe de station géothermique avec boucle fermée de puits de production et d'injection et 100% de réinjection du fluide utilisé dans le réservoir.

Parvenir à la durabilité dans le développement des ressources en eaux géothermiques nécessite une approche intégrée. Un rôle important dans la résolution des problèmes d'exploitation des eaux thermales peut être joué par l'analyse et l'estimation géostatistiques, ainsi que par la modélisation mathématique. La carte structurale ajustée de la couche XIII et une carte 3D de répartition de la température à l'intérieur du gisement Khankala sur la base du krigeage universel ont été créées. Ces cartes ont démontré l'importance du facteur structural-tectonique et du mouvement des eaux souterraines dans la mise en place de la température du territoire. La modélisation de l'exploitation des gisements géothermiques de Khankala a permis de prédire les évolutions de température, et de formuler des recommandations relatives à l'emplacement des puits d'injection-production et à la distance entre les impacts au réservoir des forages, et enfin de fournir un scénario d'exploitation possible.

Le développement de l'utilisation des eaux géothermiques présente des avantages indéniables: respect de l'environnement et renouvelabilité. Afin de promouvoir ce domaine en République tchétchène, le soutien de l'Etat est nécessaire. Les problèmes sont l'absence d'un cadre législatif spécial et de systèmes d'assurance spéciaux. L'utilisation des quatorze dépôts reconnus en République tchétchène peut être une contribution importante à la production locale d'énergie et à la stabilité économique de la région, avec des avantages environnementaux liés au remplacement partiel des combustibles traditionnels.

Resume

Introduction

Recently, considerable attention in the world is given to the use of renewable energy sources, among them geothermal waters are of great importance due to ecological safety and economic efficiency of their use. Russia has large geothermal resources, but they are not practically used on an industrial scale. One of the most promising areas for geothermal waters is the Chechen Republic, which is at the 3 place among the Russian regions on approved operational reserves of geothermal waters deposits, the largest of which is the Khankala deposit.

The study of geothermal waters of the region using geostatistics and mathematical modelling is timely and relevant due to the steady growth of the needs of the Chechen Republic in the electricity and heat. The aim of this work – to determine the features of the Khankala geothermal waters deposit formation and identify the temperature change during exploitation.

Objectives of the study

1. Analyze the hydrogeological conditions of the area south-east of the East Ciscaucasian Artesian Basin and factors defining the spread of geothermal waters.
2. Create a map of temperature distribution within the Khankala geothermal waters deposit and structural map of the main productive layer.
3. Conduct mathematical modelling in order to predict temperature changes during exploitation of the Khankala geothermal waters deposit.
4. Make recommendations for further Khankala geothermal waters deposit exploitation.

Chapter 1. Geothermal development and research

Geothermal waters are natural ground waters with temperature of 20 °C and more

(according to Russian classification). Development of their usage has more than a century history. The use of thermal waters as a source of energy began in the first half of the XIX century thanks to the development of thermodynamics, which allowed efficient direct use of the heat of hot water and steam and then even production of electricity. Russian current state on geothermal waters use and history of the Khankala deposit discovery and exploitation is considered. The initial development of geothermal energy began in two regions – Kamchatka and the Northern Caucasus. In the first case geothermal water was used to generate electricity, and in the second to produce heat.

To date, there are 66 explored deposits of geothermal waters in the Russian Federation, only 50% of these stocks is used for the production of 1.5 million Gcal of heat, which is equivalent to burning about 300 thousand tons of coal equivalent [Alkhasov, 2011].

The largest number of deposits is located on the territory of the Chechen Republic and then comes Krasnodar region, Dagestan and Kamchatka.

As back as in the 20s of the last century geothermal water source was discovered at the site of the Oktyabrsk oil field of the Chechen Republic. In the seventies, the VNIPIgazdobycha Institute conducted detailed exploration of the Khankala deposit which is located 10 kilometers southeast of Grozny. Regular water withdrawals started in 1974, when greenhouses were fully put into operation. But in 1994 because of the war on the territory of the Republic the exploitation of the Khankala deposit was stopped. Due to these tragic events a lot of data on the geothermal deposit were lost and for a long time water was used by local population in a primitive way with subsequent discharge [Farkhutdinov et al., 2014].

In 2013 Grozny State Oil Institute, LLC “ArenStroiCentr” and Vernadsky state geological museum within the consortium “Geothermal resources” and scientific accompaniment of the BRGM (“Bureau de recherches géologiques et minières”) started a pilot project to build a geothermal plant on the basis of the most promising XIII layer of the Khankala geothermal waters deposit of the Chechen Republic. Capacity of the facility is 5.45 Gcal/hour, with a greenhouse complex as a consumer. Geothermal station uses a doublet system which is represented by a closed loop of one production and one injection well.

Despite the fact that Russia has large proven resources of geothermal waters they are not widely used. Thermal waters direct use, electricity production and related domains are not well developed. There is no geothermal plant with doublet circulating loop and 100% reinjection of used fluid, besides the Khankala station, all other known Russian examples of geothermal waters use in sedimentary basins are with subsequent discharge on the ground or into surface-water bodies. The Khankala station was successfully launched in the beginning of 2016 and it is supposed to provide useful experience and begin a new phase in the exploration and development of geothermal waters of the region.

Chapter 2. Physico-geographical, geological and hydrogeological conditions of the study area

In this chapter geographical location, relief, climate and hydrography of the Chechen Republic are considered. Its territory covers the northern slopes of the Greater Caucasus and surrounding steppes and plains. About 35% of the territory of the Chechen Republic is occupied by mountain ridges, valleys and intermountain basins. The rest of the territory is plain, mostly rugged by hills.

The land relief determines general conditions of the Karagan-Chokrak deposits groundwater flow from the recharge area in the Black Mountains to the north, north-east. Climatic conditions, abundant precipitation and densely-developed hydrographic network within the Karagan-Chockrak deposits outcrops in the Black Mountains are favorable for the aquifers supply and for the creation of significant natural groundwater resources. The climatic features have also identified the need for heating only 7 months of the year (from October to April) – the period during which the Khankala deposit geothermal waters used for greenhouses heating. Hydrogeological features of the Chechen Republic territory is defined by its location in the south-east of the East-Ciscaucasian Artesian Basin.

Favorable filtration parameters of the Karagan-Chokrak deposits, high heat flux values, lithology particularities, structural-tectonic factor and movement of groundwater have caused content of the significant quantities of geothermal waters in the Middle Miocene hydrogeological stage within this artesian basin. The lithological features of the territory – a reduction in thickness of the Karagan-Chokrak productive strata and increase in clay content in the direction from south to north and from east to west, have identified the most favorable hydrogeological conditions in the south-east of the region. For this reason, as a priority for development after a long break in the use of geothermal waters the largest deposit of the Chechen Republic – Khankala was chosen, located in the southeast of the region. The thickness, consistency and transmissibility of the productive XIII layer distinguish it from the Chokrak-Karagan 22 aquifers of the deposit. It is one of the main factors together with relatively low depth for its selection as the heat source for geothermal station. Due to tectonic conditions the most favorable area for the location of the wells is a section of the axial zone of the anticline structure. Well bottoms in this case, will be located in the vicinity of the axis of the structure, which is determined by the minimum depth of the XIII layers top. Also they will be at the approximately maximum distance from the northern and southern faults, in order to avoid their possible impact on exploitation because the nature of the permeability of faults is not well-studied and the work in order to determine their conditions must be continued. The XIII layer average thickness is 47 m, transmissivity – 90 m^2/day, salinity – 0.87-1.7 g/l, waters chemical composition is sodium-bicorbanate. The XIII layer is exploited by doublet circulation system with 100% reinjection of used fluid back in the aquifer.

Chapter 3. Geostatistical analysis of the Khankala geothermal waters deposit

Nowadays, when geothermal waters have been a well-known form of energy for a long time, many researchers put to the forefront the issue of “sustainability” of the geothermal reservoir development. The most effective methods of assessment are formed on the basis of geostatistical approach and numerical modelling, which have been actively implemented in all areas of science. Geostatistical analysis (Chapter 3) and computer modelling of water reinjection (Chapter 4) were used in order to establish guidelines for the Khankala deposit exploitation.

Geostatistical analysis and estimation of the XIII layer top elevation

The initial stage of the work was data collection. A map created in 1967 was used for this purpose. Coordinates and absolute elevations are taken from this map and reinterpreted using geostatistical methods. In this work universal kriging was used.

In order to bring the data the XIII layer top elevation to stationarity trend $1\ x\ y\ x^2\ xy\ y^2$ was selected as the most appropriate. Chosen variogram model is cubic with the range equal to 667 m, and the sill equal to 1084.3 m^2. Because of the small amount of data, unique kriging neighborhood is used. Before interpolation, the selected parameters (model and the neighborhood) are checked using cross-validation: raw data one after another is "hidden" and re-estimated and then the difference between the original and obtained data is calculated. Cross-validation procedure shows sufficient accuracy of the selected parameters with correlation coefficient of 0.99. Thus, the structural map of the XIII layer was created using this model.

The difference between the forecast and the actual depth after drilling the production well is 9 m (kriging standard deviation – 10 m).

Geostatistical analysis and modelling of temperature distribution within the territory of the Khankala geothermal waters deposit

Measurements of the temperature in the wells of the Khankala deposit as well as geological observations were made in 1968 and 1988, and they are reflected in the relevant reports [Shpak, 1968f; Krylov, 1988f]. About 100 measurements were made on the whole in 14 productive wells.

Temperature measurements show linear growth in the beginning but then as the depth reaches productive formations geothermal gradient tends to decrease. This can be explained by convection mechanism caused by geothermal waters circulation. It was the main reason to divide our estimation and use two different models.

It was decided to estimate the temperature within the reservoir taking the XIII layer top as the basis for the reference plane, and to switch to the normal reference plane closer to the surface, and finally to combine these two estimations.

A three-dimensional map of temperature distribution within the Khankala geothermal waters deposit was created. The XIII layer temperature in the productive well according to geostatistical estimation is equal to 96.2 °C (kriging standard deviation – 0.5 °C), the actual temperature of water at the productive wellhead – 95 °C.

The XIII layer top structural map and 3D model of temperature distribution within the Khankala geothermal waters deposit were created for the first time using geostatistical techniques. It allows identifying the most promising areas for future work. Knowledge of temperature together with information on the productive flow rate provides preliminary assessment of the achievable capacity of geothermal power station.

Chapter 4. Numerical modelling of the Khankala geothermal waters deposit exploitation

One of the stages of work, along with geostatistical estimation, is simulation of the utilized geothermal waters reinjection in order to draw up guidelines for the exploitation and to forecast the evolution of the resource. The computer code Metis was used for this purpose [Goblet, 1980].

Regional groundwater flow model

The initial stage of the work was the creation of a regional hydrological model in order to understand general aspects of water circulation in the XIII layer of the Khankala geothermal waters deposit within the vast territory of the Chechen Republic. The XIII layer is isolated from others by impermeable clay interlayers and a two-dimensional model was adopted for this case due to the big difference in horizontal and vertical extensions.

The reservoir recharge zone is the Karagan-Chokrak deposits outcrop in the south of Chechnya within the Black Mountains, which was chosen as the southern boundary of the modeled area. The northern border is the Terek River which is assumed to act as a regional drainage axis. This problem is described by two laws: Darcy's law and the mass conservation law (continuity equation). Before modelling geometry, system parameters, initial and boundary conditions were defined.

This regional model of groundwater flow within the XIII layer of the vast territory of the Chechen Republic shows that liquid flow through the southern border is equal to 0.62 m^3/s.

The Khankala deposit XIII layer doublet model

The results of regional groundwater flow modelling were taken into account as a regional flow component in the simulation of doublet reinjection. The results of temperature estimation and structural map of the XIII productive layer obtained after geostatistical methods application are used to calculate the initial conditions of the system and as a basis for creating mesh, respectively.

The processes of liquid flow and heat transport are coupled: at each time step the program conducts an alternate resolution of their equations. Simulation time is equal to 50 years.

Different hypotheses were checked during numerical modelling:

– Influence of the distance between production and injection well (450, 750, 1000 m).

– Permeability of two general faults.

– Influence of natural groundwater flow.

The results were compared with the analytical solution for a doublet production well temperature change [Gringarten et Sauty, 1975].

Our further study was to simulate the recovery behavior of the Khankala XIII productive layer resource. The reservoir was assumed to be exploited for 50 years (the distance between the wells is equal to 450 m) and then development of the resource was stopped.

When natural groundwater flow is taken into account, the temperature will recover by 96.9% after 150 years of shut-down scenario. In case of no groundwater flow temperature recovers by 75.7%.

According to the results obtained by numerical modelling it is highly recommended to choose a distance between injection and production wells equal to 750 m or more. In such case the temperature in production well will not go down drastically after 25-30 years, the usual period of wells equipment lifetime after which its change may by required. It should be noted that it is important to place wells parallel to these two faults with production well bottom in the southern part and injection well bottom in the northern part in order to take into account natural groundwater flow direction which can slow down expansion of cold front to production well.

One of the main advantages of the Khankala deposit of geothermal waters is that it is a multilayer system and in case of significant drop of temperature in production well after some period of the XIII layer exploitation, there is a possibility to drill a new doublet at the same territory on the resource of the highly promising IV-VII, XVI or XXII layers so the geothermal station could continue working. The resource of the XIII layer could be used again in case of shut-down after some period of time taking into account the relatively high speed of temperature recovery. In perspective, periodic use from different layers could be organized in order to achieve sustainable use of geothermal waters at the Khankala deposit site.

Chapter 5. Recommendations on the Khankala geothermal waters deposit exploitation

A doublet circulation heat extraction scheme is used at the Khankala geothermal waters deposit – decision taken after studying international, in particular French experience of geothermal waters exploitation. For this reason, when drawing up recommendations for further exploitation of the Khankala deposit, comparative analysis with the Paris Artesian Basin was used.

In comparison with geothermal waters of the Paris Basin, the Chechen Republic deposits have the following advantages:

1. The higher temperature of the fluid.
2. Low salinity of waters, which means relatively low corrosivity.
3. Relatively high thickness of some productive layers.

And also the following disadvantages:

1. Many productive layers have only been tested in artesian mode, at relatively low flow rates.
2. Layers are represented by sandstones with clay interlayers and lenses, which may adversely affect the injectivity.
3. Deposits have complex tectonic structure with the presence of faults.

Using the successful experience in the development of the Paris Artesian Basin for more than 45 years in the exploitation of the Chechen Republic deposits gives a great advantage and allows taking into account the possible upcoming problems and their solutions. A numerical simulation and creation of maps for temperature, salinity, transmissivity distribution using mathematical modelling and geostatistical approach is highly recommended (in case of data availability) for better understanding the Chechen Republic geothermal waters features, for highlighting the most promising areas and achieving sustainable use. One of the main possible problems to meet during exploitation is corrosion and scaling, and exploitation of the Chechen Republic geothermal waters needs constant monitoring, chemical analyzes and tests of the corrosion and scaling speed. In order to prevent precipitation of bacteria one of the best methods is to operate wells at the highest possible flow rate. Multilayered system of the Khankala geothermal waters deposit and relatively fast recovery of the temperature regime after exploitation stoppage allows proposing installation of several doublets for different productive layers which will be great contribution in achievement of sustainable use.

Chapter 6. Ecological and economic assessment of the Khankala project

Ecological aspects

The main greenhouse gas, emitted by geothermal station is CO_2 (90%), the amount of which varies considerably (on average 122 CO_2/kWh). For binary geothermal power plants with a closed loop, such as the Khankala, the amount of CO_2 emissions are close to zero. The use of the XIII layer geothermal waters at the Khankala station allows avoiding emissions of about 7 thousand tons of CO_2 during heating season (7 months), which is equivalent to the amount of carbon dioxide emitted by a gas boiler with similar capacity of 5.45 Gcal/hour.

With regard to the negative effects that accompany exploitation of the Khankala deposit – noise pollution, violation of the earth surface, physical impacts, thermal and chemical pollution, they can be overcome with the help of modern technologies, one of which is the installation of a doublet circulation system.

Doublet technology with reinjection of used geothermal waters along with modern methods of monitoring and proper environmental management can solve the problem of the negative consequences of the Khankala deposit resource exploitation. At the same time, the use of geothermal waters, partly replacing traditional forms of energy, makes it possible to significantly improve the regional environment conditions.

Economic aspects

The Khankala geothermal station has no analogues in Russia, so the value of the investment for its construction increased by the cost of research and development (R&D). But in the future there is a possibility of engineering services delivery for geothermal circulation system (GCS) installation, the replication of the results, what could have a positive impact on the efficiency of the project and return of investment.

The cost of production of thermal energy are: basic and auxiliary materials (including inhibitors), electricity, wages, deductions from payroll, depreciation of fixed assets, repair and overhaul, fee for the extraction of groundwater and others. In order to estimate the commercial efficiency of the geothermal waters use at GCS standard indicators of investment attractiveness of the project were calculated. From the standpoint of social efficiency geothermal development has important advantages. It promotes the creation of new jobs during exploration, drilling and construction of geothermal power plants, as well as permanent jobs with the start of plant operationing. The state support, including in the framework of tariff regulation is needed for the payback of geothermal projects according to our assessment.

For the implementation of geothermal projects in Russia areas of concern are the lack of a special legislative framework and insurance, of which our country has no practice, in contrast, for example, to France and Iceland, where the government strongly supported the development of this type of alternative energy, in view of its sustainability and environmental friendliness.

In case of the Khankala project success, it is possible that works on exploitation of the 13 others discovered deposits of the Chechen Republic will be started, which can change local energy consumption scheme and will be a significant contribution to economic stability of the region.

Conclusion

Russia has confirmed high potential of geothermal water resources, but today only its small proportion is used. The Khankala project is new stage in use of geothermal waters in the Northern Caucasus as it is the only one Russian example of geothermal station with closed loop of production and injection wells and 100% reinjection of used fluid back into reservoir.

Achievement of the sustainability in geothermal waters resource development requires an integrated approach and an important role in solving the problems of exploitation of thermal waters belongs to geostatistical analysis and estimation, as well as mathematical modelling. The adjusted structural map of the XIII layer and a 3-D map of temperature distribution within the Khankala deposit on the basis of universal kriging were created, which have approved the importance of the structural-tectonic factor and movement of groundwater in the formation of the temperature regime of the territory. Modelling of the Khankala geothermal waters deposit exploitation allowed making prognosis of temperature changes, provided recommendation of injection-production wells location and distance between down holes and possible further exploitation scenario as periodic maintenance of different layers doublet systems.

Geothermal waters use development have undoubted advantages – environmental friendliness and renewability. In order to make this domain perspective in the Chechen Republic the state support is needed, issues are the lack of a special legislative framework and special insurance systems. Use of geothermal waters of the Chechen Republic 14 explored deposits can be a significant contribution to local energy production and economic stability of the region with environmental benefits of traditional fuels partial replacement.

Contents

Introduction

Recently, considerable attention in the world is given to the use of renewable energy sources, among them geothermal waters are of great importance due to ecological safety and economic efficiency of their use. Russia has large geothermal resources, but they are not practically used on an industrial scale. One of the most promising areas for geothermal waters is the Chechen Republic, which is at the 3 place among the Russian regions on approved operational reserves of geothermal waters deposits, the largest of which is the Khankala deposit.

The Chechen Republic is located within the East Ciscaucasian Artesian Basin, hydrogeological, geothermal and hydro-geochemical conditions of which are reflected in the works of a number of researchers: I.G. Kissin, B.F. Mavritsky, F. A. Makarenko, A.I. Khrebtov, V.P. Krylov, G.M. Sukharev, I.S. Zektser, S.A. Shagoyants, M.K. Kurbanov, A.B. Alhasov and others. However, questions on the use of geothermal waters are not well studied, the work on the study and forecast of geothermal waters exploitation with the use of modern computer technologies are rare.

The study of geothermal waters of the region using geostatistics and mathematical modelling is timely and relevant due to the steady growth of the needs of the Chechen Republic in the electricity and heat.

Aim of the study

The aim of this work – to determine the features of the Khankala geothermal waters deposit formation and identify the temperature change during exploitation.

Objectives of the study

1. Analyze the hydrogeological conditions of the area south-east of the East Ciscaucasian Artesian Basin and factors defining the spread of geothermal waters.
2. Create a map of temperature distribution within the Khankala geothermal waters deposit and structural map of the main productive layer.
3. Develop a mathematical model for prediction of temperature changes during exploitation of the Khankala geothermal waters deposit.
4. Make recommendations for further Khankala geothermal waters deposit

exploitation.

Scientific novelty

It was shown that the most promising for the use of geothermal waters within the Chechen Republic are the Karagan-Chokrak deposits of the Middle Miocene, thermal resources of which were assessed. The structural map of the main productive layer of the Khankala geothermal waters deposit using geostatistical methods was created. Temperature distribution map within the study area was created. Modelling of the Khankala geothermal waters deposit exploitation with doublet circulatory system was conducted for the first time, changes in temperature during reinjection of water was estimated. The recommendations for the further hydrogeological work at the Khankala geothermal waters deposit were given.

Personal contribution

Personal contribution includes collection, analysis, interpretation and synthesis of the 1964-2009 years reports; estimation of reserves and calculation of thermal resources of the Middle Miocene Karagan-Chokrak deposits groundwater within the study area, creation of maps, including the structural map of the main productive layer and temperature distribution maps within the Khankala geothermal waters deposit; modelling of geothermal waters use in order to estimate changes in their temperature regime during the implementation of reinjection of used water and after exploitation; development of recommendations on the further exploitation of the Khankala geothermal waters deposit.

Material and methods

Archive materials were used: reports 1964–2009 from the archives of the Federal State Unitary Research and Production Enterprise “Russian Federal Geological Fund”; data field work and geochemical analyzes carried out in 2013 by the Grozny State Oil Technical University named after Acad. M.D. Millionshtchikov. The results of the hydrogeological and geochemical studies of 15 wells, 5 wells tests data of the Khankala geothermal waters deposit territory. Data processing was carried out in Microsoft Office Excel, mapping carried out using Isatis and CorelDRAW software. Calculations of groundwater regime temperature changes in the process of withdrawal and the subsequent reinjection carried out on the basis of mathematical modelling using Metis code developed by Patrick Goblet [Goblet, 1980].

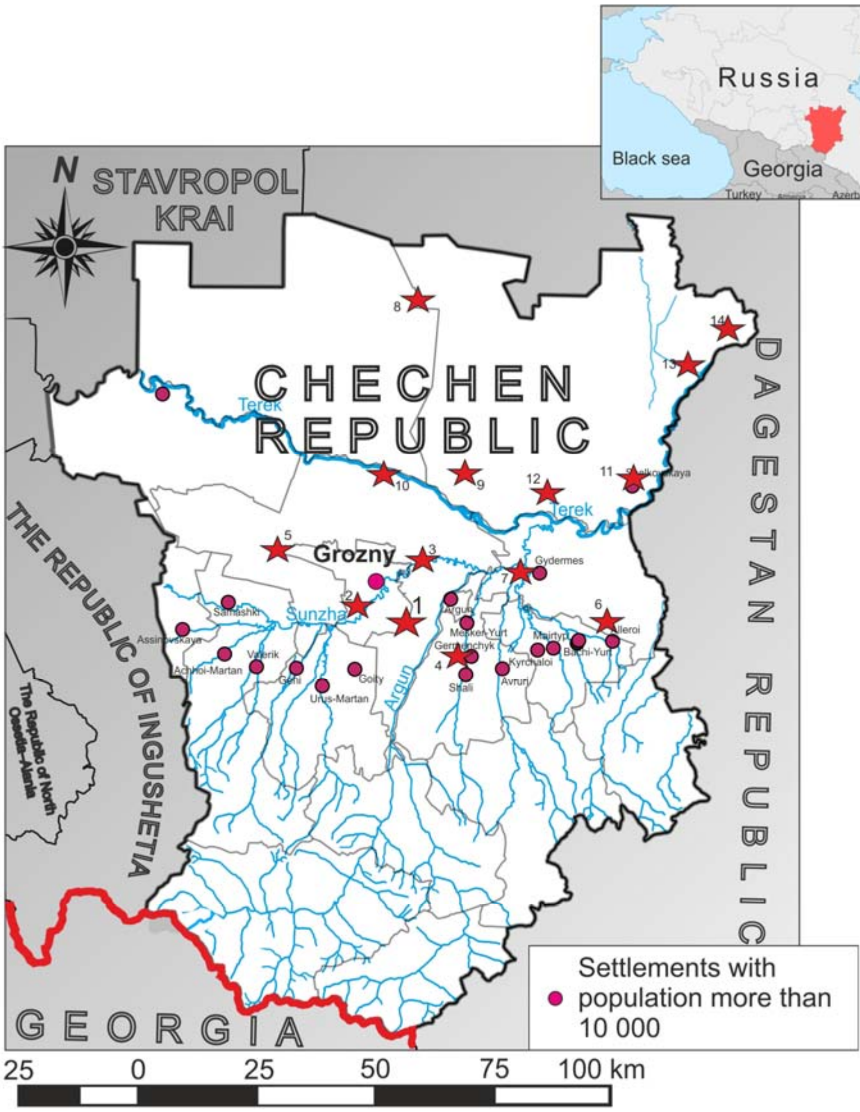


Fig. 1. Geothermal waters deposits of the survey area

1 – Khankala; 2 – Goity; 3 – Petropavlovsk; 4 – Germenchuk; 5 – Gunushki; 6 – Novogrozny; 7 – Gudermes; 8 – Central-Buruni; 9 – Chervleny; 10 – Komsomolsk; 11 – Shelkovsk; 12 – Novochedrinsk; 13 – Kargaly; 14 – Dubovsk.

Scientific and practical significance of the work

As a result of research, calculations and estimation of the Chechen Republic Middle Miocene Karagan-Chokrak deposits geothermal waters thermal resources were carried out, exploitation reserves of the Khankala geothermal waters deposit were counted. The zones of elevated temperatures on the territory of the Khankala deposit were allocated. The forecast of the use of thermal resources with the reinjection of used geothermal waters was given, the rate of temperature recovery after exploitation is stopped was estimated and recommendations on the optimum exploitation parameters were made. Developed and adapted methods for estimating temperature, creating a structural map of the Khankala deposit productive layer, as well as mathematical modelling of reinjection can be used to justify the conditions of exploitation of geothermal waters deposits of the East Ciscaucasian Artesian Basin and other regions of Russia.

The aim of this work is to study and develop recommendations on the Khankala geothermal waters deposit exploitation on the basis of geostatistical analysis and computer modelling, as well as a comparative analysis with the Paris Artesian Basin.

Chapter 1. Geothermal development and research

1.1. The world experience in the use of geothermal waters

Geothermal waters are natural ground waters with temperature of 20 °C and more. Development of their usage has more than a century history. The use of thermal waters as a source of energy began in the first half of the XIX century thanks to the development of thermodynamics, which allowed efficient direct use of the heat of hot water and steam and then even production of electricity.

One of the first examples of the use of geothermal waters is Larderello (Tuscany, Italy). There geothermal waters obtained either naturally or from wells were used for energy purposes at the beginning of the XIX century. Boron rich water from underground sources was used to produce boric acid. Initially, it was obtained by evaporation in iron boilers, heated with wood. In 1827 Francesco Larderel, a pioneer in the production of boron, built the first plant to produce heat from geothermal energy and created a system that worked on heat of waters. The geothermal source was covered with a brick dome, inside which there was the low-pressure steam boiler, heated by geothermal waters. The heat was used for evaporation of boron from saline water and additionally for pumps and other equipment operation. A little later, in 1904, at the same place in Larderello Italian scientist Piero Ginori Conti invented the prototype of the generator in which thermal steam was a source of electricity. In 1913, this geothermal station began to work and produced 250 kW of electricity, and by 2013 the amount of produced electricity was estimated as 545 MW, representing 1.6% of the total in Italy [Stober, Bucher, 2013].

Along with the development of technologies for the use of high temperature geothermal waters to produce electricity there was an extension of the use of medium and low temperature geothermal waters for heat supply.

In 1890, the first systematic work on the use of geothermal heat (68–80 °C) was completed in Boaz (Idaho, USA), which led to the creation of the heating system based on thermal waters. Later, in 1900, a similar system was installed in Klamath Falls (Oregon, USA), where in 1926 it began to be used for heating greenhouses [Stober, Bucher, 2013].

After Italy and the USA, the pioneers in the development of geothermal waters were

Japan (1919), Iceland (1928), New Zealand (1958), Mexico (1959). For example, in Iceland development of geothermal waters use reached broad scope, by 2011 about 90% of houses were heated and 27.3% (4701 GW/h) of the total amount of electricity was produced [Ingimarsson, 2012].

Since 1965, geothermal waters of medium temperature (66–90 °C) have been actively used in France, particularly in the Paris sedimentary basin, in order to produce heat. Establishing of doublet technology (closed loop of one injection and production well) allowed to achieve stability in flow rates and to avoid harm to the environment (the primary plan for discharging water into the Seine River had to be canceled due to high salinity 2–35 g/l) [Lopez et al., 2010].

The use of low-temperature geothermal resources became possible due to the invention of heat pumps in 1852 by Lord Kelvin. Later, in 1912, Heinrich Zoelly patented their application to produce heat from near-surface geothermal waters (< 30 °C). They were first used successfully in 1940, in Indianapolis (State of Philadelphia, USA) and Toronto (Canada) [Stober, Bucher, 2013].

To date, 24 countries are exploiting geothermal waters to generate electricity, 12,635 MW in total and more than 70 countries to produce heat [Fridleifsson et al., 2008; Holm et al., 2010; Matek, 2013].

Giant potential of geothermal resources is confirmed by the data from the UN Department of Economic and Social Affairs, the World Energy Council and others [Boguslavskiy, 2013]. However, only 3.5% of the world's geothermal potential is used for electricity production and 0.2% for heat supply [Alkhasov, 2006].

Recently, technological parameters needed to assess the possiblity of the practical use of geothermal waters are being added in their classification in connection with the expansion of the geothermal market [Williams et al., 2011]. Possibilities of geothermal waters use according to different temperatures are summarized in the following diagram [Povarov, 2003] (Figure 1.1).

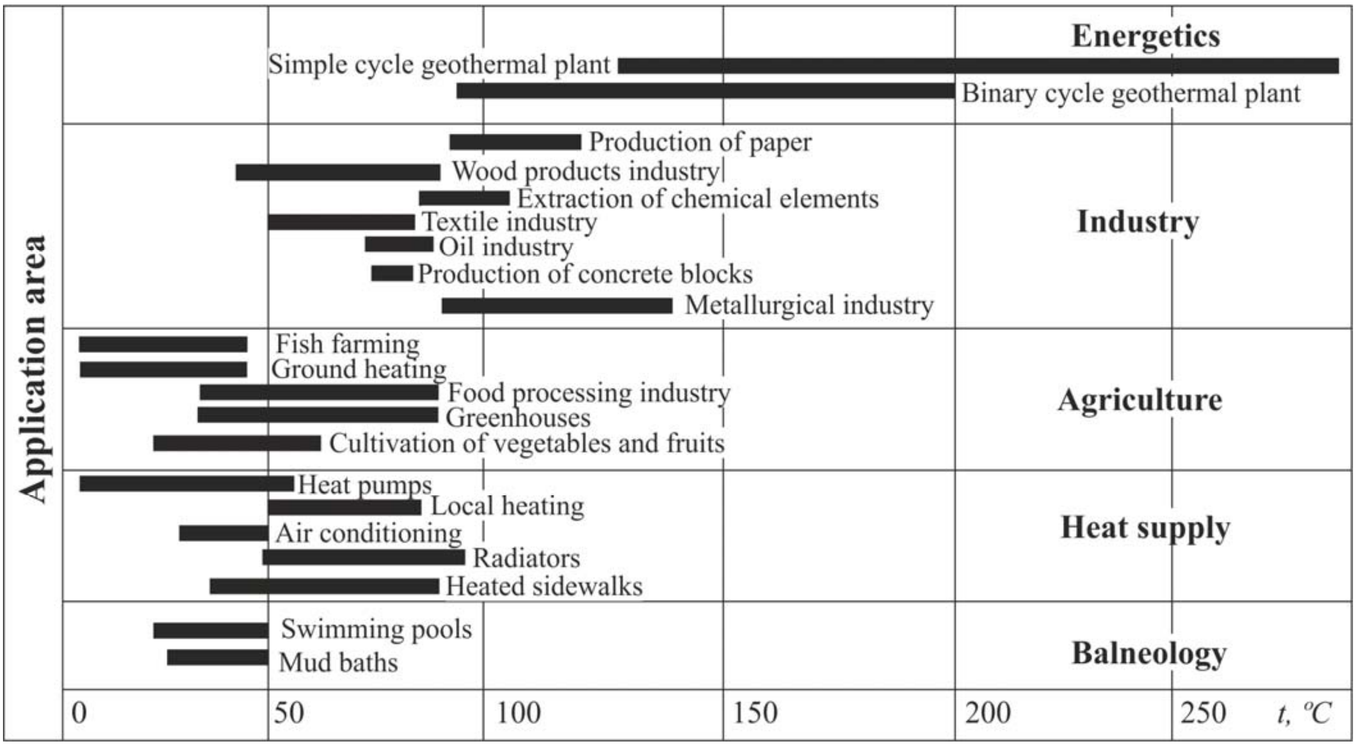


Fig. 1.1. Geothermal waters of different temperatures use [Povarov, 2003]

There has also been a sharp increase in volumes and the expansion of areas of use of geothermal resources (Table 1.1., Table 1.2).

Table 1.1. Total worldwide installed capacity from 1995 up to end of 2015 and short term forecasting for continent [Bertani, 2015]

	Installed in 1995	Energy in 1995	Installed in 2005	Energy in 2005	Installed in 2015	Energy in 2015	Forecasting for 2020
Country	MW	GWh	MW	GWh	MW	GWh	MW
Europe	722	3881	1124	7209	2133	14821	3385
Africa	45	366	136	1088	601	2858	1601
America	3800	21303	3911	25717	5089	26353	8305
Asia	1980	10129	3.290	18903	3756	22084	6712
Oceania	286	2353	441	2792	1056	7433	1440
Total	**6832**	**38032**	**8.903**	**55709**	**12635**	**73549**	**21443**

In the period from 2005 to 2010, the production of electricity on the basis of geothermal waters in Russia has increased by 419% [Bertrani, 2010]. It happened as a result of the development of this alternative energy in Kamchatka and the Kuril Islands.

Table 1.2. Examples of countries installed capacity and produced energy from geothermal resources [Bertani, 2015]

COUNTRY	Installed in 2010	Energy in 2010	Installed in 2015	Energy in 2015	Forecast for 2020	Increase since 2010			
	MWe	GWh	MWe	GWh	MWe	MWe	GWh	Capacity %	Energy %
China	24	150	27	150	100	3		12%	
Costa Rica	166	1131	207	1511	260	42	380	25%	34%
France	16	95	16	115	40		20		21%
Germany	6.6	50	27	35	60	20	-15	280%	-30%
Iceland	575	4597	665	5245	1300	90	648	16%	14%
Indonesia	1197	9600	1340	9600	3500	143		12%	
Italy	843	5520	916	5660	1000	74	140	9%	3%
Japan	536	3064	519	2687	570	-16	-377	-3%	-12%
Kenya	202	1430	594	2848	1500	392	1418	194%	99%
Mexico	958	7047	1017	6071	1400	59	-976	6%	-14%
New Zealand	762	4055	1005	7000	1350	243	2945	32%	73%
Philippines	1904	10311	1870	9646	2500	-34	-665	-2%	-6%
Russia	82	441	82	441	190				
Turkey	91	490	397	3127	600	306	2637	336%	539%
USA	3098	16603	3450	16600	5600	352		11%	
Total worldwide	**10897**	**67246**	**12635**	**73549**	**21443**	**1738**	**6303**	**16%**	**9%**

At the same time, according to the table 1.2 in the period from 2010 to 2015 there was no growth in electricity production from the use of geothermal waters in Russia. Worldwide geothermal waters direct use increased as well (Table 1.3).

Table 1.3. The direct use of geothermal waters in 2010 (first 20 countries by the number of energy used per year are listed) [Lund et al., 2010]

Country	Capacity, MW	Annual use (2010), TJ/year	Annual use (2010), GWh/year
1	2	3	4
China	8898	75348.3	20931.8
Usa	12611.46	56551.8	15710.1
Sweden	4460	45301	12584.6
Turkey	2084	36885.9	10246.9
Norway	3300	25200	7000.6
Iceland	1826	24361	6767.5
Japan	2099.53	15697.94	7138.9
France	1345	12929	3591.7

1	2	3	4
Germany	2485.4	12764.5	3546
Holland	1410.26	10699.4	2972.3
Italy	867	9941	2761.6
Hungary	654.6	9767	2713.3
New Zealand	393.22	9552	2653.5
Canada	1126	8873	2464.9
Finland	857.9	8370	2325.2
Switzerland	1060.9	7714.6	2143.1
Brazil	360.1	6622.4	1839.7
Russia	308.2	6143.5	1706.7
Mexico	155.82	4022.8	1117.5
Argentina	307.47	3906.74	1085.3
Total	**50583**	**438071**	**121696**

The prospect and expediency of geothermal waters development is justified by the following advantages of geothermal resources in comparison with traditional sources of energy: renewability, proximity to the customer, the possibility of full automation, security of production, economic competitiveness, the possibility of building low-power facilities and environmental friendliness [Kagel, 2007]. However, their specificity includes a number of disadvantages: dispersion of the sources, limited experience in industrial applications, low temperature capacity of coolant, problems with transportation, storage difficulties, lack of special legislative framework and insurance systems [Boguslavskiy et al. 2000; Boguslavskiy 2004, 2010].

In 2012, the International Agency for Renewable Energy (IRENA) and the International Energy Agency (IEA) launched the joint development of a database on renewable energy policies of countries and measures to develop geothermal energy [Cherkasov et al., 2015]. Researchers estimate that by the end of the XXI century the share of geothermal resources in the energy balance of the world economy will be from 30 to 80% [Huttrer, 2000; Lund, Freeston, 2000].

1.2. The development of geothermal waters use in Russia

Despite the fact that in Russia the share of geothermal energy in the total energy is small (< 1%) [Svalova, 2015], its development has a fairly long history.

In the Soviet Union the use of geothermal resources was divided into 5 major types [Pryde, 1976]:

1. Balneology and resorts.
2. Extraction of chemical elements.
3. Heating.
4. Agriculture.
5. Production of electricity.

The initial development of geothermal energy began in two regions – Kamchatka and the North Caucasus. In the first case geothermal water was used to generate electricity, and in the second to produce heat.

On the 15 of March, 1954, the Presidium of the Academy of Sciences of the USSR adopted a resolution on the establishment of the Laboratory for the study of geothermal resources in Petropavlovsk-Kamchatsky. Later, in 1964, the decision of the Department of Earth Sciences of the USSR formed the Scientific Council for geothermal research, which later became the Scientific Council on geothermal energy. The North Caucasian drilling and rehabilitation of oil and gas wells for geothermal heating exploring expedition was organized in the same year.

In 1965, Soviet scientists S.S. Kutateladze and A.M. Rosenfeld patented geothermal power plant to generate electricity from hot water with temperature over 80 °C [Kutateladze, Rosenfeld, 1965]. In 1966, on the Kamchatka Peninsula (the Pauzhetka River) the first geothermal power plant of 5 MW capacity with a traditional cycle was built and launched. Capacity of Pauzhetka geothermal power plant by 1980 was equal to 11 MW. In 1967 Paratunka geothermal power plant was launched, which was built on the basis of the unique technology of using a binary cycle power generation of S.S. Kutateladze and A.M. Rosenfeld. Many countries bought their patent later.

Mutnovsky and Verchne-Mutnovsky geothermal power plants (launched in 2002 and 1999 respectively) are unique not only in Russia, but worldwide. Plants are situated at the foot of Mutnovsky volcano, at an altitude of 800 m above sea level, and work in extreme climatic conditions. Stations equipment is one of the most modern in the world and is completely created by Russian enterprises of power engineering. These stations provide 40% of electricity in the overall structure of the Central Kamchatka energy hub [Degtyarev, 2013].

Heating on the basis of geothermal waters in the USSR was developed mainly through the creation of small units for heating, hot water supply and spa treatment.

Obtaining energy from geothermal waters was practiced even before the Great Patriotic War in the North Caucasus region. The Caucasian commercial control of the use of geothermal heat was established in 1966 in Makhachkala, similar Kamchatka commercial management was organized in 1967 in Petropavlovsk-Kamchatsky.

Unfortunately, low hydrocarbon prices in the 1970s, the crisis of the 90s, and then the tragic events related to the wars in Chechnya slowed down the development of geothermal energy in Russia and in the North Caucasus region in particular.

1.3. Russian geothermal potential

Currently geothermal studies are conducted in more than 60 scientific institutions of the Russian Federation. Geothermal resources of our country are well studied [Vartanian et al., 1999; Kononov et al., 2005]. As back as in 1983 on the basis of major works, employees of VSEGINGEO made “Geothermal waters of the USSR atlas”, which It includes 17 maps: “Map of thermal waters of the USSR”, “Map of potential reserves of thermal waters of the USSR”, maps of operational thermal waters reserves of the main aquifers of the most promising regions (Western Siberia, the Caucasus, Kamchatka, Kuril Islands). It is possible to create heating systems with temperatures of 70 °C at the input and 20 °C at the output almost on the entire territory of our country and about 70% of the territory – 90/40 °C [Svalova, 2009].

To date, there are 66 explored deposits of geothermal waters in the Russian Federation (Table 1.4), the reserves of thermal waters and steam are estimated at 307 and 40.7 thousand m^3/day respectively, but only 50% of these stocks is used for the production of 1.5 million Gcal of heat, which is equivalent to burning about 300 thousand tons of coal equivalent [Alkhasov, 2011].

Table 1.4. Geothermal waters deposits of the Russian Federation [Alkhasov, 2008]

The subject of the Russian Federation	Number of deposits	Temperature, °C	Exploitation reserves, thousand m^3/day	Production, thousand m^3/day	The amount of the replaced fuel, tones of coal equivalent/year
The Republic Of Dagestan	12	40 – 104	86.2	10.4	71400
The Chechen Republic	14	60 – 108	64.68	-	-
Krasnodar Krai	13	72 – 117	35.574	4.39	49400
Stavropol Krai	4	55 – 119	12.2	1.0	2800
The Republic Of Adygea	3	70 – 91	8.98	2.1	13300
The Karachay-Cherkess Republic	1	50 – 75	6.8	0.4	2900
The Kabardino-Balkar Republic	2	56 – 67	5.3	0.05	-
Kamchatka	12	70 – 300	83.8 (32.5*)	34.3	151900
Sakhalin Oblast	2	85 – 320	8.2*	-	-
Chukotka Autonomous Okrug and Magadan Oblast	3	60 – 87	3.5	-	-
Total	**66**				**291700**

*Water-steam mixture

As it can be seen from table 1.4, the largest number of deposits is located on the territory of the Chechen Republic and then comes Krasnodar region, Dagestan and Kamchatka. Kamchatka among the above mentioned regions stands out for high temperature geothermal waters, at the same time demand for electricity is low and the remoteness of the consumer significantly undermines the prospects of development of its deposits.

Geothermal water is used in 150 health centers and 40 plants for bottling mineral water. Electricity is generated by some geothermal power plants located on the Kamchatka Peninsula and the Kuril Islands (Table 1.5) [Svalova, 2012].

Table 1.5. Production of electricity by thermal power water in Russia [Svalova, 2012]

Location	Power plant	Year of commissioning	Number on the map	Total installed capacity, MW	Annual use (2008), GWh/year	Planned capacity, MW
Kamchatka	Pauzhetka	1966	3	14.5	59.5	2.5
Kamchatka	Verchne-Mutnovsky	1999	2	12	58.3	
Kamchatka	Mutnovsky	2002	1	50	322.93	
Kuril, Kunashir island	Mendeleevskaya	2007	5	1.8	-	3.2
Kuril, Ituryp island	Okeanskaya	2007	4	3.6	-	
Total				**81.9**	**440.73**	**5.7**

Currently, geothermal resources in Russia are also used to heat houses with total population of 500 thousand in several cities and towns of the North Caucasus and Kamchatka [Khutorskoi, 2011]. Furthermore, in some regions, thermal waters are used for greenhouses heating with total area of 465000 m^2.

1.4. History of the Khankala geothermal waters deposit development

The first geological survey of the North Caucasus (Figure 1.2) refers to the XVIII century and is associated with the beginning of the study of mineral waters [Sidorenko, 1968]. By order of Peter I in 1717, doctor of medicine G. Schober described the mineral springs. In 1771, I.A. Gildenshtedt examined Goryachevodsk sources, in 1828, G. German carried out chemical analyzes of mineral waters, in 1852 N.N. Zimin determined the composition of the gas dissolved in the water [Kerimov, 2012].

A new stage in the study of groundwater begins with the development of drilling. Until now, geological and hydrogeological investigations were not systematic and descriptive.

In 1860-70-ies G.V. Abikh, F.G. Koshkul and A.M. Konshin studied rocks related to mineral sources. They determined the temperature, flow rates, and the chemical composition of water. The relationship between mineral sources and oil deposits was suggested for the first time and anticlinal structure of the Terek and Sunzha ranges was found.

Fig. 1.2. Location of the Chechen Republic on the map of the Caucasus. Source: Wikipedia.

In 1880-ies I.V. Mushketov identified two large tectonic zones – the Greater Caucasus and the Stavropol uplift based on the studies of geology and geomorphology of the area, and a project for mineral waters development with a description of the reservoirs strata was sugested.

At the beginning of the XX century due to the increase in drilling operations there was a lot of factual material on the lithology, oil-content and waters of Karagan-Chokrak (the Middle Miocene) deposits, which are associated with the Khankala geothermal waters deposit.

In 1904, I.N. Strizhov detailed geological and hydrogeological structure of individual areas of the Front Ranges. He was the first to point to the presence of the anticlinal structure in Oktyabrsk district. The Oktyabrsk uplift is located in the eastern part of the Sunzha anticlinorium and in landscape is expressed by Aldynsk ridge, dissected by Khankala valley into western part – Syuir-Court and eastern part – Syuil-Court. In subsequent years, geologists Ernie and L.I. Baskakov proposed to begin drilling in the area, but it was postponed due to the absence of signs of oil at the surface.

Only in 1911 the English company “Bray”, the industrialist-engineer Makanaky established well № 1-16. It became the pioneer of the Oktyabrsk oil field from which on the February 6, 1913 at a depth of 560 m gusher was obtained with the rate of about 20 tons per day. The history of geological and hydrogeological studies of the Khankala geothermal waters deposit is inseparably linked to the exploration and development of the Oktyabrsk oil deposit at the south-eastern part of which the first is situated. As back as in the 20s of the last century a thermal water source was discovered at the site of the Oktyabrsk oil field. The highest flow rate of 2500 m^3/day with the wellhead temperature of 96 °C was obtained in 1928 from the well number 1-28.

The study of groundwaters was initiated almost simultaneously with the development of the area for oil (1913-1914). Drilling results were used by K.A. Prokopov to compile a structural map of Oktyabrsk anticline and to conduct a detailed research in its oil-bearing area. However, because of the Civil War almost all the gathered data were completely lost.

In the 1920s, complex regional hydrogeological and geological studies were conducted, which resulted in water classification according to chemical composition.

In 1925 the XXII layer of the Oktyabrsk deposit was drilled at the depth of 1600 m. By this time, N.T. Lindtrop held hydrodynamic analysis of oil field development [1925]. He came to the conclusion that was a water drive regime in Karagan-Chokrak deposits region. Engineers I.N. Strizhov and N.T. Lindtrop found that with an increase in oil production from the XIV and XVI layers of the Oktyabrsk deposit water sources which were located at a distance of several tens of kilometers ran low and vice versa, with a decrease in production yield sources flow rate restored. The flow rate of the Eastern thermal spring in Goryachevodsk which was related to the XIII productive layer at the begining of the exploitation of the layer in 1916 gave 1,220 m^3/day and in 1932, when the water level in the wells dropped to the level of the source, it dried up. Thus, it was confirmed that the oil in the formation was included in a hydraulic system with water [Kartcev, 1977].

In 1928 the work of N.A. Kudryavtsev "On the structure of the Novo-Grozny oil region", which described in detail the geological structure and tectonics of the area, was published. In 1928-1929 exploitation of the XIX, XX, XXI layers was started. In 1930 as a result of a detailed study of groundwater there was an evidence of the presence of radioactivity. The works of A.D. Arkhangelsky and E.S. Zalmanzon devoted to lithology and groundwater Grozny district belongs to this period [Arkhangelsky, Zalmazon, 1931, 1932].

The first mentioning of the use of geothermal waters in the area is related to the oil well № 10-28 of the Oktyabrsk deposit, from which thermal waters were obtained and used for heating greenhouses and sauna.

In 1934-35 K.K. Korovin conducted radio-wave prospecting works on the north limb of the Oktyabrsk anticline, created cross-sections and structural map and identified some of the tectonic features of the area: the fold dips to the east and the presence of the gap, stretching along the northern limb.

Great contribution to the study of geology, hydrogeology, hydrochemistry and geothermy was made by G.M. Sukharev [1947, 1948, 1954, 1963]. In his works he compiled a large amount of factual material on the waters of oil and gas deposits, touched the problem of the use of geothermal waters of the North Caucasus. G.M. Sukharev became a member of the editorial board of IX volume of the "Hydrogeology of the USSR" (North Caucasus), which was published in 1968. During these years, the works of V.M. Nikolaev and S.A. Shagoyants on hydrology of the North Caucasus and Ciscaucasia were published [Nikolaev, 1960, 1963, Shagoyants, 1959].

In 1962, the expedition of the "Sevkavgeolupravlenie" compiled hydrogeological maps of the entire territory of Chechnya (K-38-III, IV, IX, X). Hydrogeological survey on scale 1:200 000 on sheet K-38-III was presented and in 1965 the hydrogeological map was published (T.M. Lamanova).

As a result of exploratory drilling T.V. Loskutov (1964) and A.I. Kashin (1965) compiled hydrogeological maps of sheets K-38-IV and K-38-IX. N.A. Grigoriev, E.T. Melnikova and others conducted a great number of regional case studies, published specialized maps of the North Caucasus, scale 1:500 000 (1973).

In 1963 a monograph of G.M. Sukharev and M.V. Miroshnikov “Groundwaters of oil and gas fields of the Caucasus” with detailed analysis of hydro, geothermal and hydro-chemical conditions was published.

Next year under the leadership of K.I. Sheipak regional report “Revision examination of exploration and production wells of the North Caucasus, promising on thermal water” was compiled, emphasizing the territory of the Chechen-Ingush Autonomous Soviet Socialist Republic and containing a catalog of boreholes of the North Ciscaucasia as potential sources of thermal waters.

In 1964-66 under the leadership of A.I. Khrebtov hydrothermal maps of the most promising areas of the North Caucasus (scale 1:500 000) and more general maps of the thermal waters of the North Caucasus (scale 1:200 000) were made with explanatory notes.

Start of commercial development of geothermal resources was made possible by the accumulation of factual and theoretical material. In accordance with the Resolution of the Council of Ministers on April 19, 1963 № 445 “On the development of the work on the use of the geothermal heat in the national economy” Mingazprom of the USSR led activities on the development and exploitation of this type of energy. Since that time, work on the development of geothermal energy has been the object of constant attention of planners and policy makers.

Scientific research and production work to expand the use of geothermal waters in the economy were determined by “Measures to increase the use of alternative energy sources in the national economy in 1987-1990”. Plans for the development of geothermal energy were stated in the “Energy Program of the USSR”.

During this period, special investigations on geothermal waters of the North Caucasus were initiated and performed by A.I. Hrebtov, I.Y. Kotsareva, S.P. Vlasova, S.A. Jamalov [Jamalov, 1959; Kotsarev, Vlasova, 1963; Hrebtov, 1965].

In March 1964, in Moscow, the second All-Union Conference on the problems in geothermal development was held. On May 25, 1964 Office of the Regional Committee of the CPSU and the Council of Ministers of the Chechen-Ingush Autonomous Soviet Socialist Republic adopted Resolution № 1296 “On measures to develop the greenhouse agriculture and to increase production of vegetables hydroponically based on the use of geothermal water and industrial waste heat of the Republic”. In accordance with the resolution it was planned to build large greenhouses (100000 m^2) on the basis of thermal waters at the Khankala deposit site.

There is a great number of studies on the assessment and prospects of geothermal energy use in the area, especially the works of V.B. Krylov and A.A. Shpak [Shpak, 1968f; Krylov 1977f, 1981f, 1983f, 1984f, 1986f, 1987f, 1988f].

In the seventies, the VNIPIgazdobycha Institute conducted detailed exploration of the Khankala deposit which is located 10 kilometers southeast of Grozny (Fig. 1), filtration reservoir parameters were calculated, operating reserves of thermal waters were evaluated and approved by the State Reserves Committee of the USSR (01/01/1968). Regular water withdrawals started only in 1974, when greenhouses were fully put into operation. 2-T, 1-T, 3-T, 13-T, 14-T, 6-T, 5-T, 4-T and other wells were drilled and 27-32, 33-28, 10-28 old oil wells were restored.

Exploitation of the Khankala deposit of geothermal waters was conducted by the North Caucasian field management on the use of geothermal heat. The main exploitation objects were IV-VII, XIII Karagan and XXII Chokrak layers, the average thickness of which is 43, 47 and 28 m, respectively. Subsequently extraction of water from the XXII layer was forbidden by State Technical Supervision in order to protect Sernovodsk sources from exhaustion, although the results of the work revealed the possibility of extracting 3000 m^3/day from this layer. At the initial stage of the deposit exploitation the water levels in wells almost fully recover during the interruption of production in the summer time [Krylov, 1987f].

But since the beginning of 1978 reinjection of water obtained with oil from Karagan-Chokrak deposits at the October oil field was decreased and then was almost completely stopped. At the same time, the extraction of the geothermal waters was increased. These factors have led to a gradual progressive reduction of piezometric levels in reservoirs. For three years the piezometric levels on the main geothermal productive layers decreased by more than 20 m [Krylov, 1987f].

Analysis of the Khankala deposit exploitation revealed the inability of growth of proven reserves by expanding the existing water withdrawal without artificial reinjection.

Because of this G.M. Sukharev, S.P. Vlasova, J.K. Taranukha and E.V. Kowalski conducted in the Grozny Oil Institute (1978-79) technical-economical justification of the possibility to recover of geothermal water resources through the establishment of a geothermal circulation system (GCS).

In 1981-1982 a pilot exploitation of the XIII productive layer with reinjection of the used geothermal waters was performed in order to maintain reservoir pressure. The method of artificial replenishment of reserves was used (Figure 1.3).

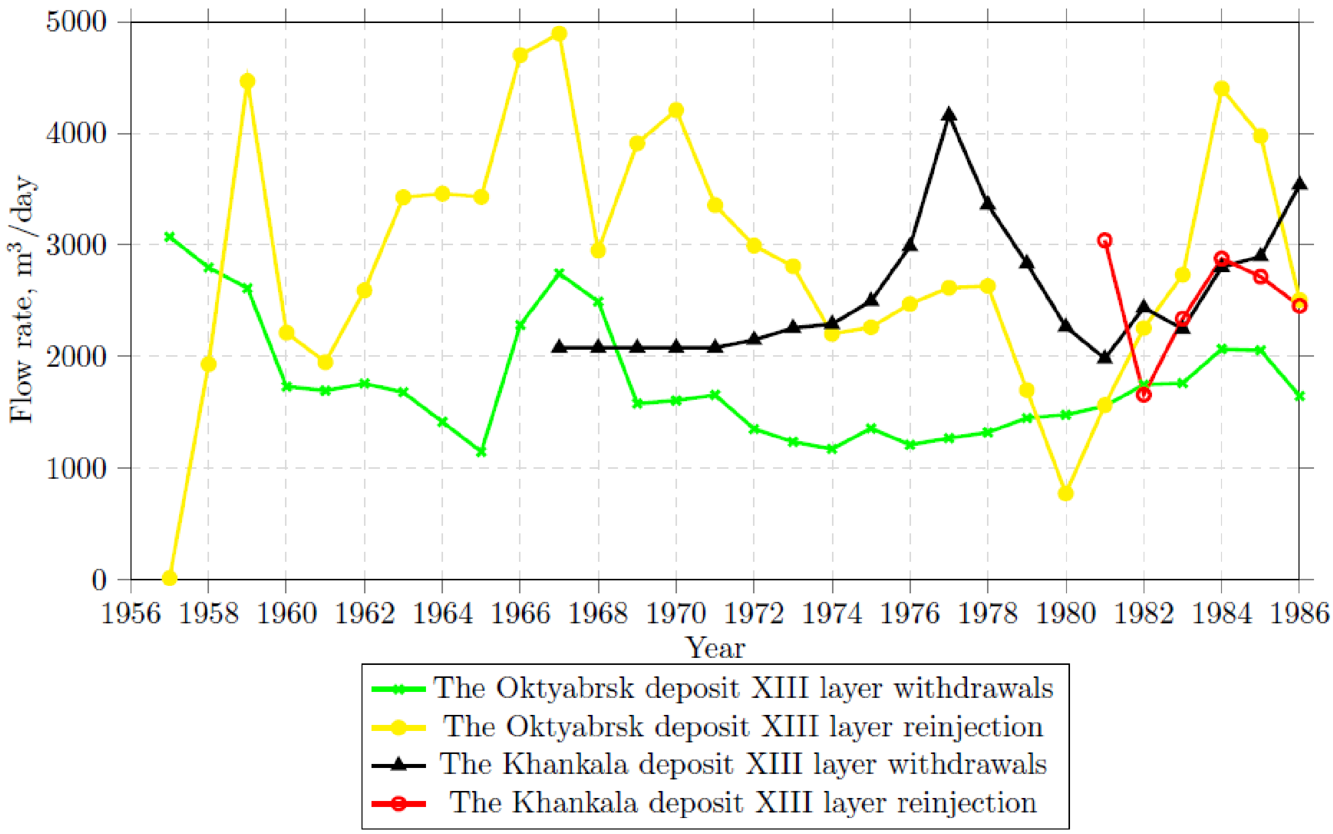


Fig. 1.3. The XIII layer production and reinjection [Krylov, 1987f]

Results of research and experimental exploitation of the XIII layer with maintaining of the reservoir pressure revealed the possibility of using this method to increase performance of the Khankala deposits exploitation. During these works an extensive program of hydrodynamic studies was carried out and it was continued in 1982. Its results form the basis of calculation for the establishment of an underground circulation system.

As shown in the diagram, the injection has stopped the decline and has significantly increased geothermal waters production rate. At the same time, the reinjection of used waters into productive layers is a very effective tool of preventing environmental pollution. The work which was performed proved the possibility of further expansion and the ability to increase production of geothermal waters through the introduction of the reservoir pressure maintenance system for all major operating facilities.

In the USSR it was the first geothermal circulation system (5 production and 4 injection wells). Recovered old oil wells 31-25, 29-25, 33-25 and 52-25 were used for reinjection into the XIII layer.

Geothermal waters of the Khankala deposit in general were used for heat supply of the state farm. Waters were directly transported from the pump station to the heating system and then partially discharged on the surface and then transported to the pump station for reservoir pressure maintenance.

The amount of injected water in comparison with the production was 50-60% [Krylov, 1984f].

Reinjection was subsequently used for exploitation of the IV-VII and XXII layers. In 1981 “Feasibility report on the possibility of heating the city of Grozny and its suburbs by geothermal waters” was made, suggesting flow-rates equal to 70000 m^3/day with subsequent reinjection. It was planned to continue this work. But in 1994 because of the war on the territory of the Republic the exploitation of the Khankala deposit was stopped [Farkhutdinov, 2014]. Due to these tragic events a lot of data on the geothermal deposit were lost and currently, the water is used by local population in a primitive way with subsequent discharge [Farkhutdinov et al., 2014]

In 2013 Grozny State Oil Institute, LLC “ArenStroiCentr” and Vernadsky state geological museum within the consortium “Geothermal resources” and scientific accompaniment of the BRGM (“Bureau de recherches géologiques et minières”) started a pilot project to build a geothermal plant on the basis of the most promising XIII layer of the Khankala geothermal waters deposit of the Chechen Republic. Capacity of the facility is 5.45 Gcal/hour, with a greenhouse complex as a consumer. Geothermal station works with a doublet which is represented by a closed loop of one production and one injection well.

Worldwide experience in the construction of geothermal power plants with circulation systems shows that the most effective solutions are represented by doublet systems. At the same time in Russia, except the Khankala, there is no geothermal plant using such scheme – all the known examples of the usage of sedimentary basins geothermal waters imply artesian wells with subsequent discharge onto ground or into surface-water bodies [Malyshev et al., 2015].

Despite the fact that Russia has large proven resources of geothermal waters they are not widely used. Thermal waters direct use, electricity production and related domains are not well developed here. There is no geothermal plant with circulating loop – doublet, besides the Khankala station, all other known russian examples of geothermal waters use in sedimentary basins are with subsequent discharge onto ground or into surface-water bodies. That is why it is essential to analyze and utilize foreign experience during the Khankala geothermal waters deposit development. The Khankala station was successfully launched in the beginning of 2016 and it is supposed to provide usefull experience and begin a new phase in the exploration and development of geothermal waters of the region.

Chapter 2. Physico-geographical, geological and hydrogeological conditions of the study area

The Chechen Republic is a part of the Southern Federal District and the Northern Caucasus economic region of Russia. The area is 16000 km^2, with the population of 1370268. The length of the territory from north to south is 170 km, from west to east – 110 km. It borders in the west with the Republic of Ingushetia, in the north-west – with the Republic of North Ossetia-Alania, in the north – with the Stavropol Krai, in the north-east and east – with Dagestan, in the south – with Georgia. The southern border of Chechnya coincides with the state border of the Russian Federation and goes along the crests of ridges.

Physical-geographical conditions of the study area are given according to the works of Gvozdetsky [1958], Gerasimova [1966] and Gordeeva [2001f].

2.1. Geographical location and relief

The Republic is located in the Northern Caucasus, in the valleys of the rivers Terek and Sunzha. Its territory covers the northern slopes of Greater Caucasus and the surrounding steppes and plains. About 35% of the territory of the Chechen Republic is occupied by mountain ridges, valleys and intermountain basins. The rest of the territory is plain, mostly rugged by hills.

There are four zones within Chechnya according to physical-geographical conditions: alpine, mountainous, foothill and plain (Figure 2.1). On the territory of the Chechen Republic from the north to the south there are large geomorphic elements: *Zaterechnaya plain, Priterechnaya plain*, *Terek ridge, Sunzha Ridge, Alhanchurtsk valley, Sunzha valley, Gudermes ridge, Gudermes plain, northern slope of the Caucasus Mountains.*

The Zaterechnaya valley is located in the northern part of the republic beyond the Terek River, in the east it goes into the Caspian lowland. Absolute elevations decrease from west to east from 120 m to 50 m. The surface of the plain is covered with fixed and unfixed sands and it forms a continuous bumpy terrain.

Fig. 2.1. Physical map of the Chechen Republic

The Priterechnaya valley is situated between the Terek River and the Terek ridge. Its surface is inclined to the northeast. In the south, the terrace turns into a gentle slope of the Terek ridge.

The Terek ridge is a system of anticlinal folds, represented by Neogene sediments and complicated by secondary folds, tears and thrusts. It has almost latitudinal direction and extends, crossing the western border of Chechnya, to the east. Its northern slope is gentle, southern is steep.

The Alhanchurtsk valley is located between the Terek and Sunzha ridges. Its width varies from 10 to 15 km. In the east, the valley is divided into two branches by Grozny ridge.

The Sunzha ridge is parallel to the Terek ridge and has the same folds system. The folds are inclined to the south, and the watershed line is shifted to the northern limb of the crease. The top of the ridge within the area under consideration have elevations exceeding 500 m. The southern slope of the Sunzha ridge, as well as the Terek ridge is steeper. The system of the two ridges has one common name Front ridges.

The Sunzha valley is situated between the Front ridges and the Black Mountains. The northern border is the southern slope of the Sunzha ridge, the southern – the northern slope of the Greater Caucasus. The plain falls to the north from 300 m to 150 m above sea level. It is a synclinal fold, which axis is shifted to the north.

The eastern extension of the Terek ridge, isolated by valleys of the Sunzha and the Belka rivers, is the *Gudermes ridge*. Its length is 32 km, the orientation is from the north-west to the south-east, the width is 4–4.5 km and the relative excess from the foothill is 320–450 m. The Gudermes ridge in the east direction gradually approaches the Black Mountains and near the river Aksai the ridge is connected with them.

The Gudermes plain is flat, slightly inclined to the north, north-east. Its northern border is the Terek River. In the east the plain is separated from the Terek-Sulak plain by Aksai alluvial cone, in the south it gradually turns into a slope of the Gudermes ridge, to the west borders with the Bragun and the Gudermes ridges, to the north it merges with the Terek-Kuma lowland.

The northern slope of the Caucasus mountain ridge in the Chechen Republic is represented by two mountain ridges – the Side and Rocky ridges. The highest point of the ridges from west to east are: the Tsuzunkort (3438 m), the Maistismta (4081 m), the Shaihkort (3942 m), the Donosmta (4174 m), the Diklosmta (4285 m), etc. There is a snow limit at an altitude of 3400 m above sea level. To the north there are mountains that separate the Side and the Rocky ridges, dissected by tributaries of the Argun and the Assa rivers.

The Khankala geothermal waters deposit is located within the Khankala valley. It is an ancient Argun River valley with strike direction close to meridional. The north-western edge of the valley is the steep slope of the Suir-Court hill. The highest point of the hill is Belik-Bartz with an absolute altitude of 396 m. The Suil-Court hill is situated to the east from the Khankala valley. The highest point (Jemi-Bartz) reaches the altitude of 435 m. In the southeast direction the hill is steeply replaced by the Argun River modern valley. Still farther to the southeast, beyond the river Argun, the Goity-Court hill is located (236.6 m). All these hills are remnants of once existed single ridge. The absolute altitude of the surface within the Khankala valley is 170–180 m. The width of the valley within the area is not more than 2–2.5 km.

2.2. Climate and hydrography

The climate of the Chechen Republic is mainly moderately continental. In the northern part of the territory the climate is dry, continental. In the southern part the climate is moderately warm, dry, continental on the plains and softer and moderately humid at foothill and mountain areas. Summer is hot (the average temperature in July is +24.5 °C), winter is moderately cold (the average temperature in January is –3.4 °C), the average annual temperature is +11 °C. The maximum temperature in summer is +42 °C, the absolute minimum in winter is –32 °C.

Distribution of precipitation is uneven both within the republic and during the year. The average annual precipitation varies widely depending on area. The greatest number of it falls in June, the smallest – in January and February, and in the northern part it is 300–400 mm and in the mountainous parts it reaches 500–800 mm.

The snow cover is unstable, it reaches 8–10 cm, rarely 35–87 cm and sometimes lasts until March. The maximum depth of freezing reaches 0.6–0.7 m, the average is 0.1–0.2 m.

In winter, cold dry easterly winds dominate. They bring low fogs from the Caspian Sea which settles in the foothills. In the spring, these winds are transformed into dry winds. In early summer, the south-westerly winds bring warm and moist air masses from the Black Sea and the Mediterranean, so maximum precipitation occurs in the first half of the summer.

The largest rivers of the area under study are Terek, Sunzha, Argun and Gudermes. The densest hydrographic network is represented within Karagan-Chokrak aquifer recharge area – in the Black Mountains. The hydrographic network fully belongs to the basin of the Terek River, originating in the Main Caucasian ridge it flows through the entire republic from north-west to south-east. The depth of the river is 3–6 m, the width varies from 190 m to 580 m. The average flow velocity is 0.8 m/s, the average annual flow – 305 m^3/s.

The only tributary of the Terek within the territory of the republic is the Sunzha River, originating from springs located near the Black Mountains. The river crosses the whole territory of Chechnya from west to east. The rivers length is about 200 km, the width of the channel in the vicinity of Grozny is up to 50 m, the average depth – 0.6 m. The average flow velocity – 0.8 m/s, the average long-term flow rate is 31.9 m^3/s. Glaciers and alpine snow are one of the river recharge sources.

The Sunzha River, in its turn, has a number of tributaries: the Khulkhulau, the Argun, the Assa and several smaller rivers flowing mainly from south to north. The largest of them is the Argun River. The depth of the river is up to 1.3 m, the width of the channel varies from 40 m to 350 m, flow velocity – 1.7 m/s. The mean annual flow is 43.3 m^3/s, the maximum flow rate – 280 m^3/s, the minimum flow rate – 11 m^3/s.

2.3. Stratigraphy

Consideration of the conditions for the geothermal water resources formation requires a detailed analysis of the stratigraphy of the area under study. The Khankala geothermal waters deposit belongs to the Oktyabrsk anticline along with the oil field of the same name, that's why there are many drilled wells and reports on the area under consideration.

The stratigraphy is presented in the works of A.A. Shpak [1968f] and V.B. Krilov [1987f, 1988f].

Description starts with the Neogene sediments, as no geothermal waters were allocated in the underlying deposits (Appendix 1A).

Neogene (N)

Miocene Division (N_1)

The Miocene Division is divided into three sub-divisions: lower, middle and upper. The Maikop formation represented by clays belongs to the Lower Miocene. The formation is a regional aquitard separating the Mesozoic hydrogeological level from the overlying formations. Its thickness within the Oktyabrsk structure changes from 1100 to 1800 m.

Middle Miocene subdivision (N_1^2)

The Middle Miocene is represented by four stages: Tarkhan, Chokrak, Con and Karagan. Due to the small thickness of the Tarkhan and Con, within the description they are combined with Chokrak and Karagan, respectively. The geothermal water deposits of the Chechen Republic are related to formations of these stages, therefore a layer by layer description is given (Figure 2.2).

Chokrak stage ($N_1^2\check{c}h$)

Sediments of the stage outcrop in the crest of the anticline of the Terek-Sunzha region, and extend along the Black mountains monocline.

Chokrak sediments are represented by alternation of sandstone and clay layers with clay-carbonate interlayers. These interlayers are composed of argillaceous limestone, dolomite, ankerite, siderites and marl.

Layers from XXIV to XV of the Chokrak are productive; layers from XXII to XV were drilled on the territory of the Khankala deposit.

The sandstones are mainly composed of quartz (85–90%), fine-grained, more rarely of fine-medium-grained structure with pore clay-carbonate cement. The Chokrak clay sediments are gray, dark gray, brown.

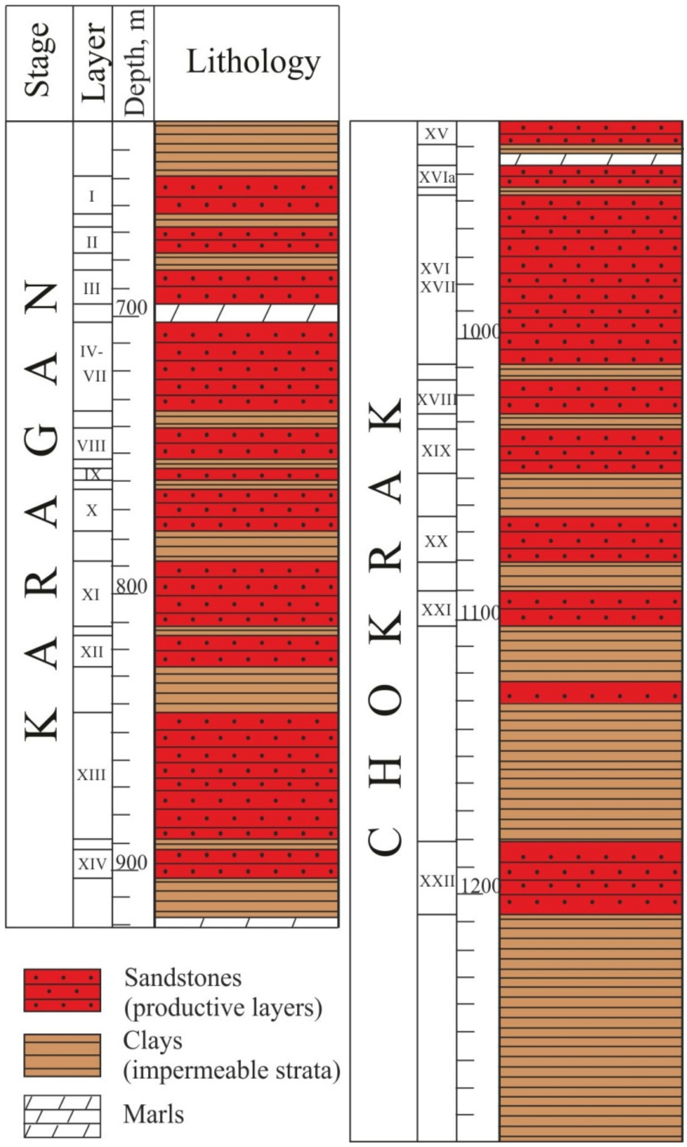


Fig. 2.2. Averaged section of the productive Karagan-Chokrak sediments at the Oktyabrsk anticline south-eastern dipping [Shpak, 1968f]

The XXII layer has the most stable thickness in the area.

The thickness of the Chokrak formation within the area varies from 600 to 450 m from east to west.

The formation in the area of Oktyabrsk territory begins with marl of 7–10 m thickness, light gray color. The fauna is represented by thin-walled shells:

Syndesmia alba Urod vor,

Syethica Sokol,

Spirialis tarchanesis Rittl,

Spirialis volvatica Reuss,

Spirialis nucleates Zhizh.

The next is the XV layer, represented by dark gray fine-grained quartz sandstone with glauconite. The thickness of the layer is 10–12 m, maximum porosity is 20%.

Between the XV and XVI layers there is a brownish-gray clay layer about 5–7 m thick.

Within Oktyabrsk structure the XVI layer is clearly seen on the well-logging records. Gray fine-grained quartz sandstone interbedded with laminated dark gray clays is situated in the upper part. The lower part is represented by gray unconsolidated quartz sandstone, interbedded with coarse-grained sandstone. Average resistivity of the layer is 450 ohm (from 50 to 1000 ohm). Porosity is up to 30%, thickness 35–60 m.

The XVII and XVIII layers are separated by dark-gray laminated comminuted clay interlayer. The fauna found in clay:

Syndesmia alba Wood,

Spaniodontella intermedia Andr.

Zeda sp.,

Mactra sp.

Thickness of interlayer is 3–6 m.

The XVIII layer is composed of greenish-gray quartz sandstone with glauconite with clay interlayers. The porosity is 21.5%, thickness of the layer is 10–20 m.

Next is dark-gray clay interlayer with inclusions of pyrite. The thickness is 15–18 m. The fauna is represented by:

Mactra sp.,

Syndesmia alba Wood.

The following XIX productive layer has varying characteristics. In the central part of the Oktyabrsk structure it is composed of fine-grained quartz sandstone with brown micaceous clay interlayers that divide the layer into several parts. In the east anticline dipping sandstone becomes more unconsolidated and clayey. Further to the east the XIX stratum is merged with the XX layer. The porosity ranges from 17 to 21.5%. Thickness of the layer is 6 m in the west and to the east it increases up to 54 m.

Next is medium-grained quartz sandstone of the XX layer with brown micaceous clay interlayers. The average porosity is 25%. The layer thickness is 6 m at the west of the Oktyabrsk structure and it increases up to 42 m in the east, where it merges with the XXI layer.

Next is the XXII productive layer. At the top layer it is presented by coarse-grained sandstone. The grain size decreases downwards the log. Thickness of the layer varies from 40 to 60 m.

The total thickness of Chokrak deposits varies from 500 to 600 m in the area under consideration.

Karagan stage ($N_1^2 kg$)

The Karagan stage deposits come to the surface in the crest and at the limbs of the anticline zones of the Terek-Sunzha area. The outcrops extend by a narrow strip along the Black mountains monocline. The thickness of the Karagan layers is rather constant within the territory, unlike the Chokrak.

The Karagan stage sediments are represented by alternating strata of sandstone and clay within the area of study. 14 productive formations are defined, identified by Roman numerals from XIV to I. They have dark-gray, gray, sometimes brown color. Sandstones are fine-grained, quartz with glauconite, clays are hydromica, illite.

Thickness of the Karagan deposits in the Terek-Sunzha region increases from west to east. The same is with the Chokrak formation. In the Terek ridge, it ranges from 200 to 270 m and on the Sunzha ridge raises from 240 to 320 m.

The Karagan sediments begin by dark-gray, almost black sandy clay. The fauna found in clays is *Spaniodontella pulchella Baily*.

The I productive layer at the top is represented by fine-grained dark gray quartz sandstone with glauconite and clay interlayers. The average porosity is 26.4%, the thickness is 10–15 m.

Layer II is represented by sandstone similar to the I layer composition. Its thickness changes from west to east from 6 to 10 m.

Layer III is composed of greenish-gray quartz sandstone, fine-grained, with glauconite. Porosity is up to 30.2%. The thickness of the layer within the Oktyabrsk structure decreases from west to east from 14 to 8 m.

Layers IV and VII are merged together, so they are not allocated separately and designated as a single productive layer of quartz fine-grained sandstone. The average porosity is 27%. Its thickness ranges from 24 to 34 m.

Next VIII layer is presented by similar deposits. The thickness varies between 4–9 m in western part, increases to 6–14 m in eastern part. The average layers porosity is 16.8%.

The thickness of the IX layer, which consists of sandy clays interbedded with marl, is 8-9 m. The X productive layer is represented by medium-grained quartz sandstone, with the porosity of 23% and the thickness of 15 to 20 m.

Dense ferruginous marl is at the top of the next XI layer. Below layer consists of quartz fine-grained sandstone. The porosity is equal to 25.4%, the layers thickness is 20–24 m.

The XII layer is represented by calcareous marl at the top; the following is fine-grained quartz clayey sandstone with glauconite. Clayiness of the layer increases with depth. The porosity is 22.2%, the thickness is 14–17 m.

The XIII productive layer, which is the Khankala geothermal plant resource, has a thickness of 40–50 m and has a nearly constant thickness over the entire area of the Khankala deposit. It is composed of coarse sandstone, quartz, with glauconite and almost devoid of clay interlayers. Due to large thickness and lithological composition, the formation is clearly seen on the log, and has a fairly high resistance (above 450 ohm). The porosity is 24.1%.

Next XIV layer is composed of fine-grained light-gray sandstone interbedded with brown clay. The thickness of the layer is 6–8 m.

The Karagan stage sediments at the Oktyabrsk structure territory are composed of alternating sandstone and clay. Sandstones are dark gray, with glauconite; their thickness mainly ranges from 4 to 50 m. In the direction from west to east clay content is increasing and thickness of sandstones is reducing. The sandstones are separated by layers of brown and dark gray clay.

The total thickness of the Karagan deposits at the area under study varies from 260 to 300 m.

2.4. Tectonic conditions

Tectonic features and structure of the study area are described in the works of I.O. Brod [1958], N.S. Shatsky [1956], E.E. Milanovsky [1963], V.E. Khain [1950] and others.

In the Terek-Sunzha region there are numerous anticlinal and synclinal folds, united in structural zones. These zones are well expressed in the relief in the form of two chains of low ridges from the western border of the Chechen Republic to the Aksai River (in the east) and allocated on the geological map by lines of the Miocene deposits outcrops, surrounded by the Pliocene sediments.

Tectonically the Khankala deposit of geothermal waters is situated in the south-east dipping axial part of the Oktyabrsk anticlinal structure which belongs to the Terek-Sunzha structural complex.

The Oktyabrsk anticline has a flat, fairly narrow and steep set of limbs, which creates its box-like structure. The size of the fold is 25x3 km, the width at the crest of the Karagan deposits top is 1.25–1.5 km, while for Chokrak it is 600–700 m [Shpak, 1968f].

The Oktyabrsk anticline is complicated by a series of longitudinal and diagonal faults (Figure 2.3), dividing it into 6 tectonic blocks [Ermolaev et al., 1953f]:

I – The western periclinal end of the anticline.

II – The western “wedge”.

III – The western part of the anticline.

IV – The northern “wedge”.

V – The southern “wedge”.

VI – The eastern part of the anticline.

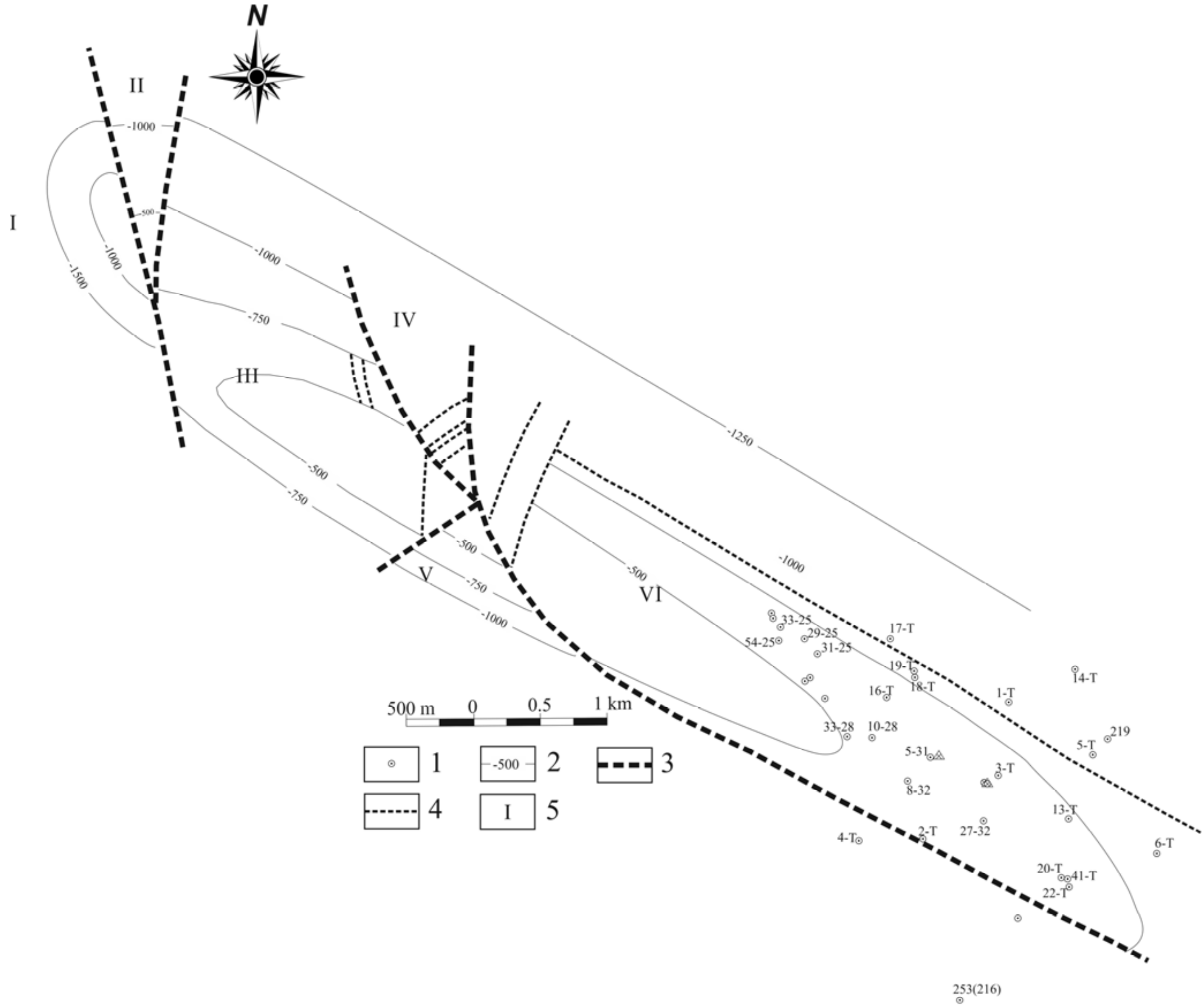


Fig. 2.3. Tectonic scheme of the Oktyabrsk anticline structure [Krilov, 1984f]
Legend: 1 – the Khankala deposit wells, 2 – isolines on the XIII layers top, 3 – major faults, 4 – minor faults, 5 – number of tectonic block.

The crest of the structure is pulled over the southern limb by the main fault. All the faults are damped in the sediments of the Upper Maikop [Krylov, 1987f].

According to the structure the abovementioned tectonic blocks differ from each other:

I – The western periclinal end of the Oktyabrsk anticline is disrupted by a fault of overthrust type oriented from northwest to southeast. The amplitude of the overthrust varies from 50 to 700 m.

II – The western "wedge" is situated in the northern part of the western pericline. It is formed by the junction of the above described northwest fault with normal fault almost of meridional direction.

III – The western part of the fold. The angle of the limbs incidence increases from west to east from 35–50° to 70°. The zone highly complicated by faults of the central tectonic knot begins after the box structure [Krylov, 1987f]. It is represented by a series of overthrust faults with steep surfaces formed by two separate units at the territory of the Oktyabrks structure: the North "wedge" and the southern "wedge".

IV – The northern "wedge" is adjacent to the northern limb of the eastern part of the anticline and separated from it by an additional normal fault with amplitude of 40–45 m. The whole area of the northern "wedge" has several nearly parallel faults.

V – The southern "wedge" separates the eastern part of the anticline from the western and is limited from the east by central normal fault-shift.

VI – The eastern part of the anticline, where the Khankala geothermal waters deposit is situated, is separated from the western part by major diagonal fault approximately parallel to the diagonal western fault. Then the diagonal fault turns to the east, south-east. The main thrust shifts the fold in a southeasterly direction with slide over the south-west.

The width of the crest of the structure at the Karagan sediments top changes to the southeast from 1160 to 1400 m, and at the Chokrak sediments top – from 1000 to 1130 m. The fault on the southern limb passes throughout almost parallel to the fold axis.

In general, the Oktyabrsk fold in the eastern part of the anticline has a box-shaped structure – wide arc and steep limbs at the crest. The angles of incidence of the northern limb in the direction from west to east range from 83° to 73°, while at the southern limb – from 78° to 84°. The plane of the fault in the southern limb has a northeast dip with 26–30° angle from the vertical. The amplitude of the normal fault decreases in the southeast direction from 200 to 90 m. The southern fault is observed within the Goiten-Court area and possibly further.

The system of two faults forms a horst within which a crest of fold is elevated relatively to its limbs (Figure 2.4). Vertical shift is not constant, with an average of 100 m. The southern fault has a dip azimuth of approximately 45° in the north-east direction and the angle of dip from the vertical varies from 35 to 45°. The northern fault has an angle of dip equal to 20–30° with dip azimuth about 235°.

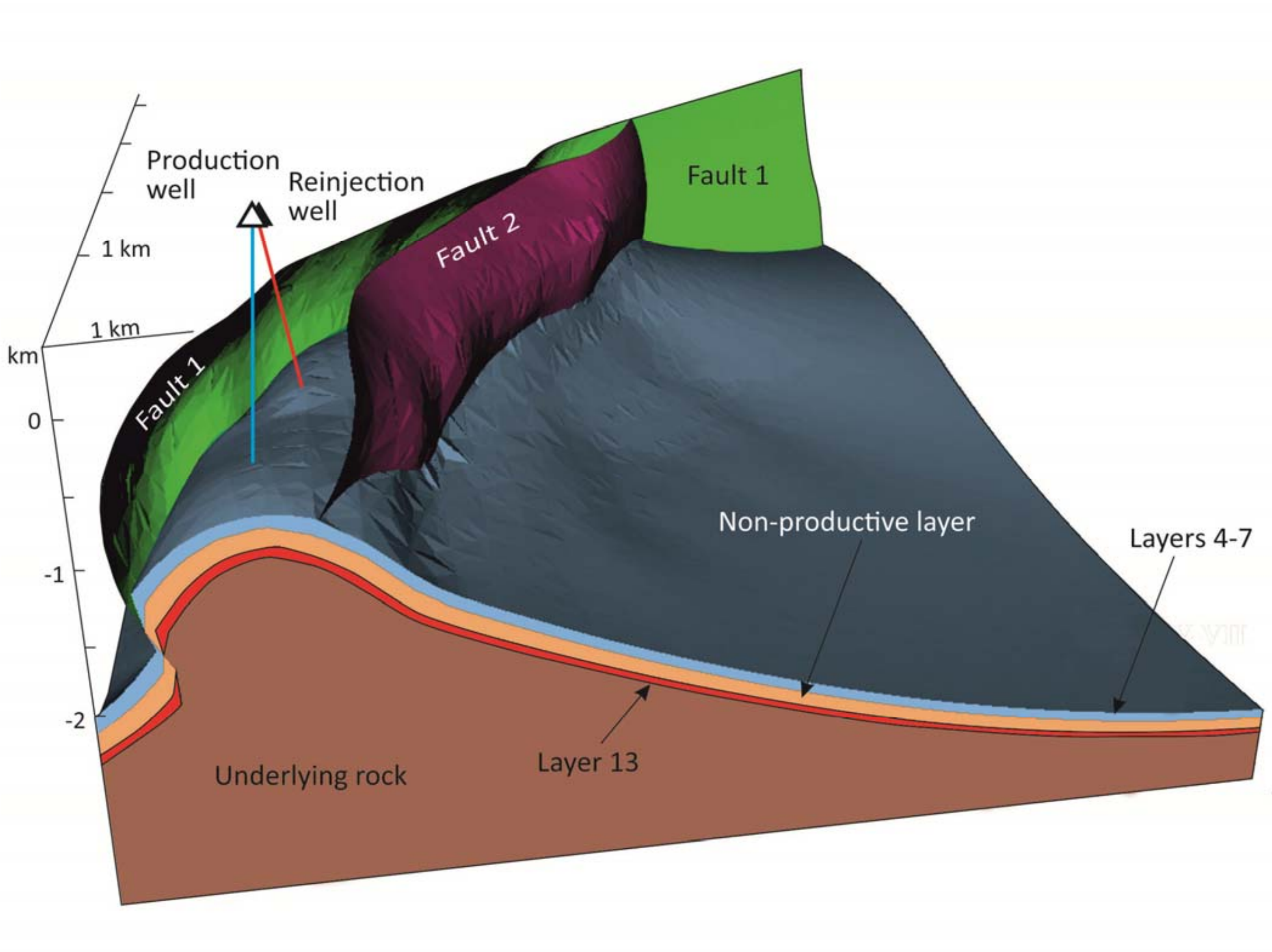


Fig. 2.4. The Khankala geothermal waters deposit 3-D geological model

The impact of two faults in the Khankala geothermal waters deposit exploitation in the eastern part of the Oktyabrsk anticline was studied by tracers injection-withdrawal in the wells at different sides of the faults. These works were carried out in 1981, 1987 and 1988 [Krylov 1983f, 1987f, 1988f]. In 1981, the researchers came to the conclusion of the impermeability of the south fault, because nor calcium carbamide nor ammonium nitrate were received in the well 4-T (Figure 2.8). During subsequent tests however tracers appeared in all the wells, including those that are at the opposite sides of the faults. Controversial conclusions about low permeability of the northern and the southern faults were made according to the results of these studies [Krylov, 1988f].

2.5. Hydrogeological characteristics of the territory and geothermal waters formation features

2.5.1. The East Ciscaucasian Artesian Basin

Hydrogeological, hydrogeochemical and geothermal conditions of the North Caucasus are reflected in the works of I.G. Kissin [1964], B.F. Mavritsky [1975], F.A. Makarenko [1963], A.I. Khrebtov [1965], V.P. Krylov [1981, 1983, 1984, 1986, 1988], S.A. Jamalov [1959, 1960], S.P. Vlasova [1963], A.A. Shpak [1968], N.A. Grigoriev [1968], G.M. Sukharev [1948, 1954, 1963, 1966], V.M. Nikolaev [1961], I.S. Zektser [2007], M.K. Kurbanov [2001], A.B. Alhasov [2011, 2012], S.V. Alibekova [2009], O.A. Mammayev [2013], G.V. Gordeeva [2001], D.G. Gonsirovsky [1966], A.S. Jamalova [1969] and others.

There are several artesian basins at the platform part of the North Caucasus within the Scythian plate: the East Ciscaucasian Artesian Basin (ECAB), the Azov-Kuban Artesian Basin, the Ergeninsky Artesian Basin [Timohin, Alibekova, 2009f]. Geological, hydrological, structural and tectonic features of the study area, administratively dedicated to the Chechen Republic, are due to its location in the southern part of the ECAB (Figure 2.5).

The ECAB in the south is bordered by the mountain-folded system of the Greater Caucasus, in the east it goes till the Caspian Sea, in the north the border with the Ergeninsky Artesian Basin is at the buried Karpinsky ridge, which is the underground watershed, western border – the area of the Stavropol uplift [Kissin, 1964]. The ECAB area is about 250 thousand km^2 [Kurbanov, 2001]. Groundwater deposits of the ECAB contain in porous and porous-fractured reservoirs [Alkhasov, 2012].

The ECAB thermal regime is formed by the heat flow, lithology, geological and structural features and movement of groundwater. The dominant influence on the geothermal regime has heat flow. Lithological, structural and hydrogeological conditions are second-order factors, which plays an important role in redistribution of geothermal heat [Alkhasov, 2012].

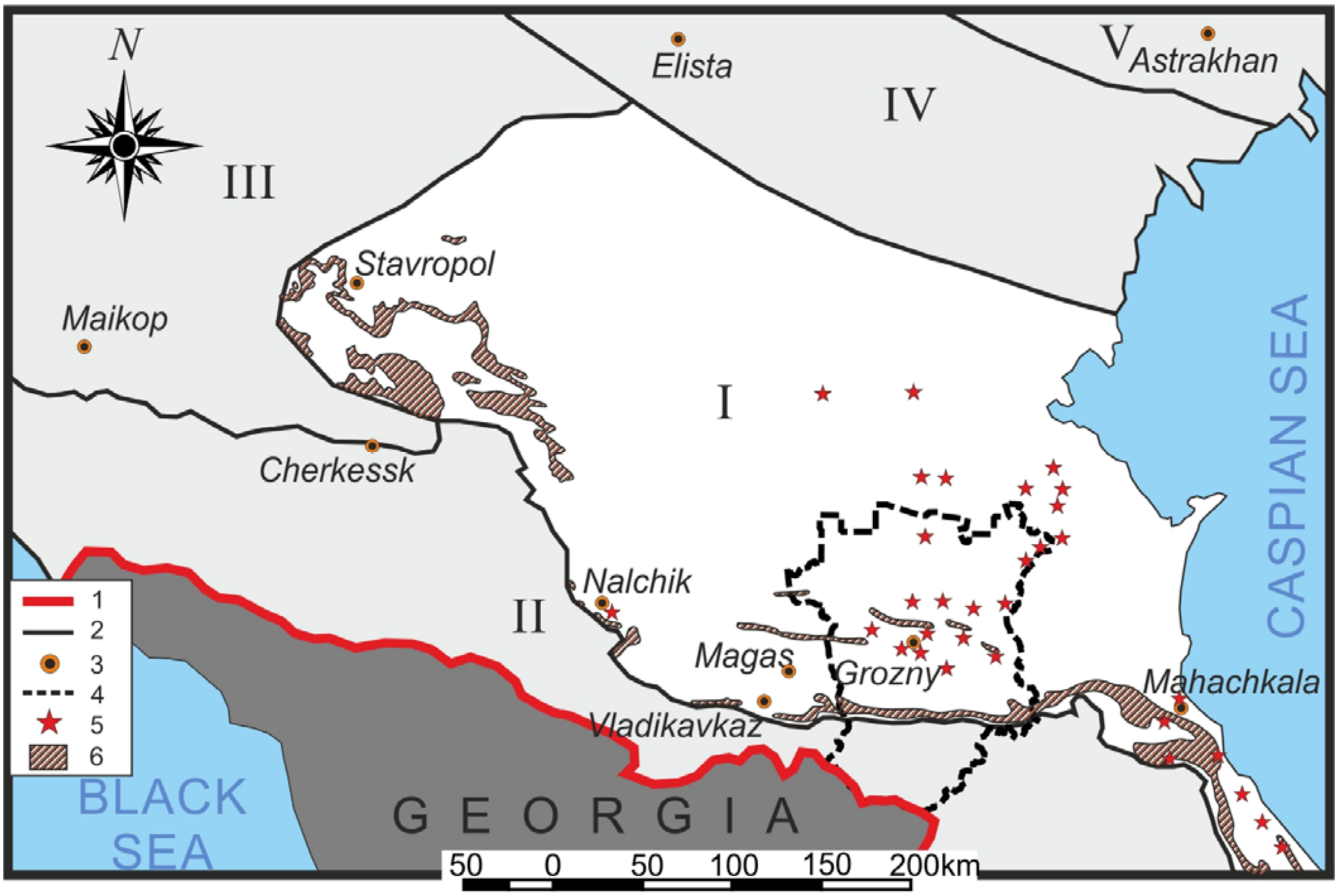


Fig. 2.5. Schematic map of the East Ciscaucasian Artesian Basin after I.U. Dezhnikova with modifications [2015].

Legend: 1 – the state border, 2 – hydrogeological structures border, 3 – regional capital cities, 4 – border of the Chechen Republic, 5 – geothermal fields, 6 – Karagan-Chokrak deposits outcrops; I – the East Ciscaucasian Artesian Basin, II – the Caucasian hydrogeological folded region, III – the Azov-Kuban Artesian Basin, IV – the Ergeninsky Artesian Basin, V – the Caspian Artesian Basin.

According to modern concepts, one of the main sources of geothermal heat is the decay of long-lived heavy radioactive elements: uranium, thorium and potassium. The overall effect of radiogenic heat production in heat flow study area reaches 20% [Jamalova, 1969]. Significant role in the formation of the thermal field of the Earth’s crust has the mass flow from the mantle. Heat input from the mantle into the crust is done not only by the conductive heat transfer, but also by the convective heat and mass flow. In addition, a significant amount of energy released during geological, tectonic, physico-chemical and metamorphic processes. The ECAB special feature is the combination of contrasting geological and tectonic environments as it is a zone of the alpine orogeny and the Epihercynian Scythian plate. Seismic events have a significant impact on the complex processes of formation and distribution of geothermal waters. According to the magnitude

M value, which characterizes the earthquake in terms of energy, the strongest earthquakes in the Caucasus region were Shemakha in 1902 (M = 6.3), Dagestan in 1970 (M = 6.6) and Spitak in 1988 (M = 7). According to the seismic zoning large part of the region belongs to the zone with $6 < M < 8$ and the depth of the earthquake focus of 10-20 km or less [Kurbanov, 2001].

Seismicity of the Eastern Caucasus is closely linked to overthrust-nappe structure of the crust and neotectonics [Kamaletdinov et al., 1991] and it has impact on geothermal waters formation and distrubution. For example, the genesis of the thermal anomaly at Yangantau Mountain in the Republic of Bashkortostan, where at a depth of 90 m reservoir temperature reaches 400 °C is explained as the result of the movement of thrust plates [Nigmatulin et al., 1998]. Tectonic factor plays not only a mechanical role in the formation of the heat, but also creates conditions for vertical migration of fluids, the higher the mobility of tectonic structures, the more intense geothermal, seismotectonic activity and higher convective heat and mass transfer from the depths. Highly heated fluids come up in zones of tectonic disturbances, warming up rocks and groundwater in the sedimentary cover, creating temperature anomalies [Mavritsky, 1971]. Overall, researchers estimate that within the study area heat flux varies from < 30 to 90 mW/m^2 [Kutas et al., 1979; Kurbanov, 2001].

There is a common feature within the area under study – the temperature increase with depth slows down, which can be seen from temperature measurements in significant number of wells. The reason, in addition to the conductive thermal conductivity growth with depth, is change of the density of the conductive heat flow under the influence of convection (advection) heat transfer [Kurbanov, 2001].

Several different from each other in their geothermal characterization sediments are allocated in the ECAB: thermal conductive stratum of Quaternary and Pliocene sediments, thermal insulating Sarmatian sediments, thermal conductive Middle Miocene sediments, thermal insulation Maikop clays.

The thermal conductivity of sandstone strata of the Quaternary and Pliocene age is 1.9–2.4 W/m·°C, clay 0.6–1.3 W/m·°C. Sarmatian clays thermal conductivity is 1.2–1.7

W/m·°C. The Middle Miocene sandstones thermal conductivity is 2–2.6 W/m·°C. The Maikop thermal insulating sediments thermal conductivity is – 1.2–1.5 W/m·°C [Sukharev, 1948]. The Maikop and Sarmatian clays play the role of thermal insulation that contributes to maintaining the heat. In case of immersed aquifers and increase of insulating sediments thickness absolute values of temperature increases with a reduction in the rate of increment. At the same time the difference in the thermal conductivity of rocks with a depth somewhat mitigated, and as a consequence the role of lithological factor in the distribution of temperatures with depth should decrease and the role of deep heat flow increase [Kissin, 1964].

The question of the transfer of heat by groundwater was investigated by many authors. The dynamics of the groundwater has a significant impact on the geothermal features of the Middle Miocene complex in the study area [Sukharev, 1948]. The following conditions determine the high heat transfer value by groundwater: high temperatures in the depressions, favorable tectonic structure and enough active hydrodynamic regime [Makarenko, 1963]. Within the Chechen Republic there is particularly intense heat transfer by groundwater from depressions to the Oktyabrsk and Gudermes anticlines. This situation is also inherent in the regional plan – due to sublatitudinal strike of the Ciscaucasia folds, with the deepest troughs in the south, and submeridional direction of groundwater movement [Kurbanov, 2001].

At the ECAB territory within the study area there are three structural and hydrogeological stages: Pliocene-Quaternary, Oligocene-Miocene and Mesozoic [Kurbanov, 2001]. Several factors have impact on the hydrodynamic link between recharge and transit zones, main ones of which are reservoir filtration parameters defined by their lithological and facies composition, thickness of aquifers and confining units, etc. [Kissin, 1964].

The southern border of the region coincides with the recharge zone and passes through the Black Mountains, where at the absolute elevation of 500–2500 m the Meso-Cenozoic up to the Lower Jurassic deposits outcrop. Piezometric surface of aquifers, with individual anomalies, reduce in a northerly direction as groundwater moves from the recharge to discharge zone. From south to north, as a rule, there is a change in quality of water from freshwater and brackish to highly mineralized. Researchers estimate doubtless role of the Caspian Sea as a zone of discharge, but the shortage of materials on investigation of various aquifers in the Sea does not allow an accurate quantification [Timohin, Alibekova, 2009f]. I.S. Zektser [2007] indicated 1.65 km^3/year as an amount of water of different hydrogeological stages of the ECAB discharged into the Caspian Sea.

There are aquifers in the following deposits: Quaternary, Neogene, Paleogene, Upper Cretaceous, Lower Cretaceous and Jurassic. The main impermeable horizons of the Meso-Cenozoic are the Maikop clayey strata, the lower Chokrak clay horizon and Sarmatian clayey strata.

Main prospects of the Chechen Republic geothermal waters use are associated with Karagan-Chokrak aquifers, so special attention is paid to the description of the Middle Miocene complex.

The Karagan-Chokrak deposits waters

The Karagan-Chokrak water-bearing deposits widely developed within the area under study. Zone of recharge passes through the Black Mountains, where sediments outcrop at an altitude from +725 to +870 m. In the north-east direction from these outcrops the Middle Miocene sediments immersed under argillaceous deposits of the lower Sarmatian and groundwater become pressurized with a piezometric level above the ground surface. Zone of partial discharge and recharge refers to the outcrops of deposits in the area of the Front Ranges: Sunzha, Gudermes, Bragun and Terek. There are mineral springs: Achaluki, Sernovodsk, Braguny, Isti-Su and others. Springs flow rate is about 0.1–0.2 l/s, depending on the amount of precipitation [Timohin, Alibekova, 2009f]. The total thickness of the complex reaches 630–1000 m, the thickness of the Karagan deposits – 350–400 m.

The main recharge source of the Middle Miocene Karagan-Chokrak deposits groundwater is precipitation, and in the foothills, water possibly comes from the river alluvium. Tectonic faults in the Front Ranges are discharge ways for the lower reservoirs of the Middle Miocene that have no outcrops at the surface, as well as the link of different aquifers. Hidden discharge occurs in the Caspian Sea and occurs in the form of water filtration through poorly permeable layers. Groundwater discharge from the Middle Miocene and Sarmatian deposits in the Caspian Sea is 0.35 km^3/year [Zekster et al., 2007]. Artificial discharge is due to the exploitation of oil and gas deposits and the simultaneous extraction of subsurface reservoir waters. After infiltration groundwater is moving to the north, north-east [Gonsirovsky, 1966f].

The Middle Miocene aquifers piezometric levels decrease from the recharge zone in the northern, north-eastern directions. On the whole, on the territory of the ECAB the Middle Miocene Karagan-Chokrak aquifers is relatively weak studied and it was not possible to create hydrogeological maps during large-scale work in 2009 "Creating a hydrogeological map of the East Ciscaucasian Artesian Basin of scale 1:500 000 with the assessment of the current state of groundwater protection and water sources" [Timohin, Alibekova, 2009f]. Information on the movement of groundwater in the Karagan-Chokrak deposits are given by generalized maps with piezometric levels created by N.S. Pogorelsky in 1968 [Hydrogeology USSR, 1968] and separately for Chokrak and Karagan stages by D.G. Gonsirovsky in 1966 (Figure 2.6). At the same time, according to researchers the basic exploitation layers are separated by impermeable layers of clay [Krylov, 1984f] and studies in this area should be continued.

There are 23 productive Middle Miocene layers allocated within the region, 10 of which relate to the Chokrak deposits and 13 to the Karagan. Significant thickness and high reservoir quality sandstones of the main layers of south-eastern part of the region (IV-VII, XIII, XVI and XXII), forming separate aquifers of high-pressure water, predetermine high flow rates of these horizons and low salinity water.

Temperature of groundwater varies from 60 to 110 °C. Artesian wells flow rates ranging from 285 to 3300 m^3/day when excess wellhead pressures ranging from 0.3 to 1.5 MPa. Artesian groundwater of the Karagan-Chokrak deposits immersion zones is bicarbonate and sodium chloride, with salinity from 0.6 to 30 g/l. Most mineralized water refers to the bottom of the complex – the Chokrak deposits.

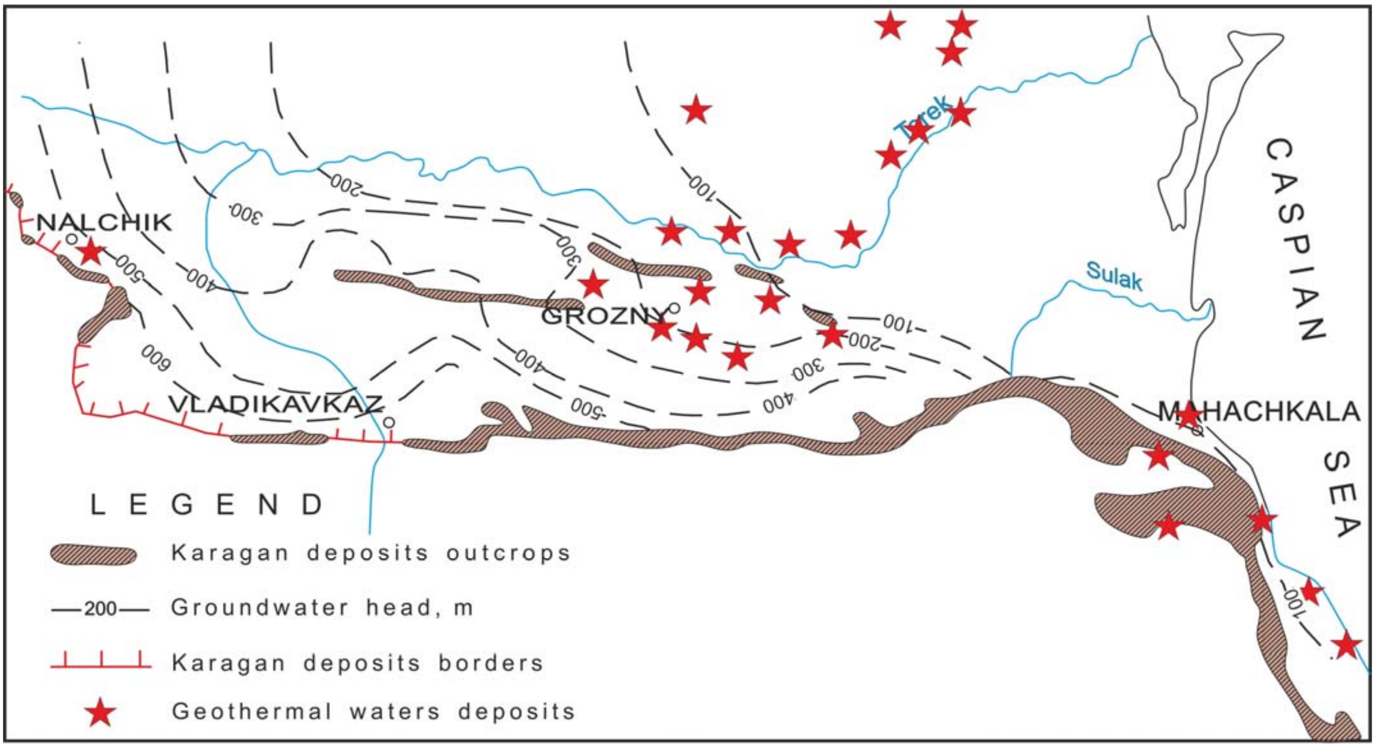


Fig. 2.6. Schematic map of the Karagan deposits piezometric levels of southeast of the East Ciscaucasian Artesian Basin by D.G. Gonsirovsky with modifications [1966f]

The Middle Miocene deposits groundwater is of infiltration type with an inferior value of sedimentary waters. In the foothills and south-western sides of the ECAB brackish freshwater of infiltration origin dominates. Along with immersion of productive layers in the northern direction salinity of water increases, and the chemical composition changes in the direction of the predominance of sodium chloride. The ECAB Miocene complex within Dagestan is characterized by δD=–(85.1±2.4)‰ and δO18=–(5.73±0.95)‰ according to isotope-geochemical study [Magomedov et al., 2001].

Facial-lithological and physical features of the reservoir led to a different rate of natural groundwater flow. Salinity of the ECAB water largely depends on the filtration parameters of aquifers. With high permeability of productive strata velocity of the water from the recharge zone to the discharge zone is high and, as a consequence, salinity of water is low. Otherwise, water has high salinity, as its movement is slow or non-existent, and salt and relict water washed out slowly [Dyunin, Korzun, 2005]. This feature is clearly expressed in the Karagan-Chokrak aquifers.

There is a total reduction in thickness and thinning of productive strata is in the east-west and south-north directions. Facial-lithological and physical properties of the layers in accordance with the pattern of their changes resulted in different zones and different rate of natural groundwater flow. This has had a decisive influence on the patterns of change within the region the dynamics and the chemical composition of the groundwater [Vassoevich, 1959]. There are five hydrochemical zones in the Karagan deposits according to the terms of recharge, transit, discharge, facial-lithological and structural-tectonic features [Nikolaev, 1960] (Figure 2.7).

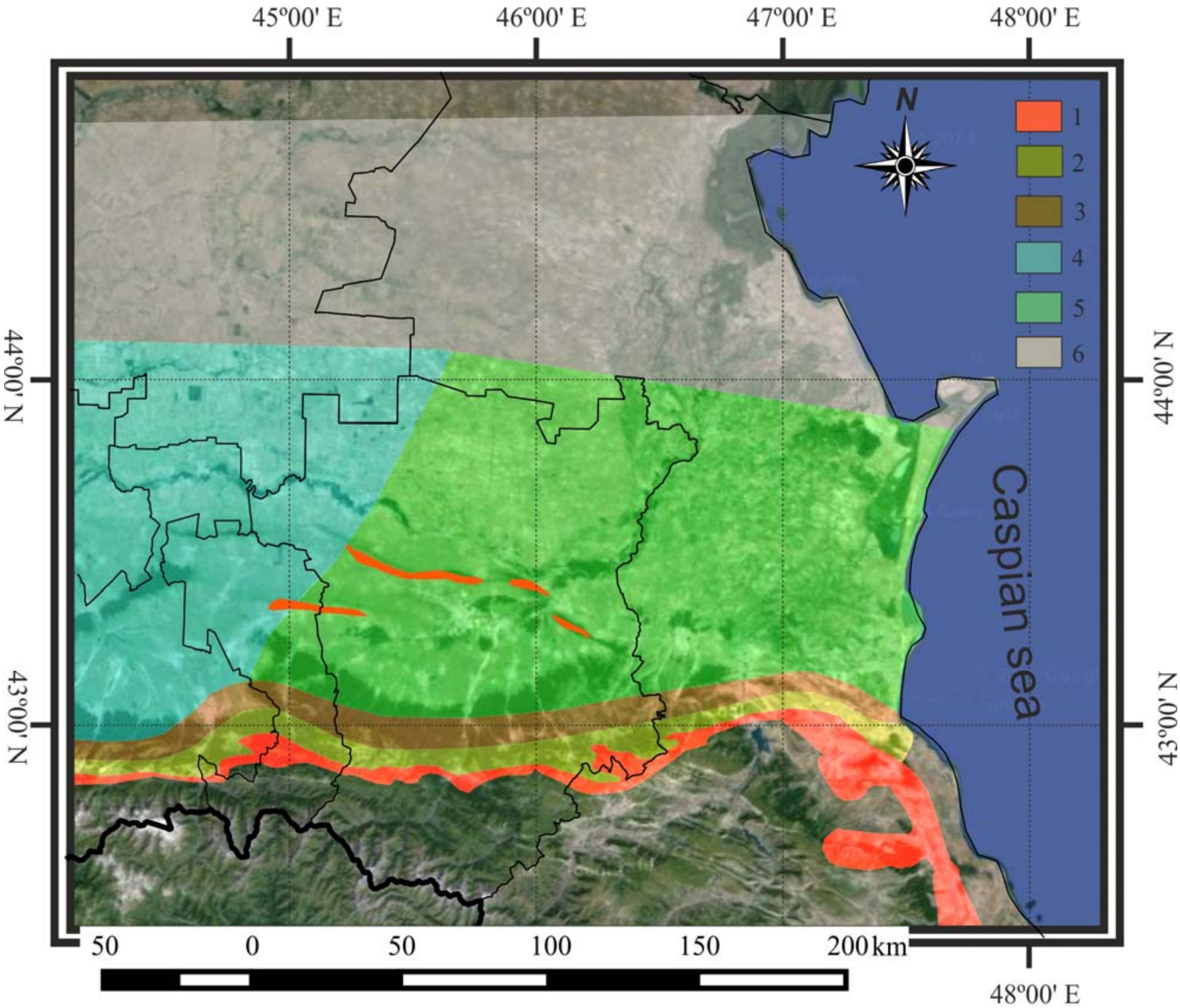


Fig. 2.7. Schematic map of the Karagan deposits hydrogeochemical zoning within south-eastern part of the East Ciscaucasian Artesian Basin [Nikolaev, 1960]

Legend: 1 – the Karagan deposits outcrops 2 – First southern zone (HCO_3), 3 – Second southern zone (Na+Ca)/(HCO_3+SO_4), 4 – Western zone Na/(HCO_3+SO_4), 5 – Eastern zone Na/(HCO3+Cl), 6 – Northern zone (Na/Cl).

The boundary of the first southern zone is arbitrary and extends in a narrow strip along the Karagan deposits outcrops in the Black Mountains. This area is territory of water infiltration of surface runoff. Groundwaters are bicarbonate and bicarbonate-sulphate calcium-magnesium type, salinity is 0.2–0.5 g/l. Piezometric levels are 600–650 m. There is also a variety of fresh cold springs with low (0.1–0.5 l/s) flow rates, which are dependent on precipitation rate.

Next second southern zone extends in a narrow strip to the north from the first. Groudwater is sulfate-bicarbonate calcium-magnesium, sulfate-bicarbonate calcium-sodium type with salinity up to 0.5−1.0 g/l. Piezometric level falls from the south to the north from 600 to 400 m.

Various types of low salinity sulphate-bicarbonate and sodium bicarbonate-sodium sulfate waters are distributed at the territory of the third eastern zone. Salinity varies within 0.6−1.8 g/l. This zone is bounded by the Caspian Sea in the east.

The fourth western zone is located to the west of the third zone. The most common for the Karagan deposits is chlorine-sodium-bicarbonate groundwater [Nikolaev, 1960]. Salinity of water varies from 8 to 18 g/l. Sulfate waters of different types are found mainly on the submerged parts of the main structures. Thus, the Karagan deposits waters of the western zone have a higher salinity than those of the eastern zone.

The fifth northern zone occupies the Zaterechnaya plain. It is characterized by predominance of chloride-sodium waters with salinity of 10–45 g/l.

The Chokrak deposits groundwater according to the terms of occurrence, lithological composition, location of the recharge zone, transit and discharge zone and other characteristics are similar to the Karagan deposits groudwater. There are five areas of similar hydrochemical zones in the Chokrak deposits as well as in the Karagan [Nikolaev, 1960] and in each zone there are general patterns of change in composition, salinity and water dynamics in the direction from the south to the north. The only difference is that the Chokrak groundwater is more mineralized, as the depth of the aquifers is increased.

All 14 discovered geothermal waters deposits of the Chechen Republic correspond to the Middle Miocene Karagan-Chokrak deposits (see Figure 1).

In order to clarify the potential thermal resources of geothermal waters of the

Middle Miocene complex of the Chechen Republic the total potential production of heat was calculated using the formula [Resources ..., 1975] adapted for installation of heat extraction circulation systems (Table 2.1):

$$G = 10^{-3} \cdot Q \cdot \eta \cdot C \cdot (T_{production} - T_{injection}),$$

where G – thermal resources, GJ/day; Q – flow rate, m^3/day; $T_{production}$ – temperature of water extracted, ºC; $T_{injection}$ – temperature of water reinjected, 45 ºC; C – specific heat of water (4.186 kJ/kg·ºC); η – efficiency of the plate heat exchanger 0.9.

Table 2.1. Thermal resources estimation of of the Chechen Republic geothermal waters deposits

Deposit	Average temperature at the wellhead, °C	$T_{production} - T_{injection}$, °C	Exploitation reserves, thousand m^3/day	Heat exchanger efficiency	Heat production, GJ/day	The total amount of heat, GJ/day
Khankala	81.5	36.5	15.6	0.9	2145	7347
Chervleny	76	31	5.2		607	
Kargaly	96.5	51.5	5.0		970	
Novogrozny	77	32	3.41		411	
Others	**87.5**	**42.5**	**20**		**3213**	

As a result of estimation total heat production is 7.4 thousand GJ/day, which confirms the high potential of the Middle Miocene Karagan-Chokrak complex at the territory of the Chechen Republic.

2.5.2. The Khankala geothermal waters deposit

The Khankala geothermal waters deposit is a multilayer aquifer type deposit (Figure 2.8). The absolute elevation of the ground surface ranges from +170 to +180 m, the area of the deposit is an ancient valley of the Argun River. From the northwest the deposit is limited by Syuir-Court hill (the highest point is +396 m), from the southeast – by Syuil-Court hill (the highest point is +435 m). The northeast and southeast borders are two reverse faults forming horst, further to north and south of which aquifer goes to great depths, which makes it impractical for exploitation.

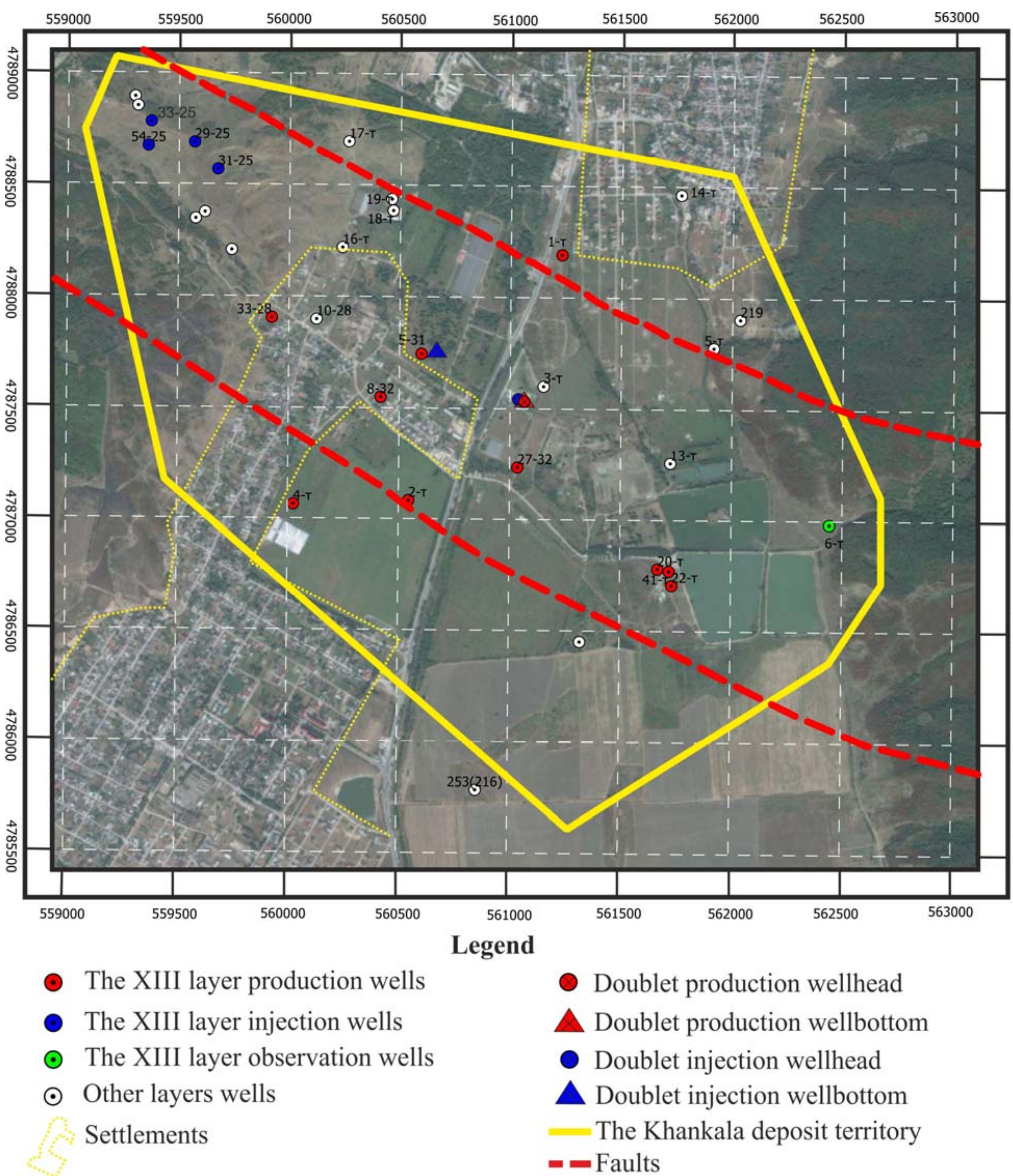


Fig. 2.8. The Khankala geothermal waters deposit territory

Natural resources of the Chechen Republic geothermal waters deposits can't provide a large demand for heat energy, what was shown during exploitation in the 1970s. Possible solution is creation of geothermal circulation systems (GCS) with reinjection of used fluid back into the aquifer, which can help to achieve multiple objectives [Krylov, 1984f]:

1. The creation of large, tens of thousands of m^3/day, geothermal waters withdrawal systems.

2. The use of any quality water (production-injection and consumer circuits are separated).
3. The solution of environmental issues – no need to find ways of disposing of used geothermal waters and protection of aquifer from exhaustion, because used fluid goes back into productive layers.
4. Reducing cone of depression radius.

According to these reasons, on the territory of the Khankala geothermal waters deposit the installation of the doublet GCS was decided (Figure 2.9), which is a closed loop of one productive and one injection wells with 100% reinjection of used geothermal water back.

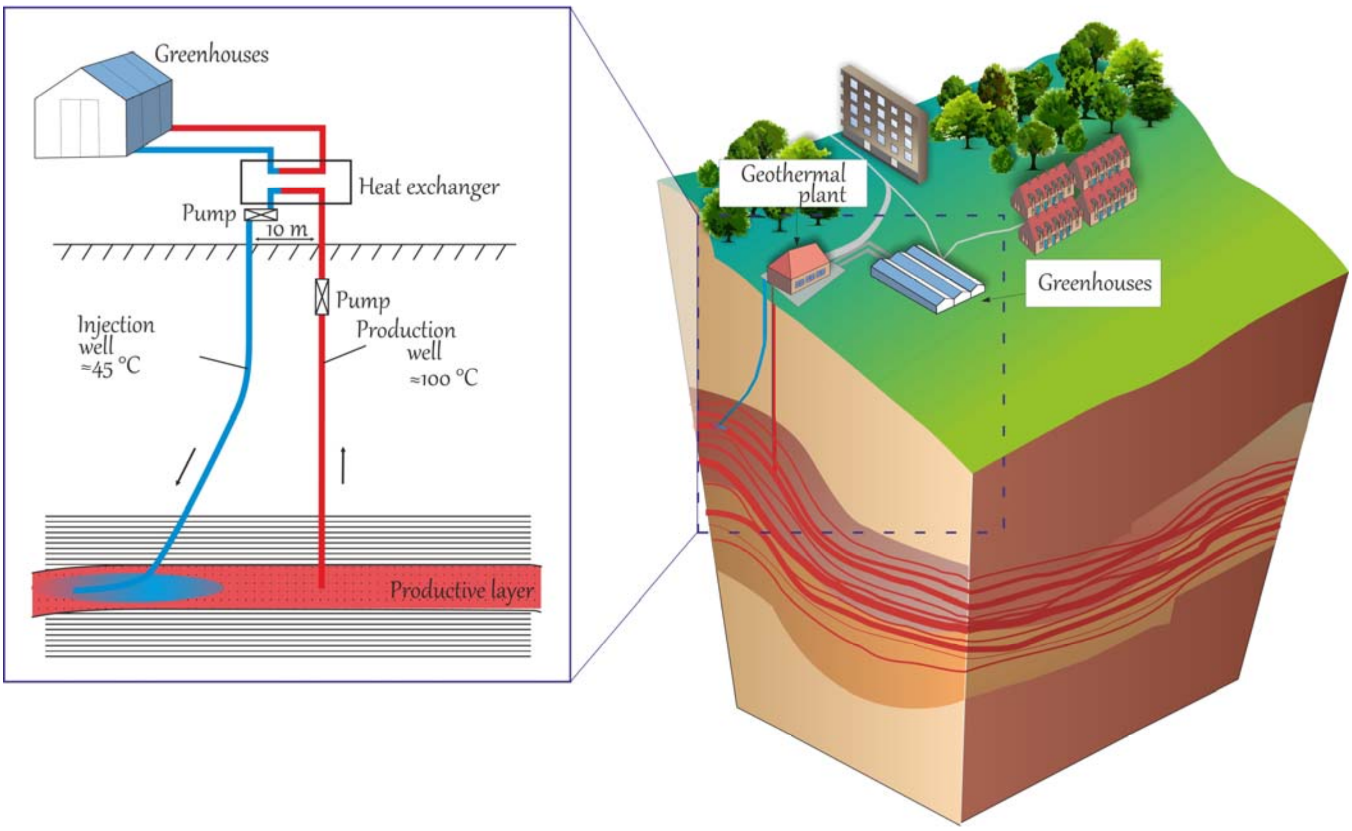


Fig. 2.9. Schematic drawing of the Khankala deposit geothermal circulation system (doublet)

The Karagan-Chokrak sediments 22 productive layers are allocated within the Khankala geothermal waters deposit, many of which are separate artesian aquifers represented by sandstones and separated by impermeable layers of clay [Shpak, 1968f]. Due to the structural features of the deposit, depth of productive layers varies widely (Table 2.2).

Table 2.2. The Khankala geothermal deposit productive layers characteristics according to V.B. Krylov with modifications [1988f]

Layer	Thickness, m	Porosity, %	Permeability, Darcy	Average absolute elevation	Average salinity, g/l
I	7.5	26.7	0.77	-422.5	3.3
II	6.4	25.4	-	-440	3
III	7.7	22.3	-	-458.4	-
IV-VII	30.0	24.8	1.01	-489	2.1
VIII	10.8	16.79	-	-518.5	-
IX	-	-	-	-531	-
X	4.6	18.4	0.4	-556.6	-
XI	18.8	23.4	0.7	-588.7	-
XII	8.5	20.4	-	-600	2.5
XIII	47	24.13	1.43	-665	1.3
XIV	6.0	16.13	-	-700	-
XV	5.5	-	-	-729	-
XVI	50	20.1	1	-745	1.4
XVII	5.4	23.8	1.46	-820	-
XVIII	11.3	14.6	-	-865	-
XIX	6.2	17.4	1.47	-885	-
XX	16.3	18.34	2.26	-925	2.1
XXI	5.3	16.3	1.96	-945	3.3
XXII	28.5	16.5	2.07	-955	1.3

Facial and lithological features of sandstone layers (the thickness and consistency, composition and permeability) completely determine the change in salinity and chemical composition of water. Vertical hydrochemical zoning is defined by filtration parameters of productive strata – when they are higher, the greater is the influence of infiltration type water and correspondingly less is salinity. That is typical in the whole for groundwater deposits of the East Ciscaucasian Artesian Basin [Dyunin, Korzun, 2005].

Several options were considered as a productive resource for a doublet GCS at the Khankala geothermal waters deposit. The most favorable are layers which had maximum flow rate and best filtration parameters: IV-VII, XIII, XVI and XXII. Currently, the XXII layer exploitation is prohibited XXII by “Gosgortechnadzor” in order to protect Sernovodsk sources from exhaustion. Along with the hydrogeological characteristics the choice of the XIII layer is due to the presence of a relatively large amount of data allowing to include it in a 3D geological model of the Khankala deposit [Cherkasov et al., 2014], as well as the positive experience of reinjection of water into the reservoir.

The XIII layer of the Karagan stage is one of the most productive on the territory of the Khankala geothermal waters deposit with a quite consistent thickness within the area. Filtration parameters of the XIII and other productive formations were studied in 1968, 1987 (Table 2.3).

Table 2.3. Filtration parameters of the XIII productive layer tests results

Well number	1-T			2-T			33/28			27/32		
Parameter	Km, m^2/day	K, m/day	a, m^2/day	Km, m^2/day	K, m/day	a, m^2/day	Km, m^2/day	K, m/day	a, m^2/day	Km, m^2/day	K, m/day	a, m^2/day
Single well pumping												
I	135.04	2.11								62.16	1.48	
II	142.08	2.22	–	–	–	–	96.5	1 .93	–	71.4	1.70	–
III regime	147.2	2.30	–	–	–	–	–	–	–	69.3	1.65	–
IV	–	–	–	–	–	–	–	–	–	60.9	1.45	–
Average	141.44	2.21		–	–	–	96.5	1.93	–	65.94	1 .57	–
Pressure buildup												
I	79.31	1.24	$2.68 \cdot 10^5$	78.54	1.51	$3.2 \cdot 10^5$	113.2	2.14	$4.75 \cdot 10^5$	82.94	1.97	$4.23 \cdot 10^5$
II	90.98	1.42	$3.02 \cdot 10^5$	–	–	–	–	–	–	–	–	–
Observation well												
	79.32 (1/28)	–	–	–	–	–	79.5 (1/28)	–	–	71.4 (1/28)	–	–
	121.90 (27/32)	–	–	–	–	–	114.05 (1/28)	–	–	68.46 (1/28)	–	–
Multiple wells pumping test	72.4	–	–	–	–	–	–	–	–	61.1	–	–

The data on the XIII layers filtration parameters in the well 6-T was obtained from the analysis of the geothermal wells exploitation for the period 1980-1986 years with transmissivity equal to 87.74 m^2/day [Krylov, 1987f]. The Khankala geothermal waters deposit XIII layer parameters vary within a small range, therefore analytical calculations and computer modelling (Chapter 4) averaged parameters were adopted – thickness equal to 47 m, transmissivity of 90 m^2/day and piezoconductivity – $3.8 \cdot 10^5$ m^2/day. Calculations of the XIII layer filtration parameters was also conducted for the Oktyabrsk oil deposit based on the data analysis for the period 1916–1956. Transmissivity in general for the area is 61.7 m^2/day [Shpak, 1969f]. This value obtained are consistent with results recieved for the Khankala geothermal waters deposit territory, as in the direction from south to north and from east to west the Karagan–Chokrak thickness decreases.

The Khankala geothermal waters deposit is characterized by vertical temperature zoning related to the temperature increase with depth and lateral zoning, caused by structural-tectonic factor and movement of groundwater, which are heated at great depths, and then rise to the surface (Chapter 3). The XIII layer waters are sodium-bicarbonate type according to chemical analysis of 2013, salinity is 0.87-1.7 g/l [Machigova et al., 2014] (Table 2.4).

Table 2.4. The Khankala deposit geothermal waters chemical analysis [Machigova et al., 2014]

Well	Layer	Units	Cations			Summ	Anions			Summ	Salinity	Dry residue	Hardness	pH	t °C
			Na, K	Ca	Mg		Cl	SO_4	HCO_3						
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		mg/l	872	43.29	3.84	919.06	574	547	780.8	1901.8					
10/28	IV-VII	mg-eq	37.9	2.16	0.32	40.39	16.19	11.4	12.8	40.39	2909	2519	2.48	7.5	71
		%eq	93.9	5.3	0.8	100	40	28.22	31.78	100					
		mg/l	248.4	17.64	0.96	267	32.2	185	427	664.2					
1-T	XIII	mg-eq	10.8	0.88	0.08	11.76	0.91	3.85	7	11.76	1032	618.5	0.96	7.5	90
		%eq	91.8	7.48	0.72	100	7.74	32.74	59.52	100					
		mg/l	271.17	36.87	3.84	311.88	54.4	251	438.8	744.2					
33/28	XIII	mg-eq	11.79	1.84	0.32	13.95	1.53	5.23	7.19	13.95	1154	934.6	2.18	8	71
		%eq	84.52	13.19	2.29	100	10.97	37.49	51.54	100					
		mg/l	455.63	38.48		494.11	148	469	475.4	1092.4					
27/32	XIII	mg-eq	19.81	1.92	-	21.73	4.17	9.77	7.79	21.73	1684	1446	1.92	8	80
		%eq	91.16	8.84		100	19.19	44.96	35.85	100					
		mg/l	690.92	6.41	2.4	704	314	160	1121.6	1596					
22-T	XXII	mg-eq	30.04	0.32	0.2	30.56	8.86	3.3	18.4	30.56	2390	1829	0.52	8	98
		%eq	98.3	1.05	0.65	100	29	10.8	60.2	100					
	IV-VII	mg/l	686.55	9.62	2.4	698.57	364	41.2	1183.4	1588.6					
3-T	VIII-IX	mg-eq	29.85	0.48	0.2	30.53	10.27	0.86	19.4	30.53	2411	1819	0.68	7.5	71
		%eq	97.77	1.57	0.66	100	33.64	2.8	63.56	100					
		mg/l	366	14.43	2.88	383.3	61.9	284	561	906.9					
14-T	IX	mg-eq	15.91	0.72	0.24	16.87	1.75	5.92	9.2	16.87	1004	724	0.96	8	80
		%eq	94.3	4.27	1.43	100	10.37	35.09	54.54	100					
		mg/l	654.81	9.62	0.48	664.9	326	259	878.4	1463.4					
16-T	XXII	mg-eq	28.47	0.48	0.04	28.99	9.2	5.39	14.4	28.99	2238	1799	0.52	7.5	70
		%eq	98.2	1.65	0.15	100	31.7	18.6	49.7	100					
		mg/l	338.33	24.05	1.44	363.82	156	164.6	500.2	820.8					
8/32	IV-VII	mg-eq	14.71	1.2	0.12	16.03	4.4	3.43	8.2	16.03	1245	995	1.32	7.5	78
		%eq	91.8	7.48	0.72	100	27.45	21.4	51.15	100					
		mg/l	168.82	32.06	4.32	205.2	32.2	115	336	483.2					
5/31	XIII	mg-eq	7.34	1.6	0.36	9.3	0.91	2.39	6	9.3	790	622	1.96	7.5	82
		%eq	79	17.2	3.8	100	9.8	25.7	64.5	100					

Operational reserves under different development conditions were calculated for the XIII layer: one pumping well and GCS (with 100% reinjection), nonstop exploitation and development during 7 months of the year (heating season), unlimited layer and with two impermeable faults (Figure 2.10, Table 2.5).

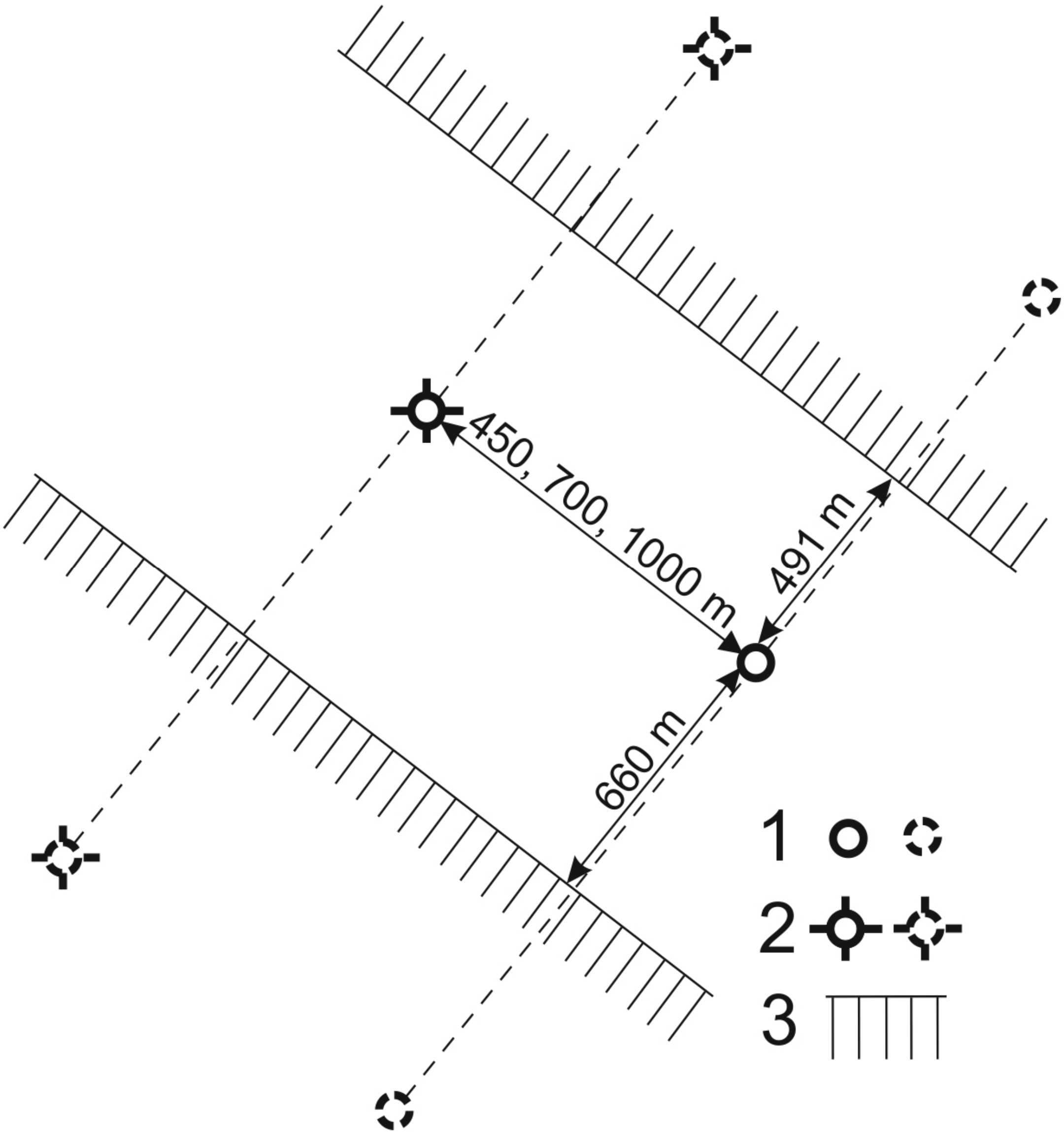


Fig. 2.10. Scheme for the XIII layer operational reserves assessment
Legend: 1 – production and mirror image well; 2 – injection and mirror image well; 3 – tectonic faults.

Dupuis formula is used for nonstop exploitation:

$$S = \frac{Q}{2\pi km} \ln \frac{R}{r} \tag{2.2}$$

where S – head loss, m; Q – flow rate, m^3/day; k – hydraulic conductivity; m/day; m

– layers thickness, m; R – radius equal to $1.5\sqrt{at}$; where a – piezoconductivity coefficient, m^2/day; t – time, 10000 days; r – well radius, m.

Theis formula is used for heating season exploitation (7 months a year):

$$S = \frac{Q}{2\pi km} W(u), \quad (2.3)$$

where $W(u) = -0.5772 - \ln u + u - \frac{u^2}{4} + \frac{u^2}{4} - \frac{u^2}{4} + \ldots \pm \frac{u^n}{n \cdot n!}$; $u = \frac{r^2}{4at}$

Operational reserves in case of GCS were calculated taking into account the full reinjection of used fluid back into the reservoir. Because reinjection is one of the main problems for productive layers represented by sandstones with lenses and layers of clay, injectivity tests are needed in order to clarify operational reserves.

Table 2.5. The XIII layer exploitation reserves

	Continuous exploitation				Exploitation during heating season (7 months)			
	No faults		Impermeable faults		No faults		Impermeable faults	
	S_e*	Q_{max}**	S_e	Q_{max}	S_e	Q_{max}	S_e	Q_{max}
One well	118	595	192	364	101	691	143	489
Doublet with distance								
450 m	73	965	74	949	73	965	74	949
750 m	76	911	80	875	76	911	80	875
1000 m	79	883	84	831	79	883	84	831

*S_e – estimated decrease in water level with flow rate equal to 200 m^3/h, m
**Q_{max} – the maximum possible flow rate with an acceptable decrease (350 m), m^3/h

The land relief determines the general conditions of the Karagan-Chokrak deposits groundwater flow from the recharge area in the Black Mountains to the north, north-east. Climatic conditions, abundant precipitation and densely-developed hydrographic network within the Karagan-Chockrak deposits outcrops in the Black Mountains are favorable for the aquifers supply and for the creation of significant natural groundwater resources in them. The climatic features have also identified the need for heating for only 7 months of the year (from October to April) – the period during which the Khankala deposit geothermal waters used for greenhouses heating. Hydrogeological features of the

Chechen Republic territory is defined by its location in the south-east of the East Ciscaucasian Artesian Basin. Favorable filtration parameters of the Karagan-Chokrak deposits, high heat flux values, lithology particularities, structural-tectonic factor and movement of groundwater have caused high temperature geothermal waters formation in the Middle Miocene hydrogeological stage within the East Ciscaucasian Artesian Basin. The lithological features of the territory – increase in thickness of the Karagan-Chokrak productive strata and decrease in clay content in the direction from south to north and from west to east, have identified the most favorable hydrogeological conditions in the south-east of the region. For this reason, the largest deposit of the Chechen Republic – Khankala was chosen as a priority for development after a long break in the use of geothermal waters. The thickness, consistency and transmissibility of the productive XIII layer distinguish it from the Chokrak-Karagan 22 other deposits layers. It is one of the main factors together with relatively low depth for its selection as the heat source for geothermal plant. Due to tectonic conditions the most favorable area for the location of the wells is a section of the axial zone of the anticline structure. Well bottoms in this case, are located in the vicinity of the axis of the structure, which is determined by the minimum depth of the XIII layer. Also they are be at the approximately maximum distance from the northern and southern faults, in order to avoid their possible impact on exploitation because the nature of the permeability of faults is not well-studied and the work in order to determine their conditions must by continued. The XIII layer average thickness is 47 m, transmissivity – 90 m^2/day, water salinity – 0.87-1.7 g/l, waters chemical composition is sodium-bicorbanate. The XIII layer is exploited at the Khankala geothermal plant by doublet circulation system with 100% reinjection of used fluid back in the aquifer.

Chapter 3. Geostatistical analysis of the Khankala geothermal waters deposit

Nowadays, when geothermal waters have been a well-known form of energy for a long time, many researchers put to the forefront the issue of “sustainability” of the geothermal reservoir development [Ungemach et al., 2005, 2007, 2011; Axelsson, 2010, 2012; Antics et al., 2005]. Computer technologies are used in order to qualify the operation of its system in terms of the interaction between groundwater and water resources of the lithosphere, the features of the exploitation of the resource during reinjection of the used geothermal waters, etc. The most effective methods of assessment are formed on the basis of the GIS analysis techniques, geostatistical approach and numerical modelling, which have been actively implemented in all areas of science. They allow determining the spatial disposition of the resource, evaluation of the utilization in order to solve various economic problems, choosing the optimal exploitation regime.

It should be noted that in the Russian Federation there is no large-scale use of the geothermal waters and as a consequence computer programs for such purposes are not well developed, unlike the countries where the above mentioned approaches have been used for a long time.

That fact was considered by the author, since it is possible to achieve long-term sustainable use of the resource taking into account all the aspects of the Chechen Republic geothermal waters deposits when selecting the exploitation conditions. Geostatistical analysis (Chapter 3) and computer modelling of water reinjection (Chapter 4) were used in order to establish guidelines for the Khankala geothermal waters deposit exploitation.

3.1. The basics of geostatistical modelling

Geostatistics is now used in almost every domain of geosciences. Its methods significantly improve the efficiency of the analysis and interpretation of information when working with spatially distributed data.

The main goal of geostatistical analysis and subsequent modelling is a numerical description of the natural phenomena, distributed in space (or in time and space). The task includes creation of probabilistic model of studied phenomenon, and then evaluation and simulation using this model [Saveliev et al., 2012].

Basic interpolation model in geostatistics is kriging. Its theoretical foundations were developed more than 60 years ago by the French mathematician G. Matheron (1962) using the results of the master's thesis of the South African mining engineer D. Krige. This method was named in his honor. Krige was the first to use an interpolator for the analysis of gold mines of South Africa [Krige, 1951]. Kriging is an optimal interpolation based on minimizing of the standard deviation; it is a type of generalized linear regression. The basic idea of kriging is estimation of the selected point or block value by calculating a weighted average of the known values of the function in the neighborhood. The studied phenomenon is considered as an infinite number of random variables or realizations of the random function $Z(x)$. Variable $z(x)$ is the realization of this function for a given location in space, thus its value depends on the location of point x. There are corresponding random values $Z(x)$ and $Z(x+h)$ for any pair of points linked by correlation. This correlation reflects the spatial structure of the phenomenon, its statistical regularity [Saveliev et al., 2012].

In geostatistics work is carried out with stationary data (either they are reduced to stationary) as a rule, i.e. for each increment h the distribution $Z(x_1), Z(x_2), \ldots, Z(x_n)$ corresponds to the distribution $Z(x_{1+h}), Z(x_{2+h}), \ldots, Z(x_{n+h})$. Stationarity in the proper sense requires that all the moments of the random variable are invariant to translation. But usually such condition is difficult to fulfill and cannot be verified by a limited number of initial data. Therefore, the assumption was made in geostatistics, meaning that consistency should retain only the first two moments – mean and covariance, which is second order stationarity [Matheron, 1967; Davis, 1990]. Thus, a random function has a second-order or "weak" stationarity if [Journel, Huijbregts, 1978]:

1) Expected value m exists and doesn't depend on x:

$$m(x) = E\{Z(x)\} = const, \forall x; \tag{3.1}$$

2) Covariance for each pair of random variables $\{Z(x), Z(x+h)\}$ exists and

depends only on the difference of the coordinates h:

$$C(h) = E\{Z(x+h)Z(x)\} - m^2, \forall x. \quad (3.2)$$

These assumptions often cannot be met in practice. Matheron (1963, 1965) has developed the so-called "intrinsic hypothesis". It admits that the increments of the function are weakly stationary, i.e. mean and variance of increments $Z(x) - Z(x+h)$ exist and do not depend on point x:

$$E\left[Z(x) - Z(x+h)\right] = 0; \quad (3.3)$$

$$Var\left[Z(x) - Z(x+h)\right] = 2\gamma(h). \quad (3.4)$$

Function $\gamma(h)$ is called variogram, which is the main tool in geostatistical analysis. The variogram is variance of the variable difference at two points as a function of distance and direction between them:

$$\gamma(x, x+h) = 0{,}5Var[Z(x) - Z(x+h)] = 0{,}5E[Z(x) - Z(x+h)]^2, \quad (3.5)$$

The sample variogram is calculated as

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2. \quad (3.6)$$

for $N(h)$ experimental points, separated by the vector h.

The variogram describes spatial variability depending on the distance between data points. It is a mathematical tool used to evaluate spatial correlation of data: "continuity" or "variability". In other words, it is the function showing variability of a parameter depending on the distance between its values, and with increasing distance variation tends to increase. In the stationary case the variogram is related to the covariance through the following formula:

$$\gamma(h) = C(0) - C(h). \quad (3.7)$$

Thus, they are mirror images of each other (Figure 3.1).

Elements of variogram:

1) Nugget effect – is a random component, which shows how great the difference is in very closely spaced values. It depends on the sampling network and the level of

variability. The name of this parameter comes from the evaluation of gold mines, where unpredictable high metal concentrations are often found.

2) Sill – this is usually the dispersion of the samples, the value of the variation at which the variogram function reaches a constant value. When the variogram reaches the sill it often flattens, if it happens it means that the assumption of stationarity is eligible.

3) Range – it is the maximum distance at which there is a spatial correlation between data values. When the distance between the two points is greater than the range, the variation between the two points becomes unpredictable and it is impossible to describe it by any law. For example, at smaller distances we (with certain probability) can predict gold concentration at some point; at big distances we can't do it.

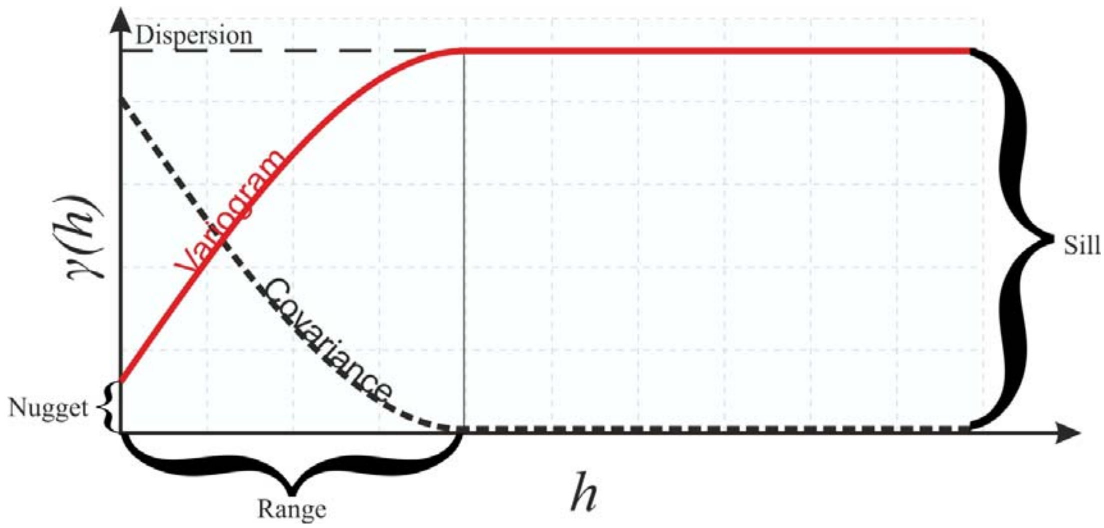


Fig. 3.1. Variogram and covariance

Second order stationarity is not required for the existence of variogram, it is sufficient to satisfy the intrinsic hypothesis [Demyanov, Savelieva, 2010]. The variogram made on the initial data is called experimental and as soon as it is described by a mathematical model, it can be successfully used to estimate the unknown parameter values at any point of the space, i.e. for interpolation [Kaputin, 2002]. The most commonly used variogram models are: spherical, exponential, Gaussian and cubic (Figure 3.2).

They are described by the following formulas:

1) Nugget effect:

$$\gamma(h) = c_0 \tag{3.8}$$

2) Spherical:

$$\gamma(h)=\begin{cases} c\left[\dfrac{3h}{2a}-\dfrac{1}{2}\left(\dfrac{h}{a}\right)^{3}\right], \textit{for } h\le a \\ c \textit{ for } h>a \end{cases} \tag{3.9}$$

3) Exponential:

$$\gamma(h)=\begin{cases} 0, \textit{ for } h=0 \\ c\left[1-\exp\left(\dfrac{-3h}{a}\right)\right], \textit{for } h\neq 0 \end{cases} \tag{3.10}$$

4) Gaussian:

$$\gamma(h)=c\left[1-\exp\left(\dfrac{-3h^{2}}{a^{2}}\right)\right] \tag{3.11}$$

5) Cubic:

$$\gamma(h)=\begin{cases} c\left[7\left(\dfrac{h}{a}\right)^{2}-\dfrac{35}{4}\left(\dfrac{h}{a}\right)^{3}+\dfrac{7}{2}\left(\dfrac{h}{a}\right)^{5}-\dfrac{3}{4}\left(\dfrac{h}{a}\right)^{7}\right], \textit{for } h\le a \\ c \textit{ for } h>a \end{cases} \tag{3.12}$$

where a – range, c – sill, c_0 – nugget effect, h – distance between data points.

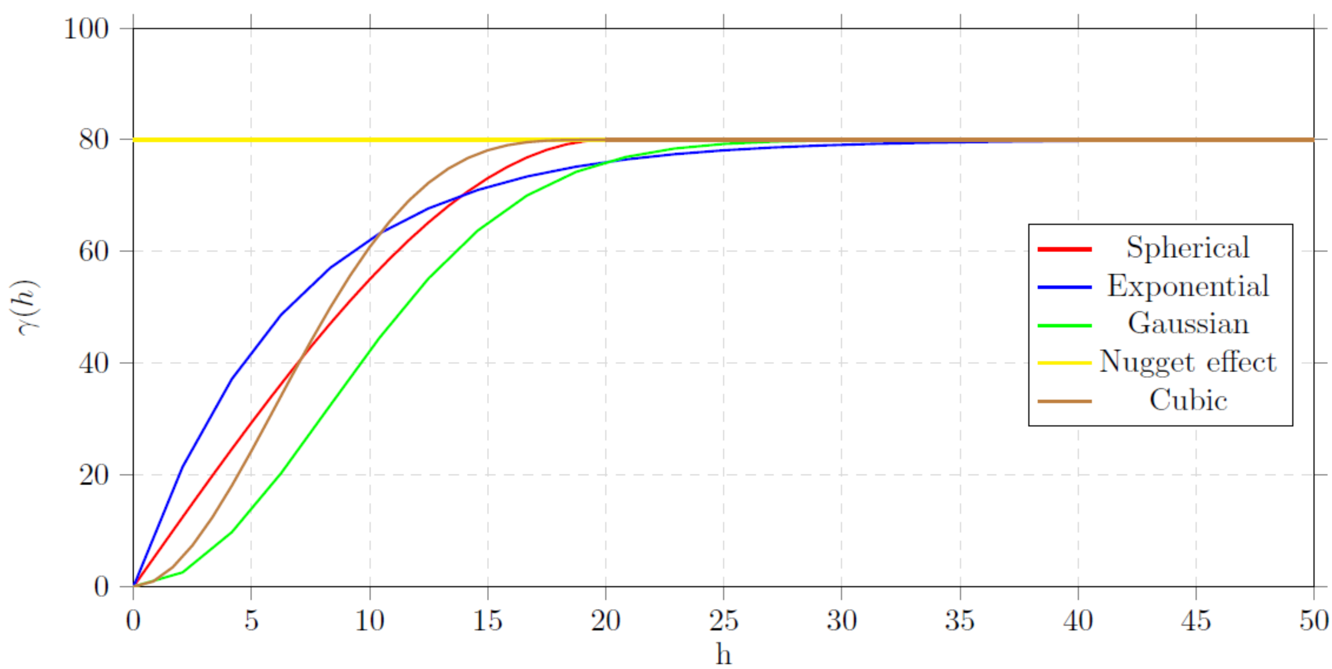


Fig. 3.2. Variogram models

Spherical variogram model is the most frequently used [Smith, 2014]. It is characterized by a smooth, uniform increase in dispersion between data up to a certain maximum. Exponential variogram model is characterized by a rapid increase in the dispersion; however, it only seeks to maximal dispersion, never reaching it. The variance in the Gaussian model grows slowly at first, then quickly, and closer to the maximum again slows down. The Cubic model is a “cousin” to the Gaussian model and belongs to a class of smooth, continuous functions models [Potekhin, 2014].

The next stage after selecting theoretical model and its components (range, sill) is interpolation by kriging. There are several types of kriging (simple, ordinary, universal, IRF-k, with external drift, etc.), which differ in the assumptions used and the information about the modeled variable. All the types are different kinds of modifications of the basic linear regression, defined as follows [Goovaerts, 1997; Chilès et Delfiner, 2012]:

$$Z^*(x) - m(x) = \sum_{i=1}^{n(x)} \lambda_i(x)[Z(x_i) - m(x_i)], \tag{3.13}$$

where $\lambda_i(x)$ – weights, corresponding to data $Z(x_i)$, $z(x_i)$ is interpreted as realizations of the random variable $Z(x_i)$, $m(x)$ and $m(x_i)$ are the unknown means of random variables $Z(x)$ and $Z(x_i)$. The amount of data used in the evaluation and weighting values may vary depending on the estimated location of the point x. There is point and block kriging. The first one allows estimating the value at the desired point; the second evaluates the average value of some defined area.

Kriging is the so-called “best linear unbiased estimator” (B.L.U.E.). It is “linear” because the estimated values are weighted linear combinations of the available data:

$$Z^*(x) = \sum \lambda_i Z(x_i), \tag{3.14}$$

“unbiased” because the mean of error is 0:

$$E\{Z^*(x) - Z(x)\} = 0, \tag{3.15}$$

and “best” since it aims to minimize the variance of the errors:

$$\sigma_E^2(x) = Var\{Z^*(x) - Z(x)\}. \tag{3.16}$$

Kriging equations are obtained after all these assumptions.

The aim of geostatistical analysis in this work is the creation of a structural map of the XIII productive layer of the Khankala geothermal waters deposit and the evaluation of the 3D temperature distribution within the area under study (Figure 3.3).

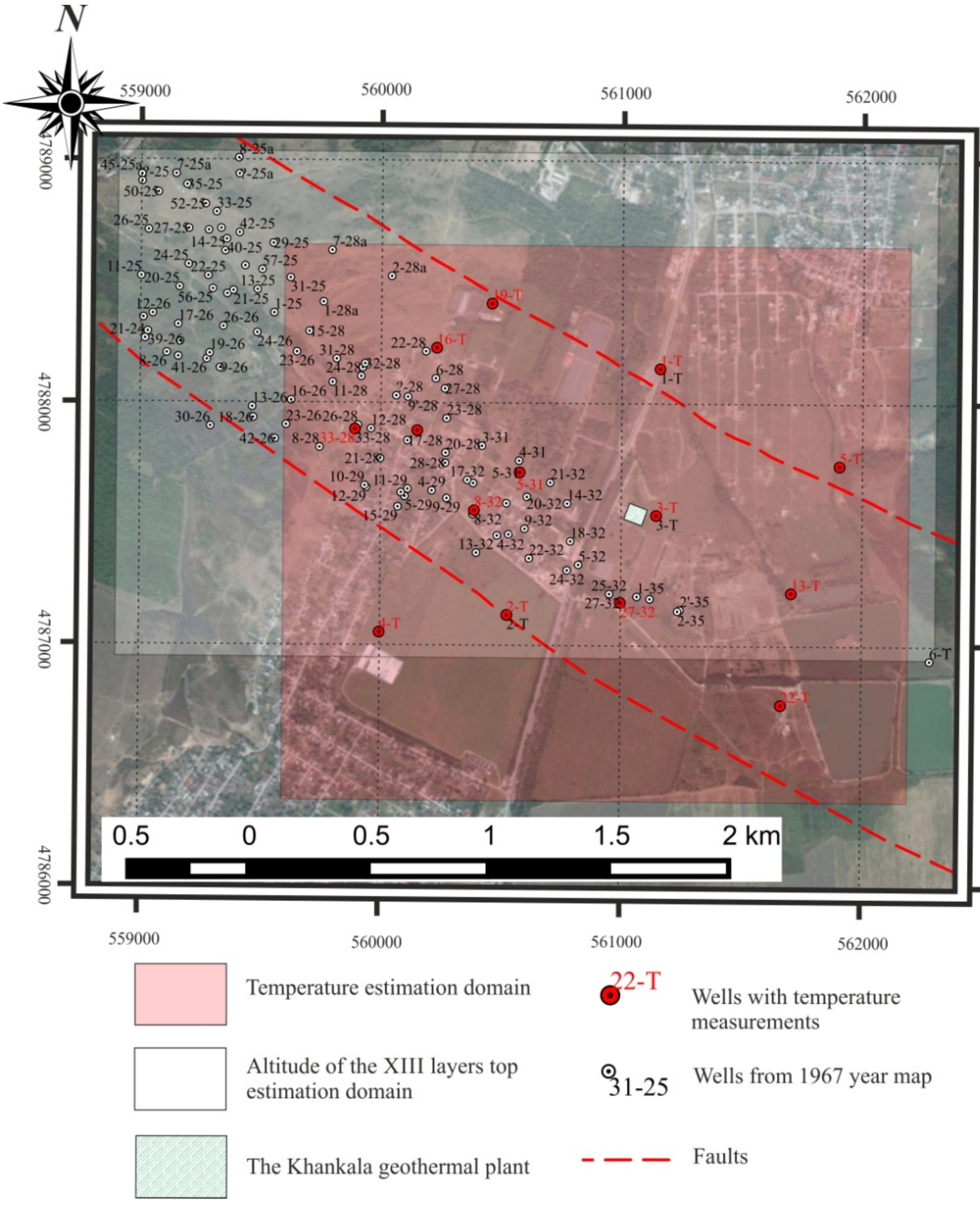


Fig. 3.3. Estimation domain of the XIII layer top elevation and temperature distribution

Data processing and subsequent estimation were performed using ISATIS program.

3.2. Geostatistical analysis and estimation of the XIII layer top elevation

The initial stage of the work was data collection. A map created in 1967 was used for this purpose. It represents more than 100 wells crossing the XIII layer as the deposit is situated in the Oktyabrsk anticline, which contains an oil deposit of the same name. Georeferencing was made in the Quantum GIS program [QGIS Development Team, 2013], using the wells found within the Khankala deposit (Figure 3.4).

Fig. 3.4. Wells 27-32, 14-T, 5-31 of the Khankala deposit of geothermal waters (from left to right)

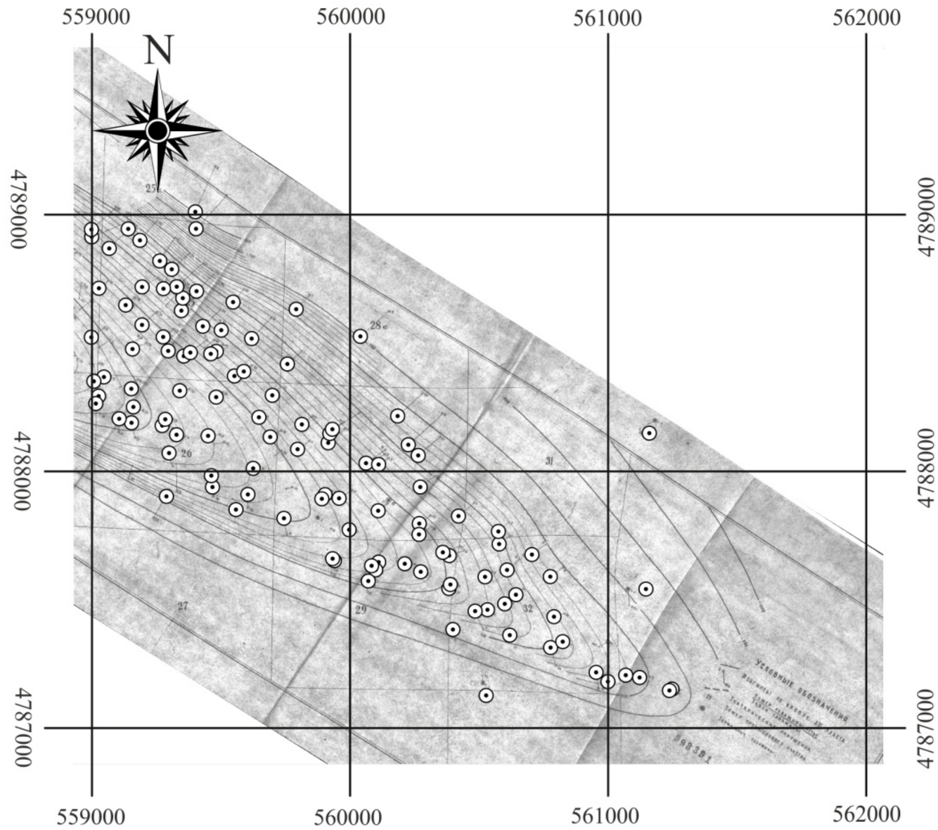


Fig. 3.5. Structural map of the XIII layer (1967) after georeferencing and digitization

In total there are 109 wells which have penetrated the XIII layer and shown on the map made in 1967. They are marked by points with values of the XIII layer top elevation (see Figure 3.5). These points were taken as raw data for the new estimation and structural map creation. Coordinates and absolute elevations are taken from this map and reinterpreted using geostatistical methods.

The first step is statistical estimation of initial data and directional sample variograms calculation, taking into account direction angle, direction tolerance, lag and bandwidth tolerance (Figure 3.6), as raw data usually have irregular distribution and there is no sufficient number of pairs of measurement points separated by precisely fixed distances in a predetermined direction. This work is performed in order to check the stationarity and anisotropy of the data (Figure 3.7). Sectors (Figure 3.6) are moving through the data field from one point to another in order to take into account all the pairs of points which are ranked according to the distance between them and fall into one or the other lag for given direction [Demyanov, Savelyeva, 2014]. 2 wells on the other side of the faults were masked as they cannot be well correlated with other points because of the faults shifts.

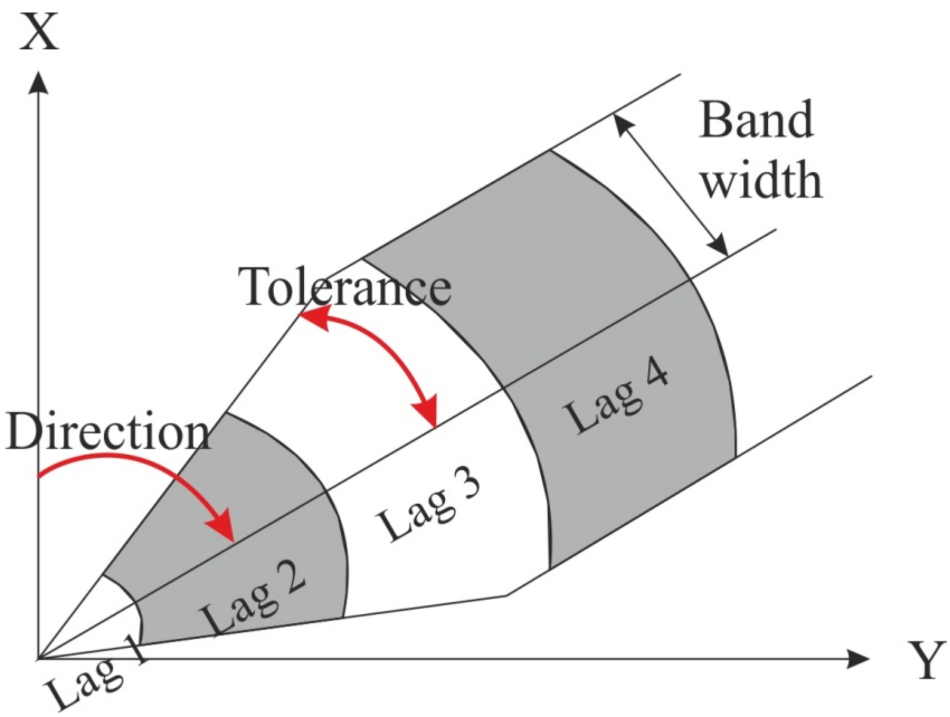


Fig. 3.6. Parameters of directional variogram

The sample directional variograms confirm the known non-stationarity: the mean smoothly increases over the area under study, as the anticlinal fold sinks in a southeasterly direction.

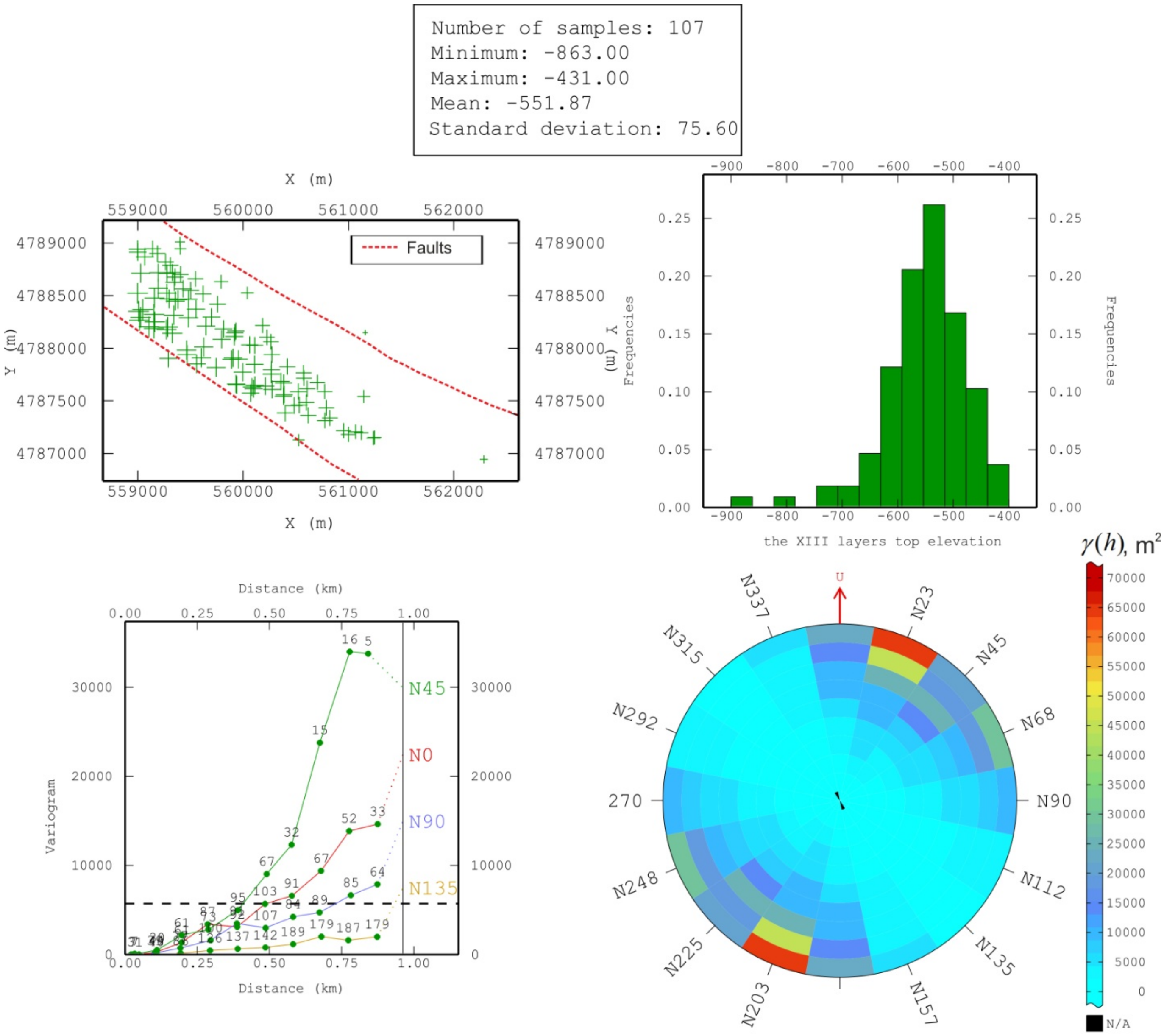


Fig. 3.7. Statistical assessment and directional sample variograms calculation (statistics, initial data location, histogram, directional variograms and variogram map)

As a rule one of the three types of kriging is used when working with non-stationary data: universal kriging, kriging with external drift or intrinsic random functions kriging (IRF-k) (Figure 3.8).

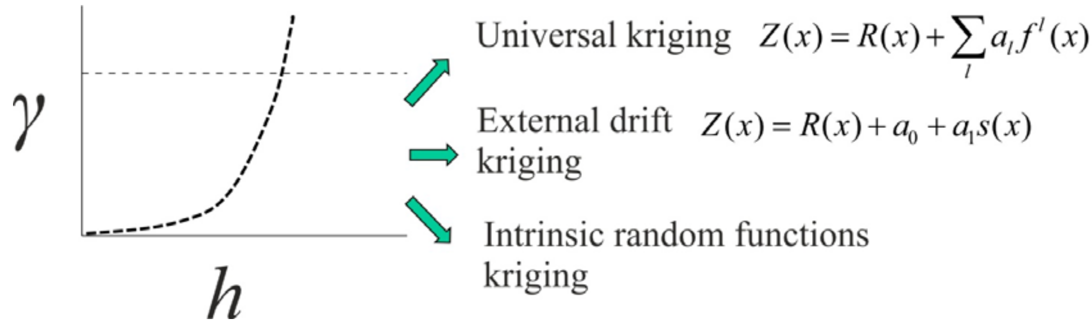


Fig. 3.8. Types of kriging used for non-stationary data

Kriging with external drift uses additional measurement data of a correlated variable as a drift model. It allows to accurately enough estimate the trend in the presence of additional data trend-variable at all points of estimation [Demyanov, Savelieva, 2010].

The idea behind IRF-k, developed by G. Matheron [1973], is that it is possible to analyze the data by considering linear combinations of the data points to achieve a stationary covariance. Instead of dividing the data into stationary residue and drift, IRF-k works with special combinations of the experimental data that filter out polynomial drift up to order k. Such linear combinations are called authorized linear combinations of order k.

In this work universal kriging was used. Universal Kriging assumes that the unknown mean value $m(x)$ varies smoothly within the area under consideration, and a random function can be decomposed into the stationary residue $R(x)$ and the drift $m(x)$: $Z(x) = R(x) + m(x)$. Drift, in its turn, can be modeled by a deterministic polynomial function $m(x)=\sum_l a_l f^l(x)$, where a_l is unknown coefficients, f^l is basic known functions and $f^0(x)=1$.

Condition of unbiasedness:

$$E\{Z^*(x)-Z(x)\}=\sum_\alpha \lambda_\alpha E[Z_\alpha]-E[Z_0]= \\ =\sum_\alpha \lambda_\alpha m_\alpha - m_0 = \sum_\alpha \lambda_\alpha \sum_l a_l f_\alpha^l - \sum_l a_l f_0^l = \sum_l a_l \left(\sum_\alpha \lambda_\alpha f_\alpha^l - f_0^l\right)=0. \quad (3.17)$$

Thus, to fulfill this condition it is required:

$$\sum_\alpha \lambda_\alpha f_\alpha^l = f_0^l. \quad (3.18)$$

The variation of error:

$$Var(\varepsilon) = Var\left(\sum_{\alpha}\lambda_{\alpha}Z_{\alpha} - Z_0\right) = \sum_{\alpha}\sum_{\beta}\lambda_{\alpha}\lambda_{\beta}C_{\alpha\beta} - 2\sum_{\alpha}\lambda_{\alpha}C_{\alpha 0} + C_{00}. \qquad (3.19)$$

Minimizing of variation of error with regard to the unbiasedness condition leads to a system of universal kriging equations. Constructing the corresponding Lagrangian, differentiating it for all the unknown variables and equating to zero the corresponding derivatives:

$$\begin{aligned} &\phi = Var(\varepsilon) + 2\sum_{l}\mu_l\left(\sum_{\alpha}\lambda_{\alpha}f_{\alpha}^{l} - f_0^{l}\right) \\ &\frac{\partial\phi}{\partial\lambda_{\alpha}} = 0 \Rightarrow \sum_{\beta}\lambda_{\beta}C_{\alpha\beta} + \sum_{l}\mu_l f_{\alpha}^{l} = C_{\alpha 0} \\ &\frac{\partial\phi}{\partial\mu_l} = 0 \Rightarrow \sum_{\alpha}\lambda_{\alpha}f_{\alpha}^{l} = f_0^{l} \end{aligned} \qquad (3.20)$$

The variation of universal kriging estimation:

$$\sigma^2 = Var(\varepsilon) = C_{00} - \sum_{\alpha}\lambda_{\alpha}C_{\alpha 0} - \sum_{l}\mu_l f_0^{l} \qquad (3.21)$$

The equations can easily be rewritten in matrix form:

Weights calculation:

$$\begin{bmatrix} C_{\alpha\beta} & f_{\alpha}^{l} \\ f_{\beta}^{l} & 0 \end{bmatrix} \times \begin{bmatrix} \lambda_{\alpha} \\ \mu_l \end{bmatrix} = \begin{bmatrix} C_{\alpha 0} \\ f_0^{l} \end{bmatrix} \qquad (3.22)$$

Unknown values estimation:

$$Z^* = \begin{bmatrix} Z_{\alpha} \\ 0 \end{bmatrix}^t \times \begin{bmatrix} \lambda_{\alpha} \\ \mu_l \end{bmatrix} \qquad (3.23)$$

Variance estimation:

$$\sigma^2 = C_{00} - \begin{bmatrix} \lambda_{\alpha} \\ \mu_l \end{bmatrix}^t \times \begin{bmatrix} C_{\alpha 0} \\ f_0^{l} \end{bmatrix} \qquad (3.24)$$

In order to bring the data on the XIII layers top elevation to stationarity trend $1\ x\ y\ x^2\ xy\ y^2$ was selected as the most appropriate. The variogram of the residue after deducing the trend is stationary. Chosen variogram model is cubic with the range equal to 667 m, and the sill equal to 1084.3 m^2 (Figure 3.9).

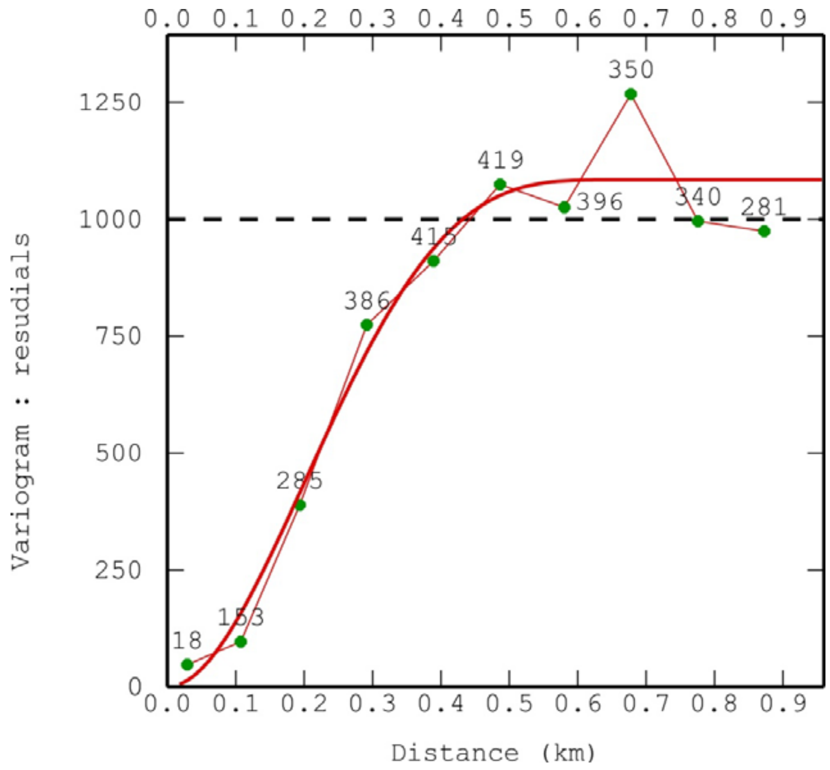


Fig. 3.9. Experimental variogram of the residue data and fitted model

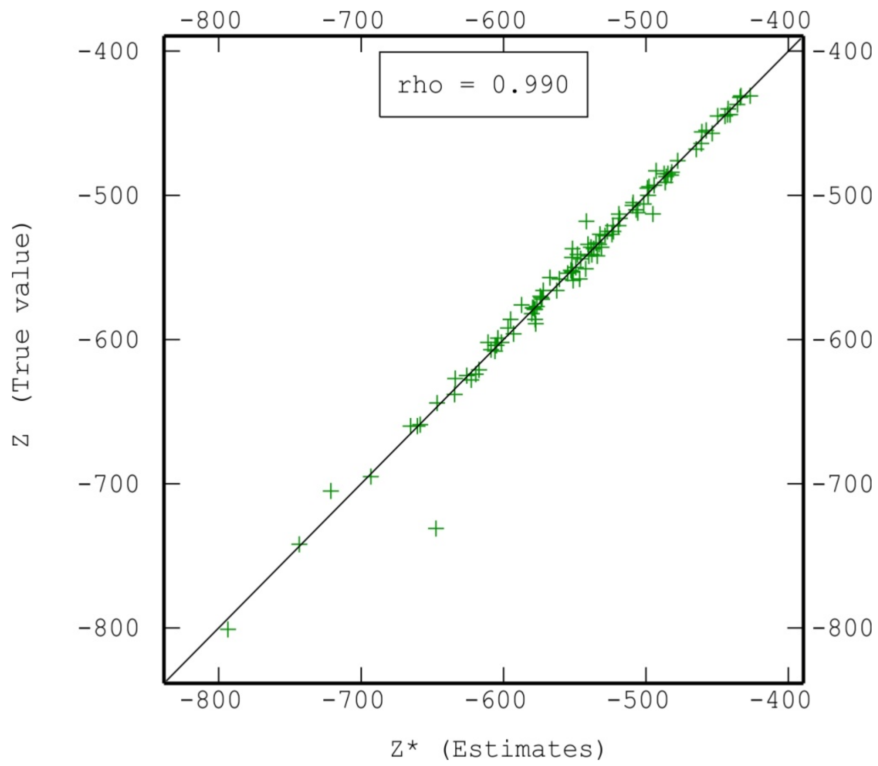


Fig. 3.10. Cross-validation of the model for the estimation of the XIII layer top elevation

Because of the small amount of data, unique kriging neighborhood is used, i.e. for each estimated point all the known values are utilized. Before interpolation, the selected parameters (model and the neighborhood) are checked using cross-validation: raw data one after another is “hidden” and re-estimated and then the difference between the original and obtained data is calculated. This procedure allows evaluating the validity of the chosen variogram model and kriging neighborhood (see Figure 3.10).

Cross-validation procedure shows sufficient accuracy of the selected parameters with correlation coefficient of 0.99 as can be seen in figure 3.10. Thus, the structural map of the XIII layer was created using this model. The faults are considered as screens for the estimation. Because there is only one well on the other side of the faults, estimations are not possible to the north-east and south-west of the anticline (Figure 3.11).

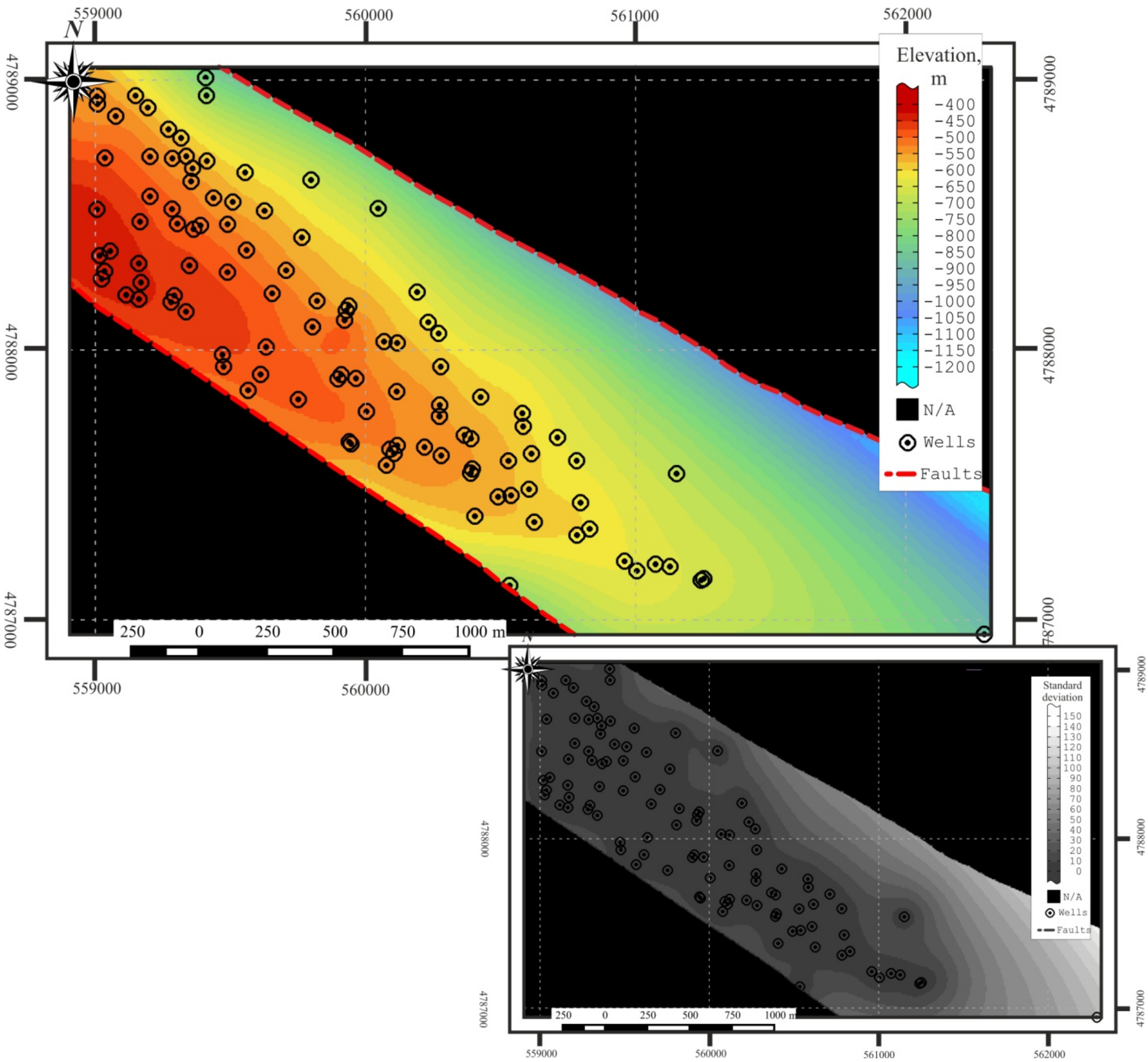


Fig. 3.11. Estimation of the elevation of the XIII layer and associated standard deviation

A standard method of linear interpolation based on the measurement points was used during creation of the map in 1967. All the data in the vicinity of any point are taken into account (plus new well 6-T in the bottom right corner) in the new geostatistical interpretation (Figure 3.12).

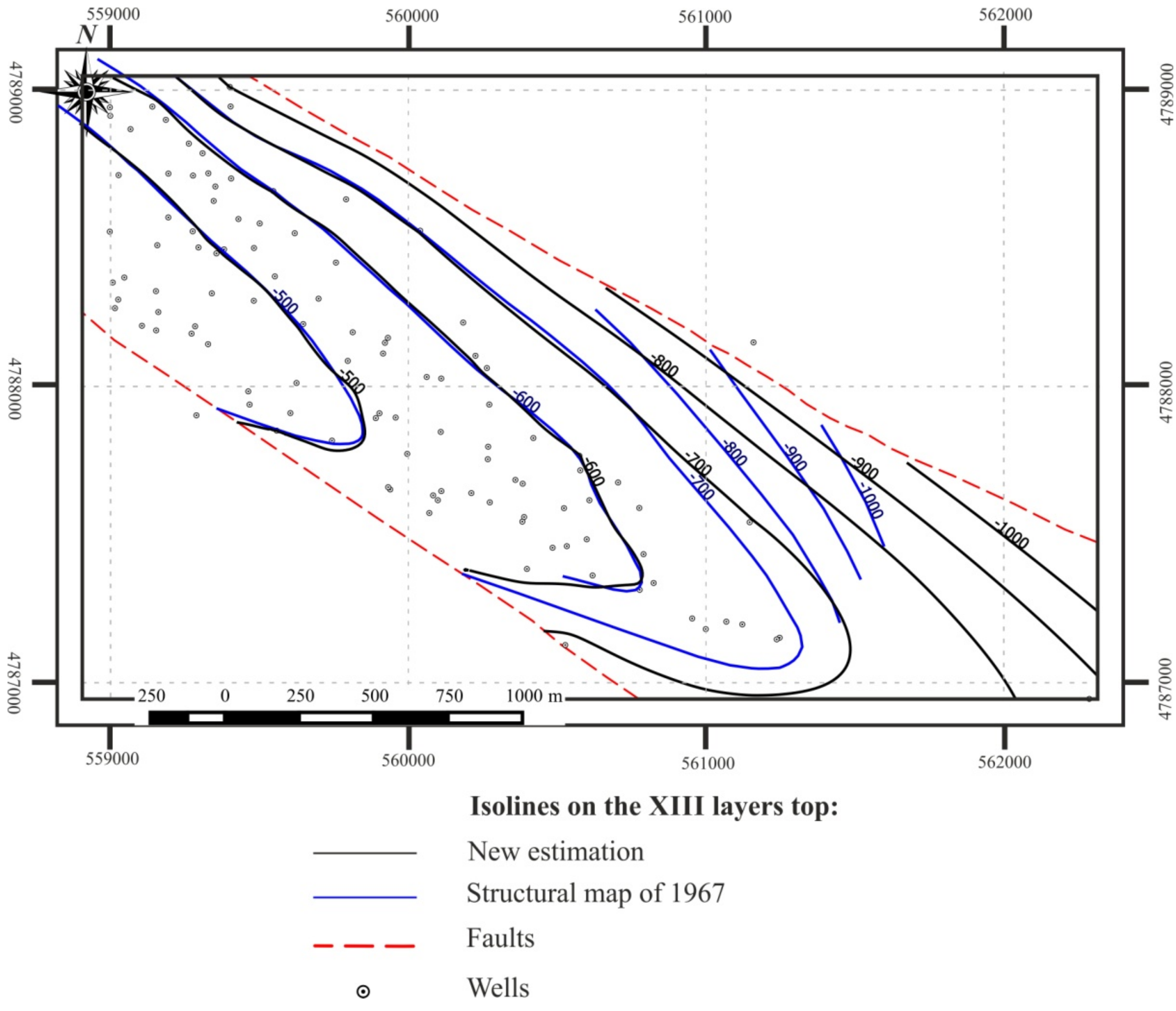


Fig. 3.12. Comparison of old and new structural maps of the top of the XIII layer

It should be noted that configurations of the XIII layers top elevation on different maps match well in the northwest of the area under study where there are many measurement points, while in the south-eastern part the differences in the depth exceed 100 m. This discrepancy is essential when selecting the location of wells, especially taking into account that the southern part is one of the most promising for the exploitation of the geothermal waters.

3.3. Geostatistical analysis and modelling of temperature distribution within the territory of the Khankala geothermal waters deposit

Measurements of the temperature in the wells of the Khankala geothermal waters deposit as well as geological observations were made in 1968 and 1988, and they are reflected in the relevant reports [Shpak, 1968f; Krylov, 1988f]. Sampling was carried out after the suspension of geothermal waters withdrawal in order to establish well-rock thermal equilibrium. About 100 measurements were made on the whole in 14 productive wells (Figure 3.13).

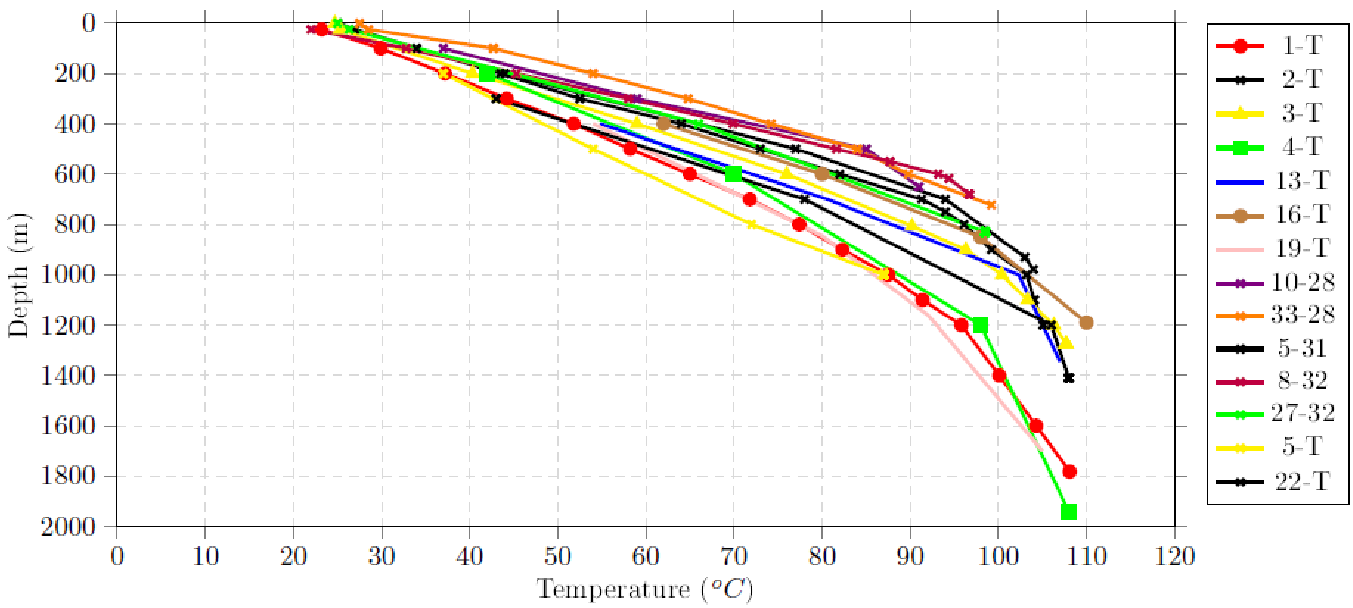


Fig. 3.13. Temperature measurement within the Khankala deposit of geothermal waters

Temperature measurements show linear growth in the beginning but then as the depth reaches productive formations geothermal gradient tends to decrease. This can be explained by convection mechanism caused by geothermal waters circulation. It was the main reason to divide our estimation and use two different models.

3 wells were masked in statistics because they are situated on the other side of faults and cannot be well correlated with other data (see Figure 3.14).

The well passports have been lost as a result of the tragic events that occurred at the territory of the Chechen Republic, so there are no data on the inclination of wells. The only available information, to enable assessment of the inclination, is corrections for the curvature of wells that reach 11 m for the depth more than 1 km, which means a relatively small bias. In this regard, all the wells were considered as vertical during geostatistical analysis.

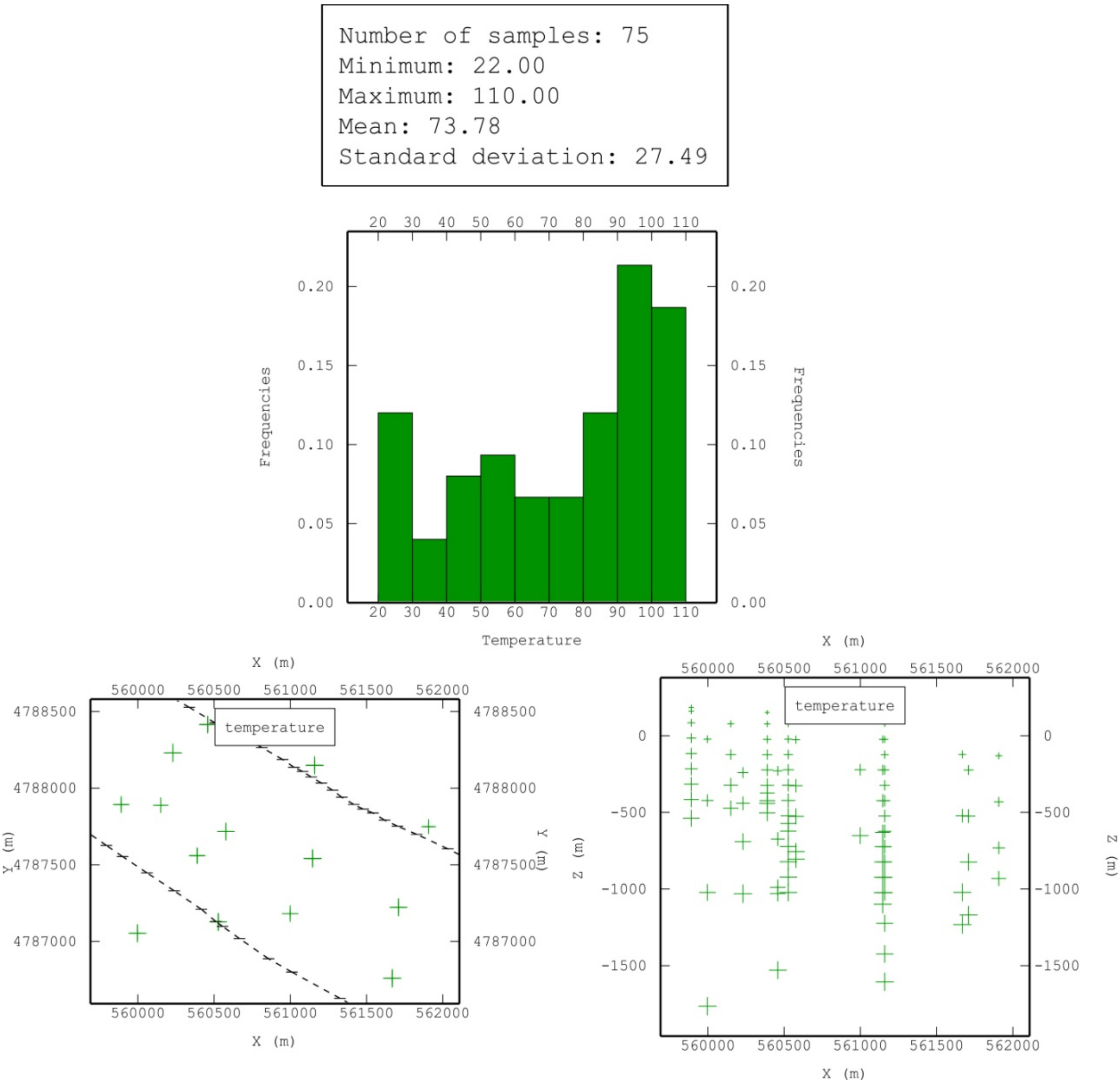


Fig. 3.14. Temperature measurements statistics and displacement (XOY, XOZ projections)

There were two options for the choice of the initial coordinate system to work with temperature measurements: a normal reference plane and the top of the XIII layer as a reference plane (Figure 3.15). Both of them were tested.

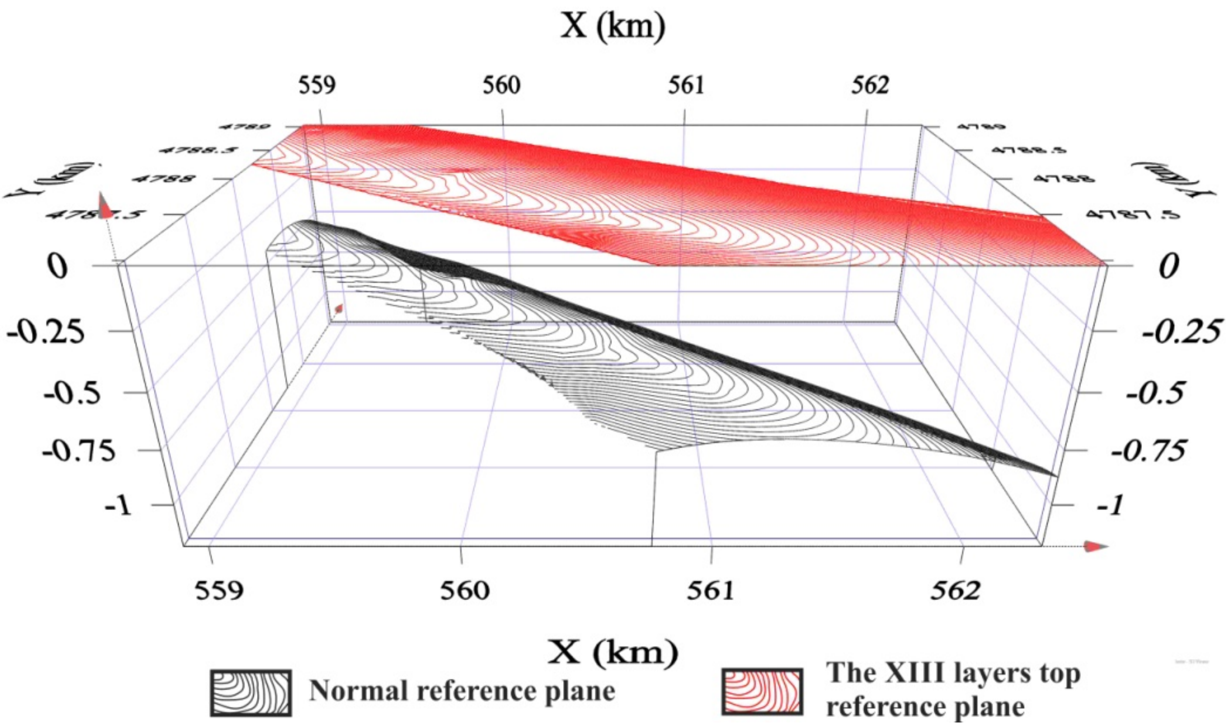


Fig. 3.15. Reference plane choice for z coordinates

As we can see from the scatter-diagrams (Figure 3.16) variance of the data is less in the case of the XIII layers top as a reference plane choice, especially in the vicinity of the layer itself. Before working with variograms, the coordinate system was rotated, so that the anticline folds directly to the east with the depth increasing from west to east and from the axis to the limbs of the structure (i.e. in x and y directions). This facilitates the drift finding as the first step of the universal kriging.

Four horizontal variograms for different directions were calculated to evaluate the benefits of choosing one or another variant of coordinate system (vertical variogram remains unchanged in both cases) (Figure 3.17).

Although the number of pairs is insufficient for reliable conclusions, especially with increasing distance, it is observed that the variation of temperature with the top of the XIII layer chosen as reference plane is reduced. Thus this variant is used as a selection for the coordinate system. It can be explained by the fact that the XIII layer presents an anticline structure containing geothermal waters and the temperature follows this structure.

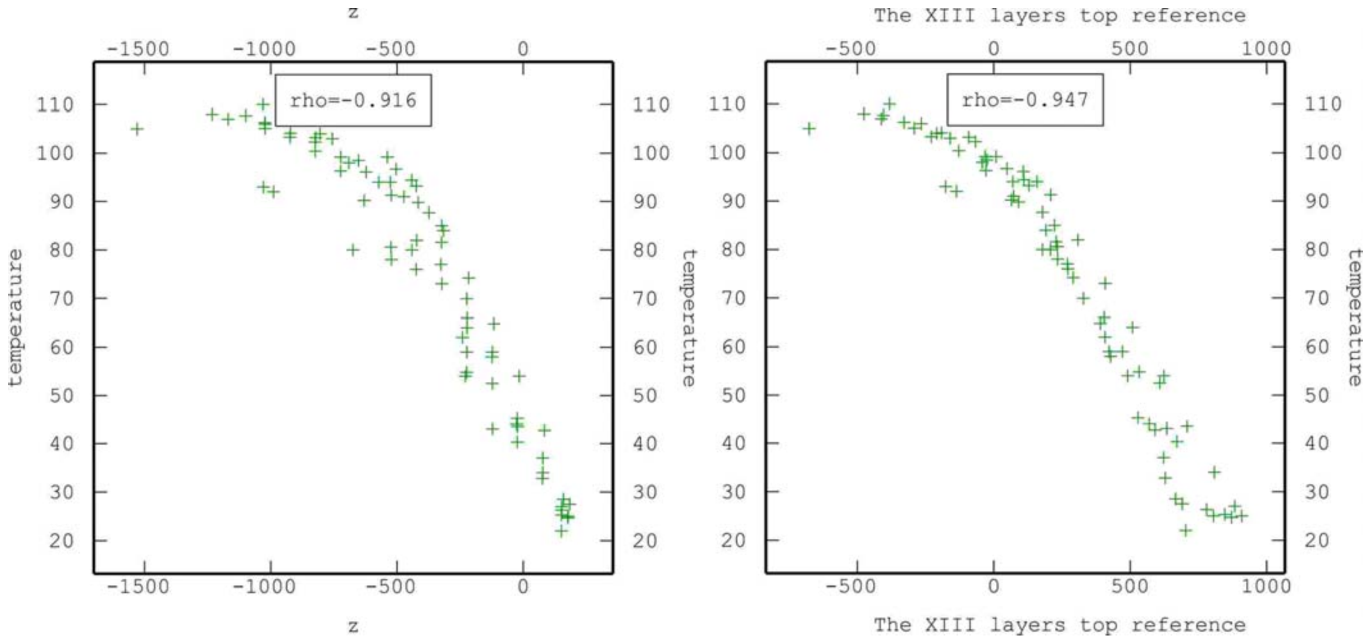


Fig. 3.16. Scatter-diagrams of the temperature versus depth in cases of two different reference planes

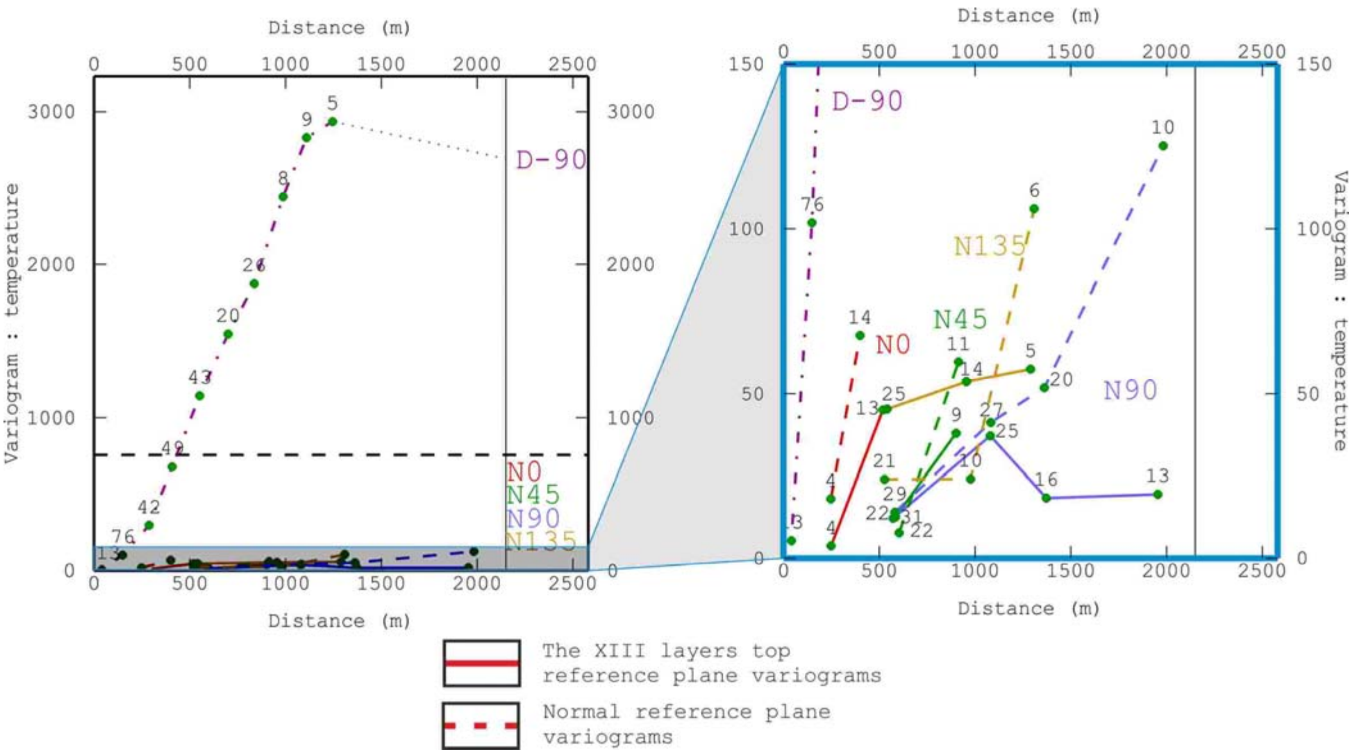


Fig. 3.17. Variograms calculation

Vertical variogram is non-stationary, which corresponds to the temperature progressive increase with depth. It was the main reason for selecting the universal kriging modelling.

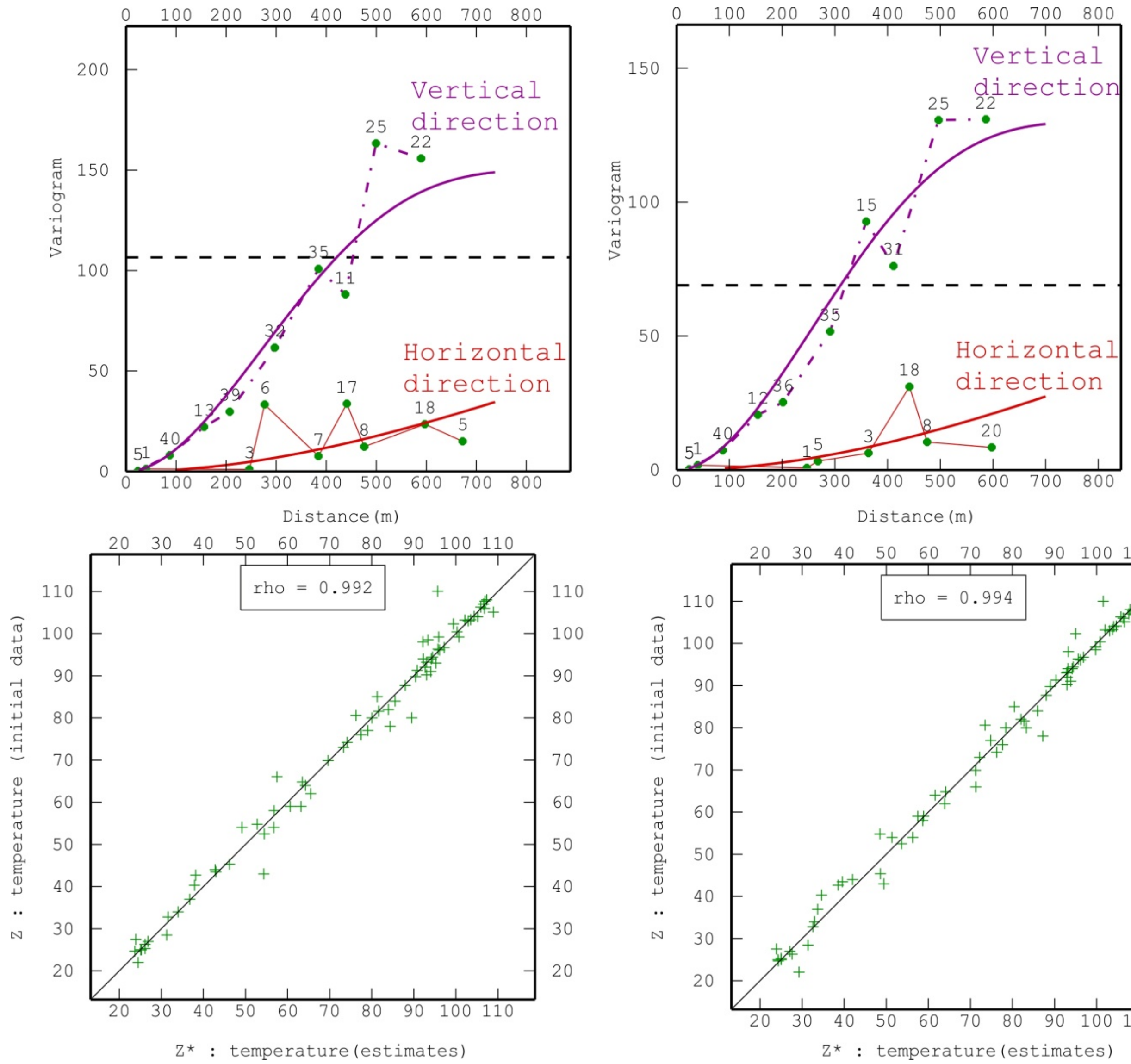


Fig. 3.18. Variogram models and the results of cross-validation for normal coordinate system (left) and the XIII layers top as the basis (right)

It was decided to estimate the temperature within the reservoir taking the XIII layer top as the basis for the reference plane, and to switch to the normal reference plane closer to the surface, and finally to combine these two estimations.

Steps for the universal kriging are as follows:

1. Selection of trend.
2. Calculation of residues.
3. Selection of variogram model for the data after removing the trend, and kriging parameters (see Figure 3.18, Table 3.1).
4. Estimation and its standard deviation.

Table 3.1. Kriging parameters for temperature estimation

Normal reference plane	
Drift	1 y z
Variogram	Cubic (range: x=y=3500 m z=900 m, sill = 150 °C^2)
Neighborhood	Moving (x=y=3000 m, z=250 m)
The XIII layers top as the basis	
Drift	1 y z
Variogram	Cubic (range: x=y=3500 m z=850 m, sill = 130 °C^2)
Neighborhood	Moving (x=y=3000 m, z=250 m)

Errors in estimation obtained by cross-validation procedure are shown in figure 3.19.

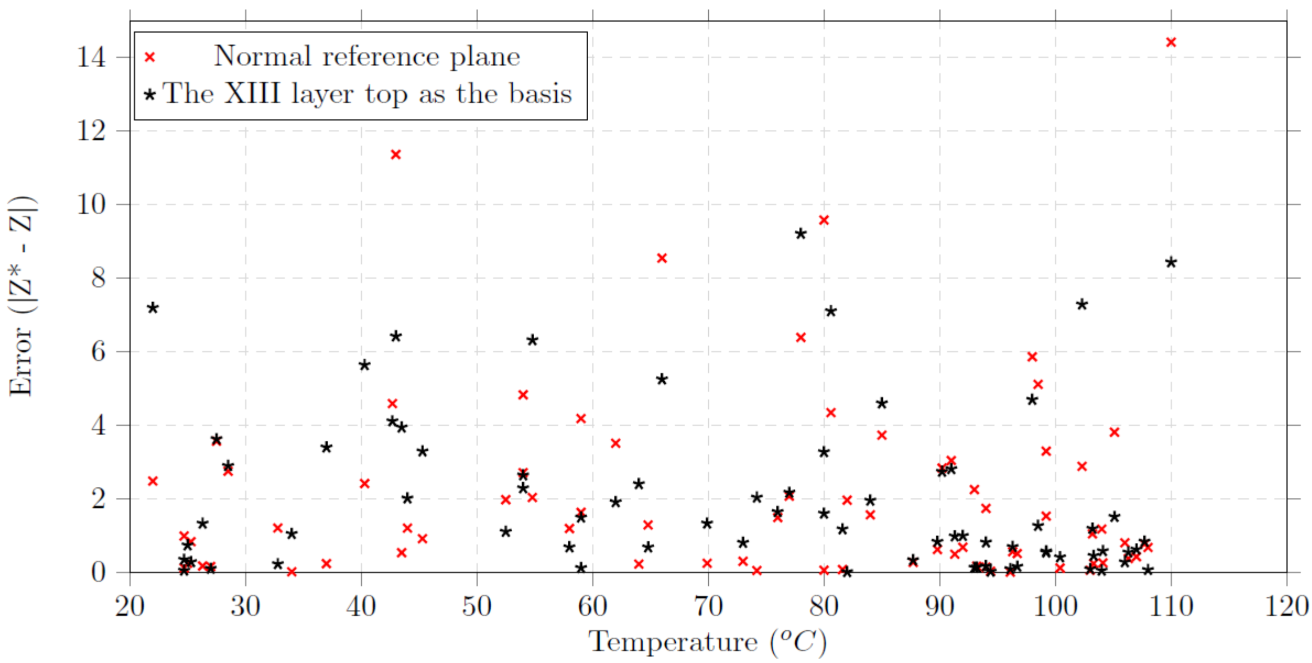


Fig. 3.19. Absolute errors for normal and modified coordinate systems

It is not apparent but can be seen from the figure that small values of the temperature, which are respectively closer to the surface, are estimated more accurately in the normal coordinate system, and modified system gives better results with an increase in temperature and therefore depth. For example total absolute error when assessing the temperature from 22 to 54 °C is equal to 35.7 °C and 47.7 °C, the temperature from 54 to

110 °C is equal to 118.1 °C and 100.9 °C for normal and modified coordinate systems respectively. Thus, the results of cross-validation confirm the correctness of assumption for the creation of the temperature estimation as a combination of the two (Figure 3.20).

Values $z\_\max$ and $z\_\min$ are arbitrary and were chosen considering scatter diagrams (Figure 3.16), cross-validation (Figure 3.18) and deviation of two estimations, with $z\_\max$ equal to -200 m, $z\_\min$ equal to difference of the XIII layers top plus 200 m. The new temperature was calculated by the following formula, in order to combine the two estimations while preserving a smooth transition:

$$T^3 = (1-\alpha) * T^1 + \alpha * T^2, \tag{3.24}$$

where $\alpha = \sin(p * \pi / 2)$ and $\begin{cases} p = 1, \; for \; z \le z\_\min \\ p = 0, \; for \; z \ge z\_\max \\ p = \dfrac{z\_\max - z}{z\_\max - z\_\min}, \; for \; z\_\min < z < z\_\max \end{cases}$

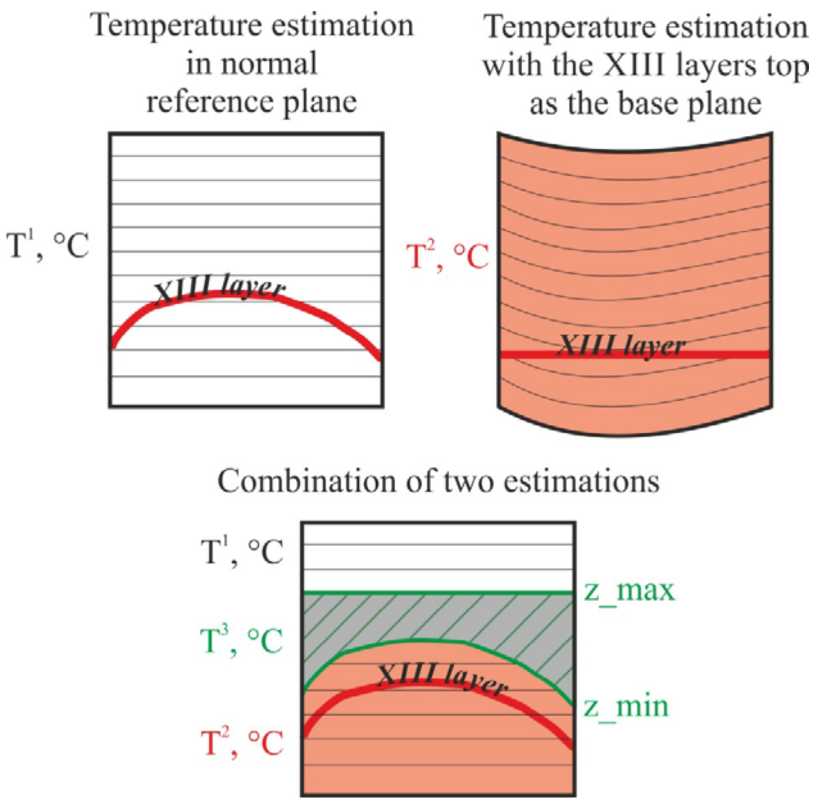


Fig. 3.20. Combination of two temperature estimations

The kriging standard deviation was calculated by the same principle (Figure 3.21).

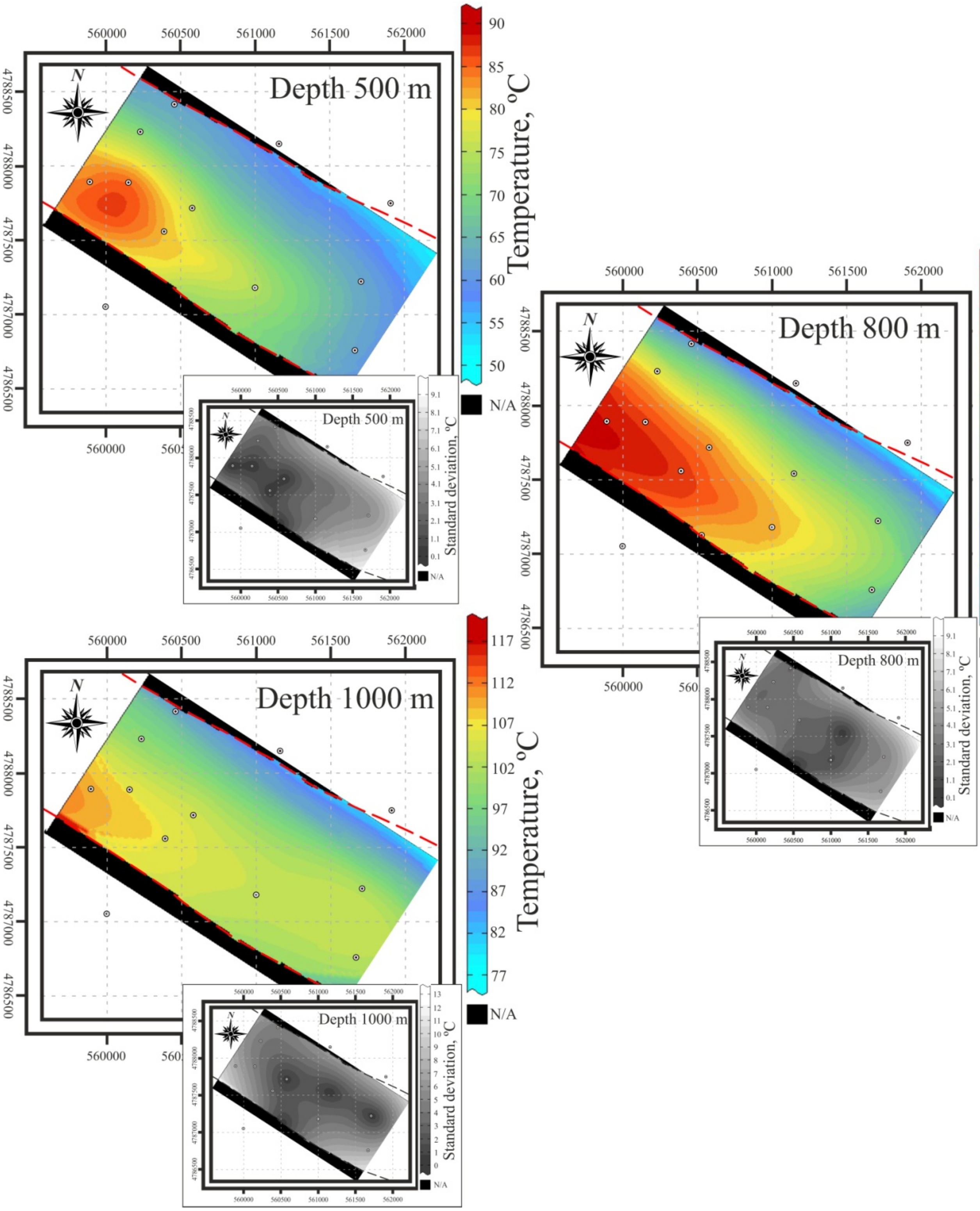


Fig. 3.21. Cross-sections of final estimation of the temperature distribution and its standard deviation on the 3D block

“Anticlinal” form of the temperature distribution can be explained by the fact that the productive layers of the deposit have an anticline structure, and the highest temperatures relate to geothermal waters contained in these layers.

Temperature estimation within the XIII productive layer planned for exploitation is shown in figure 3.22.

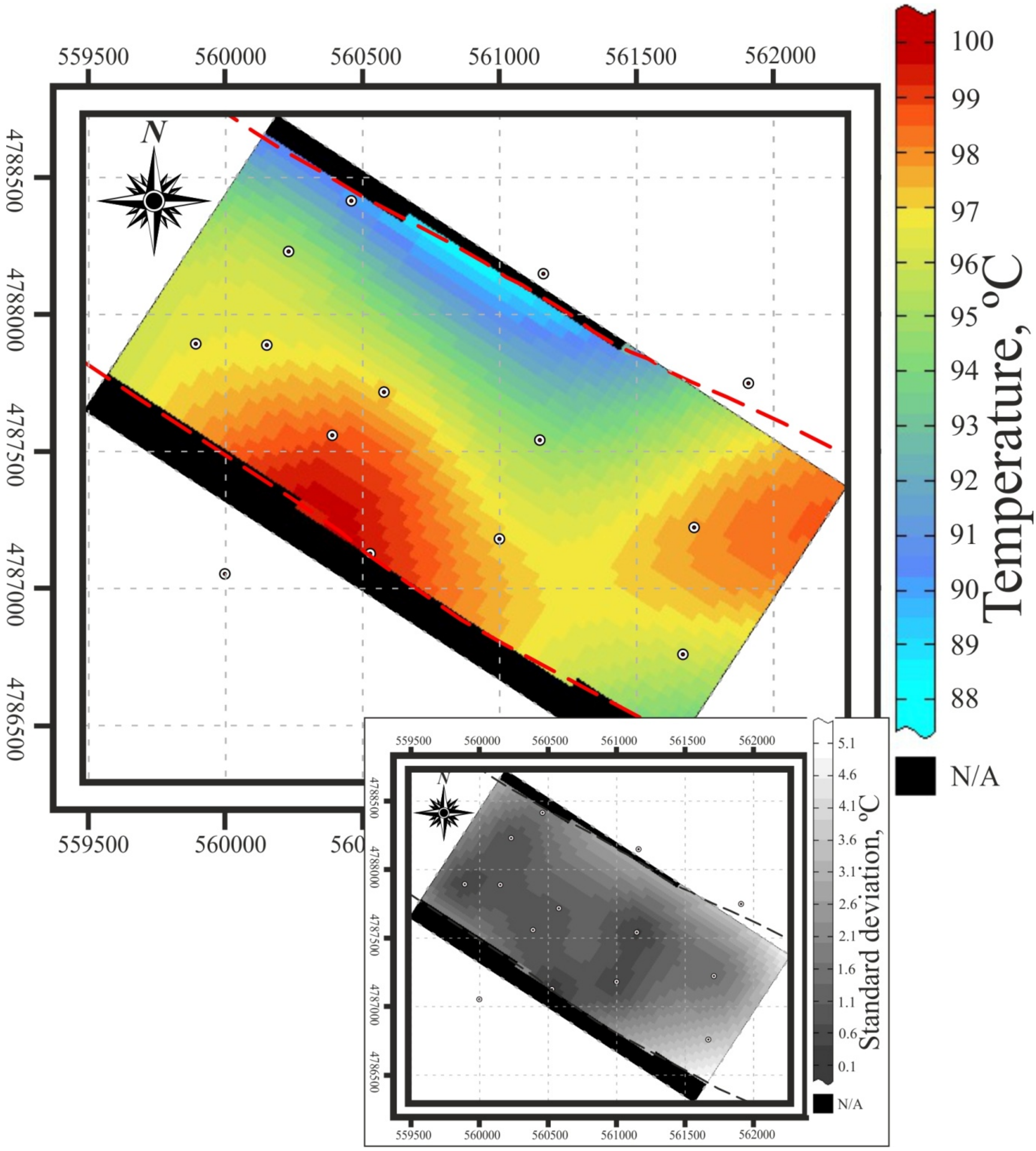


Fig. 3.22. Temperature within the XIII layer and kriging standard deviation

Geostatistical estimation of the temperature distribution showed the highest values in the southern part of the layer, which is complicated by the main fault, which was previously noted by V.B. Krylov [1983f]. It is one of the factors for the selection of the area as the most promising for further work according to temperature measurements interpolation.

The highest temperature confined to the southern part of the deposit and the main fault respectively can be explained by mechanical nature. As it is known, geothermal heat source may be divided into radioactive, chemical and mechanical compounds, so total volumetric rate of heat production is [Stüwe, 2002]:

$$S = S_{RADIOACTIVE} + S_{CHEMICAL} + S_{MECHANICAL} \tag{3.26}$$

Thus, possible additional source of heat generation is tectonic movement along the main fault of the Khankala deposit. This fact, as well as the general nature of the spread of geothermal waters in the North Caucasus is well explained within the framework of overthrust-nappe theory [Kamaletdinov, 1981], considering the North Caucasus as a mobile tectonic zone. According to this theory, the Earth's crust is composed of many tectonic plates (nappes), representing its main structural elements experiencing horizontal movements with an amplitude of tens, sometimes hundreds of kilometers over many millions of years. Movement and friction of these plates provide major geological phenomena and processes (orogeny, seismicity, volcanism, etc.), as well as the formation of important mineral resources (oil, gas, metal ores, precious stones and others.).

Adjusted structural map of the XIII productive layer top was created using geostatistical approach and estimation. The depth of the aquifers top within the area under study varies from 430 to 1191 m. The difference between the forecast and the actual depth after drilling the production well is 9 m (kriging standard deviation – 10 m). A three-dimensional map of temperature distribution within the Khankala geothermal waters deposit was created. The XIII layer temperature in the productive well according to geostatistical estimation is equal to 96.2 °C (kriging standard deviation – 0.5 °C), the actual temperature of water at the productive wellhead – 95 °C.

The XIII layer structural map and 3D model of temperature distribution within the Khankala geothermal waters deposit were created for the first time using geostatistical techniques. It allows identifying the most promising areas for future work. Knowledge of temperature together with information on the productive flow rate provides preliminary assessment of the achievable capacity of geothermal plant.

Chapter 4. Numerical modelling of the Khankala geothermal waters deposit exploitation

One of the stages of work, along with geostatistical estimation, is simulation of the utilized geothermal waters reinjection in order to draw up guidelines for the exploitation and to forecast the evolution of the resource.

As it was mentioned, a doublet (see Chapter 1.4) was implemented, i.e. one productive and one injection well with reinjection of all the water, and to predict the changes in the temperature of the resource (it goes down as a result of the injection of cold water) it is necessary to construct a mathematical model.

Necessity of hydrogeological forecasts in connection with the creation of large hydraulic structures and water deposits exploitation determined rapid development of the theory of groundwater dynamics, and since the seventies the numerical modelling using computers came into being [Vsevolozhskiy, 2007]. A large number of numerical codes was developed in order to model fluid and heat flow in aquifer systems (Comsol, Tough2 [Pruess et al., 1999], Metis [Goblet, 1980], Marthe [Thiéry, 1990], Opengeosys [Kolditz et al., 2012] and others), allowing to predict and select the right regime of exploitation of a thermal water resource, and in particular the effect of cooled water reinjection on the life span of the exploitation.

For example, the problem of cold front expansion in injection wells occurred in France after 20 years of exploitation of geothermal waters in the Paris Basin. This led to temperature decrease in one production well, and it was expected to lead to a gradual decrease in temperature in the other [Lebrun et al., 2011; Lopez et al., 2012]. Different concepts were proposed to solve this problem such as construction of reversed wells and seasonal (winter-summer) injection-production of geothermal water [Réveillère et al., 2013]. Modelling has been used for over 20 years to predict the duration of the geothermal waters exploitation and the impact of installing new doublets in the Paris Basin [Lopez et al., 2010] (Figure 4.1).

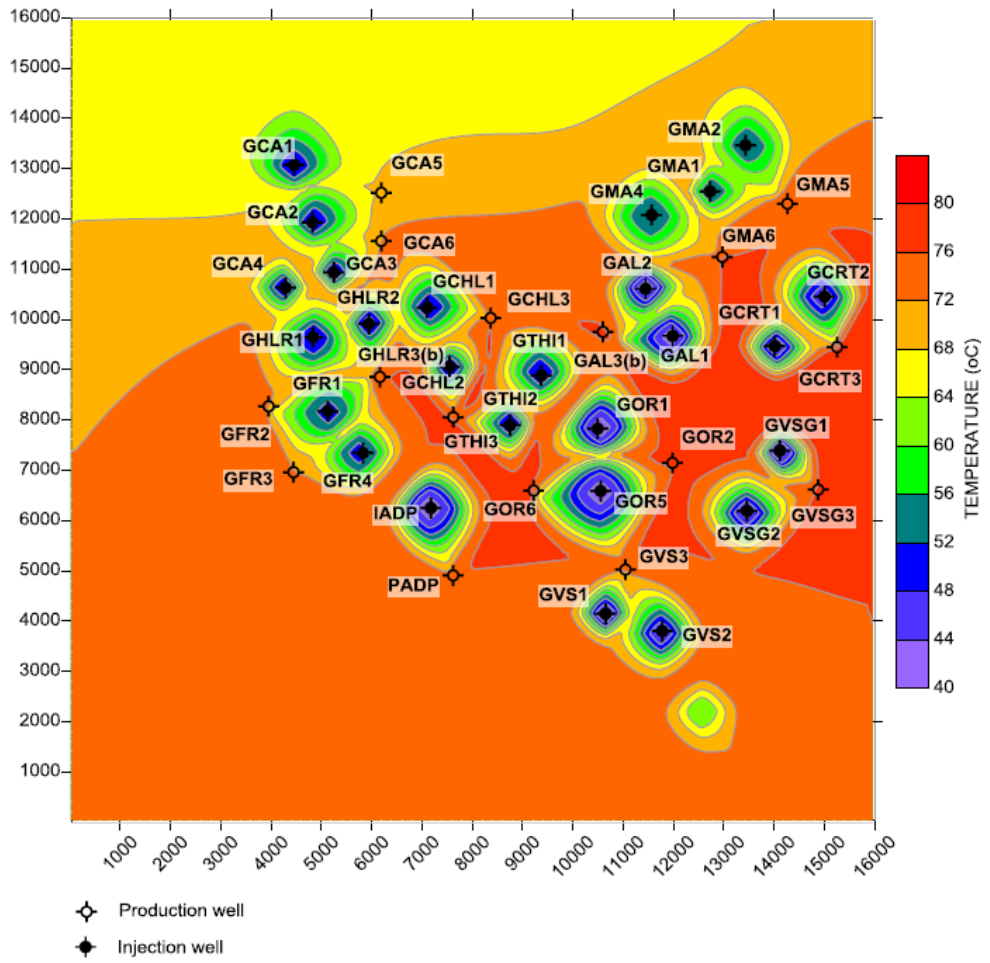


Fig. 4.1. Temperature within the Paris Basin forecast for 2035 [Papachristou, M. 2011]

Thus, it is necessary to conduct simulation of reinjection of used waters in order to draw guidelines for achieving long-term sustainable exploitation of the Khankala deposit XIII layer. The computer code Metis was used for this purpose. It was developed at the Geosciences Department of Mines ParisTech [Goblet, 1980], and it simulates liquid flow, heat and mass transport in fractured and porous medium in either steady or transient conditions. Mathematical equations describing the processes are converted into a form suitable for direct computer processing by the finite element method, which is one of the most efficient numerical methods for solving partial differential equations, describing the state of physical systems of complex structure [Rozin, 2000]. It is a grid method: the region of interest is divided into distinct volumes (elements) and the model is defined by a system of differential equations with given boundary conditions. The equations are discretized in space according to the Galerkin formalism. Systems of linear equations are solved by the conjugate gradient method [Hestenes, Steifel, 1952].

4.1. Regional groundwater flow model

The initial stage of the work was the creation of a regional hydrological model to understand general aspects of water circulation in the XIII layer within the vast territory of the Chechen Republic. The XIII layer is isolated from others by impermeable clay interlayers and a two-dimensional model was adopted for this case due to big difference in horizontal and vertical extensions.

The reservoir recharge zone is Karagan-Chokrak deposits outcrop in the south of Chechnya within the Black Mountains, which was chosen as the southern boundary of the modeled area. The northern border is the Terek River which is assumed to act as a regional drainage axis (Figure 4.2). Waters move in the north direction after infiltration [The hydrogeology of the USSR, 1968].

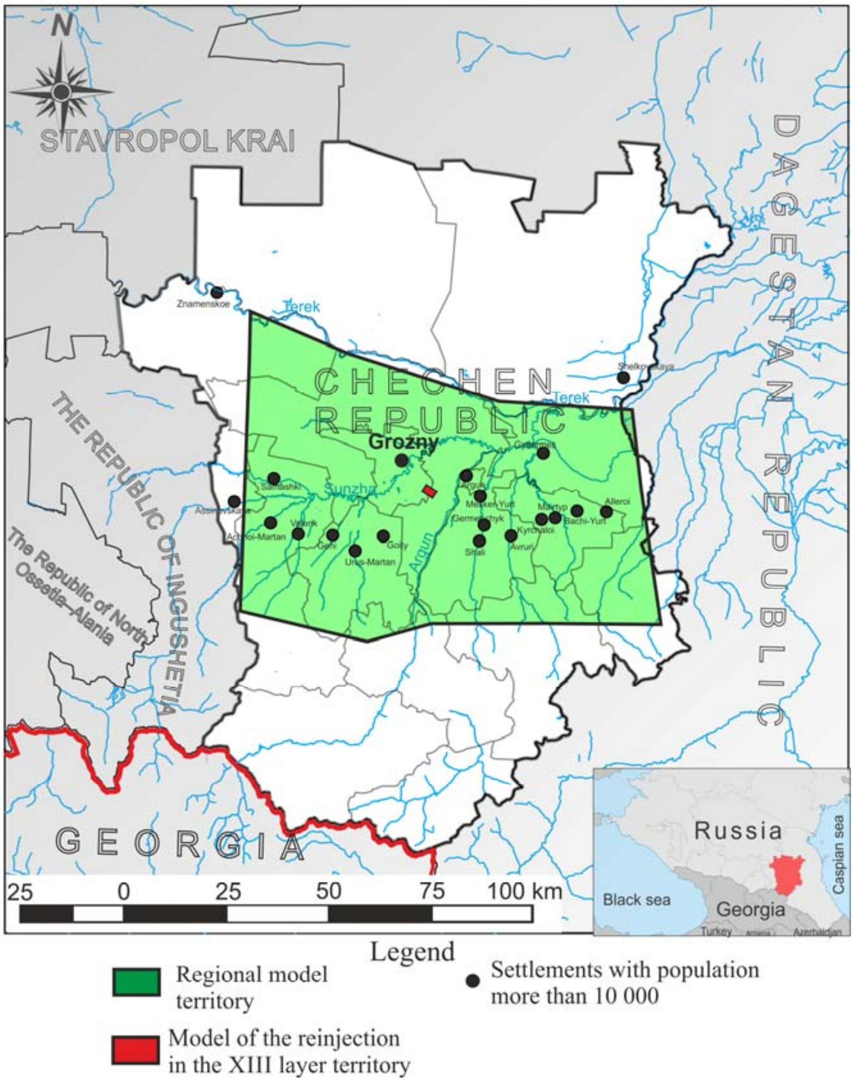


Fig. 4.2. The territory of regional and “doublet” models

4.1.1. Flow mechanisms

Porous geological medium contains solid and void parts, and must be continuously distributed in a certain volume. The concept of representative elementary volume (REV) is introduced to meet this requirement [Bear, 1972]. For instance, the value of porosity depends on the location of small control volumes and its fluctuation will decrease as the size of the control volume increases (Figure 4.3). The value of the system parameter will remain constant regardless of the size of the control volume above certain size (REV). Further increase in the control volume will lead to further variations of the system parameters only in a heterogeneous environment (large scale variations).

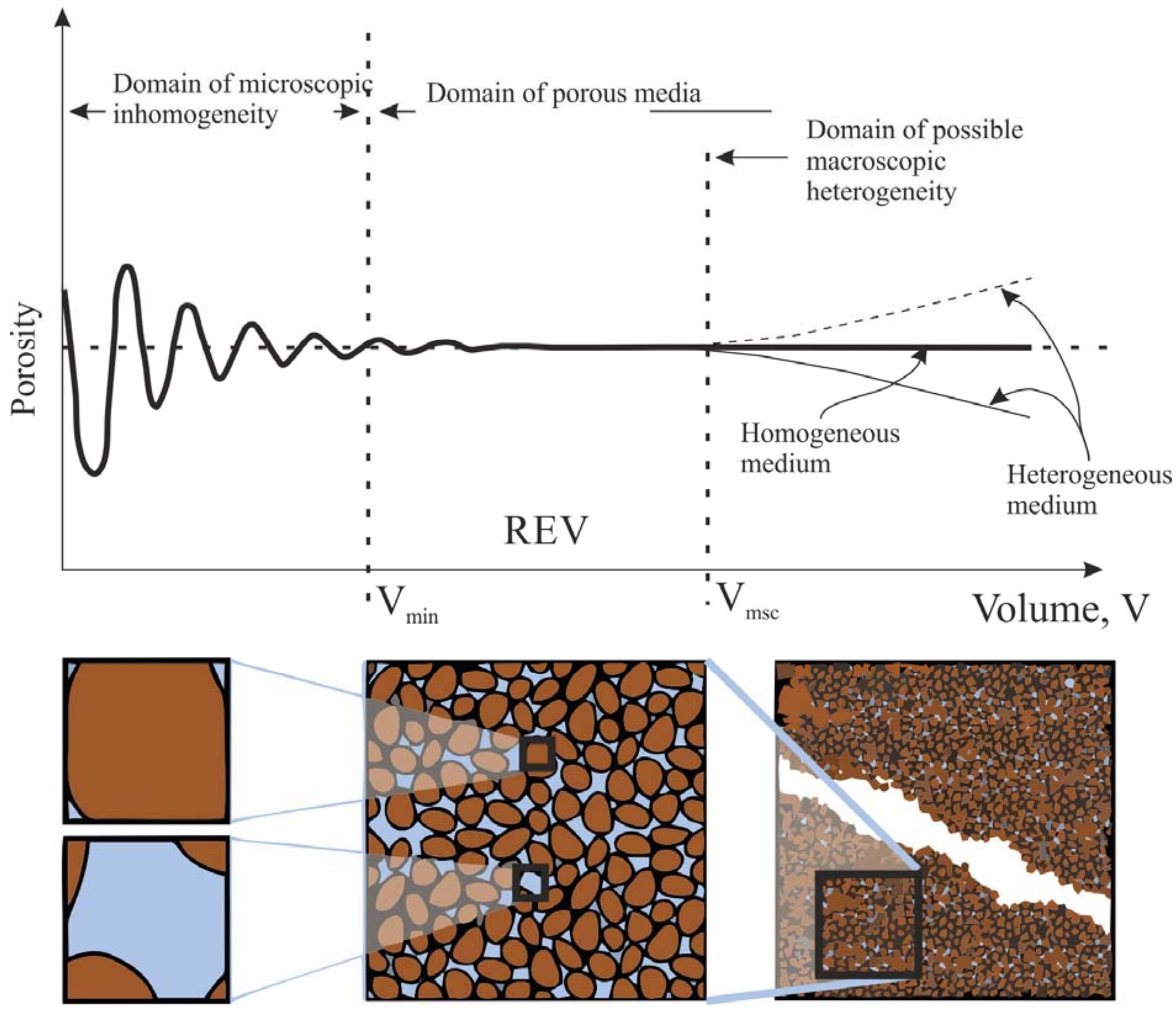


Fig. 4.3. The concept of the Representative Elementary Volume (REV) [Böttcher, 2013]

The aim is to model groundwater flow (considering incompressible fluid) in a saturated porous medium in the case of the regional model construction within the

Chechen Republic.

This problem is described by two laws:

1) Darcy's law (Figure 4.4). Darcy [1856] experimentally determined that for a particular type of sand, the volume flow Q flowing through a sample is directly proportional to the change in hydraulic head $h_2 - h_1$ and the section area A, and inversely proportional to the distance l:

$$Q = -KA\frac{h_2 - h_1}{l}, \tag{4.1}$$

where K is hydraulic conductivity.

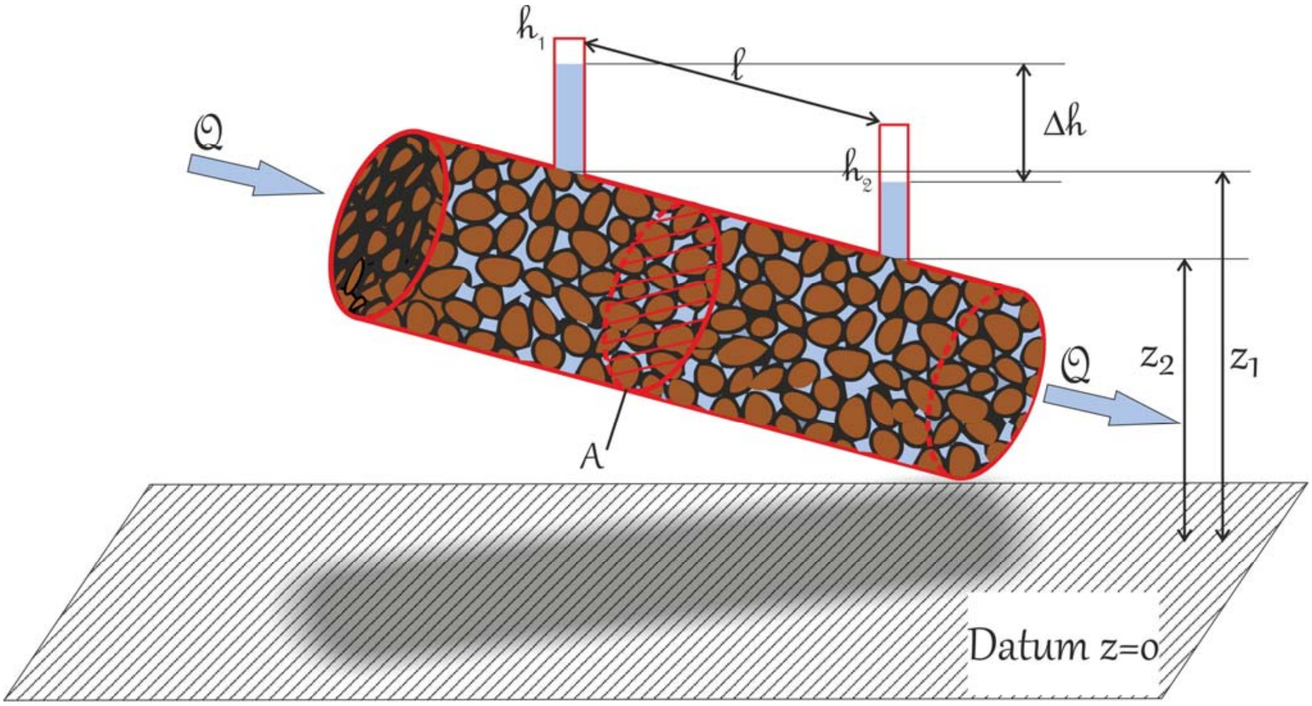


Fig. 4.4. Darcy law

Let $q = Q / A$ be the volumetric flow rate per unit area (Darcy velocity). Then the differential form of Darcy's law is:

$$q = -K\frac{dh}{dl} \tag{4.2}$$

In three-dimensional space:

$$q_x = -K\frac{\partial h}{\partial x} \quad q_y = -K\frac{\partial h}{\partial y} \quad q_z = -K\frac{\partial h}{\partial z}, \tag{4.3}$$

which could be written as:

$$q = -K \; grad \; h \tag{4.4}$$

2) The mass conservation law (continuity equation) (Figure 4.5), states that the amount of water entering the REV is equal to the amount which flows out (in a steady state):

$$\frac{\partial q}{\partial x} + \frac{\partial q}{\partial y} + \frac{\partial q}{\partial z} = 0 \tag{4.5}$$

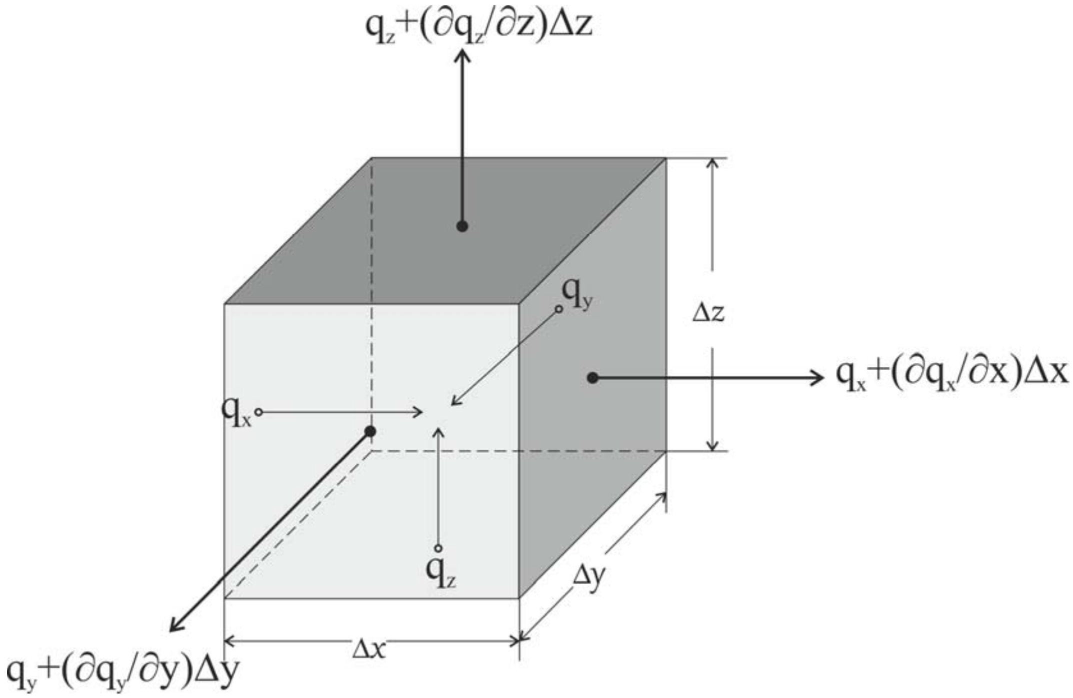


Fig. 4.5. Continuity equation [Istok, 1989]

In the case of transient groundwater flow:

$$\frac{\partial q}{\partial x} + \frac{\partial q}{\partial y} + \frac{\partial q}{\partial z} = -S_s \frac{\partial h}{\partial t}, \tag{4.6}$$

where S_s is specific storage coefficient.

This equation is a special case, valid for constant density flow, of the more general conservation equation for variable density flow:

$$div(\rho U) + \frac{\partial}{\partial t}(\omega \rho) + \rho q = 0, \tag{4.7}$$

where U is Darcy velocity,

ω – porosity,

ρ – water density,

q – injected / withdrawn flow rate per unit volume of the porous medium,

ρq – indicates the existence of a source or sink.

Darcy's law (4.3) and the continuity equation (4.6) are combined into a single equation of second order partial derivatives:

$$\frac{\partial}{\partial x}\left(-K\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(-K\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(-K\frac{\partial h}{\partial z}\right)+G=-S_s\frac{\partial h}{\partial t} \qquad (4.8)$$

where G is a general source or sink term (l/t), volume of water injected per unit volume of aquifer per unit of time.

4.1.2. Conceptual model of the XIII layer

The first step in modelling is discretization of the study area. This is done by replacing it with the nodes and elements (in this case triangles) which are designated as a finite element mesh. Material properties of the reservoir (for example, hydraulic conductivity) must be defined for each element; a number is assigned to each node and element [Istok, 1989].

Geometry, system parameters, initial and boundary conditions must be defined before modelling (Figure 4.6).

Geometry and system parameters:

– Productive layers thickness is equal to 40 m.

– Permeability of productive layer is 2.e-13 m^2.

Boundary conditions:

– Constant hydraulic head along southern and northern borders, in accordance with the average absolute elevations. This condition means that water level is mostly governed by topography on a regional scale.

This regional model of groundwater flow within the XIII layer of the vast territory of the Chechen Republic shows that liquid flow through the southern border is equal to 0.62 m^3/s.

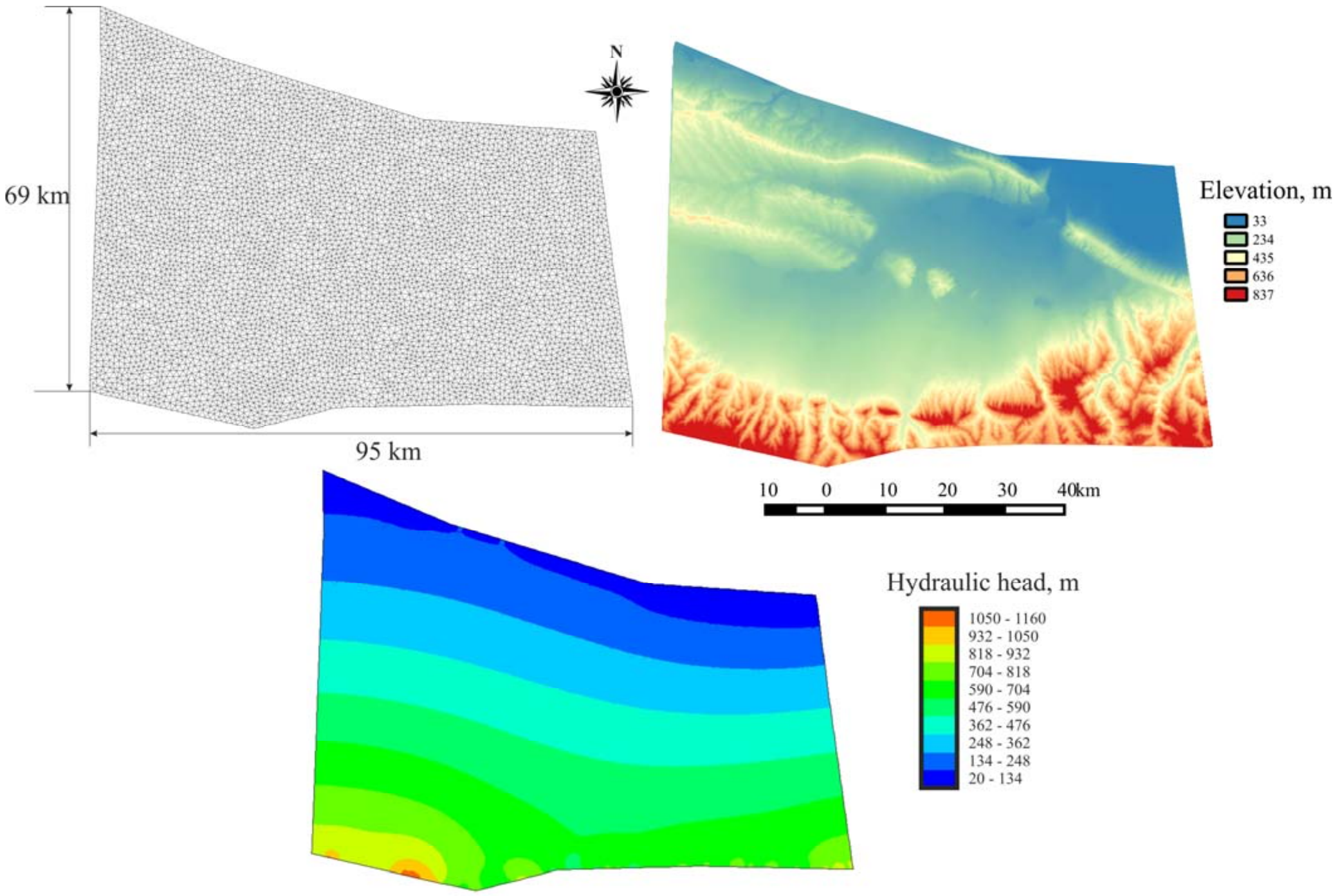


Fig. 4.6. Mesh, territory elevation and modelling results

Gonsirovsky [1966] calculated the groundwater flow of the XIII layer by the formula, which is a regional application of Darcy's law:

$$Q = k \cdot m \cdot B \cdot i, \tag{4.9}$$

where k – filtration coefficient,

m – layers thickness,

B – length of filtration front,

i – piezometric slope.

Taking k eqal to 1.5 m/day, layers thickness – 47 m, length of filtration front – 95 km, piezometric slope – 6e-3 gives us groundwater flow thorough the southern border equal to 0.47 m^3/s, which is relatively close to the results obtained by numerical modelling.

The results of regional groundwater flow modelling were taken into account in the simulation of doublet reinjection described in the next part.

4.2. The Khankala deposit XIII layers doublet model

More detailed modelling of used geothermal water reinjection in the reservoir of the XIII layer is conducted after identifying the general features of groundwater movement within the Chechen Republic. This is based on a local, 3D model of the resource.

4.2.1. Flow and heat transfer mechanisms

The global process of used geothermal water reinjection can be divided into two processes: groundwater flow and heat transport.

Change in water viscosity and density depending on temperature must be taken into account, so for variable density fluid Darcy law can be written as:

$$U = -\frac{k}{\mu}(\rho_0 g \nabla h + (\rho - \rho_0) g \nabla z), \tag{4.10}$$

where k is permeability (m^2), related to hydraulic conductivity by the ratio:

$$K = k\frac{\rho g}{\mu},$$

μ dynamic viscosity of the water (Pa·s),

ρ_0 density of the water in the reference conditions (kg/m^3),

ρ effective water density (kg/m^3),

g acceleration of gravity (m/s^2),

z vertical coordinate (m) (Figure 4.4),

h "pseudo-head", which is given as:

$$h = \frac{p}{\rho_0 g} + z,$$

where p is water pressure (Pa).

The equations (4.7) and (4.10) can be combined into one, taking into account the presence of sources or sinks:

$$div\left\{\frac{k\rho g}{\mu}(\rho_0 \nabla h + (\rho - \rho_0)\nabla z)\right\} = S_s \rho_0 \frac{\partial h}{\partial t} + \rho q, \tag{4.11}$$

where S_s is storativity coefficient (m^{-1}).

For heat transfer the following mechanisms must be taken into account:

– Advection (convection), the transfer of heat by moving water (Figure 4.7);

– Kinematic thermal dispersion in the aquifer (the heat flux due to local heterogeneity of the velocity field) (Figure 4.7);

– Thermal conductivity in the aquifer and overlying and underlying impermeable sediments (heat flow as a result of the temperature gradient).

Convection is the dominant mechanism in the reservoir. Exchange with the surrounding layers by conduction delays the development of a cold front. Thermal conductivity and dispersion in the aquifer have spillover effect of the transition zone between cold and hot geothermal water [Goblet, 2005].

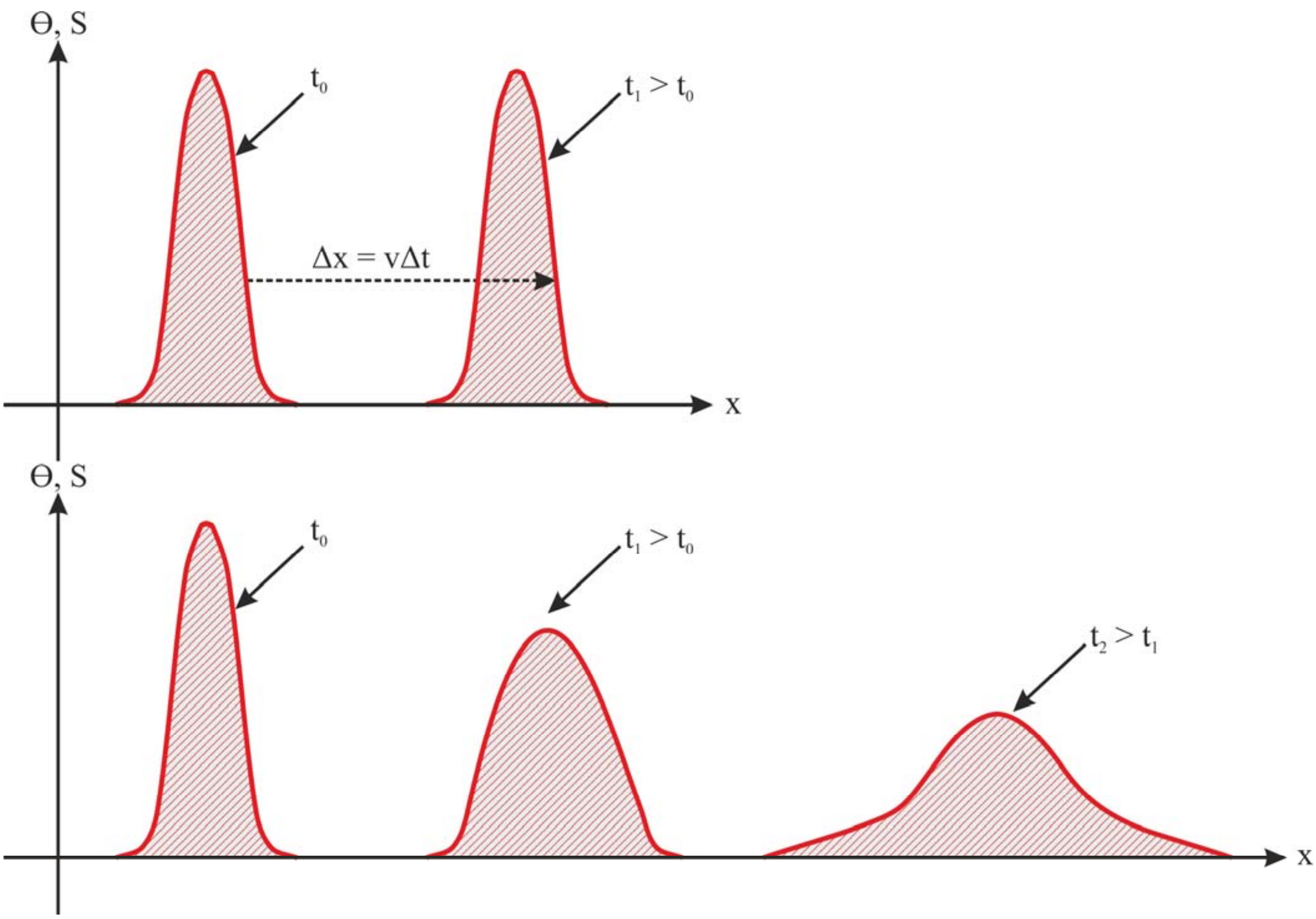


Fig. 4.7. Advection (top) and dispersion (bottom) processes in one dimensional example [Pruess, 2002]

Legend: C (concentration, solute dispersion) or theta (temperature, heat dispersion) – distribution, t – time.

The heat transfer process is described by the heat balance equation, which accounts for the amount of heat present in a volume element [Goblet, 2005]:

$$div(\psi_T) + \gamma \frac{\partial \theta}{\partial t} + qt = 0, \quad (4.12)$$

where $\psi_T = \psi_C + \psi_D + \psi_d$,

ψ_C – heat transfer by advection,

ψ_D – heat transfer by dispersion,

ψ_d – heat transfer by thermal conductivity,

γ – volumetric heat capacity for porous medium + water,

θ – temperature,

qt – heat sink or source element.

Heat flux as a result of advection:

$$\psi_C = U\gamma_E\theta, \quad (4.13)$$

γ_E – volumetric heat capacity of water.

Dispersion heat flux:

$$\psi_D = -\bar{\bar{\alpha}} \, |U| \, \gamma_E \nabla \theta, \quad (4.14)$$

$\bar{\bar{\alpha}}$ – dispersivity coefficient (m).

The flow of heat by conduction is expressed by the Fourier law:

$$\psi_d = -\Lambda \nabla \theta, \quad (4.15)$$

where Λ is the thermal conductivity for porous medium and water.

Thus, from (4.12), (4.13), (4.14) and (4.15) we have the heat balance equation, solved in the Metis code [Goblet, 2005]:

$$div\left\{\left(\bar{\bar{\alpha}}\gamma_E \, |U| + \Lambda\right)\nabla\theta - \gamma_E U\theta\right\} - \gamma \frac{\partial \theta}{\partial t} - qt = 0, \quad (4.16)$$

qt – heat sink or source element.

4.2.2. Conceptual model of the reservoir

The results of temperature estimation and structural map of the XIII productive layer obtained after geostatistical methods application [Farkhutdinov et al., 2015] are used to calculate the initial conditions of the system and as a basis for creating the mesh, respectively.

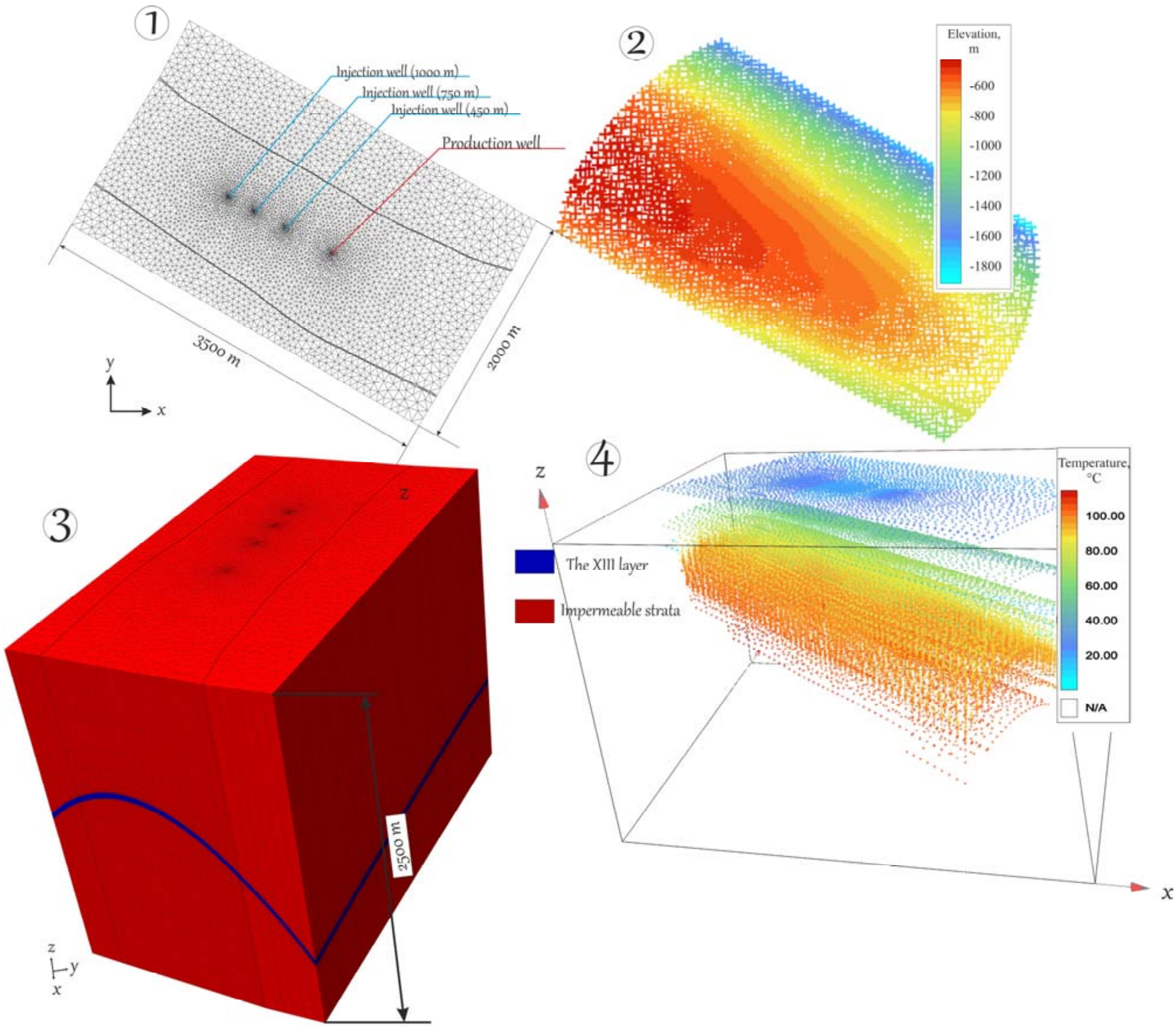


Fig. 4.8. Stages of data preparation for modelling

2D mesh (top left), estimation of the XIII layer elevation in each 2D mesh node (top right), creation of the 3D mesh taking into account step 2 and 1 with refinement near productive layer (bottom left), estimation of the temperature of the 3D mesh nodes (bottom right).

Processes of data preparing and modelling itself were made in several stages (see Figure 4.8):

1. Creation of a two-dimensional mesh using Delos program [Stab, 2006], with near wells refinement.

2. Import of the points of mesh in Isatis program for estimation of z – the XIII layers top absolute elevation according to the parameters chosen during geostatistical estimation

(see Chapter 3.2).

3. Export of the points from Isatis and three dimensional mesh creation taking into account absolute elevation of the productive layer and the borders of the domain which is being modeled.

4. Import of the points of three dimensional mesh in Isatis program for temperature and geothermal flux estimation with parameters chosen during geostatistical analysis (see Chapter 3.3).

5. Modelling of steady-state heat transfer using Metis code with obtained temperature and flux in order to calculate temperature for points which were not covered by geostatistical estimation during stage 4. An initial temperature consistent with geostatistical estimation is thus obtained.

6. Coupled hydro-thermal flow modelling using Metis code.

It should be noted that the model was simplified regarding relatively small quantity of initial data: faults were represented as vertical and during stages 2 and 4 they were not taken into account.

As it was mentioned parameters of the aquifer, boundary and initial conditions must be defined before modelling (Table 4.1., Figure 4.9). Data from archives, including results of well tests, some thermophysical parameters (Chapter 2), as well as literary resources with the parameters of the average values of thermal conductivity and heat capacity for different types of rocks [Marsily, 1981].

Reservoir properties are represented by:

– Productive layers thickness is 47 m.

– Permeability is 6.77e-13 m^2 (which corresponds to a transmissivity of 90 m^2/day with thickness equal 47 m, viscosity and density of the water with temperature of 95 °C).

– Longitudinal and transverse thermal dispersivity: 10 × 2 m.

– Specific storage is 5e-6 m^{-1}.

– Volumetric heat capacity of water 4.18 MJ/m^3/°C.

– Volumetric heat capacity of the aquifer is 2.485 MJ/m^3/°C, in calculation of which parameters of reservoir rocks and water are taken into account [Marsily, 2004]:

$$\rho^{"}C^{"} = \omega\rho C + (1-\omega)\rho' C', \tag{4.17}$$

where $\rho^{"}$ – reservoir density,

$C^{"}$ – reservoir heat capacity,

ω – rock porosity,

ρ – rock density,

C – rock specific heat capacity,

ρ' – water density,

C' – water specific heat capacity.

– Volumetric heat capacity of the impermeable strata above aquifer 2.2 MJ/m^3/°C.

– Volumetric heat capacity of the impermeable strata below aquifer 2.3 MJ/m^3/°C.

– Conductivity of the aquifer 2.3 W/(m·K).

– Conductivity of the impermeable strata above aquifer 1.52 W/(m·K).

– Conductivity of the impermeable strata below aquifer 1.5 W/(m·K).

Table 4.1. Thermal parameters used in modelling

<table>
<tr><th colspan="2">Depth, m</th><th rowspan="2">Thickness, m</th><th rowspan="2">Sediments</th><th colspan="2" rowspan="2">Conductivity, W/(m·°C)</th><th colspan="2" rowspan="2">Volumetric heat capacity, MJ/m^3/°C</th></tr>
<tr><th>from (top)</th><th>to (bottom)</th></tr>
<tr><td>0</td><td>35</td><td>35</td><td>Quaternary</td><td>2.1</td><td rowspan="3">1.53</td><td>2.1</td><td rowspan="3">2.23</td></tr>
<tr><td>35</td><td>700</td><td>665</td><td>Sarmatian</td><td>1.4</td><td>2.2</td></tr>
<tr><td>700</td><td>843</td><td>143</td><td>Karagan (above the XIII layer)</td><td>2</td><td>2.4</td></tr>
<tr><td>843</td><td>890</td><td>47</td><td>The XIII layer</td><td>2.3</td><td>2.3</td><td>2.486</td><td>2.486</td></tr>
<tr><td>890</td><td>1290</td><td>400</td><td>Karagan and Chokrak (below the XIII layer)</td><td>1.8</td><td rowspan="2">1.5</td><td>2.4</td><td rowspan="2">2.28</td></tr>
<tr><td>1290</td><td>2500</td><td>1210</td><td>Maikop</td><td>1.4</td><td>2.25</td></tr>
</table>

Boundary conditions (Figure 4.10):

– Imposed liquid flow of 200 m^3/h 7 months a year at the injection well with constant heat flow of 10051 MW, which corresponds to the water temperature of 45 °C.

– Geothermal flux is imposed at the base of the model equal to 82 mW/m^2 (according to Kurbanov [2001]).

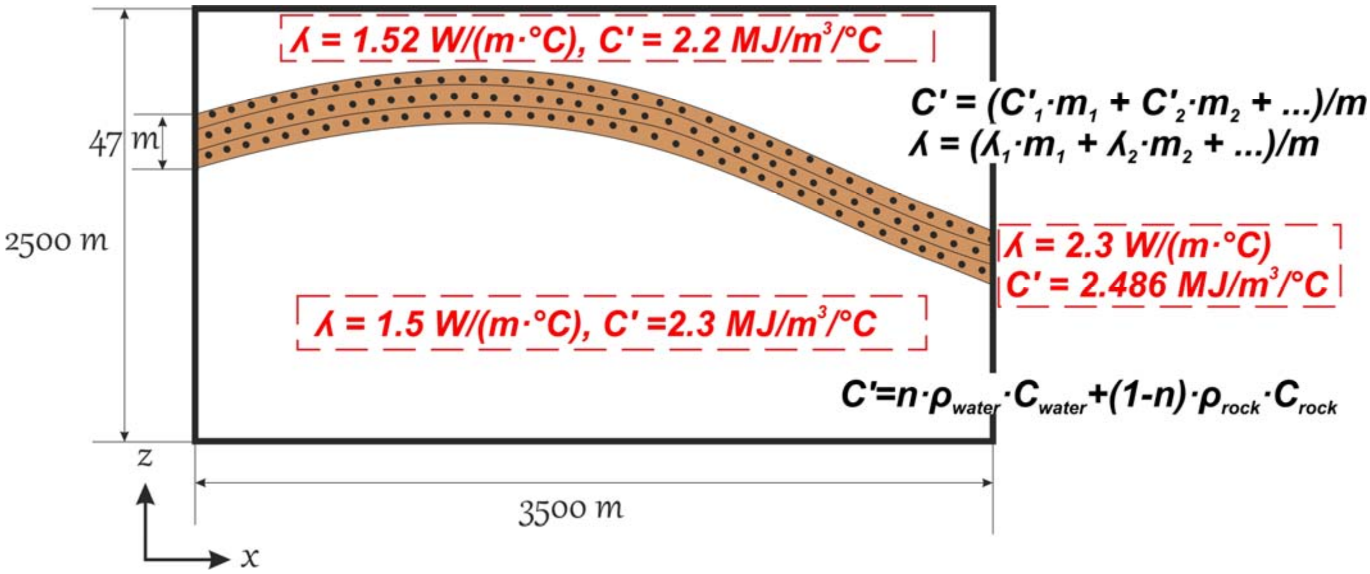


Fig. 4.9. Thermal parameters used in modelling

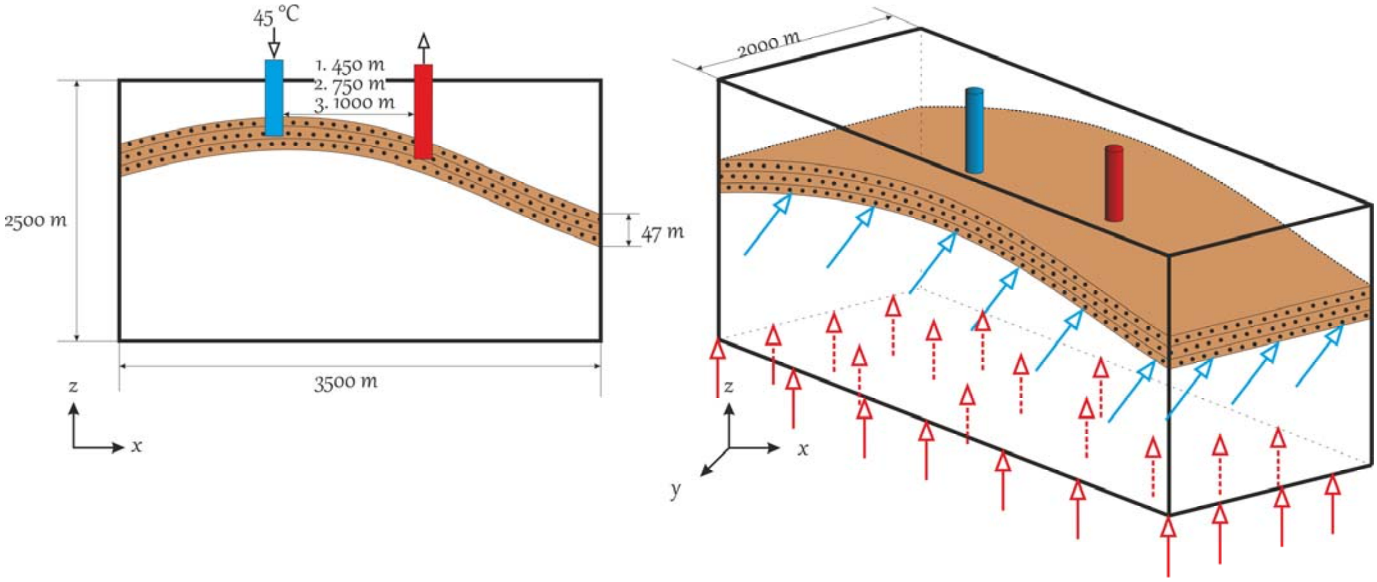


Fig. 4.10. Schematic drawing of the doublet model. Red and blue arrows indicate the direction of heat flow and movement of groundwater, respectively.

Change in liquid viscosity with temperature in Metis code is expressed by Bingham equation. Laboratory analyses of the Khankala deposit geothermal waters were conducted in 1988, including the study of viscosity dependence on the temperature [Krilov, 1988f]. The results correlate very well with the equations used in Metis (Fig. 4.11), which could be explained by the low salinity of the XIII layer geothermal waters, justifying that thermo-hydraulic modelling is fair enough without taking into account chemical components.

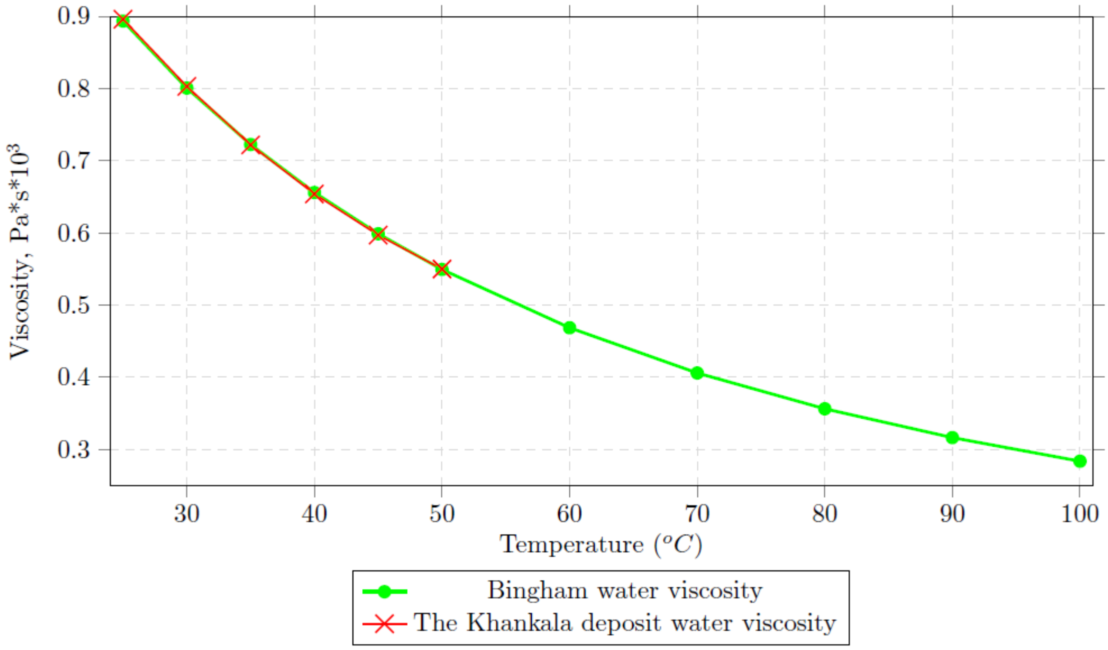


Fig. 4.11. Changes in water viscosity depending on the temperature according to Bingham and laboratory analysis

The processes of liquid flow and heat transport are coupled: at each time step the program conducts an alternate resolution of their equations (Figure 4.12). Simulation time is equal to 50 years.

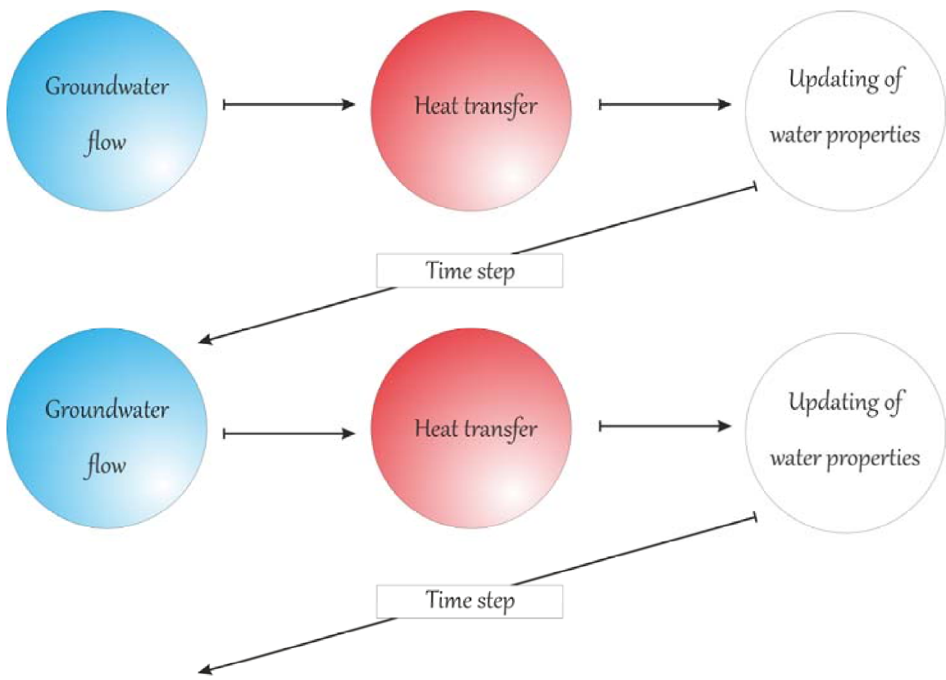


Fig. 4.12. Coupled processes of groundwater flow and heat transport

Different hypotheses were checked during numerical modelling (Table 4.1):

– Influence of the distance between production and injection well (450, 750, 1000 m).

– Permeability of two general faults.

– Influence of natural groundwater flow.

The results were compared with the analytical solution for a doublet production well temperature change [Gringarten et Sauty, 1975]:

$$\frac{T_0 - T_w(t)}{T_0 - T_i} = \int erfc\left\{\frac{d(S_{\max}/D^2)}{d(\psi/Q)} \cdot \left[\lambda(t_D - \frac{d(S_{\max}/D^2)}{d(\psi/Q)}\right]^{-1/2}\right\} d\left(\frac{\psi}{Q}\right) = T_{wD}\left[f(\psi), \lambda, t_D\right], \quad (4.18)$$

where $\lambda = (\rho_w C_w \rho_A C_A / K_R \rho_R C_R)(Qh/D^2)$, $\rho_w C_w$ – water volumetric heat capacity, $\rho_A C_A$ – aquifer volumetric heat capacity, K_R – cap rock thermal conductivity, $\rho_R C_R$ – cap rock volumetric heat capacity, h – productive layers thickness, Q – injection/production rate, D – distance between injection and production wells, $t_D = (\rho_w C_w / \rho_A C_A)(Qt / D^2 h)$, T_0 – aquifer and cap rock/bedrock temperature, T_i – injection water temperature, $S_{\max}$ – total stream channel area between injection and production wells.

Table 4.1. The modelling results

Case	$\Delta T = 1^o C$, Year	ΔT, °C (50 years)
Distance 450 m		
No liquid flow, no faults influence	7.00	-21.18
Impermeable faults	6.92	-22.26
Groundwater flow	8.17	-14.69
Analytical solution	6.3	-24.07
Distance 750 m		
No liquid flow, no faults influence	20.08	-10.71
Faults influence	19.17	-12.03
Groundwater flow	30.08	-4.18
Analytical solution	19.3	-11.92
Distance 1000 m		
No liquid flow, no faults influence	35.58	-4.08
Impermeable faults	33.42	-5.24
Groundwater flow	–	–
Analytical solution	37.8	-3.66

Thermal breakthrough occurs earlier and the temperature decreases faster in the case of the analytical solution (Table 4.1, Figure 4.13) because the temperature of reservoir, cap rock and bedrock are the same while the temperature used in the numerical simulation is obtained after geostatistical analysis and estimation and it is distributed unequally with higher temperatures deeper and to the south of the production well (Figure 4.14).

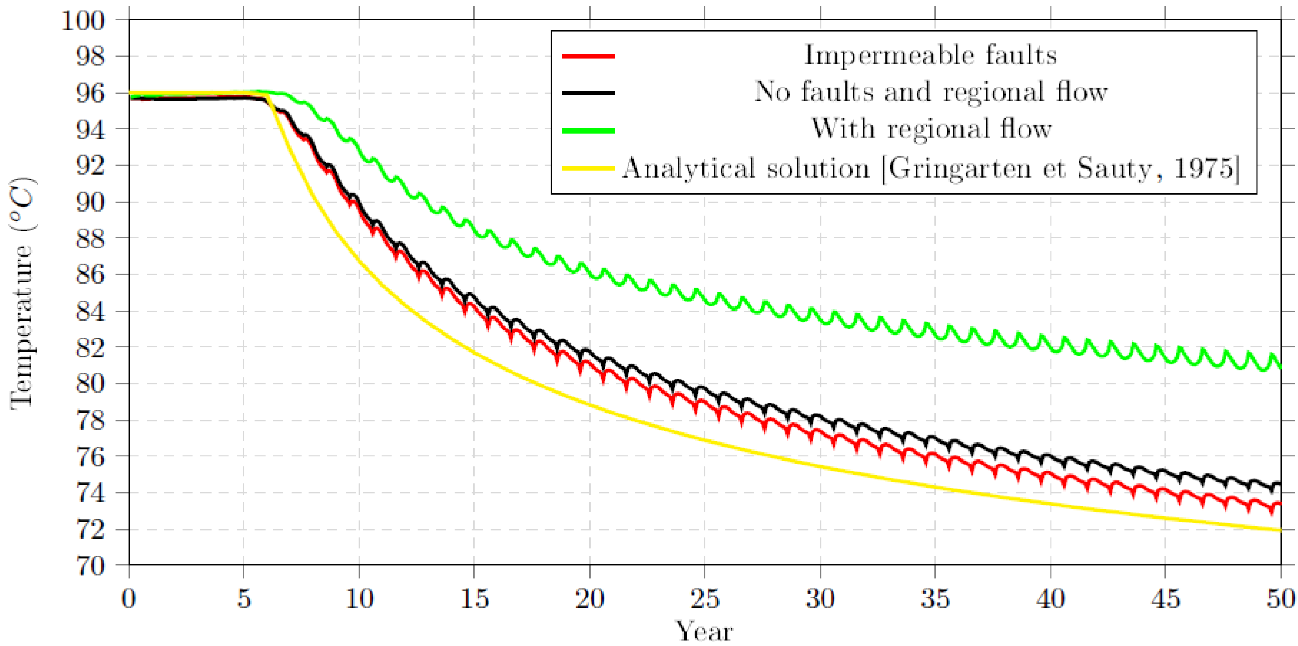


Fig. 4.13. Temperature in production well decrease (450 m distance between production and injection well bottoms)

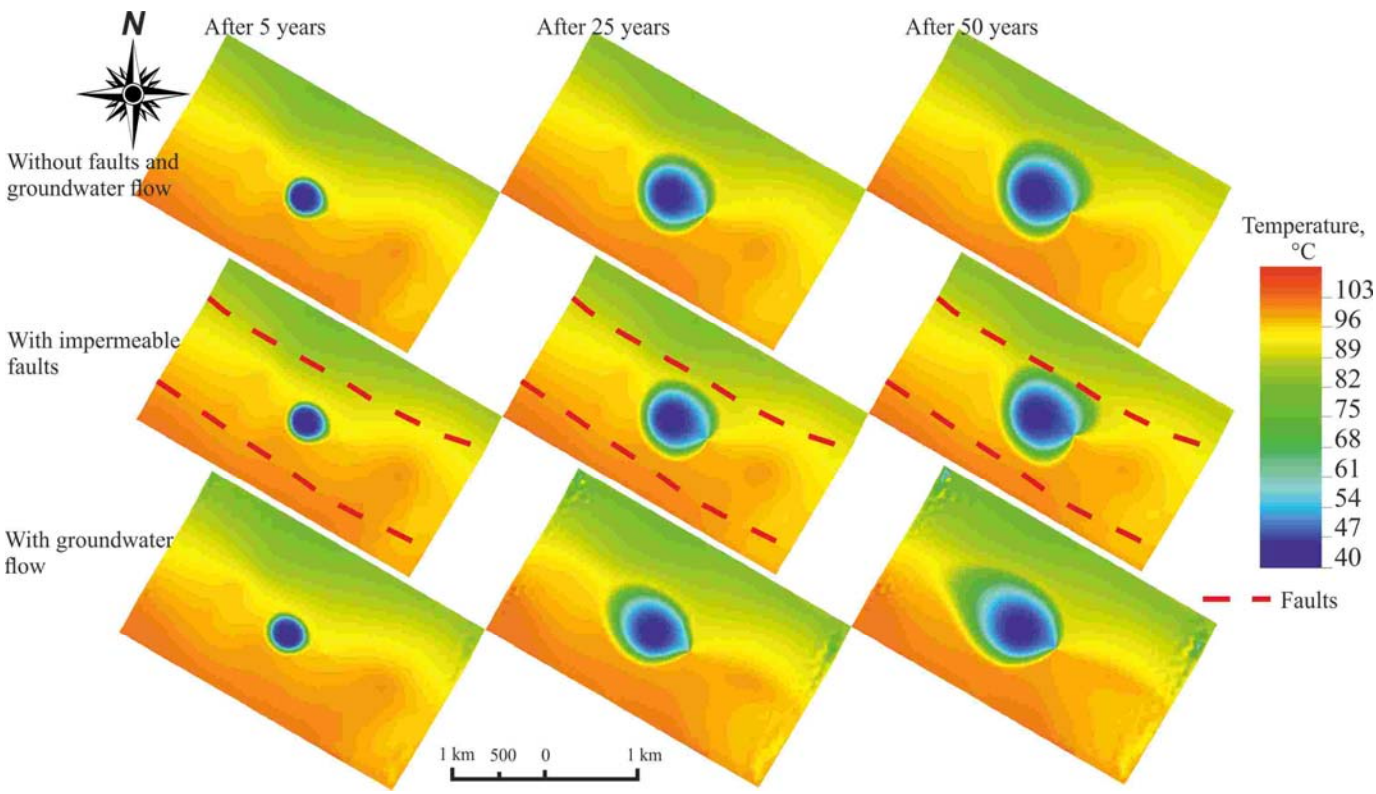


Fig. 4.14. The results of the modelling: temperature evolution in the XIII layer (450 m distance between production and injection well bottoms)

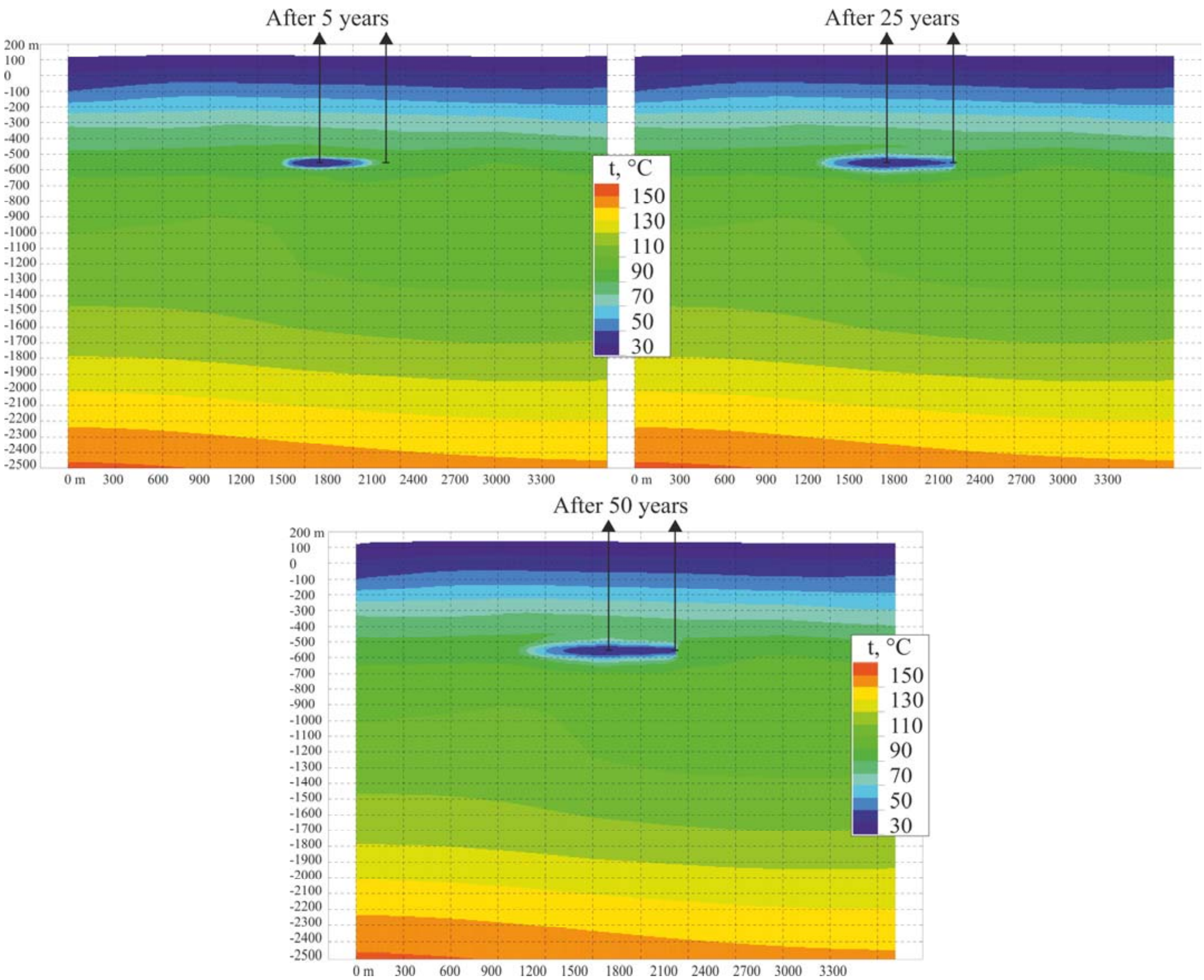


Fig. 4.15. The results of the modelling: temperature evolution in the XIII layer (side view, 450 m distance between production and injection well bottoms)

Taking into account the presence of impermeable faults does not influence much the temperature in the production well because the faults are situated far enough and the cold front does not reach them too soon. Natural groundwater flow in the XIII layer significantly delays the production temperature decrease in the production well.

Our further study was to simulate the recovery behavior of the Khankala XIII productive layer resource. The reservoir was assumed to be exploited for 50 years (the distance between the wells is equal to 450 m) and then development of the resource was stopped (Figure 4.16., 4.17).

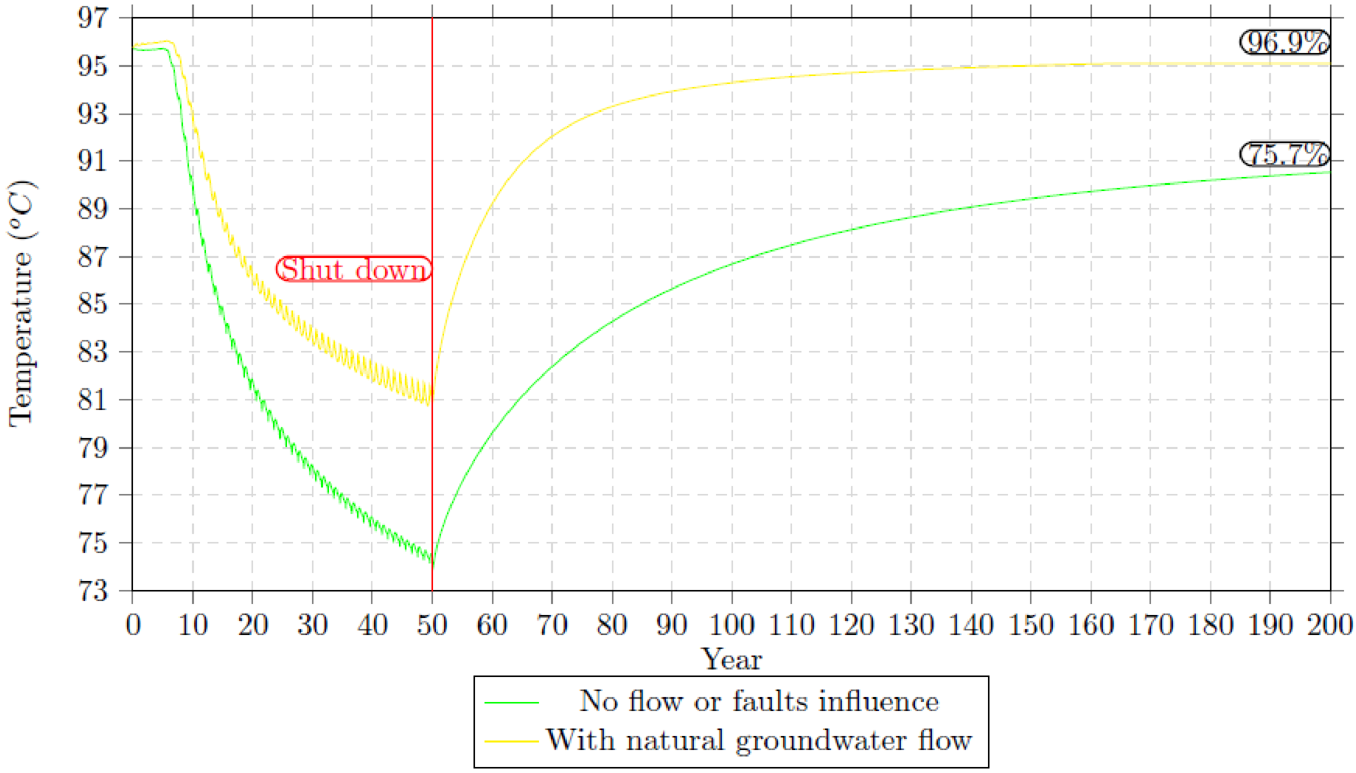


Fig. 4.16. Production well temperature for 50 year exploitation and then shut-down scenario (450 m distance between production and injection well bottoms)

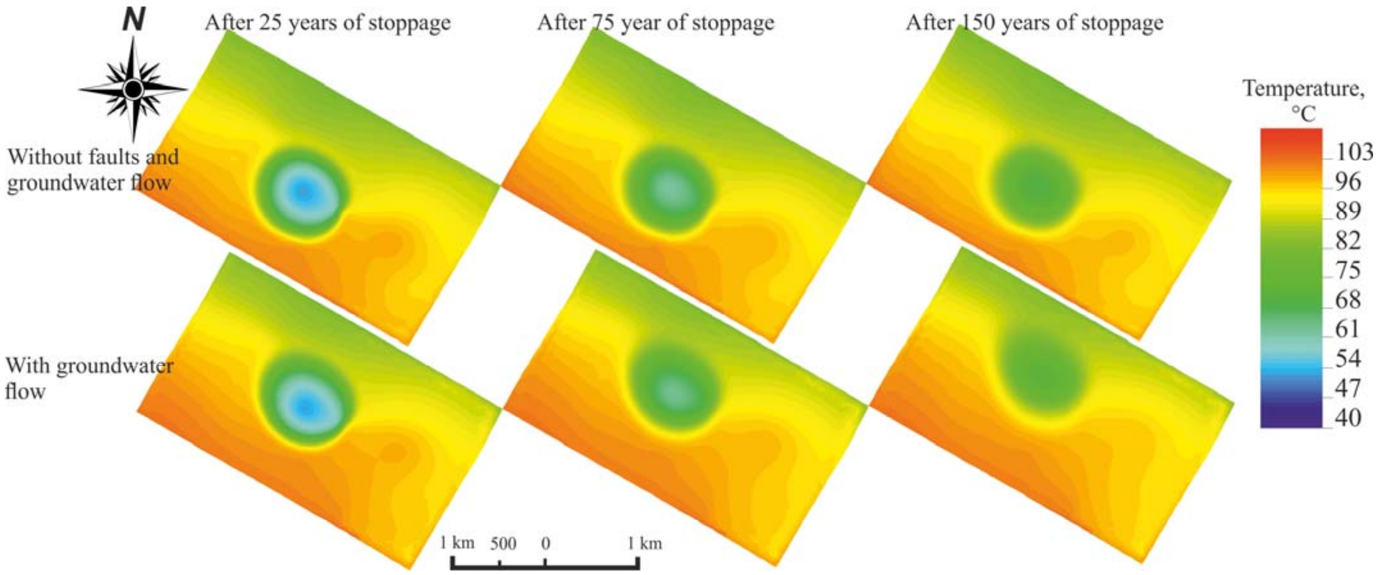


Fig. 4.17. The XIII productive layer of the Khankala geothermal waters deposit temperature change after 50-years exploitation stoppage: after 25, 75 and 150 years (450 m distance between production and injection well bottoms)

When natural groundwater flow is taken into account, the temperature will recover by 96.9% after 150 years of shut-down scenario. In case of no groundwater flow temperature recovers by 75.7%.

According to the results obtained by numerical modelling it is highly recommended *to choose a distance between injection and production wells equal to 750 m or more. In such case temperature in the production well will not go down drastically after 25-30 years, the usual period of wells equipment lifetime after which its change may by required. It should be noted that it is important to place wells parallel to these two faults with production well bottom in the southern part and injection well in the northern part and take into account natural groundwater flow direction which can slow down expansion of cold front to production well.*

One of the main advantages of the Khankala deposit of geothermal waters is that it is a multilayer system and in case of significant drop in production well temperature after some period of the XIII layer exploitation, there is a possibility to drill a new doublet at the same territory on the resource of the highly promising IV-VII, XVI or XXII layers so the geothermal plant could continue working. The resource of the XIII layer could be used again in case of shut-down after some period of time taking into account the relatively high speed of temperature recovery. In perspective, periodic use from different layers could be organized in order to achieve sustainable use of geothermal waters at the Khankala deposit site.

Chapter 5. Recommendations on the Khankala geothermal waters deposit further exploitation

Doublet circulation heat extraction scheme used at the Khankala geothermal waters deposit – decision taken after studing international, in particular French experience of geothermal waters exploitation. For this reason, when drawing up recommendations for further exploitation of the Khankala deposit, comparative analysis with the Paris Artesian Basin was used.

France is one of the countries that have achieved good results in the use of medium-temperature geothermal waters (55-85 °C). The main object of exploitation is Dogger reservoir (Middle Jurassic) in the Paris Basin. The Paris Basin is a sedimentary intra-cratonic basin with almost oval shape. It occupies a vast part of the north of France – 110000 km^2. It is the largest coastal sedimentary basin in France, located on the Carboniferous and Permian sediments. Formation of the basin is associated with the Permian-Triassic rifting. Geothermal reservoir formations extend to more than 15000 km^2, lying at depths of 1500 to 2000 meters. The most productive layers are Bathonian age layers consisting of oolitic limestones with thickness ranging from 5 to 45 m. On average, the net total productive thickness is about 20 m, with 10–15 m highly permeable (2–20 Darcy) layers. Temperatures of the reservoir formations range from 55 to 85 °C. The geothermal gradient of the territory varies from 2.75 to 4.1 °C/100 m. The minimum temperatures are characterized by areas at a depth of 1650 m to the north-east of Paris, where the average temperature gradient is 2.75 °C/100 m. This area belongs to an anomalous zone, the existence of which is due to the cold waters flow from the overlying horizons down to the reservoir. The maximum gradient of 4.1 °C/100 m relates to the area of Val-de-Marne, south-east of Paris (Figure 5.1). The average temperature of geothermal water at the production wellhead is 70 °C, the average production rate is 175 m^3/h and the average temperature of the water pumped back is 45 °C. Water salinity varies from 6.4 g/l to 35 g/l, and increases from the southeast, where the reservoir outcrops, to the deepest area where concentrations are up to 35 g/l. Salinity is specific to certain segments and is not necessarily dependent on the depth. Water contains a large amount of sulfides, which leads to corrosion of the downhole equipment [Lopez et al., 2010].

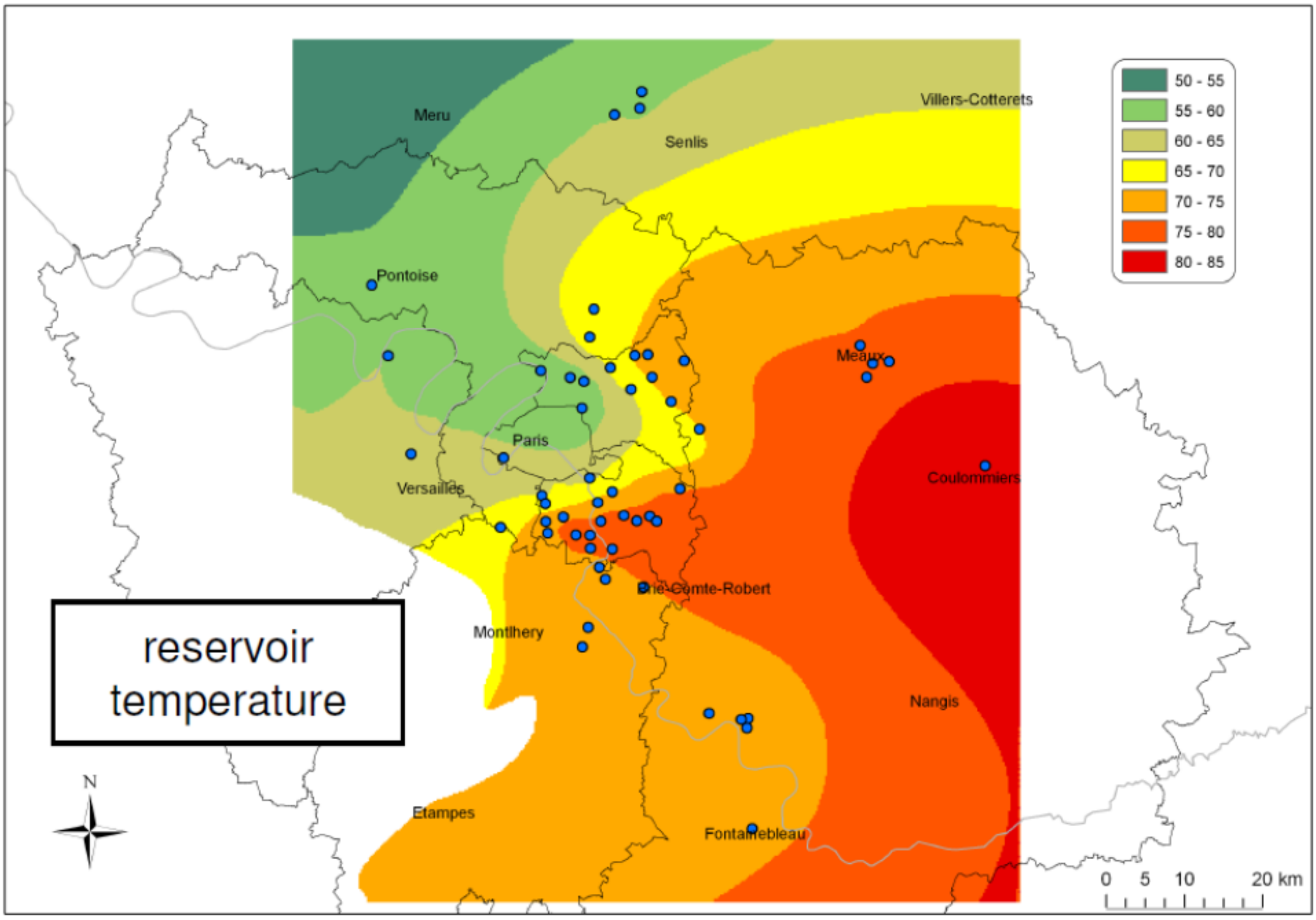


Fig. 5.1. Temperature map of the Paris Basin Dogger aquifer [Gille, 2010]

Three technical and economic factors were favorable for the development of the Paris Basin geothermal reservoir [Menjoz, 1990]:

– Productive geothermal reservoir at a reasonable depth with characteristics (temperature and flow rates) suitable for heating networks.

– Existence of a heat market with densely populated areas, suitable for low and middle-temperature waters use.

– Public policy incentives and insurance policies that favored development of new environmentally friendly sources of energy.

In addition, the most intensive development of geothermal energy in France occurred during the energy crisis.

The first geothermal well for the Paris Basin reservoir resources exploitation was drilled in 1962 in Carrières-sur-Seine. It was planned to discharge used water into the river Seine, but water salinity was much higher than expected and the well was forcedly closed.

After this first unsuccessful experience development of the doublet technology made the exploitation of geothermal in the Paris Basin possible. Doublets technology consists in reinjection of all thermal water back into the reservoir, which minimizes the impact on the environment and preserves the piezometric level of the developed productive formation. After seven years a well was successfully drilled in Melun (1969). The oil crises of 1973 and 1979 gave rise to the subsequent exploitation works. The main aim was the Dogger age reservoir and almost all operating system installations were doublets. The main "geothermal peak" in development took place in the 1980s. Among the 55 systems installed doublets, 34 are currently in use [Lopez et al., 2010].

Doublets technology has several advantages [Lopez et al., 2012]:

– There are almost no negative effects on the environment and no expenses for chemical treatment of the fluid to discharge it on the surface, because geothermal water after removal of the heat potential is fully pumped back.

– Flow rate of the productive well is maintained, whereas exploitation without reinjection reduces reservoir pressure gradually, which eventually affects the operating conditions.

– Pressure during operation stabilizes due to the reinjection, and the area of influence of its changes is limited: the exploitation territory may be legally defined by regulatory authorities, thereby enabling to develop an effective strategy for an optimal use of the resource of the aquifer.

After the first four years of intensive use of the aquifer, corrosion and scaling of the iron sulfides in the wells resulted in a widespread progressive decrease in production rates, leading to lower water withdrawal intensity. This was one of the main problems during exploitation, and for its solution wells were cleaned mechanically, and then preventive measures were applied (injection of corrosion inhibitors).

It has been over 45 years since the installation of the first working well, and there was no significant reduction in water temperature of any existing doublet. 42 wells (21 doublets) were closed because of technical and economic reasons, but not as a result of depletion of the resource. However, the natural heat flow is insufficient to maintain the temperature for an indefinite period. Reinjection resulted in a slight decrease of the temperature in one production well and it will lead to a gradual decrease of the temperature in the others in near future according to prognosis [Lebrun et al., 2011; Lopez et al., 2012]. Various concepts were suggested for solving this problem, such as the construction of reverse wells and seasonal (winter-summer) inversion of the injection-production scheme [Réveillère et al., 2013].

Currently, French scientists are working on updating and re-interpretation of data on the Paris Basin with the aim to better understand and to increase the duration of geothermal resources use. Experts predict that geothermal energy will remain an integral part of the heating system in the Paris Basin for at least another 40 years [Lopez et al., 2010]. Mathematical modelling is performed in order to forecast the temperature decrease and to select the most rational location of new doublets.

At the Khankala geothermal waters deposit site it was decided to establish a similar doublet scheme with the passage of fluid through the heat exchanger, followed by reinjection into the reservoir. The Chechen Republic deposits have the following advantages in comparison with geothermal waters of the Paris Basin (Table 5.1):

1. The higher temperature of the fluid.
2. Low salinity of waters, which means relatively low corrosivity.
3. Relatively high thickness of some productive layers (for example, the Khankala deposit XIII layer average thickness is 47 m).

And also the following disadvantages:

1. Many productive layers have only been tested in artesian mode, at relatively low flow rates.
2. Layers are represented by sandstones with clay interlayers and lenses, which may adversely affect the injectivity.
3. The complex tectonic structure of deposits, the presence of faults.

Table 5.1. Comparison of the Paris Basin and Chechen Republic geothermal waters deposits main characteristics

Name	Depth, m	Temperature at the wellhead, °C	Different wells flow rates, m^3/day	Salinity, g/l	Approved reserves	
					USSR State Reserves Commission, thousand m^3/day	Central Reserves Commision Gazprom 01.01.01, thousand m^3/day
Khankala	600–1950	65–98	285–2520	0.7–3.7	9.5 (off balance 7.6)	21.5
Goity	1560–2470	70–81	800–1800	0.6–2.0	1.15	–
Novogrozny	1245–1420	73–81	600–1000	0.7–1.6	3.41	–
Gunushki	1230	80	1500	1.6		1.5
Chervleny	3300–3500	69–83	1260–1700	1.5–6.2		5.2
Germenchuk	2800–3300	83	1000	–		1.0
Kargaly	3000–3200	90–103	1600–3300	1.3–13.6		5.0
Gudermes	895–915	61	600	1.2–2.4		1.0
Komsomolsk	2688–2710	105	2200	2.3–4.7		2.0
Central-Buruni	2730–2820	100	1200–1630	3–4		3.4
Petropavlovsk	3620–3630	71	1030	0.7–1.3		3.0
Paris Basin (Dogger)	1500–2000	58–85	1200–14400	6–38.8		

Comparative analysis confirms the high prospectivity of the Chechen Republic Karagan-Chokrak sediments geothermal waters exploitation: high values of geothermal gradient allow to reach high temperatures at lower depths, heat flow contributes to the restoration of the resource when reinjecting used water, potentially necessary costs to combat corrosion and deposition of salts are less. At the same time it is necessary to take into account the complexity of the geological structure of the study area – folding and the presence of tectonic faults, as well as the features of reservoirs lithology. Using the successful long-term experience (over 45 years) of the development of the Paris Artesian Basin gives a great advantage in the exploitation of the Chechen Republic, allowing taking into account possible problems and their solutions.

In 1980-s, at the Khankala deposit site reinjection was used. Geothermal waters directly from pump station were transferred to the heating system and then partially discharged on the relief and partly transported by surface pipeline to the reservoir pressure maintenance pump station. Drop in temperature is inevitable when transporting the used geothermal water to be pumped into the injection wells at certain distances. The amount of injected water in comparison with water withdrawal was about 50-60%. Doublet in its turn presupposes reinjection of 100% used geothermal water back into the aquifer.

In the case of installation of the doublet productive and injection wells are drilled from a single drilling site and the area allocated for the water withdrawal and its sanitary protection may be reduced several times – the distance between the injection and production wellheads is about 10 m. In terms of Russian realities advantage is that this location – two near located wellheads and geothermal station – is a compact ground space that is easier to control. At the same time approved exploitation reserves of the Khankala deposit should be recalculated since announced production rate will also depend on the injectivity of the injection well, which is one of the main problems of productive layers consisting of sandstones.

Currently, all broken reservoir wells are closed, exploitation of the layer at the Octyabrsk oil deposit is completed and is not conducted at the Goity geothermal waters deposit, so there are conditions for a more accurate assessment of filtration parameters. Before the start of the research it is necessary to make observations on the wells regime. Wellhead pressure measurement will also allow creating more detailed hydrogeologic map of the XIII layer in contrast to the previously composed generalized maps for the Karagan -Chokrak deposits. It is recommended to perform water pumping with a constant flow rate of 200 m^3/h with observations of pressure (level) reduction at the XIII layer wells followed by stoppage and pressure (level) recovery.

The main problem during the Paris Basin exploitation was corrosion and scaling in the wells. The fluid temperature and pressure change when moving from the aquifer to the surface installations may lead to solute particles precipitation. Precipitation may occur particularly rapidly at the cold side of the heat exchanger (e.g., silica), or where the pressure drops, which leads to degassing of acid gases (H_2S, CO_2). Further precipitation phenomena may occur from changes to the fluid composition. In addition to these factors, there are bacteria which may participate in the gradual formation of deposits on the pipeline walls. The absence of oxygen in the water considerably reduces the corrosion rate of the carbon steel casing. However carbon steel is not a corrosion-resistant alloy and still suffers from the presence of corrosive species inside the fluid (chlorides, nitrates, sulphates, etc.), whose rate of reaction is enhanced by the high temperature. Corrosion may also partly arise from the presence of bacteria. Once the contamination of the tubing has started, the process becomes self-accelerating as more bacteria produce more sulphides, which results in more corrosion and more bacteria deposit. It is therefore very important to delay as much as possible the start of this process. One of the best methods is to operate well at the highest possible flow rate, so that bacterial colonies find it harder to settle on a surface and start developing there [Giuglaris et al., 2014]. For these reasons, the development of the Chechen Republic deposits needs constant monitoring, chemical analyzes and tests of the corrosion and scaling speed. Monitoring and clean-up work, if necessary, can be performed in a non-heating period.

In view of the hydrogeological characteristics of the Khankala geothermal waters deposit, which is represented by multilayered system, and relatively fast recovery of the temperature regime after exploitation stoppage (Chapter 4), it is recommended to install and periodic maintain several doublets of different layers at the same territory. Periodic maintenance will allow continuing work of the geothermal plant in case of production well temperature drop to unaccepabily low level and will contribute to sustainable development of the Khankala geothermal waters deposit.

Using the successful experience in the development of the Paris Artesian Basin for more than 45 years in the exploitation of the Chechen Republic deposits gives a great advantage and allows taking into account all the possible problems and their solutions. A numerical simulation and creation of maps of temperature, salinity, transmissivity distribution using geostatistical approach is highly recommended (in case of data availability) for better understanding the Chechen Republic geothermal waters features, highlighting the most promising areas and in order to achieve their sustainable use.

Chapter 6. Ecological and economic assessment of the Khankala project

6.1. Ecological aspects

The main greenhouse gas, emitted by geothermal station is CO_2 (90%), the amount of which varies considerably (on average 122 CO_2/kWh). For comparison, gas power station emits over almost 14 times more carbon dioxide per megawatt-hour. In addition, work of gas power plant is accompanied by emissions of sulfur oxides, the amount of which is 22 times higher, as well as nitrogen oxide and particulates, which are absent in the operation of geothermal power station [Matek, 2013]. The binary geothermal power plants with a closed loop, such as the Khankala, the amount of CO_2 emissions are close to zero. All greenhouse gas emissions from geothermal plants, directly or indirectly related to the construction, use and decommissioning, are taken into account when evaluating the station "life-cycle" (life-cycle assessment). In this case, the amount of greenhouse gas emissions range from 14.3 to 57.6 g CO_2 equivalent per kilowatt-hour for district heating systems [Kaltschmitt, 2000].

The use of the XIII layer geothermal waters at the Khankala station will allow avoiding emissions of about 7 thousand tons of CO_2 during heating season (7 months), which is equivalent to the amount of carbon dioxide emitted by a gas boiler with similar capacity of 5.45 Gcal/h.

With regard to the negative effects that accompany exploitation of the Khankala deposit, they can be overcome with the help of modern technologies, one of which is the installation of a doublet circulation system:

1. Noise pollution: noise of equipment during drilling, construction. However, after the completion of construction and commissioning exploitation of geothermal power plants, as a rule, it produces less noise than "leaves rustling in the wind" in accordance with the level of noise pollution standards [Kagel et al., 2007].

2. Violation of the earth surface that occurs in the construction of the station, as well as at any other construction activities, and affects the flora, fauna, soil and surface water. If installing a circulation system, productive and injection wells are drilled from one drilling site, the distance between wellheads is about 10 m. As a result land needed for

water withdrawal system and sanitary protection zone is reduced significantly. In terms of Russian realities compact arrangement of two wells and a geothermal plant is an important advantage, as it helps their control and protection.

The area of the territory used for the Khankala geothermal plant is 4900 m^2, while area of the station, including wells – 406 m^2.

3. Physical impacts. Exploitation of groundwater is associated with such natural factors as the risk of micro-earthquakes, volcanic hydrothermal steam and ground subsidence. Assessment of geological risks and the use of reinjection to maintain underground pressure help to avoid or minimize such consequences [Goldstein et al., 2011].

4. The impact on the natural hot springs. Exploitation of the XIII productive layer influenced the flow rate of Goryachevodsk Eastern sources and exploitation of the XXII reservoir is banned by “Gosgortechnadzor” to protect Sernovodsk sources from exhaustion.

5. Thermal and chemical pollution due to discharge of geothermal water on the surface. Most harmful chemicals thermal water is a liquid phase and they are harmful to ecosystems in case of a significant excess of the natural content of chemical elements.

In the development of geothermal waters deposits one of the main danger for environmental is fluid leaks. As part of the work (partially supported by the Ministry of Education – the agreement of 16.10.2014 № 14.607.21.0081) a pilot monitoring of exploited deposit using multispectral photography from unmanned aerial vehicle (UAV) GEOSCAN 201 Pro was conducted. Thermal imaging of Gikalo settlement with adjacent to its territory Khankala geothermal waters deposit was conducted (Figure 6.1).

Agisoft PhotoScan program used for images compounding, block layout algorithm was performed. Taking images conducted in accordance with the GeoScan Planner algorithm, which is part of the UAV ground control station. The route was calculated automatically based on the parameters of the matrix imager and optics, distances were chosen based on the need of 70% overlap between adjacent photos. A thermal imager Termofreym-M-640 was used. As a result of Gikalo settlement thermal imaging 13 thermal anomalies were identified from various sources (bonfire, heating, etc.) (Figure 6.2).

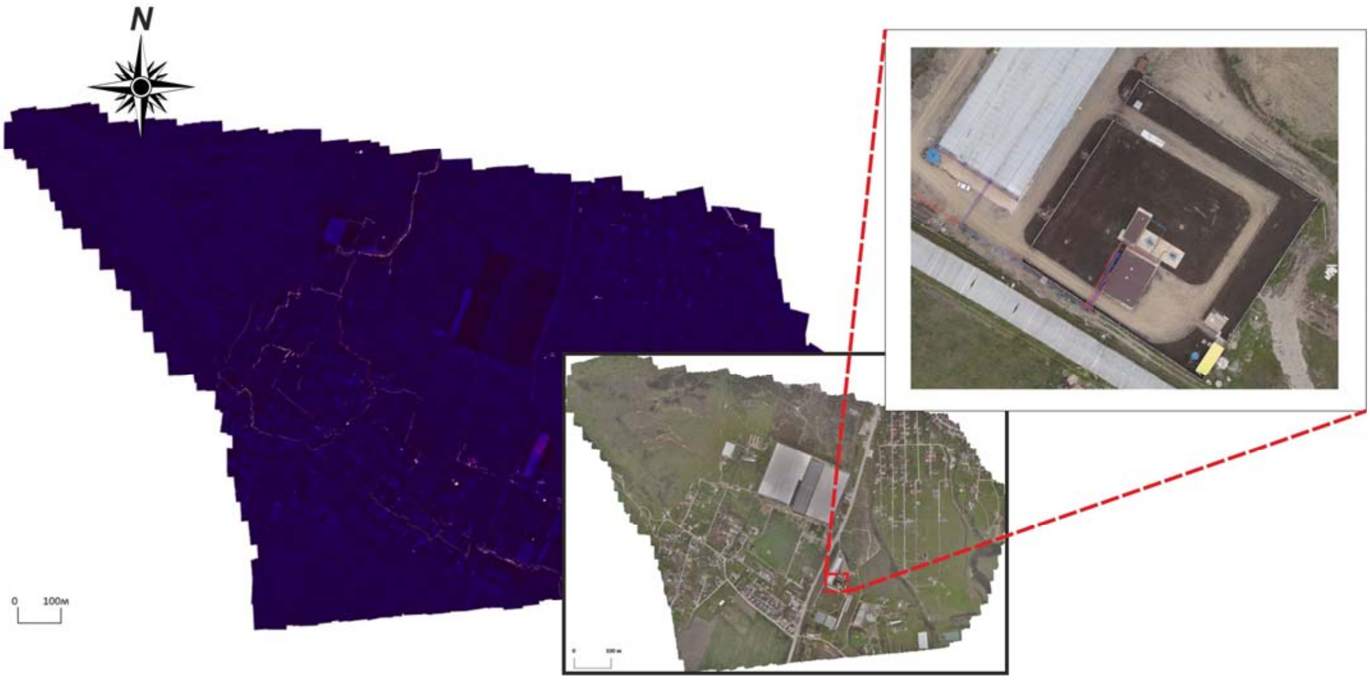


Fig. 6.1. Results of photo and thermal imaging settlement photographing

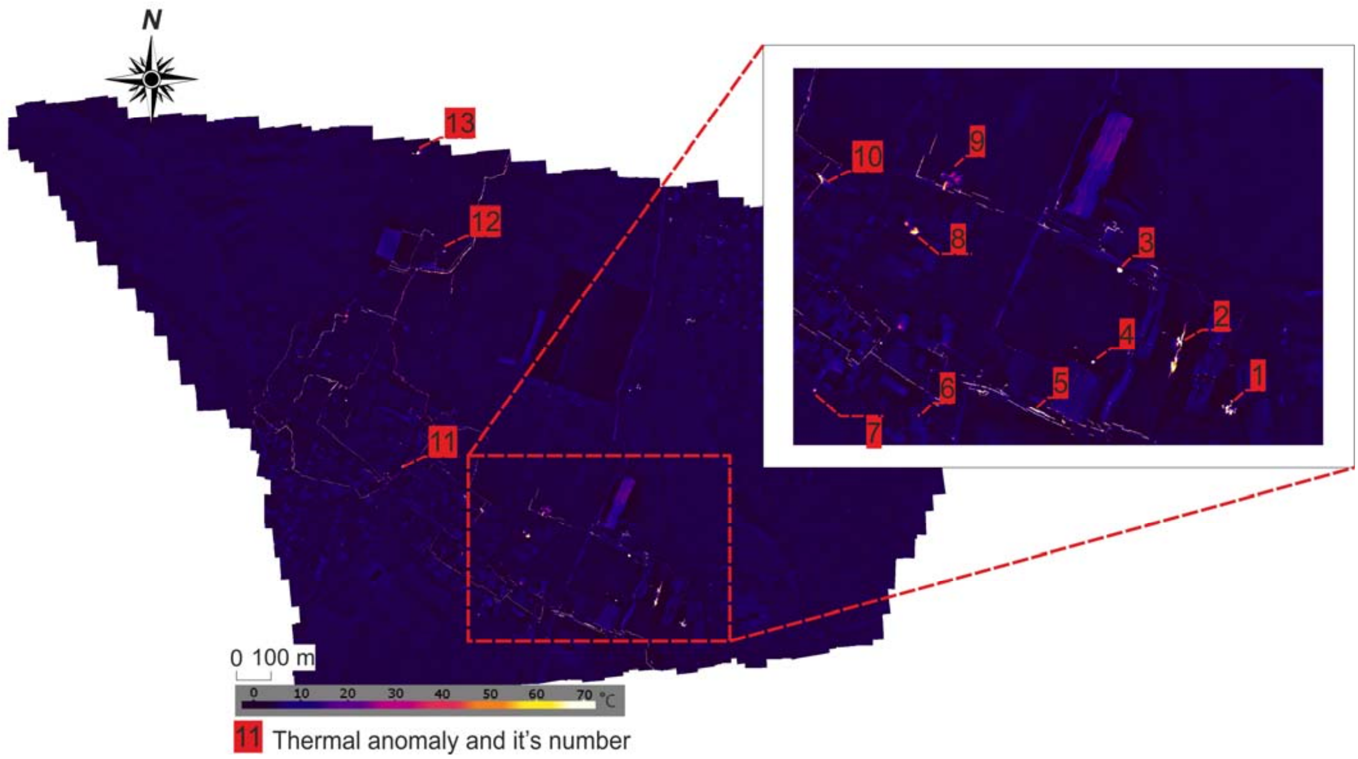


Fig. 6.2. Thermal anomalies identified

The experiment showed the possibility of the exploited geothermal waters deposits monitoring using an UAV and the thermal imager, with allocation of the anomalies caused by the leakage of the old wells, pipelines, used water disposal onto the relief, etc.

Thus, doublet technology with reinjection of used water along with modern methods of monitoring and proper environmental management can solve the problem of the negative consequences of the Khankala deposit resource exploitation. At the same time, the use of geothermal waters, partly replacing traditional forms of energy, makes it possible to significantly improve the regional environment conditions.

6.2. Economic aspects

In comparison with other technologies geothermal projects involve significant initial investments: exploration costs, including seismic surveys, drilling of wells. Creating a geothermal circulation system (GCS) also requires a relatively high investment in capital construction. However operating costs are low, although varies depending on the quantity and quality of the geothermal waters and more predictable unlike power plant based on traditional sources of energy, subject to market fluctuations. A small cost of produced heat due to the low operating costs determines the competitiveness of the GCS [Boguslavsky et al., 2000].

The Khankala geothermal station plant has no analogues in Russia, so the value of the investment for its construction increased by the cost of research and development (R&D) [Malyshev et al., 2014]. But in the future there is a possibility of engineering services delivery for GCS installation, the replication of the results, what could have a positive impact on the efficiency of the project and return of investment. Furthermore, stations of this type have a potential of beneficial effect expansion due to the possibilities of connecting a binary power unit and unit for extracting useful components from geothermal waters.

The Khankala geothermal circulation system (Figure 6.3) is designed and built taking into account the status of a supplier in Khankala energy system. The consumer is a greenhouse complex, but in the future it is able to provide power to enterprises, institutions and nearby agriculture objects. The form of state involvement in the financial support of the project is represented by subsidies from the Ministry of Education of the Russian Federation. Funding for the project at a total cost of 430 million rubles: own funds – 50%, budgetary funds of the Russian Federation Ministry of Education – 50%.

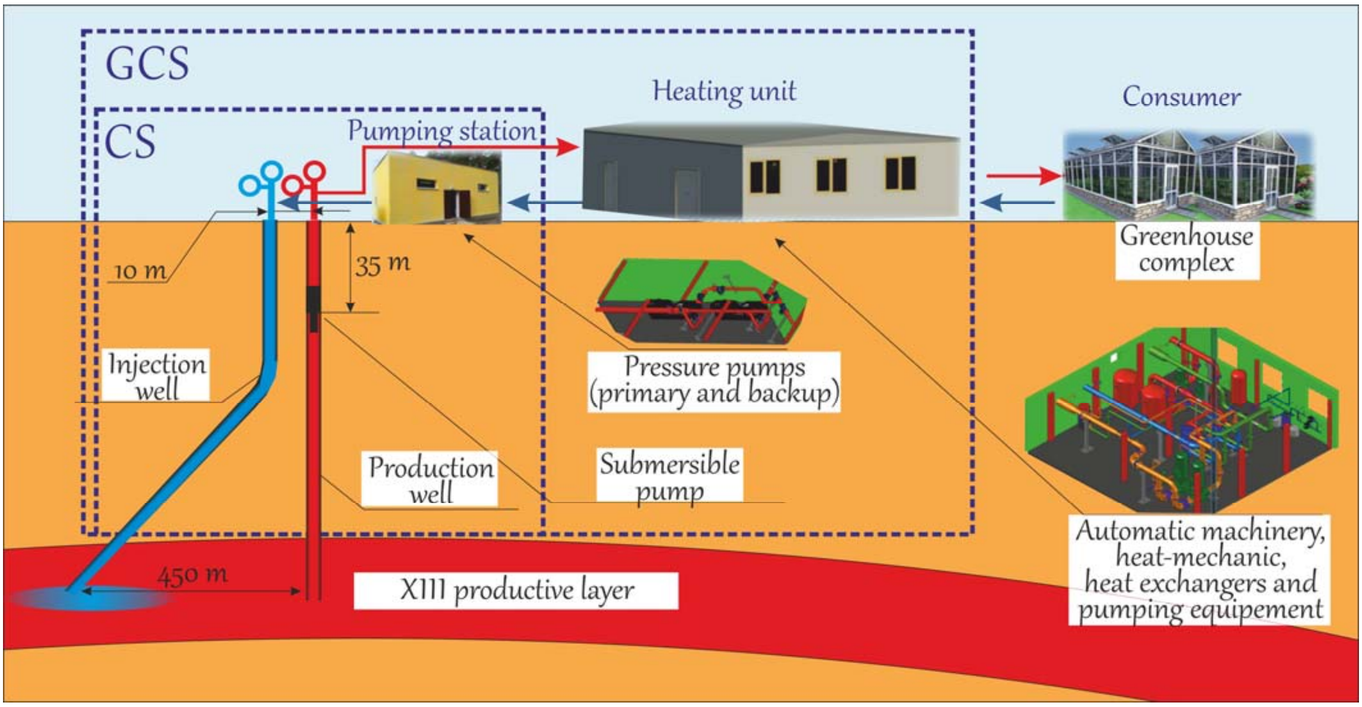


Fig. 6.3. The Khankala geothermal station with circulation scheme of heat extraction schematic drawing [Zaurbekov et al., 2015]

Station energy sales activity is regulated by current regulatory and legal framework of the Russian Federation and the Chechen Republic, as well as regulations, orders, instructions and methodological instructions of the Russian Ministry of Energy. Relations with consumers are based on a contractual basis in accordance with the civil legislation of the Russian Federation. Analysis of the thermal energy supply shows considerable range in prices of heat energy. In 2015, the price ranged from 880.64 to 1717.68 rubles per Gcal of heat at the average rate for the region – 1284.19 rubles. The calculations also took into account the forecast of the Ministry of Economic Development of the Russian Federation on the increase in the cost of utility services until 2018

The cost of production of thermal energy are: basic and auxiliary materials (including inhibitors), electricity, wages, deductions from payroll, depreciation of fixed assets, repair and overhaul, fee for the extraction of groundwater and others.

In order to estimate the commercial efficiency of the geothermal waters use at GCS standard indicators of investment attractiveness of the project were calculated [Karev, 2010]: the payback period, discounted payback period, net present value and internal rate of return. Assesement is based on the expected future cash flows and discount rates, therefore, when using this method with respect to the geological project the main problem is to measure the risk (in the assessment of the discount rate) on the analysis of historical data [Damodaran, 2012]. The discount rate is taken at a rate of 16%, based on the refinancing rate of 11% and the risk premium, as well as international practice of geothermal projects [Geirdal et al., 2015]. Calculations were made directly for the Khankala project (including R&D and the proceeds of the subsequent replication) (Figure 6.4), for the construction of similar stations (excluding R&D and replication) and for gas boiler plant of the same capacity (Table 6.1).

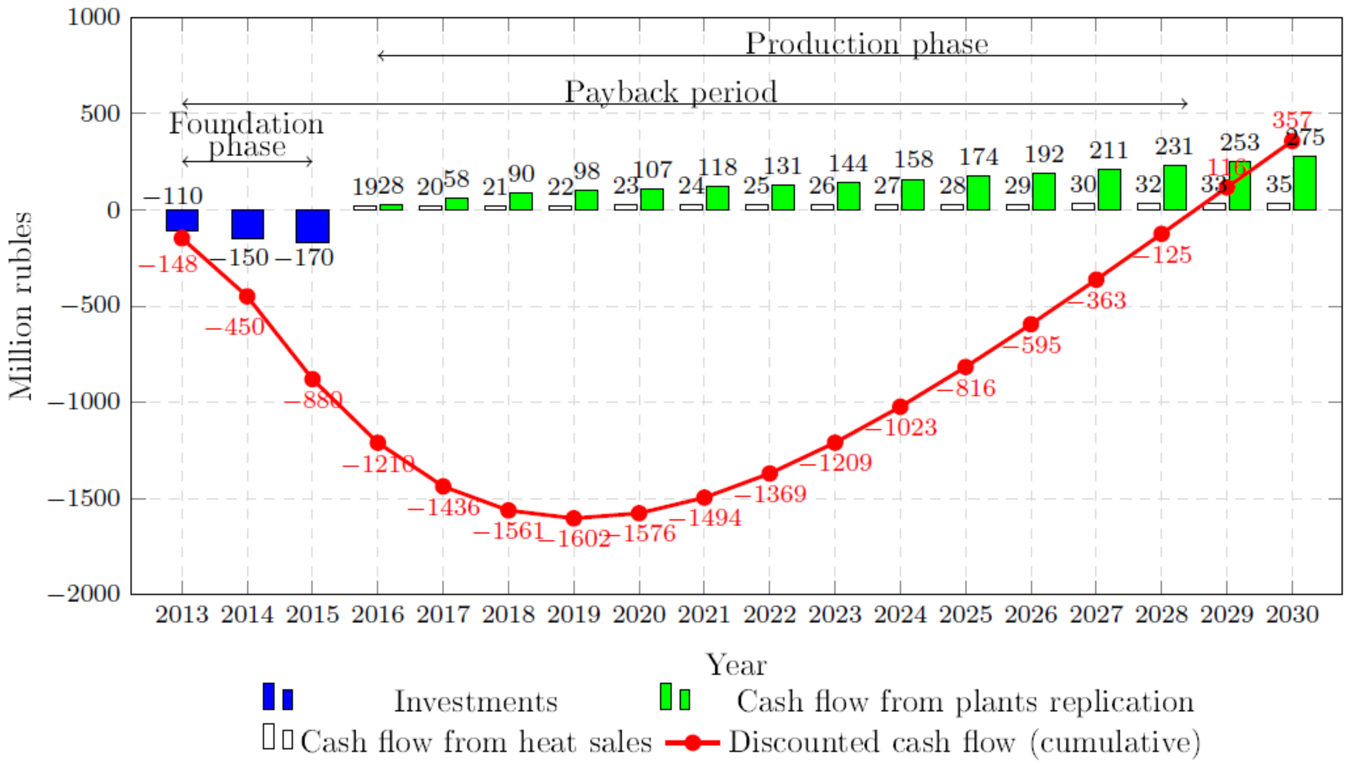
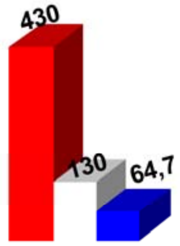
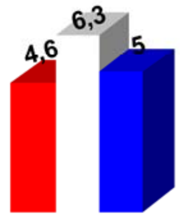
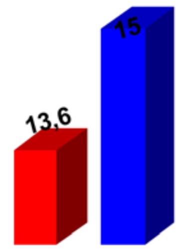
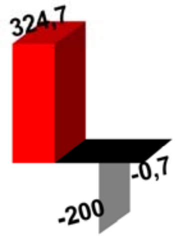
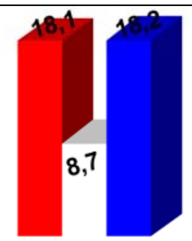


Fig. 6.4. Economic parameters of the Khankala geothermal plant project

Overall indicators show sufficient investment attractiveness of the project, except for heat sales, where the essential factor is the state regulation of tariffs.

Table 6.1. Economic performance (15-year exploitation period)

	Khankala project	Geothermal station	Gas boiler plant	Comparison
Capital expenditures, million rub.	430	130	64.7	
Payback period, years	4.6	6.3	5.0	
Discounted payback period, years	13.6	>15	≈15	
Net present value, million rub.	324.7	–200	–0,7	
Internal rate of return, %	18.1	8,7	18,2	

As shown in table 6.1 the state support, including in the framework of tariff regulation is needed for the payback of geothermal projects. From the standpoint of social efficiency geothermal development has important advantages. It promotes the creation of new jobs during exploration, drilling and construction of geothermal power plants, as well as permanent jobs with the start of plant operationing [Kagel, 2006]. Later on in the Chechen Republic it is advisable to establish a research center for the study of geothermal resources, and training and retraining of specialists. In order to conduct research on geothermic and scientific support of the construction of geothermal plants such center could be in demand in the the Chechen Republic and beyond its borders.

To complete the economic assessment of the use of geothermal resources it is necessary to take into account risks, arising from the implementation of the GCS. Any industrial project is subject to risks, even if they do not materialize in the end. The greatest risk occurs in the first stage – exploration and drilling, as there is danger of an empty well. Since the successful drilling the level of risk is reduced to an acceptable level. This risk is low in the case of geothermal development at Khankala deposit of geothermal waters, due to the high drilled area (there are many old wells of the Oktyabrsk oil deposit), where the geology is known, although it needs to be clarified.

The principal feature of the project for the construction of the GCS is innovativeness. In terms of geological, technical, economic and marketing parameters of this project it is of great interest. But as with any innovative project, all potential risks can be studied only after the implementation of the pilot project, which in the case of a positive result could change the energy consumption structure of this region.

Use of geothermal waters instead of traditional sources of energy has unquestionable environmental benefits. Work of the Khankala geothermal station allows avoiding emissions of about 7 thousand tons of CO_2 during heating season (7 months). Installed doublet with full reinjection of used fluid back into reservoir minimizes environmental risks and impact, makes exploitation at the Khankala maximum environmentally friendly.

Economical assessment shows that exploitation of geothermal waters of the Chechen Republic is not such effective as use of traditional resources of energy. But lack of fuels in the Chechen Republic, renewability and ecological friendliness and some indirect benefits of geothermal waters development make this domain important and promising. Assessment showed that state support in form of tariffs, subsidies, etc. is highly needed. If successful, it is possible that works on exploitation of the 13 others discovered deposits will be started, which can change nowadays energy consumption scheme and will be a significant contribution to economic stability of the region.

Conclusion

Russia has confirmed high potential of geothermal water resources, but today only its small proportion is used. One of the most promising areas is the Chechen Republic, situated within the East Ciscaucasian Artesian Basin, where there are 14 geothermal waters deposits discovered, among which the Khankala is the biggest. It should be noted that most of the material accumulated during their previous exploitation was lost, and geothermal development in the republic has been stopped due to the hostilities that took place in the 1994–2000.

In 2013, the Grozny State Oil Technical University named after Academician M.D. Millionshtchikov together with the members of the consortium "Geothermal resources" supported by the Ministry of Education launched a project to build a Khankala geothermal plant. Main work was to collect, synthesize and analyze available data on the geothermal waters of the East Ciscaucasian Artesian Basin and in particular of the Khankala deposit, draw up guidelines for future exploitation and geothermal development.

The adjusted structural map of the XIII layer and a 3-D map of temperature distribution within the Khankala deposit on the basis of universal kriging are created. The importance of the structural-tectonic factor and movement of groundwater in the formation of the temperature regime of the territory and the regularity of temperature rise from north-east to south-west are shown.

According to the results of mathematical modelling of reinjection at the Khankala geothermal waters deposit a gradual decrease in temperature in the production well after 6–7 years of exploitation is predicted. The recommended distance between the production and injection wells bottoms should be at least 750 m. This distance makes it possible to avoid premature temperature reduction in the production well at a sufficiently long period of exploitation. It is shown that the choice of the location of productive and injection wells placement within the Khankala geothermal waters deposit must be based on two major tectonic faults and natural groundwater flow direction, as they have a significant impact on propagation of cold front.

Recovery of temperature in the production well after a continuous 50-year Khankala deposit exploitation (the distance between the bottoms of the well doublet circulation system is 450 m) is by 96.9% after 150 years when natural groundwater flow is taken into account. In case of no groundwater flow temperature recovers by 75.7%.

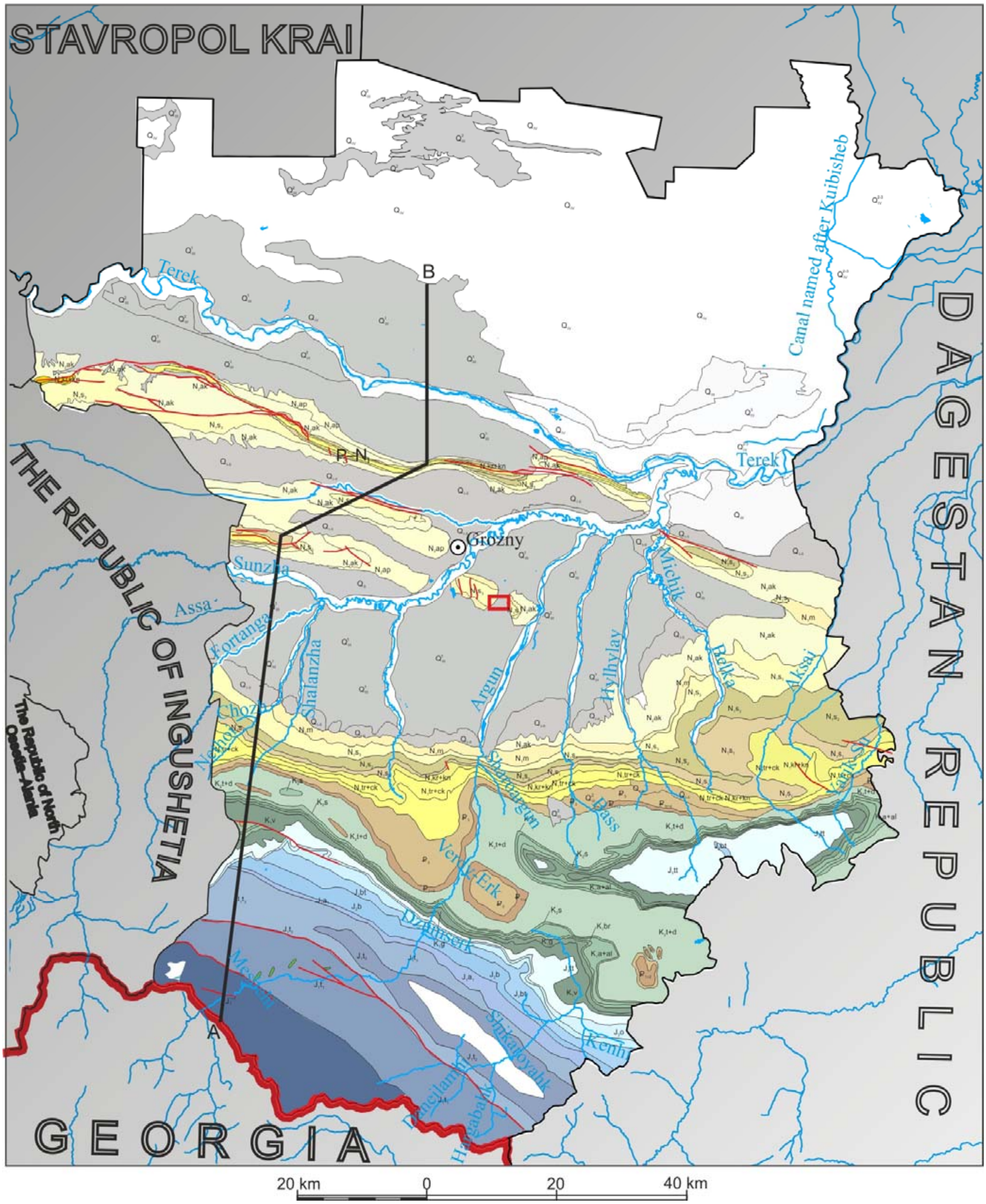
One of the main advantages of the Khankala deposit is the presence of productive multilayer system. In case of a significant drop in temperature after a certain period of the XIII productive formation exploitation with reinjection it is possible to drill a new doublet at the same territory, for example, on highly promising resources of the IV-VII, XVI or XXII layers that will continue the geothermal plant operation. After reinjection of used geothermal waters stoppage, the XIII layer can be used after a certain period again, because as the results of the simulation resource recovery is relatively fast. In order to achieve stability in the Khankala deposit exploitation in the future it is possible to install several doublets in the various productive layers and conduct periodic maintenance.

Despite less economic efficiency of the Chechen Republic geothermal waters use in comparison with traditional sources of energy, environmental friendliness, renewability, lack of fuels and other indirect advantages make this domain perspective. In order to support the development of such resource state support must be provided. Successful exploitation of the all 14 explored geothermal waters deposits of the Chechen Republic would be a significant contribution to energy production.

Appendices

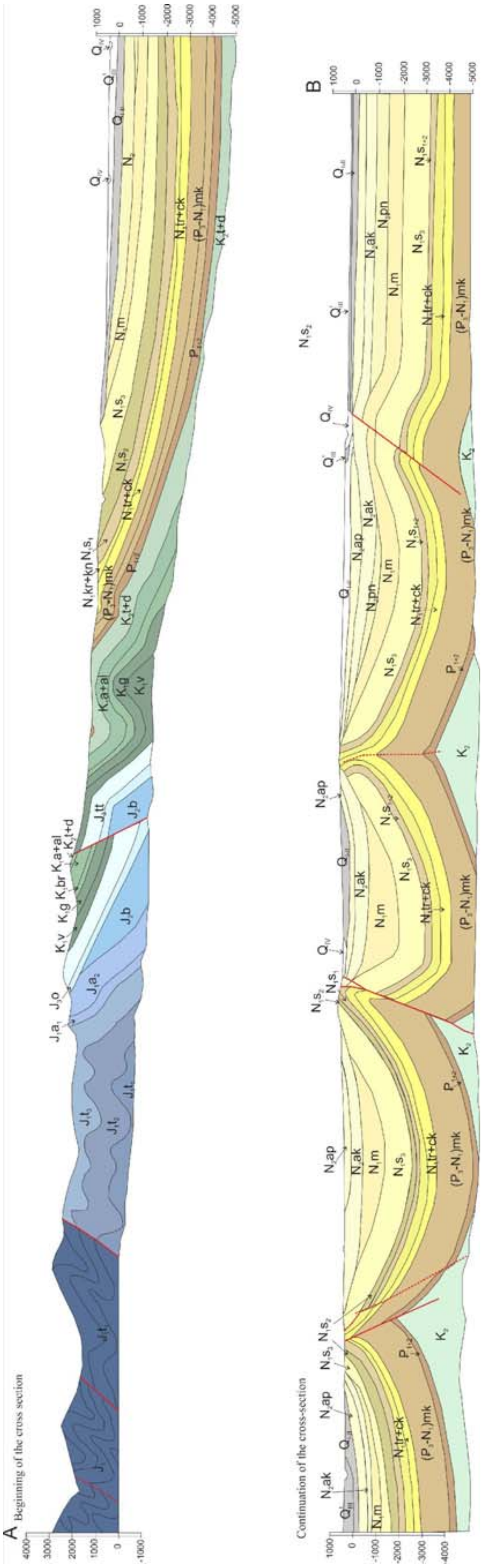
Appendix 1A.

Geological map of the Chechen Republic [Gordeeva, 2001f]



Appendix 1B.

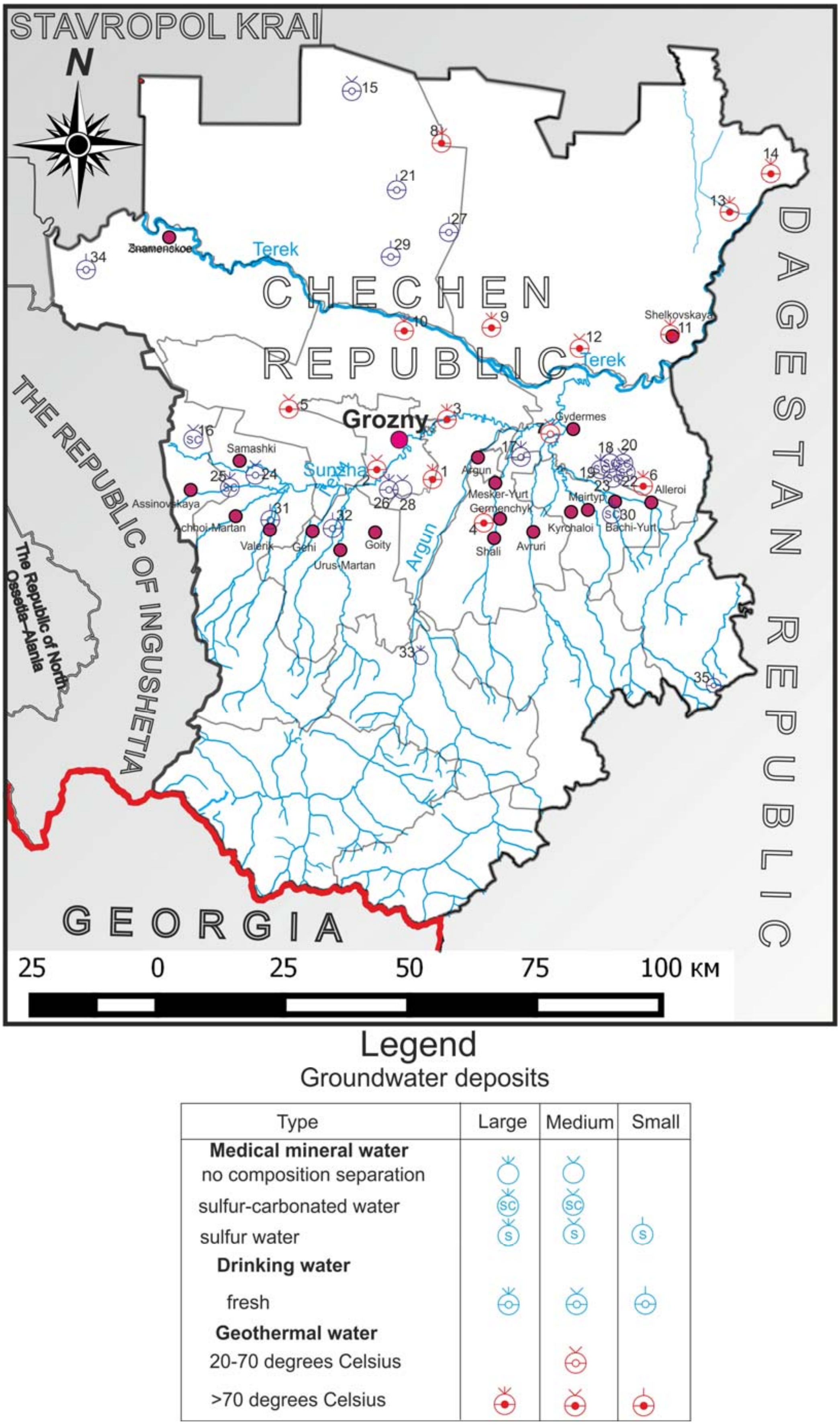
Geological cross-section on the line A-B at the geological map of the Chechen Republic [Gordeeva, 2001f]



Appendix 1C.
Legend to the geological map and cross-section

Q_{IV}^{4}	Contemporary division. Pebble gravels, sands, clays, loams. Alluvial (floodplain and I terrace), aeolian and deluvial sediments
Q_{IV}^{3}	Upper unit. Aeolian, alluvial, lacustrine, lacustrine-alluvial sediments. Sands, loams, clays, silts
Q_{IV}^{2-3}	Middle-upper units undivided. Alluvial, lacustrine, lacustrine-alluvial sediments. Sands, sandy loams, loams, clays, silts
Q_{IV}^{1}	Lower unit. Alluvial sediments. Gray sands, coarse and medium grain size, polymictic
Q_{III}	Upper division. Undivided sediments. Loessial loams
Q_{III}^{2}	Upper Quaternary alluvial deposits (upper subdivision). Sands, pebble gravels, loams (II terrace)
Q_{III}^{1}	Upper Quaternary alluvial deposits (lower subdivision). Pebble gravels, sands, clays, loams
Q_{II-III}	Middle-Upper Quaternary undivided alluvial and lacustrine-alluvial sediments. Sands, loams, sandy loams, aleurites
Q_{II}	Middle division. Alluvial pebble gravels, loams (IV and V terraces)
Q_{I-II}	Middle Quaternary alluvial and deluvial-proluvial deposits. Pebble gravels, sands, clays, loams
Q_{I}	Lower division. Alluvial pebble gravels (VI terrace)
N_2ap	Upper Pliocene sediments of the Apsheron Stage. Pebble gravels, conglomerates, sands with clay interlayers
N_2ak	Upper Pliocene sediments of the Akchagyl Stage. Alternation of clay, gravel, sand, sandstones and conglomerates
N_2pn	Upper Miocene-Lower Pliocene sediments of the Pontian Stage. Alternation of clay, sands
N_1m	Upper Miocene sediments of the Meotian Stage. Alternation of clay, sands and conglomerates
N_1s_3	Upper Miocene sediments of the Sarmatian Stage (upper subdivision). Clays and marls with sands and sandstones interlayers
N_1s_2	Upper Miocene sediments of the Sarmatian Stage (middle subdivision). Clays and marls
N_1s_1	Upper Miocene sediments of the Sarmatian stage (lower subdivision). Clays and marls
N_1kr+kn	Middle Miocene sediments of the Karagan and Konsky Stages. Marls and clays with sands and sandstones units
N_1tr+ck	Middle-Lower Miocene sediments of the Chokrak and Tarkhan Stages. Marls and clays with sands and sandstones interlayers and units
$(P_3-N_1)mk$	Oligocene - Middle Miocene lower strata. The Maikop series. Clays, sandstones, siltstones, marl lenses and siderites
P_{1+2}	Paleocene and Eocene. Marls and clays
(red line)	State border
K_2	Undifferentiated Upper Cretaceous sediments (on the cross-section)
K_2t+d	Turonian-Danish Stage. Limestones and marls
K_2s	Cenoman Stage. Limestone and marl
K_1a+al	Aptian and Albian Stages. Clays and sandstones
K_1br	Barremian Stage. Sandstones with clay and limestone interlayers
K_1g	Hauterivian Stage. Sandstones and clays with limestone interlayers
K_1v+g	Valanginian and Hauterivian Stages. Limestones, sandstones
K_1v	Valanginian Stage. Limestones and dolomites rarely calcareous, sandstones
J_3tt	Tithonian and Kimmeridgian Stages. Limestones, dolomites, gypsum and anhydrites
J_3o	Oxfordian Stage. Dolomites and limestones
J_2k	Callovian Stage. Sandstones with clays interlayers
J_2bt	Bathonian Stage. Argillaceous shales with sandstone interlayers and siderite nodules
J_2b	Bajocian Stage. Argillaceous shales with frequent sandstone interlayers
J_1a_2	Upper substage of the Aalenian. Argillaceous shales and sandstones
J_1a_1	Lower substage of Aalenian. Sandstones and argillaceous shales
J_1t_3	Upper substage of Toarcian. Alternating of argillaceous shales and sandstones
J_1t_2	Middle substage of Toarcian. Argillaceous shales with rare sandstone interlayers
J_1t_1	Lower substage of Toarcian. Schists
J_1^{1+2}	Lower and Middle Lias.. Schists
(red solid and dashed lines)	Tectonical dislocations, proved and supposed
(black line)	The boundaries of the federal subjects of Russia
A — B	Geological cross-section line
(blue line)	Rivers
(red rectangle)	The Khankala geothermal waters deposit territory

Appendix 2A. Groundwater deposits of the Chechen Republic



Appendix 2B.

Annex to the groundwater deposits of the Chechen Republic map.

Number on the map	Name	Mineral resource	Balance reserves, thousand m^3/day	Year of approval
1	Khankala GWD	GW	9.5	1969
2	Goity GWD	GW	0.88	1979
3	Petropavlovsk GWD	GW	3	1991
4	Germenchuk GWD	GW	1	1991
5	Gynushki GWD	GW	1.5	1991
6	Novogrozny GWD	GW	3.41	1981
7	Gudermes GWD	GW	1	1991
8	Central-Buruni GWD	GW	3.4	1991
9	Chervleny GWD	GW	5.2	1991
10	Komsomolsk GWD	GW	2	1991
11	Shelkovsk GWD	GW	2.3	1991
12	Novoschedrinsk GWD	GW	1.42	1991
13	Kargaly GWD	GW	5	1991
14	Dybovsk GWD	GW	3.3	1991
15	Naursk GWD	FWFI	100	1977
16	Sernovodsk GWD	MMW	0.097	1973
17	East-Sunzha UDWD	FW	380	1970
18	Isti-Su UDWD	MMW	0.005	1987
19	Isti-Su UDWD	MMW	0.306	1987
20	Isti-Su UDWD	MMW	0.136	1987
21	Shelkovsk UDWD	FWFI	22	1985
22	Isti-Su UDWD	MMW	0.216	1987
23	Isti-Su UDWD	MMW	0.03	1987
24	Samashki UDWD	FW	159.5	1970
25	Sernovodsk UDWD	MMW	0.42	1968
26	Chernorech (Grozny) UDWD	FW	350	1968
27	Selivan UDWD	FWFI	18.8	1984
28	Octyabrsk UDWD	MMW	0.059	1987
29	Kalinov UDWD	FWFI	26.4	1982
30	Isti-Su UDWD	MMW	0.073	1987
31	Achhoi-Martan UDWD	FW	4.8	1979
32	Urus-Martan (Sunzha) UDWD	FW	19	1979
33	Chanti-Argun UDWD	MMW	0.348	1985
34	Bratsk UDWD	FW	10.4	1975
35	Benoi-Yassi (spring) UDWD	FW	4.3	1984

**GWD – geothermal waters deposit; UDWD – underground drinking water deposit; GW – geothermal waters; MMW – medical mineral waters; FW – fresh water; FWFI – fresh water for irrigation.*

References

List of published literature

1. Abikh, G.V. Brief information about some of the little-known mineral waters at the Northern slope of the Caucasus / Г.В. Абих. – Тифлис, 1874. – 12 с.
2. Alkhasov, A.B. Renewable energy / А.Б. Алхасов. – 2-е изд., перераб. и доп. – М.: ФИЗМАЛИТ, 2012. – 256 с.
3. Alkhasov, A.B. Renewable sources of energy: tutorial / А.Б. Алхасов. – М.: МЭИ. – 2011. – 270 с.
4. Alkhasov, A.B. Current state and prospects of development of geothermal energy / А.Б. Алхасов // Актуальные проблемы освоения возобновляемых энергоресурсов. – Махачкала. – 2006. – С. 4-11.
5. Arkhangelsky, A.D., Zalmanzon, E.S. Comparative lithological study of the origin of groundwater in the Grozny oil fields / А.Д. Архангельский, Э.С. Залмазон // Бюлл. Московского общества испытателей природы, отдел геологический. – № 9. – 1931. – С. 3-4.
6. Beketov, S.B., Kossovich, T.A., Shtepa, S.I. Risk analysis in the implementation of scientific and technical solutions in the field of drilling and workover rigs / С.Б. Бекетов, Т.А. Коссович, С.И. Штепа // Горный информационно-аналитический бюллетень (научно-технический журнал). –№ 6. – 2005. – С. 52-54.
7. Boguslavsky, E.I. Use of geothermal energy for heating purposes / Э. И. Богуславский. – Экологические системы: Электронный журнал энергосервисной компании. – 2010. – № 3 (99). http://esco-ecosys.narod.ru
8. Boguslavsky, E.I. Prospects for the development of geothermal technology / Э.И. Богуславский // Разведка и охрана недр. – №7-8. – 2000. – С. 43-48.
9. Boguslavsky, E.I. Problems of thermal subsoil resources / Э.И. Богуславский // Горный информационно-аналитический бюллетень (научно-технический журнал). – № 12. – 2003. – С. 125-129.
10. Boguslavsky E.I., Pevzner, L.A., Hakhaev B.N. Prospects for the development of geothermal technology / Э.И. Богуславский, Л.А. Певзнер, Б.Н. Хахаев / Горный

информационно-аналитический бюллетень (научно-технический журнал). – № 5. – 2000. – С.142-148.
11. Boguslavsky E.I., Pevzner, L.A., Hakhaev B.N. Heat Russian subsoil resources / Э.И. Богуславский, Л.А. Певзнер, Б.Н. Хахаев // Теплоэнергетика. – 2004. – № 6. – С. 25-32.
12. Boguslavsky E.I. State and problems of world and domestic geothermal power, RAS Institute of Geology / Э.И. Богуславский // Доклад на Конференции по Физико-Химической Геотехнологии, Москва, МГГУ, – 2013.
13. Vassoevich, N.B. The Karagan-Chokrak oil-bearing stratum of the eastern part of the northern slope of the Caucasus / Н.Б. Вассоевич // Геология и нефтегазоностность юга СССР. – Л., ГОНТИ, 1959. – С. 402-546.
14. Vsevolozhsky, V.A. Fundamentals of hydrogeology / В.А. Всеволожский – 2-е. изд. М.: Изд-во МГУ. – 2007. – 448 с.
15. Gareev, A.M., Farkhutdinov, A.M., Farkhutdinov, I.M., Cherkasov, S.V. Current state and prospects of Russian thermal power of water (for example, Khankalskaya field) / А.М. Гареев, А.М. Фархутдинов, И.М. Фархутдинов, С.В. Черкасов // Вестник Башкирского университета. – 2014. – Том 19, № 3. – С. 887-892.
16. Geology and Petroleum Potential of the Eastern Pre-Caucasus / Под ред. И.О. Брода. – Тр. КЮГЭ АН СССР: Гос. изд. нефт. и горнотоплив. литературы. –1958.
17. Geostatistical analysis of data in ecology and nature management (using the R package): Textbook / А.А. Савельев, С.С. Мухарамова, А.Г. Пилюгин, Н.А. Чижикова. – Казань: Казанский университет, 2012. –120 с.
18. Geothermal resources of the Chechen Republic: Current state and prospects / Malyshev Y.N., Taymaskhanov J.E., Zaurbekov Sh.Sh., Mintsaev M.Sh. – Материалы Международной научно-практической конференции GEOENERGY– Грозный, 2015. – С. 83-91.
19. Geochemical study of geothermal waters of the Khankala deposit of the Chechen Republic / F.I. Machigova, A.A. Shaipov, L.R. Bekmurzaeva, S.V. Cherkasov // Устойчивое развитие горных территорий. – Владикавказ, 2014. – № 2. – С. 61-64.

20. Hydrogeology of the USSR / Ed. N.A. Grigoriev. – М.: Недра, 1968. Т. IX. – 488 с.

21. Gnatus, N.A., Khutorsky, M.D. The heat of “dry” rocks – an inexhaustible renewable energy resource / Н.А. Гнатусь, М.Д. Хуторский // Литология и полезные ископаемые. – 2010. – № 6. – С. 1-9.

22. Davis, D.S. Statistical analysis of the data in geology / Д.С. Девис. – М. Недра, 1990. – Книга 1. – 319 с.

23. Davis, D.S. Statistical analysis of the data in geology / Д.С. Девис. – М. Недра, 1990. – Книга 2. – 426 с.

24. Degtyarev, K.S. The heat of the Earth (ч.I) / К.С. Дегтярев // Наука и жизнь. – 2013. – № 9. – С. 27-31.

25. Degtyarev, K.S. The heat of the Earth (ч.II) / К.С. Дегтярев // Наука и жизнь. – 2013. – № 10. – С. 31-37.

26. Demyanov, V.V., Saveliev, E.A. Geostatistics. Theory and practice / В.В. Демьянов, Е.А. Савельева. – Издательство «Наука», Москва, 2010. – 327 с.

27. Jamalov S.A., Lewkowicz R.A. Patterns of change in temperature with depth / С.А. Джамалов // Тр. Геол. Ин-та Дагестанского филиала. – 1960. – С. 245-251.

28. Jamalov, S.A. Geothermal research at the Dagestan branch / С.А. Джамалов // Вест. АН СССР. –№4. – 1959. – С.113-114.

29. Duraeva, E. Renewable Energy in Russia. From opportunity to reality / Е. Дураева – Париж: Изд. ОЭСР/МЭА, 2004. – 124 с.

30. Zimin, N.N. Mineral waters of the Terek-Sunzha valley / Н.Н. Зимин // Военный медицинский журнал. – № 3. – 1853.

31. Use and prospects of development of mineral, thermal and industrial waters / G.S. Vartanian, V.A. Komyagin, R.I. Plotnikov and others.– М. – 1999. – 86 с.

32. On the history of the study of mineral and curative waters of the Chechen Republic / I.A. Kerimov, A.A. Daukaev, A.A. Abumuslimov, Aslan A. Daukaev // Вестник Академии наук Чеченской Республики. – 2012. – № 1 (16). – С. 59-64.

33. Kaputin, J.E. Mining computer technologies and geostatistics / Ю.Е. Капутин. –

СПб: Недра, 2002. – 424 с.

34. Kartcev, A.A. Water and oil / А. А. Карцев, С. Б. Вагин. – М. : Недра, 1977. – 112 с.

35. Kartcev, A.A. Hydrogeology of oil and gas fields / А.А. Карцев. – Гостоптехиздат, 1963. –353 с.

36. Complex project to create a pilot geothermal plant on the basis of the implementation of the circulation circuit system of geothermal heat use: Report on R&D: Grozny State Oil Technical University named after academician M.D. Millionshtchikov; Sh.Sh. Zaurbekov, M.Sh. Mintsaev; A.A. Shaipov, etc., Грозный, 2013. – 134 с.

37. Kononov, V.I., Polyak, B.G., Khutorsky, M.D. Hydrogeothermal Russian resources / В.И. Кононов, Б.Г. Поляк, М.Д. Хуторской // Георесурсы. – 2005. – № 2(17). С. 29-33.

38. Konshin, A.M. Description of the mineral springs of the Northern Caucasus / А.М. Коншин // Материал для геологии Кавказа, сер. 3, кн. 2, Тифлис. – 1899.

39. Kotsarev, I.Y., Vlasova, S.P. Geothermal conditions of the Northern Caucasus Middle Miocene deposits / И.Ю. Коцарев, С.П. Власова // Изв. вузов. Нефть и газ. – 1963. –№12. –С. 124-125.

40. Koshkul, F.G. Geological studies made in Terek and Kabardino-Sunzha ridges and the valley of Alkhan-Churt located in-between / Ф.Г. Кошкуль // Горный журнал. –т. III. –1879. –С. 170–204.

41. Kudryavtsev, N.A. On the structure of the Novo-Grozny oil region / Н.А. Кудрявцев. – Геологический комитет. Материалы по общей и прикладной геологии. – № 75. – Л. Издание Геологического комитета. – 1928. – 164 с.

42. Kutateladze S.S., Rosenfeld L.M. Geothermal power plant / С.С. Кутателадзе, Л.М. Розенфельд – Патент № 941517/24-6. – 1965.

43. Lindtrop, N.T. Modes of oil fountains of Grozny district / Н.Т. Линдтроп // Нефтяное и сланцевое хозяйство. – 1925. – №4. – С. 607-635.

44. Materon, J. Fundamentals of Applied geostatistics / Ж. Матерон – М., Мир. – 1967. – 387 с.

45. Nikolaev, V.M. Groundwater of the Terek-Sunzha oil province Karagan deposits / В.М. Николаев // Тр. ГрозНИИ, № 8. – 1960.
46. Nikolaev, V.M. Groundwater of the Terek-Sunzha oil province Chocrak deposits / В.М. Николаев // Тр. ГрозНИИ, № 9. – 1960.
47. Nikolaev, V.M. Geothermal waters of the Terek-Sunzha oil province / В.М. Николаев. – В книге «Термальные воды СССР и вопросы их теплоэнергетического использования». – Изд. АН СССР, М. – 1963. – С. 218-245.
48. Prospects for the development of geothermal energy in the Chechen Republic / J.N. Malyshev, J.E. Taymaskhanov, Sh.Sh. Zaurbekov, M.Sh. Mintsaev // Геоэкологические, медико-биологические и рекреационные вопросы устойчивого развития горных территорий. – №1(19). – 2014. – С. 63-67.
49. Povarov, O.A. The heat of the Earth. Efficient energy supply to remote areas and Russian Housing / О.А. Поваров // Возобновляема энергия. – 2003. – №4 – С. 2-3.
50. Potekhin, D.V. Optimization of the multivariate three-dimensional geological modelling of oil and gas deposits technology (PhD) : автореферат диссертации на соискание ученой степени кандидата технических наук (25.00.12) / Д.В. Потехин. – М., 2014. – 151 с.
51. Rosin, L.A. Finite element method / Л.А. Розин. – СПб.: СПбГТУ. – 2000. – С. 120-127.
52. Svalova, V.B. Complex use of hydrothermal resources / В.Б. Свалова // Георесурсы. – 2009. – № 1. – С.17-22.
53. Current state and prospects of use of geothermal resources in the Russian Federation / S.V. Cherkasov, T.G. Churikova, L.R. Bekmurzaev et al. – Материалы Международной научно-практической конференции GEOENERGY – Грозный, 2015. – С. 303-322.
54. Sukharev, G.M. Geothermal features of the Terek-Dagestan oil province / Г.М. Сухарев. – Гостоптехиздат. – 1948. – 41 с.
55. Sukharev, G.M. Hydrogeology of the Mesozoic and Tertiary sediments of the Terek-Dagestan oil and gas region and the Lower Volga region / Г.М. Сухарев. –

Гостоптехиздат. – 1954. – 400 с.
56. Sukharev, G.M. Groundwater of the Terek-Dagestan oil and gas field / Г.М. Сухарев. – Грозный. – 1948.
57. Sukharev, G.M., Vlasov, S.P., Taranukha, J.K. On the question of the use of geothermal water and resources as an example of the hydrodynamic system of the south East Ciscaucasia / Г.М. Сухарев, С.П. Власова, Ю.К. Тарануха // Изв. ВУЗ. Нефть и газ, № 4, Баку. – 1966.
58. Sukharev, GM, Miroshnikov, MV Groundwater of oil and gas fields of the Caucasus / Г.М. Сухарев, М.В. Мирошников. – Гостоптехиздат. – 1963. – 328 с.
59. Farkhutdinov, A.M. Environmental aspects of the use of the Khankala geothermal waters deposit / А.М. Фархутдинов // Геология. Известия Отделения наук о Земле и природных ресурсов Академии наук Республики Башкортостан. – 2014. – № 20. – С. 81-84.
60. Farkhutdinov, A.M., Ismagilov, R.A. Geothermal resources of the Chechen Republic and the prospects for their use / А.М. Фархутдинов, Р.А. Исмагилов // Геоинжиниринг. – 2014. – № 2(22). – С. 60-63.
61. Farkhutdinov, A.M., Farkhutdinov, I.M., Ismagilov, R.A. The history of the Khankala geothermal waters deposit discovery and development / А.М. Фархутдинов, И.М. Фархутдинов, Р.А. Исмагилов // Вестник Башкирского университета. – 2014. – Том 19, № 1. – С. 93-96.
62. Farkhutdinov, A.M., Farkhutdinov, I.M., Ismagilov, R.A., Cherkasov, S.V. Prospects for the use of geothermal waters in Ciscaucasian foothill zone (Khankala field) / А.М. Фархутдинов, И.М. Фархутдинов, Р.А. Исмагилов, С.В. Черкасов // Вестник Академии наук Республики Башкортостан. – 2014. – Том 19, № 4. С. 34-43.
63. Farkhutdinov, A.M., Chantal de Fouquet, Mintsaev, M.Sh., Cherkasov, S.V. Application of geostatistics to analyze operating prospects of the Khankala geothermal waters deposit / А.М. Фархутдинов, Шанталь де Фуке, М.Ш. Минцаев, С.В. Черкасов // Геоинформатика. – 2015. – № 1. – С. 60-68.
64. Khrebtov A.I. Geothermal conditions and geothermal waters of the Central Pre-

Caucasus / А.И. Хребтов. – М. Наука, 1965. – 110 с.
65. Hutsiev, AA Geology of the Tertiary and Mesozoic sediments of the North Caucasus and Ciscaucasia / А.А. Хуциев. – Грозненский нефтяной научно-исследовательский институт, Грозный Труды. – том 8. 1960. – 273 с.
66. Shagoyants, SA Groundwater of central and eastern parts of the North Caucasus and the conditions of their formation / С.А. Шагоянц. –Госгеолтехиздат, М., 1959. – 307 с.
67. Overthrust-nappe tectonics of lithosphere / M.A. Kamaletdinov, T.T. Kazantseva, Yu.V. Kazantsev, D.V. Postnikov. – M.: Наука. – 1991. – 255 с.
68. 40 years of Dogger aquifer management in Ile-de-France, Paris Basin, France / S. Lopez, V. Hamm, M. Le Brun et al. // Geothermics. – 2010. – № 39. – 339–356 p.
69. Antics, M., Papachristou, M., Ungemach, P. Sustainable heat mining. A reservoir engineering approach / M. Antics, M. Papachristou, P. Ungemach. – Proceedings of the 30th Workshop on Geothermal Reservoir Engineering, January 31-February 2, 2005, Stanford University, Stanford, California. – 14 p.
70. Axelsson, G. Sustainable geothermal utilization – Case histories, definitions, research issues and modelling / G. Axelsson // Geothermics. – № 39. –2010. – p. 283–291.
71. Axelsson, G. Sustainable geothermal utilization / G. Axelsson. – Proceedings of Short Course on Geothermal Development and Geothermal Wells, UNU-GTP and LaGeo, Santa Tecla, El Salvador. – 2012. – 18 p.
72. Bear, J. Dynamics of fluids in porous media / J. Bear – American Elsevier, New York. – 1972. – 764 p.
73. Bertani, R. Geothermal Power Generation in the World, 2005-2010 Update Report / R. Bertrani. – Proceedings of World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010. – 41 p.
74. Bertani, R., Thain, I. (2002). Geothermal power generating plant CO2 emission survey. International Geothermal Association (IGA) News, 49, pp. 1-3 (ISSN: 0160-7782).
75. Böttcher, N. Thermodynamics of porous media: non-linear flow processes. PhD thesis, Technische Universitat Dresden, 2013. – 47 p.

76. Bromley, C.J., L. Rybach, M.A. Mongillo, and I. Matsunaga (2006). Geothermal resources – utilization strategies to promote benefi cial environmental effects and to optimize sustainability. In: Proceedings RE 2006, Chiba, Japan, 9-13 October 2006, pp. 1637-1640. In: Science and Technology in Japan, 25(100), 2007.
77. Chilès, J.P., Delfiner P. Geostatistics: Modeling Spatial Uncertainty / J.P. Chiles, P. Delfiner, – Second Edition, N.Y.: Wiley. – 2012. – 734 p.
78. Darcy, H. Les Fontaines Publiques de la Ville de Dijon / H. Darcy, – Dalmont, Paris. – 1856. – 647 p.
79. Energy Strategy of Russia for the period up to 2030 // App. to the public and business magazine “Energy Policy”. M.: Institute of Energy Strategy, 2010. – 172 p.
80. Fridleifsson, I.B., R. Bertani, E. Huenges, J.W. Lund, A. Ragnarsson, and L. Rybach (2008). The possible role and contribution of geothermal energy to the mitigation of climate change. In: IPCC Scoping Meeting on Renewable Energy Sources, Luebeck, Germany, 21-25 January 2008, pp. 36. Available at: www.ipcc.ch/pdf/supporting-material/proc-renewables-lubeck.pdf.
81. Geothermal contribution to the energy mix of a heating network when using Aquifer Thermal Energy Storage: modeling and application to the Paris basin / A. Réveillère A., Hamm V., Lesueur H. et al. // Geothermics. – 2013. – № 47. – p. 69-79.
82. Geothermal Energy: International Market Update / A. Holm, L. Blodgett, D. Jennejohn, K. Gawell. – Geothermal Energy Association. – 2010. – 77 p.
83. Giuglaris, E., Malcuit, E., Wacogne, F. Khankala Project. Study of a geothermal loop in Grozny (Chechen Republic, Russia) / E. Giuglaris, E. Malcuit, F. Wacogne. – Technical audit of Report n°1. Report BRGM/RC-63510-FR, 2014. – 41 p.
84. Goblet, P. METIS – Tutoriel et notice d’utilisation / P. Goblet. – Rapport Ecole des Mines de Paris. Centre d'Informatique Géologique LHM/RD/05/25. – 2005.
85. Goblet, P. Modélisation des transferts de masse et d’énergie en aquifère [Modelling mass and energy transfers in aquifers] / P. Goblet. – PhD Thesis, Ecole Nationale Supérieure des Mines de Paris, University Pierre and Marie Curie, Paris, France. – 1980. – 200 p.

86. Goblet, P. Programme METIS – Simulation d'écoulement et de transport miscible en milieu poreux et fracturé / P. Goblet. – Notice de conception mise à jour le 6/09/10 Rapport Mines ParisTech - Centre de Géosciences R100907PGOB. – 2005.
87. Goblet, P. Programme METIS – Simulation d'écoulement et de transport miscible en milieu poreux et fracturé / P. Goblet. – Notice d'emploi Rapport Ecole des Mines de Paris. Centre d'Informatique Géologique LHM/RD/05/24. – 2005.
88. Goldstein, B., G. Hiriart, R. Bertani, C. Bromley, L. Gutiérrez-Negrín, E. Huenges, H. Muraoka, A. Ragnarsson, J. Tester, V. Zui, 2011: Geothermal Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
89. Goovaerts, P. Geostatistics for Natural Resources Evaluation / P. Goovaerts. – Oxford Univ. Press, New-York. – 1997. – 483 p.
90. Gringarten, A.C., Sauty, J.P. (1975), A Theoretical Study of Heat Extraction From Aquifers With Uniform Regional Flow / A.C. Gringarten, J.P. Sauty // Journal of Geophysical Research. – 1975. – № 35. – p. 4956-4962.
91. Huttrer, G.W. The status of world geothermal power generation 1995-2000 / G.W. Huttrer. – Proceedings World Geothermal Congress 2000, Kyushu – Tohoku, Japan, May 28 – June 10, 2000, v.1, p. 23-37.
92. Ingimarsson, J. Challenges for Geothermal Energy - Experience from Iceland / J. Ingimarsson. – Energy Future: The Role of Impact Assessment conference, 32 annual conference of the international association for impact assessment. – 2012. – 5 p.
93. Istok, J. Groundwater Modeling by the Finite Element Method / J. Istok – American Geophysical Union, Water Resources Monograph 13, Wash., D.C. – 1989. – 495 p.
94. Journel A.G., Huijbregts C.J. Mining Geostatistics / A.G. Journel, C.J. Huijbregts. – London: Academic Press. – 1978. – 600 p.
95. Kagel, A., Bates, D., Gawell, K. A Guide to Geothermal Energy and the Environment [Online] / A. Kagel, D. Bates, K. Gawell. – Washington, DC, Geothermal

Energy Association, 2007. http://geo-energy.org/reports/environmental%20guide.pdf
96. Kaltschmitt, M. (2000). Environmental effects of heat provision from geothermal energy in comparison to other resources of energy. In: Proceedings World Geothermal Congress 2000, Kyushu-Tohoku, Japan, 28 May - 10 June 2000 (ISBN: 0473068117). Available at: www.geothermal-energy.org/pdf/IGAstandard/WGC/2000/R0908.PDF
97. Krige, D.G. A statistical approach to some basic mine valuation problems on the Witwatersrand / D.G. Krige // Journal of the Chemical, Metallurgical and Mining Society of South Africa. – 1951. – № 52 (6) – p. 119–139.
98. Lopez, S., Hamm, S., Goyeneche, O. Optimal and sustainable use of the Dogger aquifer geothermal resource: long-term management and new technologies / S. Lopez, S. Hamm, O. Goyeneche. – SIMS 2012 The 53rd Scandinavian Conference on Simulation and Modelling. – 17 p.
99. Lund, J.W., Freeston, D.H. World-Wide direct uses of geothermal energy 2000 / J.W. Lund, D.H. Freeston. – Proceedings World Geothermal Congress 2000, Kyushu – Tohoku, Japan, May 28 – June 10, 2000, v.1, p. 1-21.
100. Lund, J.W., Freeston, H.H., Boyd, T.L. Direct Utilization of Geothermal Energy 2010 Worldwide Review / J.W. Lund, H.H. Freeston, T.L. Boyd. – Proceedings of World Geothermal Congress 2010, Bali, Indonesia, 26–30 April 2010. 23 p.
101. Management / P. Ungemach, M. Antics, M. Papachristou. – World Geothermal Congress, 24-29 April 2005, Antalya, Turkey. – 12 p.
102. Marsily, G. Hydrogéologie quantitative [Text], Masson, Paris, 215 p.
103. Matek, B. Geothermal Power: International Market Overview / B. Matek. – Geothermal Energy Association. – 2013. – p. 10-11.
104. Matheron, G. Traité de géostatistique appliquée / G. Matheron. – Editions Technip, France. – 1962. – 333 p.
105. Menjoz, A. Lectures on the characterization and the exploitation of geothermal reservoirs in France / A. Menjoz. – Report No. 2, United National Geothermal Training Program, The United Nations University, Reykjavík, Iceland. – 1990. – 89 p.
106. OpenGeoSys: an open-source initiative for numerical simulation of thermo-hydro-

mechanical/chemical (THM/C) processes in porous media / O. Kolditz, S. Bauer, L. Bilke [et al.] // Environ. Volume 67, Issue 2. – 2012. – p. 589-599.

107. Papachristou, M. The Use of Numerical Simulation in Low Enthalpy Geothermal Reservoir Management / M. Papachristou // The Paris Basin Case, PhD Thesis, 02 Dec. 2011. Aristotle University, Geology Dpt. Thessaloniki, Greece.

108. Pruess, K. Mathematical modelling of fluid flow and heat transfer in geothermal systems. An introduction in five lectures / K. Pruess – Lawrence Berkeley National Laboratory Report LBNL-51295, Berkeley, CA. – 2002. – 84 p.

109. Pryde, P.R.. Geothermal Development in the Soviet Union / P.R. Pryde // GHC Bulletin Vol 4. – 1976. – № 2. – p. 8–14

110. Smith, T.E. Notebook on Spatial Data Analysis [Online] / T.E. Smith. – 2014. http://www.seas.upenn.edu/~ese502/#notebook

111. Stab, O. Delos 2.0.3 User's manual [Online] / O. Stab. – 2006. http://people.mines-paristech.fr/olivier.stab/delos/telechargement/doc/delos_GB.pdf

112. Stober, I. Geothermal energy. From theoretical models to exploration and development / I. Stober, K. Bucher. – Springer, IX, 2013. – 291 p.

113. Stüwe, K. Geodynamics of the Lithosphere. An Introduction / K. Stuwe. – Berlin, Heidelberg, New York: Springer-Verlag. – 2002. – 449 p.

114. Svalova V.B. Geothermal energy use in Russia / V.B. Svalova. – Proceedings of the 4th African Rift Geothermal Conference 2012, Nairobi, Kenya, 21-23 November 2012. – 6 p.

115. The possible role and contribution of geothermal energy to the mitigation of climate change / I.B. Fridleifsson, R Bertani, E Huenges, J.W. Lund et al. // IPCC. Scoping Meeting on Renewable Energy Sources, Proceedings, Luebeck, Germany, 20-25 January 2008, – 2008. – p. 59-80.

116. Thiéry, D., Software MARTHE. Modelling of Aquifers with a Rectangular Grid in Transient state for Hydrodynamic calculations of heads and flows. Release 4.3 / D. Thiéry. – Report BRGM 4S/EAU n° R32548. – 1990.

117. Training Course on Geothermal District Heating Manual Book / B. Kępińska, A.

Kasztelewicz, P. Dumas, A. Latham, L. Angelino. – 2014. – 75 pp.
118. Ungemach, P., Insight into geothermal reservoir management district heating in the Paris Basin, France / P. Ungemach // GHC Bulletin. – 2001. – № 22. – p. 3–13.
119. Ungemach, P., Antics, M., Lalos, P. Sustainable geothermal reservoir management – a modelling suite / P. Ungemach, M. Antics, P. Lalos. – Proceedings of Australian Geothermal Energy Conference, 16-18th Nov. 2011, Melbourne, Geoscience Australia Record 2011/43. – p. 267-275.
120. Ungemach, P., Papachristou, M., Antics M. Renewability Versus Sustainability. A Reservoir Management Approach / P. Ungemach, M. Papachristou, M. Antics. European Geothermal Conference, 30 May – 1 June 2007, Unterhaching, Germany. – 13 p.
121. Williams, C.F., Reed, M.J., Anderson, A.F. Updating the Classification of Geothermal Resources / C.F. Williams, M.J. Reed, A.F. Anderson. – Proceedings, Thirty-Sixth Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California. January 31– February 2, 2011. – 7 p.

List of reports

122. Gonsirovsky, D.G., Sudeyko, L.I., Rudin, T.A. Evaluation of the natural resources of geothermal waters of the southern districts of the Eastern Pre-Caucasus by Pliocene, Upper Pliocene, and Karagan-Chokrak aquifer complexes / Д.Г. Гонсировский, Л.И. Судейко, Т.А. Рудина. – ТГФ СКГУ Ессентуки. – 1966. – 137 с.
123. Gordeeva, G.V. Report on hydrogeological additional exploration areas, scale 1:200 000 within the Chechen Republic, lists K-38-III, IV, V, X, XI (GGDP-200 - auditing and assessment of the work). – 2001. – 540 с.
124. Ermolaev, A.N., Lialin, L.K., Napolskikh, M.S., Feldman, S.L. Calculation of reserves of oil and gas for Oktyabrsky deposit as of January 1, 1954 / А.Н. Ермолаев, Л.К. Лялин, М.С. Напольский, С.Л. Фельдман. – 1953. – 338 с.
125. Krylov, V.B. Hydrogeological studies of geothermal complexes in the city of Grozny district / В.Б. Крылов. – 1981. – 229 с.
126. Krylov, V.B. Complex studies of wells and the assessment of operational stocks of geothermal waters in terms of geothermal circulation system at the Khankala field of the

CHIASSR / В.Б. Крылов. – 1988. – 128 с.
127. Krylov, V.B. The report on subject “Recommendations for further exploitation of Karagan-Chokrak deposits at the Khankala and Gojty CHIASSR” / В.Б. Крылов. – 1983. – 104 с.
128. Krylov, VB The report on “Analysis of exploration of the CHIASSR Grozny district geothermal water deposits” / В.Б. Крылов. – 1986. – 135 с.
129. Krylov, V.B. Report on the topic: “The study of hydrodynamic and thermal performance of Karagan-Chokrak deposits during exploration of the Khankalska Valley CHIASSR in order to increase the use of geothermal energy by creating an artificial system of replenishment of geothermal water resources” / В.Б. Крылов. – 1984. – 50 с.
130. Krylov, V.B. Calculation of operational stocks of the Khankala field XIII layer in case of the reservoir pressure maintenance by creating a GCS / В.Б. Крылов. – 1987. – 134 с.
131. Nazarethov, M.B., Merkulov, N.E. Charting the October oil field redevelopment / М.Б. Назаретов, Н.Е. Меркулов. – 1956.
132. Nikolaev V.M. Effect of long-term development of the Karagan-Chokrak oil reservoirs on natural water regime / В.М. Николаев. – 1961. – 74 с.
133. Shpak, A.A. The report on the calculation of operational reserves of the Khankala valley of the CHIASSR geothermal waters on 1/1-68 (for heating and hot water supply) / А.А. Шпак. – 1968. – 352 с.

Résumé

Récemment, une attention considérable a été accordée dans le monde à l'utilisation des sources d'énergie renouvelables. Parmi celles-ci, les eaux géothermales sont d'une grande importance en raison de la sécurité écologique et de l'efficacité économique de leur utilisation. La Russie possède un fort potentiel de ressources confirmées en eau géothermale, mais aujourd'hui, seule une faible proportion est utilisée. L'un des territoires les plus prometteurs pour les eaux géothermales est la République Tchétchène, qui se trouve à la 3ème place parmi les régions russes pour les réserves opérationnelles approuvées de gisements d'eaux géothermales, parmi lesquelles la plus importante est le gisement de Khankala.

Le développement durable des ressources en eaux géothermales exige une approche intégrée. L'analyse géostatistique et l'estimation, ainsi que la modélisation mathématique, peuvent jouer un rôle important dans la résolution des problèmes d'exploitation des eaux géothermales. La carte structurale estimée de la couche la plus productive (la couche XIII) et une carte 3-D de la distribution de la température dans le gisement de Khankala ont été créées en utilisant le krigeage universel. Les résultats ont montré l'importance du facteur structuraltectonique et du mouvement des eaux souterraines dans la formation du régime de température du territoire. La modélisation de l'exploitation des gisements géothermiques de Khankala a permis de prévoir l'évolution de la température, de fournir des recommandations sur l'emplacement des puits d'injection et la distance entre les impacts à la couche productive, et d'explorer d'autres scénarios d'exploitation comme l'utilisation périodique de couches par doublets.

Le développement de l'utilisation des eaux géothermales présente des avantages incontestables: respect de l'environnement et renouvelabilité. Afin de développer ce domaine en République Tchétchène, le soutien de l'Etat est nécessaire. L'absence d'un cadre législatif adapté et de systèmes spéciaux d'assurance pose des problèmes. L'utilisation des eaux géothermales des quatorze gisements explorés en République Tchétchène peut constituer une contribution significative à la production locale d'énergie et à la stabilité économique de la région, tout en apportant des avantages environnementaux par le remplacement partiel des combustibles traditionnels.

Le travail présenté ici est une contribution au projet de station géothermique de Khankala qui a été lancé avec succès au début de 2016. La station géothermique de Khankala représente une nouvelle étape dans l'utilisation des eaux géothermales dans le Caucase du Nord car il s'agit du seul exemple russe de station géothermique avec une boucle fermée de puits de production et d'injection ("doublet") et 100% de réinjection du fluide utilisé dans le réservoir.

Mots clés : hydrogéologie, eaux géothermiques, doublet, modélisation, géostatistique

Abstract

Recently, considerable attention in the world is given to the use of renewable energy sources. Among them geothermal waters are of great importance due to ecological safety and economic efficiency of their use. Russia has confirmed high potential of geothermal water resources, but today only a small proportion is used. One of the most promising areas for geothermal waters is the Chechen Republic, which is at the 3rd place among the Russian regions for approved operational reserves of geothermal waters deposits, the largest of which is the Khankala deposit.

Achievement of the sustainability in geothermal waters resource development requires an integrated approach and an important role in solving the problems of exploitation of thermal waters is played by geostatistical analysis and estimation, as well as mathematical modelling. The adjusted structural map of the most productive layer (layer XIII) and a 3-D map of temperature distribution within the Khankala deposit were created using universal kriging. Results approved the importance of the structural-tectonic factor and movement of groundwater in the formation of the temperature regime of the territory. Modelling of the Khankala geothermal waters deposit exploitation allowed to make prognosis of temperature changes, to provide recommendations on injection-production wells location and distance between down holes and to explore possible further exploitation scenarios such as periodic use of different layers by doublet systems.

The development of geothermal waters use has undoubted advantages – environmental friendliness and renewability. In order to develop this domain in the Chechen Republic the state support is needed. Issues are the lack of a special legislative framework and special insurance systems. Use of geothermal waters of the 14 explored deposits in Chechen Republic can be a significant contribution to local energy production and economic stability of the region while bringing the environmental benefits of traditional fuels partial replacement.

The present work was a contribution to the Khankala geothermal station project, which was successfully launched in the beginning of the 2016. The Khankala geothermal station represents a new stage in use of geothermal waters in the Northern Caucasus as it is the only Russian example of geothermal station with closed loop of production and injection wells ("doublet") with 100% reinjection of used fluid back into reservoir.

Key Words: hydrogeology, geothermal waters, doublet, modelling, geostatistics