INSTITUTE OF THE EARTH'S CRUST
Siberian Branch of the Russian Academy of Sciences

Laboratory for Integrated Research of the Arctic

INTEGRATING GEOPHYSICAL METHODS: FROM STUDYING THE ARCTIC TO THE GEOTHERMAL WATER DEPOSITS EXPLORATION WITHIN THE BAIKAL RIFT ZONE

International Conference on the 120th Anniversary of the Bulnay Earthquake: Advances in Astronomy and Geophysics

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Institute of the Earth's crust SB RAS

OUTLINE

1. Introduction
2. Geophysical methods
3. Permafrost studies in Arctic
4. Geothermal studies within the Baikal rift zone
5. Summary

INTRODUCTION

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- Nowadays, geophysics methods are used to solve a wide range of geological problems: from **exploring underground water**, **studying permafrost structure**, **oil and gas exploration**, to **fundamental research** on the structure of the Earth's crust and mantle.

- It has become increasingly clear that relying on a single geophysical method leads to significant uncertainty in the geological interpretation of the data obtained. Clearly, the **key to resolving this issue is integrating multiple geophysical methods**.

- Interpretation must be conducted within a **unified physical-geological model** (PGM) of the research object, constructed based on the geological task at hand.

- **Mathematical modeling of physical fields** for each geophysical method should be performed based on the PGM to evaluate its theoretical effectiveness in addressing the given problem.

RESEARCH OBJECTIVES

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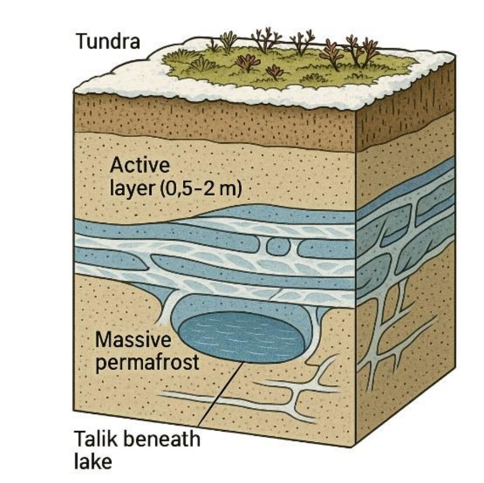
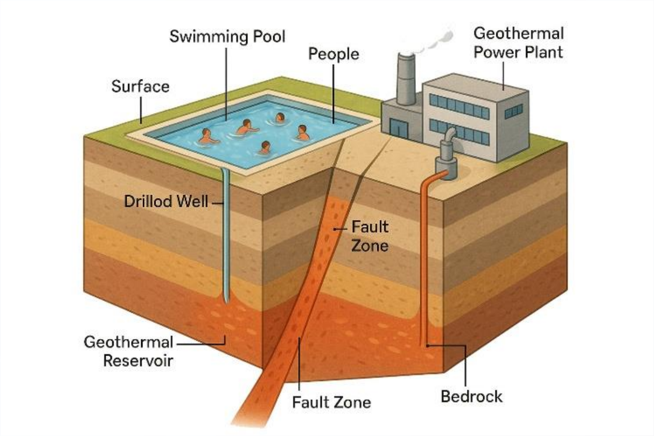
Permafrost studies



Objectives:

- Permafrost structure investigation
- Talik's mapping
- Faults/weakened zones

Geothermal systems studies



Objectives:

- Water-bearing reservoirs mapping
- Faults zones

SET OF GEOPHYSICAL METHODS

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- The **choice of the optimal set of geophysical methods** should be based on the following **main stages**:

1) Developing a **priori physical-geological model** of the proposed geothermal deposit (or permafrost section).

2) Conducting **mathematical modeling of geophysical fields** to assess the expected magnitude of anomalies from the geothermal activity (or changes in permafrost structure).

3) Analyzing the possibility of distinguishing useful **anomalies** amidst natural and anthropogenic electromagnetic noise.

4) Conducting pilot **Proof-Of-Concept (POC)** studies using the **set of methods** chosen at the previous stage.

5) Full-scale field survey planning.

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GEOPHYSICAL METHODS

GROUND-PENETRATING RADAR (GPR)

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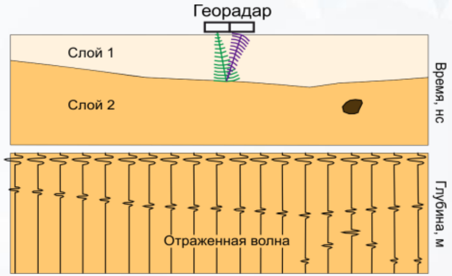
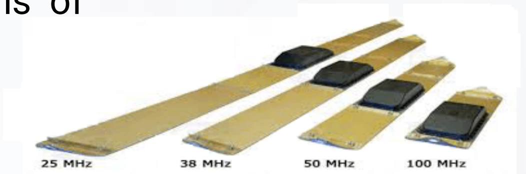


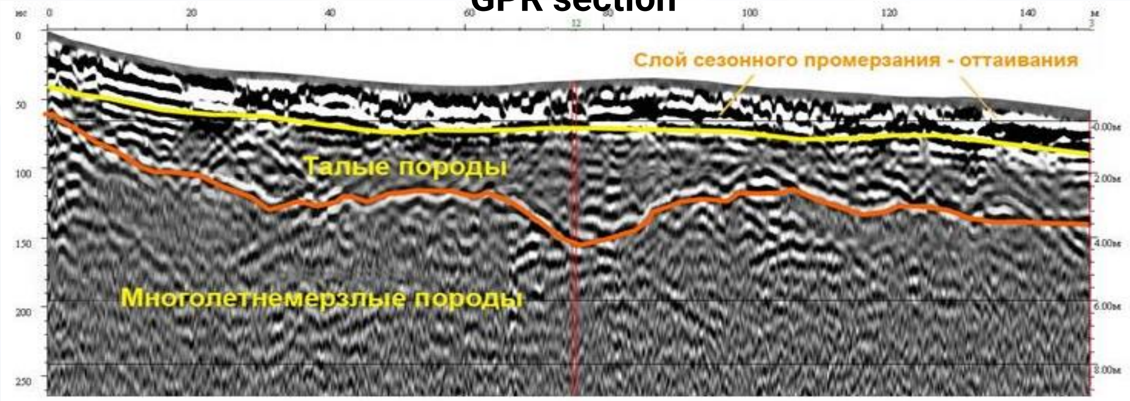
The principle of operation of **ground-penetrating radar** is based on the radio detection method: emitting electromagnetic pulses into the medium being probed and recording the signals reflected from inhomogeneities and objects within the medium.

Features of the method:

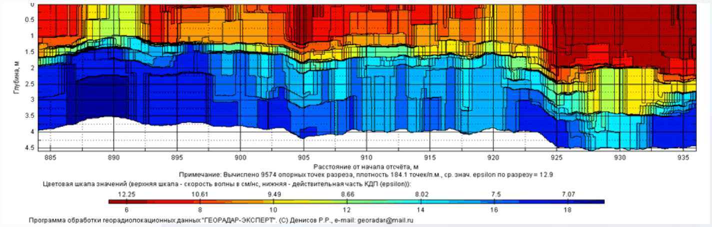
- Relatively compact equipment.
- No need for additional equipment or powerful energy sources.
- Limited depth of investigation (from the first centimeters to the first tens of meters).



GPR section



Section of dielectric permittivity



PASSIVE SEISMIC METHODS

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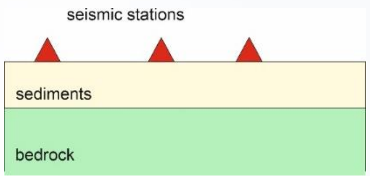
Passive seismic (PS) methods (SPAC methods, seismic interferometry, spectral ratio methods) are based on the analysis of ambient seismic noise. The resolution of the method is 0.25-0.5 λ, where λ is the wavelength. Depending on the methodology, they allow to determine the velocity structure, assess the state of the medium (permafrost, volcanoes), and identify vertical and horizontal boundaries in the medium.

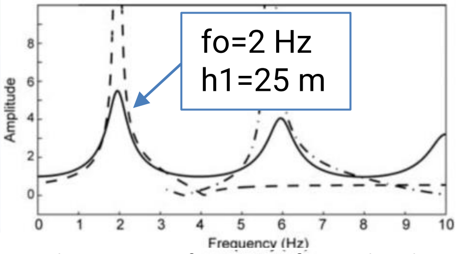
Method Features:

- Relatively cheap, non-invasive and non-destructive methods, applicable to urban environments
- Speed of obtaining results – for spectral ratio methods, the signal registration time is 30 minutes at one point
- The exploration depth ranges from a few meters to tens of kilometers.
- Allow one to confidently identify both horizontal (layering of the medium) and vertical (faults, fracture zones, supply channels) boundaries.

Scheme of the spectral ratio methods



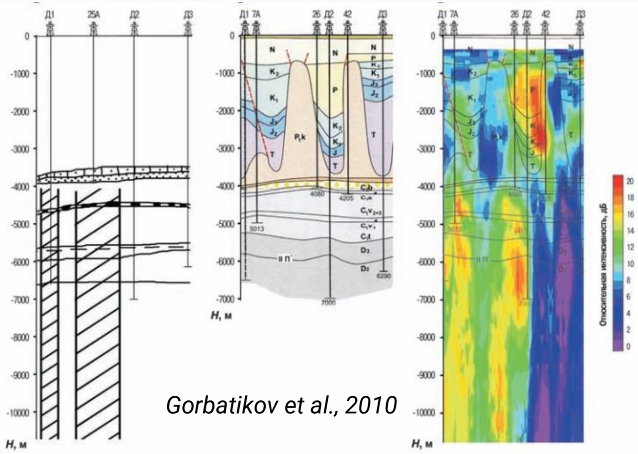
	Thickness (m)	Vp (m s^{-1})	Vs (m s^{-1})	Rho (Kg m^{-3})
Sediments	25	1350	200	1.9
Bedrock	Infinite	2000	1000	2.5



The resonant frequency **fo** is related to the S-wave velocity **Vs** and the depth of the upper boundary of the layer **h** by the relation **fo=Vs/4h**

Bonnefoy-Claudet et al., 2006

Geological and geophysical section **Geological section** **PS section**



Gorbatikov et al., 2010

DIRECT CURRENT SOUNDINGS (DC)

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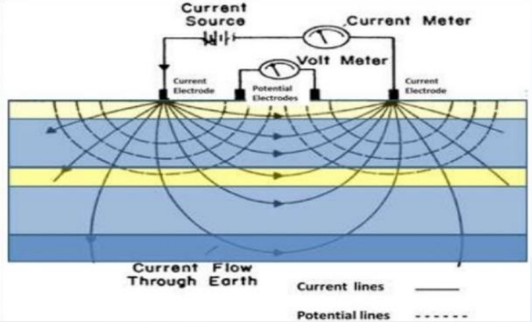
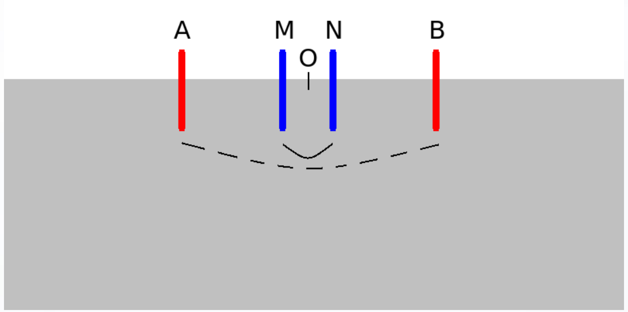
Vertical sounding is implemented by successively increasing the spacing of the transmitter line (AB) and measuring the apparent resistivity at each spacing—an effective geophysical parameter that depends on the distribution of specific electrical resistance in the section as well as the type and spacing of the template.

Method Features:

- Direct current method (DC).
- Theoretical foundations, equipment, and software are very straightforward.
- Simple fieldwork technology.
- Grounding is required. The depth of investigation is limited by the size of the template and the presence of high-resistance barriers.





* https://ru.wikipedia.org/

Penetration depth:

$$H_{eff} = \frac{AB}{6}$$

MAGNETOTELLURIC SOUNDING (MTS)

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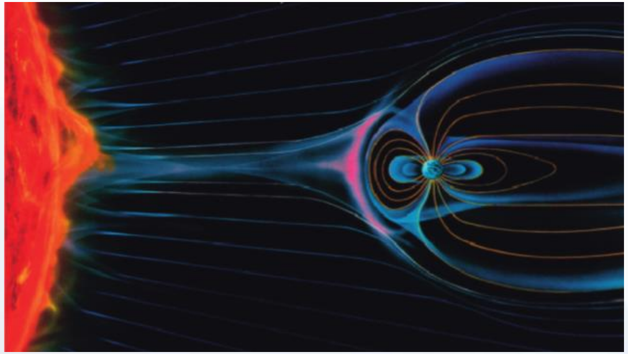
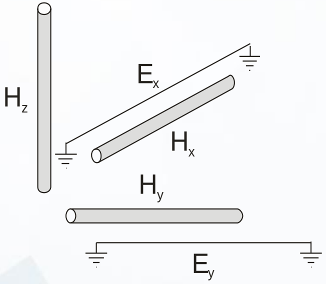
Magnetotelluric sounding (MTS) is a type of induction frequency sounding with an uncontrolled source.
The MT field is generated by electric currents in the Earth's ionosphere and magnetosphere, lightning strikes, and other sources located at a considerable distance from the observation point.

Method Features:

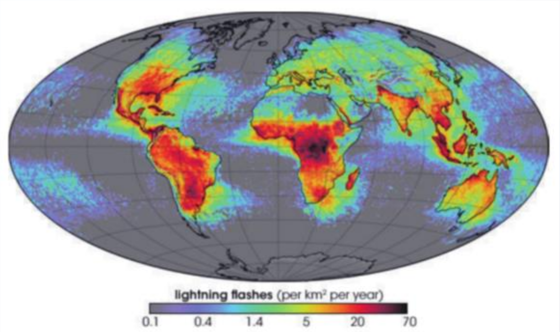
- The nearly limitless depth of investigation.
- The complexity of MTS interpretation due to the influence of galvanic heterogeneities.

Interaction of solar wind with Earth's magnetosphere





Distribution of Thunderstorm Activity (according to NASA)



TRANSIENT ELECTROMAGNETIC METHOD (TEM)

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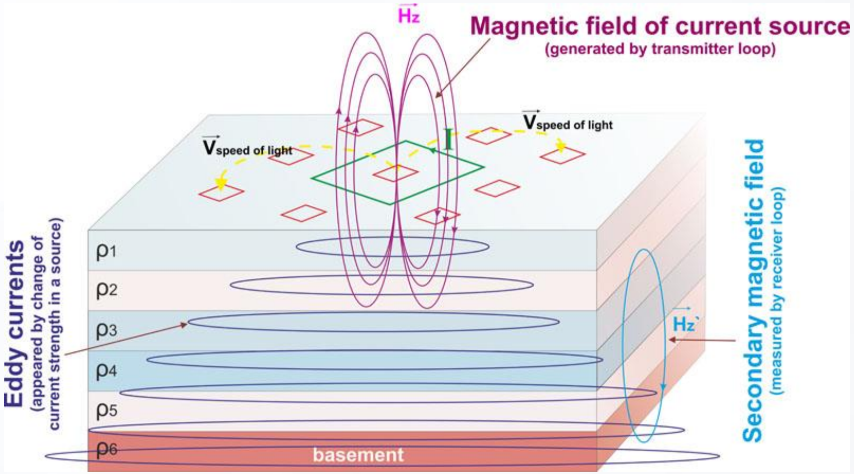
Transient electromagnetic method in the near field zone (TEM) is controlled-source induction-based sounding, square-shaped non-grounded loops are used as sources and receivers of EM fields.
The investigation depth in TEM soundings corresponds with decay time. Measured time depends on total conductivity of sedimentary cover or the average value of electric resistance of layers.

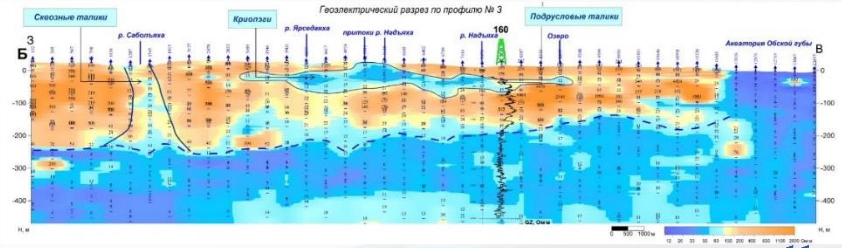
Method Features:

- No grounding is required for the probing installation.
- Fieldwork can be conducted year-round.
- The exploration depth is up to 4-5 km. It allows for the study of subsurface layers (subsalt layers).
- High sensitivity to conductors in the section, including reservoir horizons.

View of TEM current system



Resistivity section from TEM



UNMANNED AERIAL SYSTEMS

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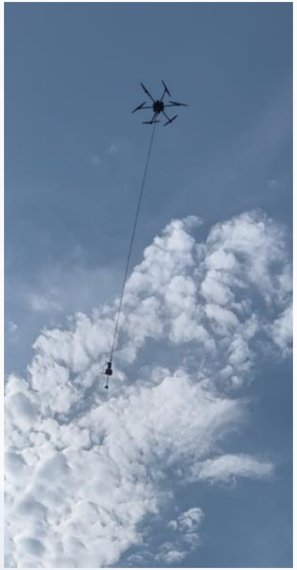
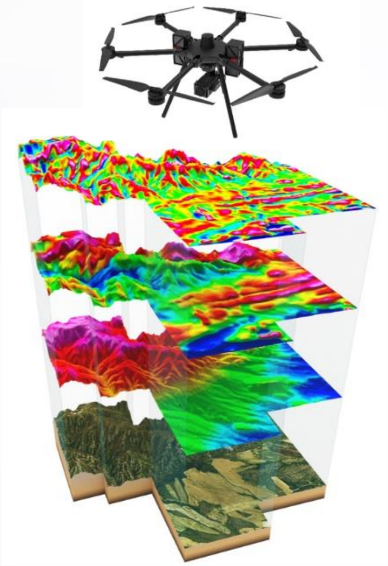
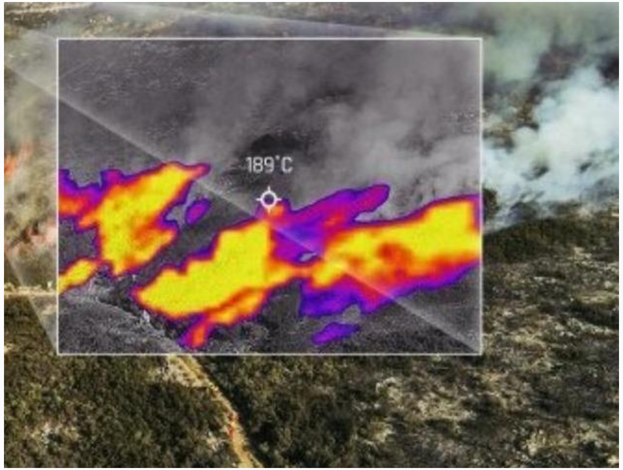
uDrone Pegasus+MaxiMag magnetometer

Modular platform for different flight time (30-60 minutes) and payload (1-7 kg). Various payload integration.

UAV temperature measurement



Application area

- Pipeline and infrastructure monitoring
- Hydrothermal deposits prospecting

GEOPHYSICAL EQUIPMENT FOR INTEGRATED STUDIES

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Hexacopter Aerodyne uDrone «Pegas»

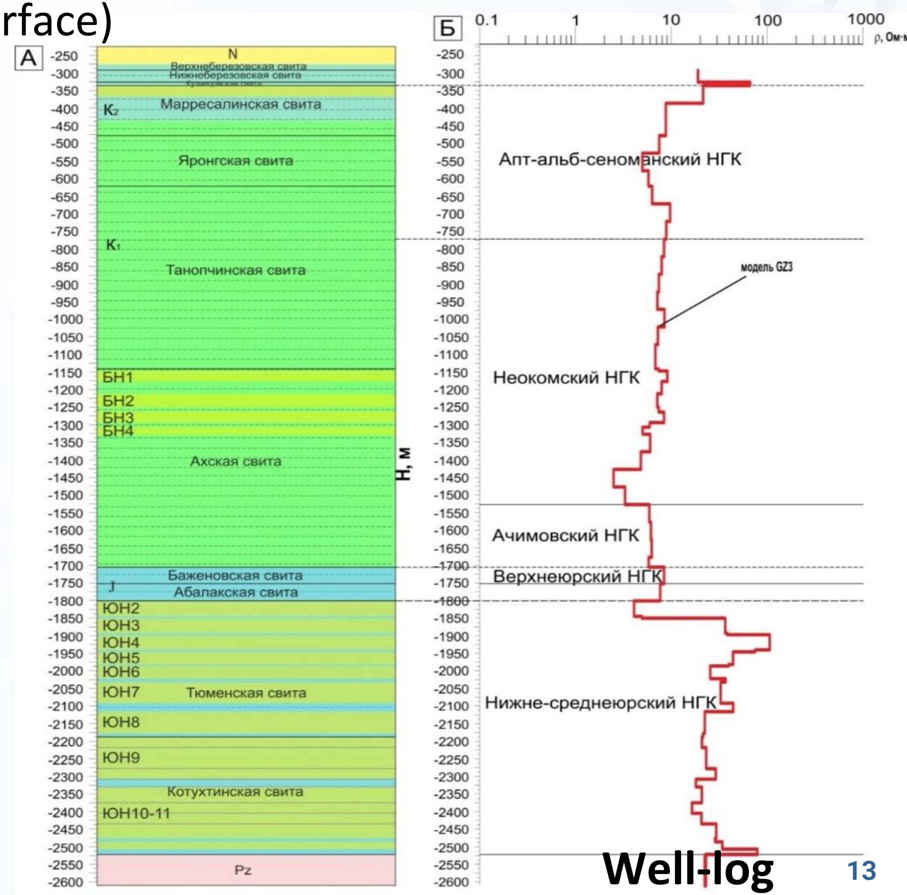
Hexacopter (surface)

TEM
ELLISS-3
SKALA-48
(10-500 m)

SKALA-48 **ELLISS-3** **FastSnap**

MTS
(500 - 20000 m)

SMT-32



Well-log

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GEOPHYSICAL RESEARCH IN THE ARCTIC

PHYSICAL-GEOLOGICAL MODEL

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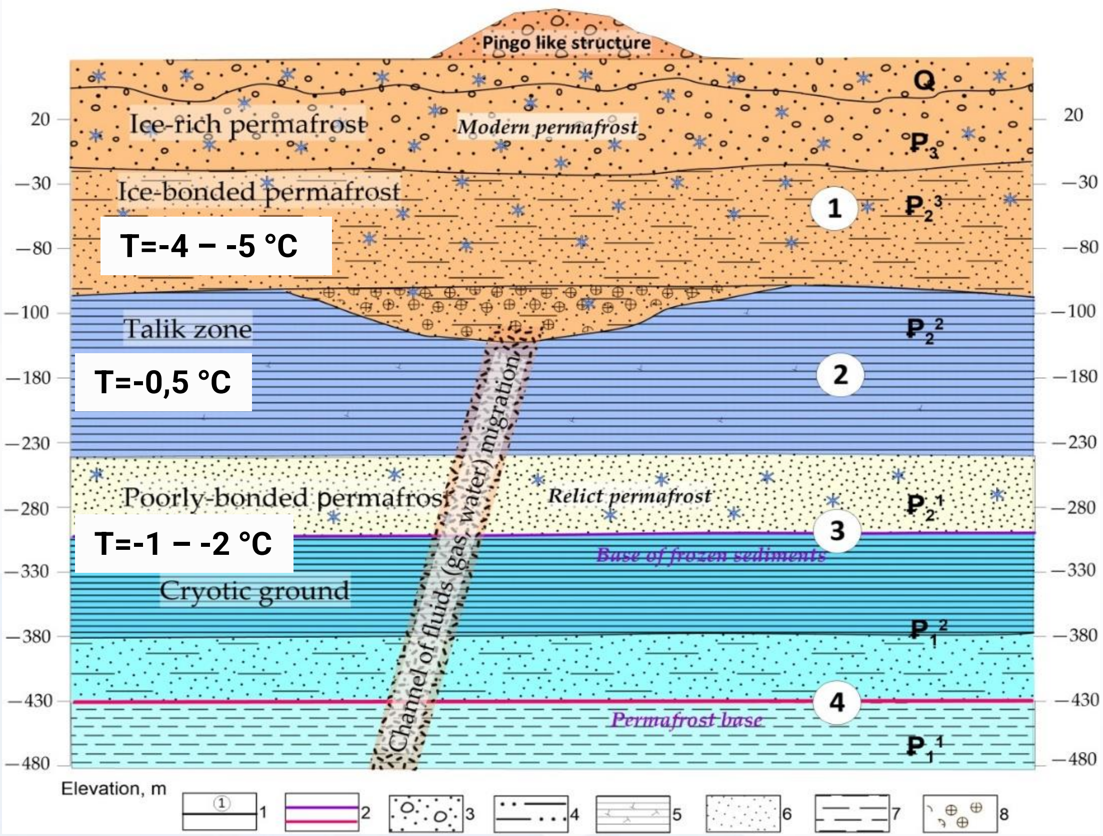

- The total thickness of the model is 480 m, the length is 5000 m.
- The number of model layers is 4.
- The scenario of the presence of a frost heave mound, as well as an increase in the thickness of permafrost rocks under it, is considered. It is assumed that the increase in thickness may be caused by the presence of gas hydrate deposits [Murzina, 2022].

PERMAFROST IMAGING IN ARCTIC WITH TEM

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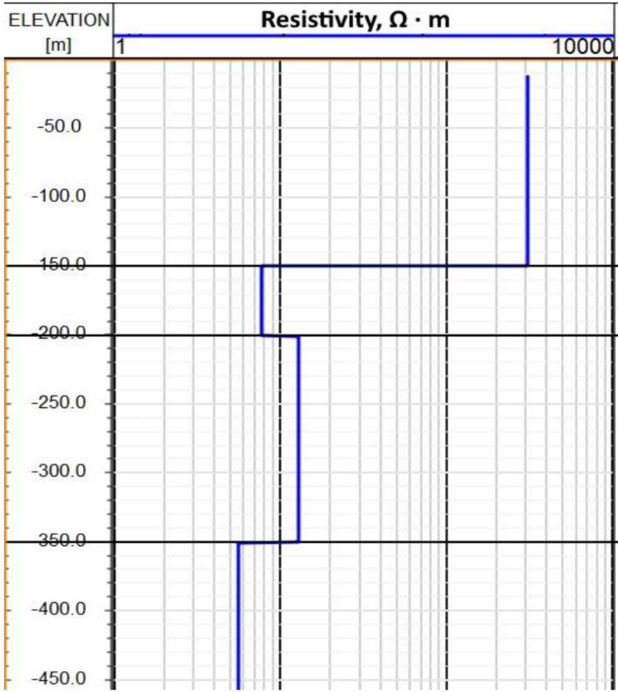
Generalized resistivity–geological model of shallow subsurface in Arctic



Resistivity range, Ω · m	Lithology
500–2000	Silt and silty clay with sand-gravel-pebble layers; possible presence of gas hydrates
10–15	Sand with clay layers and lenses
25–30	Sand with silt and clay layers; possible presence of gas hydrates and free gas
5–10	Clay with sand and silt layers

FORWARD MODELING RESULTS

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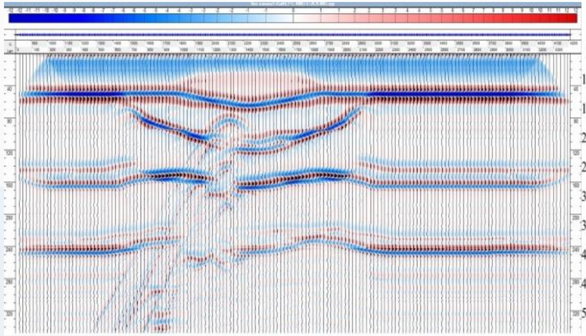
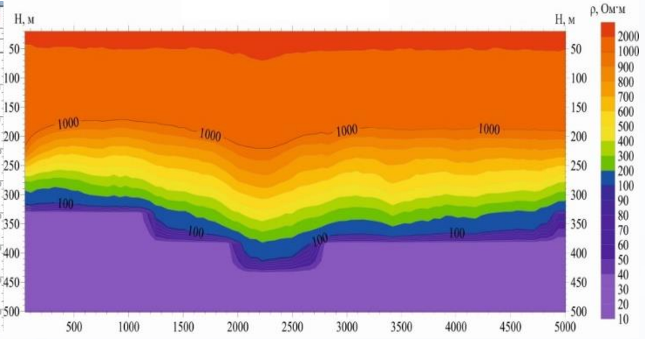
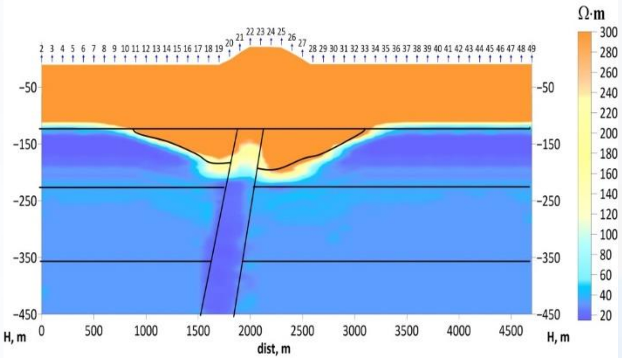
- The results of mathematical modeling have shown that all types of objects incorporated into the model (a layer of permafrost, talik, presumed gas hydrate accumulation, subvertical fluid-conducting channel) can be mapped using electromagnetic exploration with **Transient Electromagnetic Method in the near field zone (TEM).**
- **Direct current methods** and **ground-penetrating radar** have significant limitations, primarily in terms of depth of investigation.
- Seismic exploration can be used in conjunction with other geophysical methods for mapping structural features of the section, mainly subhorizontal boundaries.
- Thus, the **primary method for studying the cryolithozone up to a depth of 500 meters is TEM exploration.**



Seismic section



Apparent resistivity section form ERT



Apparent resistivity section form TEM

** Buddo, I.; Misyurkeeva, N.; Shelokhov, I.; Chuvilin, E.; Chernikh, A.; Smirnov, A. Imaging Arctic Permafrost: Modeling for Choice of Geophysical Methods. Geosciences 2022, 12, 389. https://doi.org/10.3390/geosciences12100389*

PERMAFROST IMAGING IN ARCTIC WITH TEM

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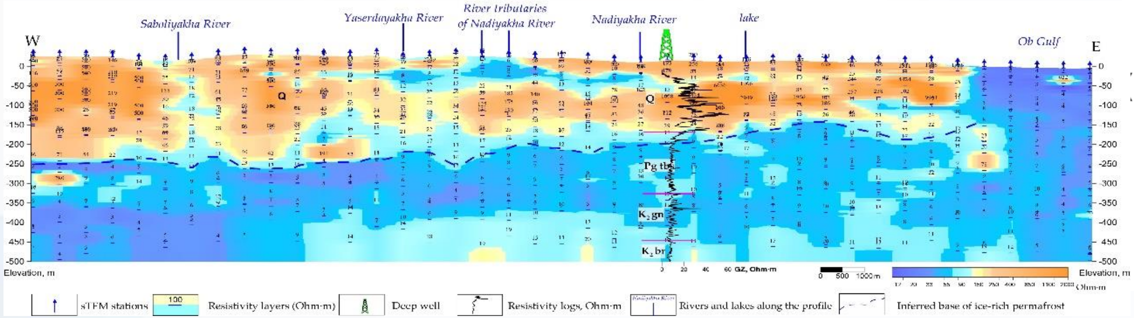
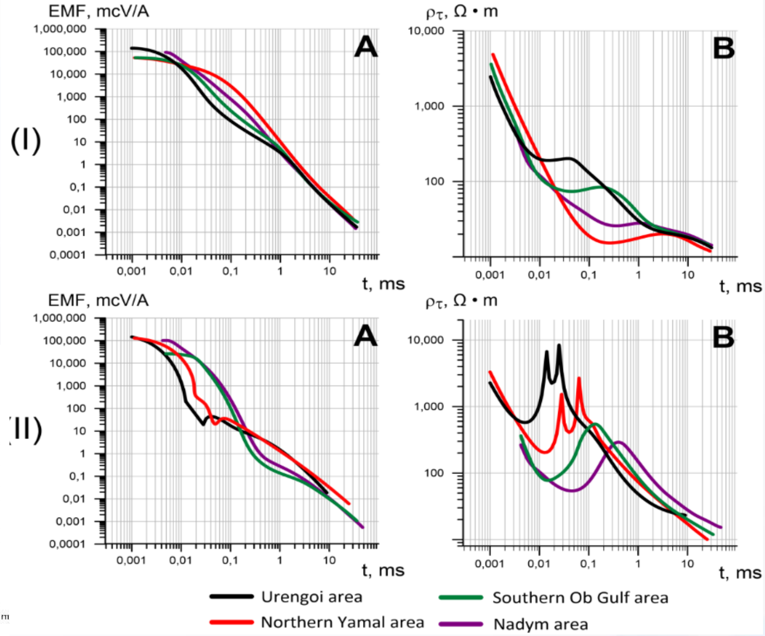
- The permafrost is continuous and 250 m thick in the western part of the area and is almost absent in the east, where the Ob Gulf is marked by low resistivity around 10 Ohm·m. An open **talik** under the Saboliyakha River is marked by a resistivity low prominent against **high-resistivity permafrost**. The rocks below the permafrost base and deeper than 400 m are highly resistive, possibly, in the presence of clathrate or free gas.

- Thus, sTEM soundings are applicable to study the permafrost structure and to **map cryopegs, taliks, pingos, and vertical faults in Arctic**.

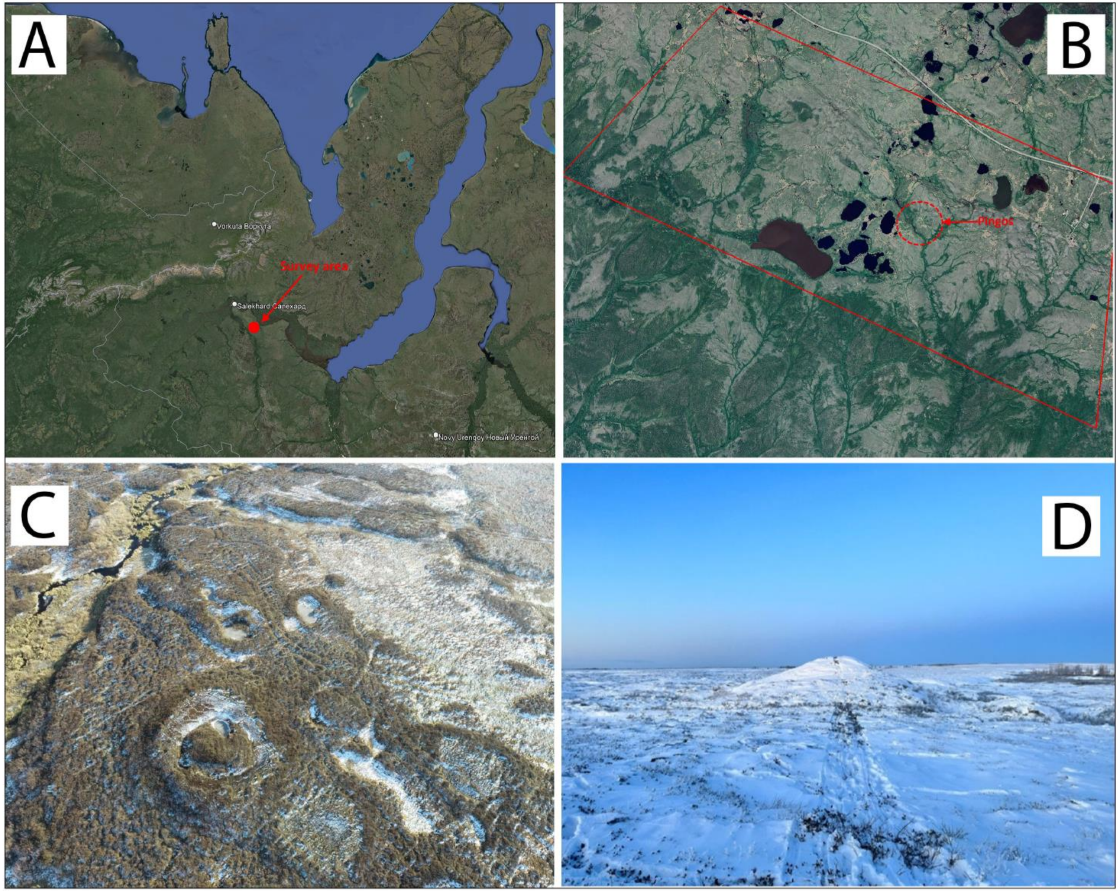




* *Buddo, I.; Sharlov, M.; Shelokhov, I.; Misyurkeeva, N.; Seminsky, I.; Selyaev, V.; Agafonov, Y. Applicability of Transient Electromagnetic Surveys to Permafrost Imaging in Arctic West Siberia. Energies 2022, 15, 1816. https://doi.org/10.3390/en15051816.*

* *Misyurkeeva, N.; Buddo, I.; Kraev, G.; Smirnov, A.; Nezhdanov, A.; Shelokhov, I.; Kurchatova, A.; Belonosov, A. Periglacial Landforms and Fluid Dynamics in the Permafrost Domain: A Case from the Taz Peninsula, West Siberia. Energies 2022, 15, 2794. https://doi.org/10.3390/en15082794.*

THE SITE FOR STUDIES



Site of planned studies.
(A): Location map in the Yamal Peninsula;
(B): satellite image of the site and the road;
(C,D): mounds detected in drone images
(C) and found in the field (D).

The site for the field studies was chosen in the Yamal Peninsula, 45 km southeast of Salekhard, the administrative center of the Yamal-Nenets Autonomous District.

Geophysical Methods:

1) GRP
2) ERT
3) TEM
4) Passive seismic

GPR AND ERT RESULTS

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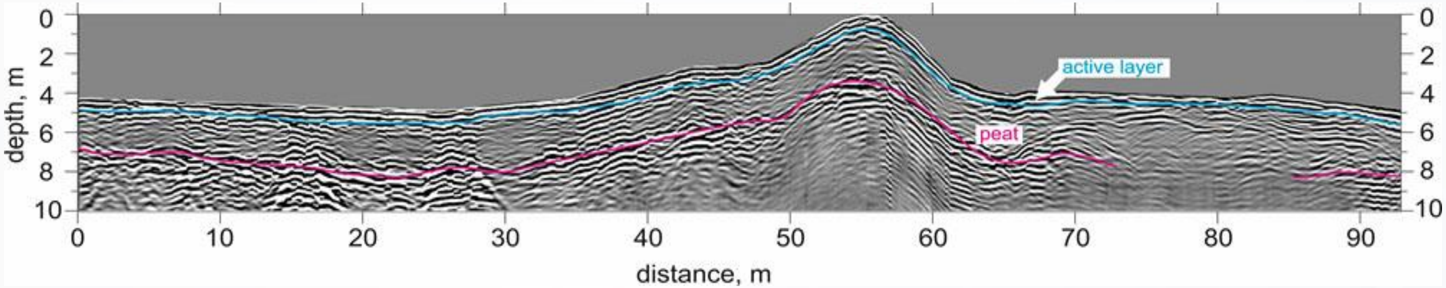
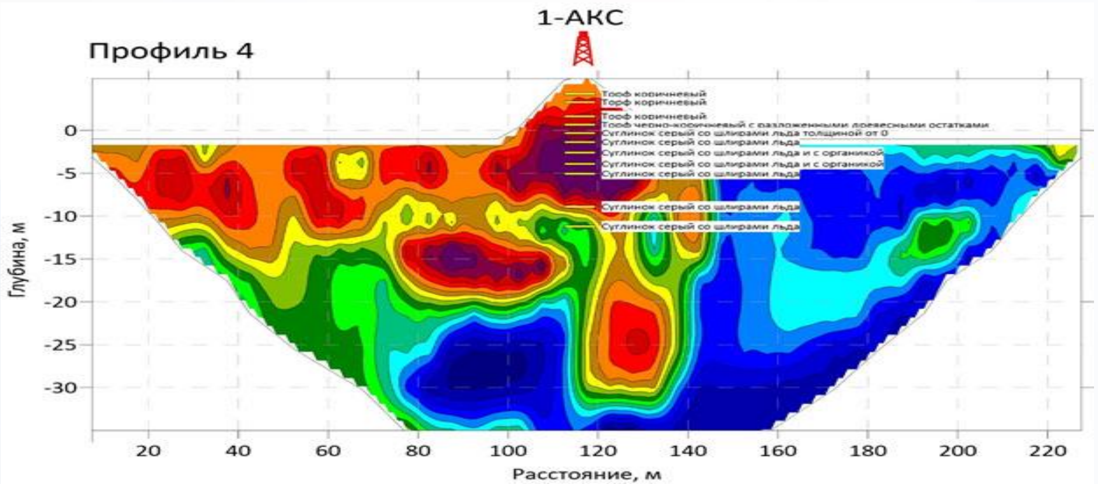
GPR section



Apparent resistivity section from ERT



- The radar image (**ground-penetrating radar method**) shows a seasonally thawed (frozen) layer about 0.51 m thick.
- In the electrical tomography (**ERT**) profiles, sections of the section can be distinguished where the structure has a layered composition up to 80 m and after 240 m, and the central part, the region of the frost heave mound, where a complex structure is observed, presumably associated with a system of water migration channels feeding the core of the frost heave.

3D GEOELECTRIC MODEL FROM ERT

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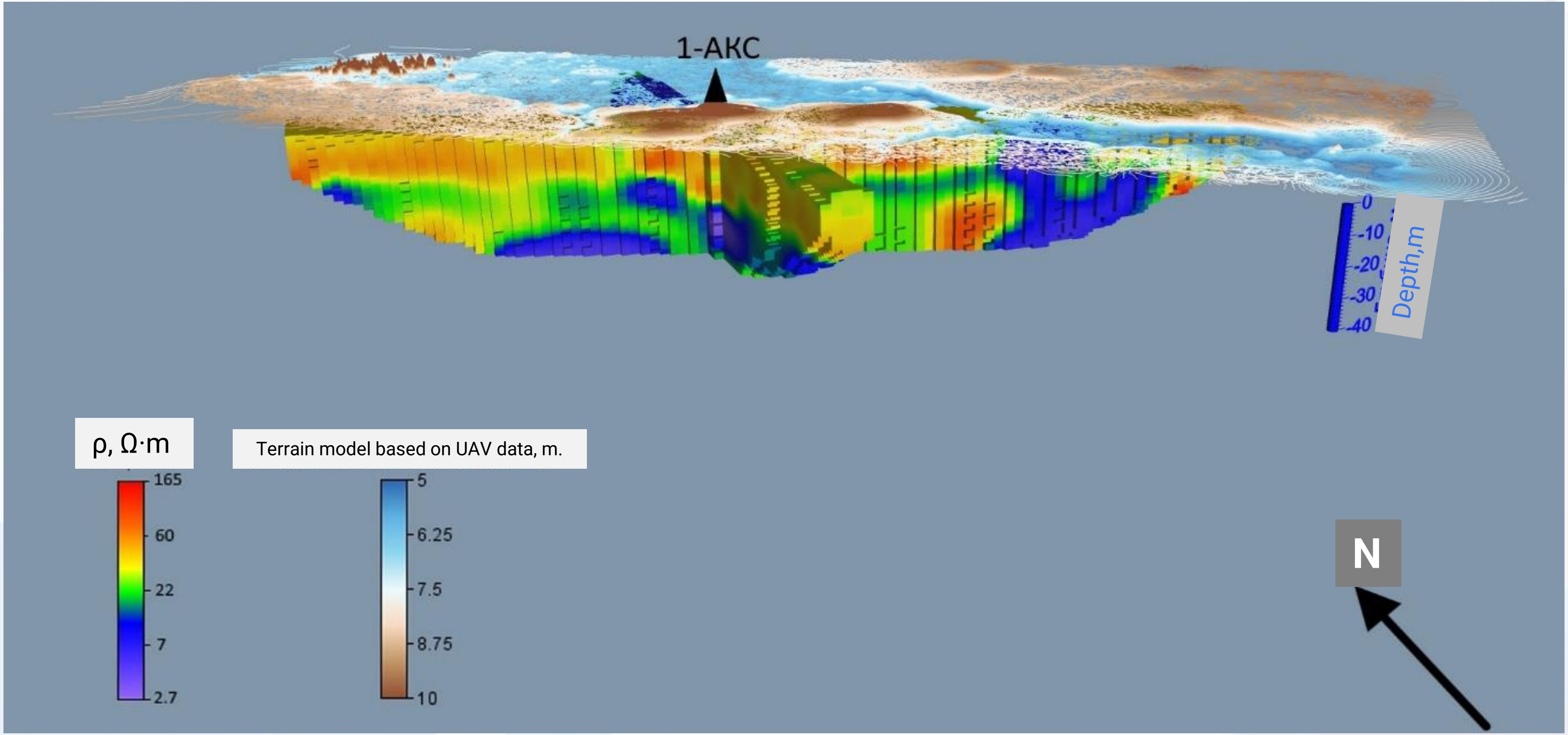

3D geoelectric model of the frost heave area to a depth of 40 m based on electrical resistivity tomography data.

TEM AND PASSIVE SEISMIC RESULTS

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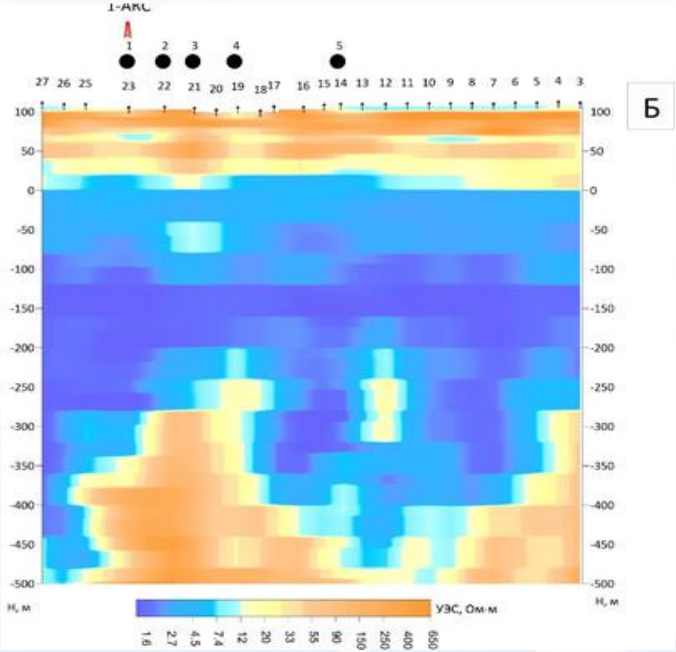
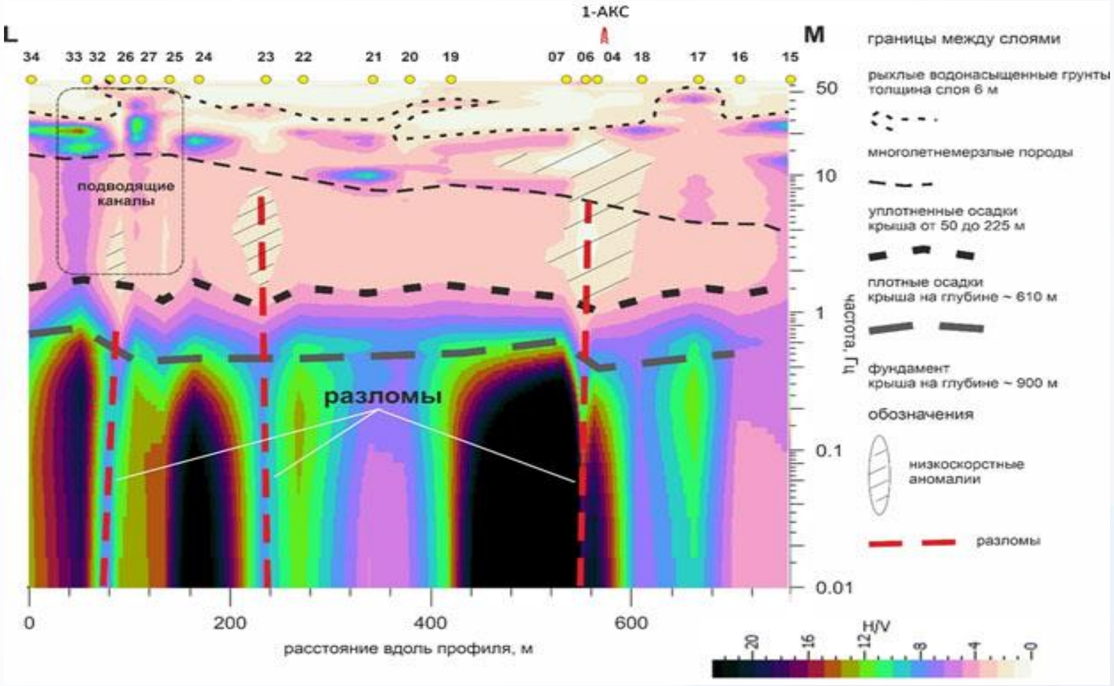
Resistivity section from TEM



Passive seismic section (H/V)



GPR AND ERT RESULTS

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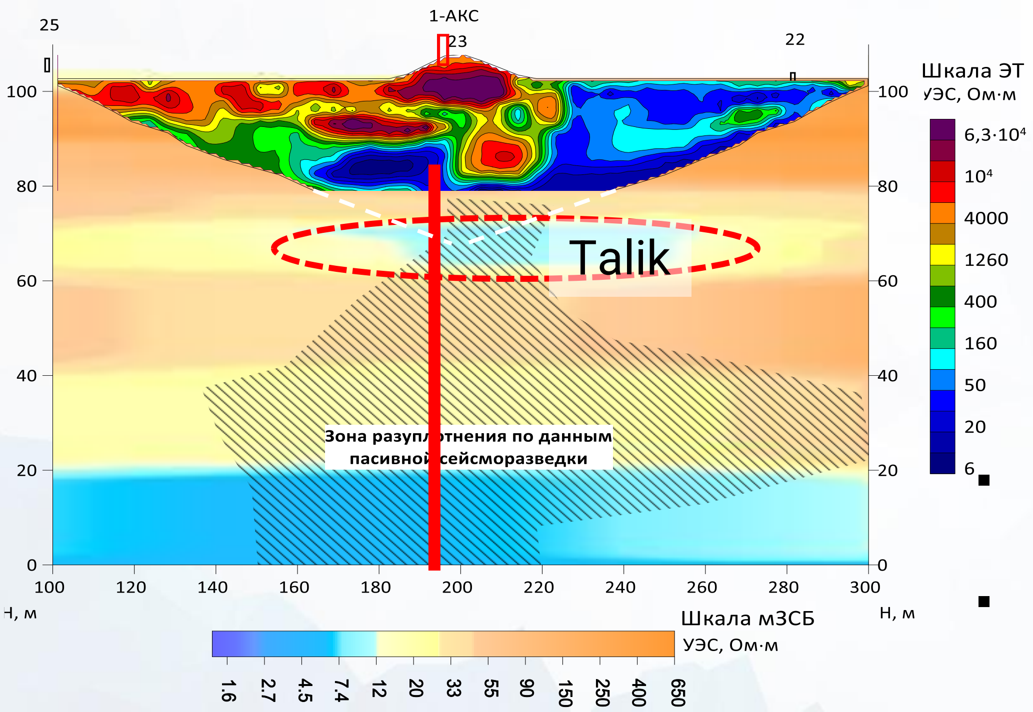
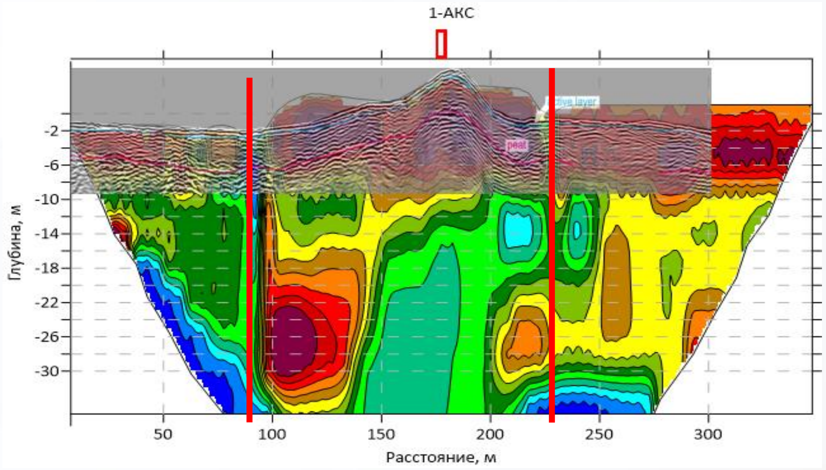
Integrated resistivity sections from ERT and TEM



Integrated sections from ERT and GPR



- In the radargram (**GPR**), a seasonally thawed layer of about 0.5 m thick can be traced.
- In the area of the supposed fluid channel identified by **ERT**, a zone of fracturing is observed by **seismic** data.

RELATED PAPERS

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1. Buddo, I.; Sharlov, M.; Shelokhov, I.; Misyurkeeva, N.; Seminsky, I.; Selyaev, V.; Agafonov, Y. **Applicability of Transient Electromagnetic Surveys to Permafrost Imaging in Arctic West Siberia.** Energies 2022, 15, 1816. https://doi.org/10.3390/en15051816.

2. Misyurkeeva, N.; Buddo, I.; Kraev, G.; Smirnov, A.; Nezhdanov, A.; Shelokhov, I.; Kurchatova, A.; Belonosov, A. **Periglacial Landforms and Fluid Dynamics in the Permafrost Domain: A Case from the Taz Peninsula, West Siberia.** Energies 2022, 15, 2794. https://doi.org/10.3390/en15082794.

3. Misyurkeeva, N.; Buddo, I.; Shelokhov, I.; Smirnov, A.; Nezhdanov, A.; Agafonov, Y. **The Structure of Permafrost in Northern West Siberia: Geophysical Evidence. Energies 2022**, 15, 2847. https://doi.org/10.3390/en15082847.

4. Buddo, I.; Misyurkeeva, N.; Shelokhov, I.; Chuvilin, E.; Chernikh, A.; Smirnov, A. **Imaging Arctic Permafrost: Modeling for Choice of Geophysical Methods. Geosciences 2022**, 12, 389. https://doi.org/10.3390/geosciences12100389

5. Buddo, I.; Misyurkeeva, N.; Shelokhov, I.; Shein, A.; Sankov, V.; Rybchenko, A.; Dobrynina, A.; Nezhdanov, A.; Parfeevets, A.; Lebedeva, M.; et al. **Modeling of Explosive Pingo-like Structures and Fluid-Dynamic Processes in the Arctic Permafrost: Workflow Based on Integrated Geophysical, Geocryological, and Analytical Data**. Remote Sens. 2024, 16, 2948. https://doi.org/10.3390/rs16162948.

6. Misyurkeeva, N.; Buddo, I.; Shelokhov, I.; Smirnov, A.; Nezhdanov, A.; Agafonov, Y. **Thickness and Structure of Permafrost in Oil and Gas Fields of the Yamal Peninsula: Evidence from Shallow Transient Electromagnetic (sTEM) Survey**. Water 2024, 16, 2633. https://doi.org/10.3390/w16182633.

GEOTHERMAL RESOURCES

GEOTHERMAL RESOURCES: INTEGRATED APPROACH

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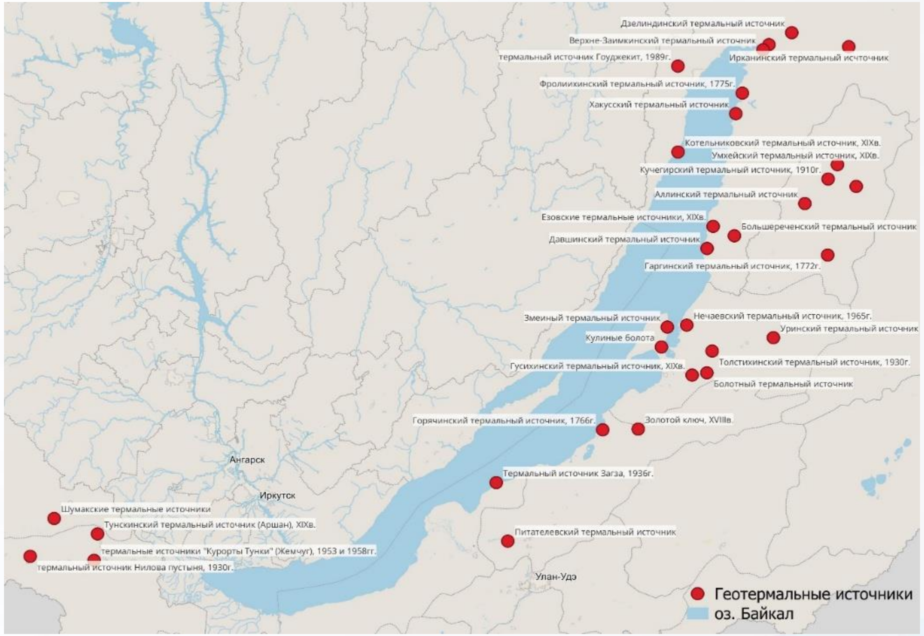
- In the last century, many **geothermal springs were discovered within the Baikal Rift Zone**, including Goryachinsk, Tolstikhinsky, Gusikhinsky, Zmeinny, Zagza, Pitatelievsky, Davshinsky, Kotelnikovsky, Florikhin, Zolotoy Klyuch, Khakussky, Korikeisky, Dzelyndinsky, Kulinye Marshes, and others.
- In recent decades, **no new springs have been discovered** because of all known springs have surface expressions, which allowed them to be discovered without the use of special tools and methods.



Location of geothermal springs in the Baikal rift zone

GEOTHERMAL RESOURCES: SITE FOR RESEARCH

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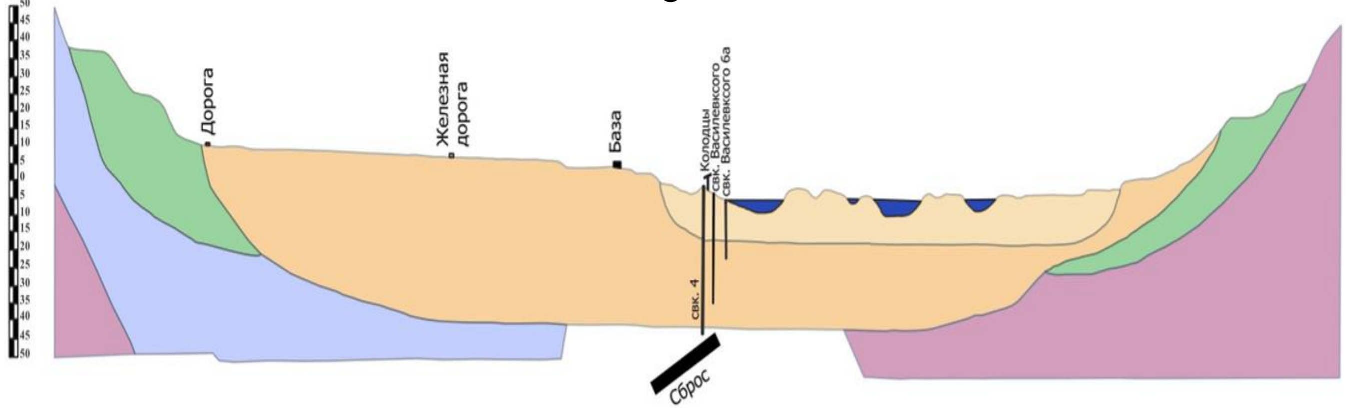
- The **reference area** chosen is located south of Lake Baikal, in the valley of the Selenga River, within which a **previously discovered thermal spring** is situated.
- The hot water emerges from a well with a depth of **310 meters** and a flow rate of 3.13 L/s. The **spring's temperature reaches 60-70°C**.

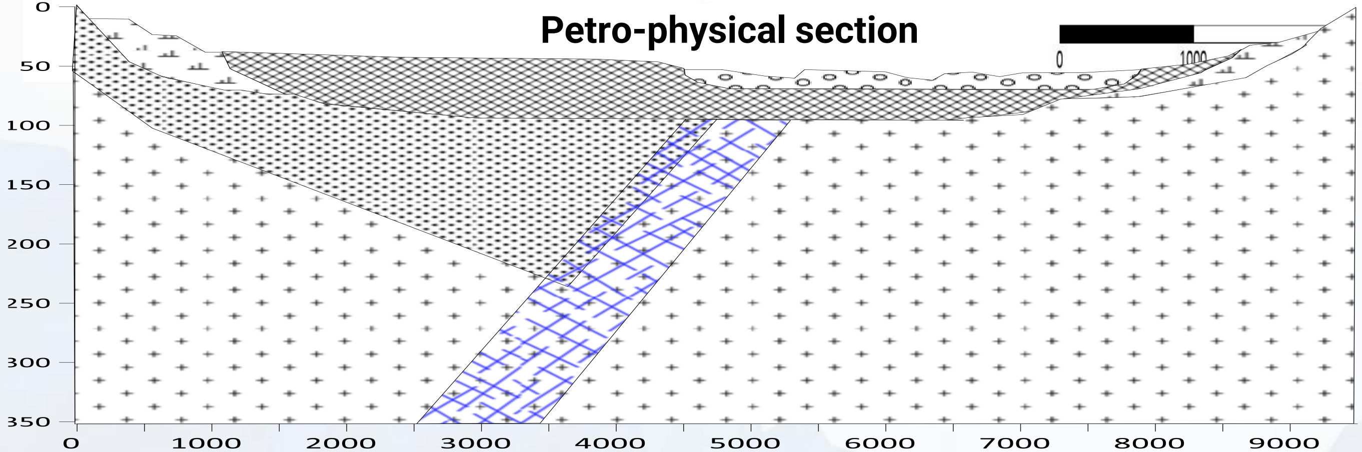
Hot swimming pool

UNIFIED PHYSICAL-GEOLOGICAL MODEL

Geological section



Petro-physical section



- ❑ Based on the vintage data of predecessors, a **geological section was constructed** through the studied hot spring.
- ❑ A **petrophysical model** of the section was also developed.

Physical properties:

- Resistivity (ρ)
- Density (σ)
- Magnetic susceptibility (æ)
- Longitudinal velocity (V_p)
- Transverse velocity (V_s)

FORWARD MODELING RESULTS

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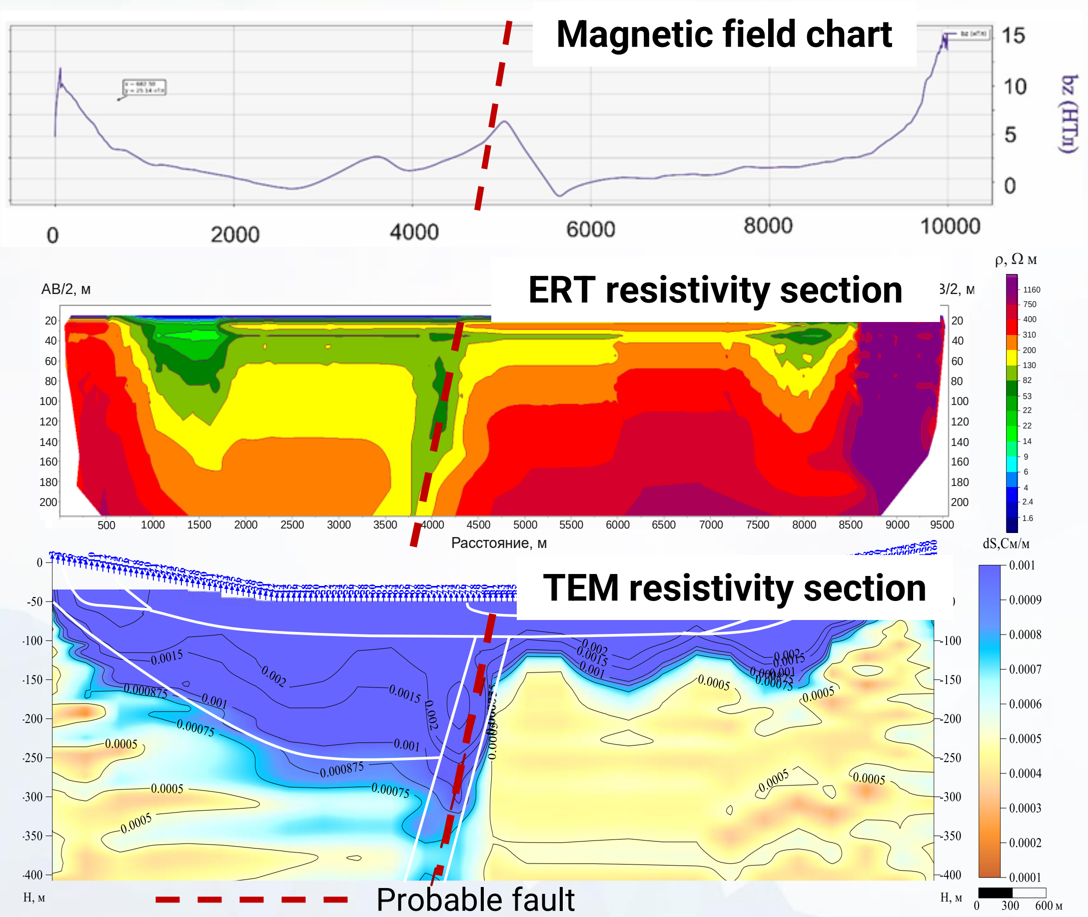

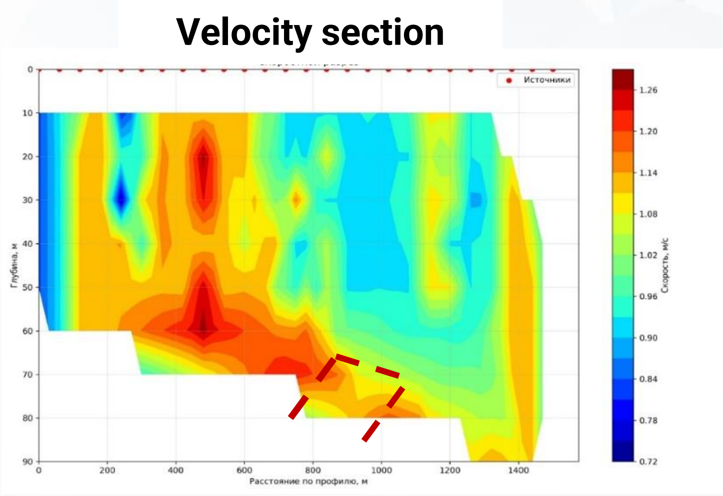

- The Forward Modeling results **confirm the feasibility of studying the geothermal system** with the selected **set of geophysical methods**.

FIELD WORKS: METHODS AND EQUIPMENT

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Aerodyne uDrone «Pegas»

Magnetic survey (MaxiMag)

Seismic (ELLISS-3)

DJI Mavic 3 (thermometry)

TEM (FastSnap)

ERT (SKALA-48)

FIELD WORKS: PRELIMINARY RESULTS

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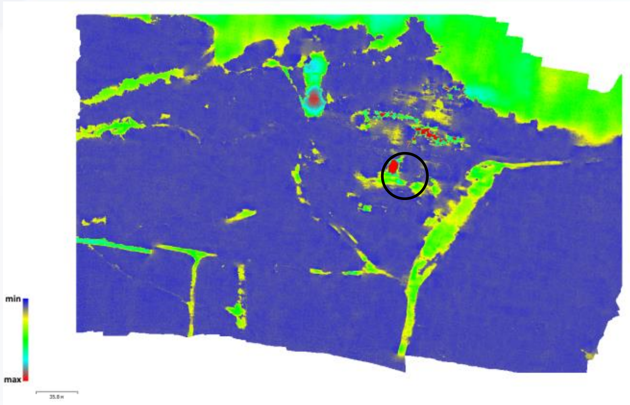
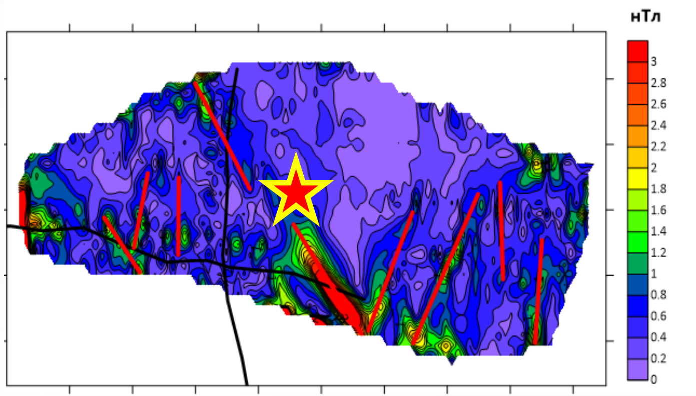
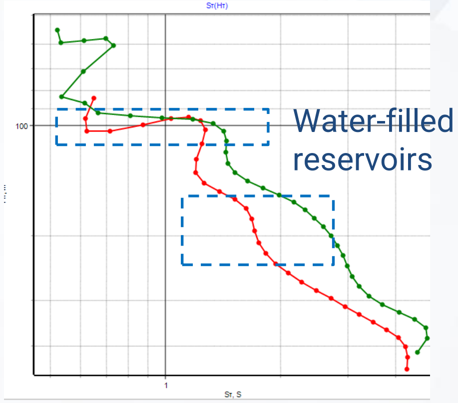


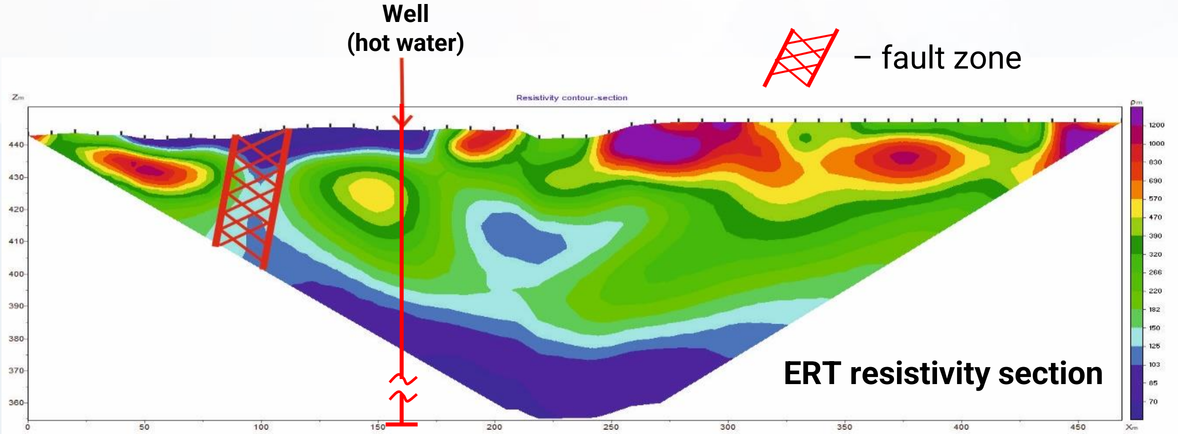
Thermal imaging orthophoto map



Gradient map of the magnetic field



TEM conductivity curves



ERT resistivity section

Within the **integrated geophysical model**, a **fluid dynamic system** is identified – a fault zone that serves as a migration channel for **thermal waters**.

SUMMARY

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- Studies have shown that employing a **combination of geophysical methods**, including ground-penetrating radar, electrical tomography, transient electromagnetic sounding in the near-field zone, and passive seismic exploration, **enables the development of geological and geophysical models of the permafrost zone to depths of 500 m or deeper, imaging the structure of permafrost, and identifying weak zones (fluid migration channels)**.
- For effective study of **geothermal systems**, it is advisable to use a **combination of investigations** including magnetic surveying and thermal imaging using drones, electrical tomography, transient electromagnetic sounding in the near-field zone, magnetotelluric sounding, and shallow seismic exploration, complemented by radon surveying.
- By **integrating geophysical methods** in this way, it's possible to **significantly enhance the reliability of the geological** models produced.

INSTITUTE OF THE EARTH'S CRUST
Siberian Branch of the Russian Academy of Sciences

Laboratory for Integrated Research of the Arctic

Welcome to cooperation!