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Refinement of geothermal zoning of the Transcarpathian Inner Depression based on Geothermal Play Classification

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This study builds upon the previous stage of geothermal zoning of Ukraine based on the classification of geothermal plays. Six principal first-order geothermal plays in Ukraine were previously identified and characterized. In the present study, one of these plays is further refined at a lower hierarchical level.

The Transcarpathian Inner Inner Depression was selected as the study area. Within its boundaries, three second-order geothermal plays were identified according to Moeck's criteria, namely the dominant heat-transfer mechanism, tectonic setting, and reservoir type. Thus, three distinct geothermal plays coexist within a single Neogene depression:

the Chop-Mukachevo Depression, which is a direct continuation of the Pannonian Depression and represents an intracratonic basin play of the Pannonian type, with predominantly conductive heat transfer and a hybrid index (CD-2a+CV3, Pannonian-type);

the Solotvyno Depression, an isolated molasse basin of the evaporite subtype with predominantly conductive heat transfer (CD-2a, Salt Basin);

the Vyhorlat-Hutyn Volcanic Ridge, as part of the Neogene volcanic complex of the Transcarpathian Inner Depression, belonging to the convective-dominated magmatic type (CV-1a, Magmatic Extrusive).

Keywords: geothermal play, geothermal zoning, conductive and convective heat-transfer mechanisms

Introduction

This study is a direct continuation of the research by Barylo & Liventseva [1] on geothermal zoning of Ukraine according to the geothermal play classification of Moeck [2]. Whereas the previous stage identified six basic first-order geothermal plays, the present study provides internal refinement of the Transcarpathian Inner Depression/ Transcarpathian Depression (TD) at lower hierarchical levels.

The thermal regime of Ukraine is largely controlled by the presence of the Ukrainian Shield and other segments of the East European Platform, which underlie most of the country.

Overall, Ukraine is characterized by a moderate thermal background, predominantly within the range of 30–50 mW/m² (from 20 mW/m² in stable platform areas to 130 mW/m² in orogenic zones).

There are no active volcanic or magmatic formations in Ukraine that are typically associated with convective-type (CV) geothermal systems. Therefore, all major geothermal systems in Ukraine belong to the conductive category, particularly types CD1 and CD2, or, in the case of lower-order structures, to hybrid types.

Structures of the Carpathian region are characterized by favorable geothermal conditions; however, the low filtration properties of the reservoirs (primarily porosity and permeability) determine their classification as CD2-type plays.

Hierarchical refinement of geothermal plays within the Transcarpathian Inner Depression

The Transcarpathian Depression is characterized by high heat-flow values and numerous manifestations of magmatism. During the final stage of its evolution, the depression underwent substantial restructuring associated with the formation of the extensive Pannonian Depression in the Neogene, accompanied by fragmentation and thinning of the Earth’s crust as well as renewed magmatic activity. Thus, formation of the

depression was accompanied by an influx of deep-seated material and a significant increase in the temperature of the crust and upper mantle in this region. Crustal thickness in the Carpathian region varies by more than a factor of two. The minimum depth is recorded in the Pannonian Depression (25–27 km), whereas the maximum is observed in the Carpathian Foredeep (55–56 km) [3].

Within Ukraine, the TD comprises two depressions that differ in structure and geological evolution – the Chop-Mukachevo and Solotvyno depressions – separated by the Vyhorlat-Hutyn Volcanic Ridge. To the northeast, the Transcarpathian deep fault separates the Transcarpathian Depression from the Folded Carpathians. To the southwest, the Peri-Pannonian deep fault separates it from the Pannonian Depression. A system of tectonic faults divides the TD into three zones elongated along the Carpathians: the northeastern zone of monoclinal subsidence, the central zone, and the southwestern zone of deep faults. The structure of the Transcarpathian Depression, including its basement, is of fold-and-thrust character. The crust in this area thins to 22–30 km and includes a sedimentary layer 1–3.5 km thick, composed of Neogene molasse deposits overlying two levels of folded basement formed by metamorphosed Mesozoic–Paleozoic deposits.

The sedimentary succession is highly heterogeneous and has a block structure. It contains numerous tectonic disturbances in the form of strike-slip faults, detachments, and thrusts, as well as numerous paleovolcanoes, batholiths, and effusive volcanic ridges, including the Vyhorlat-Hutyn Ridge. The thickness of Neogene sedimentary deposits varies within a wide range. In the northeastern part of the depression, it does not exceed 500–700 m and locally pinches out completely. Neogene deposits are often overlain by effusive rocks of the Vyhorlat-Hutyn Volcanic Ridge. Southwestward, the Neogene succession thickens to 2,000 m and more (up to 3,500 m). Brachyanticlines and salt-diapir folds are widely developed here and are particularly characteristic of the Solotvyno Depression.

The TD is the most strongly heated part of Ukraine and is characterized by highly complex geothermal conditions. High temperatures are typical throughout the TD: 40–45°C at a depth of 500 m, 70–75°C at 1,000 m, and 100–105°C at 2,000 m. At a depth of 1,000 m in the Inner Zone of the Carpathian Foredeep, temperatures are approximately three times lower, at 20–25°C. The geothermal parameters are distributed as follows (Table 1):

Table 1. Geothermal characteristics of the Chop-Mukachevo and Solotvyno depressions (after Kutas [4])

Parameter	Solotvyno Depression	Chop-Mukachevo Depression
1000 m (Temperature, °C)	45–60	55–70
2000 m (Temperature, °C)	75–100	90–115
3000 m (Temperature, °C)	100–120	130–155
Geothermal gradient	3.5–4.0°C/100 m	4.0–5.5°C/100 m
Heat-flow density	70–100 mW/m²	85–120 mW/m²

Particularly high temperatures within the TD are observed in the central part of the Chop-Mukachevo Depression.

The uneven heat distribution is controlled by the structural evolution and geological architecture of the region. Depending on tectonic conditions, geothermal gradients, heat-flow values, and the pattern of temperature increase with depth vary considerably [3].

The TD is characterized by high heat-flow values of 70–130 mW/m², while geothermal gradients vary from 5.0 to 8.0°C/100 m. The elevated thermal background is associated with asthenospheric upwelling and vertical flows of heat and mass originating in the deep mantle. Thick clay-rich deposits act as insulating layers that retain internal

heat. Deep faults serve as conduits for warm fluids, producing positive thermal anomalies. Conversely, salt diapirs act as pathways for heat dissipation, contributing to the formation of negative anomalies.

Hydrogeologically, the TD represents a complex groundwater system. Aquifers composed of sandstones, conglomerates, and tuffs are discontinuous and separated by thick clay layers. The zone of active groundwater exchange is generally restricted to depths of 100–600 m. The presence of rock salt and gypsum results in increased groundwater mineralization, while the overall water content of these aquifers is low.

The Folded Carpathians serve as the regional recharge area for numerous aquifers within the sedimentary succession of the TD: along faults and fractures in the weathering crust of the mountain structure, cold meteoric water enters the aquifers and descends to considerable depths, reaching the basement rocks, where it is heated mainly by conductive heat flow.

The filtration properties of the TD aquifer system depend largely on the degree of fracturing and karstification of the host rocks, which limits active circulation of thermal fluids.

This study proposes a novel approach to indexing the geothermal plays of the Transcarpathian Depression, refining and supplementing existing concepts.

According to the geothermal play classification, the three structures of the Transcarpathian Inner Depression correspond to the following subtypes: the Chop-Mukachevo Depression, CD-2a+CV3; the Solotvyno Depression, CD-2a; and the Vyhorlat-Hutyn Volcanic Ridge, CV-1a (Table 2).

Table 2. Geothermal play subtypes in Transcarpathian geological conditions

Structure	Geodynamic setting		Heat source	Heat storage and transfer conditions
Chop-Mukachevo Depression	CD-2a + CV3	Extensional setting	The mantle, which is the principal heat source (volcanism is absent), is uplifted as a result of crustal extension and thinning. High thermal gradients promote heating of meteoric water circulating through deep faults.	The sedimentary cover contains thick clay-rich successions that promote heat accumulation and retention.
Solotvyno Depression	CD-2a	Orogenic belt	A sedimentary reservoir located within a foredeep or an orogenic mountain belt. Heat source / reservoir capacity properties: sedimentary aquifers with high porosity and either high or low permeability.	The dominant heat-transfer mechanism is controlled by faults/fractures or lithofacies/biofacies characteristics. Salt diapirs and deep faults act as heat-transfer conduits.
Vyhorlat-Hutyn Volcanic Ridge	CV-1a	Extrusive magmatism	A shallow, intense heat source in the form of a young magma chamber, with an upflow zone and an outflow zone controlled by volcanic topography.	Magmatic-hydrothermal circulation

Conclusions

1. The Chop-Mukachevo Depression forms part of, and is a continuation of, the large Pannonian megabasin, characterized by pronounced Neogene crustal extension. The

principal controlling factor is crustal thinning and the associated anomalously high geothermal gradient and heat flow.

Heat-transfer mechanism: predominantly convective (circulation of thermal waters along faults and permeable horizons).

Geothermal play subtype: despite the unquestionably decisive role of convective heat transfer during the initial stages of structural development, the present-day thermal regime of the depression is formed to a greater extent by conductive components, i.e., by temperature gradients from more strongly heated rock layers toward less heated ones. Convective factors predominate only in areas of active tectonic faults and are local in character. The play subtype is hybrid CD-2a + CV3.

2. The Solotvyno Depression constitutes the eastern part of the Transcarpathian Inner Depression, a Neogene structure superimposed on the folded flysch basement of the Carpathian fold-and-thrust belt. The principal heat source here is normal geobaric heating of large rock masses associated with burial.

Heat-transfer mechanism: conduction dominates, while deeply buried sedimentary aquifers act as reservoirs.

Geothermal play subtype: CD-2a: Orogenic Belt (conductive-dominated play of orogenic belts / foreland and intermontane depressions).

3. The Vyhorlat-Hutyn Volcanic Ridge is a structurally complex geological body represented by interlayered lavas and pyroclastic rocks, together with packages of sedimentary and tuffaceous-sedimentary rocks, formed as a result of relatively young (Late Miocene–Pliocene) volcanic activity. The principal heat source is represented by shallow magmatic bodies or residual heat from relatively young intrusions beneath the volcanic edifices.

Heat-transfer mechanism: magmatic-hydrothermal circulation of fluids within fractured effusive and pyroclastic rocks.

Geothermal play subtype: Magmatic Play Types – Extrusive CV-1a.

The results obtained complement and refine the conclusions presented by Virshylo et al. [5].

This refinement became possible through the application of additional ranking criteria, in particular by integrating the geothermal play classification of Moeck [1], which is based on detailed analysis of geological controls and groundwater dynamics.

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