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Editorial

Geothermal Energy and Structural Geology

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Structural geology has a long tradition of applications and developments in the field of energy resources. From the balanced and restored cross-sections first used in hydrocarbon exploration, to fracture analysis aimed at reservoir characterization and the modelling of fluid flow, major advances and new fundamental techniques in structural geology developed over the decades are tightly coupled with the energy industry. Within the framework of the current energy transition, the focus has moved towards renewable energies such as geothermal energy. Geothermal plays are strongly influenced by both the regional tectonic regime and local structural setting. The former involves fundamental parameters such as the heat flow, hydrogeological regimes and fluid chemistry, which are closely related to the geodynamic setting (convergent or divergent plate boundaries, intracontinental rifts, stable cratonic regions, etc.). At a more local scale, a complex combination of various environmental factors determines the suitability of an area for producing geothermal energy. A geothermal resource is, in fact, part of a natural system in which geological characteristics including the rock type, diagenesis, mechanical behaviour of the rocks and active stress field, in addition to the parameters mentioned above, influence key features such as the occurrence and spatial distribution of domains characterised by high porosity and high permeability (and related fluid circulation), vertical and lateral temperature gradients, and reservoir behaviour during injection and production, which, in turn, are crucial for power plant efficiency. Particularly in rocks characterized by low primary porosity and permeability, the geothermal system permeability is mainly determined by the fracture aperture and connectivity. As fault zones and fracture networks represent the main pathways for fluids, obtaining quantitative fracture attributes and carrying out discrete fracture network (DFN) modelling are fundamental for performing fluid flow simulations and, where necessary, proposing reservoir stimulations (e.g., hydraulic fracturing). In summary, a multiscale, comprehensive picture of the geological setting and structural architecture of a potential geothermal site is fundamental for any site-specific, appropriate field development. Therefore, a prior geothermal suitability assessment is fundamental. This is commonly based on a series of exploration techniques often involving invasive inspections (e.g., well drilling), high costs and the need for legal permissions. However, the integrated analysis of available heat-flow patterns, aquifers' characteristics, the basin geometry and the population may be effectively used to assess the geothermal potential of large regional basins, as conducted by Majorowicz and Grasby [1] for western Canada and by Majorowicz [2] for Poland. The geothermal energy potential of the Western Canada Sedimentary Basin may support communities with populations >3000 people. Direct heat use is feasible in the western and southern parts of the basin, while the potential for electrical power production is limited to the deepest parts of the basin (where aquifers at temperatures >120 °C and fluid production rates >80 kg/s occur). In Poland, the comparison of existing heat-flow maps with rock and fluid thermal conductivity measured from cores, integrated with modelled mantle heat flow and the lithosphere–asthenosphere boundary depth, suggest possible overestimates of deep thermal conditions for enhanced geothermal energy prospects [2]. Within this context, a reference model of the thermal structure at the crustal scale may also help to save time and money during subsequent, local geothermal assessments. This approach was

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applied by Dragoni and Santini [3] for a classic geothermal region, the Chilean-Peruvian Andes, and by Santini et al. [4] for northern Albania. The analytical methodology used in these studies considered heat-flow density data coupled with geological constrains to obtain the surface heat flow, geotherms and isotherms in two dimensions. An important amount of frictional heat is produced by earthquake faulting, in both the Albanian [3] and Andean [4] case studies, particularly for megathrust events such as the Maule earthquake that occurred along the Peru–Chile Trench in 2010 (the calculated heat production in this instance was ~2 × 1017 J [3]). This approach was further expanded in three dimensions by Santini et al. [5] in their study of the geothermal setting of the Marche region (central Italy). There, an analytical methodology was implemented to produce crustal thermal models that consider geologically derived constraints and the temperature variation due to the re-equilibrated conductive state associated with faulting, as well as heat-flow density data and frictional heating. The applied analytical procedure allows the calculation of the geotherms for a network of pseudo-wells traced along a series of geological sections. The interpolation of the computed geotherms allows obtaining relevant isotherms. The results indicate that the Moho depth and geometry exert major influences on the thermal structure of the study area.

The fundamental activity of geological mapping as a pre-requisite for any successful geothermal exploration was highlighted by Filipovich et al. [6] in their work on the Tocomar Basin, Puna Plateau, NW Argentina. The tectonic evolution of this extensional basin, characterised by long-lasting volcanic activity, is unravelled by the integration of stratigraphic and structural information with new radiometric ages of travertines obtained within the framework of map preparation.

The crucial role of fracture networks in controlling permeability patterns in geothermal reservoirs is addressed in the contributions by Bossennec et al. [7] and Liotta et al. [8]. The former paper focuses on fractured basement rocks of the northern Upper Rhine Graben, where such rock units are targeted for multiple energy applications (ranging from heat storage to geothermal energy production). The authors used LiDAR and outcrop scan lines to obtain fault and fracture network characteristics that formed input parameters for the calculation of permeability tensors for the studied crystalline rocks. Similarly, input parameters for geothermal system modelling were obtained by Liotta et al. [8] by means of a comparison between the outcropping reservoir analogue of an active geothermal systems and a fossil one. In this instance, outcrop fracture analyses using scan lines and scan areas were integrated with fluid inclusion data providing information on the temperature, density, and viscosity of the paleo-fluids. The obtained hydraulic conductivity was used in conjunction with information on the present fluid flow in the active geothermal system to improve exploration strategy and de-risking practices. These case studies emphasize how the stress regime, major fault zones (active or inactive), and fracture networks are all critical elements in rock permeability and fluid flow (which may be increased by stimulation involving the opening of pre-existing fractures and/or the development of new hydraulic fractures). These concepts are effectively emphasised by Gudmunsson [9] who points out how geothermal fluid flow occurs mainly along fault zones and dykes. In the former, transport of geothermal fluids occurs mainly along the damage zone, but also in the core following fault slip. The process is controlled by the cubic law, in which the volumetric flow rate depends on the cube of fracture aperture. During non-slip stages, fluid flow along the fault core is mainly controlled by Darcy's law. Repeated earthquake activity allows maintaining the permeability of fault zones in active natural geothermal fields where secondary mineralisation tends to reduce fault-zone permeability. Fluid transport along dykes, which commonly occurs along fractures located at their margins, is also controlled by the cubic law. Dykes and inclined subvolcanic sheets constitute 80% to 100% of the rock volume within the top 1.5–2 km of Iceland's crust. There, the activity of high-temperature geothermal fields was enhanced by Holocene feeder-dikes, as dykes and inclined sheets also act as heat sources for geothermal fields.

The papers included in this Special Issue effectively address the wide range of diverse geological methodologies and techniques that may applied in the study of potential geothermal plays. The contributions range from exploration case studies integrating geological mapping and fluid–rock interaction/thermal/hydrological/mechanical constraints, to fracture analysis performed on outcropping reservoir analogues, to the study of exhumed (fossil) geothermal systems, and to the modelling of the tectonothermal settings of sedimentary basins and of entire crustal volumes. Increasing the space for renewable energy, and for geothermal energy, in particular, means avoiding the emission of thousands of tons of CO_2 into the atmosphere and, therefore, reducing the impact of greenhouse gases on the climate. Future developments will involve the increasingly important use of advanced computational methods to effectively handle multiple datasets and improve de-risking strategies. Structural geologists can address the challenge of the exploitation of both offshore and supercritical geothermal resources, the management of seismicity risks, and the development of engineered geothermal systems that could greatly expand the global production of geothermal energy.

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