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HotLime – Mapping and Assessment of Geothermal Plays in Deep Carbonate Rocks

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ABSTRACT

Hydrothermal systems in deep carbonate bedrock are among the most promising low-enthalpy geothermal plays. Across Europe, apart from a few areas where viability of hydrothermal heat and power generation has been proved, most deep carbonate bedrock has received relatively little attention, because such rocks are perceived as 'tight'. Exploration and development of the deep subsurface is an acknowledged high-risk investment, particularly in low-enthalpy systems, where tapping suitable temperatures for geothermal energy commonly requires drilling to depths of more than 3 km. In order to de-risk this geothermal exploration it is crucial to improve our understanding of generic geological conditions that determine the distribution and technical recoverability of their potential resources, specifically the possible groundwater yield controlled by fracture conduits and karstification.

HotLime is one of 15 projects under the GeoERA umbrella that has received funding from the European Union's Horizon 2020 research and innovation programme. From July 2018 to June 2021 mapping, characterization and comparison of geological situations, the structural inventory of hydrothermal plays in deep carbonate rocks and their petro- and hydro-physical characteristics is carried out in 11 different target areas across Europe in order to identify the generic structural controls of geothermal plays in carbonates. The consistent assessment and the sharing of knowledge among the 15 European partners are geared towards uniformly applicable best practice workflows for estimation, comparison and prospect ranking of these hydrothermal resources. The principal outcomes of HotLime presently prepared will be spatial representations of the areas under investigation (3D models, 2D map series) on the principal geological features and properties relevant for geothermal exploration and production, supplemented by glossaries and a knowledge base including methods and tools which can be transferred and adapted to other carbonate rock suites.

1. INTRODUCTION

1.1 Background and Inducement

Geothermal energy has a significant potential to contribute to the aims of the EU renewable energy directive (EU 2009) that establishes an overall policy for the production and promotion of energy from renewable sources. Its low carbon emissions and dispatchable supply make geothermal energy a strategic technology for the EU, geared towards achieving a renewable energy share for the EU of at least 32% by 2030 (EU 2018). However, despite its potential to provide clean, continuous base load power, geothermal energy has remained underdeveloped compared to other renewable energies – in 2017, it accounted for only 3.0 % of the EU total primary renewable energy production (Eurostat 2019). The main reason for the discrepancy between its potential and the dragging development of geothermal resources are the high up-front costs of drilling and risks related to geological uncertainties. In order to mitigate the mining risks related to geological uncertainties and thus to further unlock the potential of geothermal energy, the EU is funding several R&D projects via various funding schemes.

Considered on a world-wide scale, carbonate rocks are regarded as the most prevalent geothermal aquifers of low-enthalpy systems (Goldscheider et al. 2010). However, these deep carbonate rocks harbor a particular mining risk as low-enthalpy hydrothermal systems require drillings to great depths to reach suitably elevated temperatures, which, on the other hand, means a decreased fluid flow due to the decreased primary porosity/permeability caused by mechanical compaction.

HotLime's proposal to contribute to de-risking the geothermal exploration in such deep carbonate rock hydrothermal plays through trans-nationally identifying the generic structural controls, has been acknowledged by funding from the European Union's Horizon 2020 research and innovation programme (https://ec.europa.eu/programmes/horizon2020/en) within the frame of GeoERA (www.geoera.eu). In GeoERA overall 45 national and regional Geological Survey Organizations (GSOs) from 32 European countries have joined forces of the applied geosciences to contribute to the optimized utilization and management of the subsurface.

1.2 Rationale

Objective of HotLime is to apply established methods for characterization and estimation to hydrothermal resources in different geological settings rather than to conduct cutting edge research. Key challenge is, to do so in case studies of disparate levels of knowledge, data coverage and information available and to apply uniform methods for comparison and prospect ranking. On the one hand this inescapably means to generalize and to reduce methods of resource base assessments and comparison to the least common denominator. On the other hand this serves the revision of methods and their range of applicability and helps to share knowledge and experience, thus complying with the spirit of transnational collaboration as fostered by the EU.

This paper strives to give kind of a mid-term state-of-affairs review and perspective of the HotLime project. Rather than any preliminary description of individual target areas or generic features and their controls identified so far, we will provide only a rough overview of various carbonate aquifer environments under investigation and focus on our approaches for estimation, comparison and prospect ranking of these potential hydrothermal resources. As uniform assessments of resources in case studies that comprise areas at the very early stage of investigation require generalizations, simplifications and assumptions, it seems appropriate to put these boiled down methods up for discussion.

2. GEOTHERMAL RESERVOIR MAPPING AND CHARACTERIZATION

11 different case study areas in various geological settings were chosen by HotLime's partners for mapping, characterization and resource assessments. These areas have in common a (allegedly) hydrothermal carbonate aquifer at depth, but vary considerably in size (Figure 1), depth, gross thickness and compartmentalization of the aquifer (Figure 2). Moreover, the case study areas feature a large disparity with respect to the knowledge about their geothermal prospectivity – from almost 'terra incognita' to areas where viability and efficacy of utilization is proved by geothermal installations running smoothly for almost two decades.

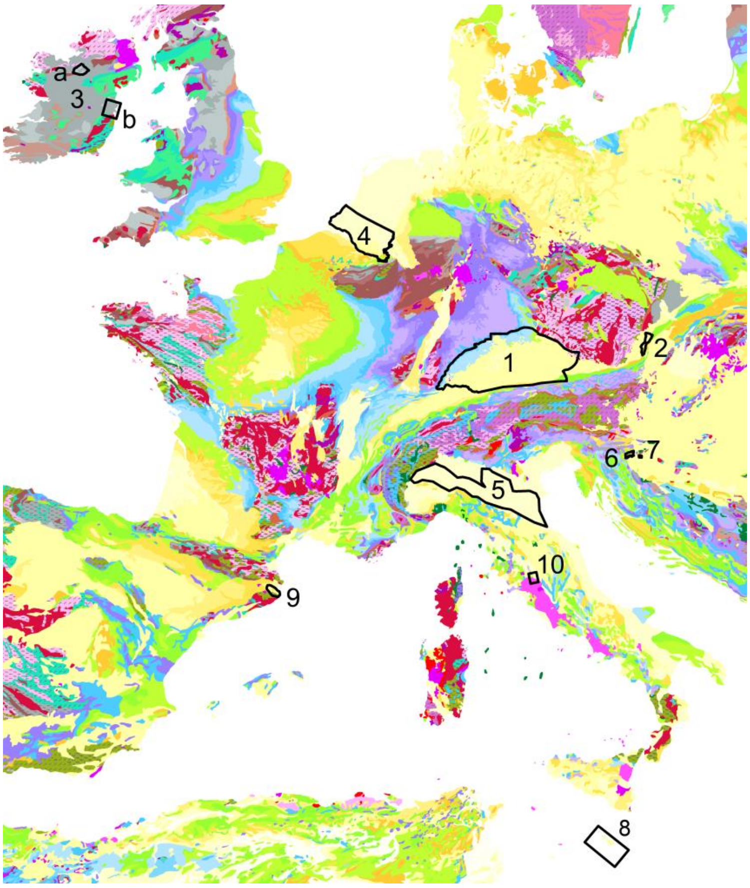

Figure 1: Location of HotLime's case study areas plotted on the 1:5m-scale International Geological Map of Europe – IGME5000 (Asch 2005). Offshore geology is omitted for clearer territory contours. For numeration see text.

The size of the case study areas varies from 54 to 47,100 km^2, and all encompass at least one suspected or proven hydrothermal carbonate horizon. #1: Upper Jurassic and Middle Triassic carbonates in the central part of the North Alpine Molasse Basin (DE/AT); #2: Upper Jurassic carbonates in the Molasse Basin-Carpathian Foredeep transition zone (AT/CZ); #3: Carboniferous carbonates in (a) Lough Allen Basin and (b) Dublin Basin (IE); #4: Dinatian carbonates at the flanks of London-Brabant Massif (NL/BE); #5: Upper Triassic to Lower Cretaceous carbonates of the Po Basin (IT); #6: Triassic carbonates of the Krško-Brežice sub-basin (SI); #7: Miocene and Triassic carbonates of Zagreb hydrothermal field (HR); #8: Triassic carbonates of the Pantelleria-Linosa-Malta rift complex (MT); #9: Eocene carbonates of the Empordà Basin (ES); #10: Triassic carbonates of Tuscan, Umbria and Marche nappes in the Umbria Trough (IT). All plays under consideration – except #6, #7 and #10 – are blind systems with no hydrothermal manifestation or measurable anomaly at the surface. According to the play type concept (Moeck 2014) and reflecting the present knowledge, thus subject to possible adaptation with further investigations, most case studies are Conduction Dominated Systems that can be assigned to the Orogenic Belt (CD-2) Play Type (# 1, 2, 5, 6, 7, 9, 10) or the Intracratonic Basin (CD-1) Play Type (# 3, 4), except for #8 which appears to be a Convection Dominated – Extensional Domain (CV-3) Play Type.

Given the disparate points of departure and data backgrounds the HotLime team agreed on the following parameters considered crucial to determine the prospectivity of any geothermal reservoir as the minimum that is tested for all case study areas:

- The presence of a reservoir
- Permeability of that reservoir (primary or secondary)
- Gross thickness of the reservoir
- Internal and external facies distribution
- Net-to-gross ratio (ratio between the total reservoir thickness and the permeable part of the reservoir)
- Basic characteristics of groundwater flow
- Total dissolved solids (water chemistry)
- Geothermal gradient

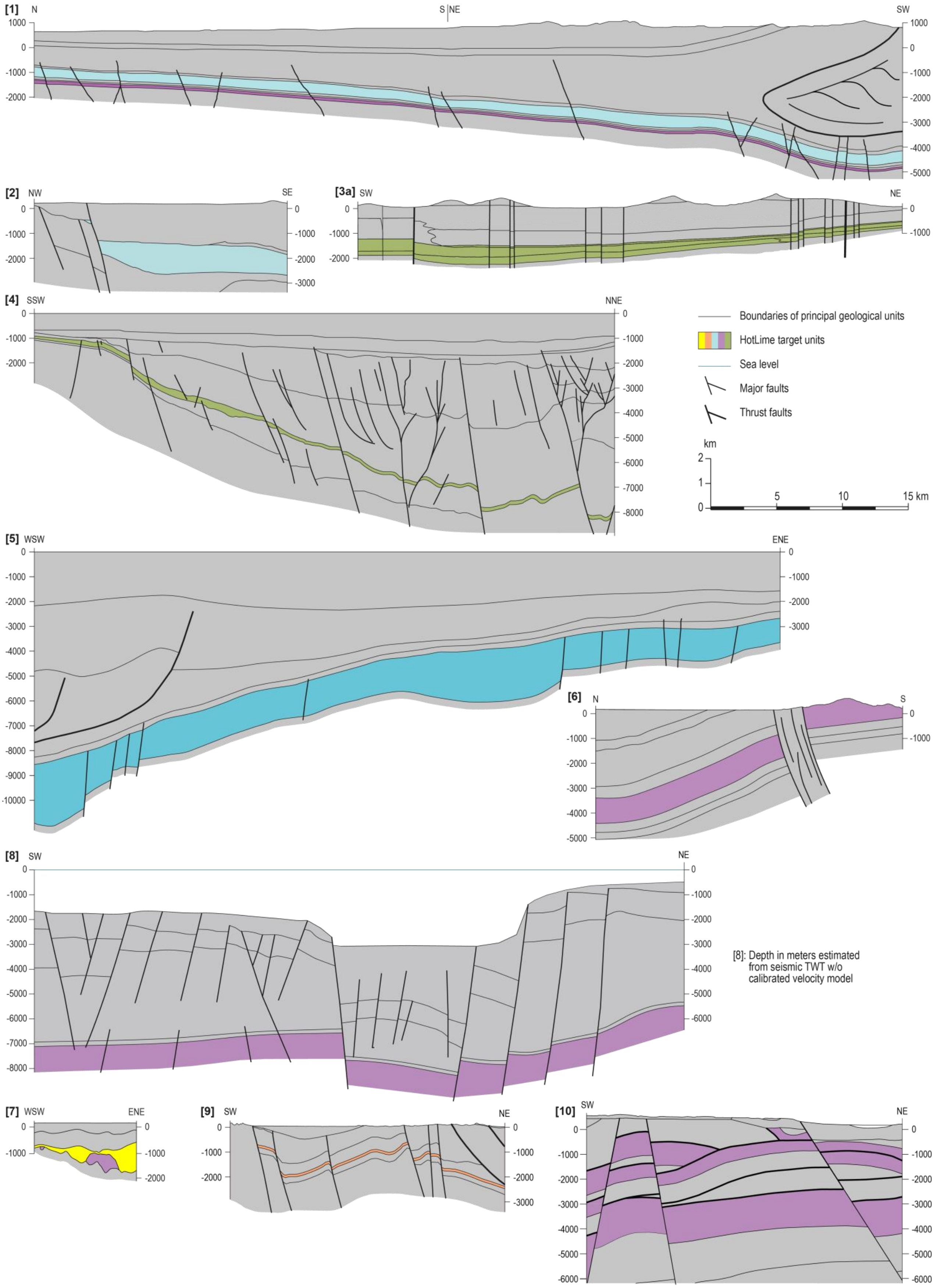

Figure 2: Comparison of (parts of) HotLime's 11 case study areas in cross-sections, as of June 2019. All sections are at the same scale and vertically 2x-exaggerated. The investigated carbonate reservoirs are highlighted using to the color codes of the ICS International Chronostratigraphic Chart (http://www.stratigraphy.org). For section numbers refer to the map in Figure 1 and the subsequent explanatory text.

2.1 Capture of Subsurface Geometries: 3D Geological Modeling

Geothermal resource assessment faces the problem of high degrees of uncertainties for both subsurface geometries and petro-physical property data: A major challenge in mapping and characterization of rock formations at great depths is the availability of data with an adequate distribution and resolution to address the geological situation properly. Legal requirements on data privacy imposing data access restrictions to some of HotLime's partners exacerbate the problem of data paucity. Only few partners can make full use of mature data bases from extensive hydrocarbon exploration campaigns.

Recent simulations for geothermal reservoir assessment (e.g. Wellmann et al. 2011) illustrate that small uncertainties in the geological structure can have significant impact on geothermal resource estimations. Correspondingly, special emphasis is placed on mapping of reservoir geometries, the structural inventory and the geological framework of all case study areas, applying state of the art 3D geological modeling methods at most partners. Differing in abundance and significance among the partners, baseline data for HotLime's case studies beyond conceptual models are scattered and clustered downhole data, various geophysical surveys, specifically seismic sections, geological maps and, rarely, legacy 3D models of subareas. As many data sets used in deep 3D modeling are classified data, access restrictions require that all mapping and model building must be implemented at the jurisdictional regional or national GSOs. Consequently, the capture of subsurface geometries is conducted with different pre-existing proprietary software package(s). Data sets of derived and re-interpreted data, however, are shared among partners for cross-border harmonization in transnational study areas (#1, #2, #4). Even though an overarching general workflow for data preparation, (seismic) interpretation, time-depth conversion and the entire mapping and modelling cascade was set up, we learned that there is no universal best practice applicable to all geological regions or project settings. With scarce baseline data, mapping and modelling is driven by geological concepts and implicit knowledge guided by the modeler and the software's algorithms. In contrast, when baseline data is sufficiently available and expert knowledge is on-hand explicit modeling is the means of choice (cf. Diepolder et al. 2019). In practice, both extremes and all facets in between may occur in the same investigation area. In all cases mapping and modelling is controlled by the geologists' expertise and results feed back into the conceptual models of the geological evolution of the target area.

Figure 2 provides a comparative overview of the present state (June 2019) of mapping the reservoir geometries, the structural features and the geological setting of HotLime's target horizons. The capture of the subsurface setup presently is under refinement, validation and incremental parameterization. This present stage gives good reasons to expect a sufficiently detailed knowledge of the reservoir geometries, i.e. the spatial distribution of the gross thickness, depth and structural setup, the by the end of 2019, to implement geothermal resource base assessments (section 3) at a reasonable level of confidence subsequently.

While the entire procedure from seismic interpretation through to model integrity checks special focus is placed on the fault and fracture network intersecting the target horizons. These discontinuities do not only define the possible compartmentalization of the reservoir and the seal integrity resp. leaks, first and foremost they usually represent high permeability zones, thus conduits for hydrothermal fluids, and as such are the prime target for hydrothermal exploration in deep carbonate rocks (cf. section 2.2.1.).

2.2 Rock Property and Temperature Modeling

For reservoir predictions and modelling, geothermal parameters such as permeability, thermal conductivity, and specific heat capacity have to be quantified. In the early stages of hydrothermal reservoir exploration, this hydrogeological and thermo-physical characterization of the reservoir is restricted to the evaluation of pre-existing downhole data and seismic surveys. However, these base data usually are inherited from hydrocarbon exploration and focused on, thus agglomerated at, prospective structures and are rarely covering larger areas (or are not available at all). Hence, characterization of deep carbonate aquifers as the first step of hydrothermal reservoir assessment is primarily based on conceptual models of the geological evolution, the regionalization of generic information derived from the aforementioned scattered and clustered base data, and the knowledge projected from near-surface analogies.

2.2.1 Hydrogeological and Thermo-physical Parameters

It is generally acknowledged that the groundwater yield in carbonate reservoirs depends on the primary rock porosity (matrix permeability) only to a minor extent, but principally is controlled by fault, fracture and karst conduits. The quality of 'regular' carbonate reservoirs with respect to the hydrothermal potential thus is governed by the fracture and fault network, and, pooled to the term 'thermofacies' (Sass and Götz 2012), the degree of dolomitization and karstification widely controlled by the facies type. Accordingly, as opposed to systems in porous rocks, carbonate plays are highly anisotropic and heterogeneous and mapping these heterogeneities at depths is particularly challenging because downhole data coverage increasingly dwindles with increasing depth of the aquifer. The only of these crucial factors that can be reliably assessed on a larger scale and at the forefront of exploration before drillings are carried out is the fracture density. Generally, the highest density of discontinuities is found in the vicinity of faults which, in turn, can be clearly identified in reflection seismic. Dussel et al. (2016) e.g., determined mechanically altered zones along main faults with a width of 50-150 m. In contrast, facies and dolomitic domains can be reliably detected only after drilling and seismic-well log correlation (Moeck et al. 2015), or can be assessed from high resolution 3D-seismics, usually available only in advanced development stages and in project size areas (cf. Diepolder and GeoMol Team 2015). From this perspective faults seem to be the most reliable target in geothermal exploration in the deep carbonate rocks (Moeck et al. 2015). Many successful drillings for geothermal installations over the last decade, specifically in the Molasse Basin (#1), have proved this approach. However, recent failures of ultra-deep explorations (> 5,500 m) show that it is not inherently propitious.

The latter implies that porosity and permeability can be significantly altered by diagenetic processes. While compaction substantially reduces conduits, karstification, in particular, is an effective way to create secondary porosity. In this context it is important to consider that different parts of a carbonate platform may have different burial and diagenetic histories. Platform slopes may be dissected by faults, which is important for predicting the presence of fractures and potential for hydrothermal karst. This adds further complexity, since fractures and faults in carbonates can become dissolutionally enhanced, or karstified, and form highly transmissive conduits. Karst conduits are often structurally controlled and heavily influenced by the past and present tectonic regimes of a region. Consequently, the importance of understanding the association between carbonate facies (the platform position), faults and karst (permeability) in carbonate bedrock in order to deliver the greatest geothermal yields becomes evident.

Identifying and mapping of hydrogeological and thermo-physical reservoir properties draws on techniques common to hydrocarbon explorations. To rigorously constrain the geothermal system and assess the petrophysical properties of the lithological units, lithostratigraphic data, core and cuttings analyses, drill-stem tests, borehole geophysical logs, and technical drilling information (circulation fluid or drill bit loss, major caliber enlargements, etc.) are required. However, such ‘hard data’ are scattered and clustered rarely covering larger areas and, for many areas of the case studies, are not available at all. Hence, our hydrogeological and thermo-physical characterization of the deep carbonate aquifers at a basinal scale is primarily based on conceptual models of the geological evolution (platform position, tectonic and burial histories), generic information derived from obtainable ‘hard data’ and literature, and the knowledge projected from surface analogues. Paleo-geographical reconstructions of the depositional environments as mapped in outcropping parts of the carbonate deposits, that distinguish reef (mass), reef slope (debris), basin (bedded) facies and dolomitized zones, are most valuable to infer these environs in buried parts of the carbonate platform.

General findings determined in well explored carbonate basins are reviewed and compared with other case study areas to assess if these findings can be considered generic in a wider context concerning the geological evolution and setting. For instance in the central Molasse Basin (cf. Figure 1), geothermal wells show higher productivities when drilled into the mass facies (reefs) and into slightly lower hydraulic conductive reef debris; dolomitic domains and karstification occur mainly at geological faults and in the mass facies, thus further increasing initial higher porosity of the mass facies; this generally higher primary porosity in the mass facies leads to higher secondary porosity, hence a connected aquifer (op. cit. in Dussel et al. 2016).

To capture the internal buildup of the reservoir and to estimate the ‘thermofacies’ of HotLime’s target horizons, our approach is to collate such information from in-depth research on a project size scale and align it with the geologists’ knowledge, experiences and conceptual models from various geological settings on a basin wide scale, all over the terrains of competence of HotLime’s partners. In the very early stage of investigation with sparse hard data, this cross-fertilization through sharing knowledge seems to be the most appropriate way to overcome the lack of data.

Parameterization of carbonate reservoirs in terms of rock properties and facies commences when the collation of the generic controls has gained a reasonable level of confidence and a reliable degree of accuracy of the spatial representations is assumed.

2.2.2 Temperature Modeling

Likewise the geological information for mapping and characterization, available temperature data for the HotLime case study areas are disparate with respect to distribution density and quality. Measurements collected for temperature modelling predominantly stem from downhole data of (legacy) hydrocarbon E&P campaigns, mostly taken as Bottom Hole Temperatures (BHT) and corrected using established weighting classifications (cf. e.g. Rühaak et al. 2010), or rarely from drill stem tests (DST). Only in the Molasse Basin (#1) a significant number of temperature measurements from recent geothermal E&P are available. The areal coverage of preexisting temperature models or temperature distribution maps for HotLime’s target horizons varies from full coverage to nil. Area-wide subsurface temperature information is available for #4 down to 6 km depth (Bonté et al. 2012), the top of the Upper Jurassic hydrothermal aquifer in #1 (Agemar and Tribbensee 2014) and for Umbria’s #10 (Mariuccini et al. 2019). Partially covered e.g. is the top of Middle Triassic of #1, (http://maps.geomol.eu/?view=geomol2&lang=de, see also GeoMol Team 2015) and, further extended and upgraded within HotLime, the top of Upper Triassic to Lower Cretaceous sequence of the Po Basin (#5). For many case study areas only and few measurements exist, in most cases too far apart for reliable interpolations.

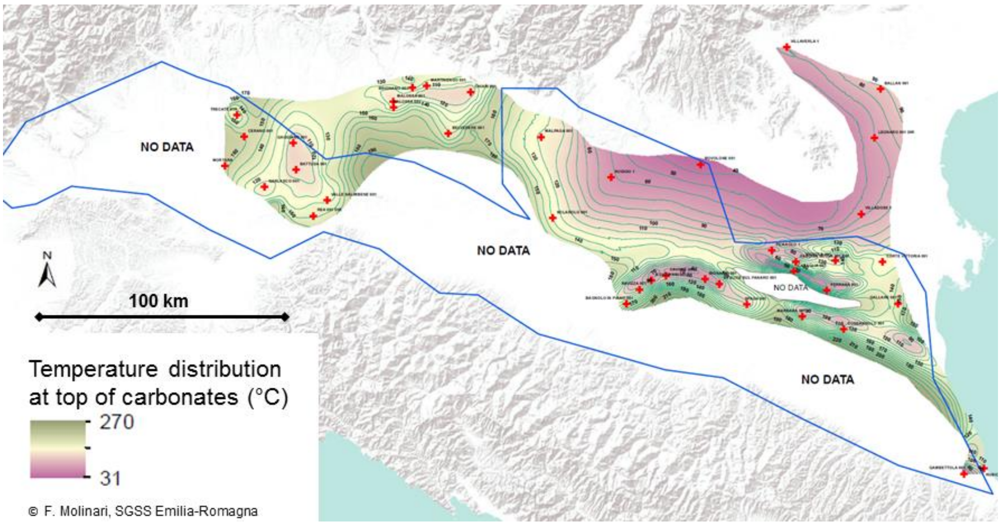

Figure 3: Temperature distribution at the top of Upper Triassic–Lower Cretaceous (T-K) shallow marine deposits in the Po Basin (#5), interpolated from BHT data (red crosses). Due to paucity of data the HotLime case study area (blue outline) is only partially covered with large no-data voids. The temperature distribution pattern implies that the depth of the reservoir is not the only determining factor.

As an area-wide temperature distribution is crucial pre-requisite for all geothermal resource base assessments (Section 3) regionalized geothermal gradients derived from downhole data (borehole loggings) and literature values of heat flow density are used to fill the voids in areas where no reliable interpolation of hard data can be performed.

In areas where the available BHT data do not allow direct interpolation, punctual gradient data can be used to infer the regional temperature distribution at the top of the reservoir by applying the following basic equation:

$$Tr = T0 + gradT * Z \tag{1}$$

where *T0* is the mean annual surface temperature; *gradT* is the thermal gradient and *Z* is the depth of the target according to the preliminary 3D model. However, such generalization neglects non-linearity of geothermal gradients, e.g. evident in #10 (Mariuccini et al. 2019). In the Empordà basin pilot site (#9), a representative regional geothermal gradient of 40ºC/km has been considered for the whole basin. This first approximation to estimate the reservoir temperature at the top of the target horizon (the Eocene carbonates of Girona Formation), was calculated using gradient values from Girona-2 and Jafre wells (47˚C/km resp. 39.6˚C/km).

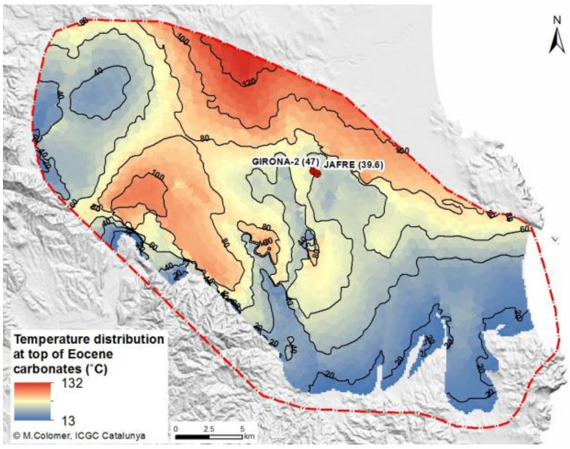

Figure 4: Case example of a preliminary temperature distribution calculated for the top of the Eocene carbonates of the Empordà Basin (#9) considering a representative geothermal gradient.

Regionalized geothermal gradients are also used to estimate temperatures at the base of the considered reservoirs usually far below the deepest BHT value measured. Specifically in reservoirs featuring a gross thickness of more than 200 m the increase of temperature with depth within the target layers has a significant effect on the geothermal resource base assessment. Correspondingly, such large thickness reservoirs are dealt with as layered incremental intervals.

3. GEOTHERMAL RESOURCE BASE ASSESSMENTS

Geothermal resource (base) assessment describes a process by which the possible future energy production from a geothermal reservoir is estimated. This is an iterative process that continuously incorporates new information gathered and interpreted throughout the various stages of the long development evolution from large-scale reservoir characterization to site specific exploration and eventually to power generation. Following the definition of UNFC-2009 in the geothermal energy context (UNFC 2016) the energy source is the thermal energy contained in a body of rock, sediment and/or soil, including any contained fluids, which is available for extraction and conversion into energy products. This source is termed the **Geothermal Energy Source**, equivalent to the terms 'deposit' or 'accumulation' for solid minerals and fossil fuels (UNFC 2016). In contrast, **Geothermal Energy Resources** are the cumulative quantities of Geothermal Energy Products that will be extracted from the Geothermal Energy Source, from the date of the evaluation forward (till the end of the project lifetime), measured or evaluated at a reference point. UNFC-2009 is geared toward classifying the resources associated with single projects. Most of HotLime's case studies, however, consider large-scale geothermal plays immature for specific projects to be defined. Thus, a classification is not meaningful. Accordingly, large-scale assessments of the geothermal energy source (section 3.1) are applied in all case study areas, and geothermal energy resource classification (section 3.2) is limited to small areas resp. site specific projects.

3.1 Geothermal Energy Source Assessment: Volumetric Heat in Place Method

To assess and to compare the geothermal resource base or geothermal energy source on larger scales, commonly the USGS volumetric 'heat-in-place' (HIP) method (Muffler and Cataldi 1978), also referred to as 'stored heat', is used. Evaluation of this measure depends on the volume of the reservoir (distribution and extent of geothermal host rocks in the subsurface), the thermal rock properties, the temperature of the reservoir and the reference temperature. The HIP approach is based on the simple concept of evaluating the thermal energy *Q* stored in a homogenous volume *V* of a rock, calculated as:

$$Q_{total} = [(1 - \Phi) c_r \rho_r + \Phi c_w \rho_w] * V * (T_r - T_{ref}) \tag{2}$$

where Φ is the porosity, $c_r \rho_r$ is the volumetric heat capacity, commonly in $Jm^{-3}K^{-1}$, (i.e. specific heat capacity c * density ρ) of the rock at reservoir conditions and $c_w \rho_w$ is the volumetric heat capacity (i.e. specific heat capacity c * density ρ) of the pore fluid, commonly water, at reservoir condition, *V* is the volume of reservoir (reservoir thickness * areal extent), T_r is the average reservoir temperature, and T_{ref} is the reference (or reinjection) temperature. Large reservoirs by its nature are more or less heterogeneous rock bodies and reservoir temperatures vary considerably with depth. Reservoir volumes, thus, must be subdivided into 'homogenous' sub-units, respectively layered intervals, each having distinct, representative properties with respect to the parameters required by equation 2.

The HIP method is rather sensitive towards various parameters usually little-known at early stages of investigation and consequently at risk of misassessment compared to estimations at more advanced stages of exploration. While c and ρ are rock (material) specific characteristics available from a variety of published work, especially rock porosity Φ is an issue, since carbonate reservoirs (as opposed to systems in porous rocks) are characterized by highly anisotropic and heterogeneous (secondary) void distribution, controlled by facies and tectonic strain. Crucial prerequisite for the reliable HIP application is the detailed knowledge of rock volumes, their compartmentalization and the features indicating secondary cavitation. To this end, we put large effort in capturing the reservoir geometries and its structural inventory (section 2.1). The characteristic reservoir temperature T_r can be interpolated, calculated or modelled in line with the available information (section 2.2.2), using a single representative mean value or (the sum of) layered incremental intervals in reservoirs with large thicknesses. The choice of T_{ref} has a decisive impact on the results: Contingent on the future geothermal utilization concept anticipated, different T_{ref}-values are assumed, (e.g. the reject temperature, injection temperature, abandonment temperature (as the threshold of economic or technological viability), or the ambient temperature, i.e. the annual mean surface temperature value). These different T_{ref}-definitions that can be applied in HIP assessment (cf. e.g. Agemar et al. (2018) for discussion), may significantly hamper the comparability of results. For a global geothermal source assessment, Limberger et al. (2018) assumed minimum re-injection temperatures (T_{inj}) by unitarily adding 10 °C to the surface temperature. To ensure the comparability of our assessments also on a large scale, we agreed to use the T_{ref}-concept of Limberger et al. (2018) for all considered pilot areas.

The HIP method takes into account porosity Φ and density ρ to calculate the volumetric heat capacity of a volume using the ratio of the rock matrix to the fraction of the volume of voids (usually filled with pore fluid), in order to assess the share of the two components having a different specific heat capacity c and density ρ. Porosity and density of rocks at depths can be obtained from core sample analysis or well log measurements, either only scarcely available for most of HotLime's deep reservoirs, but estimable from outcrop analogues or published data on comparable lithologies. In carbonate rock reservoirs, however, the rock porosity only insignificantly contributes to the fraction of the volume of voids, i.e. the bulk permeability, which is predominantly controlled by fault, fracture and karst conduits unevenly distributed over the reservoir volume (section 2.2.1). Even if permeability data is available from punctual well tests or regional-scale interpolations thereof, the challenge is to convert it into a notional porosity equivalent. Empirical approaches for that exist, however they are valid only for 'homogeneous' rock volumes with all the permeability as determined in well tests attributed to porosity, and disregarding the pronounced anisotropy of carbonate reservoirs. Presently we discuss various approaches to tackle this issue, e.g. to consider the anisotropic permeability tensor estimated from outcrops (Healy et al. 2017), which can be used to infer the equivalent reservoir permeability by means of empirical models, or, to define distinct high 'porosity' volumes along the major faults which can be reliably assessed in reflection seismic and are usually accompanied by mechanically altered zones forming high permeability zones (section 2.2.1).

In parallel, different computational methods have been suitability tested and compared in regard to the issues described, e.g. the use of fixed 'known' parameters (deterministic approach) vs. a range of values to consider their uncertainty (probabilistic approach):

- The deterministic approach: Using fixed values, the principal issue for all source assessments is the inherent uncertainty of poorly known reservoirs when dealing with paucity of petro-physical and geothermal data, prone to produce unacceptably high uncertainties with the results.
- The probabilistic approach: Due to the uncertainty associated with the parameters, the HIP application is normally combined with stochastic approaches like the Monte Carlo simulation (e.g. Garg and Combs 2015), taking into account the uncertainties by allowing the parameters to vary over a defined range, by using probability distribution functions (PDF) (triangular, normal, lognormal, etc.). Although various types of distributions can be applied in the Monte Carlo simulation, triangular distribution (minimum, most likely, maximum values) is recommended. However, with more than one parameter allowing to vary results must be reliability proved using a known, verified reference (not yet available for karstified carbonate reservoirs).

The application of the HIP method run with probabilistic Monte Carlo simulations allows for a lumped and a distributed approach:

- The probabilistic lumped approach: An aggregated approach can be used which embraces the entire geothermal reservoir as a unitary block, within that a single PDF for the different parameters is assumed. Monte Carlo simulations can be run using various commercial software packages as add-in applications to Excel, also directly using Excel's RAND function or using the MATLAB software. This methodology is most commonly used in assessing geothermal resources at early stage of exploration and to support decision-making for risk analysis (e.g. Avşar et al. 2015, Yang et al. 2015). Outcomes of this way of HIP application are generally presented as a histogram of stored energy plus a plot of the cumulative probability function of stored energy (e.g. in PJ). In line with the proposal of Sanyal and Sarmiento (2005) and UNFC-2009, usually three values are presented: the P90 (90% probability) high confidence estimate, the P50 moderate confidence estimate and the P10 low confidence estimate.
- The probabilistic distributed (2D/3D) approach: As discussed, large reservoirs by nature are heterogeneous rock bodies featuring temperatures increasing considerably with depth. The distributed approach of Monte Carlo simulation complies with that by allowing the subdivision of the reservoir volume into several homogeneous compartment blocks and/or layered intervals, each having distinct properties in terms of equation 2. 3D geological models as built during mapping and characterization (section 2.1), exported into 3D voxets and parametrized, allow the HIP estimate by Monte Carlo simulation for each separate volume, voxel or cell. Likewise, the reservoir temperature T_r can be modelled in 3D considering regional average gradients (equation 1) or more sophisticated temperature models where available. To actually run the HIP calculations, a general MATLB script can be programmed aimed to decompose the 3D voxets in a simple matrix of cells. In each cell the Monte Carlo calculation should be applied considering different PDF for different lithologies or reservoirs. Finally, the results will be compiled to export the data as raster-integrated energy values at depth for each reservoir (Zafar and Cutright 2014) to represent P10, P50 and P90 raster maps in 2D based on e.g. PJ/km^2 units.

In HotLime's case study areas, the HIP method will be applied using two different approaches but considering the same concept of T_{ref}. In cases of aquifers deemed sufficiently characterized, the deterministic 2D approach will be applied, comparable to e.g. Van Wees et al. (2010), who applied a deterministic 2D approach to assess and map the geothermal resource base of The Netherlands. With higher uncertainties concerning the aquifer characteristics, the probabilistic approach will be implemented, comparing P50 map results with previous assessments as the moderate confidence estimate. Eventually, the project will deliver temperature distribution maps at the reservoir depth (cf. section 2.2.2) and 2D heat-in-place maps for the entire pilot areas. These outcomes will allow identifying and comparing more prospective areas and will guideline further research to foster future geothermal projects.

3.2 Geothermal Energy Resource Classification: UNFC-2009

As UNFC-2009 is not a quantification system, the quantification of the available geothermal source must be conducted prior to classification. Since the classification is project-based, it is necessary to ensure the comparable level of quantification. Most of HotLime's case studies are investigations on large areas, and a classification is therefore not applicable, i.e. all regional examples would be classified as E.3; F3; G4 based on notional 'standard' projects, as exemplified for the Pannonian Basin System (PBS) in the scope of DARLINGe project (Nador 2018). In the light of these obstacles, for HotLime's pilot areas, as a rule, the geothermal resource estimation as described in section 3.1 will be applied, while the case study on Zagreb geothermal field (#7) will conduct resource classification as well. This smallest pilot area has two technological systems already in place: Mladost (in operation) and KBNZ (idle). Looking at the whole theoretical 'Zagreb Basin' (sub-basin of the PBS), the DARLINGe project classified the resource as mentioned above. The only operational system (Mladost) classifies as 7 PJ E1.1; F1.1; G1 + 5 PJ E1.1; F1.1; G2 + 3 PJ E1.1; F1.1; G3 – totally contrasting the sub-basin scale classification. This system is in successful continuous operation since 1987, so it is clearly feasible and socio-economically accepted. On the other hand, the neighboring system KBNZ of the same geothermal field must be classified as 7 PJ E3; F1.3; G1 +7 PJ E3; F1.3; G2 + 7 E3; F1.3; G3 because – although all the wells are in place since 1987, they have been tested, concession was granted etc. – the system never became operational. KBNZ case is a typical example of legislative, administrative and political barriers to project implementation, leading to E3 classification of a project which could be in operation for decades already. Probabilistic estimates of P10, P50 and P90 for this exercise were derived from the Zagreb Geothermal Field main mining design data (Zelić et al. 1995), using the DoubletCalc 1.4.3 software (TNO 2014), which is conceived for permitting purposes in The Netherlands and has been applied also for projects within the #4 case study area.

4. PRODUCTS, DATA DISTRIBUTION AND INFORMATION CHANNELS

HotLime's investigations are geared towards outcomes serving planners and decision-makers to focus further research for site selection on the most promising areas. The results of HotLime, the case studies in mapping and characterization of the key national/regional carbonate basins and the evaluation of their geothermal capacity, will deliver a variety of multidimensional spatial information, the associated feature data and methodological approaches (knowledge base, reports) via GeoERA's central information repository and dissemination portal, the European Geological Data Infrastructure (EGDI, http://www.europe-geology.eu/). Following the 'FAIR Guiding Principles for scientific data management and stewardship' (Wilkinson et al. 2016) ensures that all of HotLime's information will be **F**indable, **A**ccessible, **I**nteroperable, and **R**e-usable utilizing the EGDI Metadata Catalogue http://www.europe-geology.eu/metadata/ for search and discovery and EGDI's web services. Based on the Simple Knowledge Organization System (SKOS) within the Linked Open Data Semantic Web, the HotLime Knowledge Base will provide controlled vocabularies, glossaries, reports and underpinning information hyperlinked to HotLime's spatial information.

5. CONCLUSION AND PROSPECT

HotLime attempts to overcome deficiencies due to data paucity at the very beginning of investigating hydrothermal carbonate reservoirs through transnational exchange of knowledge and experience have been proven successful in terms of methodological approaches on geological issues, conceptual models and the identification of generic controls, although final outcomes have not been prepared yet. Alignment of more data-driven assessments like rock property distribution and temperature modelling, constrained by the pronounced disparity of baseline data available, is still under way. Thus, at present, it is difficult to predict if knowledge transfer between well and poorly explored areas will be sufficient to overcome data gaps eventually. Variants of 'heat-in-place' assessment approaches are currently tested for suitability and the procedure deemed most appropriate will be implemented consistently in all pilot areas. For the GeoERA Mid-term Review in March 2020 results by then will be compiled and will be discussed at the WGC2020.

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