A Geostatistical Approach for the Modelling of Earth's Heat Flow*

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Abstract

Heat flow plays a major role in the context of Petroleum System Modeling and the understanding of its structural and thermal evolution represents one of the key factors in the assessment of the exploration risk associated to basin potential prospects. In fact, Earth's evolution reflects the history of heat transfer from the interior, due to plate tectonics and conduction through lithosphere. In particular, the role of heat flow is crucial for the determination of temperature history, which is one of the most influencing controlling factors in the maturation of organic compounds into fossil fuels. Hence, understanding Earth's thermal history is critical in the scope of an oil exploration strategy.

Introduction

In order to reconstruct the thermal state of the basin, the modeling procedure needs three main information inputs: thermal properties of sediments and of water (conductivity and specific heat), the surface temperature and the heat-flow at the base of the sedimentary sequence. While sediments characterization can be derived thanks to petrophysical studies and surface temperature can be assigned based on paleo-climate modeling, heat flow at the base of the sedimentary sequence is probably one of the most difficult input to provide in the modeling procedure (also one of the most critical for the results). It is defined by a heat flow map for each time step of the evolving basin model. As direct measurements of heat flow are seldom available, the usual approach is based on a trial-error scheme. In practice the idea is to make a hypothesis on the heat flow value at each known well of the basin. This is used as border condition for the temperature modeling. Once the simulation has been performed, the present-day temperatures can be computed along each well. It is therefore possible to compare the simulated temperatures with the measured ones to check if the initial hypothesis on the heat flow is correct and the chosen value is effectively significant for temperature evolution reconstruction. If the fitting is not satisfactory, another value for heat flow is proposed and the simulation is performed again.

At the end of this procedure, we get the set of heat flow values at wells, which can better explain the temperature records. This is the first data source of present-day heat flow. The second source comes from thermo-tectonic modeling. The quantification of heat flow history during basin subsidence can be addressed by forward modeling of tectonic and thermal processes associated to the evolution of the lithosphere involved in extensional deformation. A numerical approach based on finite elements is devoted to this purpose (TECMOD2D by Geomodelling Solutions). It provides reconstructions of thermal history of sedimentary successions deposited in extensional basins along 2D sections. The inputs required by the procedure are present-day stratigraphy and thinning factors, respectively for crust and lithosphere. They are defined as the ratios between initial thickness and final thickness of crust and lithosphere. In this way, it becomes possible to assess the heat flow and temperature evolution through time in frontier areas characterized by a lack of well and sub-surface data. Thermo-tectonic modeling is therefore useful in situation when measurements are scarce. The output of such numerical modelling constitutes the second data source.

Discussion

The available data for present-day heat flow modeling come from two different procedures with different reliability, thus causing a potential bias in the complete set of available data. In order to solve the problem of coupling spatial biased data characterized by different qualities, a methodology based on geostatistics has been developed, starting from measurements affected by an error specific to each data procedure. It takes into account spatial correlation of both variable and errors.

Heat flow has not been deeply investigated in geostatistics, at least up to now, and so a substantial initial effort has been done both for evaluating the feasibility of the approach and for clarifying whether it is possible to state any physical or geological relationship between heat flow and other observable quantities. Secondly, we have to tackle the available realistic data set: often sets are poor, in the sense that only few evaluations are accessible.

The model proposed here is suited for treating such situations and the results of the proposed *ad hoc* kriging system are compared with classical techniques. Without loss of generality, the method is developed considering two types of data sources, *w* and *p*. Let *Z(x)* be the state variable and $Y(x) = Z(x) + \varepsilon(x)$ be the measured variable, where $\varepsilon(x)$ is the measurement error that depends on the procedure of measurements and is spatially independent from the state variable, that is $Cov[Z(\boldsymbol{x}), \varepsilon(\boldsymbol{x})] = 0 \ \forall \boldsymbol{x}$. The assumptions, under which the estimator is built, are stationarity for the state variable and the following model for the measurement error, where *V* indicates the variance of measurement error.

$$\begin{cases} E\left[\varepsilon^i(\boldsymbol{x})\right] = 0 \ \ \forall \boldsymbol{x}, i = w, p \\ Var\left[\varepsilon^i(\boldsymbol{x})\right] = C_0^{\varepsilon,i} = constant \ \ \forall \boldsymbol{x}, i = w, p \\ Cov\left[\varepsilon^i(\boldsymbol{x}_\alpha), \varepsilon^i(\boldsymbol{x}_\beta)\right] = C^{\varepsilon^i}(\boldsymbol{x}_\alpha, \boldsymbol{x}_\beta) = C_{\alpha,\beta}^{\varepsilon^i} = \begin{cases} 0, if \ \alpha, \beta \ have \ different \ nature \\ V_{\alpha,\beta}^i, if \ \alpha, \beta \ have \ same \ nature \end{cases} \end{cases}$$

Following such assumptions, we obtain an unconventional kriging system, in the sense that it is a co-kriging system not based on a model of linear co-regionalization. In particular, it considers different variances of measurement errors according to the nature of the data set, and modeling them as nugget effects. The resulting kriging matrix is modified not only in its main diagonal (like for the well-known kriging with variance of error measurements) but also for the sub-diagonal terms when comparing samples of same nature.

In order to validate the proposed method, it has been applied to a realistic case. The considered field is located offshore and it is embodied in a rectangular area of 300x400 km. The geological model consists 12 layers, the oldest of which is dated 130 My. According to the depositional model, from 130My to 118My the lithology is shaly sandstone, then we have salt deposition up to 112 My, marl is modeled from 112 My to 84 My and up to present-day the modeled lithology is 25% sandstone and 75% shale. The maximum thickness of the body is around 12 km, below which the basement is found. The sea floor depth ranges from 40 m to 3,500 m; consequently, sea floor temperature distribution ranges between 2°C and 18°C (corresponding respectively to the temperature of the deepest point of the sea floor and to the shallowest).

Fourteen wells are located in the area. They are mainly located in the northern part of the field, leaving the southern part without information. For each well, temperature measurements are available. Heat flow is evaluated at each well by means of the calibration procedure already described. In order to get additional information on heat flow in the un-drilled sectors, a Thermo-Tectonic modeling is performed along the two sections, providing both heat flow evolution along two profiles and the reconstruction of heat flow history (Figure 1a). The histogram of available present-day heat flow data set is represented in Figure 1b.

Although the information along the section is dense - it is almost continuously sampled - only two lines are not sufficient to describe the entire field. A quick statistical analysis of the data set (heat flow at wells, heat flow at sections) leads to the following considerations:

1. Heat flow at wells and at sections have different statistical properties (both in terms of average and in terms of variance);
2. The nature of the two data sources is different and inconsistencies rise from local comparisons; such inconsistencies can be reduced by applying debiasing - that is, homogenizing the statistical distribution of the data, assuming that heat flow distribution is common and attaching a variance of measurement error to each of them, taking into account the scale of the phenomenon;
3. Correlation between heat flow and basement depth exists (Figure 1c); because of the different qualities of data, it is not straightforward to understand which linear model is the most reliable; the choice depends on the modeler experience;
4. Spatial structure is well defined in the direction of the sections but not elsewhere, because of lack of data and therefore the model for spatial variability should be inferred a priori (Figure 1d).

Finally, a map of heat flow has been produced combining the linear regression model for including the variability explainable by the basement depth and the proposed estimator for the associated residuals. It is reported in Figure 2.

Conclusion

In conclusion, the proposed approach appears to be quite useful, as it allows integrating data of different sources and characterized by different qualities without sacrificing any information. The improvement obtained in modeling of the heat flow appears to be significant as it also allows integrating the expert knowledge in the definition of the optimal map. A side result is that the heat flow map, being obtained by geostatistical techniques, can also be simulated though geostatistical simulations, if we are looking for an uncertainty evaluation.

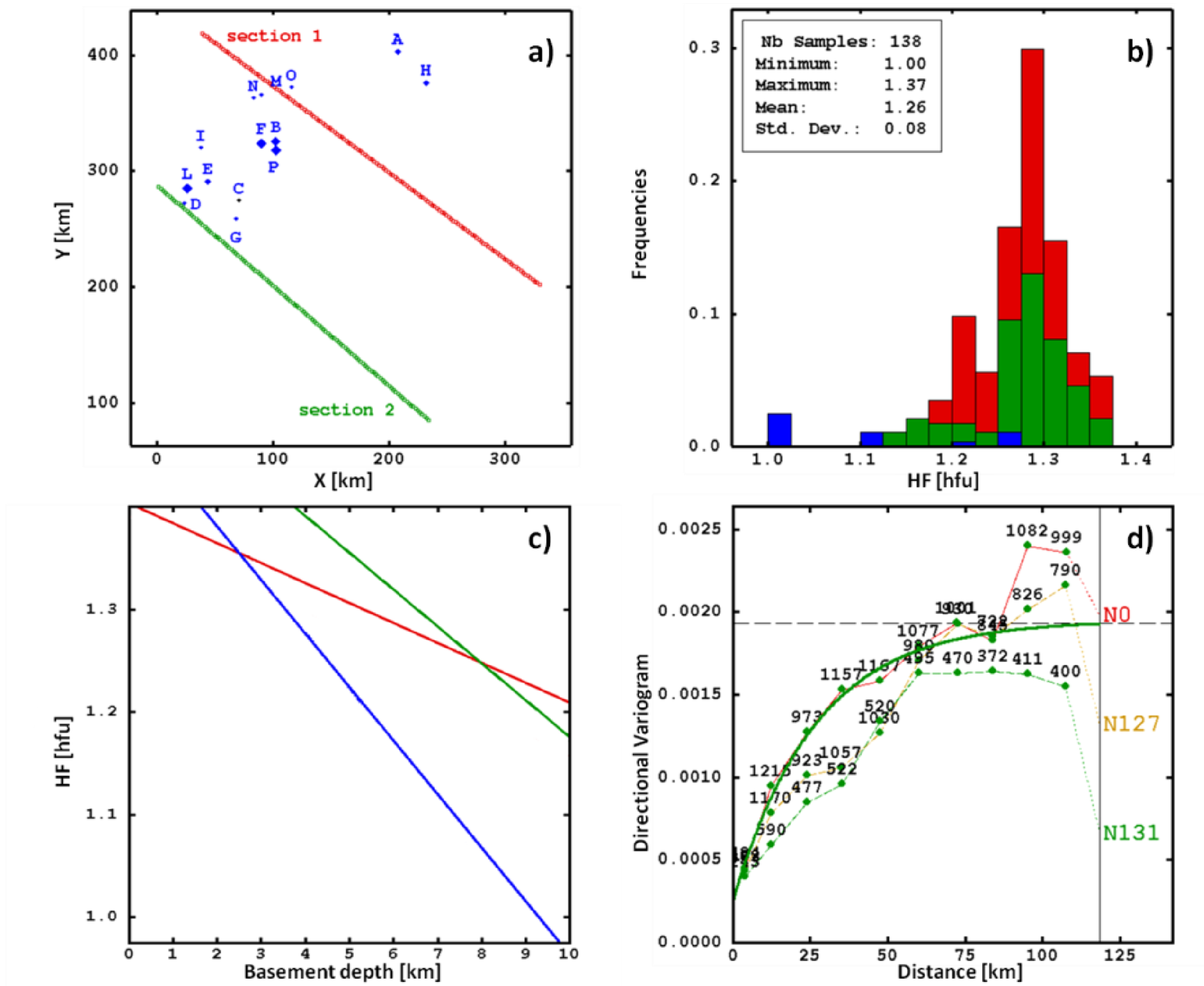

Figure 1. a) Location of available data: wells in blue, sections in green and red; b) Histogram of heat flow data set, associated to each data source; c) Regression lines for modelling the linear dependence between heat flow and basement depth; d) Experimental directional variograms (dotted lines) and modelled omni-directional variogram (continuous line) for the whole data set. [Plotted with ISATIS®]

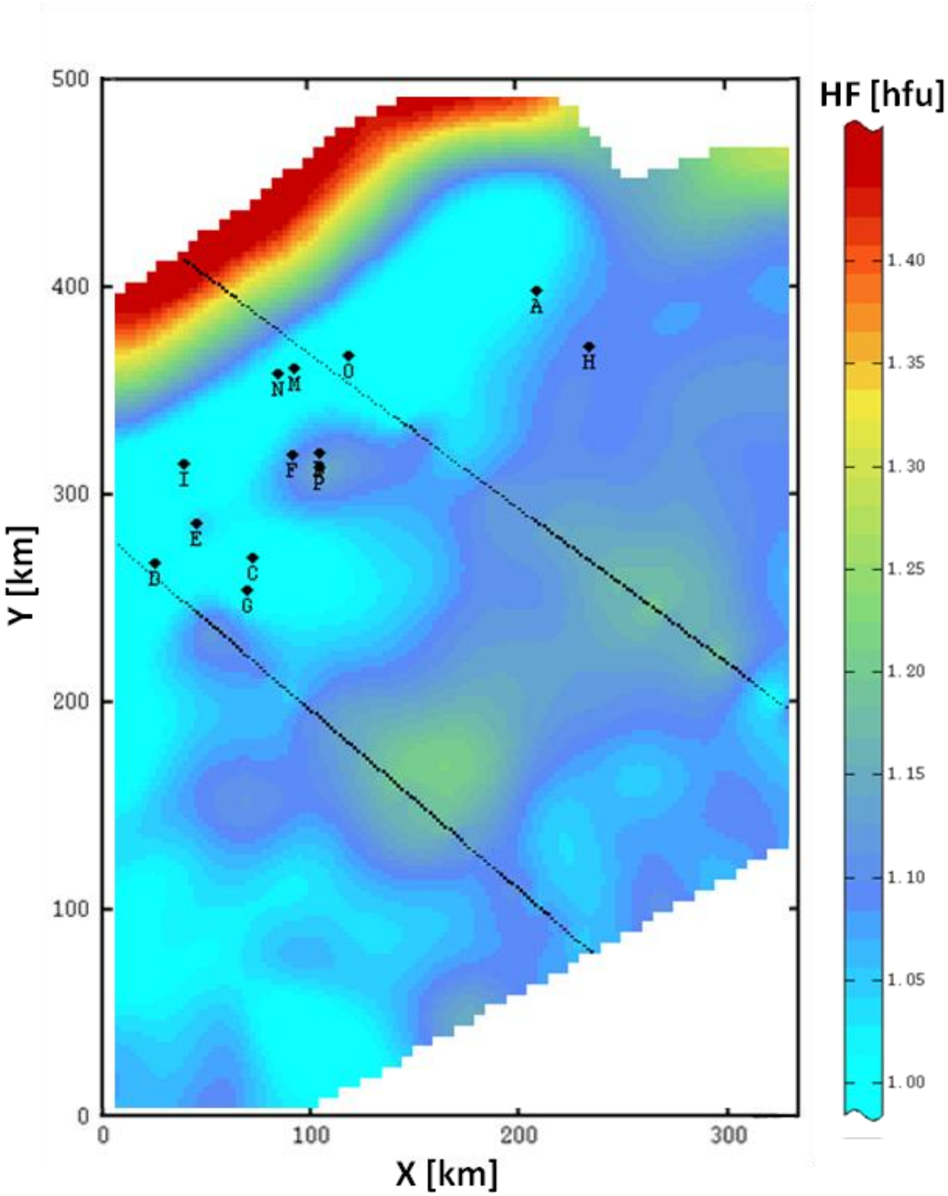

Figure 2. Heat flow map estimated by means of the proposed methodology. Wells and profile locations are superimposed [Plotted with ISATIS®].