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Modeling fluid flow and heat transport in compressive sedimentary basins: application to the Ainsa basin

Modelización de la migración de fluidos y del transporte de calor en cuencas sedimentarias compresivas: aplicación a la cuenca de Ainsa

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ABSTRACT

We present a method of modeling the hydraulic and thermal evolution of sedimentary basins that undergo compressive deformation. A finite-element mesh generator is used , that is capable of creating bandwidth optimized meshs taking into account geometrical deformations caused by sediment consolidation, lateral movements of thrust sheets and erosional events. A finite-elements model is used to solve the equations of fluid flow, sediment consolidation as well as solute- and heat transport. We apply the model of the Southern Pyrenean foreland basin of Ainsa in order to constrain fluid flow evolution during the emplacement of thrust sheets. Furthermore, we compare the data obtained by petrological and geochemical studies in the Ainsa bain host rocks and veins to corroborate the application of this method.

RESUMEN

Presentamos un método de modelización de la evolución hidráulica y térmica en cuencas sedimentarias sometidas a una deformación compresiva. Para hacer esta modelización hemos utilizado un generador de redes de elementos finitos capaz de crear una red de elementos finitos optimizada. El modelo toma en consideración las deformaciones geométricas causadas por la consolidación de los sedimentos, los movimientos laterales de los mantos cabalgantes y los eventos de erosión. El generador de redes de elementos finitos se utiliza para solucionar las ecuaciones de migración de los fluidos, de la consolidación de los sedimentos y de transporte, tanto de los solutos como del calor. Este modelo es aplicado a la cuenca del antepaís sur-pirenaica de Ainsa (Pirineo Aragonés) con el fin de determinar la evolución de la migración de los fluidos durante el emplazamiento de los cabalgamientos y para identificar el origen de los fluidos, que pueden haber alterado los sedimentos durante el emplazamiento del sistema de cabalgamientos. Además, comparamos los datos obtenidos a partir de estudios petrológicos y geoquímicos en los sedimentos que rellenan la cuenca de Ainsa y en las mineralizaciones de calcita originadas sincronicamente a la deformación compresiva debido a la circulación de fluidos a fin de verificar la aplicación de este metodo de modelización.

Key words: *Basin modeling, compressive basins, finite-element method, fluid flow, heat flow*

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Introduction

Fluid migration in a basin scale plays an important role in many geologic processes such as evolution of hydrocarbon resources and/or hydrothermal ore deposits. While directions and volumes of fluid flow are primarily controlled by the anisotropies of the basin fill and its geometry, the tectonic evolution of a basin determines to some extent the characteristics of the resulting flow system and the geochemical signature of the fluids. In general, hydrodynamics in compressive basins as well as distensive basins are controlled by compactional flow in case of submarine conditions (Bitzer and Calvet, this volume), and in case of subaerical conditions gravitational flow will contribute meteoric water from its uplifted edges. Free convection may appear in case of sufficient density contrasts. Compressive basins exhibit additional flow patterns, which are controlled by the tectonic evolution of the basin involving moving thrust sheets and strong lateral deformation. An overview over flow systems in a continental scale is given by Garven (1995).

With respect to its hydrodynamic evolution, a compressive basin can be separated into a more or less stationary part that does not undergo geometrical changes apart from sedimentation and/or erosion, and another part, which in itself is either part of thrust sheets or which is loaded by the weight of the advancing thrust sheets. The load of thrust sheets involves compactional fluid flow from underlying strata, which will be generally

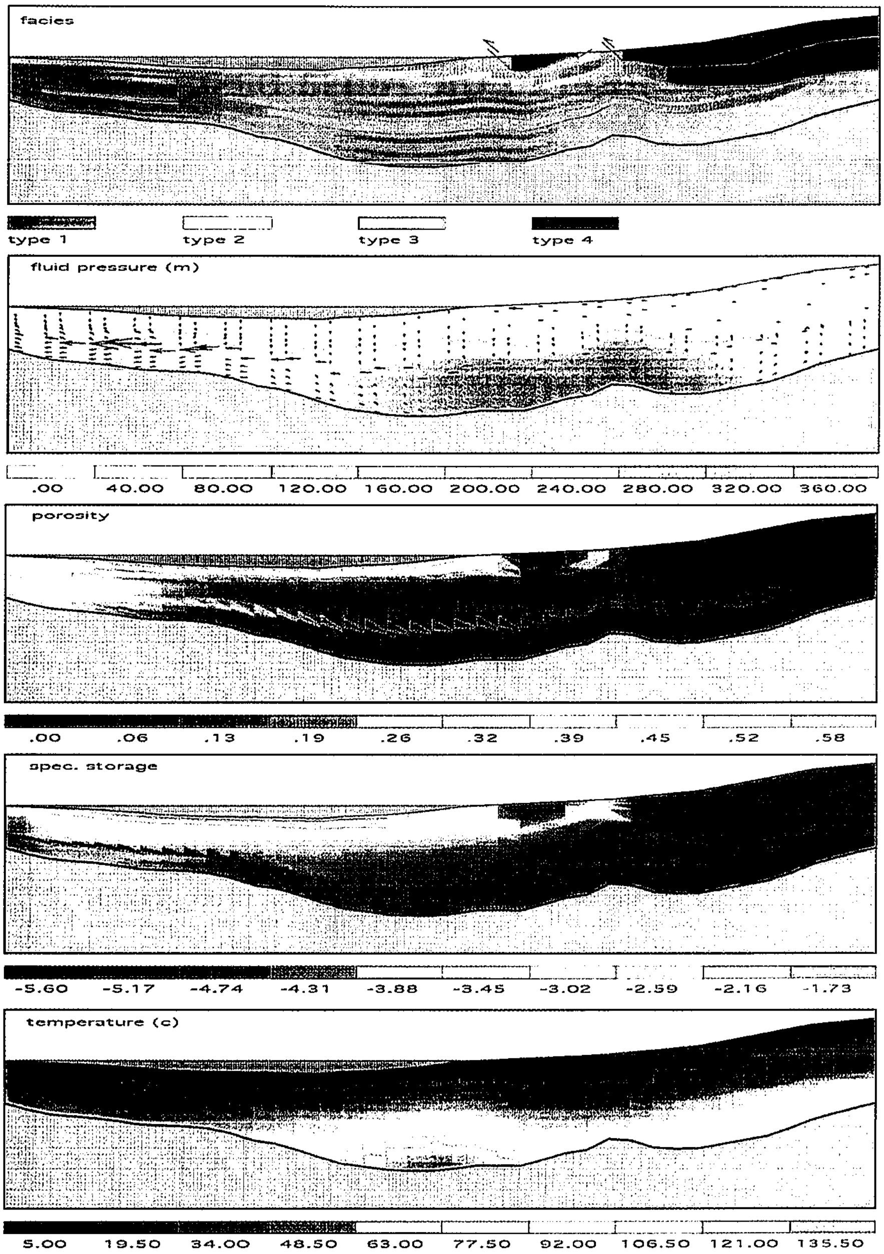

Table 1.- Cross sections along a compressive sedimentary basin extending 45 km. Height of box is 5000 m. Total time of simulation experiment: 40 Ma. Uppermost: facies distribution (type 1=coarse sand, type 2=fine sand, type 3=shale, type 4=thrust sheet), below: pressure head (given in m watercolumn) and fluid flow field, below: porosity, below: specific storage (logarithmic), lowermost: temperature (°C).

Tabla 1.- Secciones de una cuenca sedimentaria compresiva de 45 kms. La altura del gráfico es de 500 m. El tiempo de simulación total del experimento es de 40 Ma. Diagrama superior: (1: arena gruesa; 2: arena fina; 3: arcilla; 4: lamina cabalgante) Diagrama segundo: presión y migración de fluido. Diagrama tercero: porosidad. Diagrama cuarto: almacenaje específico. Diagrama inferior: temperatura (°C).

directed to the foreland. Such fluids may origin from deep sources and may eventually precipitate ore deposits. Observations of fluid vents in sedimentary wedges indicate that thrusting is an important process in dewatering the footwall sediments (Henry and Chi-Yuen Wang, 1991). Overpressured sediments are frequent in overthrusted sediments, and a decrease of overpressure can often be observed with increasing distance from a thrust front. Other parts of a compressive basin may partially and/or temporarily be elevated above sealevel. In this case topography-driven meteoric waters invades part of the basin sediments and thrusts sheets. This flow system will interfere with the compactional flowfield to some extent. Fluid volumes and velocities induced by topography-driven flow are several orders higher than those induced by compactional fluid flow. It is apparent that fluid migration in compressive basins are largely controlled by their tectonic evolution and the dimension of thrusting.

Due to moving thrust sheets, piggybag basins, uplift and erosive events, the geometry of a compressive basin undergoes considerable changes which are difficult to represent in a numerical model. Finite element meshes representing a basin geometry at a certain time step may have to be changed in the following time step due to partial erosion of sediment, advancing thrust sheets and uplift or subsidence. We use an automatic mesh generator which takes care of such changes and creates consistent meshes. The equations for transient fluid flow, solute- and heat transport as well as the nonlinear form of the equation of state for porosity are solved numerically (Bitzer, in press).

Application to the Ainsa thrust sheet system

The Ainsa basin developed during the first stages of the south-Pyrenean foreland basin evolution (Nijman and Nio, 1975). It is mainly filled by turbiditic sediments with intercalations of outer-shelf facies resting on Upper Cretaceous- Paleocene shelf carbonates (Fig. 1). The first nappe affecting the Ainsa basin-fill is the Cotiella nappe, which was emplaced syncronously to basin sedimentation (Nijman and Nio, 1975). The basin fill and the Cotiella nappe were deformed and uplifted during middle Eocene by the emplacement of underlying basement Gavernie and Nogueres thrust sheets (Séguret, 1972). Though results presented in table 1 are simulated from a preliminary model, they can be compared to some extent with the fluid migration model elaborated on the base of petrological and geochemical parameters for the Ainsa thrust sheet system.

Table 1 exhibits cross sections of a simulated compressive basin with thrust sheets. The upper section of table 1 represents a facies distribution. Type 1 sediments are coarse sands with initially 30% porosity, low compressibility and high hydraulic conductivity. Type 2 represents fine sand with initially 40% porosity, intermediate compressibility and intermediate hydraulic conductivity. Type 3 represents shales with initially 65% porosity, high compressibility and low hydraulic conductivity. Type 4 represents thrust sheets with 5 % porosity, low compressibility and low hydraulic conductivity. At the time step shown here, thrusting has already stopped and parts of the thrust sheets have already been eroded, leaving an isolated small «klippe» in the foreland. Below, the flow field and pressure head are still controlled to a large extent by the thrust sheets, that have earlier moved into the foreland basin. The flow field exhibits favorable fluid paths through the coarser lithologies and a dewatering from deeper sediments, coinciding with the model proposed for the Ainsa basin (Fig. 2). Parts of the basin above sealevel develop a topography driven flow of meteoric water. Below, the porosity distribution shows that the overthrusted sediments have lost most of their porosity and fluids, while the coarser layer has retained some of its porosity due to its low compressibility. Below, specific storage is low in the overthrusted sediments due to the intense compaction from the load of the thrust sheets (some of which have already been eroded at this time step). Finally, the temperature in the simulated basin arrives at values up to 135ºC, due to the assumption of an elevated heat flow of 3 hfu in the central and most subsiding part of the basin. Heat transfer in the example presented in table 1 is mostly diffusive as fluid flow velocities are low and do not contribute to appreciable advective heat transfer.

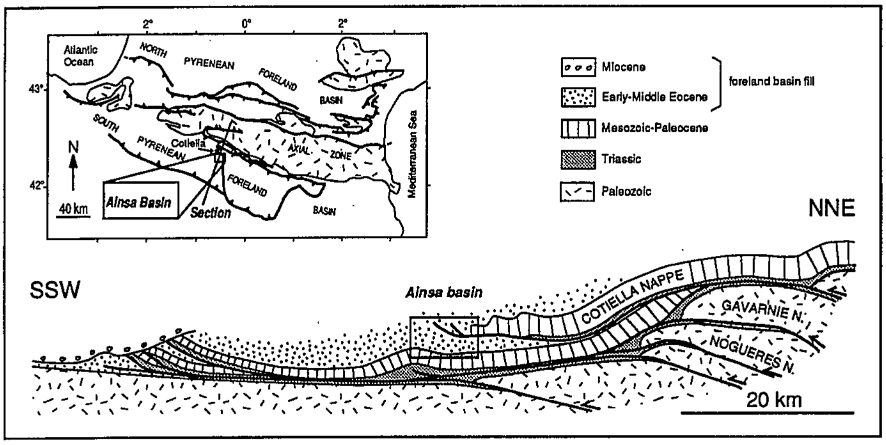

Fig. 1.- Cross section of the South-Central Pyrenean foreland basin (from Travé *et al.*, in press, modified after Séguret, 1972). Location of the Ainsa basin.

Fig. 1.- Corte esquemático de la cuenca de antepaís central surpirenaica (en Travé *et al.*, en prensa, modificado de Séguret, 1972). Localización de la cuenca de Ainsa

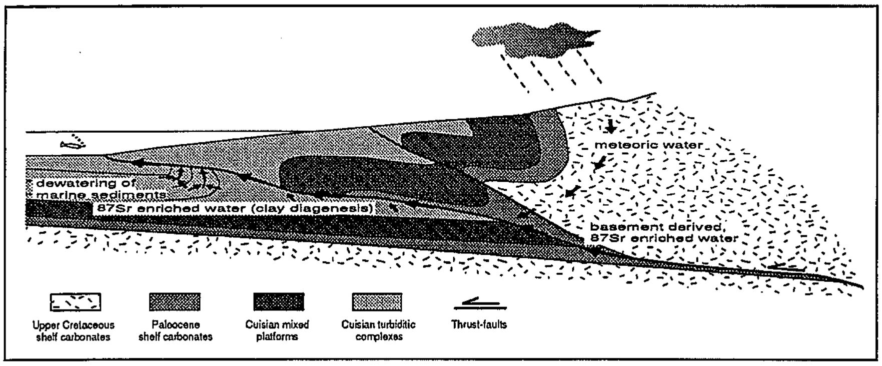

Fig. 2.- Model of fluid migration in the Ainsa basin from geochemical analysis (from Travé *et al.*, in press).

Fig. 2.- Modelo de migración de fluidosen la cuenca de Ainsa a partir de los análisis geoquímicos (en Travé *et al.*, en prensa)

Conclusions

The model presented here is a valuable tool to understand possible fluid migration paths in compressive basins. It can be used to test hypotheses on fluid origin, timing of diagenetic processes and structural evolution. Data for experiments comprise petrophysical data of sediment types, sediment thickness and timing of thrust emplacement. For the Ainsa basin data obtained by petrological and geochemical analysis (Travé *et al.*, in press) are in good agreement with fluid paths deduced from the preliminary model presented here, although modifications on the modeling parameters such as the geometry of the thrust sheet system and facies distribution in the basin will be necessary.

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