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# Fluid flow modeling in distensive basins

## *Modelización de la migración de fluidos en cuencas distensivas*

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ABSTRACT

*We present a mathematical model of consolidation, fluid flow, solute transport and heat flow capable of calculating the paleohydrogeological evolution of distensive sedimentary basins. The constituting equations are complemented by a new approach of calculating consolidation as a function of a porosity-dependent sediment compressibility.*

RESUMEN

*Presentamos un modelo matemático de consolidación, migración de fluídos, transporte de solutos y calor que permite calcular la evolución paleohidrogeológica en cuencas sedimentarias distensivas. Las ecuaciones elementales se complementan con un planteamiento nuevo en el cálculo de la consolidación como función de la relación porosidad - compresibilidad del sedimento. Este modelo se aplica a la cuenca distensiva neógena del Penedès (Cordilleras Costero Catalanas) con el fin de determinar la evolución de la migración de fluídos durante la formación y relleno de esta cuenca.*

**Key words:** *Basin modeling, fluid flow, consolidation, compressibility*

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### Introduction

Sediment deformation, expulsion of porewater and fluid flow in sedimentary basins due to sediment loading are coupled processes, controlled by the compressibility of the sediment and its permeability. Flowing porewater controls to a large extent the diagenetic evolution of sedimentary basins. It alters the physical and chemical properties of a deposit and eventually leads to the formation of mineral resources (Garven & Freeze, 1984) or hydrocarbon reservoirs. Here, we present a mathematical model that calculates the paleohydrogeological and paleothermal evolution of a sedimentary basin. Although the model is capable of calculating fluid flow, sediment consolidation and solute- and heat transport, we present in this paper only the hydraulic and sediment consolidation part of the model. Numerical solutions derived with our model (Bitzer, 1994) are in accordance with exact solutions by Gibson (1958) and numerical solutions given by Bethke & Corbet (1988). Preliminary results of an application to a distensive basin are demonstrated.

### Controls on fluid flow and consolidation

Most models published so far couple fluid flow and porosity loss through the equation of Athy (e.g. Bethke, 1985, Wangen, 1992, Pedersen & Bjørlykke, 1994). While the equation of Athy may be used as an empirical description of the changes of porosity with depth, the equation has severe limitations and should not be used for compactional fluid flow models because of several reasons:

1.The equation does not refer to a physical process and is not in accordance with the equation of state for the porous medium, which can be derived analytically.

2.The equation does not involve the sediment compressibility as the controling parameter of the deformation process.

3.Porosity does not only depend on depth or pressure load but on diagenetic processes involving chemical reactions. The equation does not distinguish between chemical and mechanical processes of porosity loss.

Athy (1930, p. 13) considered the compressibility of the sediments as a controling factor. He inferred a porosity-depth function, which was constructed from average porosities measured at different stratigraphic depths. Originally, he expressed the relation by a logarithmic equation of the form

$$P=p\ ( e^{-bx}) \qquad (1)$$

with P= porosity, p= average porosity of surface sediment, x=depth of burial and naming b a constant. This function has been used to predict porosities or to estimate depth of burial. It has been noted, that equation (1) is only applicable in case of a compaction equilibrium, when fluid expulsion has already finished and fluid pressure is hydrostatic. Therefore, the equation has later been changed to

$$\phi= \phi_0\, e^{-cs} \qquad (2)$$

with $f_0$= average porosity of surface sediment, c= compaction coefficient and s= effective stress (instead of burial depth), such that it can be used in case of fluid pressure being greater than hydrostatic, and under the assumption, that no chemical diagenesis occurs (Luo and Vasseur, 1992).

Although the equation of Athy or equivalent forms of it can be used for backstripping calculations, its application to coupling sediment deformation and

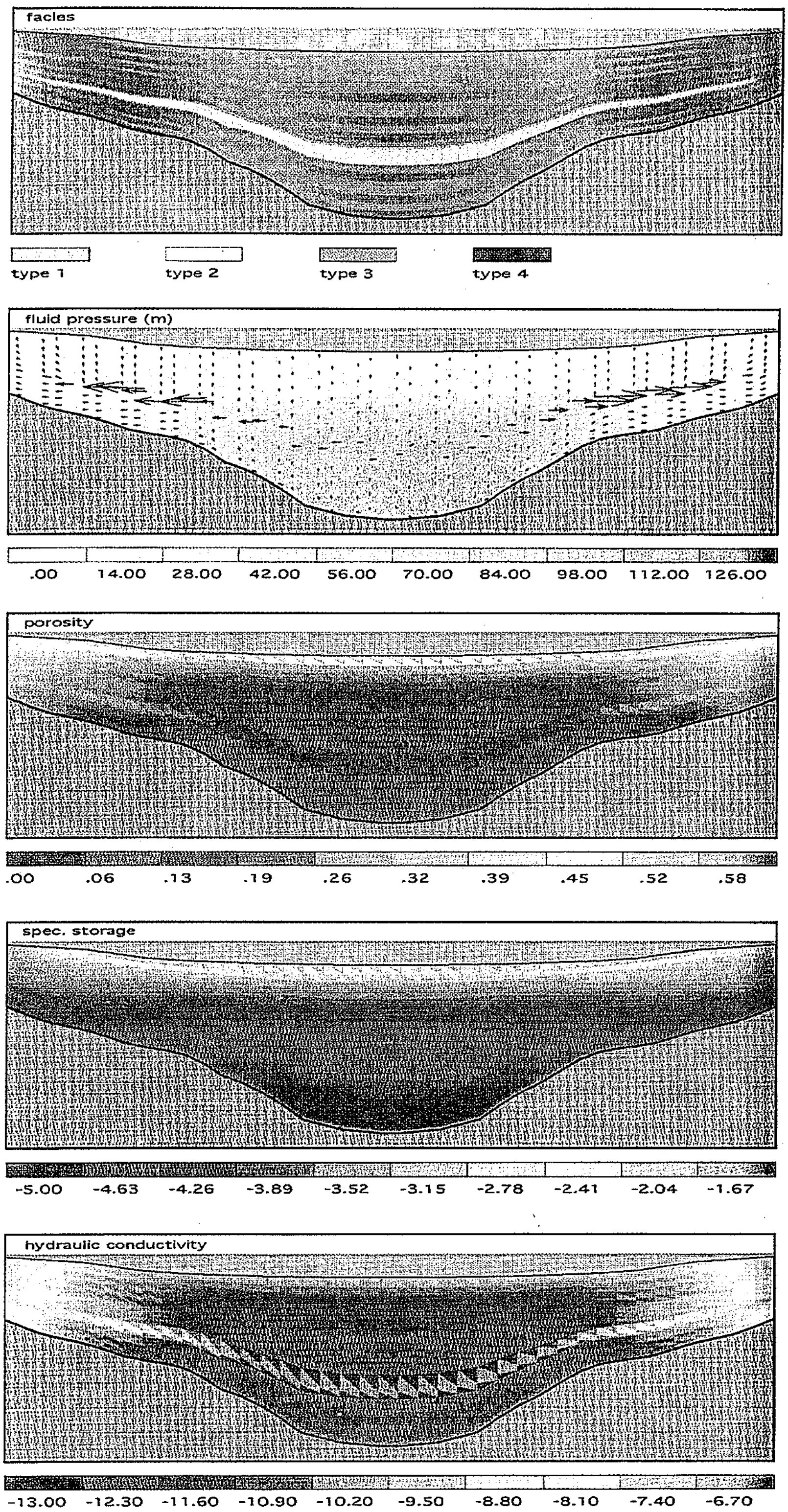


**Table 1.-_Cross sections through a distensive sedimentary basin extending 35 km and maximum sediment thickness of 2500 m. Total time of simulation experiment: 40 mio. y. Uppermost: facies distribution (type 1=gravel, type 2=sand, type 3=shale, type 4=carbonate), next: hydraulic head and consolidational flow field, next: specific storage, lowermost: hydraulic conductivity.**

*Tabla 1.- Secciones de una cuenca sedimentaria distensiva de 35 kms. de largo y un epesor máximo de 2500 m. de sedimento. El período de simulación total del experimento es de 40 Ma. Diagram superior: distribución de facies (tipo 1: gravas; tipo 2: arena; tipo 3: arcillas; tipo 4 carbonatos). Segundo diagrama: presión de agua ( expresada en m de columna de agua). Tercer diagrama: porosidad. Diagrama inferior: conductividad hidraulica.*

fluid flow is not useful and stems from a widespread misconception in interpreting the equation as a physical law. It has been attempted to give the equation a more «physical touch» by renaming the compaction coefficient c of the equation of Athy as sediment compressibility a $\phi$ (Wangen, 1992, quoting Bjørlykke), a procedure which is not justified. It should be agreed with Baldwin & Butler (1985) that the equation of Athy has outlived its usefulness. Unfortunately, it is still used in many compaction and fluid flow models.

In order to involve sediment compressibility as the principal physical property governing porosity loss, the equation of state for the porous medium can be derived analytically (e. g. deMarsily, 1986) leading to

$$\partial\phi/\partial pf=\alpha(1-\phi) \qquad (3)$$

The equivalent form of Athy´s equation

$$\partial\phi/\partial pf=(b-(pg))\phi \qquad (4)$$

exhibits two importan differences:

- the equation of Athy relates the loss of porosity to the porous portion of a sediment, while the equation of state for the porous medium relates the change of porosity to the solid portion, which represents the sediment fabric,

-the equation of state for the porous medium involves the sediment compressibility, while the equation of Athy does not.

As the sediment compressibility obviously decreases considerably during the compaction process due to rearrangement and deformation of sediment grains, sediment compressibility should be expressed as a function of porosity. Such an equation can be derived by considering the hydraulic diffusivity of sediment during consolidation. Bredehoeft & Hanshaw (1968: 1103) conclude that the hydraulic diffusivity, i.e. the quotient of hydraulic conductivity and specific storage will remain more or less constant during the consolidation process, a conclusion which is supported by data from Neuzil (1986: 1176). Consequently, if hydraulic conductivity changes during compaction, specific storage (and sediment compressibility) will change at a similar rate. We use the Kozeny-Carman equation to calculate hydraulic conductivity from porosity and a similar form of this equation to calculate sediment compressibility from porosity:

$$a = c\,(\phi^3 / (1-\phi)^2) \qquad (5)$$

with c as a scaling factor.

The equation of state of porosity can be combined with the flow equation, leading to the consolidation equation (deMarsily, 1986):

$$(\partial/\partial x)(k_x\,\partial p_F/\partial x) + (\partial/\partial z)(k_z\,\partial p_F/\partial z) = (1-\phi)\,r\,g\,a\,\partial p_F/\partial t \qquad (6)$$

which is solved for variable hydraulic conductivity and variable sediment compressibility using the Kozeny-Carman equation and eq. (5). A finite element model allows an easy incorporation of the moving boundaries and coordinates involved by the basin deformation due to sediment consolidation and tectonic processes. A derivation of governing equations of flow, deformation and transport is given by Bitzer (in press).

### Application to the Penedes basin

The Penedès-Vallès graben is located in the NW branch of the Gulf of Valencia, outcropping in the Catalan Coastal Range. The Valencia trough is asymmetric with the Iberian margin characterized by extensional tectonics and the Betic-Balear margin structured in a NW-directed thrust system (Fontboté *et al.* 1990).

The Iberian margin of the Gulf of Valencia includes the Iberian Range and the Catalan Coastal Range. The structure of the Catalan Coastal Range is dominated by longitudinal faults which trend from NE-SW to ENE-WSW. During the Alpine compressive phase, these faults moved sinistrally with local transpression (Guimerà, 1988; Anadon *et al.* 1985; Roca & Guimerà, 1992). Some of these faults were reactivated as normal faults during the Neogene extension. The Neogene structures of the Catalan Coastal Range are horsts (Garraf, Bonastre, etc.) and grabens (Vallès-Penedès, El Camp, etc.). This Neogene system is bounded by extensional faults (Vallès-Penedès fault, Camp fault) trending ENE-WSW.

The Vallès-Penedès basin is a half graben, up to 100 km long and 12-14 km wide, orientated NW-SE. The western margin (the VallèsPenedès fault in the Penedès-Vallès half graben) is downfaulted 3000 m whereas the facing eastern fault margin is only up to a few hundreds of metres. The southern part of the Vallès-Penedès basin is known as Penedès basin, where the study was carried out.

The stratigraphic record in the Penedès basin has been divided into four informal lithostratigraphic units (Cabrera *et al.*, 1992; Cabrera & Calvet, 1996) which from base to top are: (1) Aquitanian (?)-Burdigalian Lower continental units, consisting of thick, up to 2.000 m, red bed sequences deposited as alluvial fan complexes (Cabrera, 1982; Cabrera *et al.*, 1992). (2) Langhian continental and transitional units with reefal carbonate platforms (Permanyer, 1982; Cabrera *et al.*, 1992). (3) Lower Serravallian continental and transitional units with a mixed carbonate-siliciclastic shelfs. (4) Middle Serravallina-Tortonian Upper continental unit, consisting of thick red bed sequences.

As a first approach we simplified the geometry and the sedimentary filling of the Penedès basin in order to test the applicability of the model. The example given in table 1 represents some typical features of a distensive basin, where basin deformation is only caused by consolidation and tectonic subsidence. Continuous filling of the basin is calculated over a period of 40 mio.y. The final situation is shown as colored cross sections representing facies distribution, hydraulic head, specific storage and hydraulic conductivity. Cross sections extend 35 km and maximum sediment thickness reaches about 2500 m. The basin exhibits a relative simple sediment fill with mainly sediment type 3 in the center of the basin, representing shale. A prominent layer in the lower part of the deposit is defined as a mixture of sediment types 1 and 2, representing gravel and sand (red to orange colours). Due to its higher hydraulic conductivity, this layer acts as a conduct for porewater expelled from adjacent compacting shales during the evolution of the flowfield. While mainly shale is deposited in the central parts of the basin, mixtures of gravel and sand are located at the edges of the basin, interfingering with shale, a facies distribution which is reflected by the hydraulic conductivity (lowermost cross section of table 1), showing high values (yellow to red colors) at the basin edges. The change of sediment compressibility during consolidation is reflected by the specific storage in cross section 3 in table 1. Youngest surfical layers exhibit values up to $10^{-1.5}$ $m^{-1}$, while layers buried in the deeper parts of the deposit have lost most of their specific storage (and compressibility).

Although the example given here is highly simplified, some aspects of the calculated flowfield such as lateral fluid flow through pervious layers will probably coincide with the Penedès basin. Future experiments will involve a better representation of the basin geometry and basin fill and will take into account effects of hydraulic conducting faults.

### Conclusions

A mathematical model of fluid flow, solute- and heat transport in sedimentary basins is a valuable tool in constraining the evolution of sedimentary basins. It can be used to forecast petrophysical data, hydraulic and diagenetic evolution of a basin as well as putting constraints on the generation of hydrocarbons during basin evolution. With respect to the neogene Halfgrabens in Catalunya, we intend to apply the model to identify phases of fluid flow that correspond with diagenetic phases during the evolution of the basin and to determine flow paths, flow velocities and thermal history of the basin.

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