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Introduction to Special Issue on INTEGRATED BASIN STUDIES (IBS) — a European Commission (DGXII) project

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Background of the IBS project

This issue contains papers issued from the Integrated Basin Studies Project (IBS) which is part of a larger program of the European Commission DGXII, entitled Geosciences II. The IBS project (EC contract JOU2 - CT92 - 0110) originated in Geosciences consultation meetings, the first of them being held in Strasbourg in June 1989 under the auspices of Mr Hubert Curien, former French Minister for Research and Technology, and the subsequent meeting being held in Brussels. These consultation meetings have resulted in the conclusion that a main axis of future research in Geosciences should be the study of sedimentary basins, upstream of industrial activities, mainly the oil and gas industry but also water resources management, the mining industry, the storage of undesirable products and coastal engineering. They also resulted in the conclusion that future research on sedimentary basins should fulfill two requirements: integration of disciplines and modelling. Such a conclusion may now seem trivial but was not so generally accepted at that time.

In this spirit, the IBS project was designed to provide the oil and gas industry with a new generation of models for basin formation, basin evolution and basin fill architecture from basin scale to reservoir scale. Its main objectives are the linkage of crust thermomechanical behaviour to basin formation and deformation mechanics and the corresponding modelling, the quantification of tectonic control on the sedimentary record and the analysis of compaction and mass and heat transfer. The IBS strategy is to link subsurface data to field data, and an important part of the project is devoted to thematic field studies in European sedimentary basins of different tectonic styles, taken as natural laboratories.

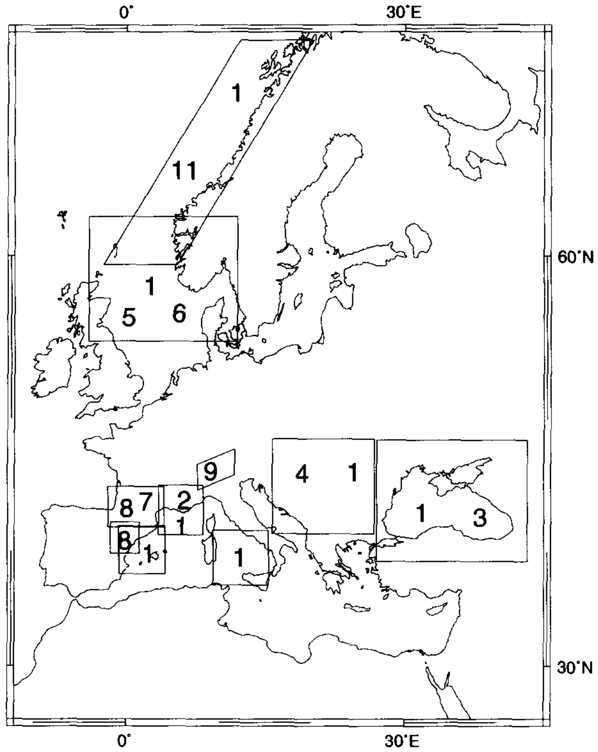
Basin research has gone through a rapid evolution during the last decade, in particular through the development of new acquisition and processing methods for seismic data and advances in drilling technology. Modelling provides an important tool to analyse different aspects of basin formation processes and find their tectonic expression in the basin fill. The need for 3-D modelling techniques and models capable of linking processes operating on basinwide to subbasin scales is increasingly recognized and a significant effort has been made in the IBS project to develop a new generation of basin formation models coping with these needs (see also Cloetingh *et al.*, 1993a; Van Wees and Cloetingh, 1994). As many data required to test these models reside in industrial companies, IBS has promoted a closer link between academic research and basin studies carried out by industry. The participation of the petroleum industry has been vital in this project and IBS has been able to establish a well functioning system of cooperation that not only facilitated data access, but most important, guaranteed the suitability of the end products of the project. This has led to an intensive exchange of modelling concepts and data sets between industry and academia. The IBS project has also used extensively the International Lithosphere Program Task Force "Origin of Sedimentary Basins" (See Cloetingh, Sassi and Task Force Team, 1994; Cloetingh *et al.*, 1993a,b; 1994) to implement planning and to discuss preliminary results. It also builds partly on joint research through the European Commission TEMPUS and PECO Programs on Pannonian basin studies (Horvath, 1993; Van Balen and Cloetingh, 1995; Van Balen *et al.*, 1995; Horvath and Cloetingh, 1995).

A stimulating aspect of the activity of the IBS group is the creation of a research network in the corresponding field of knowledge which comprises now 30 teams belonging to eight European countries (England, France, Germany, Hungary, Norway, Spain, Switzerland and The Netherlands). This demonstrates the capacity of the procedures used by the DGXII of the European community to formulate a really European research space. PhD students and young researchers form an important component of the research groups cooperating in the IBS. The integrated nature of basin research and the strong international cooperation in IBS appears to be a positive factor in their training, also in view of future employment within the petroleum industry.

Themes of the IBS and highlights of recent developments

Extensional basin formation mechanisms

Rheology forms a key factor in the dynamics of extensional basin formation (Vilotte *et al.*, 1993; Bassi *et al.*, 1993; Quinlan *et al.*, 1993). Important advances have been made over the last few years in our understanding of continental lithosphere rheology (Burov and Diament, 1995), supporting a finite strength of the lithosphere during extension. The formulation of the latter in terms of a level of necking in the extending lithosphere (Braun and Beaumont, 1989; Kooi *et al.*, 1992; Bassi *et al.*, 1993; Spadini *et al.*, 1995) has significantly affected predictions for rift shoulder development and basin fill.



Map of IBS basins discussed in the papers of this issue.
Numbering refers to the following publications:

Areas (natural laboratories) selected for the Integrated Basin Studies project (IBS)

THEME 1:
EXTENSIONAL BASIN FORMATION MECHANISMS AND BASIN FILL

1. Cloetingh *et al.* (Black Sea, Pannonian Basin, Tyrrhenian Sea, Gulf of Lion, North Sea, Barents Sea, Valencia Trough)
2. Séranne *et al.* (Gulf of Lion)
3. Robinson *et al.* (Black Sea)
4. Horváth (Pannonian Basin)
5. Jordt *et al.* (Central North Sea)
6. Nottvedt *et al.* (Northern North Sea)

THEME 2:
FORELAND BASIN EVOLUTION AND BASIN FILL

7. Vergés *et al.* (Eastern Pyrenees)
8. Millán *et al.* (Eastern Pyrenees, Ebro Basin)
9. Jin *et al.* (South-Eastern German Molasse Basin)

THEME 3:
COMPACTION AND HEAT AND MASS TRANSFER

10. Vasseur *et al.* (Laboratory study)
11. Aplin *et al.* (Norwegian Margin)

In IBS we have tested models for extensional basin formation through a systematic comparison with data sets from selected basins. North-Western Europe and the North Atlantic margin are, together with the Pannonian basin and parts of the Western Mediterranean, key areas in Europe for the study of extensional basin formation. The paper by Cloetingh *et al.* (this issue) addresses the question of whether basin extension in convergent regimes is fundamentally different from intracratonic extension. As shown by this contribution, inferred differences in necking level during extension can be largely explained by differences in the pre-rift history of the lithosphere underlying these basins. Of particular importance appears to be the pre-rift configuration of the crust and lithosphere, affecting the level of stresses required to induce extension, and yielding insight into the role of orogenic collapse in extensional basin formation. The paper by Séranne *et al.* (this issue) on the Gulf of Lion also points to a key control by pre-rift Pyrenean orogeny on the mode of extension in this young rifted margin. In the paper by Robinson *et al.* (this issue), important differences observed between the tectono-stratigraphic evolution of the Eastern and Western Black Sea are examined by using a model incorporating a finite strength of the lithosphere during extension. These authors demonstrate a key control exerted by differences in pre-rift structure of the Eastern and Western Black Sea on the post-rift evolution of this basin. All these studies show the existence of strong differential uplift at the flanks of these extensional basins, highlighting the need to quantify the amount of erosion at the basin margins. Forward modelling can now be successfully combined with back stacking of eroded sediments from rift shoulders, constrained by fission track data and modelling (Van der Beek *et al.*, 1994; Kooi and Beaumont, 1994), which will lead to a better understanding of this aspect of basin evolution.

Causal relationships predicted by large scale models for flank uplift can also be explored on the sub-basin scale, where the role of faulting has been modelled by the application of, for example, flexural cantilever models (Kusznir *et al.*, 1991). Ter Voorde and Cloetingh (1995) recently coupled a large scale model for the isostatic response of the lithosphere to basin loading with small scale models incorporating faulting developed by Waltham (1989). These models offer a framework for exploring the role of stresses on the stratigraphy of tilted fault blocks as well as the consequences of faulting on fluid flow (Knipe, 1993). Stresses form a crucial aspect of the formation (Zoback *et al.*, 1993a) and evolution of sedimentary basins (Cloetingh and Kooi, 1992; Ziegler, 1992; Daudré and Cloetingh, 1994). On a basinwide scale stresses are an important factor in the control of basin stratigraphy

(Cloetingh and Kooi, 1992; Kooi and Cloetingh, 1992; Peper *et al.*, 1994) and fluid flow (Van Balen and Cloetingh, 1993; 1994). Basins such as the North Sea basin and the Pannonian basin, formed in an extensional regime, are presently in a regime of compressional stress, documented by stress measurements in these basins (Muller *et al.*, 1992). Forward modelling and neural network analysis (Van Balen *et al.*, 1995; Van Balen and Cloetingh, 1995; Horvath and Cloetingh, 1995) has pointed to a strong effect by late-stage compression on the development of overpressures in the Pannonian basin. In the paper by Horvath (this issue), the effect of such changes in stress field on the hydrodynamic regime during the post-rift evolution of the Pannonian Basin is examined. These findings highlight the need for more stress data to be obtained through careful analysis of industry well breakouts (Muller *et al.*, 1992; Zoback and Burke, 1993) and by measurements in deep continental drill holes (Zoback *et al.*, 1993b).

The role of magmatic processes inferred from petrological and isotope studies (Wilson, 1993) and the modelling of the interplay of melts and stretching are both essential ingredients to be integrated in future modelling packages before adequate stratigraphic modelling can be carried out at volcanic rifted margins.

The paper by Jordt *et al.* (this issue) is a careful revision of the Cenozoic fill of the Central and Northern North Sea, which is used to substantiate the nature and timing of tectonic movements and sea-level changes. This will give the basis to constrain the modelling of the evolution of these basins during this period.

Along this line, the paper by Nottvedt *et al.* (this issue) is already a first and convincing attempt to derive a general model of rift formation and evolution from the data made available by the study of the North Sea examples.

Foreland basin evolution and basin fill

The topic of constraining the various controls on the sedimentary record, forms one of the key objectives of the IBS, that should be considered at crustal and basin fill sediment unit scales. It requires both advances in new modelling technology as well as the collection and interpretation of high quality data on the basin fill and its structural context.

The Southern Pyrenean foreland basin forms through its superb outcrop conditions, the availability of extensive deep crustal control, and a strong record of high quality research, probably the best natural laboratory to quantify the tectonic control on basin fill in compressional settings. The two linked papers by Vergés *et al.* and Millán *et al.* (this issue) represent a significant step in the understanding of the relative role of the various factors which interplay in the original evolution of the Southern Pyrenean foreland basin at crustal scale. Vergés *et al.* (this issue) present a new balanced cross section in the Eastern Pyrenees at pre-collisional, collisional and present-day stages, and quantify and discuss erosion and sedimentation budgets. Ongoing field studies in the Tremp and Ainsa basins will be the basis for further modelling with the purpose of testing field interpretations, to improve the modelling techniques at the scale of geometry and stratigraphy of the basin fill, and clarifying the relations between tectonics, eustasy and climate in the control of sequence architecture. The contribution by Millán *et al.* (this issue) builds on these interpretations for the modelling of the flexural evolution of the Southern Pyrenean foreland basin, supporting the existence of important lateral variations in crustal rigidity, connected to the Neogene opening of the Valencia Trough. These authors also examine, through modelling, the role of palaeo-relief in erosion and sedimentation dynamics of the basin. These studies have set the framework for detailed modelling on the sub-basin scale. The importance of coupling large-scale basinwide flexure, thrusting on sub-basin scale, and eustasy for forward stratigraphic modelling of piggy-back basins in foreland fold-and-thrust belts has been demonstrated recently by Zoetemeijer *et al.* (1993).

The paper by Jin *et al.* (this issue) focuses on the subsurface record of the Molasse basin of Southern Germany. These authors discuss sequence stratigraphic aspects of the basin fill, which will be used in future work to verify the relative roles of tectonics and eustasy by the use of large-scale modelling, developed in the IBS programme (Peper *et al.*, 1994).

Compaction and heat and mass transfer

Incorporation in basin models of the rheology of compaction, i.e. of the physical laws which link, during the course of basin evolution, deformations and failures of compactable sediments to stresses and pore pressure, is essential to perform the work dedicated to the modelling of basin deformation and fill. Indeed, compactable sediments, mostly clays, make up 60 to 70% of the basin fill on average and, therefore, compaction may have considerable effects, which have to be computed and taken into account to properly restore subsidence, thickness of sediment layers (Perrier and Quiblier, 1974), and the geothermal evolution of the basin fill. Lithology and petrofabrics of clays and shales, which rule these effects, are as variable as those of sandstones and carbonates. However they have received much less attention so far, probably because of the difficulty of their study.

Furthermore, compaction creates in compactable media, pore pressure gradients which are responsible for mass transfer in the form of an expulsion of water and hydrocarbon fluids (Magara, 1978; Ungerer *et al.*, 1984; Bethke, 1985; England *et al.*, 1987; Durand, 1988; Ungerer *et al.*, 1990) eventually accompanied by chemical effects in the environment (Franks and Forester, 1984), and are also responsible for associated phenomena such as the development of over-pressure and seal failure (Magara, 1981). Compaction is also responsible for variation of thermal conductivity in compacting sediments (Brigaud *et al.*, 1990). For all these reasons, the incorporation of compaction rheology is particularly important in 'basin simulators' dedicated to the needs of the petroleum industry, which describe the formation and the accumulation of hydrocarbon fluids in the frame of basin evolution (Doré *et al.*, 1993; Larsen *et al.*, 1992; Horbury and Robinson, 1993; Parnell, 1994). In such simulators, for instance Temispack (Ungerer *et al.*, 1990), compaction rheology is described by a set of simple pragmatical laws: (i) the so called 'effective stress law', as initially proposed by Smith (1971), following the formalism of Terzaghi

(1925) for soils, which states that in compacting sediments, the effective stress on the solid matrix can be computed as the difference between sedimentary load and pore fluid pressure. (ii) An empirical law, variable according to lithology and calibrated on well data, which links effective stress to porosity. (iii) The diphasic Darcy's law which describes the speed of fluid expulsion (water phase + hydrocarbon phase) and therefore of porosity reduction. Research is developing to refine this approach by introducing, in compaction models, parameters which describe the elastoplasticity of sediments (Biot, 1941; Kuempel, 1991; Schneider, 1993) and their viscoplasticity due to pressure solution effects (Rutter, 1983; Palmer and Barton, 1987; Schneider *et al.*, 1994) to describe more realistically the stresses–pore pressure relationships, and to take into account the chemical effects of compaction at depth. The IBS project has dedicated a large effort to a better understanding of compaction rheology, by means of observational, experimental and theoretical approaches, to incorporate into basin models as accurately as possible, the rheological laws to compute sediment layers of deformation and failure and pore pressure gradients. One approach is along the 'conventional' lines which have been described above. Another approach, which is illustrated in this issue by the papers of Aplin *et al.* and Vasseur *et al.*, builds on soil mechanics concepts. In this approach, it is assumed that the void ratio of a normally compacting sediment sample relates linearly, when the compaction equilibrium is reached, to the logarithmic value of the mean effective stress, as shown experimentally for soils (Skempton, 1970; Burland, 1990; Atkinson, 1993). The slope of the line, called the compaction coefficient C_c, and its intercept at a reference stress, are parameters which characterize the sediment sample and are strongly dependent on its mean grain size. Aplin *et al.* (this issue) have derived from these assumptions, a physical model for normally compacted mudstones, that they show to be fairly applicable to a series of mudstones from a North Sea well. The study emphasizes the importance of the mean grain size, i.e. of lithology, as a key factor of compaction rheology. It also suggests that prudence is necessary when intepreting the variations in sonic logs in terms of pore fluid pressure, because these variations might be due to lithological variations in clays as well. A composite ß log, derived from electrical logs, is proposed to follow the lithological variations in wells. The paper by Vasseur *et al.* describes compaction experiments conducted on St. Austell's kaolinite in a specially equipped oedometric cell. Measurements are made after loading by steps from 0.1 to 50 MPa so as to characterize after each step microstructure (granulometry, specific surface area measurements, transmission electron-microscopy imaging), pore space (porosimetry by mercury injection and water removal under low water vapour pressure) and macroscopic transfer properties (hydraulic conductivity, thermal conductivity). It is verified that the void ratio at compaction equilibrium is linearly dependent on the logarithm of the mean effective stress, as explained above, up to the maximum load (50 MPa). It is shown that the permeability decreases faster as a function of porosity than described by the Kozeny–Carman formula which is used in 'conventional' basin simulators. Surprisingly it is also found in these experiments that the radial thermal conductivity increases with compaction while axial conductivity appears to be constant or even to decrease.

Future steps in the IBS

IBS has just reached its mid-assessment term. A number of key questions on the dynamics of basin development remain to be solved, offering a large number of challenges for the project. In this context continued studies of the deep structure of basins and the interaction between basin development, basin structural grain and local and regional stresses are obviously required. In addition, the mechanics of crustal deformation and the architecture and development of break up unconformities promises to be an area of vigorous research in the years to come.

Furthermore, the conception of better sedimentation models thanks to a careful study of the balance between erosion and sedimentation in basins which are tectonically active at present times will be a major way of research to complete the work. This will not be possible in the frame of IBS, which ends on 31 December, 1995, but can be done by the researchers who are involved in the network which has been created thanks to IBS and to the task force 'Origin of Sedimentary Basins' of the International Lithosphere Programme.

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