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Structural controls on sedimentary basin evolution: introduction

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1. Introduction and background

This volume contains a collection of papers on structural controls on sedimentary basin evolution presented at the sixth annual workshop of the International Lithosphere Program Task Force 'Origin of Sedimentary Basins' in Sitges, at the rim of the Ebro Basin, September 1995. Previous workshops of the ILP Task Force had been in Rueil Malmaison, France (1990), in Matrahaza, Hungary (1991), on the rim of the Pannonian Basin, in Sundvollen, Norway (1992), in the Oslo graben, in Benevento, Italy (1993), in the Southern Apennines fold-and-thrust belt, and in the Dead Sea Rift of Israel (1994). The Task Force also organized a number of sessions during the 1992 and 1996 European Geophysical Society and the 1993 and 1995 European Union of Geosciences Conferences. Reports of these meetings have been published in a number of special volumes and papers (Cloetingh et al., 1993a,b, 1994, 1995a,b, 1996; Stephenson, 1993; Stephenson et al., 1996). A position paper (Cloetingh, Sassi and Task Force Team, 1994), published in *Marine and Petroleum Geology*, has outlined the Task Force strategy to pursue the development of a new generation of basin models using natural laboratories with high-quality data sets obtained through close partnership with industry. The 7th Task Force workshop was held on the Faroe Islands (Northern Atlantic) in 1996 with the aim of examining the dynamics of rifting

and volcanic rifted margin formation. The 8th Task Force meeting organized in the Palermo Mountains of western Sicily focused on the topic of time scales in basin evolution and episodicity versus continuity in the controls on the sedimentary record.

The emphasis of the Sitges workshop was on modelling studies as well as observational approaches to the dynamics of fold-and-thrust belts. Important elements of the meeting were the role of stresses in basin evolution, the comparison of kinematic and dynamic modelling approaches to extensional and compressional basins and the discussion of data sets from various natural laboratories, and their incorporation in modelling studies. Following the Task Force strategy to link subsurface data to field analogues, an important part of the meeting was devoted to a thematic excursion in the Catalan Coastal Ranges and the adjacent northeastern segment of the Southern Pyrenees fold-and-thrust belt. Field guides have been published separately (Muñoz, 1996). The twenty papers in this volume discuss various aspects of sedimentary basin research, emphasizing the connection between new conceptual advances on structural controls on basin evolution and the validation of basin models through regional studies.

2. Rationale for an ILP Task Force on origin of sedimentary basins

The Task Force was initiated to facilitate the development of a new generation of basin models by promoting a closer interaction between observational and modelling approaches. To this aim, different

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project teams and working groups were formed on the themes 'Stresses and basin evolution' (Zoback et al., 1993), 'Rheology and basin formation' (Vilottte et al., 1993), and 'Near-surface expression of lithosphere processes' (Quinlan et al., 1993). Parallel to this effort a strong focus was put on building a network of cooperating research groups jointly working on data sets from various natural laboratories. A substantial part of these data have been provided through close collaboration with industry, in particular in the framework of the EU sponsored Integrated Basin Studies Program (IBS) (see Cloetingh et al., 1995b). The ILP/IBS teams have focused in particular on the Norwegian margin/North Sea, the Pannonian Basin and surrounding areas and the Southern Pyrenean foreland-fold-and-thrust belt. The new opportunities for research cooperation with groups in eastern Europe and the FSU provided another challenge for the Task Force. The Task Force has promoted joint research in these areas in close collaboration with the ALCAPA project (Neubauer et al., 1997) and the Intraplate Tectonics and Basin Analysis team of EUROPROBE (Stephenson et al., 1996; Nikishin et al., 1996). Central in the Task Force mission has been the need to shorten the loop time between modelling development and validation, by endorsing a close feed-back between modelling and observations. 3-D modelling is becoming increasingly feasible and capable to link for example 3-D flexure with faulting (Van Wees and Cloetingh, 1994, 1996; Van Wees et al., 1996; Sassi and Faure, 1996). The new opportunities provided by information technology, visualisation techniques (Van Wees and Kok, 1997) and the growing availability of 3-D seismic data (Gabrielsen and Strandenes, 1994) make the further integration of basin modelling with data-acquisition and the construction of large data-bases a topic of high priority also in the next phase of basin research (Buchanan and Nieuwland, 1996).

3. Themes of the Task Force and highlights of recent developments

Basin modelling is shifting its focus to the coupling of different temporal and spatial scales involved in the interplay of lithospheric and near-surface processes. To this purpose, basin modelling is widening its scope from an initial focus on subsi-

dence and geometry of accommodation space into the modelling of the feed-back of the processes of sedimentation and erosion (e.g. Burov and Cloetingh, 1997). The latter invokes the need to better constrain the evolution of topography in space and time. For example, in the modelling of extensional basins, the reconstruction of rift shoulder topography and the backstacking of sediments from the rift on the rift shoulder (Van der Beek et al., 1994) is becoming increasingly important. Also basin geometry and basement vertical movements associated with lateral material accommodation during extension have been recently investigated (e.g. Zeyen et al., 1996). The availability of constraints by fission track data (Rohrman et al., 1995) and the rapid development of exposure dating has opened up a vigorous new line of research. The modelling of near-surface processes is becoming the more important as recent work is suggesting a close feed-back with deep crustal flow (Burov and Cloetingh, 1997). Better constraints on the temporal evolution of rift shoulder topography will also affect concepts on the tectonic control on sequence boundaries related to uplift history (Van Balen et al., 1995).

In compressional basin studies, the modelling of flexural evolution of foreland-fold-and-thrust belts is of increasing importance in constraining palaeotopography (Millan et al., 1995). Parallel to this, our understanding of the bulk geometry of mountain belts has revolutionized as a result of the acquisition and interpretation of deep seismic reflection data (Roure et al., 1996). Another area of increasing importance is the analysis of the tectonic controls of hydrodynamic regimes in basins and the coupling of topography with drainage patterns in basins. An increasing awareness is growing that intraplate domains are characterized by a far more dynamic history than hitherto assumed, effecting tectonic geomorphology and recognisable in shallow seismics in areas such as the Pannonian Basin (Horváth and Cloetingh, 1996). Closer monitoring and modelling of fluxes in conjunction with more focus on the neotectonics of basins is obviously a must.

4. Stresses and basin evolution

As a result of a concerted effort in the framework of ILP in the early nineties, a first-order picture

has emerged on the orientation of the present-day intraplate stress fields in major parts of the globe (Zoback and Burke, 1993). Parallel to these studies the field studies of kinematic indicators (e.g. Delvaux et al., 1995) and the modelling of present-day and palaeo-stress fields in selected areas (e.g. Bada et al., 1997) have yielded new constraints on the causes and expressions of the stress fields in the lithosphere. This work has demonstrated the need to pursue by modelling and observational studies the consequences of temporal and spatial variations in the level and magnitude of these stresses on the record of vertical motions in basins (Cloetingh et al., 1985; Cloetingh and Kooi, 1992; Zoback et al., 1993). Over the last few years increasing attention has been directed to this topic, advancing our understanding into the relationships between plate motion changes, plate-interaction and the evolution of rifted basins (Janssen et al., 1995) and foreland areas Ziegler et al. (1995, 1997). It has been increasingly evident that a whole spectrum of stress-induced vertical motions can be expected in the sedimentary record, varying from the subtle effects of faulting (Ter Voorde and Cloetingh, 1996; Ter Voorde et al., 1997), thrusting (Zoetemeijer et al., 1993; Peper et al., 1995; Den Bezemer et al., 1997), and basin inversion (Brun and Nalpas, 1996) to enhancement of flexural effects to lithosphere folds induced for high levels of stress approaching lithospheric strengths (Stephenson and Cloetingh, 1991; Nikishin et al., 1993; Burov et al., 1993; Ziegler et al., 1995; Cloetingh and Burov, 1996; LeFort and Agarwal, 1996). As pointed out by Cobbold et al. (1993), crustal and lithospheric folding can be an important mode of basin formation in plates involved in continental collision. Recently, the first steps have been made to develop numerical models for the simulation of the interplay of faulting and folding in thick-skinned intraplate compressional deformation (Beekman et al., 1996).

The first set of three papers of this volume concentrate on the orientation of the present-day stress field and the palaeo-stress field in a number of sedimentary basins and rift systems. Delvaux et al. (1997), following their previous work on the Mesozoic stress regime in the Baikal region (Delvaux et al., 1995) present new data on the Cenozoic stress field and fault kinematics in Baikal. Guiraud and Bosworth (1997) discuss the kinematics of Creta-

ceous basin inversion and rejuvenation of rifting in Africa and Arabia and its implications for plate-scale tectonics. The African plate appears to be an excellent natural laboratory to investigate the temporal and spatial characteristics of plate stress transmission and basin reactivation (Janssen et al., 1995). Ben-Avraham et al. (1997) present new data on the structure and tectonics of the Agulhas–Falkland fracture zone. The paper by Jurado and Müller (1997) gives the results of borehole breakout analysis providing new constraints on the present-day stress regime of NE Iberia. Waltham (1997) presents results of numerical modelling of diapirism, emphasizing the role of mechanical controls. Growing awareness is developing over the last few years both through observations (e.g. Stephenson et al., 1993), numerical modelling (Daudre and Cloetingh, 1994) and analogue modelling (Jackson, 1995) of the interplay of crustal-scale processes and salt diapirism.

5. Rheology and basin formation

Over the last decade considerable progress has been made in understanding the factors which control the bulk rheology of the lithosphere (Kohlstedt et al., 1995). The concept of strength envelopes based on extrapolation of rock mechanics data, combined with assumptions on petrological stratification and incorporating constraints from thermal modelling has provided a first-order framework for the analysis of the variations in mechanical structure of the lithosphere (Burov and Diament, 1995; Cloetingh and Burov, 1996). Significant lateral variations in strength distribution have been found on a plate wide scale, largely due to changes in crustal thicknesses and changes in thermotectonic age (Cloetingh and Burov, 1996). The concept of bulk rheology has also been successfully used in the investigation of spatial variations in strength along mountain belts, such as the Canadian Rockies (Ranalli and Murphy, 1987), the Carpathian belt and its surroundings (Lankreijer et al., 1997), the Eastern Alps (Genser et al., 1996) and the Central Alps (Okaya et al., 1996). Although extremely fruitful, and a major step forward compared to the use of elastic and visco-elastic models, the brittle–ductile rheologies commonly employed in tectonic modelling studies should only be viewed as providing a generalized picture of the strength distri-

bution with depth. Of continuing interest for the Task Force is, therefore, a long-term program to develop a new generation of strength profiles (Ranalli, 1996).

Dynamic models (Bassi, 1995) provide an effective tool to explore the consequences of various assumptions in rheology on the mode of extensional basin formation. These dynamic models (see e.g. Govers and Wortel, 1993) are also important in the context of questions arising on the significance and implications of the kinematic modelling studies (Braun and Beaumont, 1989; Kooi et al., 1992), exploring the concept of a finite strength of the lithosphere during extensional basin formation. These studies have cast the mechanical characteristics of the lithosphere in terms of the depth of necking, directly referring to the depth distribution of the bulk strength of the lithosphere.

The importance of the role of pre-rift rheology in extensional basin formation has become evident from a systematic study of a large number of Alpine/Mediterranean basins and intracratonic rifts carried out in the framework of the Task Force project (Cloetingh et al., 1995c). The incorporation of the mechanical strength of the lithosphere in extensional basin modelling is an important ingredient to define the conditions of tectonic reactivation in these large-scale modelling studies (e.g. Negredo et al., 1995). In addition, the coupling with the modelling of tilted fault blocks has also demonstrated its key importance for models targeting on subbasin-scale problems (Ter Voorde and Cloetingh, 1996).

Fernández and Ranalli (1997) review the implications of lithospheric rheology in extensional basin models covering from the simplest 1-D kinematic approaches to the most recent plane-stress and plane-strain dynamic models with special emphasis on initial and boundary conditions. The next set of three papers of the volume focus on thermo-mechanical properties of the lithosphere in the Carpathian region and the Eastern Alps. Matenco et al. (1997) present new constraints on lateral variations in mechanical properties of the lithosphere downflexed under the Romanian Carpathians obtained through flexural and gravity modelling of a dense net of cross-sections through different segments of the arc. Badescu (1997) discusses the tectono-thermal regimes of the Tethys–External Dacides system (Romania) for Triassic–Jurassic times. Nemes et al. (1997) inves-

tigate the mechanical controls on the formation of the Klagenfurt Basin in the Eastern Alps, presenting evidence for decoupled upper crustal and mantle lithosphere in the area.

6. Tectonic and climate controls on basin fill

The quantification of the tectonic and climate controls on the sedimentary record continues to offer a great challenge in basin analysis. It is becoming more and more apparent that this requires an integrated approach linking the different spatial and temporal scales (Cloetingh et al., 1997). Critical is the step towards a fully 3-D analysis as well as the need for refinement of the resolution of stratigraphic analysis. Goggin et al. (1997) present the results of a three dimensional accommodation analysis of the Triassic in the Paris Basin. Sissingh (1997) reviews the tectonostratigraphy of the North Alpine foreland basin, constraining the correlation between Tertiary foredeep deposition and orogen deformation discussed by Ziegler et al. (1995, 1997). Juhasz et al. (1997) present a high-resolution analysis of Late Miocene cycles in the sediments of the Pannonian Basin, emphasizing the climatic control. Yellin-Dror et al. (1997) document the subsidence history of the northern Hyblean plateau margin of southeastern Sicily and discuss the interrelations with tectonic processes active in the Central Mediterranean region. Bertotti et al. (1997) present field evidence for extensional controls on Quaternary sedimentation and geomorphology in the external Northern Apennines and adjacent Po Plain.

7. Natural laboratories for deeper lithospheric processes and near-surface tectonics: the Pyrenees and adjacent western Mediterranean basins

In this section we present work carried out in a number of natural laboratories in Iberia and the adjacent western Mediterranean, selected to highlight the connection between lithospheric processes and near-surface tectonics at different spatial scales.

These papers are a follow-up of a set of thematic papers in the previous Task Force volume (Cloetingh et al., 1996) on neotectonics and present-day stress regime of Iberia, basin development in the Catalan

Coastal Range of NE Spain exposed as a result of a phase of rapid Plio–Pleistocene uplift (Janssen et al., 1993), the Permo–Triassic Iberian basin, and of the Mesozoic evolution of the Lusitanian Basin of Portugal.

In the present volume the natural laboratories in Iberia and adjacent areas are located in the Pyrenees and the Alboran Sea. The first four papers of this section focus on the Pyrenees. The paper by Martínez et al. (1997) presents an integrated gravity and seismic interpretation of duplex structures and imbricate thrust systems in the southeastern Pyrenees. A subsidence analysis of the southeastern Pyrenees is presented in the paper by Giménez-Montsant and Salas (1997). Storti and Poblet (1997) discuss fold kinematics and their inferences for basin geometries in compressional settings. These authors present the results of quantitative modelling on the controls of decollement folds and fault-propagation folds on growth stratal architectures. Travé et al. (1997) discuss the association of thrust faults in a foreland basin setting with sediment dewatering and pore fluid migration. These authors present new data from isotopic and elemental geochemical analyses and discuss the implications of these constraints on hydrodynamic regimes in compressional settings, pointing to an important control by stresses and basin deformation on fluid flow regimes and dewatering events. Perez-Belzuz et al. (1997) present new constraints on the history of mud diapirism and trigger mechanisms in the western Alboran Sea. Estrada et al. (1997) review the Pliocene–Quaternary tectono-sedimentary evolution of the northeastern Alboran Sea. The role of neotectonics and its interplay with external forcing in sedimentary basin evolution will remain a topic of considerable interest for modelling purposes.

8. The next phase of the Task Force (1998–2000)

Major challenges remain to be addressed in the next phase of the Task Force project (1998–2000). Of key importance will be a better understanding on the fine-structure of the coupling of lithosphere and near-surface processes. In addition the further development and integration of different research methodologies and their validation by high-quality data will continue to be an area of vigorous research in basin

studies in the years to come. Further integration of different approaches, and further strengthening of the research network will be the key in the final phase of this ILP program. Partnership with industry has been the key, connecting high-quality data from natural laboratories with the development of a new generation of basin modelling. In this spirit the recently established EUROBASIN research school has initiated a program of short courses, field training and research on integrated sedimentary basin studies. The creation of a common language in basin research will contribute to the further development of an effective link between fundamental and applied research on sedimentary basins.

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