Dynamics of basin formation and strike-slip tectonics

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1. Introduction and background

This volume contains a collection of papers on the dynamics of basin formation presented at the fifth annual workshop of the International Lithosphere Program Task Force ‘Origin of Sedimentary Basins’ in the Dead Sea rift, Israel, 29 September–5 October 1994. 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, and in Benevento, Italy (1993), in the Southern Apennines fold-and-thrust belt. 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, 1994a,b, 1995a,b.c; Stephenson, 1993). A position paper by Cloetingh, Sassi and Task Force Team (Cloetingh et al., 1994a)

has been published in Marine and Petroleum Geology, outlining the Task Force strategy to pursue the development of a new generation of basin models using natural laboratories with high-quality data sets obtained in many cases through close partnership with industry. The 6th Task Force meeting, focusing on the dynamics of fold-and-thrust belts was held in Sitges (Spain) at the rim of the Ebro basin in September 1995. The 7th Task Force workshop was organized in 1996 on the Faroe Islands (Northern Atlantic) with the aim of examining the dynamics of rifting and volcanic rifted margin formation. The emphasis of the Dead Sea rift workshop was on modelling studies as well as observational approaches to the dynamics of rifting and strike-slip tectonics. Important elements of the meeting were the role of stresses in basin evolution, the comparison of kinematic and dynamic modelling approaches to extensional 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 Dead Sea rift. Field
guides have been published separately (Garfunkel, 1994).

2. Rationale for an ILP task force on the 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 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 lithospheric 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 the 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 feedback between modelling and observations. We are currently in the position that 3-D modelling is becoming increasingly feasible and capable to link for example 3-D flexure with faulting (Van Wees and Cloetingh, 1994; Van Wees et al., 1995). The new challenges in information technology and the growing availability of 3-D 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.

3. Themes of the task force and highlights of recent developments

The role of basin modelling in linking different temporal and spatial scales involved in the coupling of lithospheric and near-surface processes is becoming increasingly important. Basin modelling is also increasingly widening its scope from an initial focus on subsidence and geometry of accommodation space into the modelling of the feed-back of the processes of sedimentation and erosion. 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, 1995) is becoming increasingly important. The availability of constraints by fission track data (Rohrmann 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 feedback with deep crustal flow (Burov and Cloetingh, 1996). Obviously these findings on the temporal evolution of rift shoulder topography will also affect our concepts on the tectonic control on sequence boundaries related to uplift history (Van Balen et al., 1995). A similar development can be observed in the modelling of compressional basins, where the modelling of flexural evolution of foreland-fold-and-thrust belts is also of increasing importance in constraining palaeo-topography (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. Strongly rooted in petroleum oriented research, basin studies are also of increasing relevance to better understanding of environmental aspects of earth sciences. An example of this is provided by the intensive work on the Norwegian margin, addressing the implications of basin evolution, recent uplift of Fennoscandia and glacial processes (Solheim et al., 1996; Gölke et al., 1996). 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. 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., 1996) 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 into this topic, advancing our understanding into the relationships between plate motion changes, plate interactions and the evolution of rifted basins (Janssen et al., 1995) and foreland areas Ziegler et al. (1995). 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, 1995) and thrusting (Zoetemeijer et al., 1993; Peper et al., 1995) 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; Cloetingh and Burov, 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., 1995).


5. Rheology and basin formation

Over the last decade considerable progress has been made in the understanding of 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). Following this approach, strong evidence for the existence of lateral variations in strength distribution have been found on a plate wide scale, largely due to changes in crustal thicknesses and changes in thermo-tectonic age (Cloetingh and Burov, 1996). The concept has also been fruitfully used in the investigation of spatial variations in strength across 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 modelling studies should only be viewed as providing a generalized picture of the strength distribution 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. Zeyen et al. (1996) discuss the implications of such models, focusing on the role of extension with lateral material accommodation. These dynamic models (see, e.g., Braun and Beaumont, 1989; Govers and Wortel, 1993) are also important in the context of questions arising on the significance and implications of the kinematic modelling studies (Kooi et al., 1992; Spadini et al., 1995), 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., 1995b). Spadini et al. (1996) demonstrate through forward modelling the key importance of these pre-rift lithospheric controls on basin evolution in the Black Sea area, shedding light on observed differences between the western and eastern Black Sea evolution. The incorporation of the mechanical strength of the lithosphere in extensional basin modelling is an important ingredient in these large-scale modelling studies. 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, 1995).

6. Deeper lithospheric processes and near-surface tectonics: natural laboratories

In this section of the Special Volume we present work carried out in a number of natural laboratories, selected to highlight the connection between lithospheric processes and near-surface tectonics at different spatial scales. In this volume the natural laboratories are divided into five groups. These are the Dead Sea rift, the Eastern Mediterranean and Black Sea, the Carpathian and Pannonian region, the North Sea and the Iberian and west Africa margins. The papers on the theme Deeper lithospheric processes and near-surface tectonics deal with various aspects of structure and development of pull apart basins as well as other basins which were developed in extensional and compressional settings.

6.1. The Dead Sea rift and the Gulf of Suez

Strike-slip basins are common features on the earth surface. They are associated with large transcurrent fault systems and continental transforms both in the oceans and on the continents. The Dead Sea basin which is situated in the centre of the Dead Sea transform is one of the largest and deepest active strike-slip basins on earth.

Strike-slip basins, or pull-apart basins, vary in their internal structure owing to the complex stress field and heterogeneous crustal rheology around strike-slip faults. They are usually short-lived because slight reorganization of the relative plate motion will cause changes in the local stress field around basins (Gööke et al., 1994). Subsidence models for this type of basins are invoking the combined effects of vertical and lateral heat conduction, in order to reproduce the observed patterns of extremely rapid subsidence (Pitman and Andrews, 1985). To match for observed deviations, both in terms of very irregular intrabasinal subsidence and subsidence perturbations, characteristic for many pull apart basins (see, e.g., Cloetingh et al., 1992), we need obviously models incorporating more fully the mechanical aspects of strike-slip basin formation.

Numerous studies have been done on the structure of the basins along the Dead Sea rift and their tectonic development (e.g., Ben-Avraham, 1985, 1992, 1996; Ben-Avraham et al., 1979, 1993; Garfunkel, 1981; Ten Brink and Ben-Avraham, 1989; Ten Brink et al., 1993; Ginzburg et al., 1979, 1981; Rotstein and Bartov, 1989; Vilottte et al., 1993). Several models were suggested for the tectonic evolution of the basins (e.g., Quennell, 1959; Zak and Freund, 1981;
Schubert and Garfunkel, 1984; Arbenz, 1984; Ten Brink and Ben-Avraham, 1989). As more data are being accumulated on the subsurface structure of the basins new models are being developed and modification of previous models take place.

Strike-slip basins are also common elsewhere in the Mediterranean region. For example the North Anatolian fault is associated with many pull-apart basins. Pull-apart basins are also common in the Black Sea region, the Pantelleria rift zone in the Straits of Sicily, the internal zone of the Betic Cordilleras and the Aegean Sea region.

The first four papers of this section focus on the Dead Sea rift and the Gulf of Suez. The paper by Garfunkel and Ben-Avraham (1996) reviews the structure of the Dead Sea rift basin. A new data base on digital topography and bathymetry of the area of the Dead Sea depression is presented in the paper by Hall (1996). Wdowinsky and Zilberman (1996) discuss the observed large-scale asymmetries across the Dead Sea rift in the context of an isostatically supported half graben model. Feinstein et al. (1996) present new constraints on the thermal history of the eastern margin of the Gulf of Suez inferred from borehole temperature and organic maturity measurements.

6.2. The Eastern Mediterranean, Black Sea and the basins of the FSU

In the next three papers the focus is on the Black Sea, the Eastern Mediterranean and the basins of the FSU. Smolyanova et al. (1996) present the results of numerical modelling of neotectonics in the northern Black Sea. Many questions stand out on the propagation of stresses from the orogenic belts at the margins of the Black Sea into the Black Sea (Robinson et al., 1995). Evidently, answers to these questions are directly affected by the need to better understand the mechanical properties of the lithosphere in this area [see for a discussion Spadini et al. (1996)]. Monaco et al. (1996) discuss the transition of collisional to rifted basins using an example from the Calabrian arc. Lobkovsky et al. (1996) review the large-scale structure and constraints on basin formation mechanisms presenting results from subsidence analysis of a large number of extensional basins in the FSU.

6.3. The Pannonian basin/Carpathian area

The Carpathian/Pannonian basin has been an area of active research for the Task Force Team since the 1991 meeting in Matrahaza. A collection of papers on the area was published in Cloetingh et al. (1993b), followed by papers in Cloetingh et al. (1994a,b, 1995a,b). In addition, a special ALCAPA volume was prepared on research in the region (Neubauer et al., 1997). As pointed out by Horvath (1993), much data are accumulating now allowing to build a new generation of basin models for this area, following up the first generation models presented in Royden and Horvath (1988). Of particular importance is the growing realization of the role of neotectonics in the Pannonian basin, and its implication for basin stratigraphy and fluid flow regime (Vakarcs et al., 1994; Van Balen and Cloetingh, 1995; Horvath, 1995). Horvath and Cloetingh (1996) review the geological and geophysical evidence for Quaternary reactivation of the Pannonian basin and demonstrate by modelling that late-stage compression has played an important role in the large-scale tilting and undulations observed in the area. Sztano and Jozsa (1996) discuss the interaction of basin margin faults and tidal currents on nearshore sedimentary architecture presenting new data from the Lower Miocene of northern Hungary. Recently the first steps have been made to assess the lateral variations in mechanical structure along the Carpathian arc through flexural modelling (Zoetemeijer et al., 1996; Matenco et al., 1996). Meulenkamp et al. (1996) present a synthesis of the Late Oligocene to Pliocene depocentre migrations along the arc in the context of the evolution of the Carpathian/Pannonian system.

6.4. The North Sea and the North German basin

The next three papers focus on the evolution of the North Sea and north German basin. Van Wees and Cloetingh (1996) present the results of a 3-D modelling study, demonstrating that intraplate stresses equivalent to levels induced by ridge push forces are capable to explain up to 700 m of the documented late Cenozoic anomalous subsidence in the North Sea basin. These stress levels are considerably lower than required by 2-D models (Cloetingh et al., 1990; Kooi et al., 1991). The documented
late-stage accelerations occur simultaneously with enhanced uplift along the margins of the North Sea basin (e.g., Rohrman et al., 1995). Better constraints from new data and models are important in view of recently documented migrations in depocentre development offshore Norway, incompatible with standard stretching models (Jordt et al., 1995). The need to understand better the effect of polyphase evolution on the geometry of basin structures and its effect on the mechanical aspects of basin formation is receiving growing attention (e.g., Cloetingh et al., 1995a,b). In the paper by McCann (1996), seismic evidence for an interpretation of the North Celtic reflector in terms of a possible Variscan basement structure off southern Ireland is presented. The role of magmatism in basin formation remains a topic of considerable interest for modelling purposes (see for a review, Wilson, 1993). Benek et al. (1996) discuss the effect of Permo-Carboniferous magmatism on subsidence patterns of the northeastern German basin.

6.5. Iberia and the West African margin

The final set of papers report work by the Task Force on Iberia and the west African margin. In the first two papers by De Vicente et al. (1996) and Herraiz et al. (1996) new data on neotectonics and present-day stress regime are presented for central and southern Spain. These papers demonstrate the importance of intraplate deformation and recent processes for the basin record of Iberia (see also Friend and Dabrio, 1996). Alsaker et al. (1996) investigate the significance of fracture patterns of the Tertiary Monte Serrat Fan-Delta in the Catalan Coastal Range of northeastern Spain, an area, with excellent exposures as a result of a phase of rapid Plio-Pleistocene uplift (Janssen et al., 1993). The paper by Arche and Lopez-Gomez (1996) presents the results of a detailed study of the relationships between tectonics and sedimentation and its implications for the origin of the Permo-Triassic Iberian basin. Stapel et al. (1996) present the results of quantitative subsidence analysis of the Mesozoic evolution of the Lusitanian basin of Portugal. This work demonstrates the existence of strong correlations between large-scale tectonic reorganizations in the Atlantic and anomalous subsidence in the Mesozoic basins of Iberia, emphasizing also an important control exerted by pre-rift structures on subsidence. In the last paper of the volume, Rasmussen (1996) presents new data on the Tertiary structural evolution and its bearing on sequence stratigraphy offshore Gabon (western African margin).


A large number of challenges remain to be addressed in the next phase of the Task Force project (1997–2000). 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 this ambitious program.

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