Basin dynamics and basin fill: models and constraints

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1. Introduction

This volume contains a collection of papers on the tectonics of sedimentary basin evolution presented at the 8th annual workshop of the International Lithosphere Program Task Force ‘Origin of Sedimentary Basins’ in Sicily, at Torre Normanna, Palermo, June 1997. Following the first workshop of the ILP Task Force in Rueil Malmaison, France (1990), a series of project meetings was organized, resulting in a number of special volumes and papers (Cloetingh et al., 1993a,b, 1994a,b, 1995a,b, 1996, 1997a, 1998; Stephenson, 1993, Stephenson et al., 1996; Neubauer et al., 1997).

A key element of the Task Force strategy outlined in its position paper published in Marine and Petroleum Geology (Cloetingh et al., 1994b) has been to connect the development of a new generation of basin models with integrated basin studies in selected natural laboratories with high-quality data sets frequently obtained through a close partnership with industry.

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 9th Task Force workshop that took place in Oliana (S.E. Pyrenees) in 1998, concentrated on tectonics and geomorphology and the interplay of lithospheric and surface processes. The emphasis of the Task Force workshop held on Sicily was on modeling studies as well as observational approaches to the tectonics of sedimentary basin formation. 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 modeling studies.

This is the second meeting in southern Italy by the ILP Task Force. Sicily has outstanding outcrops of Plio-Plenocene (as well as older) rocks and structures that have been analysed in the last few years — together with their offshore counterparts — by the group of the Department of Geology and Geodesy of Palermo University (see Catalano, 1997, for example). Sicily is also the site of extensive oil exploration and production, providing the academic research institutions with a special opportunity to validate conceptual models through confrontation with high-quality subsurface data.

Following the Task Force approach to link subsurface data to field analogues, the meeting
included a 3-day thematic field excursion on Sicily, examining the surface expression of thrusting on basin fill and recent vertical motions (see Fig. 1).

The guidebook ‘Field workshop in Western Sicily’ has been published separately (Catalano, 1997). The guidebook was prepared with the aim of introducing the field workshop, with a focus on observed tecto-sedimentary structures. To this aim, most recent published and unpublished data on Sicilian geology generated by the University of Palermo geology team were compiled (Catalano et al., 1994, 1996, 1998). Equally important in this context has been the comparison of the field data of the Sicilian basins with seismic reflection data of the adjacent offshore (see Figs. 2, 3 and 5). These data are also important in constraining numerical modelling studies of fault-related sedimentation. Such modelling approaches make it possible to quantify the effects of different assumptions on modes of thrusting, as well as the consequences of different fault systems geometries (Zoetemeijer et al., 1993; Den Bezemer, 1998; Den Bezemer et al., 1998). Fig. 4 shows the results of a basin fill model simulating two faults in a forward-breaking thrust sequence. Depocentre migration of basins, shift of unconformities and grain size distribution are a direct consequence of fault activation, yielding testable predictions to be validated by field data and seismic reflection profiles (for a comparison, see Fig. 3, for example). At the same time, the modelling can provide an additional constraint on the interpretation of non-exposed fault systems imaged on seismic lines.

Fig. 5 shows a seismic section from offshore...
Fig. 2. Seismic line showing the structural setting of the carbonate thrust system in the Sciacca offshore (Southern Sicily). PP: Plio-Pleistocene deposits; M: Messinian reflector; ST: Serravallian-Tortonian deposits; Tp: top of carbonates; 0.8: age of the sequence boundaries in Ma (after Catalano et al., 1996).

Fig. 3. Geological section restored from seismics and wells with Gela thrust system (T.S.) overlying duplexes of the outer carbonate T.S., resting above a N-dipping thrust plane. Fig. conventions as in Fig. 2 (after Catalano et al., 1996).
Fig. 4. Numerical modelling of fault-related sedimentation in thrust belt settings for different spacing of fault systems. Grain size distributions resulting from forward breaking thrusting. The upper two panels show a scenario with a large fault spacing. The lower two panels display a scenario with a small fault spacing. Red lines indicate deposition during activation of the right fault (after Den Bezemer et al., 1998).
Fig. 5. Seismic sequence stratigraphy of the Plio-Pleistocene syntectonic Pina basin buried in the Scialla o\"V\"shore, southwestern Sicily. The age of the sequence boundaries is calibrated by detailed biostratigraphy and well log analysis of the Pina deep borehole (a–f refer to differences in seismic facies character) (after Catalano, 1997).
Sicily highlighting the geometry of a fault-bounded rift with a pronounced transition between syn-rift and post-rift sequences. A comparison with Fig. 6, illustrating the effects of different sequences of fault activation on rift basin fill (Den Bezemer et al., 1998, 1999), demonstrates the potential of further constraining the kinematics of rifting by an integrated approach.

3. Task Force themes and survey of recent trends

Sedimentary basin modeling is increasingly addressing the coupling of different temporal and spatial scales controlling the interplay of lithospheric and near-surface processes. In this context, basin modeling is shifting its scope from an initial focus on subsidence and geometry of accommodation space into the modeling of the feedback of the processes of sedimentation and erosion (e.g. Avouac and Burov, 1996; Burov and Cloetingh, 1997). This development creates the need for better constraints on the evolution of topography in space and time.

In modeling extensional basins and rifted margins, the reconstruction of rift shoulder topography and tectonic processes during the evolution of the flanks of rifted margins. The modeling of near-surface processes also suggests a close feedback with deep crustal flow (Burov and Cloetingh, 1997), affecting concepts on the tectonic control on sequence boundaries related to uplift history (Van Balen et al., 1995).

In compressional basin studies, integration of fission track studies (e.g. Sanders, 1998) and models of the flexural evolution of foreland-fold-and-thrust belts are of vital importance in quantifying paleo-topography (e.g. Millan et al., 1995; Andeweg and Cloetingh, 1998). Further acquisition and interpretation of deep seismic reflection data (Roure et al., 1996) will remain a key objective to constrain these studies.

It is now recognized that intraplate domains are characterized by a far more dynamic history.
Fig. 6. Different styles of extensional basin infill due to differences in sequence of fault activation (Den Bezemer et al., 1999).

Figure 4a, faults activated from left to right

Figure 4b, faults activated from right to left
than hitherto assumed, affecting tectonic geomorphology and fluid flow, and recognizable in shallow seismics in areas such as the Pannonian basin (Horvath and Cloetingh, 1996; Sacchi et al., 1999; Van Balen et al., 1999). Closer monitoring and modeling of fluxes in conjunction with more focus on the neotectonics of basins are obviously essential. The 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.

3.1. Theme 1: Stresses and basin evolution

In the early 1990s, 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). Field studies of kinematic indicators (e.g. Delvaux et al., 1997; Guiraud and Bosworth, this volume) and numerical modeling of present-day and paleo-stress fields in selected areas (e.g. Badia et al., 1998) have yielded new constraints on the causes and expressions of intraplate stress fields in the lithosphere. Temporal and spatial variations in the level and magnitude of these stresses have a strong impact on the record of vertical motions in sedimentary basins (Cloetingh et al., 1985; Cloetingh and Kooi, 1992; Zoback et al., 1993; Van Balen et al., 1998).

Over the last few years, increasing attention has been directed into this topic, advancing our understanding of the relationships between plate motion changes, plate interactions and the evolution of rifted basins (Janssen et al., 1995; Dore et al., 1997a,b) and foreland areas Ziegler et al. (1995, 1998). A continuous 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., 1998; 1999), and basin inversion (Brun and Nalpas, 1996; Ziegler et al., 1998) to enhancement of flexural effects to lithosphere folds induced for high levels of stress approaching lithospheric strengths (Stephenson and Cloetingh, 1991; Burov et al., 1993; Nikishin et al., 1993; Cloetingh and Burov, 1996).

Crustal and lithospheric folding can be an important mode of basin formation in plates involved in continental collision. (Cobbold et al., 1993; Ziegler et al., 1995) Numerical models have been developed for the simulation of the interplay of faulting and folding in intraplate compressional deformation (Beekman et al., 1996; Gerbault et al., 1998; Cloetingh et al., 1999).

Models have also been developed to investigate the effects of faulting on stress-induced intraplate deformation in rifted margin settings (Van Balen et al., 1998).

The first set of three papers of this volume concentrate on the mechanisms controlling stress fields in the lithosphere, the orientation of the present-day stress field and constraints on paleo-stress field in a number of sedimentary basins and rift systems. The paper by Negredo et al. (this volume) presents the results of a numerical modeling study carried out to examine the mechanical controls on seismotectonics of the Northern Apennines. Gauthier et al. (this volume) present the results of an analogue modeling study, constrained by high-quality field data on the kinematics and timing of Aegean extension. Guiraud and Bosworth (this volume) present paleo-stress indicator data for Northeastern Africa and the Northwestern Arabian platform, and discuss the relationships between lithospheric stress fields in the area and the Phanerzoic evolution.

3.2. Theme 2: Rheology and basin formation

Bulk rheological models of the lithosphere (Kohlstedt et al., 1995), employing the concept of strength envelopes are based on extrapolation of rock mechanics data, combined with assumptions on petrological stratification and incorporating constraints from thermal modeling. These models have provided a useful, first-order framework for the analysis of the variations in mechanical structure of the lithosphere (Burov and Dikanov, 1995; Cloetingh and Burov, 1996). Spatial variations in strength distribution occur on a plate-wide scale, largely related to changes in crustal thicknesses and thermo-tectonic age (Cloetingh and Burov, 1996). Spatial variations in strength have also been
recognized along mountain belts, such as the Carpathian belt and its surroundings (REF44 Zoetemeijer et al., 1999; Lankreijer et al., 1997, 1999) and the northern Apennines (Gualteri et al., 1998).

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 modeling is an important ingredient in these large-scale modeling studies (see also Brun, 1999; Ter Voorde, 1998).

The integration with the modeling of tilted fault blocks has also demonstrated its key importance for models targeting on subbasin scale problems (Ter Voorde and Cloetingh, 1996).

The next four papers of this volume focus on rheology and basin structure. Liotta and Ranalli (this volume) present constraints on lateral variations in mechanical properties of the lithosphere in an extended lithosphere in southern Tuscany and the inner northern Apennines obtained through modeling of cross-sections through the area. They examine the evidence for a correlation between seismic reflectivity and rheology in extended lithosphere. Previous work by Gualteri et al. (1998) has also emphasized the importance of strong lateral variations in rheology in the area.

The importance of pre-orogenic tectonics on subsequent basin evolution is discussed by Marchegiani et al. (this volume), presenting data for the Umbria-Marche sector of the Afro-Adriatic continental margin. Fritz and Messner (this volume) present new data on intramontane basin formation during oblique island arc accretion in the eastern desert of Egypt. They present a case history of orogeny without mountain relief. Cipollari et al. (this volume) focus on extension-and-compression-related basins in Central Italy in the context of the Messinian Lago-Mare event.

3.4. Theme 4: Constraints on vertical motions and fracture systems

In the final section of the Special Volume, research is presented on constraints on vertical motions and fracture systems. Van de Meulen et al. (this volume) provide evidence from backstripping studies for Late Miocene rebound in the Romagnan Apennines following detachment of subducted lithosphere. Ascione and Romano (this volume) present new data from Mt. Bulgheria (southern Apennines, Italy) constraining vertical motions on the eastern margin of the Tyrrhenian extensional basin. D’Argenio et al. (this volume) highlight the importance of high precision correlation. Their paper on macrostratigraphy focuses on carbonate platform superbasin as an instrument for obtaining higher temporal resolutions.
In a supplementary issue of Tectonophysics (Cloetingh et al., 2000), a number of additional papers on the topic of vertical motions and fracture systems will appear. Noguera and Rea (supplement to this volume) concentrate on the deep structures underlying the Campano Lucano arc segment (southern Italy).

The two papers by van Dijk et al. (supplement to this volume) focus on the implications of tectonics on high-resolution spatial scales, in 3D fracture network analyses, and its application to data from Southern Italy.

Sulli discusses the structural framework and crustal composition of a section through the Sardinian Channel.

Cantini et al. present an interpretation of the tectonostratigraphy of the Pleistocene Monte Carlo basin constrained by new gravity and stratigraphic data.

Scisciani et al. focus on the tectonic control on basin fill examining the role of foreland-dipping normal faults bounding synorogenic basins in the Central Apennines.


A better understanding on the fine structure of the coupling of lithosphere and near-surface processes is required. 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. Integration of different approaches and further strengthening of the research network will be a main target in the final phase of this ILP program. To this purpose, two topical conferences on the themes 'From continental collision to break-up' and 'Mechanical (un)coupling within the lithosphere' will be held in 2000 in the Dead Sea rift and Amsterdam, respectively. These meetings concern a joint initiative of the ILP task force 'Origin of Sedimentary Basins' and the European Geophysical Society (EGS). Partnership with industry has been the key, connecting high-quality data from natural laboratories with the development of a new generation of sedimentary basin modeling. Building on these steps, the EUROBASIN research school has initiated a program of short courses, field training and research on integrated sedimentary basin studies. Sedimentary basin research appears to be a good vehicle for narrowing gaps between fundamental and applied Earth sciences.

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