Thrust Tectonics

Thrust Tectonics

Edited by

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CONTENTS

<i>Contributors</i>	viii
<i>Acknowledgements</i>	x
<i>Introduction</i>	xi
 Part One	
Theoretical aspects and thrust mechanics	
Erosional control of active compressional orogens <i>C. Beaumont, P. Fullsack and J. Hamilton</i>	1
Dynamic and kinematic growth and change of a Coulomb wedge <i>S.D. Willett</i>	19
A developmental stage of a foreland belt <i>E.G. Bombolakis</i>	33
One-dimensional models for plane and non-plane power-law flow in shortening and elongating thrust zones <i>S. Wojtal</i>	41
 Part Two	
Physical modelling	
Centrifuge modelling of the propagation of thrust faults <i>J.M. Dixon and Shumin Liu</i>	53
Physical models of thrust wedges <i>Huiqi Lui, K.R. McClay and D. Powell</i>	71
Generation of curved fold-thrust belts: Insight from simple physical and analytical models <i>S. Marshak, M.S. Wilkerson and A.T. Hsui</i>	83
Thrust faults in inverted extensional basins <i>K.R. McClay and P.G. Buchanan</i>	93
 Part Three	
Thrust geometries and thrust systems	
Rates of folding and faulting determined from growth strata <i>J. Suppe, G.T. Chou and S.C. Hook</i>	105
Role of shear in fault-propagation folding <i>J. Mosar and J. Suppe</i>	123
2-D reconstruction of thrust evolution using the fault-bend fold method <i>R. Zoetemeijer and W. Sassi</i>	133
Kinematic models of deformation at an oblique ramp <i>T.G. Apotria, W.T. Snedden, J.H. Spang and D.V. Wiltschko</i>	141
Stress controls on fold thrust style <i>W.R. Jamison</i>	155
Kinematics of large-scale asymmetric buckle folds in overthrust shear: an example from the Helvetic nappes <i>M.G. Rowan and R. Kligfield</i>	165
Forelimb deformation in some natural examples of fault-propagation folds <i>J.L. Alonso and A. Teixell</i>	175
The geometric evolution of foreland thrust systems <i>M.P. Fischer and N.B. Woodward</i>	181

Some geometric problems of ramp-flat thrust models <i>J.G. Ramsay</i>	191
The duplex model: Implications from a study of flexural-slip duplexes <i>P.W.G. Tanner</i>	201
Palaeomagnetic techniques applied to thrust belts <i>A.M. McCaig and E. McClelland</i>	209
Evolution of crystalline thrust sheets in the internal parts of mountain chains <i>R.D. Hatcher, Jr. and R.J. Hooper</i>	217
 Part Four	
Pyrenees	
Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section <i>J.A. Muñoz</i>	235
Thrusting and foreland basin evolution in the Southern Pyrenees <i>C. Puigdefabregas, J.A. Muñoz and J. Vergés</i>	247
South Pyrenean fold-and-thrust belt: Role of foreland evaporitic levels in thrust geometry <i>J. Vergés, J.A. Muñoz and A. Martínez</i>	255
Contrasting rotations within thrust sheets and kinematics of thrust tectonics as derived from palaeomagnetic data: an example from the Southern Pyrenees <i>J. Dinarès, E. McClelland and P. Santanach</i>	265
 Part Five	
Alps	
The Alps – a transpressive pile of peels <i>H. Laubscher</i>	277
Structural evolution of the western Chartreuse fold and thrust system, NW French Subalpine Chains <i>R.W.H. Butler</i>	287
Kinematics of a transverse zone in the Southern Alps, Italy <i>G. Schönborn</i>	299
Hangingwall geometry of overthrusts emanating from ductile decollements <i>P. Jordan and T. Noack</i>	311
The Venetian Alps thrust belt <i>C. Doglioni</i>	319
 Part Six	
Himalayas	
Thrust geometries, interferences and rotations in the Northwest Himalaya <i>P.J. Treloar, M.P. Coward, A.F. Chambers, C.N. Izatt and K.C. Jackson</i>	325
Balanced and retrodeformed geological cross-section from the frontal Sulaiman Lobe, Pakistan: Duplex development in thick strata along the western margin of the Indian Plate <i>I.A.K. Jadoon, R.D. Lawrence and R.J. Lillie</i>	343
 Part Seven	
NW American Cordillera	
The Monashee decollement of the southern Canadian Cordillera: a crustal-scale shear zone linking the Rocky Mountain Foreland belt to lower crust beneath accreted terranes <i>R.L. Brown, S.D. Carr, B.J. Johnson, V.J. Coleman, F.A. Cook and J.L. Varsek</i>	357
The Skeena fold belt: a link between the Coast Plutonic Complex, the Omineca belt and the Rocky Mountain fold and thrust belt <i>C.A. Evenchick</i>	365

Geometric evidence for synchronous thrusting in the southern Alberta and northwest Montana thrust belts <i>S.E. Boyer</i>	377
The analysis of fracture systems in subsurface thrust structures from the Foothills of the Canadian Rockies <i>M. Cooper</i>	391
Thrust tectonics and Cretaceous intracontinental shortening in southeast Alaska <i>C.M. Rubin and J.B. Saleeby</i>	407
Glossary K.R. McClay	419
Index	435

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Thrust Tectonics: An introduction

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Since the first Thrust and Nappe Tectonics Conference in London in 1979 (McClay & Price 1981), and the Toulouse Meeting on Thrusting and Deformation in 1984 (Platt *et al.* 1986) there have been considerable advances in the study of thrust systems incorporating new field observations, conceptual models, mechanical models, analogue and numerical simulations, together with geophysical studies of thrust belts. *Thrust Tectonics 1990* was an International Conference convened by the editor and held at Royal Holloway and Bedford New College, University of London, Egham Surrey, from April 4th until April 7th 1990. There were one hundred and seventy participants from all continents except South America. The conference was generously sponsored by Brasoil U.K. Limited, BP Exploration, Chevron U.K. Limited, Clyde Petroleum, Enterprise Oil, Esso Exploration and Production UK Limited, and Shell U.K. Exploration and Production.

One hundred and five contributions were presented at the meeting, - seventy six oral presentations (together with poster displays) and an additional twenty nine posters without oral presentation (McClay 1990, conference abstract volume).

The thirty six papers presented in this volume represent a distillation of the material presented at the conference and are grouped into thematic sections that follow the main topics of discussion at the meeting. To an extent the grouping of papers into specific thematic sets is somewhat arbitrary as there are many common linkages between the various sections. In particular many papers focus upon both the geometries of thrust systems and their kinematic evolution - a recurring theme throughout the volume. Space limitations prevented publication of all of the papers presented at the meeting but it is hoped that this volume will provide the reader with an appreciation of the current research themes and concepts of thrust systems. The contents of the volume are summarized below.

The first section of this volume is headed '*Theoretical aspects and thrust mechanics*'. **Beaumont *et al.*** describe an elegant finite element model of the evolution of the Southern Alps of New Zealand. The model incorporates tectonic data, erosional and orthographic data and demonstrates surprisingly that the climate, erosion and fluvial systems are coupled to the orogenic evolution such that the structural and metamorphic style of this thrust belt may be controlled by the fluvial erosion and climate on the western flank of the Southern Alps. **Willett** presents a finite-element model of Coulomb wedges in order to simulate the growth of accretionary prisms and foreland fold and thrust belts. The model demonstrates self-similar growth of the Coulomb wedge and investigates the kinematics and particle velocities of critical wedges growing by accretion. Changes in the boundary conditions of the wedge (e.g. a change in the basal friction) changes the wedge geometry and thus may permit out of sequence thrusting (increase in basal friction) or extensional collapse of the wedge whilst in compression (decrease in basal friction). **Bombolakis** examines the partitioning of elastic strains and strain-rate dependent ductile deformation in the emplacement of the frontal parts of thrust systems. He demonstrates that significant thrust movement in these environments can occur by aseismic processes. **Wojtal** presents a one-dimensional model for plane and non-plane power-law flow in shortening and elongating thrust zones. He concludes that viscous creep is significant along external thrust faults and that fluid assisted diffusive mass transfer processes (pressure solution) are important deformation mechanisms in the fine-grained banded cataclasites of such thrust systems.

The second section of this volume titled '*Physical modelling*' contains four papers on analogue modelling of thrust structures. **Dixon & Liu** investigate the formation of foreland fold and thrust belts using scaled centrifuge models. They demonstrate that folding precedes thrusting, and that the thrust periodicity is inherited from the buckling wavelength of the antecedent fold systems. The models also demonstrate the 3D coalescence of small thrusts to form larger thrust systems. **Liu *et al.*** present a detailed study of sandbox models of thrust systems found in accretionary wedges and foreland fold and thrust belts. The boundary conditions of the models were systematically varied and the results are in broad agreement with Coulomb wedge theories (cf. Davis *et al.* 1983; Dahlen 1990). Low basal friction models are characterised by both foreland-vergent and hinterland-vergent thrust faults (i.e. backthrusts) as well as low critical tapers of the resultant Coulomb wedge. Intermediate basal friction models show a dominance of foreland-vergent thrust systems whereas models in which the coefficient of friction at the base is equal to that within the wedge, depart from ideal Coulomb wedges and show greater tapers than predicted by theory. **Marshak *et al.*** investigate the generation of curved thrust belts using viscous analogue models,

finite difference models and sandbox models. They conclude that curved fold and thrust belts may be generated by differential displacement such as that resulting from the interaction with obstacles or along strike variations in sediment thicknesses. **McClay & Buchanan** investigate the geometries of thrust systems formed by inversion of extensional basins. Sandbox models demonstrate the complexities of thrusts produced by inversion - steep angle thrusts, footwall shortcut thrusts, backthrusts and both 'forward-breaking' and 'break-back' thrust sequences.

The third section of this volume is titled - *'Thrust geometries and thrust systems'* and focuses upon geometric and kinematic problems of thrust systems. **Suppe *et al.*** set out the theory for the geometry of growth folding associated with kink band folding, fault-bend folding and fault-propagation folding. They demonstrate that the stratal geometries of growth sequences may be used to determine fault slip rates and illustrate their results with both seismic and map examples of growth fold systems. **Mosar & Suppe** introduce the theory for fault-propagation folding with variable shear. They show how the geometries of fault-propagation or tip-line folds may be significantly altered by layer parallel shear. **Zoetemeijer & Sassi** describe a computer method for 2D reconstruction of thrust systems using the fault-bend fold model. The method can incorporate syntectonic sedimentation and erosion. The problems of three dimensional thrust geometries developed over oblique ramps are tackled by **Apotria *et al.*** They describe a detailed kinematic analysis of fault-bend fold interactions at frontal and oblique ramps and illustrate their results with both cross-sections and map views. The stress controls on thrust related folding are addressed by **Jamison**. He proposes that the style of folding in a thrust belt is a result of the competition between buckling and faulting and as such is dependent upon the depth of burial and tectonic regime. The hypothesis is illustrated with examples from the Rocky Mountain thrust belt. **Rowan & Kligfield** present a kinematic analysis of asymmetric detachment folds from the Wildhorn nappe, Helvetic Alps. They propose that overthrust shear between the nappe boundaries generated buckle folds and rotational strains within the nappe system. **Alonso & Teixell** describe an analysis of fault-propagation folds in which the forelimbs are thinned by heterogeneous simple shear localized at ramps and not penetrative through the whole of the thrust sheet. The progressive geometric evolution of thrust faults and related folds is examined by **Fischer & Woodward**. They propose, using examples from both Wyoming and the Appalachians, that fold-thrust systems do not evolve in a self-similar fashion but argue that variations of fold-thrust structures along strike in a thrust belt do not represent temporal variations in evolution but rather reflect intrinsic variations in the mechanical response of the stratigraphic package to contraction.

Ramsay argues against unquestioning acceptance and wholesale application of preconceived geometric models for thrust-fold systems - particularly those where the deformation is concentrated in the hangingwalls of thrust faults. He describes examples where footwall deflection is important and advocates many more detailed studies of natural thrust systems. The geometries and kinematics of duplex structures are addressed by **Tanner** who proposes that the Boyer & Elliott (1982) model does not universally apply and that many natural duplex systems show indications of synchronous fault movement. The use of palaeomagnetic studies to determine rotations about vertical axes in thrust belts is reviewed by **McCaig & McClelland** whereas **Hatcher & Hooper** review the main characteristics of thrust sheets that involve crystalline basement in the interior parts of mountain belts.

The fourth section on the *'Pyrenees'* concerns recent research which integrates structural, sedimentological and geophysical results. An overview and balanced crustal cross-section of the Pyrenean continental collision belt is presented by **Munoz**. He points out the discrepancy between the cross-sectional length of the upper crust and that of the lower crust and argues for subduction of Iberian lower crust northwards under the European crust. The structural, stratigraphic and sedimentological evolution of the southern Pyrenean foreland basins is synthesized by **Puigdefabregas *et al.*** The evolution of the foreland basin sequences is described with reference to the patterns of thrusting. **Verges *et al.*** investigate the role of the foreland evaporitic sequences in controlling the evolution and emplacement of the frontal thrust systems and demonstrate their influence on the strike of the thrust system and on the location of oblique ramps. The palaeomagnetic study of **Dinares *et al.*** demonstrates that up to 45° rotation about vertical axes occurs in thrust sheets associated with oblique ramps in the southern Pyrenean thrust belt.

The fifth section of this volume contains five papers on the *'Alps'*. **Laubscher** addresses the problems of linked compression and strike-slip tectonics in the central Alps and quantifies the E-W strike-slip components. **Butler** describes the western Chartreuse fold and thrust system and emphasizes the role of folding and preexisting extensional structures in the evolution of the belt. The detailed geometries and kinematics of a transverse zone in the southern Alps are analysed by **Schonborn**. **Jordan & Noak** develop models for the evolution of the hangingwall geometries of thrust systems developed above ductile decollements and apply these to examples in the Jura. The final paper in this section by **Doglioni** describes the structure of the Venetian Alps.

The sixth section of this book contains two papers on the *'Himalayas'*. **Treloar *et al.*** summarize the kinematic evolution of the northwest Himalayas linking displacement patterns, thrust sequences with the analysis of rotations of the thrust sheets using palaeomagnetic data. **Jadoon *et al.*** describe the geometry and kinematics of the Sulaiman fold belt, Pakistan.

The final section contains five papers on the 'North American Cordillera'. **Brown *et al.*** describe the Monashee decollement in the southern Canadian Cordillera. Using new LITHOPROBE data they are able to demonstrate the existence of a linked detachment from the Rocky Mountain foreland fold and thrust belt through to the accreted terranes on the western margin of the Canadian Cordillera. **Evenchick** describes the newly recognized Skeena fold belt and demonstrates a kinematic linkage between the Coast Plutonic complex and the Omineca and Rocky Mountain fold and thrust belts. The geometric and kinematic evolution of duplex systems is addressed by **Boyer** with reference to duplexes in the southern Canadian Rocky Mountains and in the Rocky Mountains of Montana. He argues that these duplexes evolved through synchronous thrust movement - not by a sequential, forward-breaking 'piggy-back' sequence. **Cooper** describes a detailed subsurface fracture analysis of thrust-related folds in the Foothills of the Canadian Rocky Mountains. The last paper in this section by **Rubin & Saleeby** describes the thrust belt features in the interior of the orogen between the Intermontane and Insular terranes of the North American Cordillera.

It will be evident to a reader of this volume that the theoretical and conceptual models for the geometries and kinematic evolution of high-level foreland fold and thrust belt systems are well developed and highly sophisticated (Suppe *et al.* 1991, this volume; Mosar & Suppe 1991, this volume). However, detailed field observations are still needed to test their applicability particularly with respect to the question of whether thrust structures evolve in a self-similar fashion (Fischer & Woodward 1991, this volume) (cf. fault related folds) or whether they evolve through different structural forms (e.g. from detachment folds - to fault propagation folds - to fault bend folds). It is also apparent that whilst the external zones of thrust belts are relatively well studied, the interior parts of orogens are less well understood and require much more detailed research on the more complex thrust systems found therein. Field work will need to be integrated with geophysical data and sections of the whole crust and lithosphere will need to be constructed. Petrofabric, strain and P-T-t data are needed in order to interpret the processes operating during thrust emplacement. The mechanics of thrust belt evolution are now being addressed using Coulomb wedge models (cf. Willett 1991, this volume), variations of which may provide answers for the problems of fault sequencing in thrust belts. It is apparent that, from both analogue modelling (Dixon & Liu 1991, this volume; Liu *et al.* 1991, this volume) and from field studies (Boyer 1991, this volume), synchronous thrust movement is a significant element in the kinematic evolution of foreland fold and thrust belts. This therefore will have important implications for thrust sequences and the balancing and restoration of cross-sections in thrust terranes.

Field based research, however, is the ultimate test of the theoretical, conceptual, numerical and analogue models. It is clear that the better understanding of thrust belts - for example that of the Canadian Rocky Mountains (e.g. Price 1981; Evenchick 1991, this volume; Brown *et al.* 1991, this volume) and of the Pyrenees (e.g. Munoz 1991, this volume; Puigdefabregas *et al.* 1991, this volume), stems from detailed fieldwork that integrates structural geology, stratigraphy, sedimentology and geophysical data. Future research on thrust tectonics will still need to be firmly based upon multidisciplinary field studies if progress is to be made in the understanding of the geometries, kinematics and mechanics of thrust systems.

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