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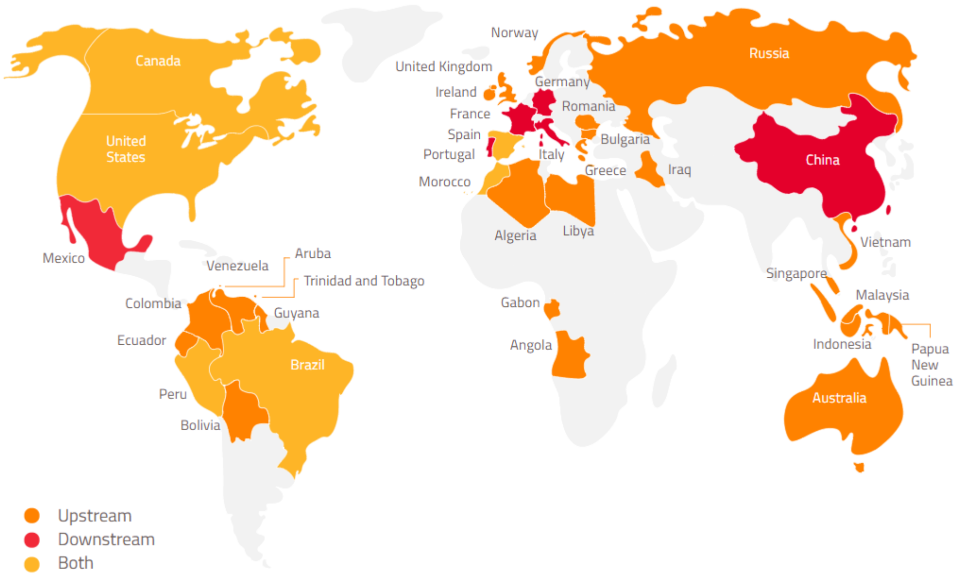

PETROLEUM GROUP

Fold and Thrust Belts: Structural style, evolution and exploration

31 October – 2 November 2017

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Fold and Thrust Belts: structural style, evolution and exploration

31st October – 2nd November 2017
Geological Society of London, Petroleum Group
Burlington House, London

Welcome to the Fold and Thrust Belts: Structural style, evolution and exploration conference, which has been organized by the Petroleum Group of the Geological Society. In this booklet you will find the programme and the abstracts for all of the talks and poster presentations over the three days of the conference. Also, information on the meeting can be found using the Petroleum Group Conference Application, downloadable for free from all app stores.

The organizing committee would like to thank the conference sponsors for their support of this event. The Petroleum Group and the Geological Society would not be able to continue to organize events of this scale without continued industry sponsorship.

Fold and thrust belts have formed in all eras of geological time and, represent some of the planet's most complex geological environments. Deformation styles may evolve spatially and temporally according to the type of sedimentary sequence involved, the presence of main detachment zones, and the orientation and evolution of the stress field with respect to the plate boundaries. At the same time, fold and thrust belts contain many substantial producing fields and some of the world's largest remaining hydrocarbon reserves. The complex interaction of fold and thrust processes, and their effects on potential reservoir quality and deliverability makes accurate characterization of such fields and reserves extremely difficult. Therefore this conference covers a wide range of topics and geographic locations. Case studies evaluate how a range of techniques can be applied to understand the structural style, evolution and deformation of thrust belts through the Zagros, South East Asia, Europe and South America geographic themes. The application, usefulness and analyses of physical and digital models are explored in the Analogue and Numerical Modelling themes. The integration of timing of thrust movement, hydrocarbon maturation, migration and trapping, and brittle strain distribution through fold and thrust belts are explored in the Thermochronology, Petroleum Systems, and Fractures themes.

Our thanks go to the Geological Society staff for their help and organization, particularly Sarah Woodcock and Paul Johnson for all of their hard work. The committee would like to take this opportunity to thank all contributors for their abstracts, presentations and posters. Finally, a very big thank you to all conference attendees; we hope that you will find the meeting interesting and enjoyable, with plenty of opportunities to exchange ideas and learn something new.

Convenors:
Paul Griffiths (Shell)
Raffaele di Cuia (Delta Energy Limited)
Michael Cottam (BP)
Davide Casabianca (Total)
Robert Butler (University of Aberdeen)
Gonzalo Zamora Valcarce (Repsol)
Fernando Alegria (Shell)
James Hammerstein (Royal Holloway)

Reference:
Abstracts of 'Fold and Thrust Belts: structural style, evolution and exploration', Petroleum Group of the Geological Society of London, Burlington House, London, UK, 31st October – 2nd November 2017.

PROGRAMME

CONFERENCE PROGRAMME

	Day One
08.30	**Registration**
09.00	**Welcome - Safety, Notices, Introduction**
09.10	**Conference Keynote : Rob Butler, *University of Aberdeen* Interpreting structural geometry in fold-thrust belts: why style matters.**
	Session One: Zagros
09.40	**Salt tectonics in fold and thrusts belts: examples from case studies and analogue modelling** Josep Anton Muñoz, *University of Barcelona*
10.00	**Tectonics and petroleum system comparison of fold-thrust belts: the Sevier of the western US, the Pyrenees of Spain, and the Zagros of Iraq and Iran** Jerome Kendall, *University of New Mexico*
10.20	**Structure and kinematics of the central Sivas Basin (Turkey): A fold-and-thrust belt with salt tectonics** Etienne Legeay, *Total*
10.40	**BREAK: Posters in the Lower Library (30 mins)**
11.10	**Crustal-scale pure shear in fold-and-thrust belts? Thoughts on the deformation style in the Kurdistan Zagros** Oscar Fernandez, *Repsol*
11.30	**Along-strike variation of a large scale anticline: Bekhair Anticline of the Zagros-Tauride belt** N. Bozkurt Çiftçi, *Genel*
11:50	**Evolution of the NW Zagros Fold-and-Thrust Belt in Iraqi Kurdistan from balanced and restored crustal-scale sections and forward modelling** Edouard Le Garzic, *Université de Pau et des Pays de l'Adour*
12.10	**Styles of compressional deformation and tectonic inheritance in the Kurdistan Zagros Thrust Belt of NE Iraq** Raffaele Di Cuia, Paolo Pace, *G E Plan*
12.30	**LUNCH: Posters in the Lower Library (90 mins)**
14.00	**A review of Central Kurdistan Region of Iraq Structures: Integrating field geology, wells and seismic to understand the different parameters controlling their formation** Francois Sapin, *Total*
14.20	**Structure of the Lurestan region of the Zagros fold-and-thrust belt, Iran** Stefano Tavani, *University of Naples*
14.40	**Structural Variation in Himalayan Fold and Thrust Belt, a Case Study from Kohat-Potwar Fold Thrust Belt of Pakistan** Humaad Ghani, *Univeristy of Potsdam*
15.00	**Remote sensing application to the Fars Region of the Zagros Mountains in Iran** Jorge Gines, *CGG*
15.20	**BREAK: Posters in the Lower Library (40 mins)**
	Historical Map display in the Council Room
	Session Two: South East Asia
16.00	**Fold & Thrust Belts of the Banda Arc** Peter Baillie, *CGG*
16.20	**Interaction between the folded structures of the PNG highland** Reinaldo Ollarves, *Santos Limited*
16.40	**Variation in Structural Style Between Two Complex, En-echelon Forelimb Structures in the Papua New Guinea Fold Belt** Ruth Wightman, *Oil Search Limited*

17.00	**Evolution of the North West Fold and Thrust Belt, Papua New Guinea: constraints from new data and multi-method structural modelling** Luke Mahoney, *University of Melbourne*
17.20	**Finish**
17.40	**Wine Reception (18.00-19.30)** **Sponsored by StructureSolver**

	Day Two
08.30	**Registration**
	Session Three: Europe
09.00	**The Pre-orogenic Template is not a Layer-cake: the Role of Rift Inheritance in Orogeny Highlighted by the Western Pyrenees Case-study** Emmanuel Masini, *Total*
09.20	**The inversion of the North-Iberian hyperextended margin** Jesús García-Senza, *Instituto Geológico y Minero de España (IGME)*
09.40	**Post-orogenic evolution of Mountain/Foreland basins systems: case study of the Pyrenean retro-foreland** Charlotte Fillon, *Université Toulouse /Total*
10.00	**Polyphase fold-and-thrust tectonics in the Belluno Dolomites: mapping, kinematic analysis, and 3D modelling reveal superposition of Dinaric and Alpine deformations** Andrea Bistacchi, *Università degli Studi di Milano Bicocca*
10:20	**Introducing salt tectonics in the Northern Calcareous Alps (Austria): a first-order element from continental margin to compressional rejuvenation** Pablo Granado, *University of Barcelona*
10:40	**BREAK: Posters in the Lower Library (30 mins)**
11:10	**Testing thin- and thick-skinned tectonics ahead of foreland thrust belts: an application to the deformed Adriatic foreland of Italy** Paolo Pace, *G E Plan*
11:30	**The Maiella Anticline Cretaceous platform margin (Italian Apennines) and insights for Mediterranean exploration** Davide Casabianca, *Total*
11:50	**Structural Interpretation of a Regional Section in the South Carpathian Foredeep** Pablo Hernández, *Repsol*
12:10	**New Discoveries and New Plays in the Carpathian Fold and Thrust Belt: Innovating New Structural and Stratigraphic Concepts for Future High Impact Exploration** Mark Enfield, *EPI*
12:30	**Thrust tectonics and hydrocarbon exploration in the Patraikos gulf (Western Greece offshore)** ClaudioTurrini, *Hellenic Petroleum Spa*
12.50	**LUNCH: Posters in the Lower Library (90 mins)**
	Session Four: Analogue Modelling
14.00	**Shortening accommodation in deepwater contractional fold belts: an experimental investigation** L. Mattioni, *ENGIE E&P*
14.20	**Insights into detachment folds and subsalt duplex geometries in the Eastern Carpathian Bend Zone, Romania: an analogue modelling approach** Dan M. TĂMAȘ, *OMV Petrom*
14.40	**Analogue models of multi-layer brittle/ductile wedges, and comparison with natural examples** Jean-Paul Callot, *Univ. Pau&Pays Adour*
15.00	**New devices to predict deformation for a geometrically non-uniform accretionary wedge. Applications to fold-and-thrusts belts** P. Souloumiac, *University of Cergy-Pontoise*
15.20	**BREAK: Posters in the Lower Library (40 mins)**

	Session Five: Fractures
16.00	**Are fracture networks easy to predict in the subsurface? The lesson learned from a discovery in Northern Iraq (Kurdistan Region)** Raffaele Di Cuia, *G E Plan*
16.20	**Fold evolution and natural fracture prediction using multi-scale geomechanical modeling with application to a Kurdistan Zagros fold** Rodrick Myers, *ExxonMobil*
16.40	**Development Of Fault-Parallel Veins (Slickenveins): An Example From The Hudson Valley Fold-Thrust Belt, New York** Stephanie Mager, *BP America*
17.00	**Controls on fracture intensity in a carbonate anticline, Sawtooth Range, Montana** Hannah Watkins, *University of Aberdeen*
17.20	**Finish**
	Wine Reception (17.30-19.30) **Sponsored by StructureSolver**

	Day Three
08.30	**Registration**
	Session Six: Numerical Modelling
09.00	**Mechanical controls on structural styles in shortening environments: A discrete-element modeling approach** Amanda Hughes, *University of Arizona*
09.20	**Effect of fluid pressure distribution on the structural evolution of accretionary wedge** Jonas B. Ruh, *ICTJA-CSIC*
09.40	**Quantitative Structural Analysis of Newly Acquired Data from Mexican Ridges Fold Belt** Nathan W. Eichelberger, *StructureSolver*
10.00	**Coupled Geomechanical Forward Model Of A Gravitationally-Driven Fold-And-Thrust Belt** Juan Manuel Jiménez, *Repsol*
10:20	**Role of tectonic inheritance in the latest Cretaceous to Paleogene Eurekan Orogeny (NE Canadian Arctic)** Berta Lopez-Mir, *CASP*
10:40	**BREAK: Posters in the Lower Library (30 mins)**
	Session Seven: South America
11:10	**An Integrated Approach To De-Risking Exploration And Appraisal In Structurally Complex Fold And Thrust Belts: Application To The Incahuasi Field (Bolivia)** Vincenzo Spina, *Total*
11:30	**Structure and Hydrocarbon potential of the Northern Bolivia Subandean thrust belt (Beni Basin)** Mélanie Louterbach, *Repsol*
11:50	**3D Structural Style Along a Transfer Zone, Southern Subandean Zone, Bolivia** Massimo Bonora, *Repsol*
12:10	**LUNCH: Posters in the Lower Library (90 mins)**
	Session Eight: Thermochronology
13.40	**Using thermochronometry to date thrust related exhumation in the Western Taurides fold-thrust belt (Turkey)** Peter J McPhee, *Utrecht University*
14.00	**Quantifying vertical movements in fold and thrust belts: subsidence, uplift and erosion in Kurdistan, Northern Iraq** Richard Tozer, *Maersk Oil*
14.20	**The Polish-Ukraininian hydrocarbon province of the Carpathians fold and thrust belt: constraints from balanced cross-sections coupled with low-temperature thermochronometry** Stefano Mazzoli, *University of Naples*
14.40	**BREAK: Posters in the Lower Library (40 mins)**

	Session Nine: Petroleum Systems
15.20	**Modelling complex hydrocarbon migration and accumulation in fold and thrust belts** Lawrence Gill, *BP*
15.40	**A New Kinematic Tool for Petroleum System Modeling in Complex Structural Settings: Application to the Foothills Region of Kurdistan** Marie Callies, *Beicip-Franlab*
16.00	**Modelling Trap integrity in a Deepwater Toe thrust: The role of geo-history** Neil Grant, *ConocoPhillips*
16.20	**Conference Closing**
16.30	**Finish**

POSTER PROGRAMME

Posters Day 1

Review of Papuan-Aure Fold Belt Structural Models (PRL15), Papua New Guinea, based on structural forward modeling, recent well results and surface analysis.
Charlie Kergaravat, *Université de Pau et des Pays de l'Adour*

An Insight into the Lesser Himalayas of Pakistan for their hydrocarbon potential
Gohar Rehman, *University of Peshawar*

Estimating the hidden layer parallel strain (LPS) in Brunei deep water fold-thrust belt
X. Yang, *University of Southampton*

Comparison between two DWFTBs: the Outer Tuscan Nappe (Northern Apennines, Italy) vs. offshore Sabah (NW Borneo)
Filippo Carboni, *University of Perugia*

Influence of syn-tectonic sedimentary rate on the geometry and kinematic evolution of growing experimental wedges: Comparison to Kuqa fold-and-thrust system (NW China)
Oriol Pla, *Universitat de Barcelona*

Structural style of a fold-and-thrust belt involving laterally-changing, multiple décollements: the Kuqa fold-and-thrust belt (NW China)
Esther Izquierdo-Llavall, Universitat de Barcelona

Variation in sedimentation patterns from internal to external basins in accretionary settings: examples from the East Coast Basin of New Zealand
McArthur, A.D, *University of Leeds*

Nature of oroclinal bending in the Main Frontal Thrust of Himalayan foreland fold and thrust belt in Pakistan
Taqweemul Haq Ali, Bach*a Khan University*

Geological development of the offshore Timor Orogen
Pedro Martinez Duran, *CGG*

Posters Day 2

Along strike structural variation in the French Sub-Alpine chains
Hannah Watkins, *University of Aberdeen*

Structural styles and evolution of a submarine fold and thrust belt, South Falkland Basin
Dave McCarthy, *BGS*

Along-strike variation of thrust-related folds in the curved thrust systems of the Central-Northern Apennines of Italy
Paolo Pace, *G E Plan*

Inferring foreland-directed gravitational collapse along curved thrust fronts from the analysis of a minor thrust-related shear zone in the Umbria-Marche thrust belt (Central-Northern Italy)
Paolo Pace, *G E Plan*

A small but perfectly-formed and prospective fold-thrust belt in the southern Irish Sea and central Pennines of England
Tim Pharaoh, *BGS*

Structural inheritance of Triassic–Jurassic normal faults in a Cretaceous thrust and fold belt based on seismic and field data (western Transdanubian Range, Hungary)
Gábor Héja, *MTA-ELTE Geological*

Contrasting styles of compressive deformation in the Central Adriatic foreland fold-and-thrust belts: implications for traps and source rocks distribution
Vittorio Scisciani, *Università degli Studi 'G. d'Annunzio' di Chieti-Pescara*

Structural inheritance of fault displacement profiles from continental rifting to thrust fault propagation – from observations to mechanics.

Simon J Oldfield, *University of Leeds*

Structural architecture of the northern part of Lesser Caucasus: an eastern Achara-Trialeti fold and thrust belt, Georgia
Victor Alania, *Tbilisi State University*

The geometry and kinematic evolution of central Lesser Caucasus basement wedge, Georgia: Implication for building an eastern Achara-Trialeti fold and thrust belt
Nino Sadradze, *Tbilisi State University*

Multiscale characterization of fracturing in folded platform carbonates: the case study of the Island of Pag, External Dinarides of Croatia
Silvia Mittempergher, *Università degli Studi di Milano Bicocca*

Posters Day 3

Along-strike variation of thin-skinned thrusting style controlled by pre-existing basement structure in the easternmost Jura Mountains (northern Switzerland)
Herfried Madritsch, *Nagra*

Basement-involved thin-skinned thrusting and associated structures in an intraplate fold and thrust belt – an example from the southern Altmark area, Central Germany
A Malz, *Landesamt für Geologie und Bergwesen*

Newly-observed Caledonian and Devonian fold and thrust structures in the UK North Sea
Stefano Patruno, *PGS*

Structural styles and the 4D evolution of the Maranhao deepwater fold belt, NE Brazil
Javier Tamara, *Royal Holloway, University of London*

Integration of different vintage data for revitalising exploration of proven and prospective plays in the Apulian thrust belt of southern Italy
Paolo Pace, *G E Plan*

Concealed fold-and trust belt in the Congo Basin, Central Africa, revealed by structural analysis of the Dekese fully cored 1850m deep well.
Damien Delvaux, *Royal Museum Central America*

Modeling Growth Strata to Constrain Development of Contractional Structures
Nathan W. Eichelberger, *StructureSolver*

Microstructural changes and dehydration of slates in the temperature window 180-330°C
Vénice Akker, *University of Bern*

Seismic in Over Thrust Environment; Approaching the challenge
Jose Olaya, *Repsol*

Understand and Model Complex Geology of Fold and Thrust Belts - from Interpretation to Fluid Flow Prediction
Melanie Morin, *Paradigm*

Oral Presentation Abstracts

(Presentation order)

Tuesday 31ST October 2017

Session One: Zagros

Interpreting structural geometry in fold-thrust belts: Why style matters

Robert W.H. Butler[1], Clare E. Bond[1], Hannah, M. Watkins[1], Mark A. Cooper[1,2]
[1] *Fold-Thrust Research Group, School of Geosciences, University of Aberdeen, Aberdeen, United Kingdom.*
[2]*Sherwood Geoconsulting*

Notwithstanding the inherent limitations of thrust belts caused by the timing of structures vs charge and the propensity for water flushing, many systems offer exceptional targets for hydrocarbon exploration. However, definition of traps and the volumetric calculations can still be fraught. Thrusts and folds can show a range of different geometries and inter-relationships that, together with challenging seismic imaging, makes the prediction of subsurface structure uncertain. Many existing interpretation strategies apply a narrow range of fold-thrust relationships that make arbitrary choices for strain and fault localisation, especially in the forelimbs. This routine application of this standard spectrum of styles engenders an overly optimistic appreciation of structural risk. The published array of examples has created significant bias in interpretations of fold thrust belts that has probably contributed to a large number of drilling surprises during hydrocarbon exploration.

We address these challenges and discuss strategies to assist in subsurface interpretation of structural geometry in thrust belts. The development of fold-thrust concepts are outlined and illustrated with an array of outcrop examples. The structural interpretations of the outer Canadian Cordillera have evolved considerably since Dahlstrom's "foothills family" of structures was established through the iteration of outcrop, seismic and well data. Yet now-abandoned interpretations are still used to illustrate theoretical fold-thrust models. Structural styles vary along the thrust belt, in harness with stratigraphic variations. The foothills family is larger than once thought! These styles are contrasted with those developed in the equivalent tectonic setting of the external French Alps. Significant variations in the structural geometry exist between the Jura, where the stratigraphic template is dominated by closely spaced carbonate formations, and the Subalps, where these carbonate formations are separated by thick, shale-prone units. In the Jura, folding is broadly harmonic but still shows variations between buckles ("detachment folds") and imbricate thrusting. In the Subalps deformation is disharmonic with layers showing variations in thrust localisation and in the propensity for folding. Many of these contractional structures appear to localise upon pre-existing faults. These heterogeneities apparently give rise to lateral changes in thrust belt architecture. Forecasting these deformations demands consideration not only of the mechanical properties of the stratigraphic template but also of any pre-existing structures contained with in it. Both the external Rockies and the Subalps apparently involve simple detachment above basement. Elsewhere thrust systems can involve basement – as exemplified by the front ranges of Papua New Guinea. Basement involvement, and reactivation of pre-existing normal faults, can exert a first-order control on thrust system evolution and greatly increase the solution space for structural interpretation.

These studies indicate that successful subsurface interpretation needs to embrace uncertainty – especially when planning wells. Single deterministic pre-drill interpretations are commonly unhelpful – so that wells that aim to miss structural crests but are side-tracked to reservoir targets offer better strategies. Seismic data may become more useful if fully integrated and iterated with evolving structural interpretations.

NOTES:

Salt tectonics in fold and thrusts belts: examples from case studies and analogue modelling

Josep Anton Muñoz[1], Eduard Roca[1], Oriol Ferrer[1], Mark Rowan[2], Esther Izquierdo[1], Oriol Pla[1],
Núria Carrera[1], Pablo Santolaria[1], Pablo Granado[1] and Oscar Gratacos[1]
[1]Geomodels Research Institute, University of Barcelona
[2]Rowan Consulting Inc.

Salt plays a dominant role in the structural style of fold and thrust belts. In many mountain belts, such as the Zagros and the Pyrenees, deposition of the salt predates the contractional deformation. In other cases (Zagros, Pyrenees, Kuqa basin), the salt was deposited in the foreland basin during the deformation. Distribution of the preconvergence salt is one of the main factors controlling the regional structural grain of fold and thrust belts, determining the xistence of thrust salients and reentrants as well as major changes in structural style. In addition, pre-existing salt structures, mainly developed at passive margins, control the geometry of the subsequent contractional structures. Shortening of the salt structures results into diapir reactivation, squeezing, welding and afterwards the development of folds and thrusts. Position of the former diapirs with respect the fold and thrusts structures and the linkage between them is determined by the thickness of the mechanical beam folded above the salt detachment as well as the geometry of the previous salt structures. Most of the diapirs of pre-convergence salt observed in fold and thrust belts result from the reactivation of former diapirs. However, new diapirs can also form triggered by local extensional faults coeval with thrusting (for example extensional faults formed by longitudinal stretching or by extensional collapse), or by folding and erosion of inflated salt in the footwall of the main thrusts. Reactivated older structures show a different style, with a significant development of secondary welds as well as megaflaps.

Salt deposited in foreland basins mostly result into the development of salt-cored detachment folds with limited amount of diapirs triggered by syn-orogenic erosion. In some occasions pre-orogenic and syn-orogenic salt horizons are overlapped, determining some characteristic structural features. Apart from multiple detachment features, such as disharmonic fault-related folds, salt structures from the lower salt horizon may trigger salt structures of the upper salt layer, giving rise to interference patterns.

Syntectonic sedimentation plays a major role on the structural style and evolution of fold and thrust belts. It controls the wavelength of the structures, delays the activation of the deformation at the salt pinch-out in the foreland and determines the orientation of the structures.

Field and seismic examples illustrate all these different structures and will be complemented by images from analogue models.

NOTES:

Tectonics and petroleum system comparison of fold-thrust belts: the Sevier of the western US, the Pyrenees of Spain, and the Zagros of Iraq and Iran

Jerome Kendall[1], Jaume Vergès[2], Renas Koshnaw[3]
[1]*University of New Mexico - Albuquerque*
[2]*Group of Dynamics of the Lithosphere, Institute of Earth Sciences Jaume Almera ICTJA CSIC,*
[3]*University of Texas – Austin*

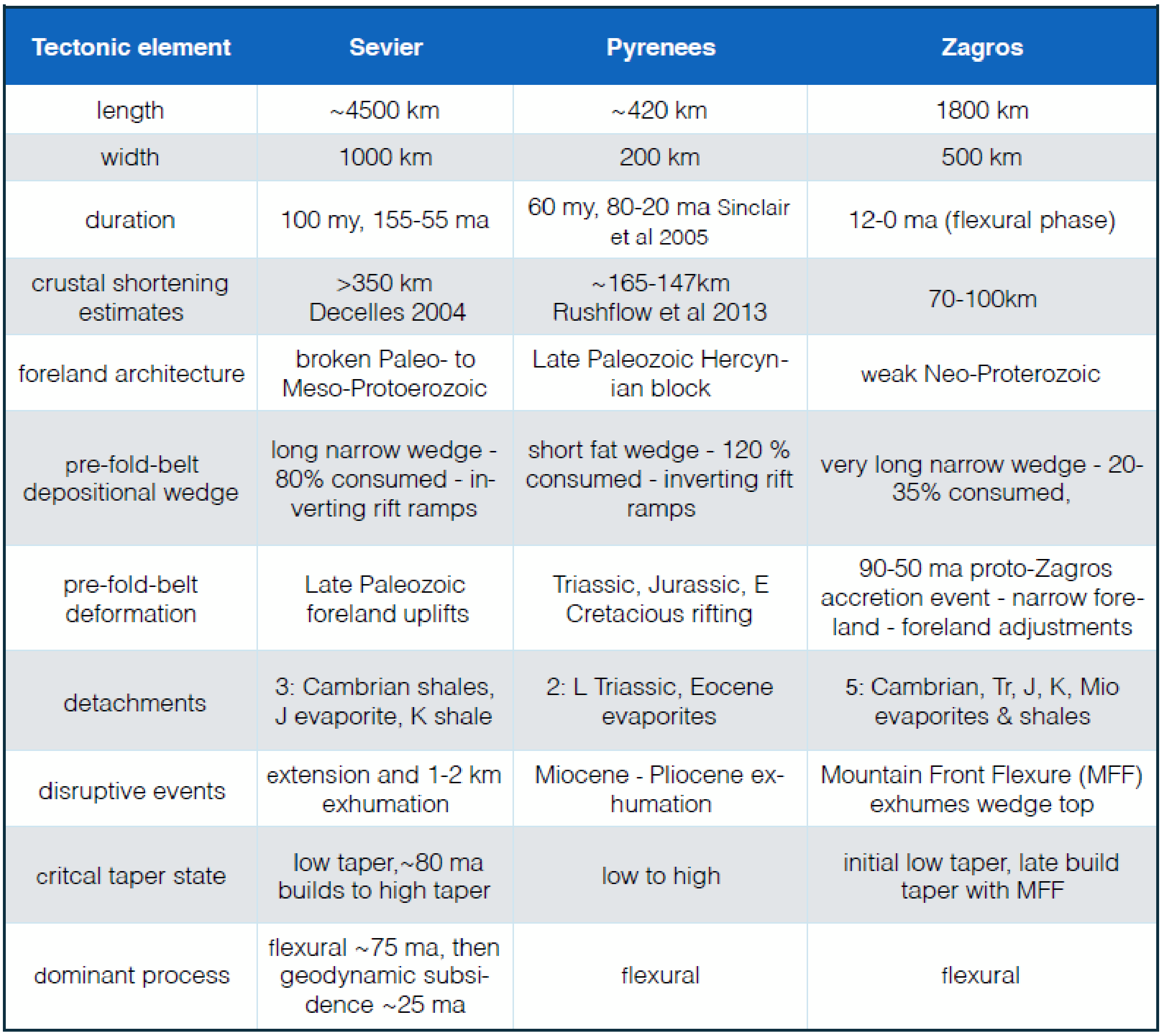
Petroleum system analysis of orogenic systems provides an audit of the processes that control the structure and properties of the earth's crust. The distribution and deformation path of source intervals is a key factor in the petroleum system evolution of fold-thrust belts. The comparison of orogenic systems illustrates the importance of flexural vs. dynamic processes, orogenic wedge taper, mechanical stratigraphy and inherited crustal architecture on the creation, preservation and destruction of petroleum accumulations. These convergent systems share several characteristics of fold-thrust belts with major differences in scale, degree of fold-thrust belt and foreland evolution, and preservation of fold-thrust belt wedge top cover. The Sevier of the western U.S. is a flexural foreland system that was later dominated by geodynamic subsidence. It also has a major post-tectonic extension and exhumation. The Pyrenees is a small flexural system that has completely consumed its pre-tectonic cover. The Zagros is at an early stage of fold-thrust belt evolution with thick wedge top and foredeep deposits.

The Sevier has incorporated and exhumed most of its pre-tectonic source intervals but has significant syntectonic source intervals. Late in the orogenic system the fold-thrust belt evolved into a high taper orogenic wedge while geodynamic subsidence overwhelmed flexural subsidence. The dynamic subsidence shifted maximum accommodation ~ 200 km into the foreland. At the end of Sevier shortening the fold-thrust belt and foreland probably housed world-class accumulations. Post-orogenic extension and regional uplift exhumed most foreland and surviving fold belt traps.

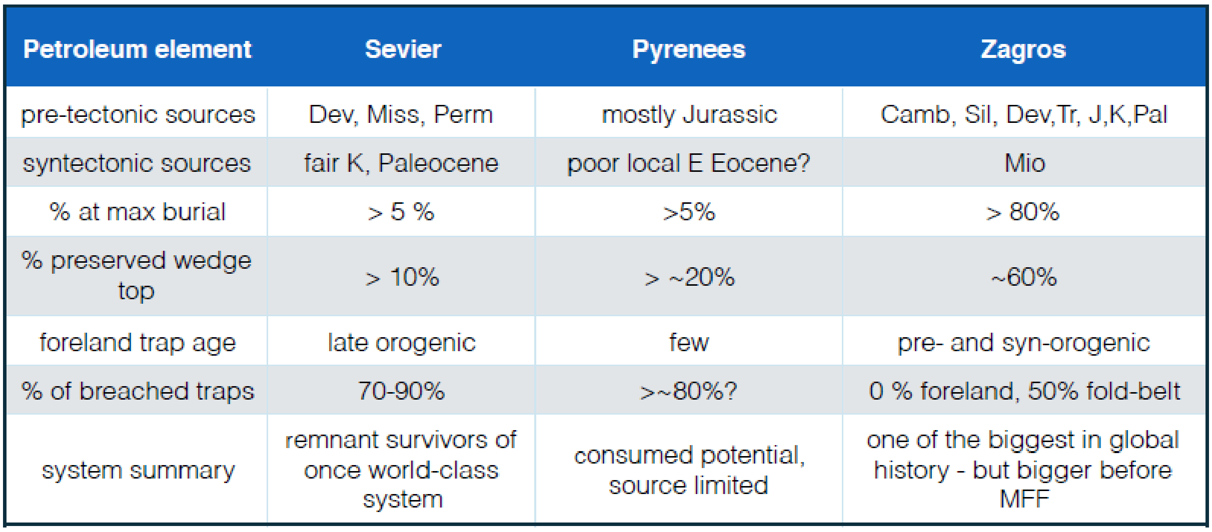
The Pyrenees has few syntectonic source intervals and consumed pre-tectonic source intervals early in the orogenic system. In addition, scarcity of foreland traps and the greater degree of fold-thrust belt exhumation hinder its potential for successful petroleum accumulations.

The Zagros is an active system near the peak of its petroleum potential, having multiple preand early tectonic source intervals that are less than half consumed. The foreland has major accumulations in pre- and early fold-thrust belt traps. The exhuming portion of the orogenic system has a some surviving accumulations, while segments of the orogenic system covered by wedge top deposits have a much better success rate, and nearly every trap in the foreland is a success. The differences in success rate are probably due to intricacies of trap vs. hydrocarbon charge timing and accumulation preservation.

From a petroleum tectonics view, the Sevier was a great petroleum system but only a remnant survived post-tectonic processes. The Pyrenees probably generated and consumed its more limited potential early in it's orogenic cycle. The Zagros, with its multiple active source intervals, large wedge-top deposits, and gently deformed foreland is a near peak petroleum system. This comparison highlights the use of petroleum accumulation timing and preservation in probing the processes in evolving fold-thrust belt orogenic systems.



Tectonic element	Sevier	Pyrenees	Zagros
length	~4500 km	~420 km	1800 km
width	1000 km	200 km	500 km
duration	100 my, 155-55 ma	60 my, 80-20 ma Sinclair et al 2005	12-0 ma (flexural phase)
crustal shortening estimates	>350 km Decelles 2004	~165-147km Rushflow et al 2013	70-100km
foreland architecture	broken Paleo- to Meso-Protoerozoic	Late Paleozoic Hercynian block	weak Neo-Proterozoic
pre-fold-belt depositional wedge	long narrow wedge - 80% consumed - inverting rift ramps	short fat wedge - 120 % consumed - inverting rift ramps	very long narrow wedge - 20-35% consumed,
pre-fold-belt deformation	Late Paleozoic foreland uplifts	Triassic, Jurassic, E Cretacious rifting	90-50 ma proto-Zagros accretion event - narrow foreland - foreland adjustments
detachments	3: Cambrian shales, J evaporite, K shale	2: L Triassic, Eocene evaporites	5: Cambrian, Tr, J, K, Mio evaporites & shales
disruptive events	extension and 1-2 km exhumation	Miocene - Pliocene exhumation	Mountain Front Flexure (MFF) exhumes wedge top
critcal taper state	low taper,~80 ma builds to high taper	low to high	initial low taper, late build taper with MFF
dominant process	flexural ~75 ma, then geodynamic subsidence ~25 ma	flexural	flexural



Petroleum element	Sevier	Pyrenees	Zagros
pre-tectonic sources	Dev, Miss, Perm	mostly Jurassic	Camb, Sil, Dev,Tr, J,K,Pal
syntectonic sources	fair K, Paleocene	poor local E Eocene?	Mio
% at max burial	> 5 %	>5%	> 80%
% preserved wedge top	> 10%	> ~20%	~60%
foreland trap age	late orogenic	few	pre- and syn-orogenic
% of breached traps	70-90%	>~80%?	0 % foreland, 50% fold-belt
system summary	remnant survivors of once world-class system	consumed potential, source limited	one of the biggest in global history - but bigger before MFF

Structure and kinematics of the central Sivas Basin (Turkey): A fold-and-thrust belt with salt tectonics

Etienne LEGEAY[1,2], Jean-Claude RINGENBACH [2], Charlie KERGARAVAT[1], Alexandre PICHAT[1], Geoffroy MOHN[3], Jaume VERGES[4], Kaan Sevki KAVAK [5], Jean-Paul CALLOT[1]
[1] *E2S UPPA, Univ. Pau&Pays de l'Adour CNRS Total, LFCR, Université de Pau et Pays de l'Adour, Pau, France.*
[2] *Structural Geology Department, Total SA, CSTJF, Pau, France*
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The Sivas Basin in central-eastern Anatolia, is a north-verging fold-and-thrust belt involving Late Cretaceous to Neogene sediments. It belongs to a group of Anatolian basins that developed after the northern Neotethys closure. The Sivas Basin formed above the northern leading edge of the Tauride platform, the Kırşehir micro-continent, the edge of the Pontide arc and the related ophiolitic suture. It is all together the richest, the most studied and also most complex of the group of Tertiary basins in Turkey. Its complex structure is that of a fold-and-thrust belt with syn-orogenic salt tectonics.

To decipher the complex geometries and structural evolution of the basin, we remapped the whole area and constructed five regional cross-sections supported by 2D seismic data. From the analysis of the whole seismic dataset, we define three tectonics domains from south to north: (i) a Maastrichtian to Eocene north-verging fold-and-thrust belt (FTB) passing northward to (ii) an Oligo-Miocene salt domain controlled by a mix of shortening and salt tectonics, forming the foreland fold and thrust belt (FFTB), then (iii) a Late Miocene to Pliocene preserved foreland basin (FB) (***Figure 1***). The restored cross-sections show that shortening increases from west (~15km) to east (~25km) in relation with the implication of the Kirsehir block in the collision zone.

After the Late Cretaceous ophiolite obduction, the Sivas basin recorded a relative quiet tectonic phase from Maastrichtian to Paleocene with basinal pelagic sedimentation and carbonate platform on its southern edge (***Figure 1 A***). Shortening started in the Early Eocene with the development of north-verging thrusts. It is recorded by a coarse clastic input, with conglomeratic deltas fans grading up to basinal turbidites until the Late Eocene. Then the basin is gradually isolated with favorable conditions for the deposition of a thick evaporite level on large surface (***Figure 1 B***).

Early Oligocene sediment loading on salt formed primary minibasins during a quiescent tectonic period with salt extrusion and canopy emplacement (***Figure 1 C***). Middle Oligocene to Miocene continental clastics deposition was controlled by halokinesis: secondary minibasins, salt ridges and salt sheets development formed on the canopy level. Salt ridges and diapirs recorded two pulses of shortening: during the Middle Oligocene (***Figure 1 D***), prior to an Early Miocene regional transgression (***Figure 1 E***), then a second in Middle to Late Miocene (***Figure 1 F***). Halokinetic structures are described until the Early Pliocene, then the Sivas Basin was possibly covered by tabular sediments (***Figure 1 F***). Strong erosion took place during Quaternary as a result of the Anatolian uplift (***Figure 1 G)***.

The geometries of the Sivas Basin are unique due to the volume of salt integrated in the deformation. Salt-related structures are comparable to classical salt basins on passive margins (e.g.: West Africa, Gulf of Mexico), but in a compressive context. Generally, halokinesis in salt related fold-and-thrust belts occurred early in the evolution (e.g.: Zagros), while is strongly active in Sivas until final stages of the contraction. In fact, a thick syn-orogenic salt level formed a very efficient detachment which will be strongly recycled during contraction. Successively, the primary salt, then the canopy, were reincorporated in the system by mechanical and geochemical processes.

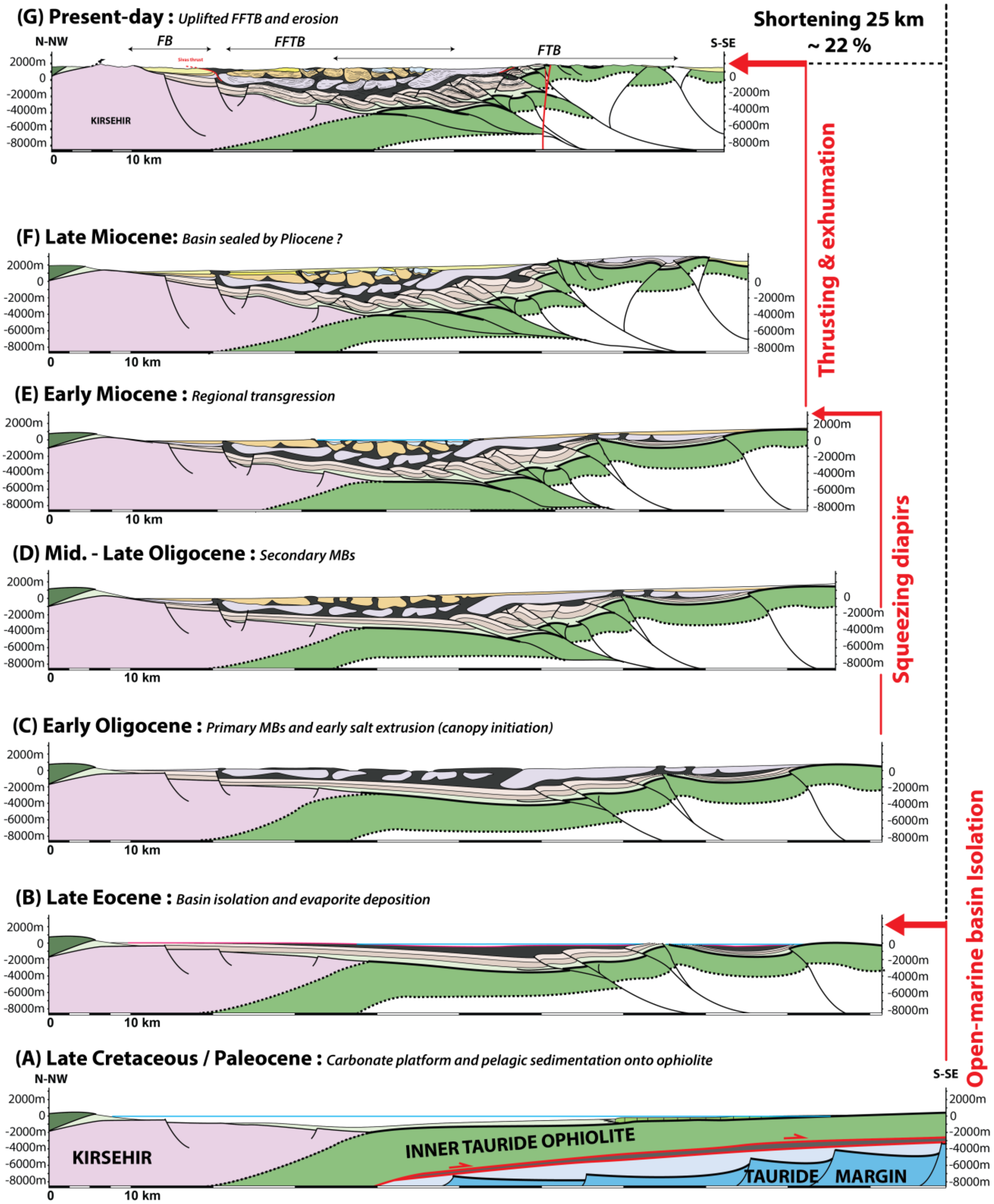

Figure 1. Evolution of the Sivas Basin from Late-Cretaceous to present-day.

NOTES:

Crustal-scale pure shear in fold-and-thrust belts? Thoughts on the deformation style in the Kurdistan Zagros

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Repsol Exploracion, Spain

The Iraqi Kurdistan Zagros are a fold-and-thrust belt characterized by the presence of multiple mechanically weak layers (detachments) within its Phanerozoic sedimentary cover. Evolution of this fold-and-thrust belt is normally interpreted in terms of multiple, punctuated phases of deformation that progress in sequence (from hinterland to foreland and from shallower detachments to deeper ones). However, evidence from growth strata, amounts of shortening, and interaction between shallow and deep structures suggests that an alternative model of progressive 'pure shear' deformation may be more suitable in explaining the present-day structure. This 'pure shear' model implies that all layers in the sedimentary cover and the underlying basement are shortened synchronously and by equal amounts, producing broad uplift that compensates area or volume lost by horizontal shortening.

Observations are based on a series of regional-scale transects across the Mesopotamian Foreland and the uplifted part of the fold-and-thrust belt (Simply Folded Belt). These sections have been constructed based on field geology and reflection seismic. On these sections, mechanically strong units ('beams') bounded by upper and lower detachments are each observed to deform in shortening with different styles. Four main 'beams' have been identified that encompass, in broad terms: 1) Paleozoic strata and underlying basement; 2) Mesozoic strata (locally presenting further internal detachments); 3) Paleogene strata; and 4) Neogene strata. Deformation of the 'beams' is vertically stacked, defining a 'pure shear' system at the crustal scale (i.e., shortening is accommodated by vertical thickenning). Similarities between the structural style in the internal (Simply Folded Belt) and external (Mesopotamian Foreland) zones makes it likely that this 'pure shear' model can be applied across most of the Kurdistan Zagros fold-and-thrust belt.

A 'pure shear' mechanism implies that deformation at all structural levels occurred synchronously, and most likely migrated from the hinterland to the foreland. This observation can have a major impact on the understanding of hydrocarbon systems in this fold and thrust belt. The timing of folding and thrusting in the external parts of the fold-and-thrust belt (Mesopotamian Foreland) can be determined from the age of pre- and syn-tectonic strata to have occurred less than 10Ma ago in one or two phases of deformation. Indications of active migration in some structures may indicate that deformation may still be ongoing. It is interpreted that deformation is older in the more internal parts of the system (Simply Folded Belt).

NOTES:

Along-strike variation of a large scale anticline: Bekhair Anticline of the Zagros-Tauride belt

N. Bozkurt Çiftçi[1], John Fisher[1], Mike Adams[1]
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The Bekhair anticline is a 70km long surface structure located on the Zagros/Tauride fold-thrust belt in the north of the Kurdistan region of Iraq. Trending NW-SE to E-W, the Bekhair anticline defines the southwestern limit of the Zagros mountain front adjacent to predominantly undeformed sediments of the Mesopotamian foreland. The Bekhair anticline is divided into the Ber Bahr, Linava and Peshkabir segments from east to west based on minor variations in structural trend.

The principal culmination is observed towards the eastern tip of the Ber Bahr segment where the Cretaceous sediments are exposed at the core of the anticline. Directly to the east of this culmination the structure terminates abruptly over a distance less than a 10th of its entire length. To the west the anticline extends for more than 50km along the Linava and Peshkabir segments forming a number of secondary culminations and depressions exposing the Paleogene strata. In planform the geometry of the structure also varies east to west from an approximately 10km wide open fold to a 2km wide tight fold with very distinct kinks along the hinge line.

Subsurface data provides evidence that along-strike differences in the geometry of the anticline are associated with variation in structural style, vergence direction and the influence of the pre-existing structural fabric that was reactivated during the folding phase.

To date, exploration wells drilled on the Bekhair trend have had mixed results with structural compartmentalization and trap integrity often cited as the key issues driving disappointing tests. The exploration history of the Bekhair anticline illustrates that generic anticlinal models should be applied with caution when contributing to drilling decisions but that opportunities for exploration may still exist in structures that appear at face value to have been tested.

NOTES:

Evolution of the NW Zagros Fold-and-Thrust Belt in Iraqi Kurdistan from balanced and restored crustal-scale sections and forward modelling

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The Zagros orogenic belt extends over 2000 km from Turkey to SE Iran and resulted from the closure of the Neo-Tethys Ocean between the Arabian and Eurasian plates. The development of the Zagros Fold-and-Thrust belt begun in the Late Cretaceous and culminated in the Tertiary. Two main tectonic stages are known: (i) initial obduction of oceanic crust above the Arabian continental margin from Campanian to Paleocene times, and (ii) continental collision between Arabian and Central Iranian blocks since Miocene time. The Kurdistan region of the Zagros Fold-and-Thrust belt is one of the world's most petroleum-rich provinces and, in the near future, it could become one of the main producers. In recent years, with the end of the second Iraq War, the Kurdistan of northern Iraq has regained a strong interest for both structural studies and petroleum exploration-related investigation. However, fold mechanisms have been interpreted differently and the nature of the basal detachment level is still discussed. Furthermore, orogenic evolution and timing of deformation, although crucial for hydrocarbons, are still poorly known in this folded region.

The main goals of this study are (i) to discuss the role of the mechanical stratigraphy, and its control on folding style, (ii) to address the significance of basement involvement and its role on the stepwise morphology of the basal decollement level towards the hinterland, (iii) to calculate the shortening by comparing the regional balanced and restored cross sections as well as individual structures, (iv) to determine the relative ages of tectonic deformation since Late Cretaceous, and (v) to propose a 2D kinematic model illustrating the evolution of the orogenic system since the Late Cretaceous. For these purposes, regional balanced and restored cross-sections (Fig. 1) were constructed across the Central part of the Kurdistan Fold-and-Thrust Belt and the Mesopotamian basin, based on surface and sub-surface data (seismic lines and well data). In addition, a new detailed geological map was performed, combining several fieldwork campaigns, remote sensing mapping using high resolution satellite images and published geological maps. Field observations and seismic interpretations allow to better define timing of syn-tectonic deposition in particular parts of the foreland basins, and 9 new vitrinite reflectance data, collected in several stratigraphic units in the field, have been used for constraining amount of erosion in the Simply Folded Belt. By combining all this dataset, a semi-quantitative forward model is proposed to provide a robust geological history of this region from the latest Cretaceous to present.

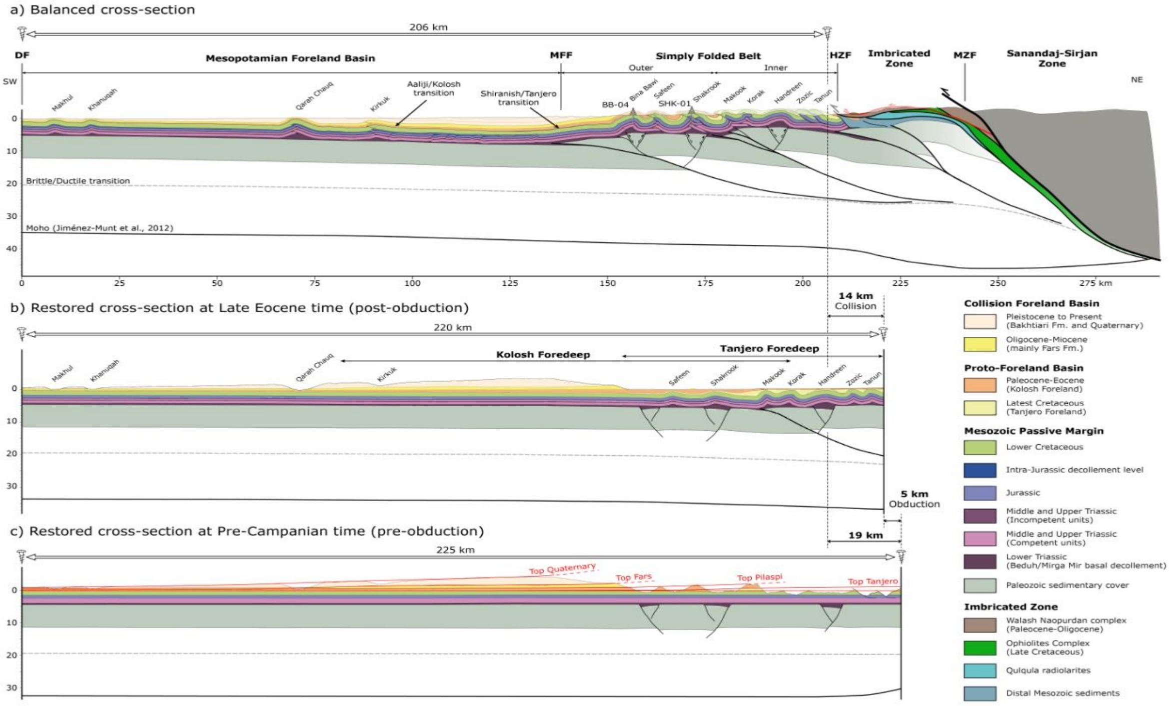

Fig. 1. Balanced and restored cross-sections through the Central Kurdistan Fold-and-Thrust Belt. (a) Balanced cross-section. (b) Restored cross-section after obduction at Late Eocene time. The top Pilaspi is used as the horizontal datum. (c) Restored cross-section before obduction at Pre-Campanian time. The top Qamchuqa is used as the horizontal datum. Red lines correspond to the tops of the units used to estimate the flexure. The comparison with the balanced cross-section yields a minimum of 19 km of total shortening and a minimum of 5 km of shortening for the obduction event.

This study shows that folding style in the Kurdistan Fold-and-Thrust Belt is mainly characterized by multi-detachment folds detached above the Early Triassic Beduh/Mirga Mir basal ductile level (Fig. 1), with intermediate decollement levels that induced complex geometries like accommodation thrusting and/or disharmonic folding. The Late Triassic Kurra Chine anhydritic level, the latest Triassic Baluti Fm., and the earliest Cretaceous Chia Gara Fm. are the main intermediate detachment levels in the sedimentary succession. We proposed that the structural steps situated below the Simply Folded Belt are related to low-angle thrust faults rooted at the brittle/ductile transition and connected with the Beduh/Mirga-Mir basal decollement level (Fig. 1). Syn-tectonic growth strata of Late Cretaceous and Paleocene times have been recognized for the first time in the Kurdistan Fold-and-Thrust Belt. This allows to constrain timing of folding in the foreland from Late Cretaceous to Pliocene and to estimate the evolution of the shortening and the advance of the deformation front. Section restoration yielded 19 km of total shortening in the sedimentary cover. This shortening was separated in 5 km during the obduction and 14 km during the collision phase (Fig. 1). Forward modeling results performed in this study kinematically validate the proposed cross-section at different scales using a sequence of deformation constrained by syn-tectonic sediments and cross-cutting relationships.

NOTES:

Styles of compressional deformation and tectonic inheritance in the Kurdistan Zagros Thrust Belt of NE Iraq

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The Zagros fold-and-thrust belt represents one of the major and prolific hydrocarbon provinces. The distribution of the hydrocarbon discoveries and the styles of compressional deformation vary along the strike of the entire Zagros fold-and-thrust belt. Intense exploration concentrated on the productive Fars Zone and Dezful Embayment regions of Iran in the central sector of the Zagros thrust belt. In the Kurdistan region of northeast Iraq, hydrocarbon exploration has been mainly focused in the foothills and then moved increasingly across the Low/High Folded Zone boundary. In this sector, the most important discoveries lie within fractured carbonate reservoirs hosted in four-way-dip closure thrust-related anticlines aligned to the main thrust belt trend. As a consequence, a comprehensive and regional understanding of: i) the compressional deformation styles, ii) the distribution and development of the thrust-related folds and iii) the control of pre-existing structures is crucial for assessing prospectivity and exploration strategies. In this study the styles of compressional deformation with respect to the influence of the pre-existing structures are discussed with some cases from the Kirkuk Embayment in the Kurdistan region of northeast Iraq (Fig. 1).

The Zagros is the most prominent orogenic belt of the Middle East. It is the result of convergence with related subduction-collision processes between the Arabian and the Eurasian Plates starting from the Late Cretaceous-Cenozoic times onwards. The tectonic evolution is characterized by Permian-Early Triassic rifting and Triassic break-up of Pangea with the opening of the Neo-Tethys Ocean, Mesozoic passive margin and subsidence, followed by convergence and continental collision with thrust belt development during Upper Cretaceous-Cenozoic (Alavi, 2004; Jassim & Goff, 2006; Mouthereau *et al.*, 2012). It is widely accepted that, the current setting of the Zagros orogenic belt can be subdivided into distinct NW-SE-trending tectonic domains, extending sub-parallel to the fold-and-thrust belt itself (Fig. 1). These zones are, from the northeast hinterland to the southwest foreland: the Orogenic Zone, the Zagros Suture Zone, the Imbricated Zone, the High Folded Zone and the Low Folded (Foothills) Zone (Jassim & Goff, 2006; Al-Qayim *et al.*, 2012). All these tectonic domains are separated by regionally important thrust/reverse faults (Fig. 1). Over these tectonic domains, the major surface-breaching thrusts associated with closely-spaced southwest-verging anticlines, characterize both the Imbricate and High Folded zones, whereas from the mountain front towards the foreland more gentle folds are mostly buried underneath wedge-shaped syn-tectonic sediments and associated to blind thrusts (Low-Folded Zone). Moving towards the Mesopotamian foreland the sedimentary units are progressively undeformed.

In the analysed sector, the Zagros Thrust Belt is dominated by long, linear NW-SE- to E-W-trending and SE- to NE-verging doubly-plunging thrust-related anticlines (Fig. 1) that locally change vergence along strike resulting from different folding mechanisms and/or on multiple detachments in response to the heterogeneous mechanical stratigraphy. By integrating surface geology with seismic interpretation and well data the compressional subsurface geometries are reconstructed with the aim to better understand the relationships between surface exposures and deep structures. Structures are characterized by different styles ranging from fault-bend/fault-propagation thrust-related folds, inversion anticlines, pop-up and flower-like structures. This implies the development of distinct fracture patterns thus influencing dramatically the distribution and occurrences of hydrocarbon accumulations. The variety in compressional structural geometries is mostly due to the heterogeneous mechanical stratigraphy (i.e., several detachment levels) and to the inherited structures, as basement faults and Tethyan rift-related structures. These inherited extensional features have caused thrust ramp localization and reverse normal fault reactivation during tectonic inversion. Such evidences of the influence of pre-existing faults on the development of compressional structures suggest that a thick-skinned deformation style is more coherently applicable in that region (de Vera *et al.*, 2009) rather that a thin-skinned tectonics (Hinsch & Breetis, 2015).

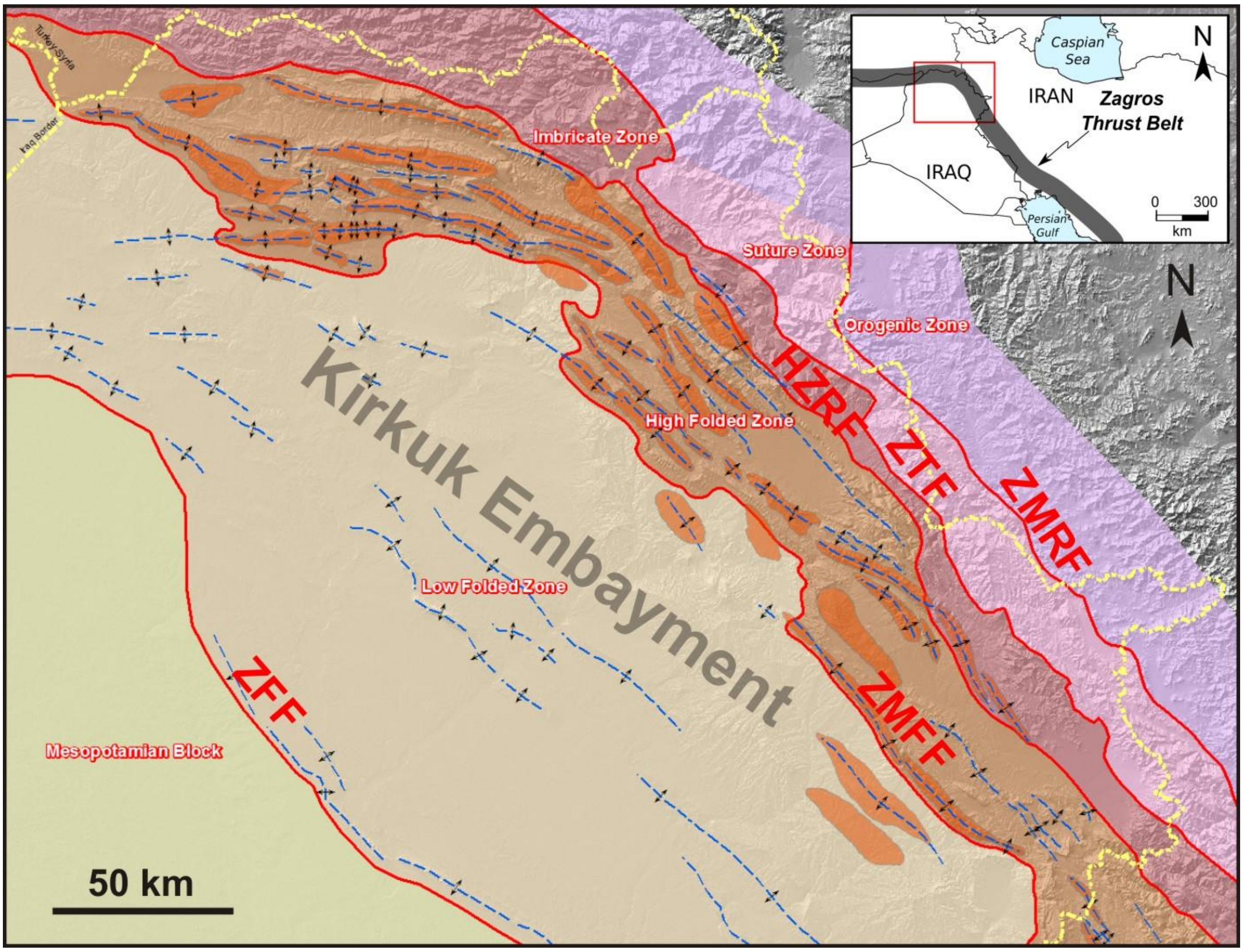

Figure 1. Map showing the tectonic subdivision of the Zagros thrust belt through the Kurdistan region of northeast Iraq (Kirkuk Embayment). The main fold structures are highlighted in orange and their trends are represented by the axial traces. Abbreviations: Zagros Main Reverse Fault (ZRF), Zagros Thrust Front (ZTF), High Zagros Reverse Fault (HZRF), Zagros Mountain Front Fault (ZMFF) and Zagros Foredeep Fault (ZFF).

NOTES:

A review of Central Kurdistan Region of Iraq Structures: Integrating field geology, wells and seismic to understand the different parameters controlling their formation.

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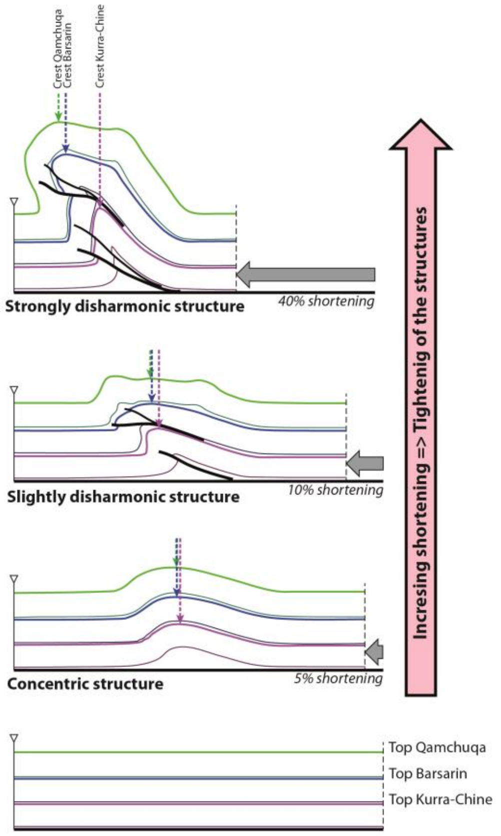
The exploration of foothills remains challenging especially because of the poor seismic imaging. The complexity of the structures (high dips, overturned beds, presence of disharmonies, etc.) demands a good knowledge of what can be observed from the field and a complete integration with seismic and wells data.

The very active on-going petroleum exploration in Central Kurdistan Region of Iraq (KRI), added with field constraints help us to revisit the global scheme of the evolution of this area. This domain of the Zagros Fold-and-Thrust Belt can be divided into 4 main units, form NE to SW: The Nappes Unit (1), The Internal Foldbelt (2a), The External Foldbelt (2b) and The Foreland (3).

Each of them present differences both in terms of timing of deformation and mechanical stratigraphy. The Nappes and Foldbelt domains mainly formed during a first compressive episode that happened from Campanian to Mid-Eocene related to the Obduction of oceanic floor over the Arabian Plate; whereas the Foreland exclusively deformed during a second phase of deformation, the Eurasia/Arabia collision, from Mid-Miocene to Pleistocene. This second event also re-deformed the early structures. Appearance/disappearance of internal detachment levels also increase the level of complexity of some of the structures making it difficult to work on a general case. In Central Kurdistan, in addition to the basal detachment (Beduh Shales), two major internal detachment levels were identified from field works: the Late Triassic Baluti Shales and the Lower Cretaceous Chia-Gara Shales.



From our drilling experiences in Central KRI Foldbelt and the integration of field observations, a mode of deformation can be proposed for most of the folds of this area. Folds in the Central KRI Foldbelt are detachment folds over the Triassic Beduh Shales, which may evolve into faulted folds with increasing shortening. Activation of the internal detachments with increase of shortening is particularly well expressed in the Baluti Shales (Fig. 1). Several wells drilled in the area have shown major bedding dips change while drilling this interval. Moreover, it is frequent to find repeated sections in the Jurassic, evidencing thrusts, while it is rare in the Triassic.

Figure 1: Mechanical behavior of the Central Kurdistan folds. *The Kurdistan Foldbelt exhibits mainly detachment folds over the Beduh/Mirga-Mir formations. With the growth of the fold, internal disharmonies may be expressed because of the presence of several internal secondary detachments. In consequence, the more a structure accumulates shortening, the more important is the risk to have strong disharmonies between petroleum objectives.*

The understanding of this sequence is crucial in planning a well. Depending on the amount of shortening, it may be difficult to reach the structural apex of reservoirs located above and below an internal detachment. A clear definition of the objectives and side-track planning become mandatory in that case.

Observing the External Foldbelt of Central Kurdistan, it is striking to see that the structure accumulating the more shortening is one of the more external ones (Safen-Jisik trend). It also display a high length/width ratio compare to the other structures of the area. Accumulation of shortening along a single structure is often related to a change in the behavior of the detachment level. In this area, the changes of thickness or global rheological properties (lithological variations) of the Beduh/Mirga-Mir basal detachment are poorly known. However, several basement trends have been described in the literature and may play a role in the detachment level behavior by controlling its thickness for example.

NOTES:

Structure of the Lurestan region of the Zagros fold-and-thrust belt, Iran

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Geological fieldwork and seismic interpretation were combined to build regional balanced cross sections across the Lurestan sector of the Zagros fold and thrust belt. The structural framework of this area resulted from the interplay between thin and thick-skinned thrust tectonics during the Late Cretaceous to Paleocene and Mio-Pliocene crustal shortening events. Deeply-rooted extensional structures formed within the Arabian margin of the Tethyan Ocean during Jurassic time, and their positive inversion, governed the thick-skinned evolution of the belt. On the other hand, the occurrence of alternating weak and stiff units within the Mesozoic succession controlled the thin-skinned deformation, promoting the geometric and kinematic decoupling between the Meso-Cenozoic sequence and the underlying crustal rocks.

Thrusts and folds of the area are NW-SE striking and SW-verging. The two major thrusts of the Lurestan fold and thrust belt of Iran are located to the NE of the study area, and divide the belt into three major nappes, also corresponding to three different Mesozoic paleogeographic domains: (i) Arabian; (ii) Radiolarite and (iii) Bisotun. To the SW, the Arabian sector constitutes the lower and more external thrust sheets and it is made of rocks of the inner portion of the Arabian passive margin. Tectonically on top, the Radiolarite nappe includes Mesozoic sediments deposited within the deep-water NW-SE elongated Radiolarite basin, whose development was related to the Neo-Tethyan rifting. Further to NE, the Radiolarite nappe is overthrust by the Lower Triassic to Upper Cretaceous carbonates of the Bisotun domain, which formed the NE margin of the Radiolarite basin. The emplacement of the Radiolarite nappe is dated to the Late-Cretaceous to Paleocene, as evidenced by clasts sourced by such a nappe and included within the Paleocene foredeep infill of the Zagros belt. In the footwall of the Radiolarite nappe, the Arabian zone includes a folded, thick sedimentary pile that can be further divided into two areas, corresponding to the inner and outer portion of the passive margin, being located to the SW and NE respectively. The southwestern one is the Simply Folded belt, and mostly exposes Upper Cretaceous to Cenozoic rocks of the inner portion of the Arabian margin. The northeastern area, where Triassic to Cretaceous rocks are widespread, is the High Zagros zone and corresponds to the outer Arabian margin.

To the SW, in the Simply Folded Belt, major regional-scale folds affect the entire Meso-Cenozoic succession and are cored by low-displacement reverse faults, many of which resulting from the weak Cenozoic positive inversion of inherited extensional structures. Seismic interpretation suggests that the boundary between the Simply Folded Belt and the High Zagros zone corresponds to a major basement step (High Zagros Fault), produced by the Cenozoic inversion of a Jurassic extensional fault system. The inversion of this system caused the uplift of the entire High Zagros zone, the development of a SW-directed footwall shortcut located in the basement and of a suite of folds and associated thrusts soled in the Triassic sequence, interpreted as buttressing structures. Inthe High Zagros zone, low displacement thrusts and Jurassic extensional faults are exposed, the former frequently resulting from the reworking of the latter. The major crustal-scale anticline of the area occurs in the central portion of the High Zagros zone. This anticline exposes Triassic rocks in its core, and its forelimb is affected by a positively inverted NE-dipping extensional fault~~s~~. To the north, in the backlimb of the crustal scale anticline, thin-skinned structures occur. These are represented by two major leading imbricate fans, having a cumulative displacement in the order of several kilometres. These thrusts have cutoff angles of 20-30° and splay off from a basal décollement located within the Triassic strata of the Arabian margin. Many folds associated with these thrusts are cut by the Radiolarite thrust. This indicates a Late Cretaceous to Paleocene age for the thin-skin thrusting in this NE portion of the High Zagros zone. On the other hand, the occurrence of tectonic slices of Radiolarite nappe rocks sandwiched between Arabian-derived thrust sheets, testifies for the out-of-sequence re-imbrication of these thin-skinned structures.

NOTES:

Structural Variation in Himalayan Fold and Thrust Belt, a Case Study from Kohat-Potwar Fold Thrust Belt of Pakistan

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Fold and thrust belts (FTBs) show structural variations along and across strike due to changes in detachments, basement architecture and wedge thickness. Classical models build with analogue or numerical techniques examine the geometry and causes of these structural variations. Analogies between these models and field data based structural models are discussed in order to get a better understanding of the driving factors for such structural variations in FTBs.

The Kohat and Potwar fold thrust belts (K-FTB and P-FTB) in Pakistan represent the outermost external zone of the Himalayan fold and thrust system. Main boundary thrust (MBT) mark their northern boundary which shows both are genetically linked to Himalayan orogenic deformation propagated from north to south toward foreland. However it is interesting to observe distinct contrast in their structural style. This contrast becomes even more obvious at the southern P-FTB range front where the active strike-slip Kalabagh fault zone (KFZ) links it to the K-FTB. Previous studies explained the structural evolution for each of these belts separately, disregarding the structural architecture and compatibility of fold and thrusts on surface extending from one to other. This research focuses on a 3D structural model at the contact of the two thrust belts, evaluating similarities and differences in their structural style. The model is constrained by integrating field, seismic and well data. The northern parts of P-FTB and K-FTB are intensely internally deformed above ramps originating in a brittle basal detachment. The southern P-FTB, in contrast, is less internally deformed above a ductile salt detachment. The K-FTB surface structures evolved above an active roof thrust in Eocene evaporites form a secondary detachment. The Ramps which formed duplexes in the K-FTB extend in the P-FTB as blind thrusts tip lines of fault propagation folds. The basement slope changes from flat ($\beta < 1°$) below the K-FTB and northern P-FTB to north dipping ($\beta > 1°$) below the southern P-FTB and Kalabagh reentrant. The KFZ, linking the K-FTB and P-FTB, is interpreted as a complex dextral strike slip rotational fault block. The Precambrian salt, highly mobile within the KFZ had resulted in normal faulting and formation of lobe structures in the western salt range, reshaping its original geometry. Based on the comparison of our model with analogue ones, we suggest that the structural variation in the K-FTB and P-FTB can be attributed to the change of detachment cohesion, change in basement slope, presence/absence of a secondary detachment and salt mobility (expulsion vs accumulation in different zones).

NOTES:

Remote sensing application to the Fars Region of the Zagros Mountains in Iran

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This study demonstrates and summarises the use and value of satellite images and digital elevation models (DEM) as tools in the creation of accurate geological maps and cross-sections, with an example from the Zagros Fold and Thrust Belt in Iran.

We present a geological map and a balanced cross-section that illustrate the variation in structural styles along dip and along strike in the Fars Region, from the High Zagros Fault to the Mountain Front Flexure. These have been produced from the interpretation of satellite data. We have processed a dataset of satellite images (Landsat 7 ETM+, Landsat 8 OLI and ASTER) and used a SRTM-1 30 m resolution DEM.

We have also carried out structural and hydrogeological analyses, in order to assess the relationship between the geomorphology and the tectonic evolution of the area. This enabled the identification of the subtle effect of basement influence within the thin skinned tectonics responsible for majority of the deformation within the fold and thrust belt.

NOTES:

Tuesday 31ST October 2017

Session Two: South East Asia

Fold & Thrust Belts of the Banda Arc

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The horseshoe-shaped Banda Arc ("arc" in the geometric rather than geological sense), situated north of Australia and including parts of eastern Indonesia and the country of Timor Leste, is the product of complex collision between the Indo-Australian, Pacific (Caroline and Philippine Sea) and Eurasian tectonic plates (many authors, see Hall 2012 for summary).

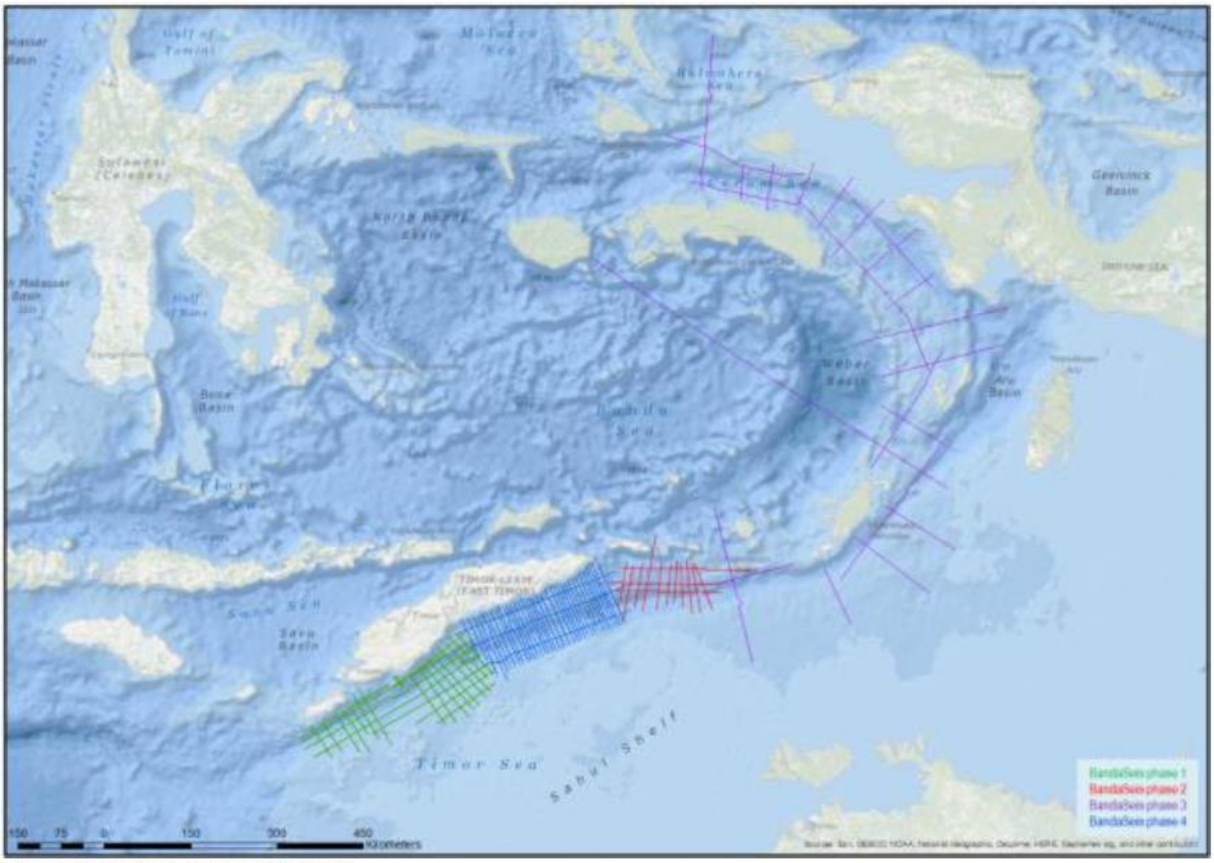

Figure 1: Banda Arc locality map.

Regional 2D broadband seismic data(BandaSeis) acquired around the Banda Arc has provided improved imaging of both deformed and (relatively) undeformed Mesozoic and Cenozoic sedimentary successions in the region.

The Banda Arc comprises the deep and ultra-deep Banda Sea enclosed by a magmatic inner arc (the Inner Banda Arc) reflecting subduction-related arc magmatism at point-focus island volcanoes and volcano clusters, outer islands (the Outer Banda Arc, the largest islands are Timor in the south and Seram in the north) and a series of fore-deeps (the Seram, Tanimbar and Timor troughs) marginal to the edge of the Australian continental crust and more-or-less parallel with the outer arc. Immediately outboard of the outer arc islands and inboard of the fore-deeps is a series of fold-and-thrust belts (FTB) – the Seram and Tanimbar FTBs and the Timor Orogen.

The characteristic shape of the Banda Arc is the result of Late Jurassic rifting and breakup of part of the East Gondwanan margin which resulted in the formation of an embayed continental shelf inboard of Jurassic ocean crust. Banda subduction began around 15 million years ago (Spakman & Hall, 2010) with southwards rollback of the dense Jurassic oceanic crust; first contact of Australian continental material with the subduction system took place at around 12 Ma. Final jamming of the system occurred around 6 million years ago (Haig, 2012). Although having similar gross morphology, each of the FTBs has a different geological history directly or indirectly related to ongoing subduction. As noted by many previous authors, associated troughs are not subduction troughs and more correctly referred to as fore-deeps.

The Seram FTB resulted from Late Miocene 12–10 Ma oblique convergence between the Outer Banda Arc (specifically Seram) and the Birds Head: loading of the emerging FTB resulted in formation of the Seram Trough (Hall et al., 2017).

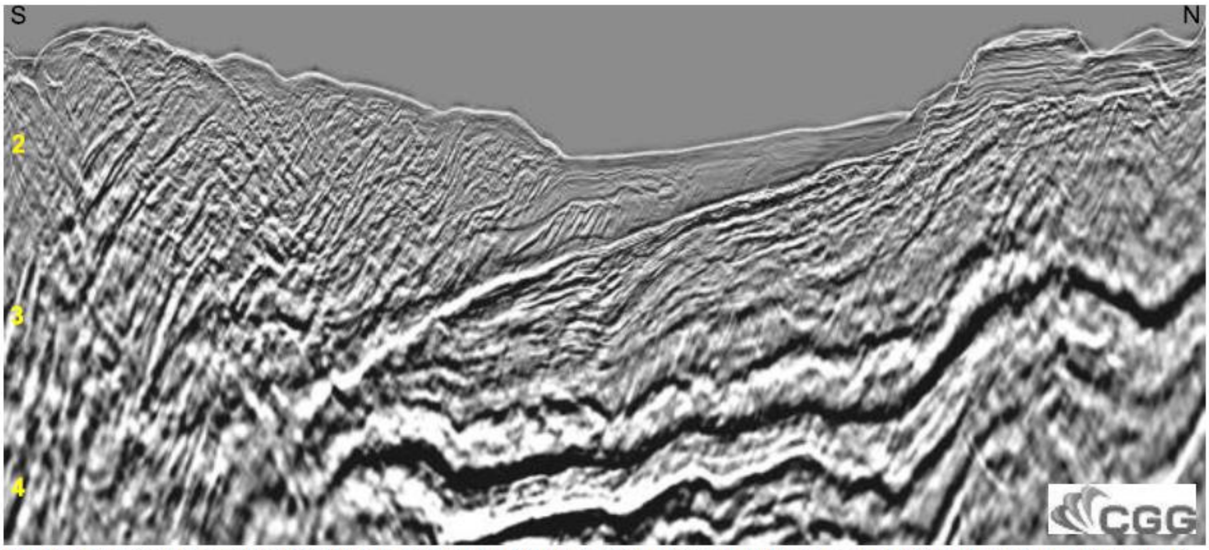

Figure 2: Seismic section illustrating Seram FTB and Seram Trough; numbers on LHS depth in km, figure width is approx. 30km.

The Timor Trough is the foredeep of a post-Miocene foreland fold and thrust belt, the Timor Orogen, formed as result of compression caused by jamming of the Australian continental plate around 6 Ma. A period of quiescence followed in Timor with continuing active tectonic in the Banda Sea. Following cessation of subduction, deformation became predominately strike slip which continues to the present day.

Pliocene obduction of the Banda fore-arc (Timor to Tanimbar) took place under NE-SW compression and resulted in the exhumation of high P/T hyper-extended metamorphic rocks together with low P/T metamorphic rocks of the Miocene accretionary wedge. Rapid exhumation of the high P/T metamorphic rocks resulted from clockwise rotation of the Wetar- Timor region. Very high angular velocity and contraction deformation close to the pole of rotation, contrast with the extreme extension in the Weber Deep.

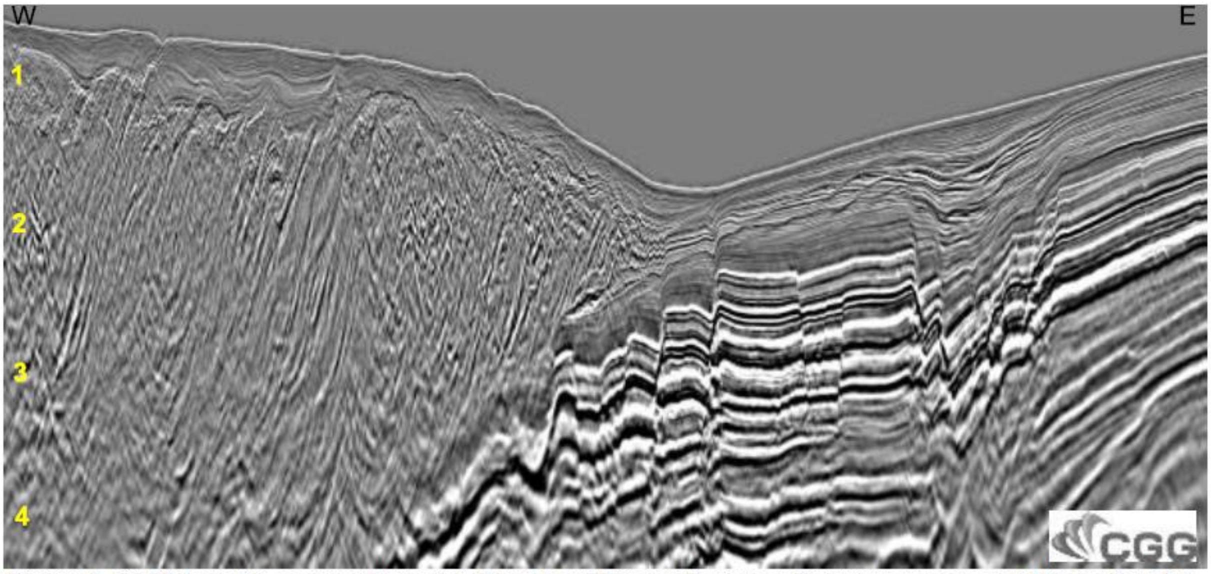

Figure 3. PSDM seismic section illustrating Tanimbar FTB and Tanimbar Trough; numbers on LHS depth in km, figure width is approx. 50km.

The structurally-complex Tanimbar FTB is interpreted as an orogenic wedge resulting from NE-SW compression. The Tanimbar Trough, the outer margin of the prism becomes discontinuous in the Kai islands and becomes a transform margin south of Seram (see also Hall et al., 2017).

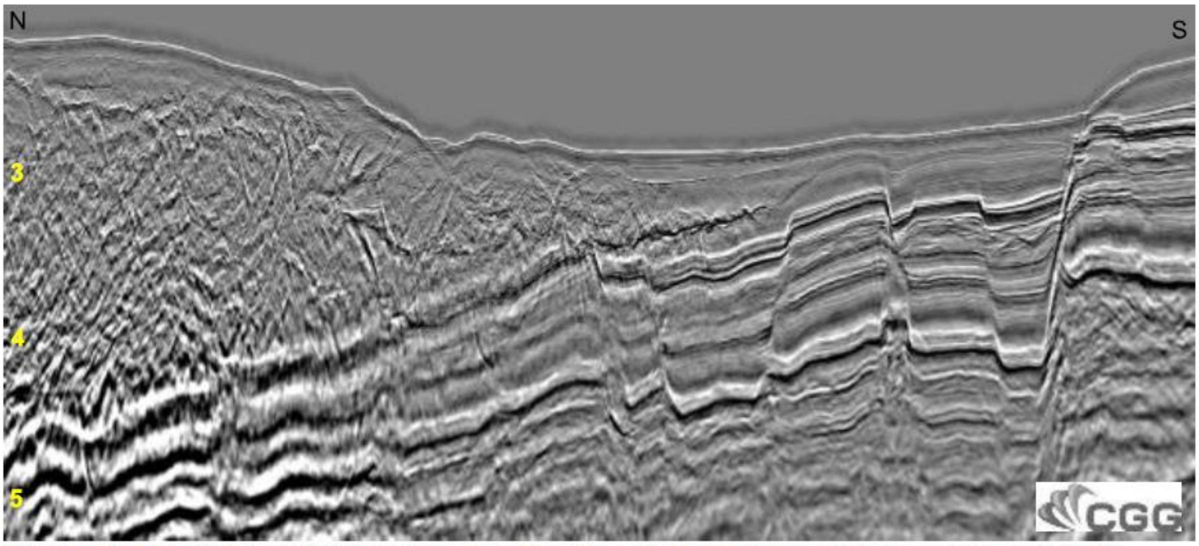

Figure 4. PSDM seismic section illustrating Timor Orogen and Timor Trough; numbers on LHS depth in km, figure width is approx. 30km.

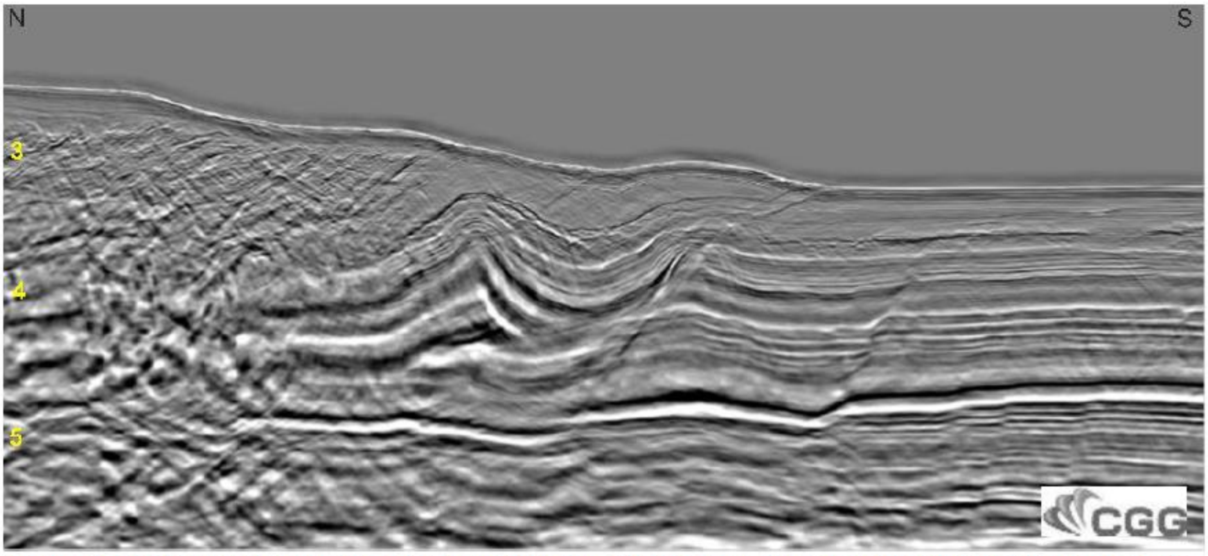

Figure 5: PSDM seismic section illustrating edge of Timor Orogen and Timor Trough (different section to Fig. 3); numbers on LHS depth in km, figure width is approx. 10km.

Post 5.5Ma uplift of coral terraces, interpreted as isostatic rebound following jamming of the subduction system (Haig, 2012), may be flexural contraction.

NOTES:

Interaction between the folded structures of the PNG highland

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The PNG fold-thrust-belt is a structurally complex, proven hydrocarbon exploration and development province. The Darai Limestone is the dominant lithology at surface with a thickness of between 1,200 and 1,600 m. Variable karstification, combined with stacked limestones and sub-cropping overpressured shales, reduce the quality and resolution of 2D seismic. There are no 3D surveys over the highlands. Thus seismic interpretation is a challenge and requires validation by integrating detailed structural analysis of surface and subsurface data.

Diverse authors agree that the structural deformation in the PNG fold-thrust-belt comprises a combination of thick-skinned and thin-skinned tectonics (I.e. Mason, 1997; Hill, 1990; and others). However, there are discrepancies in the timing and interaction between these tectonic styles. These discrepancies are largely driven by the lack of syn-compressional sediments and poor seismic imaging. Therefore, a detailed geomorphological, surface geometry study, inspired by previous workers (Burberry et al., 2010; Ollarves et al. 2006; and Tomkin & Braun, 1999) and log analysis was carried out to test the possible interactions between these structural styles.

The log analysis focused on defining a log signature across a known detachment level to then extrapolate and define other potential detachment levels.

The surface analysis of the folds determined the aspect ratio and symmetry of each fold in order to find groups of structures with similar geometry. This was combined with analysis of the drainage network to provide additional insights on the relative timing of uplift between the different folds.

This study found a clear signature in the sonic log over the detachment intra Ieru Formation. This signature was not found in the intermediate sequence between the latter detachment and the Imburu Formation. The existence of deeper detachments however was unconfirmed due to the lack of logs or weak log signatures. In addition, the deepest stratigraphic sequence remains unexplored with few well penetrations and/or limited log data available.

Based on their surface geometry, three groups of folds were identified and mapped:

- High to mid symmetric rounded structures, related to basement tectonics (inc. wedges or beheaded inversion structures);
- Mid-rounded structures with variable symmetry, associated with multiple detachment levels; and
- Elongated asymmetric structures, correlated with shallow detachment intra Ieru Formation.

Rounded and symmetrical structures dominate toward the north-west, while more elongated and asymmetric structures are more prevalent towards the south-east. A relative age plot was prepared by using geomorphic indexes, such as fold and mountain front sinuosity, which was supported by drainage pattern and degree of karstification analysis. The results from this study show a trend along the fold thrust belt with the north-western structures being older compared to the south-eastern ones. Similarly, another trend was observed where the structures get younger from the foreland towards the hinterland.

Considering the position and distribution of the different structural styles, these results would suggest that the shallow detachment folds (Ieru related) are intimately related to thick-skinned structures in a more hinterland position. While the deeper detachment structures are associated with buttressing against more foreland positioned thick-skinned structures.

NOTES:

Variation in Structural Style Between Two Complex, En-echelon Forelimb Structures in the Papua New Guinea Fold Belt

Ruth Wightman[1] and Romain Darnault[2]
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2: IFPEN France.

The Agogo and Kutubu structures within the Papua New Guinea Fold Belt are *en-echelon* NW-SE trending anticlinal structures truncated by near-planar thrusts, with producing oil and gas fields in both their hangingwall folds and the forelimb structures beneath the thrust (Figure 1). The two structures are 15 km apart along the strike of the fold belt, and although their overall structural form is similar, there are significant lateral variations in geometry that suggest local controls on structural style and evolution. Understanding and predicting differences in folding and thrusting along the length of the structures is crucial to help optimise development of these fields.

The Agogo structure is a gentle anticline that is truncated by a near-planar thrust that verges southwest with ~2 km of offset, interpreted to be a relatively late-stage breakthrust. The fault surface trace is continuous with that of the larger Kutubu structure to the southeast, with a relatively constant apparent offset along its length, but offset by a right-lateral relay. The stratigraphic sequence involved in the Agogo deformation includes the Miocene Darai Limestone at surface, a sequence of Late Cretaceous Ieru shales, the Neocomian Toro-Digimu reservoir sands, and a thick sequence of syn- and post-rift late Jurassic shales (Figure 1). In contrast, to the southeast, the Kutubu Complex comprises a larger double-anticline (Hedinia and Iagifu), with a northeast verging backthrust bounding the Iagifu Anticline, as well as the planar breakthrust underlying both structures. A similar stratigraphy is incorporated in the folding in the Kutubu Complex but the base of the hangingwall includes a mid-Jurassic sandstone not seen at Agogo, suggesting the detachment level of the breakthrust is deeper at Kutubu. This deeper detachment is consistent with the higher topographic elevation observed at Kutubu relative to Agogo (Figure 1).

Beneath the main thrusts are large (>800 m high) vertical to overturned forelimb structures, containing repeated Toro-Digimu oil- and gas-filled sands. Both hangingwall and forelimb structures at Agogo and Hedinia are producing fields; the timing of charge of the four fields with respect to deformation is uncertain, although each field has different hydrocarbon contact and water pressure gradients. The Agogo forelimb is near-vertical, heavily compartmentalised by small-scale faults, and over 1 km high whereas the Hedinia forelimb is overturned and with a significantly higher fault density, suggesting accommodation of a larger scale shearing compared with the Agogo structure along strike.

The structure of the upper 3 km is relatively well constrained from surface data, >70 wells (including 10 that penetrate the breakthrust), and poor quality 2D seismic data, but the deeper structure relies on interpretation combined with geometrical forward modelling and balanced cross sections. The right-lateral bend in the surface trace of the breakthrust linking the two structures is coincident with the inferred saddle between the subsurface folds. In the subsurface, multiple interpretations are possible beneath this step in the fault trace. These include a breached compressional relay system, a lateral ramp, inversion of an extensional relay system, or inversion of a single extensional fault subsequently offset by right-lateral strike-slip.

To differentiate between the different models a series of sandbox experiments are being undertaken inside an X-ray tomography device which records the 3D deformation through time. Brittle rheologies are simulated with alternating sand and pyrex layers, while ductile layers are simulated with a silicone putty. Each of these experiments incorporates a different mechanism to produce the right-lateral relay in the surface fault trace to determine the underlying linkage between the forelimbs. The whole sequence is subjected to pure and/or oblique compression across the underlying 3D structure using a relatively slow rate of deformation of 0.6 cm/hr of compression in the model, equivalent to 1.2 km/M.Y. in PNG.

The key structures that influence deformation style that are being tested include:

- A compressional relay with an intervening lateral ramp and different detachments
- Inversion of extensional relays with subsequent breakthrusts
- Inversion of a single extensional fault with subsequent strike-slip offset
- Oblique compression across a lateral ramp.

The sandbox experiments are ongoing, but will facilitate the understanding of the relative timing and nature of the subsurface structure, which is crucial to developing 3D models to explain how the anticlines, their breakthrusts, and the underlying forelimbs relate and link along strike. Understanding the evolution of the two structures together, both the initial fold formation and later stage faulting, allows a better understanding of the overall sub-thrust forelimb geometry, allowing further development of these recently discovered fields. Evaluating the small-scale complexity in tandem with the larger-scale evolution helps minimise structural uncertainty during well planning and reserves estimation.

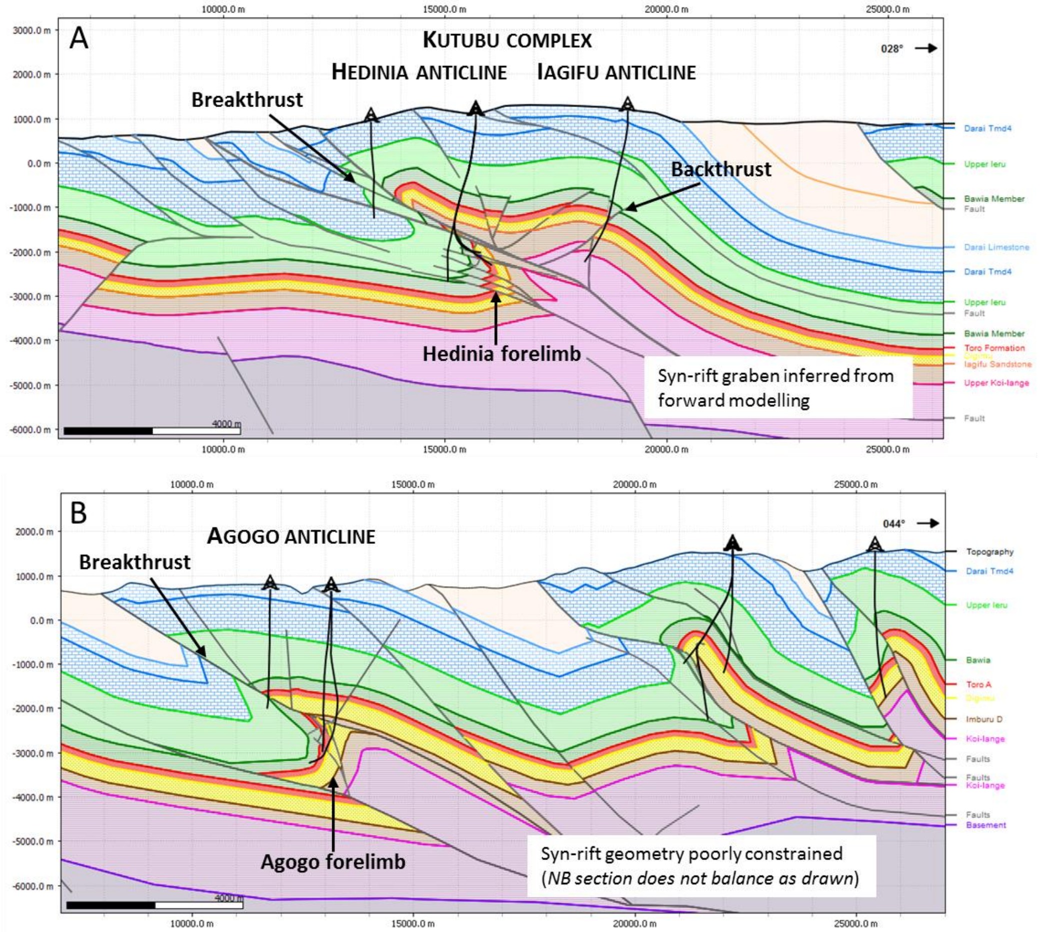

Figure 1. Structural cross sections through the Hedinia-Iagifu (A) and Agogo (B) structures. Cross sections are 14.5 km along strike from each other. Toro and Digimu reservoirs are shown in red and yellow, respectively, Miocene Darai Limestone is blue, Cretaceous Upper Ieru mudstones in green, and the syn-rift shales in pink. Basement is schematically shown in purple. Key wells on the sections are shown to illustrate data constraints. The Kutubu section has been balanced through restoration and the basement graben inferred from forward modelling. The Agogo section is schematic at depth.

NOTES:

Evolution of the North West Fold and Thrust Belt, Papua New Guinea: constraints from new data and multi-method structural modelling

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[2]*3D-Geo, formerly at Oil Search Ltd*

Recent data acquisition and structural analyses have considerably improved our understanding of the remote and inhospitable frontal region of the North West Fold and Thrust Belt in Papua New Guinea (Fig. 1). Structural sections across the 30 km wide and 3.6 km high Eastern Muller Ranges (EMR) reveal very low shortening < 21% within the exposed Cenozoic Darai Limestone despite > 3 km of surface uplift. In contrast, Darai Limestone within the neighbouring Kutubu Fold and Thrust Belt is characterised by ~40% Darai Limestone shortening and structural elevations < 1.5 km. Here, we use a multi-method forward modelling approach to investigate the structural style and evolution of the EMR. Kinematic forward modelling necessitates crustal scale faults beneath the EMR, suggesting Mesozoic rift architecture has a major influence on structural evolution. Thermo-mechanical forward modelling reveals a complex interaction between pre-compression basin architecture, mechanical stratigraphy and the evolution of structural styles. The best-fit thermo-mechanical models, as compared with regional- to outcrop-scale geological data, have significantly improved our understanding of the relationship between mechanical stratigraphy and deformational style. In particular, the competent Cenozoic Darai Limestone is commonly characterised by discrete, steep-dipping faults, while the underlying incompetent Mesozoic sedimentary sequence is complexly deformed with detachments and triangle zones that are key to understanding the uplift of the EMR. We highlight the importance of considering mechanical stratigraphy in structural modelling and suggest thermo-mechanical modelling is a powerful inclusion in any structural workflow.

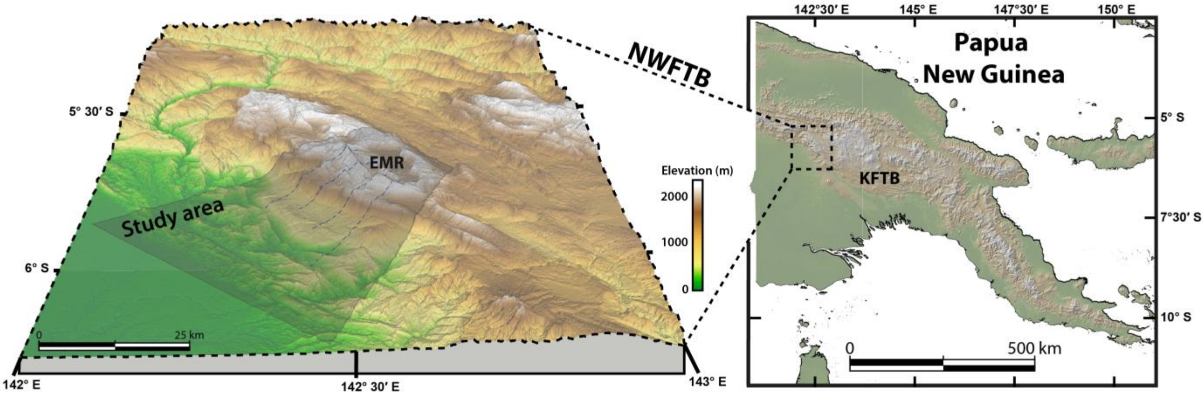

Fig. 1. Study area within the North West Fold and Thrust Belt in Papua New Guinea. KFTB, Kutubu Fold and Thrust Belt; NWFTB, North West Fold and Thrust Belt; EMR, Eastern Muller Ranges. SRTM digital elevation model retrieved from USGS (2015).

NOTES:

Wednesday 1 November 2017

Session Three: Europe

The Pre-orogenic Template is not a Layer-cake: the Role of Rift Inheritance in Orogeny Highlighted by the Western Pyrenees Case-study

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Exploration of Fold and Thrust Belts (FTB) petroleum systems is very often focused on the study of foreland basin formation. FTB basin evolution is assumed to be controlled by the propagation of thrusting and folding, foreland basin isostatic-flexure and the interaction of erosion and sedimentation. In many cases, basin modeling considers the pre-convergent geology to be a simple layer cake at a crustal and basin scale which limits the distribution of source/reservoir rocks and decollement levels to an over-simplistic initial geometry. However it is noteworthy that it is generally observed that the petroleum systems of FTB are usually dependent, at least in part, on the pre-orogenic geological history. This is especially true when earlier continental rifting or passive continental margin history controls the occurrence and quality of syn- and post-rift source, reservoir and sealing rocks and structural and thermal evolutions. The pre-orogenic geological template must be included in robust basin modeling.

Significant advances have been made in understanding the crustal and basin architecture of passive continental margins which often correspond to the pre-convergent template of orogens. Far from being tabular with laterally uniform layer thicknesses, they are taper-shaped at the crustal scale and are constituted of necked and hyper-thinned continental crust leading to oceanic crust or exhumed mantle. Conjugate rifted margins are usually asymmetric and non-cylindrical, and inherited structures are not restricted to tilted blocks geometries but also contain supra-detachment basins. All of these pre-orogenic components are often poorly integrated (if not simply ignored) when exploring FTB foothills and their basins. In a low-price context for the oil and gas industry, it is especially important to include our new understanding of deep-water rifted margins into the exploration of FTB basins.

In this talk, we use the NW part of Pyrenees and Aquitaine basin of SW France as a demonstrator. In this part of the FTB, Cretaceous rift systems resulted in local mantle exhumation (and high-temperature anomalies) that are today exposed in the field and were intensively explored by industry during the last century. The distribution of the main hydrocarbon source and reservoir rocks are very rift-dependent as also are maturation and migration histories. Initial hyper-thinned crustal rift domains and their basins escaped from destructive orogenic deformations. This can be explained by the modality of rifted margin compressional inversion (early orogeny) and by the initial non-cylindrical rift basins. Using the “Rifter-Orogeny” software (implementing kinematic structural-stratigraphic forward modeling) we are able to reproduce both the rifting and orogenic histories which gives strong insights into the primary control of rifted margin architecture on orogeny and the fate of their basins along the FTB. The importance of rift inheritance during orogenic processes demonstrated for the Aquitaine Basin is not restricted to this example and has general applicability to many (or the majority of) other FTB basins globally.

NOTES:

The inversion of the North-Iberian hyperextended margin

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Gravity and magnetic data suggest the presence of zigzag exhumed mantle bodies inside the attenuated crust of the North-Iberia continental margin (Fig. 1). We speculate that these bodies highly conditioned the structural domains of the Cantabrian-Pyrenean fold and thrust belt during their transition from hyperextension in Early Cretaceous times to shortening and inversion in the Cenozoic.

The main extensional basins of the North-Iberian Margin (Le Danois, Basque-Cantabrian, Mauléon, Arzacq, Tarbes and Organyà) define together an ESE-WNW oblique rift offset by NE-SW left-stepping and right-stepping faults. Border faults root into major extensional detachments, their kinematics determine the formation of asymmetric margins and the exhumation of the lithospheric mantle that occurs later in the rift history. Detachment faulting beneath Le Danois and the Basque-Cantabrian basins is characterized by south-dipping low-angle normal faults with a ramp-flat-ramp lithospheric-scale geometry. In contrast, the genesis of the Mauléon Basin has been linked to a north-dipping extensional detachment. If this is correct, the dip of the master detachment changes in the Pamplona transfer fault. Far to the east, south-dipping and north-dipping lithospheric-scale detachments have been proposed for the Central Pyrenees.

Five structural cross-sections constrained by the results of 3D gravity inversion permit to discuss the complexities of the bivergent Pyrenean orogen in terms of the inversion of a precursor hyperextended margin. In all sections crustal rocks underthrust the lithospheric mantle in the hyperextended region supporting the point that the near-surface exhumed mantle lithosphere acts as a rigid buttress allowing the weaker continental material to be expulsed outwards and upwards by thrusting, giving place to two crustal triangle zones at the boundaries with the uplifted mantle. Contractional slip localizes into these lithospheric-scale thrusts which in turn reactivate parts of the extensional system. In that respect, the NE-SW transfer zones that offset the rift behave as compartmental faults during the orogenic phase. The amount of shortening increases from 20-34 km in the Cantabrian Cordillera, where Le Danois and the Basque-Cantabrian basins preserve their original extensional geometry and the exhumed mantle remains connected to the present-day lithospheric mantle; to 140-150 km of shortening in the nappe stack of the Central Pyrenees.

Four main inversion styles are recognized within the upper crust: (a) high-angle basement normal faults reactivated as reverse faults often accompanied by folding of the sediments against the fault; (b) shortcuts of basement pieces; (c) decoupled thrust-ramps above the preceding basement normal faults; and (d) inverted minibasins and squeezed diapirs with duplications of the cretaceous-eocene sequences.

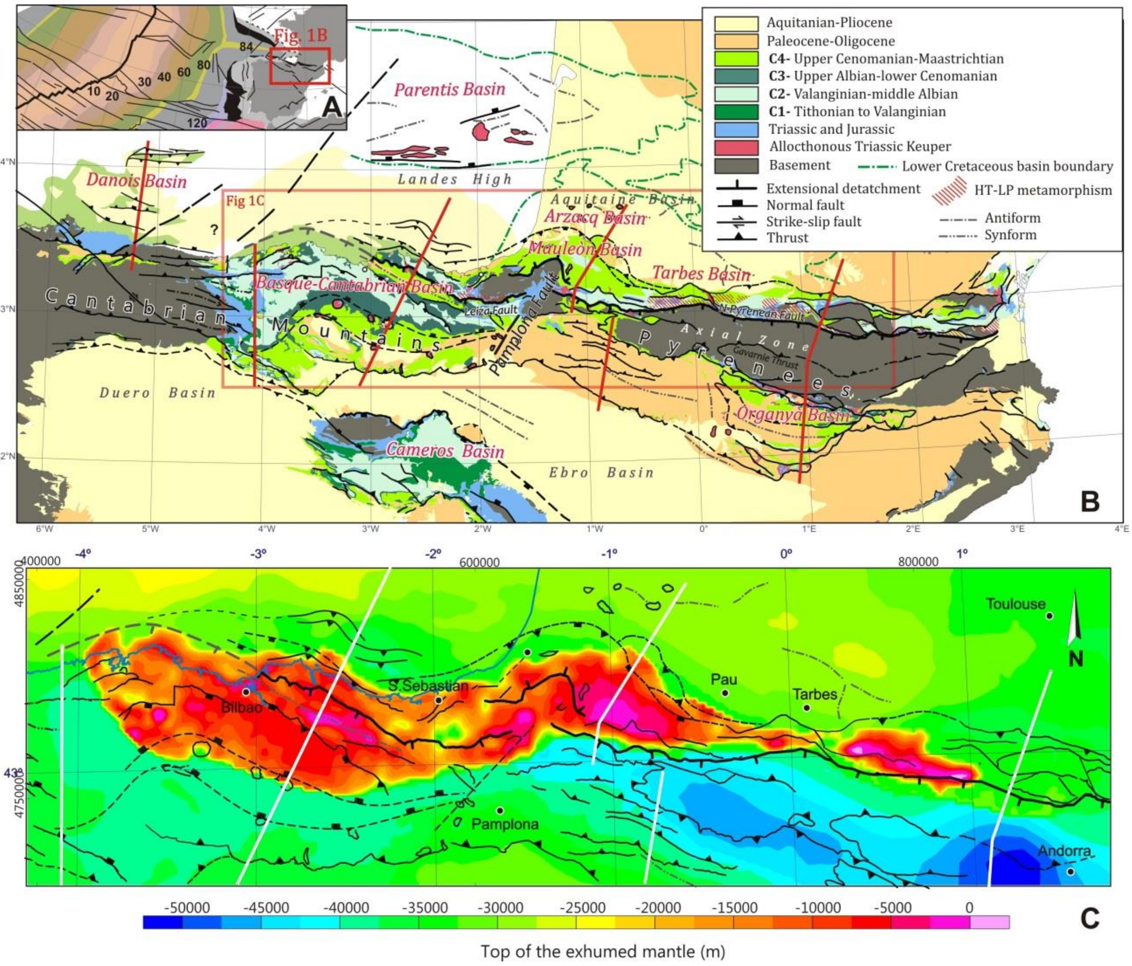

Fig.1. Tectonic setting of the North-Iberian Margin. (A) Inset showing the Iberian Peninsula in the framework of the Central Atlantic and the Bay of Biscay. Numbers refer to the age of the oceanic crust in Ma. Exhumed mantle along the Iberian margins is shown in black and continental crust in grey. Location of figure 1B is framed. (B) Geological map of the Cantabrian-Pyrenean thrust belt with location of the main extensional basins and the studied sections. Figure 1C is framed. (C) Top of the exhumed mantle modelled by 3D gravity inversion.

NOTES:

Post-orogenic evolution of Mountain/Foreland basins systems : case study of the Pyrenean retro-foreland

C. Fillon [1,2], S. Calassou[1], E. Masini [1]

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Forelands and mountain ranges are linked through the coupling between tectonics, surface processes and drainage evolution. During syn-orogenic periods, the intense tectonic activity induces important vertical movements that are associated to thickening and sediment deposition in the fold-and-thrust belt and in the foreland basins. The fluid migration to the external areas makes the syn-orogenic times the moment of trapping and emplacement of reservoirs. In particular, the retrowedge -classically narrower and deeper- allows the sediments to accumulate and the fluids to be generated, migrated and trapped. However, most of fold-and-thrust belts are not “active” anymore in a so-called post-orogenic stage. How are these structures preserved after orogeny? And what are the key processes controlling their evolution? To answer these questions, we aim at constraining the post-orogenic evolution of the foreland basins.

By definition, a foothills area in post-orogenic period is supposed to be tectonically inactive, but it can be very dynamic in terms of surface processes and vertical movements. Erosion occurs in both range and basin, inducing isostatic rebound and enhanced incision of the basin, with the potential of causing disruption or destruction of traps and hinterland-ward fluids migration. These processes can also be balanced by local sediment deposition according to the drainage conditions in the basin. Therefore, understanding the causes for vertical movements and the feedback between the dead mountain belt and its foreland is key to understand the preservation or destruction of HC prospective structures in these proximal foreland basins.

In order to do so, methods of identification and quantifications are used to understand the evolution of 1) vertical movements in the range and in the basin, 2) the sedimentary budget from the source to the sink, and 3) the geomorphologic processes responsible for erosion, transport and deposition.

We adress these questions to the Pyreneean belt, of which the retro-foreland (the Aquitaine basin) had an efficient petroleum system. Although the pyrenean belt switched from syn- to post-orogenic period around 20 Myr ago, the mountain belt relief and crustal root are still present today, and important vertical movements have been documented. This renewed uplift activity during post-orogenic times could have favored an enhanced erosion or deposition in the Aquitaine basin. Understanding how the basins are formed in syn-orogenic period and evolve in post-orogenic times is thus of first importance to face preservation issues for foothills exploration.

NOTES:

Polyphase fold-and-thrust tectonics in the Belluno Dolomites: mapping, kinematic analysis, and 3D modelling reveal superposition of Dinaric and Alpine deformations

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The Belluno Dolomites represent the eastern outer sector of the Southern Alps, which corresponds to the fold-and-thrust belt at the retro-wedge - active mainly in the Miocene - of the Alpine belt. It is still a matter of debate, however, whether Oligocene deformations related to the Dinaric belt can be found in this area, resulting in an interference between the two belts. We have tackled this problem in the Vajont area, where a sequence of Jurassic, Cretaceous and Tertiary units have been involved in multiple deformations.

Geological mapping and detailed outcrop-scale kinematic analysis allowed us to characterize the kinematics and chronology of deformations, which are tested in a 3D model. Particularly, relative chronology was unravelled thanks to diagnostic fold interference patterns and crosscutting relationships between thrust faults and thrust-related folds.

The onset of contractional tectonics is constrained to be Post-Eocene by relationships with the Erto Flysch, whilst in the Mesozoic tectonics was extensional. We have recognized two contractional deformation phases (D1 and D2 in the following). D2, already recognized in previous studies and attributed to Miocene Alpine deformations, is characterized by classical top-to-S Alpine transport directions and E-W fold axes. On the other hand, D1 is characterized by N-S fold axes and top-to-WSW transport directions, compatible with Dinaric deformations.

The 90° rotation of the regional-scale shortening axis between D1 and D2 results in complex thrust and fold interference and reactivation patterns. For instance a km-scale N-S trending D1 syncline (the “Erto syncline”), is filled with the Eocene Erto Flysch and “decapitated” by a D2 thrust fault, providing the best map-scale example of D1-D2 crosscutting relationships. Due to the strong competence contrast between Jurassic carbonates and Tertiary flysch, in this syncline spectacular duplexes were developed during both D1 and D2.

In order to quantitatively characterize the complex interference pattern resulting from two orthogonal thrusting and folding events, we performed a dip-domain analysis that allowed categorizing the different fold limbs and reducing the uncertainty in the reconstruction of the fault network topology in map view. This enabled us to reconstruct a high-quality, low-uncertainty 3D structural and geological model, which unambiguously proves that D1 deformations with a top-to-WSW Dinaric transport direction propagate farther to the west than previously supposed in this part of the Southern Alps, predating top-to-S D2 Alpine deformations.

Besides being a challenging natural laboratory for testing structural analysis and modelling methodologies, the Vajont area also provides useful clues on the still-enigmatic structures in the frontal part of the Friuli-Venetian Southern Alps, buried in the Venetian Plain foredeep. These include active seismogenic thrust-faults and, at the same time, represent a growing interest for the oil industry.

NOTES:

Introducing salt tectonics in the Northern Calcareous Alps (Austria): a first-order element from continental margin to compressional rejuvenation

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The Northern Calcareous Alps (NCA) of Austria comprises a complexly deformed Alpine fold-andthrust belt (FTB) in the Eastern Alps. The NCA-FTB forms a 50 km wide and 700 km long E-Wstriking belt, extending eastwards beneath the Neogene Vienna Basin. There, hydrocarbons are produced from up to 6000 m deep, seismically poorly-imaged traps. The NCA are dominated by thick sequences of Triassic carbonates belonging to the former northern continental margin of the Neo-Tethys ocean, and were deposited onto aerially extensive Permian salt. Recent deep-drilling from the Vienna Basin floor (i.e., STRIT-1 well) encountered a thicker-than-expected (and ever published) section of Middle Triassic Anisian carbonates overlying Permian salt. These results have triggered a regional review of the NCA 1:200,000 geological maps, followed by LIDARassisted geological mapping of potentially analogue structures in the eastern NCA-FTB. Structural mapping, stratigraphic logging and sedimentary facies analysis plus balanced cross-sections construction provide evidence for the formation of salt-related mini-basins, salt diapirs/walls and their subsequent Alpine rejuvenation by shortening, thrust-welding and imbrication. These structures are comparable in terms of geometries, dimensions and aspect ratios to published structures from the offshore Atlantic salt-basins and the Spanish Pyrenees. Based on our recent work, we propose for the first time that salt tectonics in the NCA has been a first-order architectural element from the continental margin stage to the subsequent fold-and-thrust belt development. Salt tectonic concepts introduced to the Austrian NCA can significantly assist a new phase of understanding for the long-debated NCA tectono-stratigraphic framework, providing new hydrocarbon exploration opportunities in the mature Vienna Basin exploration province.

NOTES:

Testing thin- and thick-skinned tectonics ahead of foreland thrust belts: an application to the deformed Adriatic foreland of Italy

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The external zones of thrust belts, also known as foreland fold-and-thrust belts and their adjacent foreland domains involved in contractional deformation, have long been matter of debate concerning the deep tectonic style by either applying thin-skinned or thick-skinned deformation models (e.g., Butler *et al*., 2004). The Adriatic foreland belongs to the Adria continental block that, at present, extends northwest-southeast including, from north to south, the Po Plain, Istria, Adriatic basin, Gargano Promontory and the Apulian Peninsula. It represents a common foreland domain shared by three different thrust belts that developed in distinct times: the Apennines to the W/SW, the Southern Alps to the N/NW and the Dinarides-Albanides to the E/NE. This region records a polyphase tectonic history with repeated events of basin formation associated with normal faulting, reworked by compressional deformation (Pace *et al*., 2015). In the Central Adriatic, compressive and transpressive deformation developed a NW-SE-trending (Mid-Adriatic Ridge). Various controversial interpretations have been proposed. Some authors (Scisciani & Calamita, 2009) consider the Mid-Adriatic Ridge to be an intraplate inversion-dominated foreland deformation. Conversely, other workers envisage this area of contractional deformation as the thin-skinned thrust front of the NE-verging Apennines (Scrocca, 2006) or SW-verging Dinarides (Finetti & Del Ben, 2005) linked to the onshore thrust belts via flat-laying detachments. In this study, we selected and reconstructed two compressive structures from the Adriatic foreland. Since the deep interpretation of these structures is not univocal, a 2D kinematic forward modelling is performed in order to test which style of deformation (thin- vs thick-skinned inversion) is more coherent. The modelling aims to reproduce the final thrust-related fold geometry. The modelled structures are further constrained using the patterns of growth strata because such patterns are widely considered to be diagnostic of different deformation mechanisms and folding styles. In fact, forward modelling with thin- and thick-skinned thrusting produces different patterns of the syn-kinematic strata. Modelling results show that a thick-skinned inversion successfully reproduces the fold characteristics and the growth strata geometries of the syn-kinematic succession observed and interpreted on seismic data. The modelling validated the proposed interpretation of the analysed inversion structures developed during basement-involved thrusting. More regionally, this further supports that the contractional structures belonging to the Mid-Adriatic Ridge can be explained in terms of intraplate deformation that chiefly acted through reactivation of Mesozoic normal faults.

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The Maiella Anticline Cretaceous platform margin (Italian Apennines) and insights for Mediterranean exploration

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Since the 80s several models have been proposed to describe the geometries and the evolution of the Apulian carbonate platform margins throughout Cretaceous and Tertiary times. These models, based on outcrop or subsurface datasets, can be broadly grouped in two main categories: either recognising structurally controlled margins cut by syn-sedimentary faults active during the Cretaceous (Accarie et al., 1986; Accordi et al., 1987; Casabianca et al., 2002); or assuming passive paleo-escarpments inherited from Triassic or Jurassic rifting and passively filled by Cretaceous to Tertiary sediments (Eberli et al., 1993; Rusciadelli et al., 2005).

The application of one of these two models has very significant implications for hypothesised margin geometries, sediment transport mechanisms, sediment distribution and consequently for the characteristics of potential exploration plays both on the platform and in the adjacent slopes and basins.

The Maiella Mountain in the Italian Central Apennines, offers a spectacular and extensive exposures of Cretaceous platform and basin facies giving the opportunity to study in detail the geometry of the intervening margins. This work reports the findings obtained by a study carried out along the northern margin of the Maiella platform by integrating surface and subsurface data.

The Maiella Mountain represents the easternmost outcropping salient structure of the Central Apennine fold-and-thrust belt. The Cretaceous-Miocene carbonate succession records platform-to-margin and slope-to-basin depositional environments, respectively well-exposed in the southern and northern sectors. Such carbonate sequence is covered by Messian evaporitic and Lower Pliocene foredeep siliciclastic deposits, entirely involved in the thrust-fold development during the middle-Upper Pliocene.

The data collected during this study indicates that during the Cretaceous the platform margin was affected by a series of N to NW-striking and E-W-striking ones which have caused differential subsidence across the margin. The age of these faults is constrained by the thickening of Cretaceous sedimentary sections in their hanging-walls. Some of the Cretaceous normal faults have been also reactivated in transpression mainly during the main Pliocene thrusting event. These faults controlled the palaeogeography of the Cretaceous platform and the entry points of the sediment flows transporting calciturbidites and catastrophic debris flows within the basin to the north of the platform where thick resedimented carbonate megabreccia and turbidite bodies are observed. The megabreccia bodies and the calcareous turbidites intervals may represent interesting exploration targets in similar settings if their origin, distribution and extent be sufficiently constrained.

NOTES:

Structural Interpretation of a Regional Section in the South Carpathian Foredeep

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Repsol Exploration

The Carpathian orogen is an Alpine mountain belt which was formed as a result of the collision between continental blocks with the Moesian and East European platform. The Carpathian foredeep, known as the Getic Depression, is a 200km wide basin located between the axial part of the South Carpathians and the undeformed Moesian platform. This area is characterized by a thick package (more than 6km) of Cretaceous to Tertiary sediments deposited during polyphase thrusting that was active from Middle Cretaceous to Pliocene times. The Carpathian foredeep has proven to be one of the most prolific hydrocarbon provinces in Europe.

Seismic data acquired along the South Carpathian foredeep area has been integrated in order to construct a consistent structural evolutionary model for the South Carpathian - Moesian platform area. Our study is mainly focused on the interpretation of a regional NW-SE trending 2D seismic section acquired in 2010 across the Southern Carpathian foredeep (figure 1).

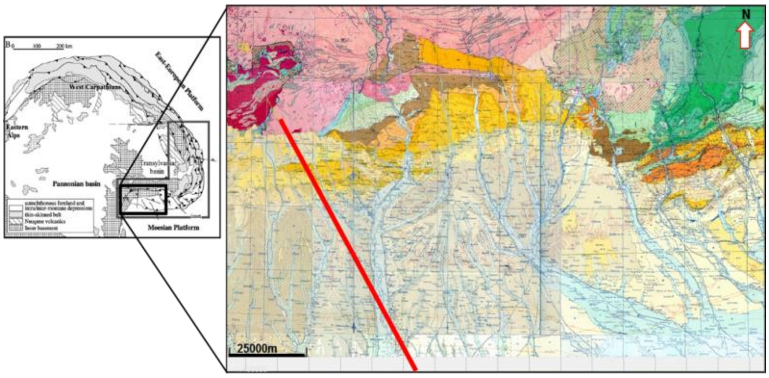

Figure 1: structural map of the Romanian Carpathians and location of the section interpreted in the geological map.

This section (figure 2) is characterized by a domain of basement involved deformation in the north and a thin-skinned tectonic wedge to its south. In the northwest end of the section, two basement units have been emplaced southwards onto foredeep sediments. To the south, the foredeep basin accumulated up to 9km of Cretaceous to Lower Miocene sediments that thinned progressively towards the southeast. The foredeep sediments are deformed in a thin-skinned tectonic wedge that was thrust and transported southward by tens of kilometers on the Sub-Carpathian thrust over the Moesian platform. This thrust cuts near the original onlap surface of the South Carpathian foredeep onto the platform. Within the foredeep wedge, a region with poor-quality seismic in the center of the section has been interpreted as a structure that doesn’t involve basement and deforms Cretaceous to Quaternary sediments. Growth strata flanking this structure indicate that it accumulated ongoing deformation from Early Miocene to present-day. South of this central structure, the foredeep wedge is affected by imbricate thrusts (known as the Burdgialian wedge as it only involves Miocene sediments, detached above Lower Burdigalian evaporites) that accommodated up to ~10 km of shortening. The southern limit of the Burdigalian wedge is the leading edge of the Sub-Carpathian thrust and the deformation front of the Southern Carpathians. Undeformed Sarmatian (Late Miocene) sediments are observed to onlap onto the Burdigalian wedge along its southern tip.

This structural model is supported by the interpretation of a seismic 3D cube, regional surface geology, gravity modelling and wells previously drilled in the area. Gravity modeling allowed us to reduce the structural uncertainty by identifying the presence or absence of high density material (basement) in areas where the seismic quality was poor. It also helped us to define the depth of the autochthonous Moesian platform below the Sub-Carpathian thrust beyond the area of well control.

The few wells that drill the pre-Miocene section were also critical in providing three key constraints: 1) one well drilled through the Burdigalian wedge and encountered Badenian (Middle Miocene) sediments below the Sub-Carpathian thrust; 2) dip information in the central part of the cross-section, where seismic was of limited use; and 3) the depth to the top of the Oligocene (the deepest unit drilled) north of the Burdigalian wedge.

Finally, a structural evolutionary model was constructed in order to validate the proposed thick- and thin-skinned deformation mechanism and the consistency of the interpretation with the evolution recorded by growth strata. This model shows an original foreland basin with Cenozoic sediments wedging towards the South-East and onlapping on the Cretaceous of the Moesian platform. This foredeep was originally 34 km longer than the present-day section.

The basin was affected by five main periods of deformation. Firstly, the uppermost basement unit (seen in the northern end of the section) was emplaced over the foredeep basin in Paleocene times. After a long period of relative quiescence, a mild deformation event is recorded in the central structure of the section by gentle wedging of Lower Miocene sediments. This deformation event was followed by the most important period of compression during Badenian times (Middle Miocene) in which Pre-Badenian sediments (Cretaceous to Burdigalian) are shortened by 27km in 2Ma. This period is characterized by the development of the Burdigalian wedge. The fourth stage of deformation, from Badenian to Sarmatian times (Middle to Late Miocene), is characterized by much slower shortening rates (5km in 8Ma). Out-of-sequence thrusting in the central structure continued during this time, slightly deforming Upper Miocene sediments. Finally, a Pliocene to Quaternary stage of deformation led to uplift and erosion in the axis of the Southern Carpathians.

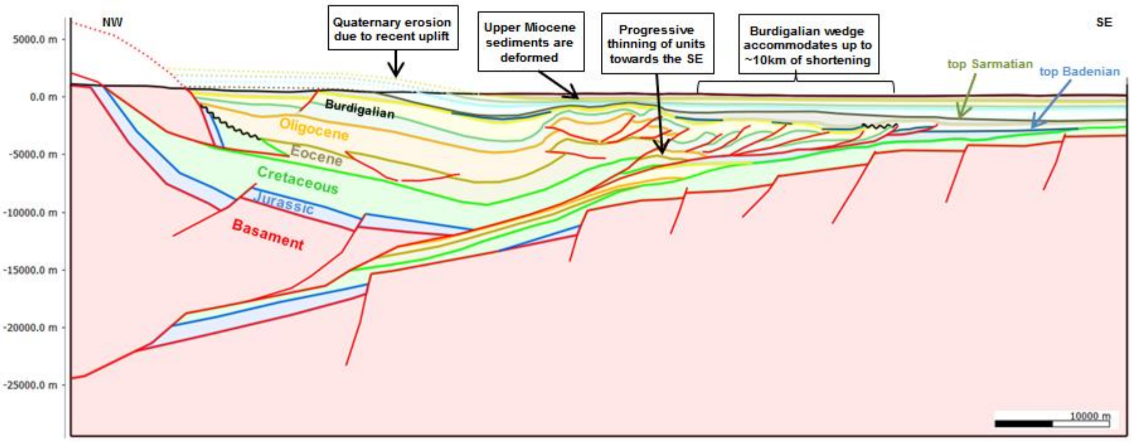

Figure 2: regional structural section with proposed interpretation.

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New Discoveries and New Plays in the Carpathian Fold and Thrust Belt: Innovating New Structural and Stratigraphic Concepts for Future High Impact Exploration

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Introduction

The Carpathian fold & thrust belt is the sixth largest fold & thrust belt globally, in terms of discovered hydrocarbons. It has the longest production history of all thrust belts worldwide and is generally considered to be a mature hydrocarbon province. However, most of the oil and gas has been discovered prior to the availability of modern exploration methodologies, including modern reflection seismic data. So, can the Carpathians really be considered to be a mature province?

We have been involved in exploration in the region since the 1990's and have been involved in several significant new discoveries resulting directly from application of new concepts into this 'old' area. Successful exploration for hydrocarbons in fold and thrust belts generally and the Carpathians in particular requires the careful and effective integration of surface geology, subsurface data (e.g. seismic, other geophysical data, well-data, production data) and critical re-evaluation and re-calibration of legacy data (including updating biostratigraphy and upgrading to sequence- and chronostratigraphy and redrawing/reassessing geological maps) and interpretations. Modern seismic data is invaluable, albeit it is difficult to obtain good imaging, and we cannot over-emphasise the importance of care in seismic survey planning, acquisition and processing for better data.

Obtaining useful, exploration-predictive interpretations is critically dependent on integration of all data sets, especially relying on the upgraded understanding of surface geology and stratigraphic/structural relationships and styles. In this presentation, we demonstrate that exploration as an Operator across the entire Carpathians fold-thrust belt chain (from Poland and Czech Republic through Slovakia to Romania) has resulted in a number of oil & gas discoveries within the complex, more internal zones of the fold-thrust belt. The carefully conducted technical work has led to a fundamentally and radically new understanding of the structural and stratigraphic / syn-tectonic basin development of the Carpathians, and the complex petroleum systems of this region, with positive indications for future exploration potential.

The Challenges

Prospectivity within the Carpathians fold and thrust belt, and especially at depth in the interior part of the thrust belt, has been traditionally regarded as high risk, in large part because of the perceived extreme complexity of the structures, structural configurations and the difficulty of correlating stratigraphy between wells and between different zones within the fold and thrust belt and the very large thrust displacements that have been traditionally assumed. In addition, existing models generally do not allow for large structural closures, seal & reservoir quality and presence is poorly understood, the charge systems are poorly understood and may require dependence on, as yet, un-proven source rocks.

This work, which is the result of exploration and operations on many exploration concessions over the Carpathians region (Poland, Slovakia, Czech Republic, Ukraine, Romania, Hungary) since 1995, has demonstrated how regional structural and sequence stratigraphic traverses, based on stream sections tied to new and reprocessed legacy 2D seismic, has led to the generation of new structural models, which depend more on basin inversion and less on thin-skinned tectonics, and a predictive tectono-sequence stratigraphy framework which, for the first time, links the undeformed foreland geology to the deepest legacy wells and which can be used to correlate between structures and between thrust 'nappes'. The extensive integration of field and seismic data across the whole region has proven to be of critical value. Field exposures are generally challenging, being of limited extent (generally within small stream sections), and cannot easily be put into a wider context without ties to seismic data. Even the best modern seismic data in the region leaves the interpreter with many 'degrees of freedom' and requires careful integration with the surface geology. However, key seismic data in relatively undeformed parts of the thrust belt system, and field geology data from exceptional exposures, has provided the key to re-interpretation of difficult data elsewhere in the thrust belt. Extensive legacy well and core data, often from deep 'stratigraphic' wells, has provided critical constraints on structure and stratigraphy at depth, but needs to be interpreted with care because of inconsistencies in the reported stratigraphy in particular. A critical element in exploring this area has been utilisation of the vast amount and knowledge and experience of local geoscientists and explorationists who are open to critically challenging past assumptions and models.

New Ideas & Exploration Concepts

The importance of new structural models that invoke inversion of half-graben basins is emphasised. Better seismic data evidences inversion geometries and appears to reduce the need for the very large shortening estimates that are common within the region. Out-of-sequence thrusts and 'thicker-skinned' thrust models, linked to kinematics and geometries associated with inversion, allow newer interpretations with larger structural culminations at depth. Moreover, important reconfiguration of the regional structure is required, as evidenced from fieldwork and surface geology, with the identification of important back thrusting relationships that are interpreted as related to inversion tectonics. The need for reassessment of mapped relationships is not surprising since most maps were made prior to the advent of plate tectonics and modern ideas of thrust tectonics.

Much of the high estimates of tectonic shortening seems to come from field scale observation of highly folded and deformed exposures of the mud dominated flysch successions. However, our work indicates that much of this is in fact soft sediment deformation, sometimes with moderate overburden, and indicates early gravitationally driven deep water slides (such as observed for example in the Niger Delta), which we interpret as having been driven by north to NE-vergent migration and over-steepening of the thrust front during early development of the Carpathians. This is predominantly evident in the Magura nappe, and its lateral equivalents. The understanding of the structure and stratigraphy has been assisted by the identification of several separate and contrasting thrusting/shortening events, which have different transport directions.

Fundamental reinterpretation of the stratigraphic evolution and tectonic subsidence mechanism for the basins has been required, which profoundly changes the controls on and prediction of the distribution and nature of the reservoirs and key stratigraphic play elements.

Our work suggests that there are more and older, pre- Oligocene ('Menilite/Dysodile'), source rocks active within the petroleum systems of the Carpathians and that there have been multiple phases of hydrocarbon generation. This is strongly suggested by a lack of correlation between the regional configuration of discovered fields with respect to large scale Miocene thrust structuration.

Conclusions

The results of exploration studies across the Carpathian fold and thrust belt has resulted in the development of fundamentally new structural and stratigraphic ideas and models which have directly led to two new gas discoveries and one new oil discovery and potentially the discovery of a new resource play in Southern Poland. There are strong indications that there remain new plays to be discovered and new discoveries to be made within existing plays. In addition there is a large potential for significant resources to be held in tight reservoirs, especially within more internal parts of the thrust belt. The Carpathian fold and thrust belt is complex and has its challenges, however it has indications that it may yet have significant upside.

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Thrust tectonics and hydrocarbon exploration in the Patraikos gulf (Western Greece offshore)

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The external Hellenides are part of the Alpine s.l. belts which faces the Adriatic and Ionian seas (Fig.1). They represent the southern continuation of the Dinarides-Albanides mountain chains as they mostly trend NW-SE with dominant tectonic transport towards the SW.

While stratigraphy is mainly related to Mesozoic carbonates, pertaining to the so called Ionian domain, and Cenozoic terrigenous sediments, structures along the Hellenides belt segment can essentially be referred to thrust tectonics with strong control from the regional mechanical stratigraphy and the geodynamic framework.

In the Patraikos gulf, 2D legacy data (1977-2000) and newly acquired 3D seismic volumes (PSTM and PSDM, 2016-2017) allowed the region geology and prospectivity to be illustrated and evaluated in great detail.

In general:

- folding and thrusting of the deep Mesozoic carbonates are confirmed as the major deformation mechanisms across the area,
- transpressive-transtensive structures can be documented especially within the Plio-Pleistocene sedimentary series,
- sheet-type and diapir-type salt-related features are clearly shown, as they occur at the tip of major thrusts and along localized wrenching zones, respectively.

In particular:

- Field-scale normal faults can be mapped using automating picking and attribute visualization
- complex thrust-related imbricates can be interpreted and modeled in their three-dimensional dimensions

Eventually, the evolution of the structural setting can be unraveled and the related deformation kinematics is documented by

- detached folding,
- thin-skin thrusting of the Mesozoic carbonates,
- late-stage wrenching,
- out-of-sequence structures with possible involvement of the crystalline basement.

Thanks to the final 3D seismic data quality, Hellenic Petroleum and Edison Gas could evaluate the exploration potential of the Patraikos block and its surrounding which, at present, clearly represent one of the few under-explored region in the western Mediterranean.

Figure 1 – Schematic trace of the orogenic belts, location of the study area in the Ionian offshore and main oil fields

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Wednesday 1st November 2017

Session Four: Analogue Modelling

Shortening accommodation in deepwater contractional fold belts: an experimental investigation

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Many continental margins have deepwater, contractional fold belts that formed above a ductile level such as salt or shale. Margin failure, accommodated by proximal extension and distal shortening, is caused by some combination of gravity gliding above a basinward-dipping detachment and gravity spreading of a sedimentary wedge with a seaward-dipping bathymetric surface. In areas with significant tectonic activity, the structural styles of the deep-water contractional fold belts are primarily driven by the interplay between the regional far field stress and the continued shelf and upper-slope deposition. The island of Borneo in SE Asia is a remarkable area for hydrocarbon exploration, encompassing several different deltaic provinces with deepwater potential that formed in a continental convergent tectonic setting. Amongst them, Mahakam Delta and NW Borneo Trough all have proven deepwater hydrocarbon fields.

So far, a lot has been said about the control of the nature of the decollement layer (shale vs salt) at the base of the sliding sediments on the structural styles of these contractional fold belts. On the contrary, quantitative measurements of the amount of shortening are rare and they are derived from structural restorations of interpreted seismic profiles. Also, the interplay between the sedimentation, shortening by gliding and the far field stress is not fully understood. In this paper, these problems have been addressed by means of analogue modelling techniques.
Analogue models were built in a 70 x 40 cm deformation box. There were three fixe sides and one mobile wall linked to a stepper motor allowing compression (Figure 1a). All the experiments have been performed under a X-ray tomograph for a 3D imagery. Three kinds of analogue materials were used to simulate different rheological behaviors: dry granular materials to simulate brittle sedimentary rocks, viscous Newtonian material to simulate ductile rocks such as shales or salt, and a mixture of viscous material (silicone putty) with granular material (sand) to increase the viscosity of this layer and allowing a greater cohesion. In all the models, we added a sand wedge in the half model to simulate the delta system (Figure 1b).

In order to test the impact of the sedimentation on the structural styles of the contractional fold belts, three sets of sandbox experiments have been carried out: a) low syn-kinematic sedimentation rate (no delta propagation; sedimentation in the synclines only), b) low syn-kinematic sedimentation rate (delta propagation, outside the delta, sedimentation in the synclines only and c) high syn-kinematic sedimentation rate (delta propagation all across the model).

In all the experiments, fore-thrusts initiated at the lower edge of the prograding delta and the deformation developed in-sequence, i.e. towards the basin. In those experiments were the sedimentation rate was high to very high, the thrust that was active at the delta front system, is rapidly buried by the load of the delta progradation sediments and ceases to be active. We found that the presence of the prograding delta strongly controls the structural style of the compressional fold belt. In fact, in front of the delta, the sedimentary thickness being higher, fold wavelength is large and the whole deformation is taken by few major thrusts. This results in wide synclines developing between two adjacent thrust sheets. On the contrary, in the transition and in the distal domains, thrusts are more closely spaced. Hence, the synclines are narrower and the accommodation space smaller but deeper than in front of the delta system. In a map view, the curved traces of the thrusts and fault-related folds are strongly influenced by the presence of the prograding delta system (Figure 1c).

In our experiments, we found that the compression was primarily accommodated by a shortening of synclines of about 20 to 40%. That is approximately what we observed in the Mahakam Delta and the Bunguran Fold Belts of SE Asia. This showed us that in such kind of tectonic environment, characterized by a huge amount of syn-tectonic, non-compacted and mostly shaly sediments, a large part of the deformation is accommodated by shortening of synclines. This observation differs from what is seen in orogenic belts, where the deformation is most likely accommodated by faulting, anticlines shortening and thickening of series. Our results pointed out that the shortening of synclines varies as function of the sedimentation rate and their position within the system. The evolution through time in 3D also highlights the relative uplift of syn-kinematic deposits and a delta foreset and bottomset deformation in all the experiments.

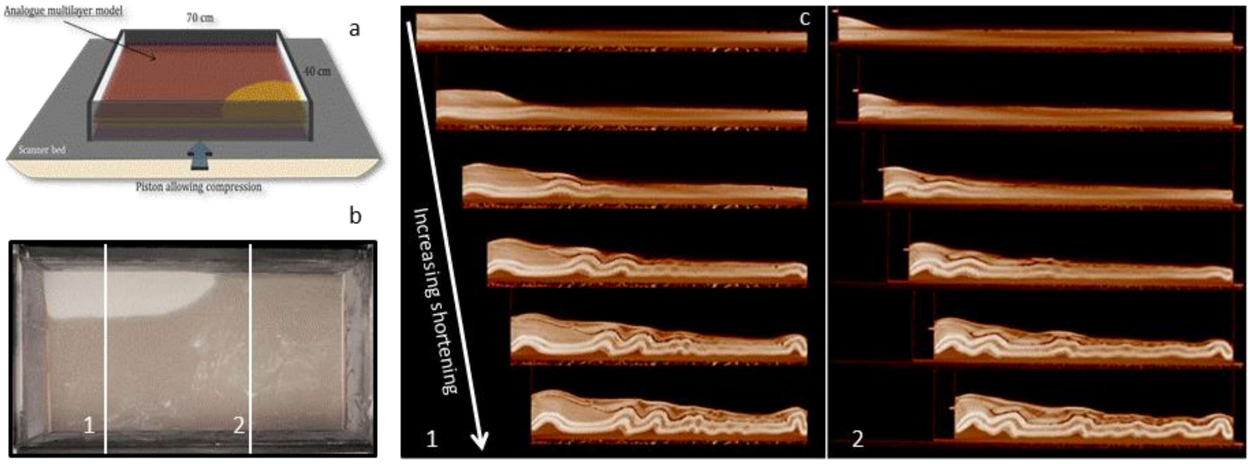

Figure 1: a) Schematic representation of the experimental box. b) Surface view of the sandbox before starting the experiment. c) Vertical sections showing five consecutive stages of compression.

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Insights into detachment folds and subsalt duplex geometries in the Eastern Carpathian Bend Zone, Romania: an analogue modelling approach

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The Eastern Carpathian Bend Zone (ECBZ) is part of Romanian Carpathians which are an arcuate Alpine orogen, recording the closure of the Alpine Tethys. The ECBZ is a prolific hydrocarbon province with a strong relation to salt tectonics and hosts largest onshore oil fields in Romania. The reservoirs are structurally complex due to superposed tectonic events (from Miocene to Recent). Poor seismic quality (mostly sub-salt and in the proximity of the diapirs) brings difficulty in mapping the structures. As most of the shallow fields have been discovered the current focus of exploration and production are the sub-salt, deep reservoirs. The most recent structural interpretation of the area (Schléder et al., 2016, in prep.) evokes the formation of detachment folds and sub-salt duplexes in the early stage of shortening (mid-Miocene).

To better understand the structural evolution of this area we adopt an experimental approach which is known to provide critical insights in fold-and-thrust belts. In order to be quantitatively and qualitatively representative, the analogue models have been geometrically, kinematically and dynamically scaled. The brittle behavior of both the subsalt layers and the overburden has been modeled using a Mohr-Coulomb granular material (colored dry quartz sand; Fig. 1, 2) and the ductile behavior of the salt was modeled using silicone. The lower detachment was modeled using 200-300 µm glass beads (Fig. 2).

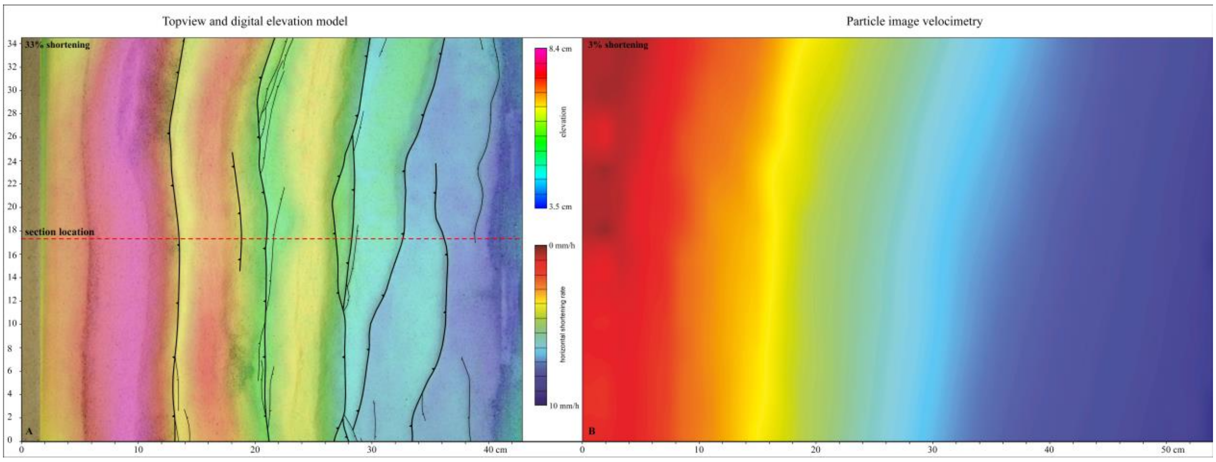

Figure 1. A- Interpreted topview of analogue modeling experiment at 33% shortening, showing deformation style, lateral variations of geometries. The image displays a digital elevation model (DEM) overlapped on a topview photo. Location of section in Fig. 2 is represented by a dashed red line. B- Particle image velocimetry (PIV) map, illustrating the rate of leftward horizontal displacement at ~3% shortening. At this time no structures are formed and the model deformation is dominated by layer parallel shortening.

The experimental setup consists of a fixed horizontal box with one glass sidewall. A stepper motor driven, mobile base plate with a buttress is pulled against the box at a constant rate (10 mm/h). The filling and layering of the granular materials in the deformation box was achieved using the same procedure as described in Schreurs et al. (2016). Deformation monitoring has been achieved with the use of side- and top-view 2D digital image correlation techniques (DPIV- Digital Particle Image Velocimetry) (Fig. 1B). 3D digital elevation models (DEM) of the experiments were obtained with the use of an IR projector and camera (Fig. 1A). After post-experiment treatment, the model was serially sectioned and photographed (i.e. Fig. 2). These vertical sections were used to build 3D digital models of the experiments.

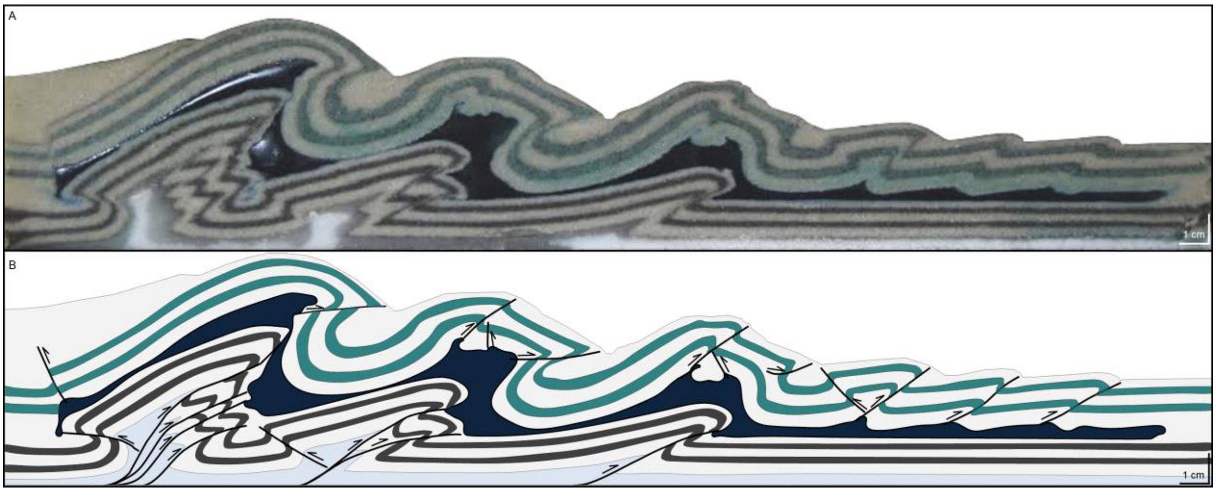

Figure 2. Vertical cross section through the experiment at 33% shortening. All layers in section are pre-kinematic. (section location in Fig. 1). A- photo of model section, B- interpreted section.

The models were characterized by detachment folds formed above duplex structures and salt pillowing in the core of these anticlines (Fig. 2), supporting the interpretation of Schléder et al., (in prep.). Low angle thrusts in the near vertical limbs of the detachment folds are observed in all experiments (i.e. Fig. 2). These features are missing from most previous interpretations, probably because the vertical layers are not properly imaged on the seismic. The integration of all deformation monitoring data with the 3D model highlighted the high layer parallel shortening that goes on both supra- and sub-silicone layers. It is well known that this type of deformation can also lead to volume loss, thus porosity reduction of the reservoir layers.

Experimental results show the overall fold-belt geometry (Figs. 1, 2), position of the duplex structures and highlight the complex geometries that can be expected both sub- and supra-salt layers (Fig. 2). Those findings can be used to improve seismic interpretation and predict subsurface geometries in the poorly constrained areas. At the reservoir scale, understanding the small-scale fault networks and how they can vary on strike can aid in a better characterization of reservoir compartmentalization. Understanding the impact of layer parallel shortening can lead to a better estimation of reservoir properties and volumes in hydrocarbon exploration.

NOTES:

Analogue models of multi-layer brittle/ductile wedges, and comparison with natural examples

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The dynamic of orogenic wedges detached above a ductile decollement level has been studied by the means of analogue modeling. 2D Multi-layer sand/silicon wedges have been subjected to various shortening at variable velocities and imaged by X-ray tomography to obtain 4D scenarii of tectonic evolution, and define a structural style.

The model database is composed of more than 60 experiments. To enlarge the range of the studied modeling parameters (decollement strength, velocity, rheological layering), we developed the use of sand-loaded silicons with calibrated viscosities (e.g. Schreurs et al.,2016). The first order data from the experiment are the prism geometry as well as its structural style (detailed as fish-tail, pop-up, asymmetric folding and in-sequence thrusting), and its sequence of propagation.

The models show that the overall geometry of the prism is entirely controlled by the basal decollement properties, whereas the structural style is controlled jointly by the decollement properties and by the rheological layering. The observed trends between the models mechanical boundary conditions and the observed structural styles are affected by the rheological layering and vertical strength profile, and modulated by the maturity of the prism. Similar first order data from natural examples of orogenic prims detached over a salt layer have been collected, and display a very similar pattern. The influence of parameters such the belt maturity, erosion and sedimentation are also discussed.

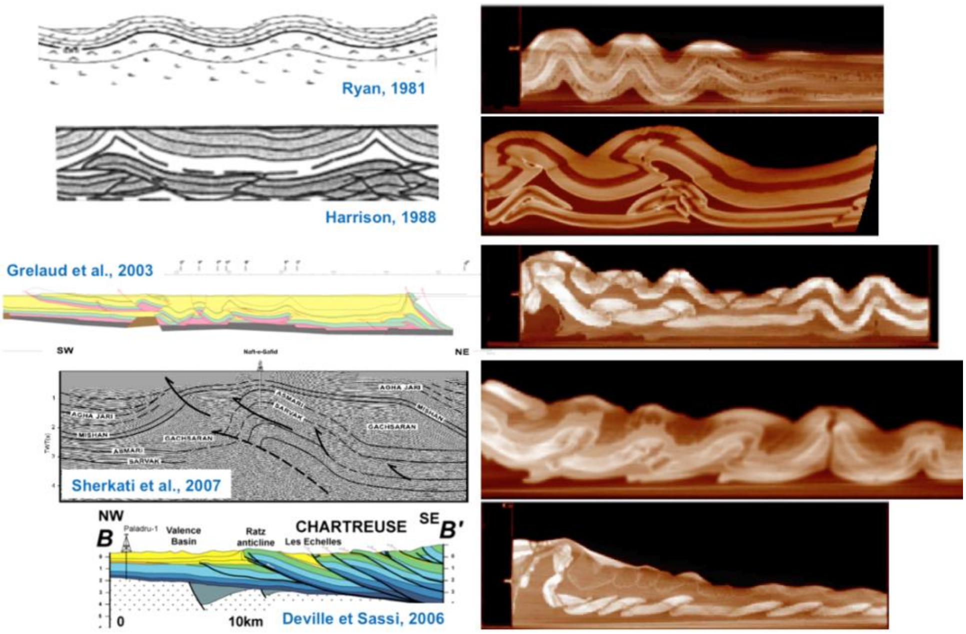

Figure 1 : Comparison between natural examples (left column) and equivalent analogues models (right column) for each structural style (fro top to bottom : buckling, fish tail, duplex, Asymmetric folding, stacked thrusts).

NOTES:

New devices to predict deformation for a geometrically non-uniform accretionary wedge. Applications to fold-and-thrusts belts

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The mechanical understanding of fold and thrust belts and accretionary wedges strongly relies on the Critical Coulomb Wedge Theory (CCWT). In this theory, the mechanical analogous is sand pushed by a moving bulldozer along a frictional décollement. At the critical state, the whole wedge including the basal décollement is on the verge of Coulomb failure. The CCWT requires a wedge with a perfectly triangular shape, a planar décollement and homogeneous and brittle material properties. In these conditions, the solution of the CCWT is analytical.

However, even if this theory provides useful first-order solutions to explain deformation in wedges or in fold and thrust belts, it suffers from several limits. Indeed, the critical taper is shaped by internal thrusts that lead to a non-uniform topographic slope. This variability in the topography could also be explained by a high sedimentation rate concentrated on a specific zone of the wedge or by erosion. Furthermore, steps on the basal décollement as in the North of the Jura fold and thrust belts prevent from considering a planar basal décollement at the base of the prism. So in this context one question is raised: what is the influence of basement and topography irregularities on the deformation in a wedge? We aim to provide simple solutions to structural geologists to evaluate the critical state and to predict deformation of their field case. We here show how the limit analysis theory can help us to overcome these limits.

By sandbox experiments, we illustrate the general behaviour of the wedge for each type of irregularity and by numerical modelling, we are able to propose sets of parameters for each kind of behaviour.
We demonstrate that for a given set of physical parameters (friction/cohesion), a lowered portion of the décollement can be activated depending on the height of the step and on the topography above it. Therefore, we have a geometrical criterion to predict the activation of a deepen décollement.
We demonstrate that there is a competition between the surface of potential hanging-walls and the surface of theoretical critical hanging-walls.
In the simple case where the geological structures present a completely flat zone, specific geometrical conditions may involve a passive carrying of this zone without internal deformation.
We compare our results to natural cases such as the Jura (France) fold and thrust belt and the Zagros (Iran) fold and thrust belt.
This mechanical analysis therefore allows structural geologists to improve their structural interpretations considering new tectonic styles and to propose new interpretations of their natural cross sections.

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Wednesday 1st November 2017

Session Five: Fractures

Are fracture networks easy to predict in the subsurface? The lesson learned from a discovery in Northern Iraq (Kurdistan Region)

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Understanding fracture network in tight carbonate reservoirs is a key task to be able to correctly asses the hydrocarbon potentials and productivity of HC discoveries and to design an appraisal and a field development plan. The initial structural and fault and fracture (F&F) conceptual models built during the exploration phases are based on the integration of different data (seismic, outcrop and regional information). They offer a first-hand picture about the organisation of the F&F network. The subsequent drilling of the exploration well and the data acquired consequently can be used to update and tine the initial models especially considering: i) the subsurface conditions, ii) the local stress field, iii) the mechanical properties of the different lithological units and iv) the type and characteristics of hydrocarbons. The new updated F&F network model allows to better plan the next appraisal phase and to find out which would be the most efficient design for the appraisal wells. Lastly, the new geological and dynamic data can be then used to understand the effective productivity of the discovery and to better perceive the main risks and uncertainties associated to the following development phase. In this interactive approach to the characterisation of fractured carbonate reservoirs the immediate integration of newly acquired information is fundamental to avoid any further delay on the development of the discovery. The use and integration of data acquired from drilling, logging, coring and testing is the key for realise where are located the complexities and the uncertainties always present in fractured carbonate reservoirs within thrust belt domains.

The case study presented in this study is located in the external fold zone of the Zagros Thrust Belt in Northern Iraq (Kurdistan region). The discovery includes three lower Cretaceous reservoir units with different lithological and petrophysical properties. This reservoir variability contributes to the complexity of the fault and fracture network and to the productivity of the field. The field development plan has been taken into consideration this zonation. The initial F&F model was build by integrating: an extensive outcrop dataset collected in the same area with exposures of rocks equivalent to the subsurface reservoir units, the data acquired on the exploration well and on another nearby well, high resolution satellite images, regional data and information on the regional stress field characteristics. The resulting model helped to design the appraisal campaign that included the drilling of horizontal/highly deviated wells crossing the different reservoir units. The data acquired with the appraisal wells are contradicting and show that the F&F network is more complex and less predictable than expected. The new data highlights: the structural complexity approaching the edges of the structure (frontlimb and backlimb), the complexity along the core of the structure that may have an impact on the reservoir compartmentalisation, the impact of the mechanical properties of the different reservoir units on the development of the F&F network and on the drilling (formation on induced fracturing and damage of the formation), the presence of stress field anomalies, the possible impact of diagenesis and the paragenetic evolution on fracture aperture.

The uncertainties related to some of these complexities can be partially overcame with further data acquisition, technical studies and DFN modelling. This will certainly led to an improvement and to a better definition of the F&F conceptual model modelling even if all the related uncertainties are far to be completely resolved due to the intrinsic nature of these reservoirs and to the deformation complexities that are typical of thrust belts.

NOTES:

Fold evolution and natural fracture prediction using multi-scale geomechanical modeling with application to a Kurdistan Zagros fold

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The majority of the world's hydrocarbons are stored in traps formed by folds, commonly under conditions conducive for producing natural fractures. In many folded reservoirs, these fractures are an important element in the subsurface flow. Unfortunately predicting fractures continues to be challenging despite decades of outcrop work and subsurface case studies. This lack of predictive capability can lead to costly mistakes or missed opportunities during hydrocarbon exploration, development or production.

In the absence of fracture prediction capabilities, fracture distributions in the subsurface have relied heavily on outcrop analogs. However, the dependence on outcrop analogs for subsurface reservoir fracture predictions are usually flawed since outcrops by their nature have experienced a different stress and strain path than any subsurface reservoir. Modern numerical methods exist to more explicitly simulate the stress and strain history of any particular reservoir interval and use this information to inform a more accurate fracture prediction that mimics the actual fracture causes. A new geomechanical approach for explicit fracture prediction has been developed that combines a finite element "global" model, that recreates strain history through iterative forward modeling, with a "local" Extended FEM (XFEM) embedded model, that creates fractures at fine scale in response to initial conditions and evolving boundary conditions extracted from the global model at discrete time-steps. The 3D fractures emerge at the bed scale from local models when tensile failure conditions are met. Their growth, interaction and intersections are governed by physical laws, producing realistic fracture networks as a function of rock mechanical properties and imposed strain history.

This process-driven methodology enables fracture prediction away from well control, or even in the absence of wells, with a degree of confidence not possible with statistical or empirical methods. It does not rely on flawed outcrop analogs and can predict attributes difficult to obtain from subsurface data sets, such as fracture apertures, connectivity, lengths and heights. The combination of global and decoupled local modeling allows fast fracture generation for sensitivity and scenario testing using permissible global model(s) strain histories.

The methodology is demonstrated using an application to a detached buckle fold in the Zagros foothills of the Kurdistan Autonomous Region of Iraq. The fold is a doubly plunging anticline of approximately 30 km length and 10 km width with limb dips up to 40°. Cross-sections based on 2D seismic interpretations are modeled at the kilometer scale and form the basis for embedded local explicit fracture predictions. A well with image logs and DST's is used to understand the causes and controls on fracturing and their effective hydraulic properties. No fracture pre-conditioning is required in the local XFEM models, however a pre-folding fracture set is pre-seeded in the models to accelerate calculations and focus on the variability of the folding-induced fracture set and its interactions with the pre-existing fractures. The mechanical model predictions are calibrated to match the well-based image-log fracture observations and dynamic data. Fracture intensity and lengths are matched by varying rock tensile strength heterogeneity in the local embedded fracture models. Field-wide fracture predictions are made using the global-local finite element approach with calibrated properties for hundreds of local models to predict variations in fracture connectivity and flow throughout the fold; testing a range of structural positions and stratigraphic intervals. Effective fracture permeability and porosity are calculated for each local model and sampled into a 3D geologic model to make full-field fracture permeability and porosity predictions. The results strongly resemble fracture heterogeneity observed in other nearby Kurdistan folded reservoirs.

This approach is applicable for a wide range of structural deformation styles and fold types and only limited by the ability to create a permissible global-scale model. Fracture prediction uniqueness is dependent on the quality of the interpreted deformation history. A correct and robust interpretation is essential for a highly accurate fracture prediction. An inaccurate history interpretation may yield a permissible match to present day fold shape but would yield erroneous fracture predictions.

NOTES:

Development of Fault-Parallel Veins (Slickenveins): An Example from the Hudson Valley Fold-Thrust Belt, New York

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Fault-parallel veins are sheets or lenses of minerals precipitated from an aqueous solution such that the plane of the vein is parallel and adjacent to the plane of the fault. Surfaces of such veins contain lineations indicating the relative direction of slip along the fault. Numerous examples are found in the Hudson Valley Fold-Thrust Belt (HVB; Marshak, 1986) of eastern New York State, in the foreland of the northern Appalachians. These veins, which occur along detachments, ramps, and bedding-parallel flexural-slip surfaces within Devonian limestones, argillaceous limestones, and shales, are composed mostly of calcite, although a few examples may contain quartz. Field and petrographic analysis of these veins using plane polarized light, cathodoluminescence, and an environmental scanning electron microscope provides new insight into the process by which these veins formed. In recent decades, such lineations have been commonly referred to as slickenfibers or fibrous slip lineations and have been described as thin sheets or shingles of linear fibrous crystals covering the surface of a fault (Twiss and Gefell, 1990; Doblas, 1998; Fagereng et al., 2011). This terminology is rooted in the previous work by Durney and Ramsay (1973) and Ramsay (1980) on the formation of fibrous slip lineations. These authors interpreted the veins to contain fibers formed by micro-scale crack-seal deformation. On close examination, however, the veins in the Hudson Valley displayed characteristics that have not been previously documented in the vein literature. Fault-parallel veins are not necessarily thin, but wedge-shaped with a highly variable thickness ranging from less than a millimeter to a few centimeters. The wedges grow incrementally along their length in a direction parallel to the slip direction of the fault. Their internal morphology is blocky to elongate blocky rather than fibrous (terminology of Bons et al., 2012). Lineations on the vein surfaces are grooves carved into the surfaces (as recognized by Fossen, 2015) by asperities on the overriding wall, and also affect the adjacent and overlapping screens of wall rock.

Several specific observations were made of fault-parallel veins in the HVB: (1) Veins are a composite of overlapping wedges; (2) The upper and lower surfaces of the wedges are more irregularly shaped in thin sections that are perpendicular to lineations, and more planar in thin sections parallel to lineations; (3) Wedges are typically separated by screens of clay or wall rock; (4) Ends of the wedges can be step-like or tapered; (5) Individual wedges contain segments with varying crystal textures, of which the long axes of the elongate crystals are parallel to the vein wall; (6) Crystal growth patterns in the veins vary between these segments in a direction parallel to the vein walls rather than in a direction perpendicular to the vein wall, as is typical of non-fault-parallel veins; (7) High-angle veins commonly coincide with the step-like ends of wedges and contain crystal growth patterns that are congruent to those in the fault-parallel veins; (8) Slip lineations on the surfaces are not formed by elongate crystals, but are grooves that cut across blocky vein crystals and wall rock.

Slickenveins form via a series of steps. They begin when short *en echelon* veins, oriented at a high angle to the fault, form in a weaker layer undergoing shear. During each increment of slip on the fault, a new segment adds to the vein. The nature of vein fill depends on the rate of shear—a sudden large increment will fill a segment with blocky crystals; a series of small increments will fill with elongate blocky crystals; and an increment growing very slowly may create a segment with stretched or even fibrous crystals. Segments tend to become thinner further from the initial vein segment, so the vein generally tapers in the direction of shear and has a wedge shape. As the wedges grow, they will overlap each other, preserving the wedge underneath. Grooves are carved into the surfaces of the wedges by asperities on the overriding wall. Once overlapping takes place, the grooves beneath the wedge effectively become "fossilized" (preserved) and no longer evolve. Because the lineations are grooves, the term “slickenveins” serves as a better label for such fault-parallel veins.

NOTES:

Controls on fracture intensity in a carbonate anticline, Sawtooth Range, Montana

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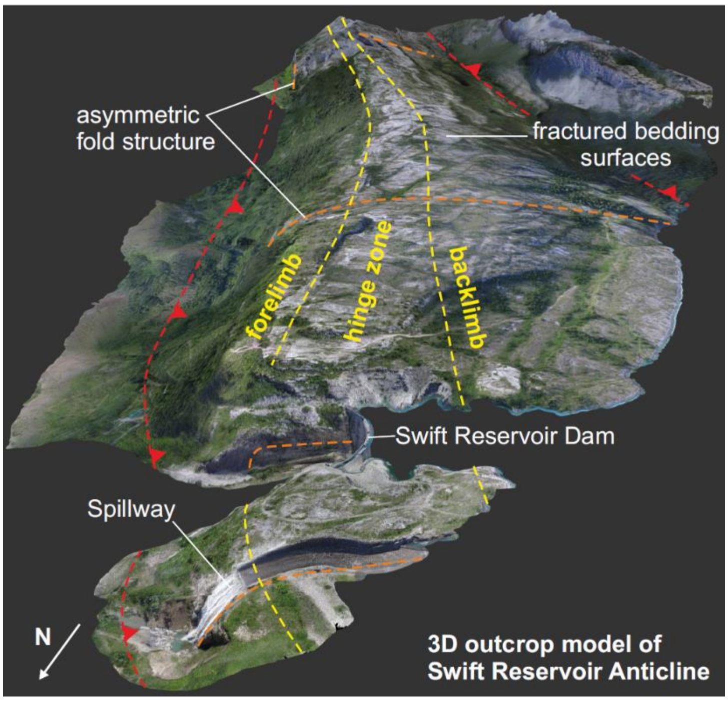
Where primary porosity and permeability of a rock are very low, fractures can significantly enhance permeability and reservoir potential by linking isolated pores and creating migration pathways. Higher fracture intensity is likely to create a better connected network of fractures, which improves fractured reservoir quality. Investigations into the controls on fracture intensity commonly conclude that either structural factors such as bedding curvature and proximity to faults, or lithological factors such as mechanical layer thickness, composition and primary porosity, have the greatest influence on fracture abundance. We use the Swift Reservoir Anticline in western Montana to investigate how fracture intensity varies throughout the structure, and what might control the observed distribution.

The Swift Reservoir Anticline exposes bedding surfaces of the Upper Carboniferous Madison Formation (Castle Reef Dolomite) on the north-eastern front of the Sawtooth Range in Montana. The range is part of the Cordilleran Orogenic belt, and is seen as a partial equivalent to the Canadian Front Ranges further north. The anticline is an asymmetric structure, exhibiting a narrow, steeply eastward dipping forelimb and a broad, shallow westward dipping backlimb. The forelimb, hinge zone and backlimbs are all well exposed meaning the structure can be used to determine how fracture intensity varies depending on structural position. Variations in lithological properties of the Castle Reef Dolomite allow for determination of lithological controls on fracture intensity.

Bedding data collected in the field is used in combination with a 3D outcrop model constructed from UAV photography and photogrammetry to build a 3D model of the anticline. Fracture intensity data is collected along eleven hinge-normal transects using a circular scanline method. Fold curvature data, extracted from the 3D anticline model, along with bedding data collected in the field are compared with fracture intensity data to determine structural controls on fracturing. To determine whether lithological factors influence fracture intensity, grain size/field lithological classification are used, along with observations made from thin sections. Data suggests only a weak correlation between fracture intensity and fold curvature or bedding and a much stronger correlation to lithology. This suggests that lithological variation has a stronger control on fracture formation than structural factors.



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Thursday 2nd November 2017

Session Six: Numerical Modelling

Mechanical controls on structural styles in shortening environments: A discrete-element modeling approach

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It has long been recognized that the structures that accommodate shortening within fold-and-thrust belts exhibit a wide variety of styles that reflect the mechanical behavior of the stratigraphic units that are being deformed. The ability to characterize and identify these different structural styles accurately, and to understand the factors that drive the variability in structural styles that occur naturally in fold-and-thrust belts, is essential to many practical applications, including petroleum geology, earthquake hazard assessment, and regional geologic and tectonic studies. To this end, I will present the results of several recent numerical studies using the discrete element modeling (DEM) method, in which I investigate the role and relative contributions of different aspects of the mechanical strength, layering, and boundary conditions of a shortening system. Modeling emergent contractional structures with this method demonstrates that a.) the major different styles of shortening structures can all be reproduced under different mechanical circumstances within the range of realistic mechanical conditions, and b.) different aspects of the mechanics of the deforming rock units (peak strength, strain weakening, layer strength anistropy) and conditions at the free surface (erosion, and syntectonic sedimentation) exert various degrees of control on the styles of structures that emerge from the models as shortening progresses. Observations of the distribution of stress and strain throughout model development demonstrate the degree to which flexural slip, second-order structures, and localized shear contribute to the development of different overall structural styles. These analyses inform our understanding of the relative importance of these different factors in determining the style of structures which accommodate shortening in different fold-and-thrust belt systems.

NOTES:

Effect of fluid pressure distribution on the structural evolution of accretionary wedges

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Numerical experiments of evolving accretionary wedges usually implement predefined weak basal décollements and constant strength parameters for overlying compressed sequences, although fluid pressure ratio, and therefore brittle strength, can vary strongly in sedimentary basins due to compaction, cementation, and phase transition related fluid release (Figure 1).

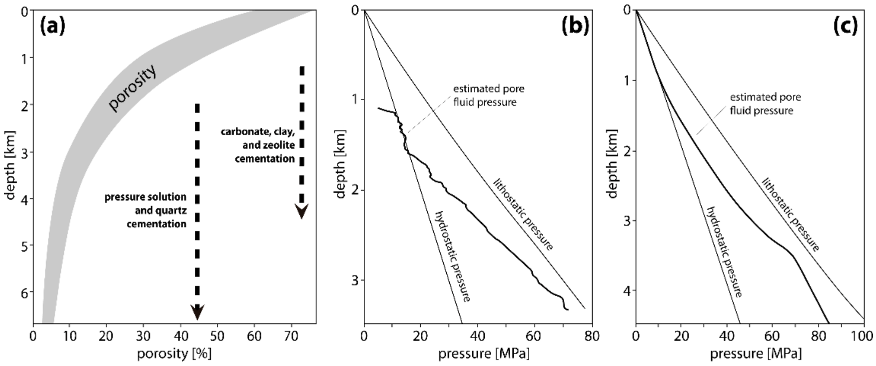

Figure 1: (a) Depth distribution of porosity. (b, c) Natural examples of estimated pore-fluid pressures from Brunei (b) and Norway (c).

A two-dimensional finite difference model with a visco-elasto-plastic rheology is used to investigate the influence of different simplified fluid pressure ratio distributions on the structural evolution of accretionary wedge systems. Results show that simulations with a predefined décollement (green) form conjugate shear zones supporting box-fold-type frontal accretion (Figure 2a). A linear increase in fluid pressure ratio towards the base leads to toeward-verging thrust sheets and underplating of strata (Figure 2b).

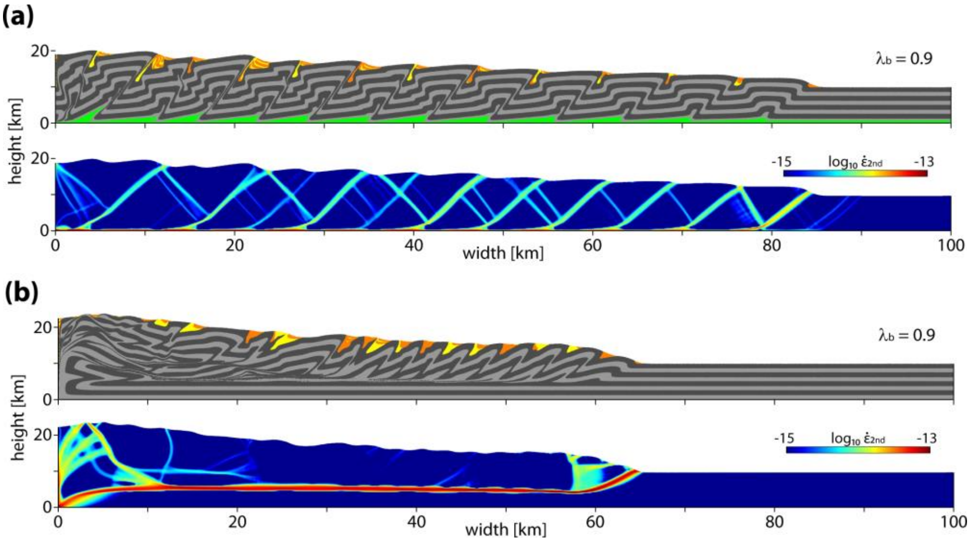

Figure 2: Composition inferred from Lagrangian markers and second invariant of the strain-rate tensor. (a) Experiments with a predefined décollement with λ = 0.9. (b) Experiment with linear increase of fluid pressure ratio to λ = 0.9 at 4 km depth below seafloor.

Additionally, a modified critical wedge theory is presented to account variable vertical fluid pressure distribution. Surface tapers of here presented numerical accretionary wedges are in agreement with the adapted critical wedge theory. Furthermore, numerical results resemble findings from natural examples of accretionary wedges. Because the structural evolution of numerical experiments with variable fluid pressure ratios conforms well with natural observations and differs from simulations with predefined décollements, the importance of fluid pressure in sediment accretion, particularly in physical models, should not be underestimated.

NOTES:

Quantitative Structural Analysis of Newly Acquired Data from Mexican Ridges Fold Belt

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New broadband long-offset regional seismic data was recently acquired and processed by TGS from the Mexican Ridges Fold Belt (MRFB) in the western Gulf of Mexico. The new data provides significantly improved resolution of the complex gravitationally-driven contractional structures within the MRFB. The MRFB is linked to a network of extensional faults on the continental shelf (Quetzalcoatl extensional system) by an over-pressured shale detachment. Despite the clarity of the seismic images, developing a robust structural framework and defining the geologic implications of gravitationally-driven deformation is still a challenging interpretation task. We show that an effective way to define and understand the structural complexity imaged in modern seismic datasets is to apply diverse quantitative structural interpretation techniques, namely kinematic forward models and area-depth-strain (ADS) analyses.

Compared with legacy data available for the region, the new data provide significantly clearer images of the normal faults within the Quetzalcoatl system, the regional detachment, and the folds within the MRFB. To develop robust interpretations of the extensional and contractional structures, we apply kinematic forward modeling in conjunction with depth-to-detachment calculations using the ADS method. Structural modeling is used within the Quetzalcoatl extensional system to define horizon correlations, displacement, and the sequential development of the growth structures based on the synkinematic growth strata geometry. Quantitative animations based on these models shows the faults initiated simultaneously but extension ultimately localized along a single dominant structure at the shelf margin. Models for the Quetzalcoatl system estimate 11 km of total extension.

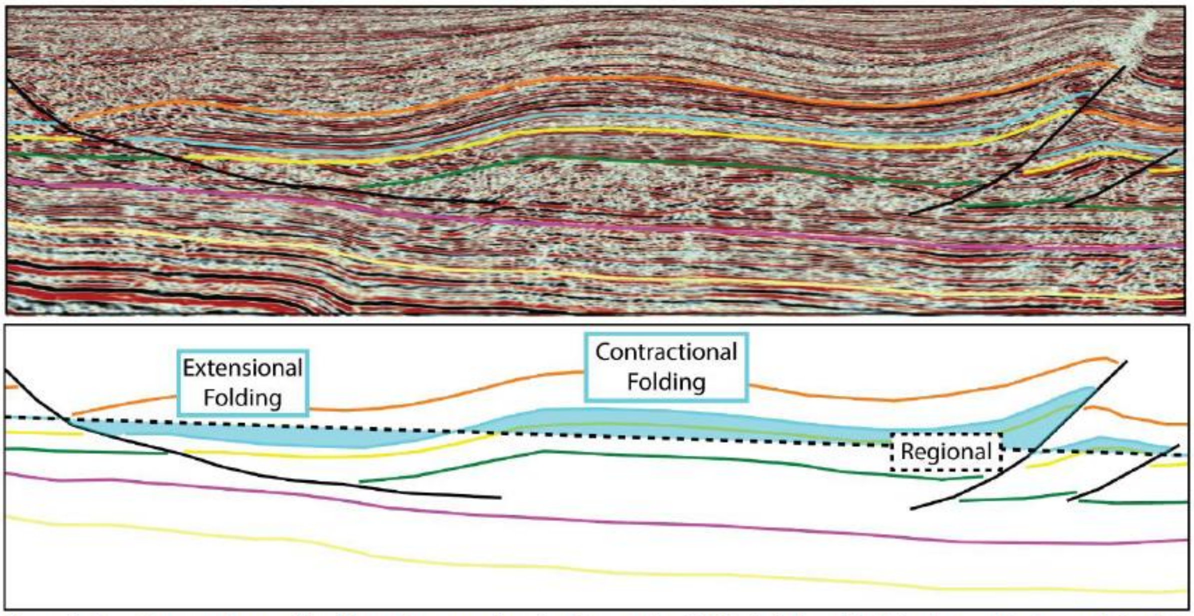

Figure 1: Top: Structural transition from the extensional regime to the MRFB. Left hand fault is the terminal growth fault in the Quetzalcoatl system. Right hand faults are the proximal MRFB structures. Bottom: Folded horizon areas are both above and below the respective regionals for each horizon. This indicates a combination of extension and contraction at the transition.

The structural transition from the Quetzalcoatl extensional regime to the MRFB is clearly imaged, but kinematically complex. The hangingwall of the terminal Queztalcoatl growth fault smoothly transitions into an antiformal fold that merges downdip with the hangingwall of the first MRFB fault (Figure 1). The growth fault and accompanying antiformal fold can be reproduced using an extensional forward model. However, closer examination of horizon folding relative to a tilted regional across the structural transition indicates a combination of extension (where the horizons are below regional) and contraction (where the horizons are above the regional, bottom of Figure 1). ADS analysis is ideal in this situation as the method directly relates fold area to displacement and detachment depth by

assuming constant-area deformation. As a result, ADS can integrate the combination of extensional and contractional folding to estimate the net displacement. The ADS-computed detachment for the transitional structure matches the seismically imaged detachment and the method estimates a net contractional displacement of 3 km.
The more outward MRFB structures are characterized at shallow levels by continuous folding and internal faulting with minor displacement. Each structure is bound by synclines where horizons return to regional depths, implying a horizon-parallel detachment. The new data reveals that the continuous folds are underlain by imbricate structures immediately above the main detachment. The level of structural complexity exceeds most modeling algorithms but the horizon-parallel detachment lends the structures to ADS analysis. In order to reduce interpretation uncertainty, we perform ADS calculations for each structure using the fold areas from the structurally simple concentrically folded section overlying the imbricates (Figure 2). The computed detachment for each of the folds is consistent with the seismically imaged detachment. The cumulative shortening on the MRFB structures is 5 km, less than the magnitude of extension estimated for the Quetzalcoatl system.

Further investigation of the deepwater extent of the line reveals four broad yet subtle folds with wavelengths of up to 20 km. ADS analyses of these structures indicates that they accommodate an additional 3 km of shortening. Collectively, the shortening within the transitional structure (3 km), the deepwater detachment folds (3 km), and the MRFB (5 km) balances the total extension in the Quetzalcoatl system (11 km).

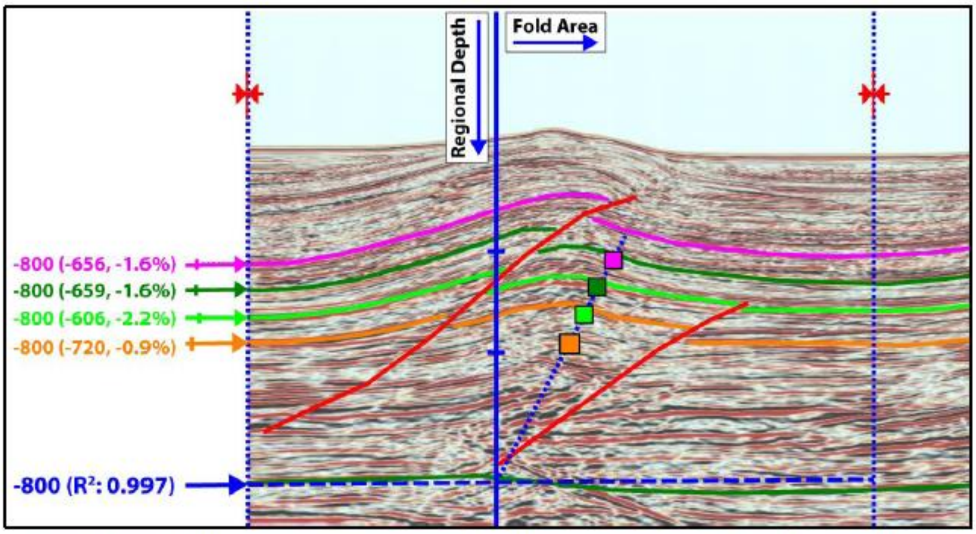

Figure 2: Area-depth graph of an interpreted fault-related fold within the Mexican Ridges Fold Belt. The area-depth graph is overlain on the seismic data, vertical and horizontal axes are labelled. Heavy blue dashed line is the detachment computed from the linear fit of the plotted fold areas (colored squares). Computed contraction on the structure is 800m.

NOTES:

Coupled Geomechanical Forward Model of a Gravitationally-Driven Fold-And-Thrust Belt

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There are many uncertainties in the exploration fold and thrust belts that may impact well planning: stress regimes, compaction or pore pressure profiles amongst others. Reducing these uncertainties demands the utilization of non-standard modelling tools instead of traditional methodologies. Here we present a study in a gravitationally driven fold and thrust belt, in which a coupled 2D geomechanical forward modelling was performed in an early stage of the exploratory project. The aims of the study were to simulate the observed deformation to help constrain the pore pressures, stresses and deviation from uniaxial conditions developed while honoring the sparse well and velocity data available.

The structure subject to this study is a submarine fold-and-thrust belt. The origin of the thin-skinned shallow thrusts in this belt is associated with the gravitational collapse of an aggradational wedge above a basal detachment causing shortening towards the basin center. One of the key challenges in this system is to understand the presence of uncompacted, highly-pressured, shale units (as documented by offset wells).

Forward modelling of this fold-and-thrust belt was performed in the finite element analysis software ELFEN. The coupling between porous-fluid flow and plane strain deformation in this evolutionary model allows the estimation of the build-up and dissipation of tectonically-derived excess pore pressure. With this approach the current day stress field and formation pressures are obtained as a result of the structural evolution rather than deterministically. This helps to calibrate the basin modeling, to assess the prospectivity in the area and to provide a theoretical framework that can be challenged and improved as new data arrives and wells are drilled.

The workflow applied starts with a structural restoration to pre-tectonic, deposition conditions, from where the total shortening experienced in the basin and the original thickness of the deformed sedimentary package are calculated. This geometry is then used to build a simplified, near-layer-cake initial geological state. Two zones comprise the key focus of interest: a basal, homogeneous shaly layer (detachment) and above, a wedge-shaped alternation of shale-sand-shale layers with a marked lithological and mechanical contrast between them. Both regions are bounded by friction contacts, can deform freely and are fixed in the basin margin. A non-deformable indenter was used to impose the shortening estimated from the structural restoration and then the stress and strain response is analyzed.

The geological domain in the pre-tectonic initialization phase has a lithology-controlled and depth-dependent porosity and rigidity distribution to account for the consolidation pressure experienced during deposition and subsequent uniaxial compaction. Porous flow is controlled by a non-linear, porosity-dependent permeability distribution described with the Kozeny-Carman relationship for each lithology so that seepage performance is directly linked with the tectonically-induced strain.

The key variables controlling the simulation (permeability, friction in the faults, normal compaction, basal friction) have been refined, corrected and cross-checked with the offset well observations in an iterative process so that the final model provides a reasonable framework in agreement with the deformation observed on seismic data and the available well log data.

The model predicts a differentiated deformation pattern in the domain above the detachment conditioned by the lithological contrast, where the stiffer sandstone layer takes up most of the stress and deforms coherently with brittle behavior where there are pre-existing discontinuities. The Effective Stress Ratio (S_{hor} / S_{vert}) in the sandstone remains high with values of around 3 and the perturbation of the horizontal stress originated by the shortening is maintained up to 30 km ahead of the thrust front. In the shale interval, however, the ESR does not rise above 1.2, the perturbation is propagated 21 km ahead of the thrust front and the layer tends to increase its thickness by pure shear (Figure 1). Consequently there is a wide region in the external domain of deformation where the maximum stress is horizontal in the sandstone and vertical in the shale. The friction on the basal detachment plays a key role in the stress distribution and transmission of stress to the sub-detachment domain.

The model also predicts the sandstone unit to be in critical state up to 20 km from the thrust front while the shale remains in isostatic compression close to the thrust limit and in uniaxial conditions in the far field. The preservation of porosity in the supra-detachment shale units could only be matched in the model with the addition of up to 4MPa overpressure at the initialization stage.

The low permeability associated with the shale formations induces a gradual increment in pore pressure during the tectonic shortening that leads to a pore pressure perturbation proportional to distance from the thrust front; consequently, most of the load originated by the tectonic compression is transferred to the pore fluid leading to the low effective stresses seen in some of the wells (Figure 2). The sandstone, however, can bleed off the extra pore pressure more efficiently acting as a fluid conduit and remains in magnitudes closer

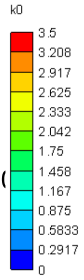
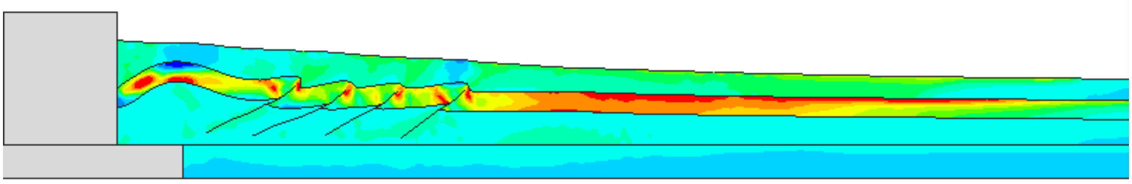


Figure 1. Effective Stress Ratio after the tectonic

to hydrostatic as observed in the offset wells. Due to the low friction basal surface, the pre-detachment shaly domain remains almost unaffected by the tectonic event.



We believe that this study demonstrates that despite the number of unknowns in the early exploration phase, forward geomechanical modeling can provide valuable insights into the evolution of key properties in the basin. When coupled with the results of offset wells, seismic velocity analysis and basin modeling, even underconstrained geomechanical modeling can actually reduce the uncertainties on the conditions in frontier basins by allowing us to test a wide range of hypotheses.

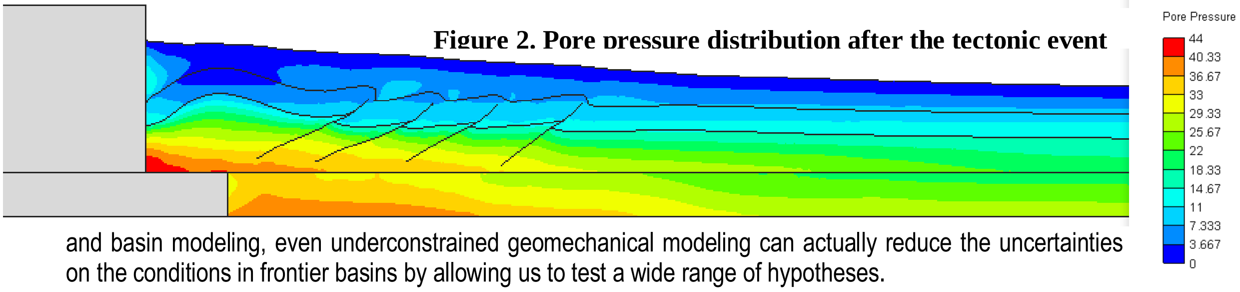


Figure 2. Pore pressure distribution after the tectonic event

NOTES:

Role of tectonic inheritance in the latest Cretaceous to Paleogene Eurekan Orogeny (NE Canadian Arctic)

Berta Lopez-Mir[1], Simon Schneider[1] and Peter Hülse[1]
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The Eurekan Orogeny is a contractional deformational event that occurred during latest Cretaceous to Paleogene times along the eastern Canadian Arctic and northern Greenland, and which possibly reached as far as Svalbard (Figure 1). It was caused by the reactivation of the Late Devonian to Early Carboniferous Ellesmerian Orogen because of relative plate motions between Greenland and Ellesmere Island. De Paor et al. (1989) highlighted the atypical nature of the orogen when compared with the general structure of standard thrust and fold belts: it does not contain a metamorphic zone nor a well-developed foreland basin, the exposed rocks are younger towards the hinterland and the orogen is anomalously wide. Despite recent research in the region, the atypical nature of the Eurekan Orogen remains largely unexplained.

This study presents a set of restored cross-sections through Ellesmere and Axel Heiberg islands in order to discuss the structural development of the Eurekan Orogen. In the study area, Eurekan structures are characterised by easterly and south-easterly directed thrusts which involve different amounts of strike-slip. These thrusts incorporate Proterozoic to Mississippian rocks of the Ellesmerian Orogen, Mississippian to Late Cretaceous rocks of the Sverdrup Basin and latest Cretaceous to Paleogene syn-orogenic strata. Our structural restorations reveal that, besides the reactivation of Ellesmerian structures, the style of Eurekan deformation was significantly controlled by the tectonic inversion of structures related to Sverdrup Basin development (Figure 1).

During the Mississippian to Late Cretaceous, the structural evolution of the Sverdrup Basin was dominated by salt diapirs and extensional faults. The distribution and structural style of both the diapirs and the extensional faults were determined by the presence and extent of a Carboniferous salt layer at the base of the sedimentary succession. Diapirs were concentrated along the basin axis, where a thick Late Carboniferous salt layer was present. Generally, diapirs were associated with salt withdrawal minibasins that developed over autochthonous salt, except on southern Axel Heiberg Island, where the minibasins sank over an allochthonous salt canopy. Marginal areas of the basin, where no salt was deposited, were cut by Carboniferous to Jurassic extensional faults.

During the latest Cretaceous to Paleogene, Eurekan shortening resulted in the reactivation of earlier structures and subsidence in the Sverdrup Basin ended. The style of tectonic inversion was controlled by the amount of salt: extensional faults at the basin margin were inverted whilst in the basin centre the diapirs were squeezed and the minibasins continued subsiding. Some of the diapir walls formed thrust-welds that merged into larger thrusts detached at the base of the salt layer. Therefore, both the current thrust geometry and distribution were inherited from the Sverdrup Basin original structural framework. Tectonic inheritance explains both the anomalous width of the orogen and the younging of exposed statigraphic units towards the foreland (towards the basin centre) as well as the vergence of the orogen towards Greenland. In addition, the presence of salt at the base of the sedimentary succession helps to explain the total absence of a metamorphic zone.

Previous work in the area focused on differentiating Ellesmerian from Eurekan structures, which was important to constrain the regional tectonic framework. However, our study demonstrates that the style of Eurekan deformation on the Canadian Arctic was determined by the original structural framework of the Sverdrup Basin. This highlights the importance of tectonic inheritance in the development of thrust and fold belts.

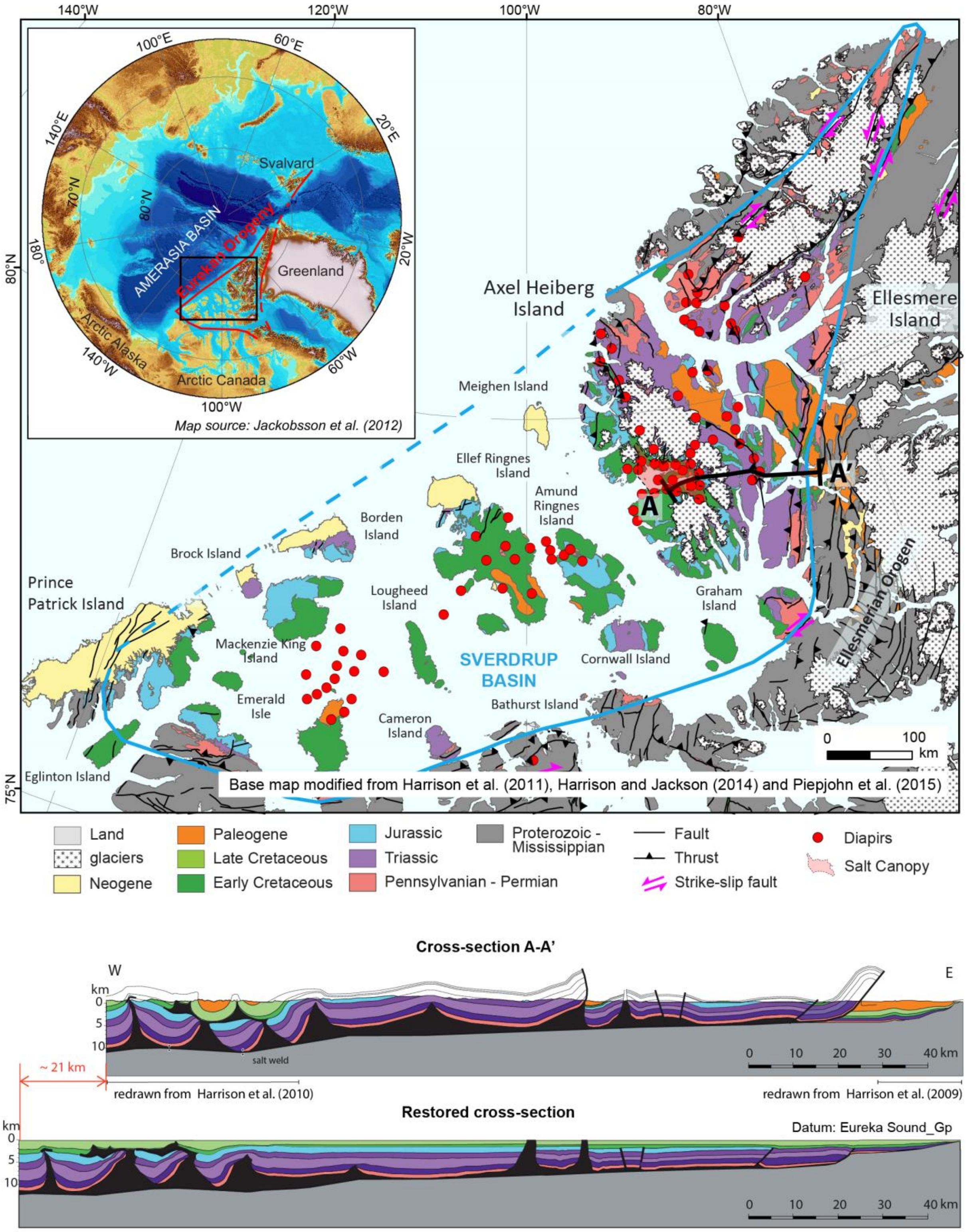

Figure 1. Above: Geological map of the Eurekan Orogen in the Canadian Arctic Islands, showing the location of the cross-section below. Inset map shows the extent of the Eurekan Orogeny (in red) and the location of the studied area within the Arctic Ocean. Below: Cross-section and restoration depicting the structure of Ellesmere and Axel Heiberg islands. The horizon used as the datum for the restoration marks the onset of the Eurekan Orogeny.

NOTES:

Thursday 2nd November 2017

Session Seven: South America

An Integrated Approach to De-Risking Exploration and Appraisal in Structurally Complex Fold and Thrust Belts: Application to the Incahuasi Field (Bolivia)

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The South Sub-Andean Zone of Bolivia is characterized by east-verging thrusts, detaching within Silurian and Devonian series, and associated to a series of N-S to NNE-SSW regional anticlines and synclines holding large gas accumulations. This paper is a case history of the multi-TCF Incahuasi discovery, and how an integrated, multi-disciplinary approach allows a progressive improvement in the understanding of the trap geometry, reducing the uncertainty during exploration and field appraisal.

While-drilling structural interpretation and biostratigraphic analyses suggested that the discovery well, prognosed mainly by surface geology and targeting the top of the Huamampampa Formation as a bright discontinuous seismic reflector on a 2D seismic test line, was drilling the overturned limb of the surface anticline instead of penetrating the core of the structure. The top reservoir was found deeper by a side track well.

The appraisal wells all contributed to progressively constrain the complex geometry of the trap, whilst leaving several possible geometric interpretations of the reservoir structure. The Huamampampa Formation is repeated and overturned by a series of thrusts that increase the internal complexity of the field. These results also confirmed that the shales of the Icla Formation behave as an effective detachment below the reservoir, contributing to the structural complexity of the field.

A calibrated/constrained inversion of 3D Magnetotelluric acquisition performed over the structure shows the near top Huamampampa Formation resistivity anomaly plunging to the north, which helps to identify the possible structural spills. In map view, the variation of orientation, provides information on local bends of the target and hence is an important element to be considered for optimizing future appraisal wells.

The Incahuasi discovery provided the opportunity to test the validity and efficiency of many geological and geophysical tools, while noting their limitations in a context where only a few hundred meters of horizontal error can lead to missing the reservoir and trap.

NOTES:

Structure and Hydrocarbon potential of the Northern Bolivia Subandean thrust belt (Beni Basin)

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Despite the presence of a widespread Late Devonian world-class source rock and several non-commercial discoveries, the northern Bolivian Beni Basin and its associated fold-and-thrust belt is one of the most under-explored Sub-Andean basins in South America. In order to address the petroleum potential of the region, we carried out an integrated study based on surface and sub-surface data (geological maps, field data, stratigraphic sections, 2D seismic sections and well data) to address the tectono-stratigraphic settings and the kinematics of thrusting of the Northern Bolivian Subandes (NBS). The potential plays and the main exploration risks of the NBS are also discussed.

We first constructed several stratigraphic correlations and several distribution maps of key stratigraphic units in order to constrain the presence and quality of each sedimentary formation across the NBS. The revised distribution maps show that the Devonian (Tequeje-Tomachi Formation) and Carboniferous-Permian (Retama Group and Copacabana Formation) source-rocks are present over most of the Sub-Andean Fold-and-Thrust Belt (Subandean Zone or SAZ), whereas the Silurian (Kirusillas Formation) and Late Cretaceous (Flora Formation) source-rocks are limited to the southern or northern segments of the SAZ. Present-day distribution of the main reservoirs, corresponding to the Jurassic (Beu formation), the Late Cretaceous (Eslabón Formation) and the Oligocene to Miocene (Bala Formation) sandstones have also been revised and show global widespread distribution in the whole NBS.

Then, we provide two new balanced cross-sections constructed through the northern sector and the central sector of the NBS. In both sections, shallow thin-skinned deformation affects the Devonian to present sedimentary cover. Contrary to the northern section, the section through the Central sector includes Silurian strata. Unlike the central sector section, the northern section involves Ordovician duplex structures in depth. High-angle faults involving the basement are interpreted in both sections and are thought to have played an important role in the recent (Plio-Pleistocene?) vertical uplift, exhumation and erosion suffered by the area.

Tentative sequential restorations of both sections are provided and suggest a first period of forelandward-migrating thin-skinned deformation during the Miocene. This is followed by a Plio-Pleistocene period of vertical uplift and exhumation along the eastern edge of the Eastern Cordillera and the SAZ.

Based on both the stratigraphic and structural reviews of the study area, the potential plays and the main exploration risks of the NBS are discussed. Analysis indicates that the key unexplored plays in this area are Paleozoic reservoirs in sub-thrust locations in the internal SAZ. Hangingwall and sub-thrust plays in the external SAZ have already been tested without commercial success.

The lack of adequate seismic image across the SAZ is a major limitation in defining structures at depth. However, the presence of these structures is reasonable and consistent with the structural understanding of the area. The risk associated to these structures is mainly due to limitations in data, which preclude their precise definition. Other uncertainties are: a) the possible absence (by erosion and/or non-deposition) of the Paleozoic units in the SAZ; and b) the timing of formation of the Subandean structures versus the timing of generation of the hydrocarbons in the area.

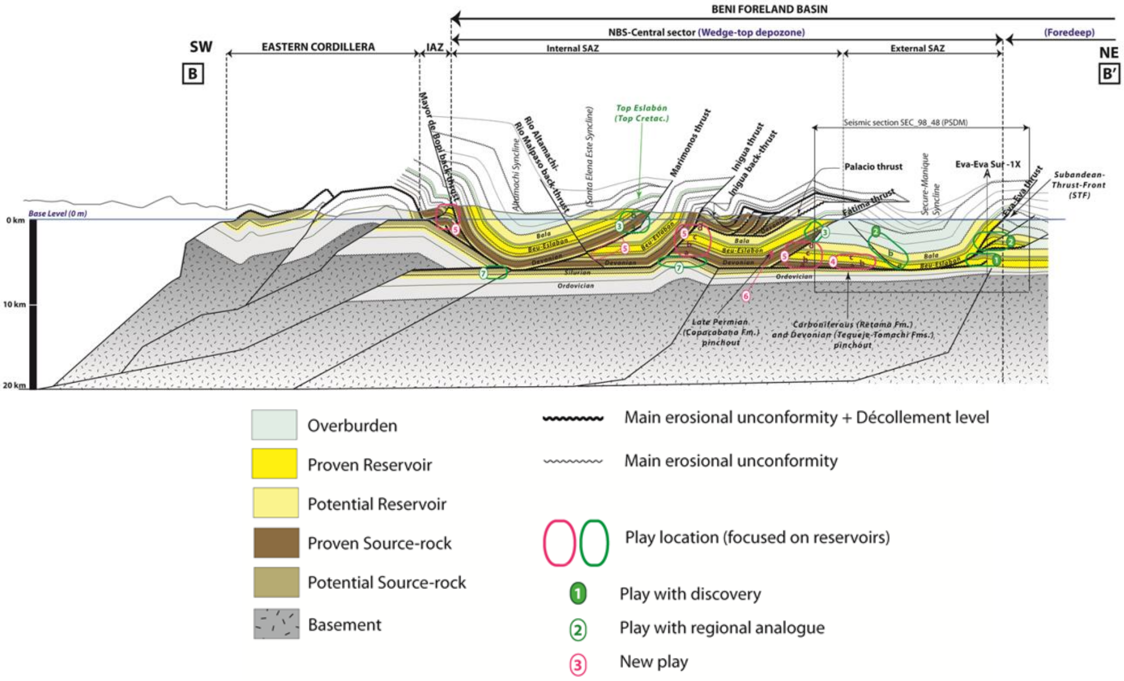

Figure 1: Secure play cross-section (Central NBS).

NOTES:

3D Structural Style along a TRANSFER zone, Southern Subandean Zone, Bolivia

Willy Gil1, Olivier De Mena[1], Rodrigio Limachi[2], Gonzalo Zamora[1] & **Massimo Bonora[1]**
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The southern Subandean ranges of Bolivia is a thin-skinned fold and thrust belt that have shortened through a Silurian to upper Ordovician detachment a ~10 km-thick stratigraphic pile of post-Ordovician to Neogene deposits. Hydrocarbon accumulations in this fold-thrust belt include a variety of plays, with reservoirs ranging in age from Devonian to Neogene. Giant gas fields, however, are restricted to deep structures involving Devonian reservoirs.

The present work shows balanced and forward modelled structural sections along the Mandiyuti and Iñiguazu Ranges from the Margarita field in the north to the Iñiguazu wells in the south. Seismic data is challenged by geological and topographical conditions and left almost blind the area of interest; therefore exploration for this play relies on structural models. The challenge of the present work is to build a reliable 3D model to explore the area located in a relay zone between two major fault systems.

While the typical Sub Andean deep structures are characterized as tight fault-related folds, the deep geometry of the Margarita trend is formed by few imbricated thrust sheets developed above the Mandiyuti thrust system. The thrust system basal detachment is within the older Silurian shales of the Kirusillas Formation, while upper detachments in the younger Devonian Los Monos Formation.

The transfer zone between the Mandiyuti and Iñiguazu thrust faults is clearly seen in the geological maps and interpreted as lateral fault system.

In this study we perform several systematic cross sections, tied to detailed surface geology. These cross sections show the interference between the northern Mandiyuti thrust, responsible for the uplift and structuration in the Margarita field with the southern Iniguazu thrust, responsible for the Suaruro Range. The 3D model illustrates how the Margarita trend is plunging to the south due to the Mandiyuti thrust loosing displacement and realying with the southern Iniguazu thrust.

These two structures were formed in sequence and grew laterally until the linkage into a single surface structure. As deformation continued a new thrust developed below these two, the San Alberto Thrust, which transfer deformation to the eastern range and created a footwall structure, below the Mandiyuti thrust.

This works allowed building a structurally consisted 3D (figure1) model that shows the interference between the two thrusts fault systems and helped identifying new exploration potential to the south of the Margarita Field.

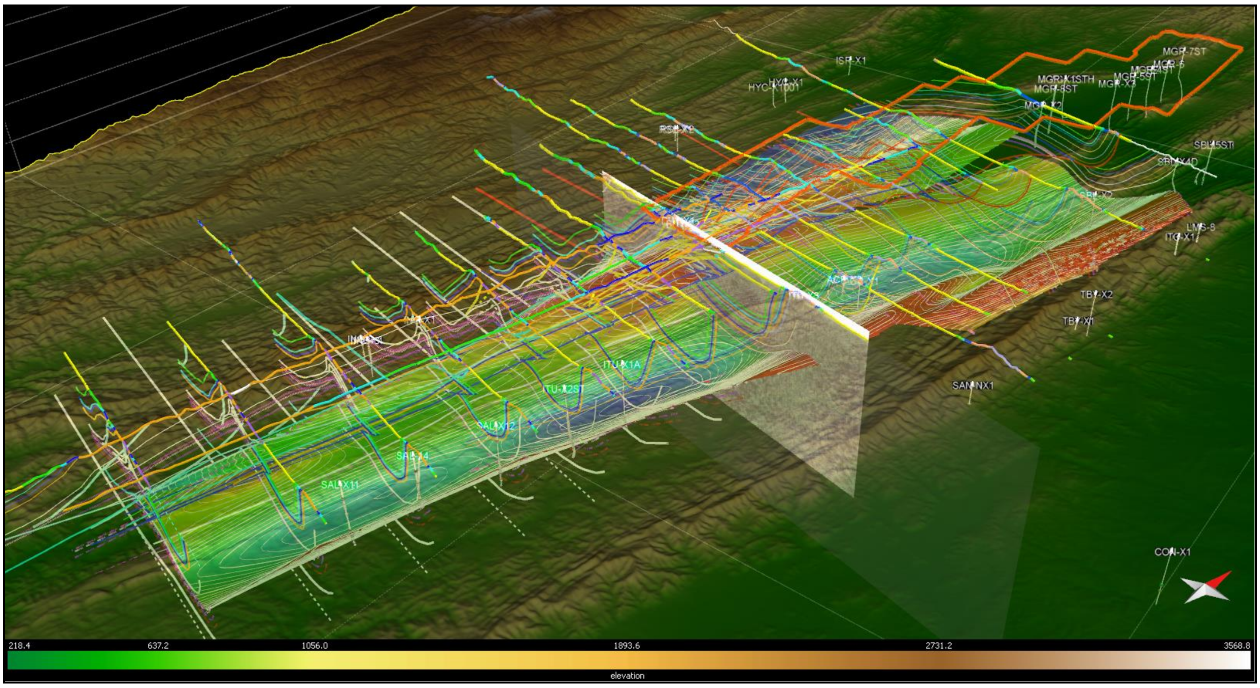

Figure 1: Integrated 3D structural model

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Thursday 2nd November 2017

Session Eight: Thermochronology

Using thermochronometry to date thrust related exhumation in the Western Taurides fold-thrust belt (Turkey)

McPhee, P.J.[1]**,** van Hinsbergen, D.J.J.[1], Reiners, P.[2], Thomson, S.[2]
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Southern Turkey contains the well-known, but structurally poorly studied Taurides fold-thrust belt. We show the first balanced cross section through the Taurides, in which identify a two-stage structural evolution. The first stage involved thin-skinned thrusting, which is straightforwardly related to accretion during Paleocene-Eocene continental subduction. The second stage is characterised by thick-skinned thrusting which refolded the pre-existing thin-skinned belt, and propagated towards the foreland. This second stage occurred almost orthogonally to regional plate convergence, and the driving force remains enigmatic.

The thin-skinned phase of the Taurides formed as a duplex, below a long-lived roof thrust, at a subduction plate contact, between the converging African and Eurasian plates. The duplex rotated clockwise during or after accretion so that the thrusts became oblique to Africa-Eurasia convergence. By Late Eocene times, the subduction thrust at the base of the duplex jumped structurally below the Taurides, which were abandoned in the overriding plate of the subduction zone.

The minimum age of deformation in the thick-skinned phase is constrained by deformation of Miocene to Pliocene age sediments. The onset of thrusting however is poorly constrained as there is no depositional record between the Middle Eocene and Lower Miocene, and Miocene sediments in the area were deposited onto already eroded and deformed rocks of the Taurides, including deeply exhumed clastic rocks that contained zircon and apatite grains.

Proposed causes of the thick-skinned thrusting conceptually rely on well-dated regional tectonic events such as the onset of Anatolian extrusion (~11-5 Ma), the onset of extension in the western Anatolia (~25 Ma) or the rotations of SW Anatolia during formation of the Hellenic orocline (~15-5 Ma). The links of these events to the Central Taurides are critically depending on the age of onset of thick-skinned thrusting of the Taurides.

Here, we present the first apatite U-Th-He (AHe), apatite fission track (AFT), and zircon U-Th-He (ZrHe) ages from sedimentary rocks of the Western Taurides fold-thrust belt. We place the sampling sites in a structural context, within the framework of our first orogen-scale cross-section. We use these data to demonstrate cooling, and evaluate connections to the thick-skinned thrusting restored in our cross-section. We then discuss the possible dynamic causes of the Neogene shortening in the Central Tauride mountain range.

NOTES:

Quantifying vertical movements in fold and thrust belts: subsidence, uplift and erosion in Kurdistan, Northern Iraq

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Traditional structural analysis in fold and thrust belts has focussed on quantifying horizontal movements. In this study we show the importance of quantifying vertical movements using a case study from Kurdistan. The subsidence history of this area can be determined by analysis of the stratigraphic record from deep exploration wells. A phase of thermal subsidence from Early Triassic to middle Cretaceous (tectonic subsidence >1 km) was followed by incipient collision and the onset of flexural subsidence in the Late Cretaceous (tectonic subsidence >0.5 km). The main phase of continental collision during the Neogene resulted in development the Zagros fold and thrust belt; the amount of uplift at individual anticlines can be estimated from their amplitude (typically 1-2 km), but regional cross-sections indicate that 2 km or more of additional basement-involved uplift is present to the north of the mountain front. The timing of basement-involved uplift is interpreted to be coeval with deposition of a Pliocene-Quaternary growth sequence adjacent to the mountain front. Subsequent erosion can be estimated from vitrinite reflectance and seismic reflection data; these estimates show a similar pattern with maximum erosion in the mountains to the north of the mountain front (>1.5 km) and lesser erosion in the adjacent foreland basin (typically <0.7 km). The results provide a quantitative understanding of subsidence, uplift and erosion, and have been used to evaluate prospective areas for hydrocarbon exploration.

NOTES:

The Polish-Ukraininian hydrocarbon province of the Carpathians fold and thrust belt: constraints from balanced cross-sections coupled with low-temperature thermochronometry

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[2] *Department of Geosciences, University of Padua, Italy*
[3] *Polish Geological Institute-Carpathian Branch, Poland*
[4] *Jackson School of Geosciences, The University of Texas, Austin TX, USA*
[5] *Institute of Geophysics, Polish Academy of Science, Poland*

The Polish Carpathians represent one the earliest-discovered hydrocarbon provinces in the World. They are located in the northernmost, W-E–trending segment of the more than 1500 km long, curved Carpathian orogen (Fig. 1). In this contribution, a new interpretation for the tectonic evolution of the Polish-Ukrainian Carpathians is provided based on the construction (carried out with Move software) of a series of balanced and restored cross-sections (Fig. 2), validated by 2D forward modelling, coupled with a large thermochronometric dataset (apatite fission tracks and apatite and zircon (U-Th-(Sm))/He ages). The latter work included thermo-kinematic modeling using FetKin, a finite element solver that takes as input a series of balanced cross-sections. The software solves the heat flow equations in 2D together with the predicted thermochronometric ages, which can be compared with the measured data. Moreover, the spatial distribution of burial depths, cooling ages and the rate of exhumation were correlated with heat flow, topographic relief, crustal and lithospheric thickness. This process allowed us to obtain the cooling history along each balanced cross-section and test the response of low-temperature thermochronometers to the changes in the thrust belt geometry produced by fault activity and topography evolution. Our sequentially restored, balanced cross-sections, showing a mix of thin-skinned thrusting and thick-skinned tectonic inversion involving the reactivation of pre-existing basement normal faults, effectively unravel the tectonic evolution of the thrust belt–foreland basin system.

The non-homogeneous burial and exhumation history unravelled by our work suggests that different exhumation processes controlled the Neogene stages of the Carpathian evolution. In particular, the data point out a significant along-strike variation of exhumation mechanisms in the Polish-Ukrainian fold and thrust belt, ranging from Early Miocene syn-thrusting erosion to the west, to post-thrusting tectonic denudation in the central sector, to post-thrusting exhumation associated with uplift of the accretionary wedge to the east. The effective integration of structural and thermochronometric methods carried out in this study provided, for the first time, a high-resolution thermo-kinematic model of the Polish-Ukrainian branch of the Carpathians fold and thrust belt.

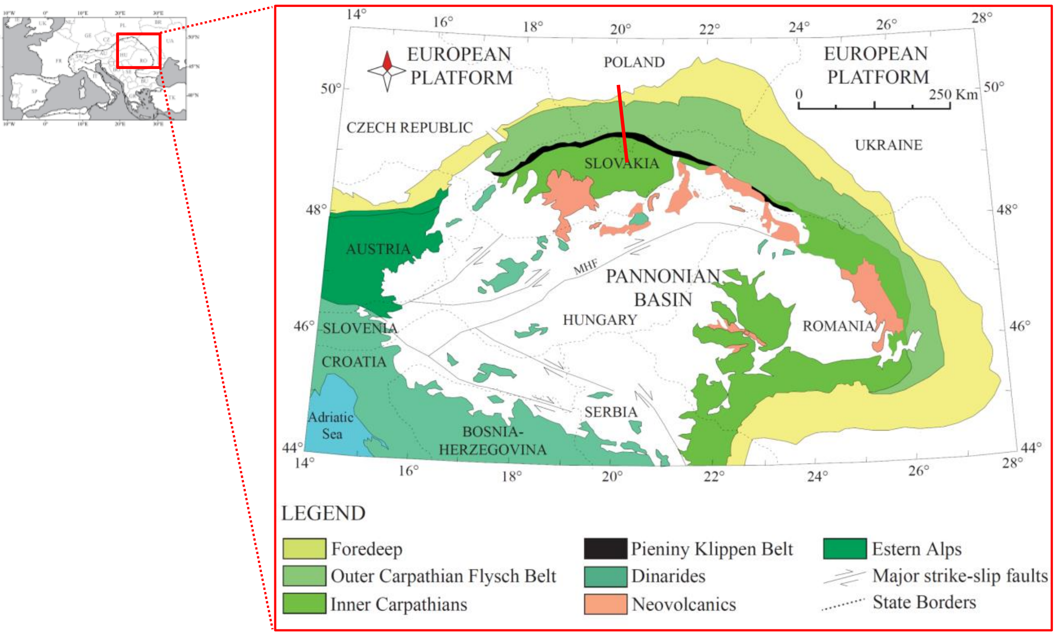

Fig. 1. Tectonic sketch map of the Carpathian orogen, showing location of the cross-section of Fig. 2.

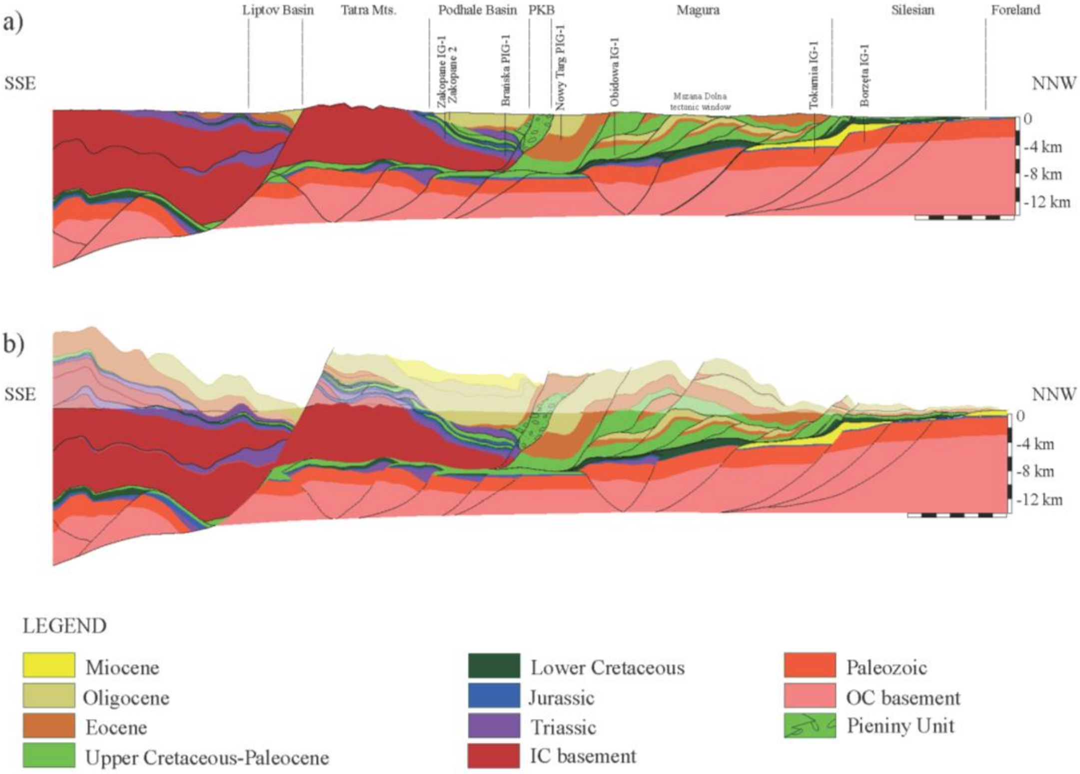

Fig. 2. (a) Balanced cross-section through the Polish Carpathians at the longitude of Cracow. (b) Balanced cross-section including reconstructed eroded portion.

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Thursday 2nd November 2017

Session Nine: Petroleum Systems

Modelling complex hydrocarbon migration and accumulation in fold and thrust belts.

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Fold and thrust belts contain significant global hydrocarbon resources with as much as 750 billion barrels of oil equivalent estimated to reside within the largest 30 or so belts. However, they are typically perceived as difficult, high risk environments in which to explore for hydrocarbons.

Shortening typically results in structurally complex subaerial belts that are characterised by significant uplift and erosion, resulting in an imperfect stratigraphic record of structural growth that is difficult to interpret, and a characteristically rugged terrain that makes data acquisition – and indeed any geological operations – extremely challenging and expensive. This intense structuration typically leads to smaller structural wavelengths and increasing compartmentalisation within traps that are formed late and often reactivated through time. Progressive deformation also brings fundamental changes in the loci of maturity and charge focus through time, making accurate petroleum systems modelling extremely difficult.

This study addresses the latter of these issues by attempting to model the structural, thermal and petroleum systems evolution of a section through the Zagros fold and thrust belt. In the absence of good quality seismic data, a present day section was created from published surface geology and isopach maps using classic cross-section construction techniques. Computational software was used to restore this section to pre deformation. A basic mechanical restoration was used to create a third, intermediate, syn-deformation section. All three sections were recreated in petroleum systems modelling software and populated with age, lithology and thermal boundary conditions to create a 2D basin model, with each time step forward modelled for hydrocarbon generation, migration and accumulation. The software has limited ability to translate rock volumes and hydrocarbon accumulations from one 2D time step to the next.

Although restricted to three semi-linked 2D time steps, the results of this modelling represent a significant step forward in our understanding of hydrocarbon migration and accumulation within the Zagros fold and thrust belt. Results suggest that significant resources may remain within the structures along the front of the main belt. Hydrocarbons are modelled to have migrated in to – and accumulated within - both hanging wall fault bend fold structures and sub-thrust traps. Perhaps most excitingly, these relatively simple models allow us to explore the ramifications of uncertainties associated with key variables such as the distribution of source rock lithologies and potential sealing horizons.

NOTES:

A New Kinematic Tool for Petroleum System Modeling in Complex Structural Settings: Application to the Foothills Region of Kurdistan

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Petroleum system modeling is today recognized as a critical step in exploration workflows. However, fold and thrust belt regions are particularly challenging as most of basin modeling tools do not accurately manage the combination of lateral and vertical tectonic displacements. In basins where hydrocarbon expulsion from source rocks is prior or simultaneous to compressive tectonics, there is a need for a more accurate modeling approaches integrating active faulting, folding and fluid flow (hydrocarbon and water). In these complex areas indeed, the reconstruction of basin burial and geometry, faults connectivity and fluids movements through time implies accounting for the actual horizontal deformation, and requires an appropriate methodology for explorationists. New workflows linking structural-restoration packages to basin modeling tools have thus emerged in the industry in the past years, albeit with strong limitations which impact their operational use.

This communication discusses these limitations from a practical point of view and presents a new workflow intending to overcome these problems with a new 2D kinematic tool designed specifically for basin modeling purposes. Honoring both structural geology and basin modeling constraints, this tool aims at producing easily and rapidly consistent geological scenarios to feed new generation basin simulators. In addition to classic geometrical reconstruction methods, a new mechanical engine taking into account compaction and rock mechanical properties is available along with several deformation models. The ability to provide geologically valid results in all structural contexts and an intuitive definition of deformation parameters to optimize productivity constitute the core of the tool. Dynamic mesh deformation is guaranteed through the model topology preservation as restoration work progresses.
An application case from the Kurdish foothills is used to illustrate this new technology and its ability to quickly generate tens of paleo-sections continuously deformed for basin modeling simulation. Foothills are typical regions where classic approaches do not apply and where explorationists use, when possible, time-consuming methodologies to evaluate petroleum systems. This example shows to what extent this new approach allows easily increasing basin models structural complexity while meeting the industrial operations constraints, both in terms of execution time and results quality.

NOTES:

Modelling Trap integrity in a Deepwater Toe thrust: The role of geo-history

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One of the key uncertainties in trap analysis is the geo-history and how it affects charge and trapping of hydrocarbons. The static view we observe today cannot always be used to suggest a trap has been effective in the past when active charge may have occurred while burial, stress regimes and pore pressures may all have been markedly different. This is particularly the case for active deep-water toe thrust plays where recent rapid burial and/or uplift related to structural growth can play havoc with trap integrity predictions. This presentation attempts to model the geo-history of a deep water thrust anticline trap using simple concepts of burial, compaction, isostasy, structural elevation changes and erosion/mass wasting to try and forward model a present-day structure and thus shed light on how trap integrity may have evolved through time (Figure 1). Focus is given to the pore pressures within a target reservoir interval. The formulation of the model has been outlined in Kreuger & Grant (2011). The model is 1D and looks at two locations to describe the thrust evolution: the crest of the growing anticline and the adjacent deep trailing syncline. Together these enable a deterministic structural growth model to be created that can enable estimation of pore pressures in an evolving high relief toe thrust trap, employing the centroid model for pore pressure prediction. Comparison of capillary and mechanical top seal control on trapped hydrocarbon column heights is linked to the burial and compaction history of the anticline and used to recognise if, and when, a toe thrust anticline can offer a viable trap for migrant hydrocarbons. Application of this deterministic model to recently drilled toe thrusts will be discussed and results compared to model predictions.

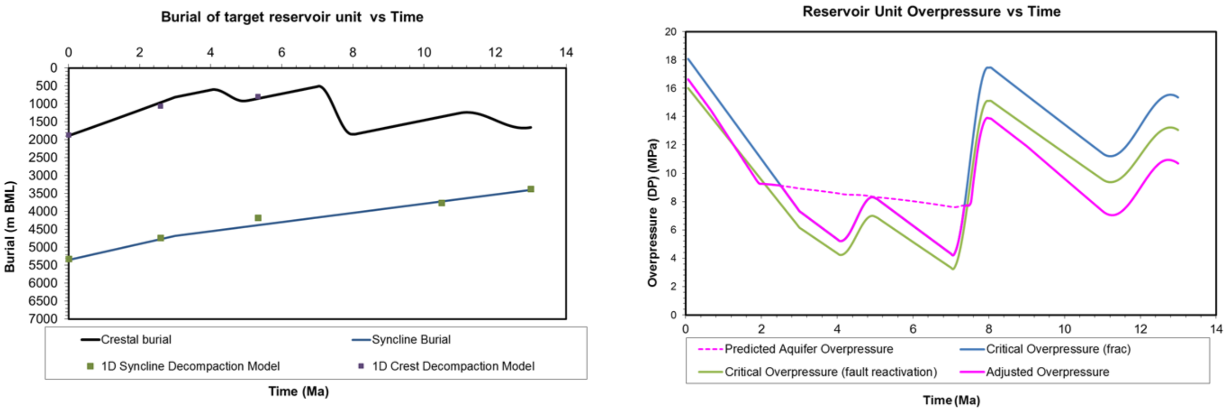

Figure 1. a) Example output from a thrust growth model showing how crest burial fluctuates due to uplift and erosion while the adjacent syncline shows monotonic burial. Comparison between the forward model and 1D back stripping is shown. Onset of thrusting at 13Ma. Present day at 0Ma. b) Modelled overpressure vs time for target reservoir section. Uplift and erosion of the anticline crest are associated with depressurisation as pore pressures adjust to fracture pressure only to be re-established due to post tectonic burial. Trap integrity is compromised from 8Ma onwards due to loss of mechanical seal integrity. The toe thrust is not predicted to offer a good trap.

Kreuger, S.W & Grant, N.T., 2011. The growth history of toe thrusts of the Niger Delta and the role of pore pressure. In K. McClay, J. Shaw and J. Suppe, eds, Thrust related folding. AAPG Memoir 94, 357-390.

NOTES:

Poster Presentation Abstracts

Day One

Review of Papuan-Aure Fold Belt Structural Models (PRL15), Papua New Guinea, based on structural forward modeling, recent well results and surface analysis

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[1] IPRA-LFCR, UMR 5150 CNRS, Université de Pau et des Pays de l'Adour, Pau Cedex, France
[2]Total SA, CSTJF, Avenue Larribau, 64000 Pau (France)
[3]Total Asia Pacific, PNG Group, Singapore

The PRL15 block containing the Elk-Antelope multi-Tcf gas field, discovered in 2008, is located in a complex syntax deformation zone at the junction between the ENE-WSW trending Papuan and the NS-trending Aure Fold Belt. The Elk-Antelope reservoir is constituted of thick Miocene carbonate platform deposits later deformed in a thrust sheet system by Plio-Pleistocene Papuan compression.

Inherited WNW-ESE Mesozoic rift structures as well as several NE-SW Australian Basement regional lineament structures (i.e. the Aure lineament) play an important role on later compression structural style and resulting fold geometries.

In addition, the rheological variations (Miocene carbonate series interbedded between Mesozoic and Plio-IV shale series acting as efficient decollement level) act as a major factor controlling the tectonic evolution and make it difficult to relate shallow structural style with that in the deeper section.

Consequently, inherited structures, rheological variations combined with poor and sparse seismic imagery led interpreters to propose contrasted structural styles for Antelope and peri-Antelope area (PRL15) thus impacting thrust-sheet geometry and carbonate facies distribution (Shallow versus Deep shelf facies distribution relative to displacement and paleobathymetry).

Major retained structural styles are:

- Pure thin-skinned deformation with low angle thrusts using the well-known Cretaceous Ieru detachment. This model has no direct relation between preexisting fabric regarding the location of carbonate platform.
- Pure thick-skinned deformation which involves inversion and short-cutting of pre-existing listric normal faults.
- Mix of thin-skinned and thick-skinned deformations using both the Ieru decollement level and involving listric normal fault inversion.

In order to discriminate between these structural models, this study presents a forward modeling approach that allow us to reconcile the result of recently-drilled wells (FMI, dip meter…) along with regional deformation at depth (cumulative shortening rate) and surface (remote sensing mapping based on radar imagery). Present understanding favors a mixed thin-skinned and thick-skinned model related to two distinct and non co-axial and diachronic compressional phases: 1/ Papuan FB (NS-compression?) and 2/ Aure FB (EW-compression?).

An Insight into the Lesser Himalayas of Pakistan for their hydrocarbon potential

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Part of the foreland fold and thrust belt south of the Main Boundary Thrust Fault (MBT) which is also knows as Sub-Himalayas in Pakistan has a long history of hydrocarbon exploration. These southern basins have been well explored and understood for their subsurface structural style and potential trap geometries. The Lesser Himalayas which include the areas north of MBT have long been ignored for their hydrocarbon potential because of poor understanding of the structural style and tectonic setting of the area.

The current research aims to create a balanced structural model based on the surface structural patterns on the geological map for the presence of the potential hydrocarbon traps. Five structural traverses were used to collect the surface data and then the structural cross sections were produced by extrapolating the ground data into the subsurface based on the geological map created at 1:25000 scale. 3D models were generated between the cross sections to generate an internally consistent geometry to understand the presence of structural traps in the research area. Cross sections were sequentially balanced to validate the model and remove geometric errors as well as to understand the sequential evolution of the model.

Fault patterns on the geological map show that fault lines are folded along with the surface anticlines which signifies the presence of a folded thrust sheet in the subsurface. The presence of the horizontal thrust windows at places also proves that the thrust faults become shallow dipping in the subsurface. The lesser Himalayas cannot be simply explained by the imbricate thrust faults steeply joining the basal decollement in the subsurface because the Jurassic package is well exposed on the surface. The depth of the basal decollement in the sub-Himalayas has been marked on the seismic data between -8000 to -10000 meters while the thickness of the platform sequence from Eocene on the top to Triassic rocks at the bottom is almost 4000 meters. Therefore, the whole stratigraphic package which is consistent between the Sub-Himalayas and the Lesser Himalayas needs to be repeated several times by putting long traveled thrust sheets before the decollement is reached. Based on the map relationships, ground data and knowledge from the sub-Himalayan fold and thrust belt, it can be concluded for the lesser Himalayan fold and thrust geometry that long traveled folded thrust sheets repeat the stratigraphic package three times before the regional decollement is encountered. Cross section balancing shows 45% of the crustal shortening in the area which indicates that the depositional basin extends almost 100km north of the study area. 3D modelling results also show that potential hydrocarbon traps exist in the lower thrust sheets which fall around the drillable depth of around 5000meters and can be further validated by the seismic and drilling data.

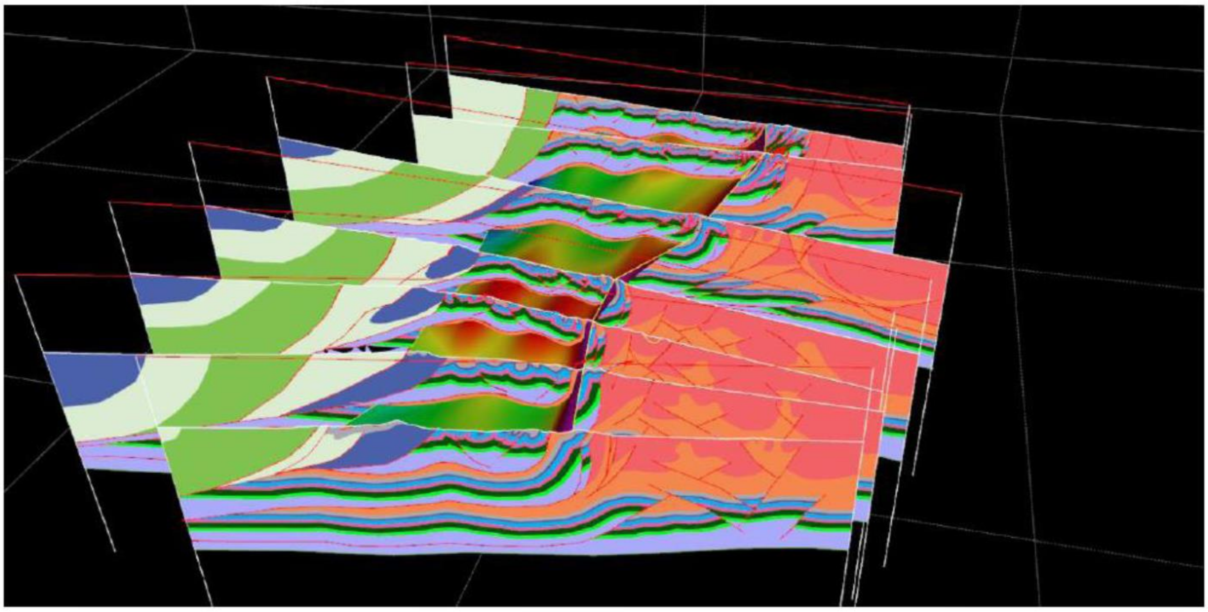

Figure 1 Showing the northeast view of the project area along with the 3D model

Estimating the hidden layer parallel strain (LPS) in Brunei deep water fold-thrust belt

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Due to the existence of layer parallel strain (LPS), apparent shortening derived from the restoration of macroscopic structures (e.g., folds, thrusts) in a geological cross section is typically cited as a minimum estimate. Several deformation mechanism are proposed to account for the LPS, among them are porosity reduction, lateral compaction, pressure solution, diagenesis, and etc. As the LPS is often invisible from the current state of deformation, to evaluate its significance on the crustal shortening becomes very challenging.

To address this issue, we applied seismic interpretation, flexural-slip restoration and area balancing reconstruction to 3 high-resolution seismic profiles through Brunei deep water fold-thrust belt. Through integrating the two categories of shortening results, we estimated the LPS of studied area, analysed its timing and mechanism, and discussed its implication on subsurface prediction and hydrocarbon exploration. Our new results show : (1) A considerable portion of LPS is recognized across Brunei fold-thrust belt, it accounts for 2.9%-4.2% of overall deformation which is greater than 0.9%-3.5% of strain taken by apparent shortening through thrusting and folding; (2) The LPS decreases from deep levels to shallow levels as longer bed length is preserved by thrusting at the depth; (3) Two distinct stages of strain accumulation involve the evolution of deep water fold-thrust belt : a) the initial LPS through the reduction of porosity and volume loss after gravitational loading and structural compaction, and b) the subsequent apparent shortening through the formation of folds and thrusts; (4) The bed-length doesn't remain constant during the deformation, the application of theoretical fold-thrust model to predicting subsurface structure and reservoir volume should be corrected with the estimated LPS.

Various uncertainties involve in this analysis, among them are seismic interpretation, approximation of regional and detachment location. Future efforts should aim to minimize these uncertainties in order to better quantify the LPS in a geological cross section.

Comparison between two DWFTBs: the Outer Tuscan Nappe (Northern Apennines, Italy) vs. offshore Sabah (NW Borneo)

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Fold-and-Thrust Belts occur worldwide in a variety of tectonic settings. Most of them develop in deepwater environment (Deep Water Fold-and-Thrust Belts, DWFTBs), at both continental passive and active margins, driven by gravity (near-field stresses) and tectonic forces (far-field stresses) respectively (Morley et al., 2011). Some margins entail a mixed-mode, where both the stresses act concurrently (Morley et al., 2011).
This study aim to compare the kinematic and mechanic evolution of two different examples of DWFTBs: i) the presently exhumed (i.e fossil) Outer Tuscan Nappe (Italy) and ii) the modern (i.e. active) Sabah fold-and-thrust belt (Borneo).

GEOLOGICAL FRAMEWORKS

The Outer Tuscan Nappe (OTN) is an imbricate thrust system in the Northern Apennines of Italy, emplaced during the Early Miocene in the framework of the collision between the continental lithosphere of the Adria microplate (a promontory of the African plate; e.g., Reutter et al., 1980) and the already formed Alpine orogeny (Barchi, 2010).

It consists of two domains (i.e. Ligurian and Tuscan domains) piled one above the other, stacked above the foredeep deposits, made up by syn-tectonic turbidites. The Ligurian Domain comprises the units from the Jurassic ophiolites up to the Early Eocene flysch deposits (Marroni et al., 2001), while the Tuscan Domain consists of several WSW-dipping imbricate thrusts involving the basal Eocene calcareous-marly Scaglia Toscana Fm. (the main detachment unit) and the overlain Chattian-Aquitanian arenaceous turbidites of the Macigno Fm. (Barsella et al., 2009). The post-kinematic units sealing the OTN are of marine origin, testifying the deepwater emplacement of the thrusts.
The Sabah DWFTB, (NW Borneo) developed since the Early Miocene, due to the subduction of the Proto South China Sea and the thinned passive margin of South China under the north Borneo. The collision caused deformation, uplift and crustal thickening (Franke et al., 2008). Deep marine sedimentation stopped and the Sabah orogeny began. The Early Miocene rise of the Central Borneo shed sediments to the surrounded basins, accreted within the still active DWFTB offshore Sabah (Hall et al., 2008).

The fold-and-thrust belt involves a pre-kinematic section consisting of deep marine shales and turbidity sandstones of Middle Miocene age (Cullen, 2010) and a syn-kinematic section consisting of Upper Miocene-Pliocene clastic shallow sediments.

DATA AND METHODS

Since the OTN is exhumed, the available data include surface data (1:50.000 geological maps) and subsurface data (seismic lines recorded in the 1980’ by the Eni oil company). In the case of the Sabah DWFTB the only available data include seismic reflection profiles recorded in the 1986 by BGR.

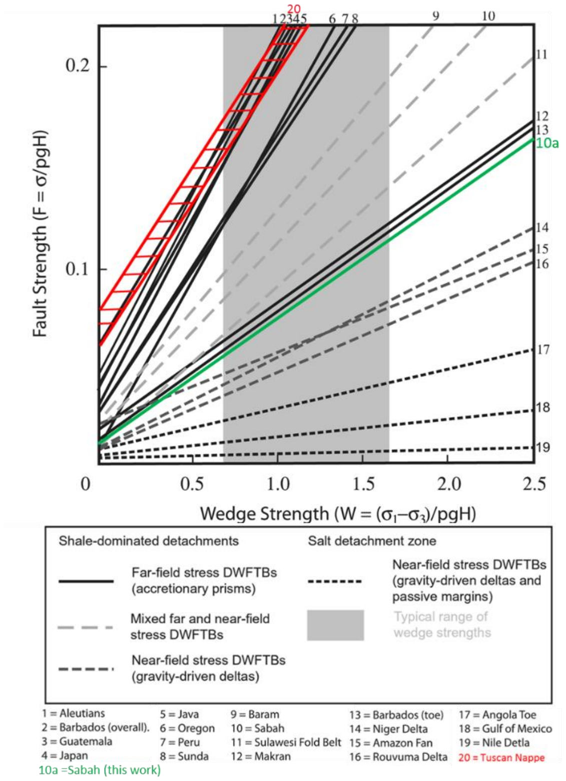
We have drawn three geological cross sections through the OTN, and we combined them with the depth-converted interpretation of the most representative seismic line in order to obtain a 33 km long integrated section, roughly parallel to the tectonic tansport direction. This section effectively shows the original wedge geometry, therefore we performed a kinematic analysis based on the 2D sequential restoration.

We interpreted four depth migrated seismic lines, crossing the Sabah DWFTB from N to S. The profiles are subparallel between each other and orthogonal to the strike of the compressive structures. The interpretation was based on the seismic stratigraphy proposed by previous works (e.g. Cullen, 2010; Hesse et al., 2009; Hesse et al., 2010b), but we interpreted a different basal detachment; we think that a deep detachment, above the Dangerous Grounds carbonatic Fm. is not in agreement with the thrusts geometry and the fold wavelenght. Therefore, we propose a shallower detachment based on the data from Franke et al. (2008).

Finally, for the both case-studies, we performed a speditive mechanic analysis, based on the critical taper modeling of fold-and-thrust belts as recently provided by King and Morley (2016). This method, let to define the range of fault strength and wedge strength associated to a given total taper angle, and therefore to classify the DWFTBs according to their driven stress type (i.e. near-field, far-field or mixed-mode).

RESULTS AND CONCLUSIONS

Our reconstruction of the OTN post-kinematic geometry entails a high critical-taper angle ($\alpha + \beta = 8°$), in agreement with the values typically reached by the Type 2, far-field stress-driven DWFTBs (see King and Morley, 2016). The internal shortening decrease toward the frontal thrust and is accommodated by 19 km of internal imbrication (42%). Based on the mechanic, and also on the kinematic, we propose to classify the OTN as a case of Type 2aii DWFTB based on the DWFTBs' classification of Morley et al. (2011).



The offshore Sabah origin is still debated due to its complex evolution related to the origin of deformation and sedimentation rate. From a mechanic point of view, based on the values from this work ($\alpha + \beta = 3.7°$) plotted in the Plot of Fault strength vs. Wedge strength, the offshore Sabah DWFTB falls in a particular area of the plot: the far-field stress DWFTB affected by high sedimentation rates. High sedimentation rates may have three different effects in wedge mechanics by influencing: 1) wedge geometry; 2) overpressure generation mechanisms, and 3) permeability of the wedge (King and Morley 2016).

The kinematic was also analysed, assuming a shallow detachment. The measured shortening, based on the displacement of each thrust sheet, has an average value between 13% and 16%, dependingly on the analysed section.

To reach some conclusions related to the origin and the evolution of the Sabah case study, we still need more information about the mechanics (relations between thrust geometry, amplitude and wavelength of folds and the basal detachment depth and geometry) and more precise values of shortening, obtained from a proper sequential restoration.

Influence of syn-tectonic sedimentary rate on the geometry and kinematic evolution of growing experimental wedges: Comparison to Kuqa fold-and-thrust system (NW China)

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Syn-tectonic sedimentation is one of the main parameters controlling the geometry and kinematic evolution of thrust wedges. Its influence has been extensively tested trough analogue models consisting of homogeneous sand packages that evidence the increase in the syn-tectonic sedimentary rate decreases the taper angle of the wedge and the number of thrusts forming it. Nevertheless, less attempts have been carried out in orogenic wedges involving evaporitic *décollements*, which are extremely common in natural case studies such as the Pyrenees, the Zagros, Sub-Andean belt or the Kuqa fold-and-thrust belt.

In this scenario, we analyzed the influence of syn-tectonic sedimentation in compressional wedges involving two interlayered weak *décollements*. The lower *décollement* is constant thickness and consists of a mixture of sand and silicone polymer that changes its mechanical properties laterally. The upper *décollement* is made of pure silicone polymer, it is syn-compressional (i.e., thins progressively towards the foreland) and its length (and consequently the overlap with the lower *décollement*) varies along-strike.

Using this set-up, three syn-tectonic sedimentary rates were tested and results were compared to a baseline model without syn-tectonic sedimentation. Experimental results evidence that increasing syn-tectonic sedimentary rates yield to a progressive change from (i) fold-and-thrust systems where shortening is distributed into several smaller wavelength ad closely-spaced folds and thrusts to (ii) fold-and-thrust systems where deformation is localized into few, higher wavelength thrusts located over *décollement* boundaries.

Our analogue models are comparable to the Kuqa fold-and-thrust belt, in the southern foreland of the Tian Shan Range (NW China) (Fig. 1).

This deformed basin involves two weak *décollements* interlayered in the stratigraphic sequence: thin Triassic and Jurassic coal layers and Cenozoic syn-orogenic evaporites. Shortening was accompanied by the sedimentation of thick syn-tectonic units that favored localization of deformation along the *décollement* pinch-outs. The geometry, distribution of deformation and kinematic evolution of the Kuqa basin are consistent with analogue models with higher sedimentary rates (Fig. 2).

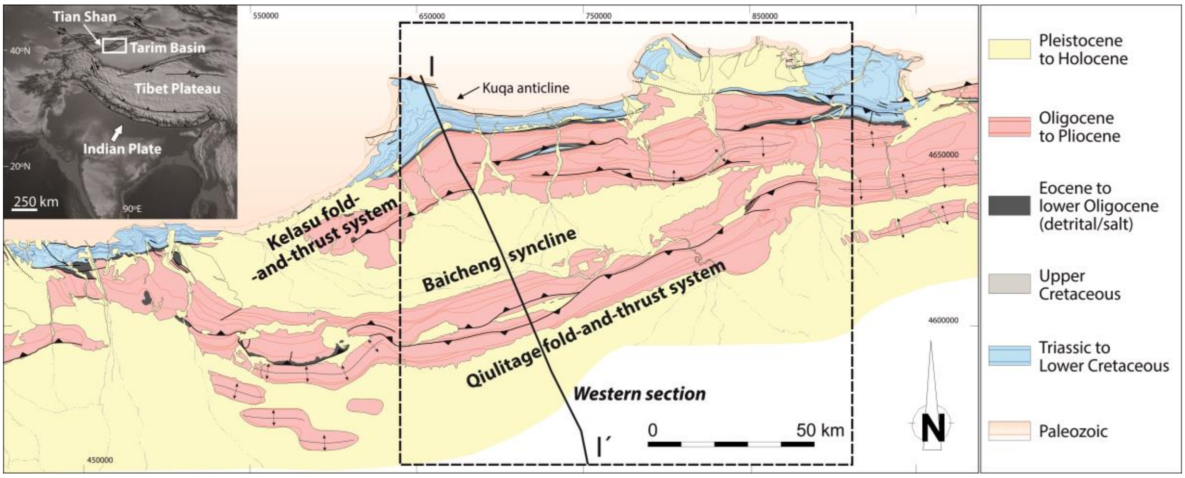

Fig. 1. Geological map of the Kuqa fold-and-thrust system. Black dashed line show the modeled area.

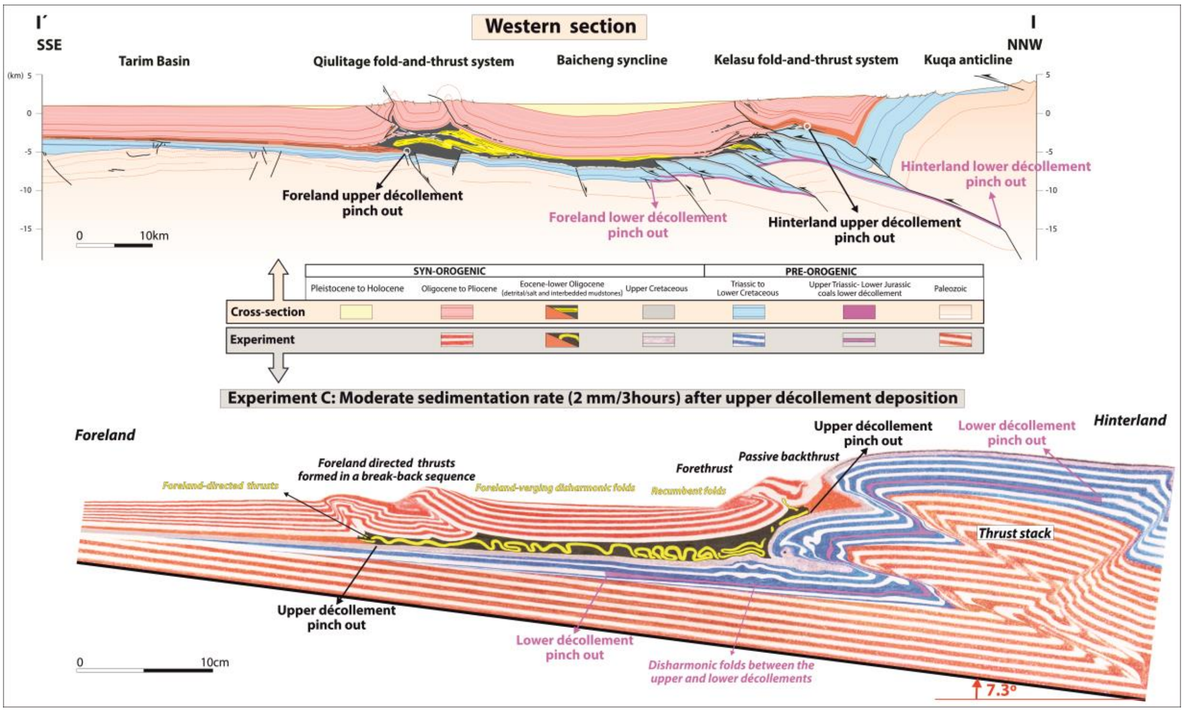

Fig. 2. Comparison to a seismic-based section (top) across the Kuqa fold-and-thrust system and the final geometry of experiment C in which an intermediate sedimentary rate was tested (bottom). See location of cross section in Fig. 1.

Structural style of a fold-and-thrust belt involving laterally-changing, multiple décollements: the Kuqa fold-and-thrust belt (NW China)

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The oil-bearing Kuqa fold-and-thrust belt is Cenozoic in age and is located in the southern foreland of the Tian Shan Range (NW China). It deforms a thick, continental sequence made of up to 12 km of Permian to Pleistocene units that unconformably overlie Paleozoic basement. This fold-and-thrust belt consists of a northern, E-W-trending fold-and-thrust system and a southern frontal structure, arcuate in map view, that are separated by an open syncline. To the south of the frontal structure is the scarcely deformed Tarim foreland basin.

Three regional cross sections have been constructed along the strike of the Kuqa fold-and-thrust belt. They are anchored to 2D, depth-converted seismic lines and incorporate new and previously published field and geological mapping data. The cross sections reveal the superimposition of three main fold-and-thrusts systems: (i) a lower one consisting of south-directed basement thrusts, (ii) an intermediate one detached along Triassic-Jurassic coal layers and (iii) an upper one detached on Eocene-Oligocene salt units. The rheology of the décollements in the intermediate and upper fold-and-thrust systems triggers different structural styles: thrusts with fault-bend hanging-wall anticlines are dominant above the coal whereas tight detachment folds, source-fed thrusts and diapirs are developed above the salt.

The cross sections highlight important lateral variations in the three superimposed thrusts systems whose interplay results in strong along-strike changes in the geometry of the Kuqa fold-and-thrust belt. The basement thrust system narrows to the east, unlike the fold-and-thrust system detached along Triassic-Jurassic units that is well-developed in the central and eastern cross sections (Fig. 1b, c) but dies out westwards (Fig. 1a). Overlying them, the salt-detached fold-and-thrust system is wider in the western sector where salt-cored anticlines cut by south-directed thrusts dominate (Fig. 1b, c). Beneath these structures, Mesozoic units remain almost undeformed except for several steeply-dipping normal and reverse faults. Salt-detached structures die progressively out towards the east (Fig. 1c).

The strong structural variation in the Kuqa fold-and-thrust belt results primarily from the spatial distribution, and thus the presence or absence of overlap, of the two main décollements. Coal layers are present to the north in the central and eastern domains but thin or disappear to the west and south, whereas salt units were extensively deposited in the western part of the fold-and-thrust system but narrowed to the east. Where these décollements overlap, a duplex system developed between them. The degree of overlap increases in the central cross section (Fig. 1b) where the number of thrust sheets forming the duplex is higher, and decreases to the east, where the number of structures is lower (Fig. 1c).

Variation in sedimentation patterns from internal to external basins in accretionary settings: examples from the East Coast Basin of New Zealand

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Concepts of evolution in deformation style in deep-water fold and thrust belts are evolving, giving rise to new perceptions of the controls upon and variation in sedimentation patterns across accretionary wedges. Understanding sedimentary pathways on active margins is important for unravelling the distribution of elements of the petroleum system, with deep-water fold and thrust belts often considered prospective, e.g., Sabah, NW Borneo. Here we investigate the stratigraphic development of an active trench-slope basin, the East Coast Basin of New Zealand, by integrating onshore and offshore studies of internal and external mini-basins, respectively. A key question is whether internal mini-basins are suitable analogues for their prospective external counterparts.

A digital outcrop data set was collected during study of the Miocene stratigraphy of internal mini-basins. These basins were mapped and examined in detail by logging of over 3000 m of dominantly deep-marine siliciclastic sediments at bed-for-bed scale (1:50) in lateral and longitudinal transects of the Akitio, Coastal and Tawhero mini-basins. Twenty-five heterogeneous lithofacies associations were identified, each of which represents a distinct architectural element. Biostratigraphic control was provided by GNS New Zealand, enabling the temporal distribution of outcropping elements identified to be constrained, and thereby providing calibration timings for sediment bypass and delivery of clastics to the downstream minibasins. Seismic scale elements include major lobe complexes in excess of 200 m thick, whose mapped extent exceeds 60 km^2, submarine channel-levee complexes within mini-basins and the fill to major submarine canyons, which acted as sediment conduits between mini-basins. The distribution of architectural elements and palaeocurrent data demonstrate that there were numerous sediment input and output pathways linking mini-basins. Modern sea-floor data provides insight into the large scale nature of basin dynamics, in particular the style of submarine canyons, the influence of mass-transport complexes and the distribution patterns of sediment within and between mini-basins. The outcrop study can be linked to subsurface studies of the fill of outboard mini-basins. Mapping of key stratigraphic surfaces within 2D seismic data demonstrates significant complexity in the structural and stratigraphic evolution of the external portion of the basin. Identification of architectural elements such as channel fills in the subsurface provides evidence that significant volumes of sediment were delivered to the external portion of the basin, giving confidence to apply learnings from high resolution outcrop studies to assist subsurface exploration.

Modelling of sedimentation patterns from internal to external mini-basins provides new insights into the dynamic evolution of trench-slope basin stratigraphy. Despite the recognition of common architectural elements, external basins may develop different structural styles and hence rates of accommodation generation and may experience markedly different rates of sediment flux towards the trench-slope terminus. Therefore predicting variations in tectono-stratigraphic style from internal to external basins remains challenging, impeding attempts to unlock the full potential of deep-water accretionary prisms. Integrated studies of whole systems, such as this, have the potential to produce better-calibrated understanding of systems at the frontier of exploration.

Nature of oroclinal bending in the Main Frontal Thrust of Himalayan foreland fold and thrust belt in Pakistan

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The Main Frontal Thrust (MFT) in Pakistan marks the outermost and southern most deformational signature of the Himalayan orogeny. Juxtaposing Precambrian rocks against the Miocene strata, the MFT extend in east-west direction bounded on either side by wrench faults. Apparently straighter looking fault trace takes a strong oroclinal swing towards east (Figure 1) and then straighten to join the major transpressional ramp of the Jhelum Fault. This structural swing has been attempted by many researchers and most of them put the MFT along the base of the uplifted ridgeline which also include the Back-thrust (Figure 1) which does not complement to the direction of throw along the MFT. This research is an effort to trace the exact surface trajectory of the MFT and to propose a paleo dynamic setup of the area which was responsible for creating the major structural swing in the Himalayan frontal ridge.

The area was mapped at the scale of 1:50000 after extensive field data collection and then the subsurface modelling was conducted to understand the interaction of faults with depth. The Rad7 electronic locator by Durridge Company, USA was used during the research work to check the radon emission along the fault traces to know if the fault is active or static. This device utilizes a vacuum apparatus and a strong state alpha indicator which comprises of a semiconductor material that changes over α- radiation to an electrical signal which ultimately gives the radon gas emission values.

Geological map relationship and field observations show a contrasting behavior in the lithological character as well as the opposite vergence between the MFT and its associated Back Thrust. It has been found that the Back Thrust is a separate fault which was generated after MFT went through the tight oroclinal bending through east west compression. The sequence of tectonic events in the research area can be established from the initial formation of MFT as a simple south verging regional fore-thrust which was followed by another episode of oblique stresses oriented in the northwest-Southeast direction creating the bending in the MFT. This fact also point towards the counter clockwise rotation of the Indian Plate after its northwestern leading edge collided with the Eurasian Plate. This Back-thrust is the recent most event thrusting the Precambrian strata on the Miocene rocks towards west. The results of Radon gas emission show a very consistent higher readings which were taken on the surface expression of the MFT. These higher radon gas emission values are found in the valley between the Back-thrust and MFT which shows the presence of a sub-cropping thrust fault in the valley.

Therefore, the map expression, the topographic behavior and the radon gas values all supplement the idea of the MFT to take a sharper turn towards north and then continues its northeast trajectory while the Back-thrust remains as a separate fault.

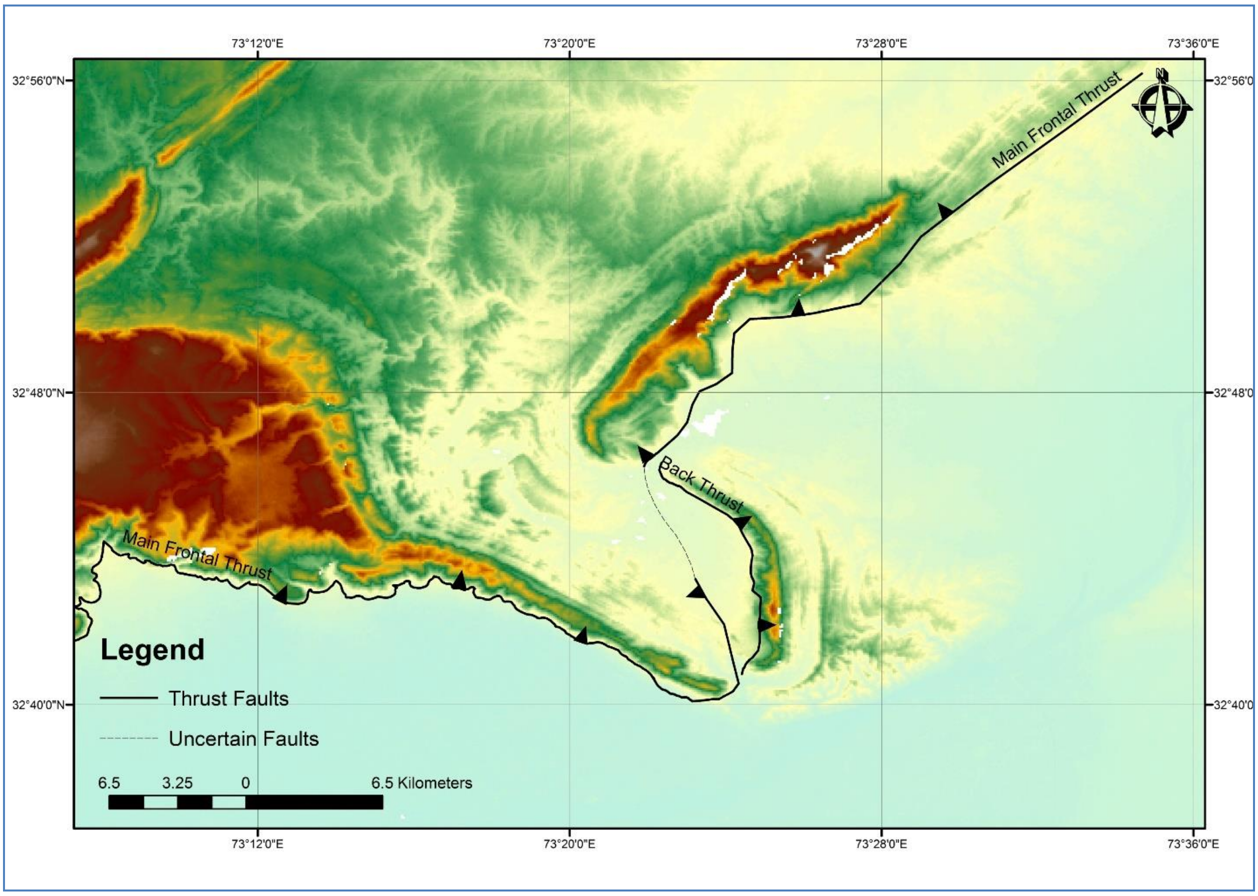

Figure 2 Fault overlay on the digital elevation model of the research area

Geological development of the offshore Timor Orogen

Pedro Martinez Duran[1], Peter Baillie[2], Eduardo Carrillo[3] and Gregor Duval[2]
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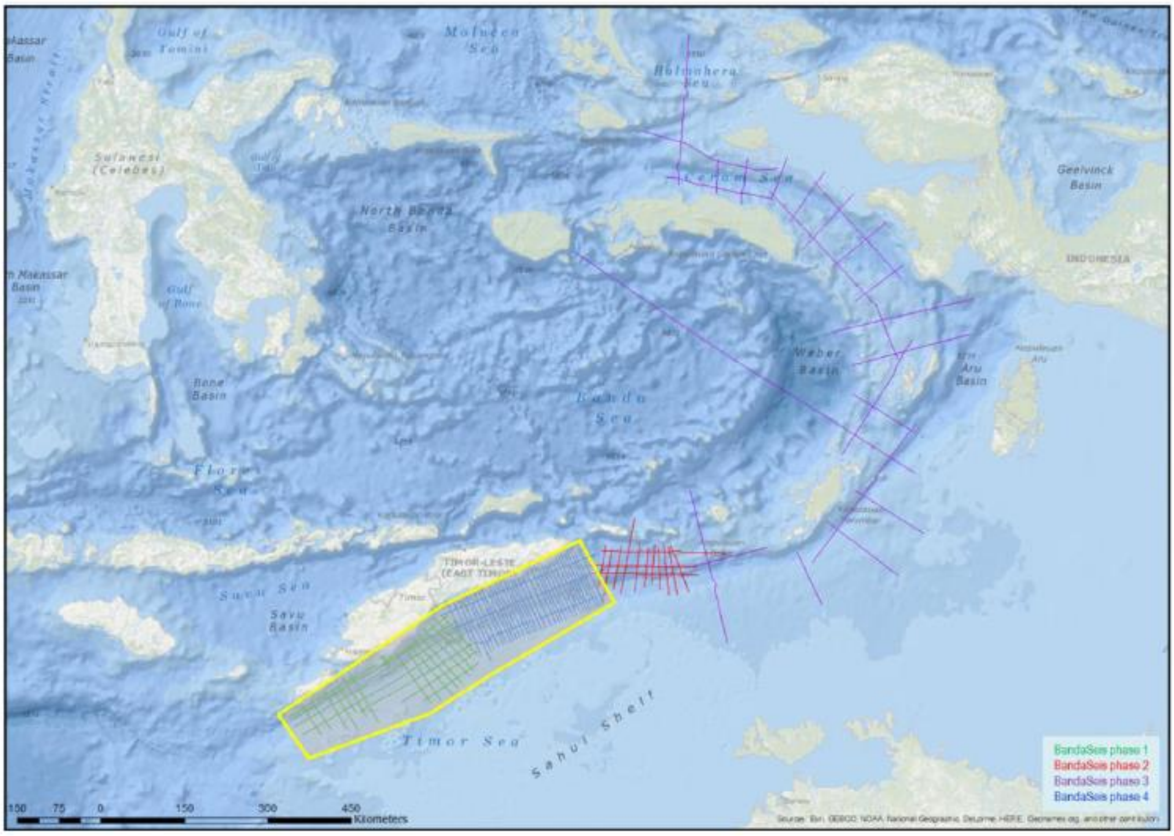
From 2012 to 2014, a new regional seismic 2D survey (BandaSeis) was acquired around the Banda Arc region in order to provide improved imaging of the deeper sedimentary section, analyse the tectonic mechanisms that shaped this unique arc of islands and understand the implications on hydrocarbon systems. The area of interest (highlighted in yellow in Figure 1) focuses on the Timor Trough region. The BandaSeis 2D seismic survey has imaged the geometry of the offshore fold-and-thrust belt which occurs north of the Timor Trough. The structural framework of the incoming and recently overthrusted Australian Plate is paramount to understand the geodynamic processes involved in the orogenic wedge of the Timor Orogen.

Figure 1. BandaSeis Seismic Survey



We propose that the downward flexure of the Australian Plate shown in the seismic data is due to the vertical loading of the orogenic wedge, which grows as the scrapped-off sediments from the overthrusted Australian Plate are uplift and stacked by the continuously overthrusting of the wedge. In general terms, the whole structural framework, as far as the seismic data allows, can be described as a thin-skinned tectonics. The key builders of the orogenic wedge are:

a) Piggy-back thrust sequences thrusting Cenozoic sediments bulldozed by the horizontal advance of the orogenic wedge.

b) The relict palaeogeography defined by Palaeozoic and Early Mesozoic structures from both the Australian and Timor Terrane.

The main process responsible for building the orogenic wedge is the inversion of the inherited horsts and graben provoked by the recent overthrusting of the incoming wedge. Palaeogeographic features not described before in the Australian Plate, including paleohighs or small sub-basins, also play an important role shaping the geometry of the orogenic wedge by providing major obstacles to the advance of thrust front. The set of Mesozoic horsts and graben coming from the Australian Plate and now found within the Timor Trough have been tectonically reactivated through oblique thrusting, which generates a number of unique and complex structures. The seismic 2D lines show how these faults controlling the development of these structures behave depending on whether they dip toward the trough (NNW-dipping) or away from it (SSE-dipping).

The dipping-away faults are bent due to the advance, weight and friction of the overthrusting orogenic wedge. This results in arcuate-shaped inverted faults and "decapitated or truncated" horsts by low angle NNW-dipping thrusts detaching on the Miocene, Jurassic, or Late Permian horizons. The length and strike orientation of these decapitated faults seem to control the length and orientation of the ramps of these thrusts. Sometimes, this situation can be also described in dip-toward faults (Figure 2). The scraped-off Triassic and Jurassic potential reservoirs and source rock levels are constantly uplifted by thrusting and stacked.

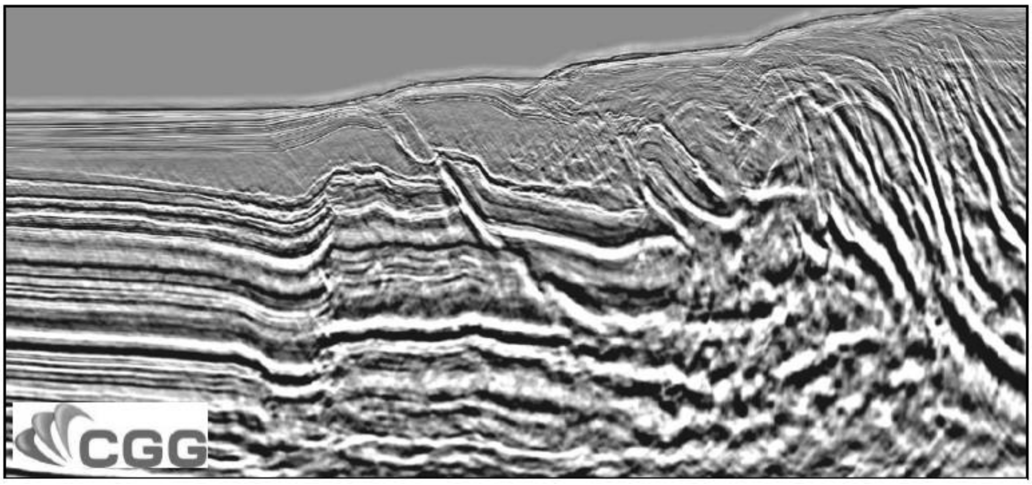


Figure 2. Truncated horst

On the other hand, where horizontal compressional stress do not dominate, the NNW-trending faults are usually reactivated as normal faults due to the vertical loading of the incoming wedge bringing down graben filled with source rock within the hydrocarbon window which form interesting kitchen areas for petroleum exploration (Figure 3).

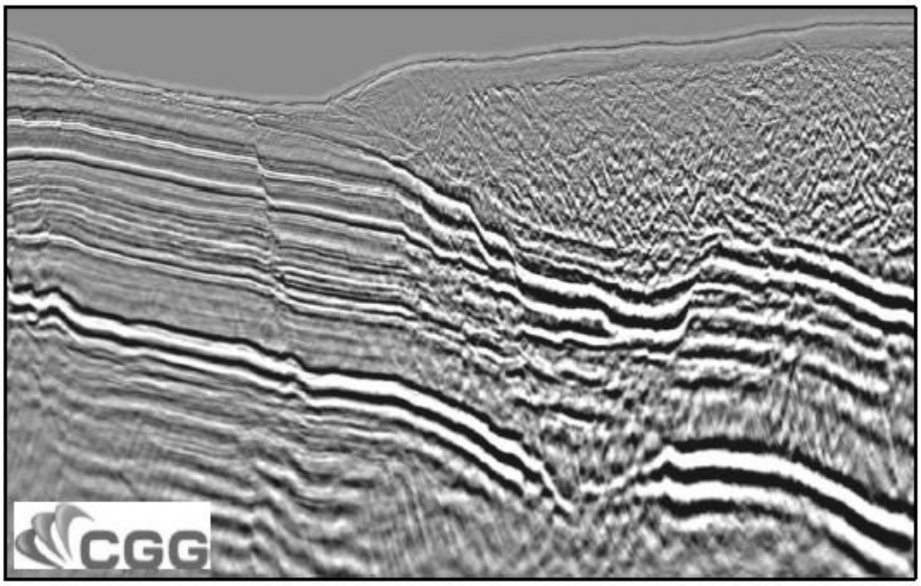


Figure 3. Clear imaged graben underneath the orogenic wedge.

Day Two

Along strike structural variation in the French Sub-Alpine chains

Hannah Watkins, Rob Butler and Clare Bond
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The geometry of fold-thrust structures can have great impact on the petroleum system they support, be it relating to reservoir capacity, fault leakage or maturation by structural loading. These geometries are seen to change along strike, often in response to variation in thrust displacement, thickness of mechanical layers and external conditions such as temperature. We use the French Sub-Alpine chains to illustrate some of the geometrical changes that may occur along strike in fold-thrust belts.

The French Sub-Alpine chains are composed predominantly of carbonate Jurassic to Miocene-aged sedimentary rocks, which were folded and thrusted during the Miocene in response to WNW-directed compression associated with the Alpine Orogeny. They form an arcuate fold-thrust belt on the western edge of the Alps. In the south, the Sub-Alpine chains mark the most westward large scale structures associated with Alpine deformation, whereas in the north, the Jura Mountains are found further west of the Sub-Alpine chains. Our study area can be sub-divided into four main regions, which, from south to north, are named the Vercors, Chartreuse, Bauges and Bornes. All are well exposed, with many gorges and valleys oriented parallel to regional compression allowing for fantastic cross-section views onto the fold-thrust structures. We use field observations and structural data to construct cross sections through the fold-thrust belt to analyse along-strike structural variation.

The Vercors and Chartreuse form the southern Sub-Alpine chains. Folds in these regions have narrow, steeply dipping forelimbs and usually form in the hangingwalls to moderate-displacement multi-strand thrusts. Further north, in the Bauges and Bornes regions, the structural style begins to change. Folds with overturned forelimbs are seen and are associated with well-developed footwall synclines, often in the absence of through-going thrusts. Previous studies on palaeotemperatures of the Sub-Alpine chains have concluded that the northern Sub-Alpine chains have undergone higher maximum temperatures than regions further south; this could account for the differences in structural style. The northern Sub-Alpine chains have been subjected to more structural loading due to emplacement of a ‘pre-Alpine‘ thrust sheet onto the Bornes and northern Bauges regions prior to fold-thrust belt formation. This structural loading may be the cause of higher temperatures in the north.

We develop on the conclusions of previously published studies on the Sub-Alpine chains by presenting closely spaced cross sections that enable us to remark not only on the changes in observable structural style, but also on how those changes occur along strike, how shortening varies on a small scale, and what might control changes in fold-thrust geometry. As well as investigating the role of palaeotemperature on structural style, we analyse how variations in the thickness of mechanical units might control the resultant fold geometries in the Sub-Alpine chains, and in other global fold-thrust belt examples.

Structural styles and evolution of a submarine fold and thrust belt, South Falkland Basin

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High quality seismic data from submarine fold and thrust belts provide spectacular opportunities to study the kinematic evolution of these complex settings. The South Falkland Basin is no exception. Subduction beneath the South American plate along the Magallanes–Fagnano Fault becomes dominantly strike slip along the North Scotia Ridge, whereby the Burdwood Bank, a continental block, has been accreted on to the southern margin of the Falkland Plateau. This resulted in the downwarping of the underlying Mesozoic shelf sediments, with reactivation and development of normal faults that displace both the basement and Cenozoic sediments. This accretion thought to have initiated in the Miocene, was accompanied by the development of a fold and thrust belt and foreland basin, the South Falkland Basin. This fold and thrust belt can be considered to be an offshore extension of the Magallanes fold and thrust belt of Terra Del Fuego and has a similar complex of north-vergent thrust geometries.

This contribution provides a detailed description of the fault architecture using a 2D and 3D seismic dataset from the South Falkland Basin. Key reflectors and faults were mapped to produce contour maps in depth of the main horizons. The foreland basin displays a range of fault structures of varying generations, suggesting reactivation of pre-existing fault structures, as well as development of new structures.

The FTB itself displays the characteristic range of structures from the deformation front to the hinterland. The frontal thrusts cut through post-Early Paleogene sediments and appear to have a decollement at approximately the Top Cretaceous unconformity, although thrusts in the hinterland appear to detach at a deeper level.

Furthermore, the style of thrusting varies from thin-skinned in the east to thick skinned in the west. The thin-skinned deformation is illustrated whereby undeformed Mesozoic reflectors are visible beneath thrust sheets, while thrusts in the western area are more complex and include basement and sedimentary packages. This variation is largely controlled by the increasing depth to basement from west to east.

This study draws on modern 2D and 3D seismic reflection data, integrated with recent exploratory well data, and will focus on the evolution and structural style of the South Falklands fold and thrust belt.

Along-strike variation of thrust-related folds in the curved thrust systems of the Central-Northern Apennines of Italy

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Contractional fault-related fold models are fundamental for reconstructing structures deriving from fold-thrust interaction, which are important because they constitute the most prevalent hydrocarbon traps in both subaerial and submarine compressional belts worldwide (McClay *et al*., 2011). Reconstructing their geometry, understanding their mechanisms, and defining their spatial variability through naturally exposed structures are valuable in developing predictive models, which are instrumental in guiding the interpretation in the subsurface, reducing uncertainty. Since the pioneering research on the geometry and kinematics of thrust-related folding (Suppe, 1983; Suppe & Medwedeff, 1990), there has been considerable research in different tectonic settings incorporating surface observations, subsurface seismic data, and experimental studies. Fault-bend and fault-propagation folding represent the two end-member mechanisms of thrust-fold interaction and are characterised by distinctive fold shape profiles. Their selective development is a function either of the mechanical stratigraphy or contrasting styles of compressional normal-fault reactivation.

The Central-Northern Apennines of Italy developed during Neogene-Quaternary time following the closure of the Alpine Tethys. The orogenic stacking involved Triassic-Miocene carbonate platform-slope-basin sequences deposited on the Adria Mesozoic continental margin and overlying Miocene-Pliocene syn-orogenic siliciclastic sediments. Significant lateral variations in structural style and stratigraphy occur along the strike of the Apennines and are mostly related to the inherited pre-orogenic setting (Tavarnelli *et al*., 2004). Thrust-related folds, spectacularly exposed in the Central-Northern Apennines (Gran Sasso and Olevano-Antrodoco-Sibillini thrust systems) are analysed with the aim of reconstructing their along-strike variation in thrust-related folding mechanisms and unravelling their interference fold patterns. The Central-Northern Apennines are characterised by curved thrusts and remarkable lateral variations in thrust-related folds occur (Calamita *et al*., 2012; Pace & Calamita, 2015). Different folding mechanisms involve the same Lower Jurassic-Miocene carbonate slope-basin multilayer and their development has been selectively controlled by contrasting styles of compressional normal-fault reactivation. Pre-thrusting normal-fault transpressive reactivation promoted fault-bend folding along the N-S and NNE-SSW oblique ramps, whereas shortcut-propagating thrusts developed fault-propagation folds along the WNW-ESE and NW-SE frontal ramps. These two laterally changing thrust-related folds interact with a characteristic interference fold pattern produced by their synchronous/in-sequence growth and interaction in the salient apex of the curved thrust system.

Inferring foreland-directed gravitational collapse along curved thrust fronts from the analysis of a minor thrust-related shear zone in the Umbria-Marche thrust belt (Central-Northern Italy)

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Gravitational collapse occurs during the mature evolution of orogenic belts, but its signature is difficult to discriminate in macroscopic structures from that of pre-, syn- or late-/post-orogenic extension, so reliable mesoscopic examples are particularly useful. This phenomenon is increasingly recognised during the evolution of many orogenic belts (McClay *et al*., 1986; Holdsworth *et al*., 2006) as well as for the Apennines of Italy (Mazzoli *et al*., 2014). It has been mostly inferred by analysing kilometre-scale structures exposed along mountain fronts worldwide (Butler *et al*., 1987; Figure 1a) and has also been successfully reproduced via experimental sand-box analogue models (Bonini *et al*., 2000).

In this study, we analysed a composite fabric within a well-exposed thrust-related shear zone developed along a lateral ramp of a regionally important thrust (Coscerno-Rivodutri Thrust – CRT) resulting from positive tectonic inversion from the Umbria-Marche sector of the Central-Northern Apennines of Italy. A remarkable thrust-related, brittle-ductile shear zone is well exposed in the footwall of a local WSW-ENE lateral ramp that connects two distinct frontal ramp dip-slip segments along the CRT developed during the Cenozoic compression. A composite fabric containing both compressional and extensional elements characterises this remarkable and structurally complex thrust zone.

Detailed structural analysis along the thrust-related shear zone reveals mesoscopic normal faults that truncate the thrust surface, overprint the S-fabric and merge downwards in a foreland-directed splay, leaving the thrust footwall undeformed. The study of cross-cutting and overprinting relationships within the composite shear fabric and kinematic data defines the modes and timing of thrusting, which has been accommodated through the superposition of structures produced during two main steps of deformation: i) Late Miocene thrusting, including reactivation of NNE- and ENE-trending, pre-thrusting normal faults along the CRT; and ii) syn-/late-thrusting, foreland-directed listric extensional faulting localized in the hanging-wall of the CRT and within the thrust-related shear zone exposed along the lateral ramp connecting two frontal segments within the CRT.

The observed overprinting relationships amongst the early, hinterland-dipping thrust-related shear fabrics and the late, foreland-dipping mesoscopic normal faults are best explained as due to a phenomenon of syn-thrusting foreland-directed gravitational collapse. These findings allow to: i) unravel the locally complex deformation history; and ii) establish a sequence of deformation events, from syn-thrusting shear zone development to syn-/late-thrusting extensional collapse (Figure 1b). The composite fabric reported in this contribution provides an exceptionally clear example of foreland-directed gravitational collapse documented at the mesoscopic scale, illustrates its structural complexity, and enables the correct unravelling of the relative timing of thrusting and syn-/late-thrusting, top-to-the-foreland extension. The mesoscopic composite shear fabric along a lateral thrust ramp presented here, therefore, is diagnostic of frontal collapse processes and provides critical constraints to help correctly unravel the kinematic and dynamic history of gravitational instabilities affecting thrust fronts of orogens that bear the signature of both pre- and post-thrusting extensional episodes.

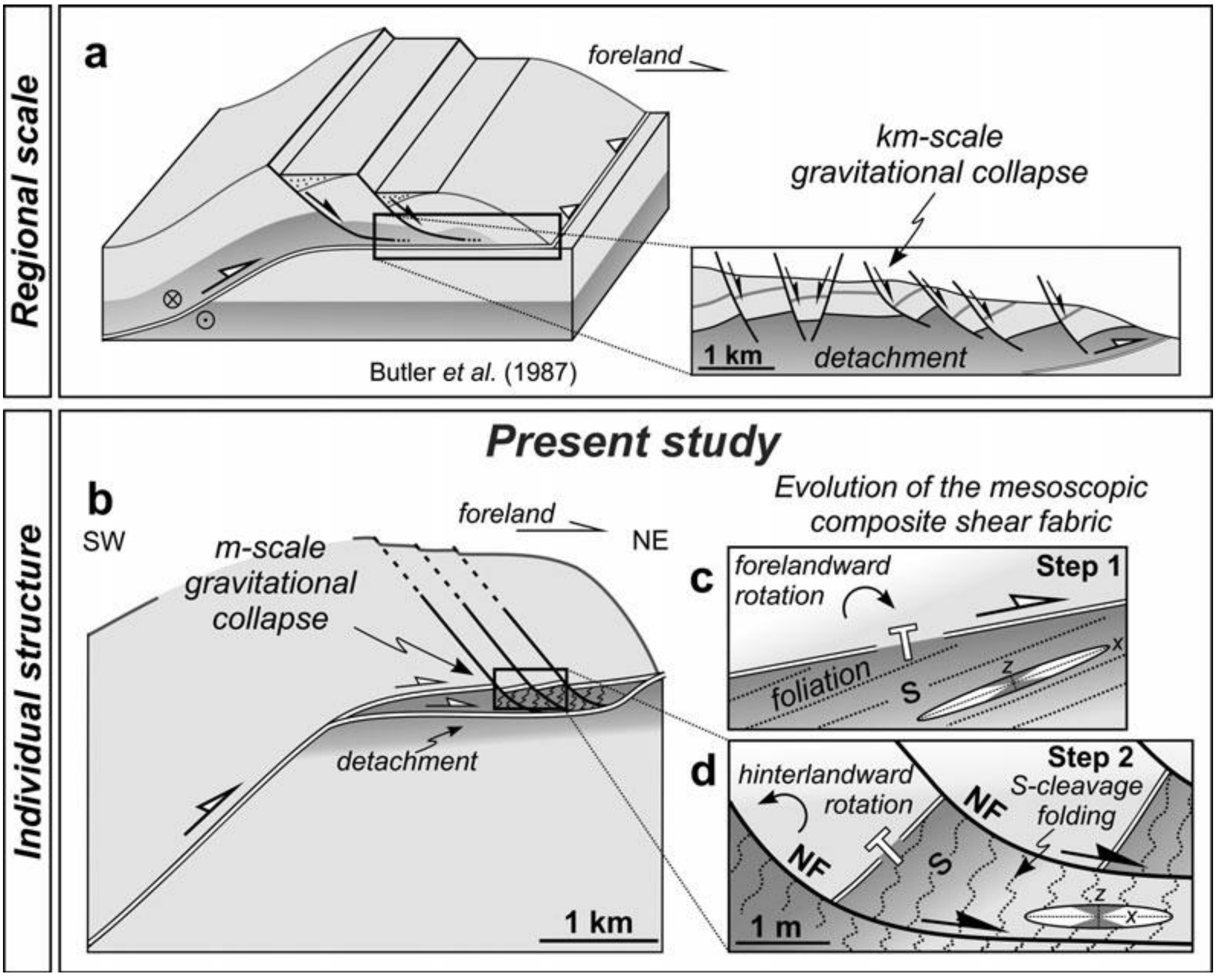

Figure 1. Modes of syn-to-late-thrusting foreland-directed gravitational collapse. (a) Macroscopic kilometre-scale foreland-directed gravitational collapse affecting an orogenic mountain front (modified from Butler et al., 1987). (b) Foreland-directed gravitational collapse deforming the hanging-wall of a thrust-related anticline along a frontal thrust ramp and relative evolution of the composite shear zone fabric (modified from Pace et al., 2016).

A small but perfectly-formed and prospective fold-thrust belt in the southern Irish Sea and central Pennines of England

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Seismic interpretation in the southern Irish Sea recently carried out by BGS on behalf of the OGA for its 21st Century Exploration Roadmap (21CXRM) Palaeozoic project, has confirmed the extension of the Bowland Basin (and its inversion, the Ribblesdale Fold Belt) southwestward towards Anglesey. The Môn-Deemster Fold-Thrust Belt comprises a series of southward-vergent, WSW-trending anticlines with thrusts developed on their steep limbs. Exploration wells have demonstrated that the folded strata are of Mississippian age, including the Carboniferous Limestone Supergroup and Bowland Shale Formation. However, the thrusts extend into the pre-Carboniferous basement where they are terminated by a prominent northward-dipping mid-crustal reflector set, interpreted as a Caledonian detachment. The fold-thrust belt is about 30 km wide. Its southern limit appears to be coincident with the Menai Strait Lineament, an inferred Caledonian terrane boundary with a complex history of strike-slip reactivation throughout Palaeozoic time (e.g. Gibbons, 1987). It can be mapped on high quality 2D and 3D seismic reflection data to NE through the Deemster Platform towards the Lancashire coast near Formby. In the onshore, the correlative structures are the Pendle Fault System defining the southern edge of the Bowland Basin (Kirby et al., 2000). The northern limit of the Môn-Deemster-Ribbledale Fold-Thust Belt corresponds to the southern edge of the Quadrant 109 Arch just to north of Anglesey, where a northward-vergent structure is imaged by the seismic data. This may be the counterpart of faults such as the Doeford and Thornley faults, which define the 'Bowland Line' on the northern edge of the Bowland Basin (Kirby et al., 2000). The mapped length of the combined Môn-Deemster-Ribblesdale Fold-Thust Belt exceeds 160 km, but may well exceed 300 km if putative extensions via the North Craven and Flamborough Head fault systems into the southern North Sea are valid. Two generations of Variscan inversion structures are recognised in the eastern Irish Sea (Pharaoh et al., in press). The SSW-trending Môn-Deemster-Ribblesdale Fold-Thust Belt belongs to the first generation, of inferred late Westphalian age; second generation inversion (fold and thrust) structures are oblique to the first, with a N-S trend, and are correlated with late deformation in the Uralian Orogen, in Stephanian-early Permian time. These were subsequently reactivated as extensional faults (e.g. Keys, Godred Croven etc) which define the Permian-Mesozoic graben of the East Irish Sea Basin.

A proven hydrocarbon system is present throughout the fold-thrust belt. The Bowland Shale Formation has been a prolific source of gas for the Permo-Triassic reservoirs of the Morecambe Bay fields and Elswick onshore, but potential Namurian and Westphalian reservoirs likely suffer from low porosity and permeability due to the combined effects of multiple Variscan inversion, deep burial in a Permian-Mesozoic rift, Cenozoic inversion, magmatism and thermal effects associated with the rifting of the North Atlantic. The superimposition of the Triassic-reservoired Douglas (gas), Hamilton (gas) and Lennox (oil and gas) fields upon culminations within the Variscan fold-thrust belt cannot be a coincidence. Westphalian strata have largely been removed here and cannot therefore provide a source. The Namurian sequence is under-tested, so the presence of possible reservoir sands (and their poroperm characteristics) within the section is poorly understood. Onshore, oil is present at Formby and gas at Elswick in the Fylde. This region is currently the focus for exploration for non-conventional hydrocarbons in the UK targetting the Bowland Shale source. Farther afield, in north Yorkshire, fields within Permian reservoirs at Pickering, Malton, Marishes, Caythorpe and Lockton (all gas) may lie within the cover of the same fold-thrust belt system, while the Bowland Shale source is currently being appraised as a non-conventional play at Kirby Misperton.

Structural inheritance of Triassic–Jurassic normal faults in a Cretaceous thrust and fold belt based on seismic and field data (western Transdanubian Range, Hungary)

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Pre-existing normal faults have strong influence on the evolution of fold and thrust belts. These early structures often act like obstacle during shortening, therefore pre-existing normal faults often redound the formation of curved thrusts (salient and reentrant) and back-thrusts. We introduce a case study of this topic, from the western Transdanubian Range, west Hungary. We used both 3D seismic and field data.

The Transdanubian Range is situated in the Miocene Pannonian back-arc basin (Fig. 1). It is built up by low-grade metamorphic Variscan shales and non-metamorphic Permian to Miocene succession. The western part of the Transdanubian Range is affected by Triassic-Jurassic NE-SW extension (D1), and E-W compression (D2) during the „mid-Cretaceous" orogeny. Consequently the strike of D1 normal faults is oblique to the general trend of D2 thrusts.

In the eastern part of the study area (Keszthely Hills) the pre-Senonian basement is on the surface, there field observations were done. NE-SW trending Late Triassic syn-sedimentary normal faults were identified in the southern edge of the Keszthely Hills, on the basis of talus cone breccia in the hanging wall. The structural pattern is marked by N-S trending D2 folds and thrust folds. In the vicinity of D1 structures deviation of D2 fold axes was observed. The southern, NW-SE trending oblique segment of the D2 Büdöskút thrust is diverted by a parallel D1 normal fault (Fig. 2). In the hanging wall of the D1 normal fault, passive back-thrust (Pilikán anticline) of the Büdöskút thrust was developed, due to the blocking effect of the D1 normal fault. The initially east-vergent Pilikán anticline (D2) shows similar curved trace like the Büdöskút thrust (D2), approaching the D1 normal fault (Fig. 2). A perpendicular, short NE-SW trending Molnárkő anticline occurs, what we interpret as a reactivation of a relay ramp of two D1 normal fault segments (Fig. 2).

We classified the salient based on the observed stress-field dispersion, according to the end-member models of Kwon and Mitra (2004). On the oblique ramps (Büdöskút thrust, Molnárkő anticline) $\sigma 1$ perpendicular to the trace of the ramp was calculated in the terms of D2 phase, based on fault-slip analyses. However, the NW-SE trending oblique segment of the Pilikán anticline shows E-W striking $\sigma 1$ regarding both the pre-tilt (pre-folding) and post-tilt (post-folding) fault-slip data. Therefore the development of Pilikán anticline could be explained by transport-parallel simple shear, which is developed due to the blocking effect of the D1 normal fault. In other words, the Pilikán anticline was dragged along the D1 normal fault.

The western part of the study area (Zala basin) is covered by thick Miocene succession, were the pre-Senonian basement was studied by 3D seismic. In this sub-area the relationship between pre-existing normal faults (D1) and compressional structures (D2) was similar to the Keszthely Hills. A concave reentrant of a west-vergent D2 thrust was observed, which developed in front of a NW-SE trending extensional horst, (Fig. 2). In this case the study of stress-field dispersion is impossible, however, the displacement gradient along the thrust could be well investigated. The reentrant of the Zala basin was probably an initially curved thrust and therefore it could be considered as a system of oblique ramps. These structures may develop due to the blocking effect of the D1 normal faults. However significant displacement gradient occur along this thrust, while the off-set of the thrust is decreasing toward the reentrant, and increasing toward the salient (Fig.2). This decreasing displacement is due to the presence of a pre-existing D1 horst, and not simply connected to an oblique ramp.

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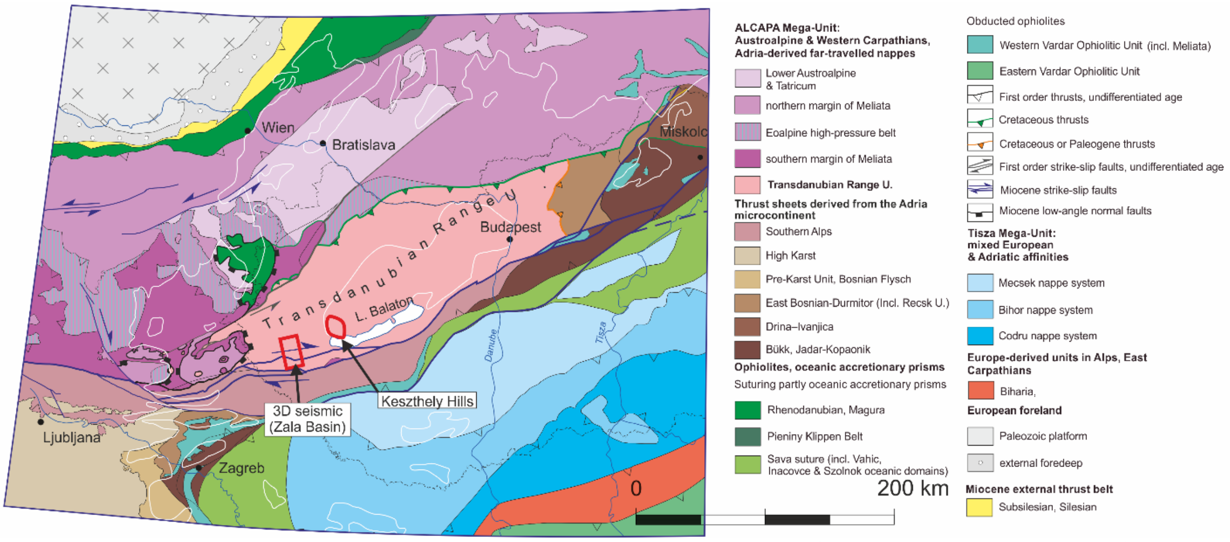

Fig. 1: Position of the study area in the Alpine-Carpathian-Dinaridic orogens (Schmid et al. 2008, modified).

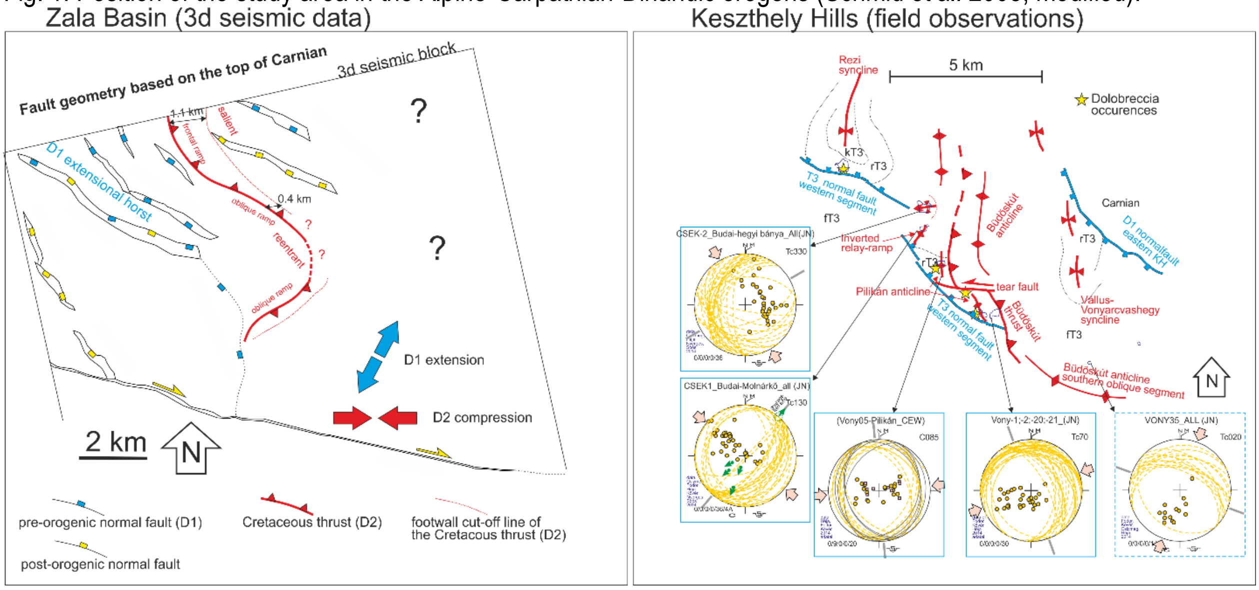

Fig. 2: Structural sketch of D1 and D2 structures in the 3d seismic of the Zala Basin (left side) and in the Keszthely Hills (right side).

Contrasting styles of compressive deformation in the Central Adriatic foreland fold-and-thrust belts: implications for traps and source rocks distribution

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The Central Adriatic is a peculiar area within the Mediterranean basin which includes two opposite verging foreland fold-and-thrust belts. In the Croatian off-shore, the W-SW verging Dinarides compressive structures developed starting from Paleogene (Wrigley et al., 2015) and since Pliocene times interacted with the E-NE verging Apennines structures located in the Italian offshore (Scisciani, 2009; Scisciani and Calamita; 2009; Pace et al., 2015). Both the fold-and-thrust belts affect a very thick sedimentary succession, in places exceeding 10000 meters, which exhibits substantial facies changes in the Late Paleozoic-Mesozoic sections where different proven source rocks occurs (Scisciani and Esestime, 2017). In particular, thickness and facies changes reflect the inherited distribution of shallow-water continental clastic to carbonate-platform domains separated by basins where evaporitic and deep pelagic, mainly carbonate, sedimentation occurred.

A dense grid of 2D seismic reflection profiles acquired by Spectrum Geo Ltd. in 2013 currently allow an unrevealed image of the deepest sedimentary units, up to ten seconds two-way travel times, through the entire offshore Croatia and at the water boundary with Italy, where additional vintage 2D seismic profiles were also reprocessed. Seismic sections, after the application of a specific pre-stack depth migration sequence (Esestime et al., 2016), image over 15 km deep into the crust and shed light on the deep structural setting of the Adriatic basin.
Several along-strike variations of the style and rate of shortening achieved by thrust-related folds, and in turn also enhanced by salt tectonics, appear strictly controlled by the inherited paleogeography, and related mechanical stratigraphy.

Slightly deformed domains In the Adriatic foreland mainly correspond with pre-existing structural highs where basement is capped by persistent carbonate platform successions (Fig.1).

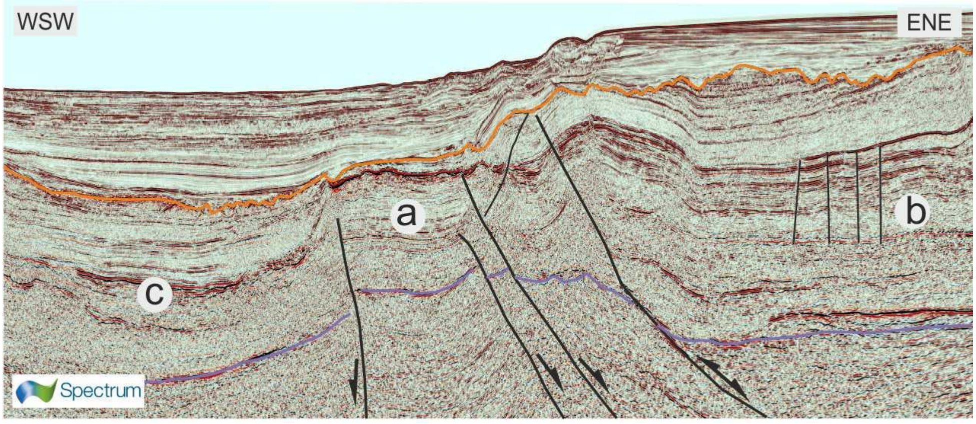

Fig. 1 – 2D seismic line showing the positive inversion tectonics in the southern part of the Central Adriatic (Croatian offshore). a): Persistent carbonate platform ; b) drowned inner platform; c) Jurassic pelagic basin

The adjacent folded domains are characterized by positive inversion-tectonics structures that affect and vertically extrude the basinal or drowned inner platform successions. In this setting, evaporite and shaly intervals act as secondary decollement levels triggering short-wavelength disharmonic folds.

Structural inheritance of fault displacement profiles from continental rifting to thrust fault propagation from observations to mechanics.

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Fold thrust belts often feature compressional overprinting of former rifted margins. Using an example from the Eastern Cordillera of Colombia, we demonstrate spatial correlation of fault displacement-profiles and structural geometries between the orogenic structures and the former extensional terrane.

We use an extensive seismic reflection database and field observations to evidence the spatial relationship of structures and constrain their similarities. Using two-dimensional discrete element modelling we then simulate their structural development to investigate controls on their evolution.

Our results suggest inheritance is dominated by the rift's structural architecture and subsequent deposition. Both form a first-order controls on strength distribution and anisotropy, mechanically guiding their formation. In particular, simulations demonstrate that the geometry of the metamorphic basement can mechanically force the system, leading to duplexing within half-grabens, overlain by forced and fault-propagation folds.

Combining field and numerical studies in this manner allows us to demonstrate that an inactive extensional basement may guide overlying thin-skinned deformation. However, the presence or extent of reactivation in the basement is unconstrained. This presents a blurring of the lines between traditional models of thin- and thick-skinned tectonics.

Considering some thin-skinned systems as competent beams that may be; actively deformed, or passively guided, as they pass over older terranes provides an intermediary step between thin- and thick-skinned end member geometries.

Structural architecture of the northern part of Lesser Caucasus: an eastern Achara-Trialeti fold and thrust belt, Georgia

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This study shows preliminary results of an integrated structural interpretation of a fold and thrust belt in the frontal part of Lesser Caucasus. *On the basis new field data, interpreted 2-D seismic profiles and regional balanced cross-section within study area have been found* several principal structural units from south to north: south-vergent backthrust zone, north-vergent forethrust zone and triangle zone. South-vergent backthrust and north-vergent forethrust units are represented by fault-related folds and are interpreted as an asymmetric fault-propagation folds whose front limb is broken by thrust faults. The kinematic evolution of south-vergent backthrust zone is related to northward propagating structural wedge. Regional balanced cross-section shows structural wedge and duplex at the triangle zone beneath the thrust front monocline belt and is represented by Cretaceous-Paleogene strata. Interpreted industrial seismic profiles and regional balanced cross-section indicated that the growth of eastern Achara-Trialeti fold and thrust belt structures at northern part of the Lesser Caucasus, formed by basement wedge that propagated along detachment horizons within the cover generating thin-skinned structures. 2-D seismic profile reveals that perspective structural plays mainly are represents by shallow fault-propagation folds and duplex.

Acknowledgments. This work was funded by Shota Rustaveli National Science Foundation (SRNSF) (grants YS15_2.1.5_78 and 217942).

The geometry and kinematic evolution of central Lesser Caucasus basement wedge, Georgia: Implication for building an eastern Achara-Trialeti fold and thrust belt

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We present a new model for the kinematic evolution of the eastern Achara-Trialeti fold-and-thrust belt (ATFTB) based on interpreted seismic profile and regional balanced cross section across the northern Lesser Caucasus. The proposed model links the formation of ATFTB through the creation and propagation of basement wedge thrust. The ATFTB is located in the northern part of the active collisional Lesser Caucasus orogen associated with Arabia-Eurasia convergence and represents the best example of mountain building processes in late Alpine time. The collision between the Arabian and Eurasian plates caused inversion of the relief and at the place of intra-arc and back-arc basins were formed two fold-and-thrust belts of Achara-Trialeti and Greater Caucasus with the intermontane basin in between. Our interpretation has integrated seismic profiles, several oil-well, and the surface geology data to reveal structural characteristics of eastern ATFTB. Seismic reflection data reveals the presence of basement thrust sheet, basement wedge, south- and north-vergent fault-propagation folds, and some structural wedges. The rocks involved in the deformation range from Paleozoic basement rocks to Mesozoic-Tertiary rocks. Based on the interpreted seismic reflection profile, triangle zone (southern part of seismic profile) was recognized under Pliocene-Quaternary basaltic lava flows. South- and north-vergent fault-related folds are represented by Cretaceous-Paleogene strata. Regional balanced cross-section shows that building of thick-skinned structures of eastern Achara-Trialeti was formed by basement wedges propagated along detachment horizons within the cover generating thin-skinned structures. Deformed Pliocene-Quaternary lavas from southern part of ATFTB and analysis of growth strata of the frontal part of eastern ATFTB indicate that exhumation and evolution of deformation has been continuing during the last ~ 15-14 Ma (M. Miocene) together with the thrust system kinematics.

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Multiscale characterization of fracturing in folded platform carbonates: the case study of the Island of Pag, External Dinarides of Croatia

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Fractures are a primary factor controlling the fluid storage and transport properties of hydrocarbon reservoirs. The quantitative characterization of fractures in outcrop analogues allows a better understanding of natural fracture systems, to extrapolate predictive laws useful for integrating the limited data available for buried reservoirs. Here we present the methodological workflow we are applying for a multiscale characterization of fracturing in a folded Cretaceous carbonate platform in the Island of Pag, in the External Dinarides of Croatia, along with our preliminary results.

The External Dinarides are a fold and thrust belt developed between the Paleogene to Miocene, characterized by general SW vergence. The Pag anticline involves about 1 km of Cenomanian-Santonian rudist-bearing limestones overlain, through an unconformity, with transgressive Foraminiferal limestones of Eocene age. The outcrops are almost free of vegetation and display nice pavement and cross sectional exposures, although strongly affected by karst dissolution. The exceptional exposure conditions allowed us integrating remote sensing techniques with drone and ground-based photogrammetric surveys for characterizing the fracture network at multiple scales. For the analysis of digital outcrop models we developed a semi-automatic fracture detection method, combined with the 3D analysis tools available in Gocad. Traditional geological surveys and structural stations served for determining the crosscutting relations between multiple fractures and stylolites sets.

At the km-scale, the fold shows a high along-axis continuity for ca. 30km between the NW and SE periclinal terminations. In cross section, it has a box geometry, with sub-vertical to overturned limbs and a gently undulating hinge zone. The gently NE-dipping hinge zone is overthrusted over the NE limb through a sub-horizontal thrust fault. The fold is crosscut by other minor thrust faults verging both to NE and SW, and by sub-vertical strike-slip faults striking either NS or EW. Thrust and strike-slip faults determine an increase in fracture intensity clearly visible in drone imagery. At the outcrop scale, fractures and stylolites occur in both systematic and non-systematic arrays. Non-systematic, locally very intense fracturing is mostly found in thick mudstone-wackestone banks, while in packstone-grainstone dominated intervals fractures are more systematic and evenly spaced.

Our preliminary data suggest that the observed kilometer-scale tight folding of the Cretaceous platform is associated with multiple thrusts and back-thrusts at the decametric to hectometric scale. The organization and distribution of fractures is primary controlled by sedimentary facies, being more intense in mudstone-wackestone, and by the vicinity of thrust or strike-slip faults.

Day Three

Along-strike variation of thin-skinned thrusting style controlled by pre-existing basement structure in the easternmost Jura Mountains (northern Switzerland)

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It is widely accepted that the style of faulting in thin-skinned fold-thrust belts is often guided by the pre-existing structural configuration of the underlying mechanical basement. Models of the relationship between cover and basement deformation are most often of a conceptual nature. The case study presented here aims to contribute to a better understanding of the actual modes of along-strike structural cover-basement interactions in thin-skinned foreland settings.

Our study is devoted to a detailed analysis of the Late Miocene Mandach-Thrust, a key tectonic structure of the easternmost Jura Mountains in the northern Alpine foreland of Switzerland (Fig 1A). The influence of the basement configuration on the structural characteristics of this thrust had already been recognized during early pioneering studies (for example by the late Hans Laubscher). It was shown that the thin-skinned thrust within the Mesozoic sedimentary sequence is located above a major normal fault zone in the underlying basement. The detailed interpretation of the structural and kinematic relationships between faulting in the cover and basement remained the subject of scientific debate, for example including hypotheses of alternate detachment horizons or even a thick-skinned nature of the fault (Fig. 1B).

The revised analysis of the Mandach-Thrust builds on the construction, restoration and forward modelling of eight closely spaced cross-sections across the fault. These sections were developed on the basis of a recently densified and newly depth-migrated 2D seismic dataset and under consideration of published geological maps. The restoration and forward modelling were carried out using the software Move™. The workflow applied during our analysis involves the development of an “initial interpretation” providing the best possible integrative interpretation of the reflection seismic image and the surface geology. This interpretation was then restored to a pre-thin-skinned thrusting scenario using geometric restoration techniques (bed length balancing), applied in the form of multiple trial and error cycles. The revised and restored cross-section was subsequently used as a “starting model” for forward modelling using the fault-bend-folding algorithm in Move™. As part of this process, the amount of shortening across the Mandach-Thrust was also determined along each section.

The approach outlined above yielded internally consistent results for each individual cross-section, with little deviation between the different interpretations / models for one and the same section. The results indicate that the Mandach-Thrust can be explained by thin-skinned thrust tectonics with a main basal detachment horizon in Middle Triassic evaporites. A significant inversion of the basement structure underlying the Mandach-Thrust is not suggested either by restoration or by forward modelling. What is clearly demonstrated, though, is that pre-existing, basement-rooted structures exerted a strong control over the along-strike variation of the thin-skinned thrusting style.

A comparison of the eight cross-sections shows distinct structural variations along the Mandach-Thrust. Along its western segment, the Mandach-Thrust exhibits a gentle dip. The seismic data show vague indications of normal faults that appear to have been passively transported here during thrusting, without being reactivated. Further to the east, the Mandach-Thrust appears as a steeply dipping reverse fault. Our analysis suggests that this is due to the increased influence of a well-documented pre-existing normal fault. In the basement this normal fault was hardly reactivated at all. Its upper part cutting through the sedimentary sequence, however, was severed by the basal detachment, transported northward and partly inverted.

We conclude that the variation in structural style along-strike of the Mandach-Thrust occurs in relation to a basement-rooted precursor structure. It is confirmed that the latter controlled the structural configuration of the basal detachment and acted as a pre-existing mechanical weakness during thin-skinned thrusting. The newly available seismic data reveal that, along strike, this normal fault zone steps back from underneath the Mandach-Thrust towards the north. These results imply the existence of a roughly WNW-ESE trending transfer structure that is not apparent in the existing 2D seismic data. As such, the detailed structural analysis of the Mandach-Thrust not only allowed an improved understanding of the fault's kinematics and evolution but also served to highlight existing exploration uncertainties.

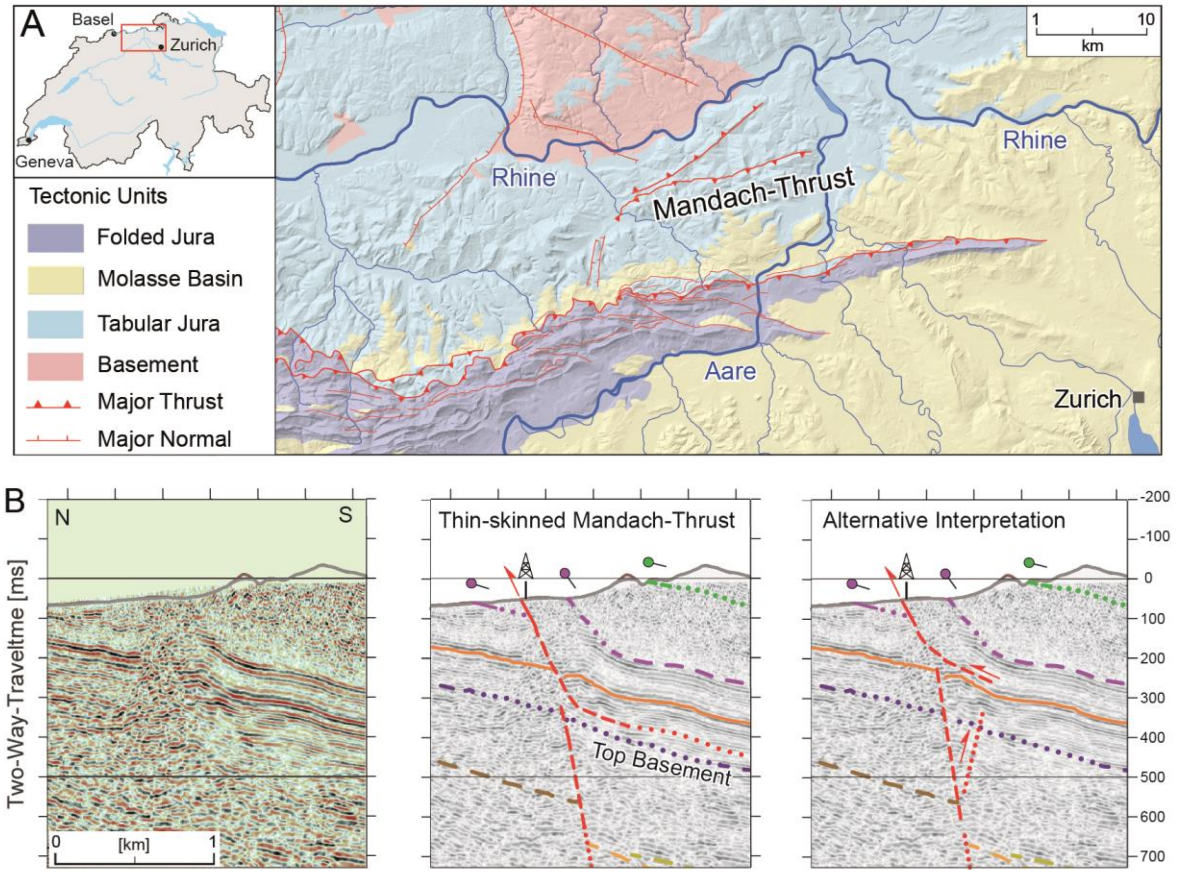

Fig. 1: A) Location of the Mandach-Thrust in northern Switzerland. B) Exemplary 2D seismic section (prestack-time-migrated) across the Mandach-Thrust with previously developed, opposing interpretations of the structure that are in both cases non-balanced.

Newly-observed Caledonian and Devonian fold and thrust structures in the UK North Sea

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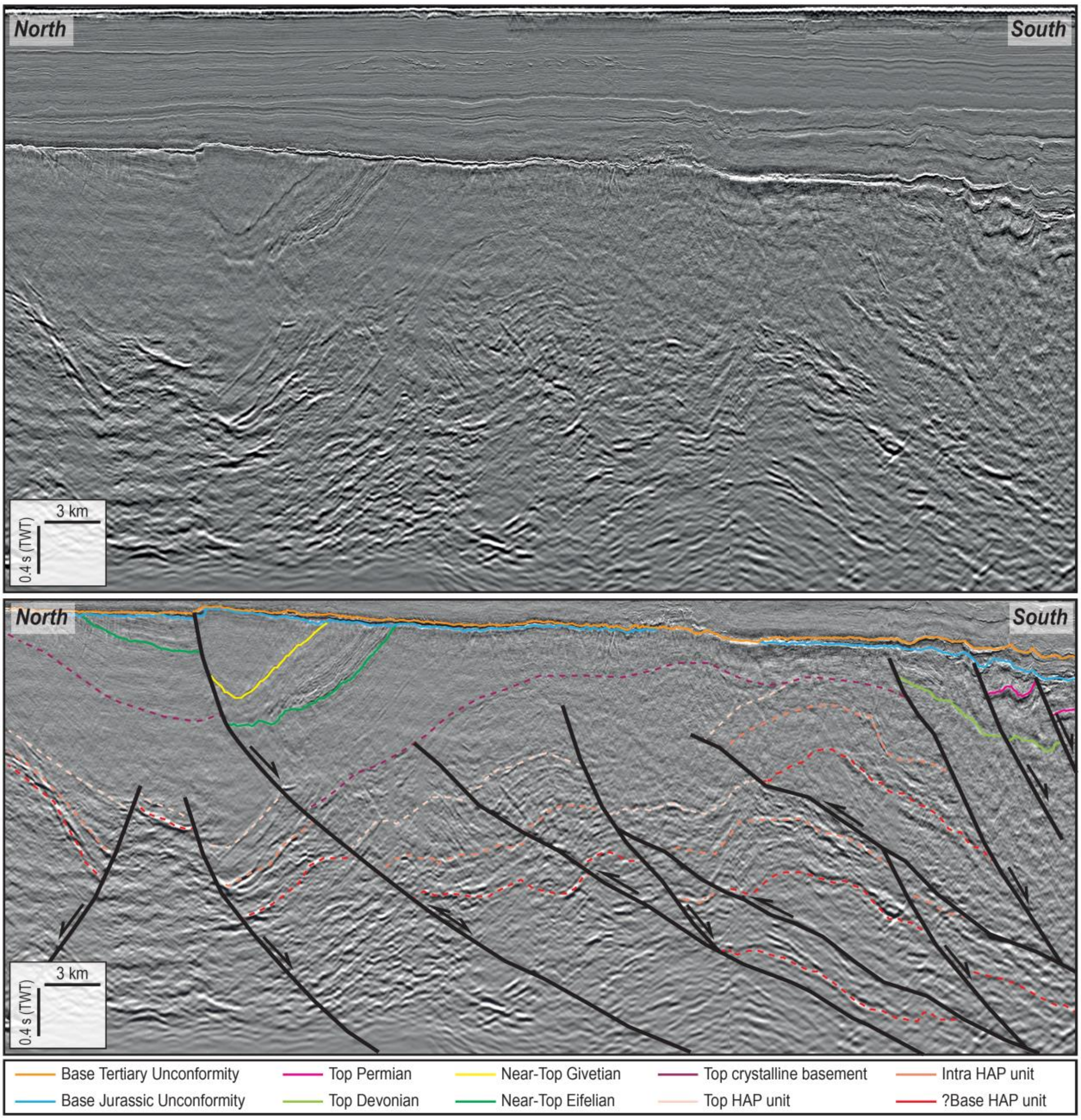
Lower Paleozoic igneous and metamorphic rocks assembled during the Caledonian Orogeny (or "Caledonides") are commonly thought to underlie the entirety of the North Sea sedimentary basin. The Caledonian fabrics are widely regarded to have been reactivated and inverted during subsequent tectonic phases, playing a pivotal role for the inherited structural grain of the North Sea. Until recently, however, offshore Caledonian basement structures have remained elusive to most industry-standard seismic surveys. Caledonian-, Devonian- and Variscan-age fold and thrust and related extensional structures have nevertheless been clearly imaged by 3D broadband dual-sensor towed-streamer (GeoStreamer®) surveys, acquired in 2011-2015 on the outer portion of the East Shetland Platform (ESP). Here, the Caledonian and Devonian compressional structures are described, and their hydrocarbon exploration potential is briefly discussed.

Below the Devonian sedimentary reflectors, a distinctly opaque seismic-stratigraphic unit underlies the whole ESP region, with TWT-thickness of 0.5-1.5 seconds. Few wells penetrated this unit, encountering either meta-sedimentary or igneous (granite) rocks. Below this seismically opaque "crystalline basement", a seismic package with high amplitude and low frequency reflections is seemingly affected by both extensional faults and compressional folds with shear planes. Hornblend-biotite gneiss or schists, with a metamorphic cooling age of 393 Ma (Early Devonian), were reported by the only well (9/4a-1) which is likely to have fortuitously penetrated this highly reflective deep-seated package ("HAP Unit" in the figure below). This seismic package is therefore interpreted to represent intra-crystalline reflectors, suggesting a regional-wide transition between major crystalline units characterized by substantially different compositions and acoustic impedance values (e.g., granites over gneiss, or acidic crystalline rocks over Iapetus-domain meta-basalts, as suggested by the hornblend-biotite mineralogy). The Early Devonian cooling age and the presence of likely thrusts suggest that this high-amplitude seismic package could represent pre-Devonian Caledonides.

Beneath the Paleocene Kraken Field, a major NNE-trending Devonian half-graben, is one of the largest structures developed during the fast extensional collapse of the thickened Caledonide crust, an event resembling the post-orogenic collapse of the Neogene Apennines belt (Italy). The deep-seated intra-metamorphic reflectors in this area are deformed by thrusts and folds to the south-east of the Devonian master-fault and by extensional faults to the north-west. A possible explanation is that the frontal thrust of the Caledonian belt was inverted into a Devonian extensional master-fault, and that the area to the north-west represents the Caledonian palaeo-foreland. The north-northeast strike of the Devonian master-fault closely resembles the main known lineaments associated to the Caledonian Orogeny (e.g., the Great Glen Fault and Iapetus Suture).

The Devonian interval in the ESP is itself variously deformed by folds and reverse faults, as well as extensional fault blocks, oblique-slip and inverted structures. The majority of the compressional structures are compatible with a Variscan age of deformation (Late Carboniferous). The northern portion of Quadrant 8, however, is characterized by likely flower-structure motifs within the well-imaged lower-middle Devonian interval, where several north-striking faults show either normal or reverse net-throw, with occasional association to fault-related folds or signs of inversion. These structures deform the lower-middle Devonian package, but do not seem to affect the upper Devonian and younger intervals. This is therefore more likely consistent with a transient middle Devonian compressional/wrench event rather than with Variscan foreland deformation, and was possibly associated with net sinistral transtension due to the relative expulsion of Baltica.

The possibility to map the Paleozoic strata and structures bears substantial positive consequences for the North Sea exploration efforts. The deep-seated anticlines and fault-blocks might represent large unexploited exploration targets, with fractured basement or Devonian reservoirs. Furthermore, the analysis of the Early Paleozoic structural fabrics allows for an improved understanding of the recurrent inversion, reactivation and inheritance patterns, which in turn influenced the Meso-Cenozoic depositional/erosional trends, inheritance-related trap formation and breaching during later events, as well as the heatflow and hydrocarbon migration history.



Regional cross-section across the partly inverted Devonian half-graben beneath the Kraken Field (Quadrant 9, ESP). A high-amplitude, low frequency seismic package (HAP unit) is visible, about 0.5-1.0 s (TWT) below the interpreted top crystalline basement. This package highlights the presence of possible Caledonian-age thrust-related folds and potential lateral-equivalent extensional horst-and-grabens, respectively to the south and to the north of the Kraken Devonian master-fault.

Structural styles and the 4D evolution of the Maranhao deepwater fold belt, NE Brazil.

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Sub-aerial thin-skinned fold and thrusts belts are typically characterised by stacked thrust systems formed by duplexes and imbricate fans with complex three-dimensional geometries. The detailed 3D geometries of sub-aerial fold belts are generally poorly understood due to outcrop limitations and the poor quality of seismic data in these mountainous belts.

A high-quality, depth-migrated 3D seismic volume across the Maranhao deep-water fold belt on the continental margin slope offshore north-eastern Brazil offers a unique opportunity to document a 3D fold and thrust belt with well-imaged duplexes, imbricate fans and overlapping detachments that are similar in style to the frontal sectors of many thin-skinned sub-aerial fold and thrust belts.

The Maranhao deepwater fold belt extends for at least 60 km NW-SE along the passive margin slope and 35 km NE-SW down slope (limited by the extent of 3D coverage). It deformed 3 – 4 km of Late Cretaceous to Pliocene, slope to deep marine strata and consists of multiple thrust - fold systems that sole into different detachment levels above a gently landward-dipping basal detachment on an over-pressured shale unit. Up-dip listric extensional faults link down dip to the stacked fold and thrust belt system.

The fold and thrust belt is divided into a northern and southern domain separated by a large volcanic complex at the base of the slope. The northern domain consists of a frontal imbricate fold belt underlain by a duplex, and up-slope an inner imbricate fold belt and a single large faulted detachment fold separated by a lateral ramp. The faulted detachment fold is a 5 km long anticline located in front of the rollover anticline in the transitional domain between the up-dip extensional zone of listric faults and the down-dip contractional systems. The anticline has a wavelength of 3 - 4 km and its forelimb is cut by a fan of thrusts faults. The southern structural domain consists of a well-developed frontal imbricate fold belt that was over-ridden by a younger major thrust sheet.

The northern frontal imbricate system consists of 12 well-imaged thrust sheets, 0.5 to 1.5 km thick, 1.5 to 2 km wide and more than 15 km long terminating in fault-related folds with half-wavelengths than range from 0.5 to 2 km. The displacements of individual thrusts increase to the north, and the spacing between thrusts decreases. Crest of the thrust tip-line folds are eroded by a major unconformity. The frontal imbricates are folded by the underlying duplex - 10 km long and 8 to 6 km wide and formed by 5 main horses, 0.5 km thick and 2 to 4 km wide. From south to north the duplex height varies from 0.7 to 1.4 km as it changes from a hinterland-dipping duplex to overlapping ramp anticlines (antiformal stack). The duplex looses displacement to the south whereas to the north it terminates against a lateral ramp.

Behind the frontal imbricates the inner imbricate fan detached at the same level as the duplex system but it deformed the entire pre-kinematic sequence as well as the syn-kinematic units of the piggyback basin of the frontal imbricate system. The inner imbricate system is 6 km long and is formed by 4 thrusts sheets and their fault-related folds. This imbricate system is bounded by a lateral ramp to the north and the lateral ramp that separates it from the faulted detachment fold to the south.

Between the northern and southern domains the northern frontal imbricate belt curves into a NNW-SSE direction as it bends around the flank of the volcanic complex and is cut by NE-SW trending thrusts. The southern extent of the northern frontal imbricate systems ends in a major sinistral tear fault that separated the northern and southern domains in the vicinity of the volcanic complex.

In the southern domain the NW-SE striking frontal fold belt is 30 km long and is characterised by an imbricate system of 10 to 15 overlapping thrust sheets that are 2 to 3 km wide and deform a sequence 0.7 to 2 km thick. Each thrust terminates in a fault-related fold of half-wavelengths from 1 to 2 km. Further south in this domain, the thrust sheets are 3 to 5 km wide. In the southern part of the this domain, the imbricate system was overridden by a major thrust system that is parallel to the fold belt and connects the basal detachment with a detachment level deposited on top of the imbricate system. Displacement on the main thrust increases to the south where this thrust over-rides more than 6 km of the underlying imbricate system. The thrust sheet is compartmentalised by lateral ramps that separate detachment folds, imbricate thrusts, and second order duplexes.

Detailed mapping of the thrust systems, related growth stratal patterns and unconformities has permitted the unravelling of the progressive deformation as this passive margin, linked extensional and contractional system evolved. In the contractional domains an initial imbricate fold belt formed followed by hinterland-back-stepping contractional folding and thrusting. The volcanic complex induced bending of the frontal imbricate fold belt and produced compartmentalization into the major northern and southern structural domains with accommodation along lateral ramps and a major sinistral tear fault system.

The overall geometries of the thrust complexes are presented together with detailed 3D analyses of the imbricate and duplex systems. Evolutionary models for the linked extension-contractional system are presented as well as 4D models for the duplexes and imbricate fold belts. Comparisons are made with existing models for the frontal zones of sub-aerial contactional fold and thrust belts.

Integration of different vintage data for revitalising exploration of proven and prospective plays in the Apulian thrust belt of southern Italy

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Hydrocarbon distribution in the Southern Apennines thrust belt is directly related to the geologic characteristics and evolution of the thrust units. In this structural-stratigraphic context, the main exploration target is represented by the carbonate units of the Apulian Platform, which contain the largest and deepest oil fields in the region (Val d'Agri oil fields). Thrust-related folds affect the Apulian carbonate platform succession (2.5-3 s TWT) in thickness, corresponding to 6000-7000 m, which is buried beneath the Lagonegro-Molise-Sannio allochthonous thrust sheet (Butler et al., 2004; Nicolai & Gambini, 2007). The stratigraphic sequence of the Apulian platform crops out in the Maiella Mt. and in the Puglia foreland. The shallow water carbonates belonging to the Apulian Platform represent the main reservoir units mostly trapped within anticlines formed in the hanging walls of major reverse faults (Shiner et al., 2004). Generation of hydrocarbons in the region started as soon as a critical load/thickness at the top of the Apulian carbonates had been reached with the emplacement of the allochthonous wedge. This means that hydrocarbon generation started soon after the early Pliocene first-phase tectonic event that controlled the emplacement of the allochthonous. Therefore, the expulsion and migration of hydrocarbons only began after the late Pliocene, during or soon after the final structuring of the deep Apulian thrust belt (Turrini & Renninson, 2004).

In this study, we reconstructed the subsurface structural setting of contractional Apulian structures around the Benevento discovery, which dates back to the early 70's. The reservoir consists of Turonian-Lower Miocene calcarenites and limestone at a depth of around 3000m below mean sea level and bearing both oil and gas. The traps are mainly structural as faults and folds and the seal is represented by the Messinian evaporates and Lower Pliocene shales. Different types (e.g., wells, seismic, maps, reports) of public and confidential vintage data were integrated with the aim to better characterise both proven and prospective hydrocarbon plays within the analysed area belonging to the buried Apulian thrust belt. The data that were used had been acquired mainly during the intense exploration phase between the 70's and the 90's in the well-known, but still underexplored, hydrocarbon province of the Southern Apennines of Italy. Through the renewed digital interpretation and integration of the data the known structures were better characterised and new prospective areas were identified. Various types of thrust-related structures were reconstructed as symmetric or asymmetric pop-up/push-up structures and anticlines interfering with pre-existing normal faults. The reconstructed setting of the top Apulian carbonates reveal that the buried highs mimic the morphological reliefs exposed at surface above the allochthonous units. This suggest that the last phases of deep contractional deformation that affected the Apulian thrust belt are also reflected at surface level. The time-to-depth conversion of the interpreted top carbonates allowed the visualisation of the real geometry of the buried structures and aided the assessment of potential hydrocarbon resources.

Concealed fold-and trust belt in the Congo Basin, Central Africa, revealed by structural analysis of the Dekese fully cored 1850m deep well.

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The Congo basin in Central Africa is believed to have been initiated as a failed rift in the Neoproterozoic and to have evolved subsequently by thermal relaxation, but this evolution was affected by two regional compressional events. Seismic reflection data evidenced compressional structures in the axial part of the basin which are related to in the early Palaeozoic (Pan-African) and the late Permian-Triassic (Gondwana) regional tectonic events. Two fully cored ~ 2000m deep stratigraphic wells have been drilled in 1954-55 and one of them (the Dekese well) revealed highly tectonised (folded and faulted) glacial-lacustrine sediments of Late Carboniferous-Permian age overlain by undeformed sub-horizontal Jurassic and Cretaceous sediments. As the Dekese Well was drilled at the southern margin of the Congo basin, at the vicinity of the Kasai Archean cratonic block, this suggests interactions between the Kasai block and the Congo basin, which could not be seen on the seismic profiles.

In this work, we used structural measurements of bedding, slickensided faults and fractures as an attempt to reconstruct the associated stress field and the 1-D deformation geometry. Unfortunately the cores are not oriented, but the most of the Permian and older series are significantly inclined, allowing to use the bedding plane as a strike reference.

The structures observed can be explained by folding and faulting during a main compressional stage with a thrust faulting stress regime, and a later wrench-faulting reactivation under a strike-slip stress regime. The structural geometry is that of a series of internally faulted and tilted blocs, separated by brittle tectonic discontinuities marked by strongly deformed fault-rock. Deformation was mainly localised in the varval clay layers, and the massive diamictite in between being passively involved in the deformation.

Modeling Growth Strata to Constrain Development of Contractional Structures

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Continual improvements in seismic data acquisition and processing have provided geoscientists with increasingly detailed images of the folds and faults that define structural petroleum traps. In particular, many seismically imaged structures show complex, depth-dependent variations in synkinematic growth strata geometry that directly record changes in fault slip and sedimentation over time. Growth strata can effectively constrain the timing of trap development but can be difficult to interpret based on observation alone. This study shows how interactive digital fault-bend-fold and fault-propagation-fold forward models can be used to decode complex structural histories that include changes in sedimentation rate relative to fault slip and multiple phases of deformation such as contractional reactivation of normal faults. We will examine a basement-involved fault propagation fold from the Tarim basin (Figure 1) and an inversion structure in the Peruvian sub-Andes that records two phases of contraction in addition to early extension. In both cases, the growth strata are complex, featuring internal angular unconformities that reflect their dynamic history. A third example from the Outeniqua Basin in South Africa shows how complex hangingwall unconformities can arise from movement along fairly simple faults. (Figure 2).

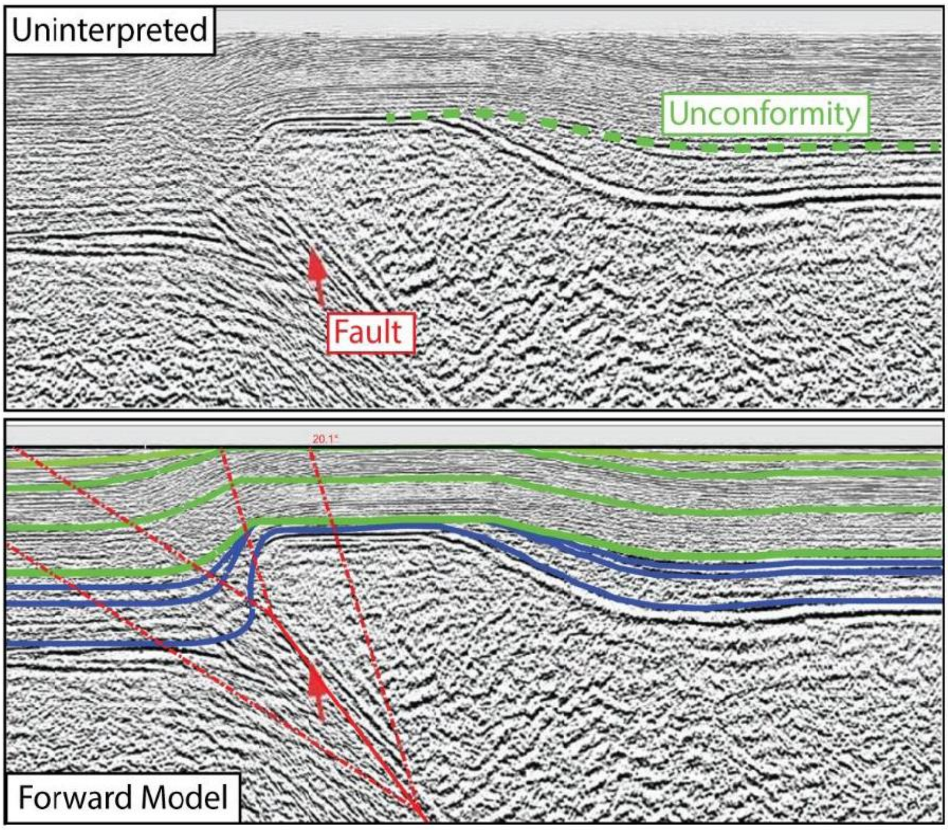

Figure 1: Tanan uplift in the Tarim basin. Image from Shaw et al. 2005.

The flexibility of the interactive modeling approach greatly facilitates modeling structures with internal angular unconformities. In the examples shown here, unconformities within the growth section reflect variations in the rates of fault slip and syntectonic sedimentation, regional shifts in base level, and structural inversions. However, deciphering the stratigraphic and kinematic implications of these unconformities can be difficult because footwall or hanging wall strata may be partially or entirely eroded. Interactive structural models allow us to continually modify footwall to hangingwall correlations until the computed horizon shape matches the observational data. By parameterizing the model surfaces by age, the footwall and hangingwall burial histories can be arbitrarily complex, allowing younger surfaces to erode older ones. Where younger surfaces intersect older surfaces, the younger surfaces truncate older surfaces giving rise to angular unconformities within the model.

Figure 1: Tanan uplift in the Tarim basin. Image from Shaw et al. 2005.

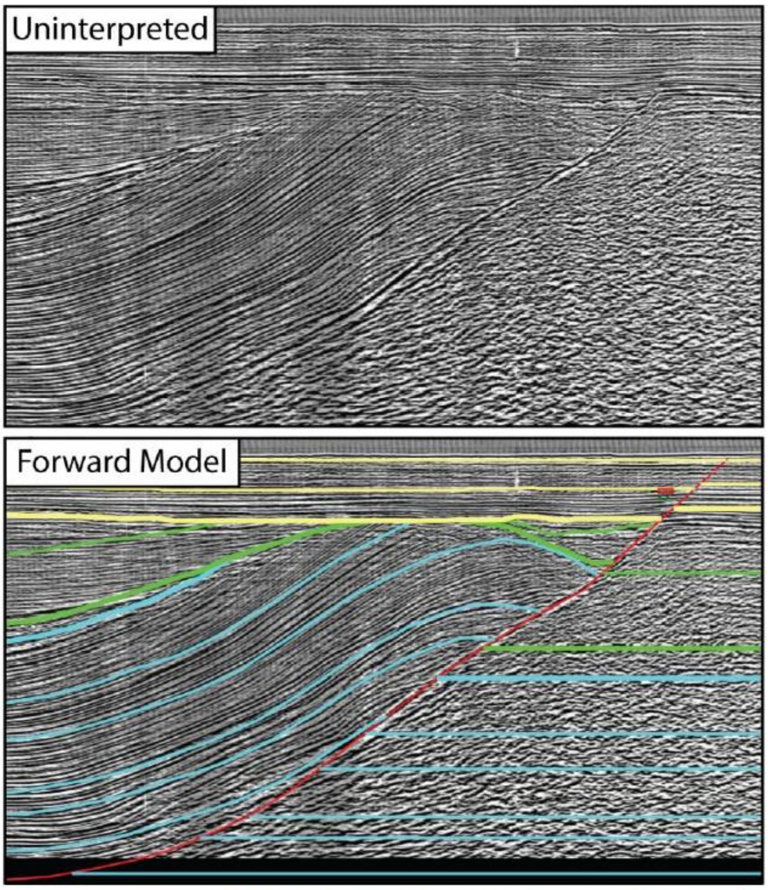

Figure 2: Gamtoos Fault in the Outeniqua Basin. Image from Thompson (1999)

The models presented here use inclined shear fault-bend-fold and trishear fault propagation fold modeling algorithms. The structural model parameters are interactively adjusted until the modeled surface geometries match the growth strata imaged in the seismic data. The model parameters include fault geometry, horizon ages and displacements, shear angles, trishear angle, and initial and final fault tip locations. The structural history arises organically from the model geometry and is displayed visually through animation.

Microstructural changes and dehydration of slates in the temperature window 180-330°C

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In fold-and-thrust-belts sheet-silicate-rich rocks often present a mechanically weak phase in which substantial deformation is accommodated either as detachment or intensely folded domains. Sheet silicate minerals, such as illite/muscovite and chlorite dominate their rheological behaviour. Besides the highly anisotropic deformation behaviour (crystallographically - controlled) of the sheet silicates, the water content represents a second component reducing the overall strength of such aggregates either by reducing the strength of the individual grains (i, crystal and interlayer water) or of the entire aggregate by (ii) interstitial pore fluids. With increasing compaction (pressure) and temperature, both the amount of (i) and (ii) decrease, respectively, requiring a dehydration of the system. In the current study we aim to gain a profound understanding about the ‘where’, ‘when’ and ‘why’ of these dehydration processes as function of increasing temperature and their effects on the overall mechanical behaviour of the slates. Presented is the microstructural evolution of the Intra Helvetic Flysch Units in the Glarus Alps in Switzerland along a temperature gradient from 180°C to 330°C.

The Flysch units are deposited in the underfilled Northern Alpine Foreland Basin and accreted in-sequence to the Penninic accretionary wedge during subduction of European margin (Lihou, 1996). Out-of-sequence thrusting, such as the Glarus thrust, placed the Helvetic nappes on top of the Infra Helvetic Flysch units. Note that the Flysch units are extremely heterogeneous comprising layered mineralogical variations owing to turbiditic sedimentation processes. In this study we mainly focus on shaly and silty layers. We collected a N-S sample profile across these Flysch units, covering a change in peak metamorphic conditions from 180°C in the north to 330°C in the south (Ebert et al., 2007; Lahfid et al., 2010; Rahn et al., 1995). The temperature gradient positively correlates with a background strain gradient, as the southern units are subducted to the deepest levels.

Different lithological and strain end members, respectively silty vs. clay layers and low vs. high strain, of slates are sampled from surface and subsurface outcrops along the above mentioned gradient, after which porosity analyses are performed on several scales (cm to nanometer). The applied methods include water-loss porosity, helium pycnometry, mercury intrusion porosimetry (MIP) and finally image analysis on SEM and BSE images. These data are completed with a full geochemical XRD quantification and EDS analyses.

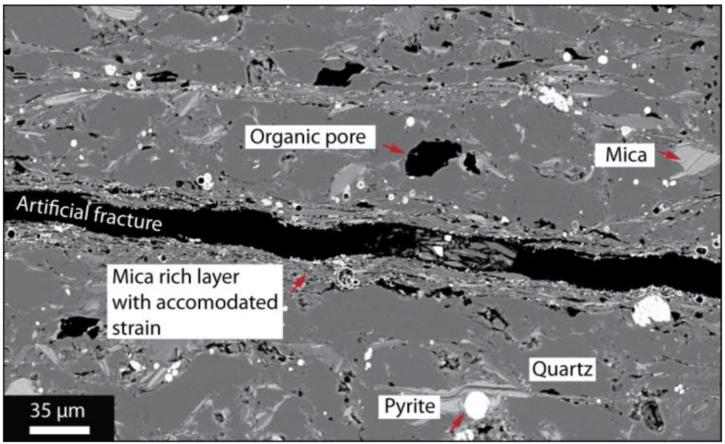
Along the metamorphic gradient, microstructural investigations reveal the change from a compaction induced soft-sediment microstructure in the north to the evolution of a spaced cleavage towards the south. Cleavage develops from randomly orientated micas in a calcite clay matrix at 180°C to a fully developed spaced cleavage or pressure solution cleavage around 300°C. According to Dielforder et al. (2016) earliest deformation recorded by the sediments in the north reflect ductile folding assisted by particulate flow under soft sediment conditions. While sediments consolidated and accreted into the orogenic wedge brittle deformation was dominant, indicated by out-of-sequence thrusting and brittle deformation recorded in quartz-calcite veins (Dielforder et al., 2016).

Three major types of pores are discriminated: (1) fractures, defined by an aspect ratio of $b/a < 0.2$. These can be further subdivided into type (1a) open fractures without mineralisation >10micron in width that are orientated parallel to bedding and cut the complete thin section, type (1b) microfractures with a width of about 1-5 microns and not continuous throughout the whole thin section. These microfractures are often located along the grain boundaries of micas, (1c) open veins and (1d) mineralized veins. Type (2) porosity is related to fossil fragments with and without inorganic shells (here called “organic” porosity). This type of porosity developed large slightly elongated pores with an average diameter given by the longest axis of 22 µm and areas >64 $\mu m^{2.}$ Sometimes this type of porosity is associated with the growth of framboidal pyrite. The last pore type comprises (3) matrix pores, which include slightly elongated pores with diameters given by the longest axis of about 3 µm and areas <64 μm^2. These pores are either interlayer pores associated with mica and clay minerals, intraparticle pores in calcite or quartz or intergranular pores (classification after Cao et al., 2016).

Porosity of the bulk rock of the slates, obtained by helium pycnometry and MIP, show that most samples are falling in the 1 - 4 vol% range. Sample heterogeneity is reflected by a comparison between helium pycnometry and MIP data. These data are strongly influenced by the presence of fractures and the amount of “organic” porosity. The matrix porosity does not vary with temperature and shows constant values of 0.5 - 0.7 vol%. The number of fractures is higher in clay layers than in silty layers and varies along the strain gradient. Increasing strain results in a fracture porosity increase from 0.03 vol% in low strained samples to 0.6 vol% in high strained samples.

Image analyses on BSE images yield substantial differences in porosity between the different sedimentological layers. Clay- and mica-rich layers, i.e. relatively fine-grained layers, have a lower quartz content and show a higher porosity than silty layers. The matrix porosity is inversely correlated with grain-size. Pores in the clay rich layers are located along the grain boundaries of micas, which is responsible for their elongated shape. Pores in quartz rich layers are round and mostly sitting around quartz grain boundaries. Interesting is that deformation is localised by fine-grained mica and clay rich layers resulting in an elevated porosity (Figure 1). These layers contribute greatly to the effective porosity and act as important fluid pathways.

With increasing temperature, compaction and background strain, a spaced cleavage forms. As mentioned before, the fine-grained mica-rich layers show a higher porosity than their silt-rich neighbours do. In the latter, cementation processes particularly the growth of diagenetic calcite and quartz plays an important role as porosity reducing mechanism. Quantification demonstrates that fine-grained mica-rich layers host a large part of the porosity and localise strain, thereby acting as important fluid pathways. The ultimate link between dehydration (pore destruction), water release and spatial distribution during migration along preferential pathways provides the key for an improved understanding of the link between fluid release and deformation in fold-and-thrust belts.



which localise strain and show an elevated porosity compared to the matrix.

Understand and Model Complex Geology of Fold and Thrust Belts - from Interpretation to Fluid Flow Prediction

Melanie Morin
Paradigm

Building an accurate 3D model that honors structural and geological complexities is a key factor in reliable reserves estimates and flow prediction.

Many plays are now located in challenging Fold and Thrust Belt geological environments- with high variability of structure geometries, complex thrust faults and overturned structures. In particular, new exploration occurs in areas that have, until recently, been too complex to capture successfully all the geological complexity. Additionally, ongoing hydrocarbon production from existing plays often needs more detailed study than was originally carried out to reduce uncertainty and mitigate E&P risks.

First, the existing available data may be limited: complex areas with intense deformations are challenging for seismic imagery due to complex geology and large variations in topography. Therefore, a good understanding of the asset requires to get also the most from other data types. It becomes also important to evaluate data reliability and assess of the impact this subsequent uncertainty on final results.

Second, the model will have to capture all the complexity with no limitation. In complex areas we can't base the key business decision on simplistic layer-cake models and there is a need to create models without technology limitations in highly faulted reservoirs, in compressive environment with complex thrust faults and imbricated folds, with overturned structures, with vertically variable structures due to de-coupling, etc.

Finally, at the reservoir engineering stage, the flow model has also to capture the structural complexity to be predictive while still meeting the requirements of the current flow simulators technology. And it will necessarily request interactions and changes in a geologically consistent manner.

In this poster we will present how this unique volume-based technology enables the geoscientists to create a geologically-consistent 3D subsurface model honouring available data without simplifications from interpretation to fluid flow prediction for a better understanding and characterization of the play to get accurate volume estimates and forecasts.

Burlington House
Fire Safety Information

If you hear the Alarm

Alarm Bells are situated throughout the building and will ring continuously for an evacuation. Do not stop to collect your personal belongings.

Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshal on that floor.

Fire Exits from the Geological Society Conference Rooms

Lower Library:
Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.
Lecture Theatre
Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.
Main Piccadilly Entrance
Straight out door and walk around to the Courtyard.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS**.

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society. Event organizers should report as soon as possible to the nearest Fire Marshal on whether all event participants have been safely evacuated.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid

All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities

The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.

Ground Floor Plan of the Geological Society, Burlington House, Piccadilly