Global and Planetary Change 90–91 (2012) 1–19

Contents lists available at SciVerse ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Review paper

Coupled Deep Earth and surface processes and their impact on geohazards

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ARTICLE INFO

Article history:
Received 4 October 2011
Received in revised form 19 January 2012
Accepted 20 January 2012
Available online 31 January 2012

Keywords:
geohazards
geo-energy
Deep Earth
topography

ABSTRACT

Better understanding of coupled Deep Earth and surface processes is the key for resolving the evolution of the continental lithosphere and its surface topography. The thermo-mechanical structure of the lithosphere exerts a prime control on the interaction of mantle instabilities and tectonic forces operating on the lithosphere. These processes are fundamental for differential vertical motions at or near the Earth's surface and have a strong impact in the domains of geohazards and geo-energy. Stress fields exert a main control on volcano dynamics and in the conduits of fluids and melts. Integrated Solid Earth sciences intrinsically link different spatial and temporal scales and involve an interdisciplinary approach, with strong feedbacks between observational studies and imaging of Earth structure, reconstruction of the geological record and process-modelling.

Contents

1. Introduction

The Deep Earth is the driver of many of the processes that shape the Earth's surface and the interaction between Deep Earth processes and surface processes, affected by for example climate, is far more intensive than realized till recently. This interaction has direct consequences for natural hazards, including seismicity and landslides, but it also exerts a main control on the location and occurrence of natural resources and geo-energy. In this context, sedimentary basins, mankind's largest resource of energy and fresh water, are paramount. Quantitative insight in the evolution of sedimentary basins has dramatically increased over the last decades as a result of major conceptual advances in understanding their tectonic settings and thermo-mechanical evolution (Roure et al., 2009). At the same time, due to massive acquisition of new data, partly in conjunction with intensive energy exploration, novel constraints are available to further test and refine model predictions. It is the integration of novel monitoring and imaging, high-resolution geological reconstruction and process modelling that holds great promises for better process-based geo-prediction. The lithosphere, being the interface between the Deep Earth and the Earth's surface, plays a key role in integrated solid Earth Sciences (Faccenna and Becker, 2010; Tesauro et al., 2011, 2012–this volume). It represents the best studied part of the plate tectonic engine and is a theme of vigorous research also in the years to come. As pointed out in recent reviews (Jones et al., 2010; Artemieva, 2011; Burov, 2011), an integrated approach reconciling inferences from geophysical and petrological studies is essential (Schuberth et al., 2009a,b). Seismological constraints provided by deep seismic reflection profiling of the continents carried out in a process-oriented frame such as pioneered by the Lithoprobe project (Clowes, 2010) has been vital in this respect. The same is true for the constraints provided by seismic tomography, indispensable for tectonic interpretation of lithospheric processes (e.g. Wortel and Spakman, 2000; Spakman and Hall, 2010; Van der Meer et al.,

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0921-8181/$ – see front matter © 2012 Published by Elsevier B.V.
doi:10.1016/j.gloplacha.2012.01.010

2010). At the same time, the role of surface processes (Willett and Brandon, 2002) and their interaction with tectonic processes operating on the lithosphere is now increasingly realized to be of fundamental importance for understanding of the evolution of the continents and their margins (Cloetingh et al., 2007).

The International Lithosphere Programme (ILP) promotes and coordinates lithospheric research with an emphasis on better understanding of System Earth dynamics, with a keen eye for its implications for issues of societal importance (Cloetingh and Negendank, 2009).The papers in this volume provide a survey of some recent developments in integrated Solid Earth sciences, with a focus on the connection of Deep Earth and surface processes, linking a range of spatial and temporal scales.

2. Continental topography and lithosphere dynamics

Thinking deep in space and time is also in the heart of novel approaches to continental topography, linking sediment sources from eroding mountains to sediment sinks in subsiding basins (Cloetingh et al., 2007, 2009, 2011; Braun, 2010; Matenco and Andriessen, in press). An example of such an integrated solid Earth approach is provided by the European Large Scale Collaborative Research Effort (EUROCORES) TOPO-EUROPE, coordinated by the European Science Foundation and initiated by the International Lithosphere Programme. In this programme, with a focus on the topography of continental Europe and its margins, researchers from 23 countries are cooperating. TOPO-EUROPE is not only advancing fundamental understanding of the coupling between the Deep Earth and Earth's surface but its efforts have also led to novel models for the strength of the Earth's crust and its thermal state, of direct impact for enhanced geothermal energy exploration (Cloetingh et al., 2010) and carbon dioxide storage. The challenges for sustainable geo-energy require further development of novel concepts for basin exploration and reservoir engineering. For conventional resources improved reservoir production concepts for enhanced recovery are required whereas exploration in frontier basins such as the Arctic and complex geological

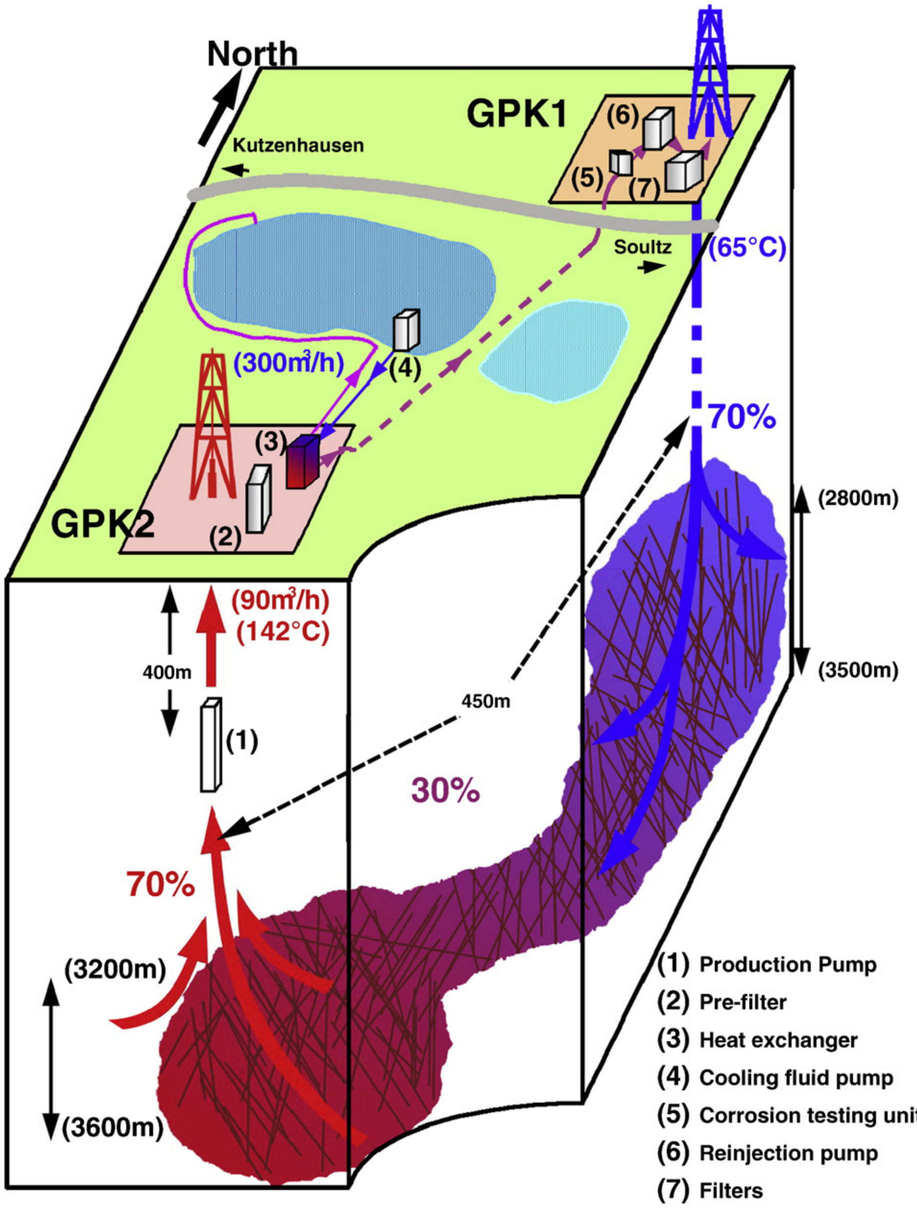


Fig. 1. Schematic diagram of an Enhanced Geothermal System (EGS) experiment conducted at Soultz (Cloetingh et al., 2010). Hydraulic fracturing has been used to stimulate flow properties of the basement rock. During simulation induced seismicity did not exceed M = 3.

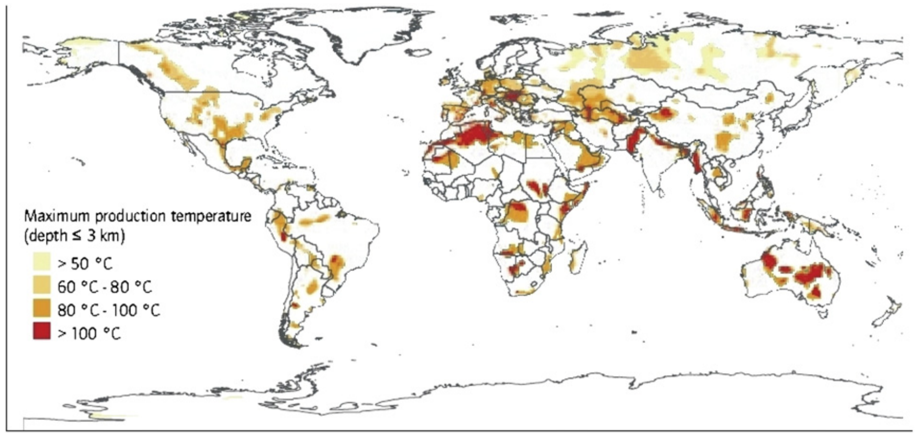


Fig. 2. World deep geothermal aquifers, suitable for direct heat production for heating and cooling and, if marked by sufficiently high temperatures, for electricity production. Source: www.thermogis.nl/worldaquifer.

settings can strongly benefit from novel integrative multi-disciplinary approaches (Roure et al., 2009; van Wees et al., 2009). For unconventional resources and geothermal energy (Fig. 1), better exploration techniques are also needed to outline prospective subsurface locations (e.g. geothermal hot spots, deep natural fluid conduits, and naturally fractured shales). For reservoir simulation improvement in robustness of models in predicting rock–fluid interactions affecting productivity and induced seismicity is particularly needed (Cloetingh et al., 2010). Fig. 2 gives an example of the incorporation of in-depth global insight on sedimentary basin distribution and deep thermal gradient, on the geothermal potential for geothermal energy production from aquifers.

During the last few years a large number of studies have addressed the mechanical structure and long-term rheology of continental lithosphere (see Burov, 2011 for a recent review). These studies benefitted from constraints on lithological and thermal structure of the lithosphere, new findings from rock mechanics data and inferences from flexural and thermo-mechanical modelling of continental lithosphere in various tectonic settings. As a result, first order models have been established for the present-day structure of several continents, including Europe (Tesauro et al., 2009a,b) as well as models with lower resolution of a global scale (Audet and Burgmann, 2011; Tesauro et al., 2011, 2012–this volume). These models suggest a strong control by thermo-tectonic age and inherited structure on the bulk strength of the lithosphere in intraplate settings (Cloetingh and Ziegler, 2007; Burov, 2011). Mechanical decoupling between crustal and mantle layers within the lithosphere strongly affects the interaction between Deep Earth and surface processes. This topic has been addressed over the last few years by a successful integration of numerical approaches (e.g. Burov and Cloetingh, 2010) as well as by their coupling with field studies and analogue modelling (Cloetingh et al., 2004; Matenco et al., 2010; Sokoutis and Willingshofer, 2011). Fig. 3 illustrates the pronounced influence of the rheology on the mechanical coupling between the foreland and a weak orogenic wedge inferred from analogue modelling (Sokoutis and Willingshofer, 2011). As shown by Fig. 3, this has a strong impact

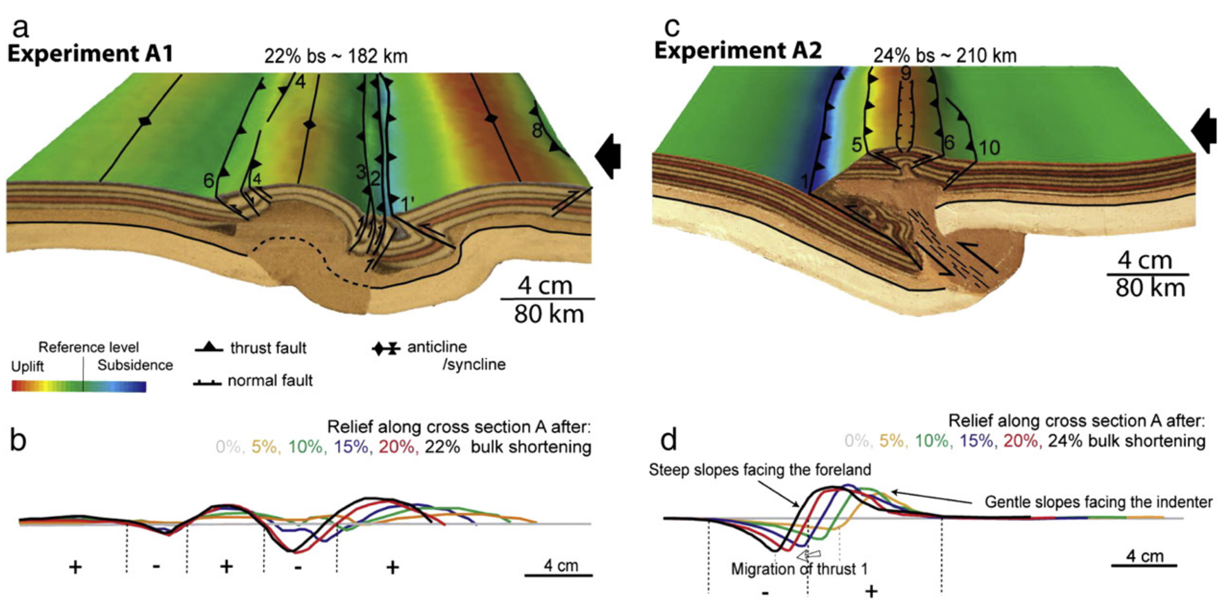
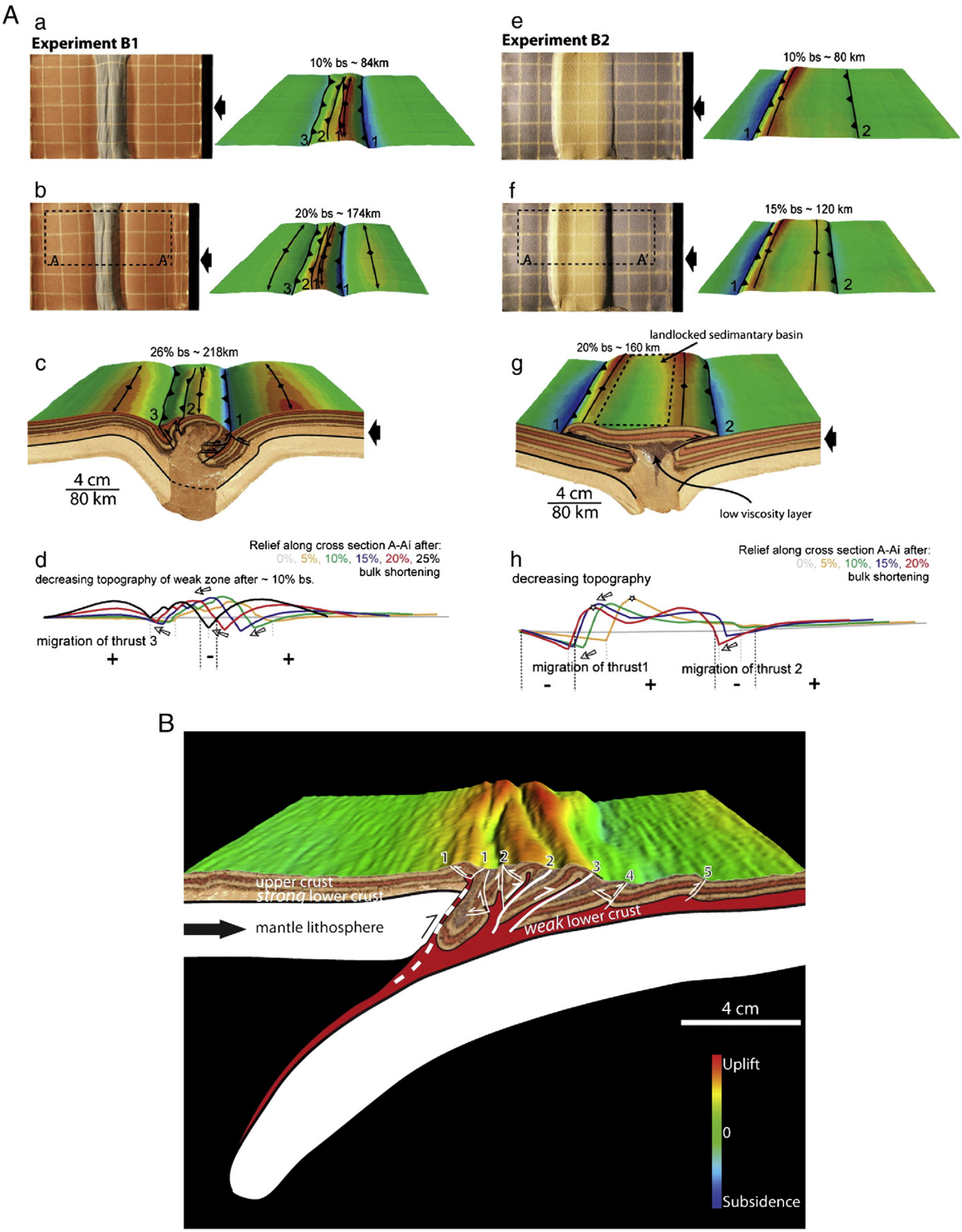


Fig. 3. Modelling results of experiments A1 (a and b) and A2 (c and d) showing the influence of the strong (experiment A1) versus weak (experiment A2) coupling between the foreland and a weak orogenic wedge. The finite geometry (Fig. 3a and 3b) is displayed as composite of a digital elevation model and a selected cross section from the model. Numbers indicate the sequence of deformation. Grid spacing is 4 cm. Black thick arrows indicate the direction of shortening. The evolution of topography through time along the cross-section is shown in 3b and 3d.
After Sokoutis and Willingshofer (2011).


A
a
Experiment B1
10% bs ~ 84km
3 2 1 1
b
A A'
20% bs ~ 174km
3 2 1 1
c
26% bs ~ 218km
3 2 1
4 cm
80 km
d
Relief along cross section A-Ai after:
0%, 5%, 10%, 15%, 20%, 25%
bulk shortening
decreasing topography of weak zone after ~ 10% bs.
migration of thrust 3
+ - +
e
Experiment B2
10% bs ~ 80 km
1 2
f
A A'
15% bs ~ 120 km
1 2
landlocked sedimantary basin
20% bs ~ 160 km
g
1 2
4 cm
80 km
low viscosity layer
h
Relief along cross section A-Ai after:
0%, 5%, 10%, 15%, 20%
bulk shortening
decreasing topography
migration of thrust1
migration of thrust 2
- + - +
B
1 1 2 2 3 4 5
upper crust
strong lower crust
mantle lithosphere
weak lower crust
4 cm
Uplift
0
Subsidence

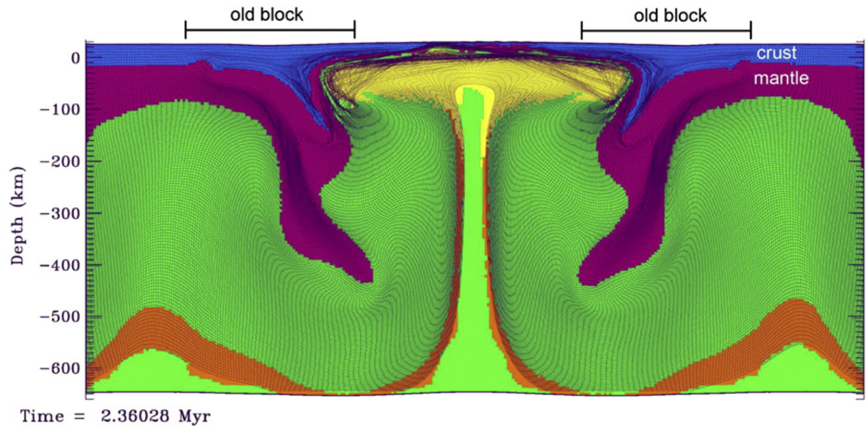


Fig. 5. Experiments on plume-lithosphere interactions below a horizontally heterogeneous continental plate with stratified rheology (300 km-long 300 Ma old continental blocks embedded in a younger 150 Ma old lithosphere). Colour code: purple — mantle lithosphere, blue — upper and lower crust, green — deep mantle, yellow — plume, orange — bottom marker layer (same as deep mantle). The rheology profile corresponds to viscous-elastic–plastic crust and mantle with granite and olivine dislocation flow law, respectively. Plastic properties are controlled by Mohr-Coulomb failure criterion for the crust and Peierls plasticity for the mantle.
Modified after Burov and Cloetingh (2010).

on the topography evolution of the deforming lithosphere. In this context, the presence or absence of weak mid-crustal layers appears to be crucial for the shape of the topography (Fig. 4A,B). As demonstrated by Luth (2011) the role of crustal rheology is crucial in the onset of continental lithosphere subduction (see Fig. 4B). Important in this context is for example the role of the rheological stratification of the lithosphere in preservation of ancient cratonic blocks (Francois et al., 2011), in surface expression of plume-lithosphere interactions and its impact on the 'dynamic' topography and stability of continental platforms (see also Moucha et al., 2008) in general. This impact results in possible appearance of short tectonic wavelengths of surface deformation that overprint and attenuate long-wavelength dynamic topography (e.g. Burov et al., 2007; Burov and Cloetingh, 2009; Burov and Cloetingh, 2010, Fig. 5). The same is true for the effect of large-scale lithospheric folding on intraplate basin formation and associated differential vertical motions and, in some cases, enhanced distributed brittle faulting, that may occur at different spatial scales determined by the internal structure of the lithosphere (Cloetingh and Burov, 2011; Fig. 6). In addition to the role of the internal mechanical stratification of the lithosphere, the geometry of the plate contact and its rheology (Fig. 7) itself also appears to exert a main control on the style of lithosphere deformation and its topographic expression (Luth et al., 2010; Luth, 2011). Initiation of continental lithosphere subduction, crucial for linking orogenic deformation to intraplate deformation appears to be facilitated by plume lithosphere interactions (Burov and Cloetingh, 2010, Fig. 8). Cloetingh and Burov (2011) present a discussion of these aspects, focusing on better process understanding of continental deformation, in the context of a number of well-documented cases of intraplate deformation for Europe, including Iberia (Fernandez-Lozano et al., 2011), the Pannonian Basin (Dombrádi et al., 2010) and Central Asia (Cloetingh and Burov, 2011).

The first set of six papers has a focus on constraints on mantle and crustal structure and implications for thermo-mechanical structure of the lithosphere and for dynamic processes of mass transfer and vertical motions. As pointed out above, constraints by seismic tomography provide key insights on the structure and evolution of the coupling between lithosphere and mantle dynamics. An example of this approach is provided by Cheng et al. (2012–this volume) who present new findings on the tomography of the southern Taiwan subduction zone and possible emplacement of crustal rocks into the fore-arc mantle. These authors investigate the velocity structure of the active plate boundary in southern Taiwan by joint analysis of gravity anomaly and seismic arrival time data. The total available Ocean Bottom Seismometer (OBS) data set consists of ~700 detected earthquakes, from which around 500 could be well located where about 450 events have been used in simultaneous inversion for hypocenters, three-dimensional Vp and Vp/Vs models for the study area. Gravity data are used to improve the model for the offshore area, where it is poorly sampled by local earthquakes. Their study found a low-velocity zone existing above the subducting South China Sea slab in the mantle wedge. Their analysis suggests that the subduction complex is characterised by a low P-wave velocity and low Poisson's ratios beneath southern Taiwan. This duplex structure is characterised by a zone of low P-wave velocities in the range of 6.2–6.8 km/s between 25 and 40 km depth. Their research shows that earthquake hypocenters do not fall within this low velocity zone. The authors have also used seismic tomography velocities to estimate the volume percentage of serpentinite and silica concentrations in southern Taiwan. The calculated serpentinite is about 30% and the volume percentage of quartz estimated is about 20% at the base of the fore-arc lower crust.

Seismic tomography is also important in the context of planetary dynamics at large and for a comparative analysis of planets. In this spirit, Zhao et al. (2012–this volume) present inferences from seismic tomography and geochemical evidence for lunar mantle heterogeneity and a comparison with Earth. They review seismic tomography and geochemical evidence for the existence of significant lateral heterogeneities in the lunar mantle and make a comparison with the Earth's heterogeneity and seismicity. The Procellarum KREEP Terrane (PKT) is a unique province on the nearside of the Moon. It constitutes only about 15% or less of the lunar surface, but appears to owe a large portion of the Moon's radioactive heat-producing elements. Zhao et al. (2012–this volume) found a good correlation between the Thorium (Th) abundance distribution on the lunar surface and seismic tomography of the lunar nearside. The area with high Th abundance exhibits a distinct low shear-wave velocity, and the low-velocity anomaly extends down to 250–400 km depth below the PKT,

Fig. 4. A. Modelling results of experiments B1 (a–d) and B2 (e–h) emphasising the strong influence of the presence of weak mid-crustal layers (experiment B2) on the shape of the resulting topography. Interpretation was assisted by top view photos, surface DEMs, cross-sections from the models and diagrams of topographic evolution through time. Fig. 4B. Cross-section and topography of a lithosphere-scale analogue experiment after 25% bulk shortening. A combination of an inclined plate boundary and a weak lower crust in the lower plate resulted in subduction of dense continental mantle lithosphere, meanwhile the upper crust deforms by thrusting towards the lower plate.
Panel A is after Sokoutis and Willingshofer (2011). Panel B is after Luth (2011).

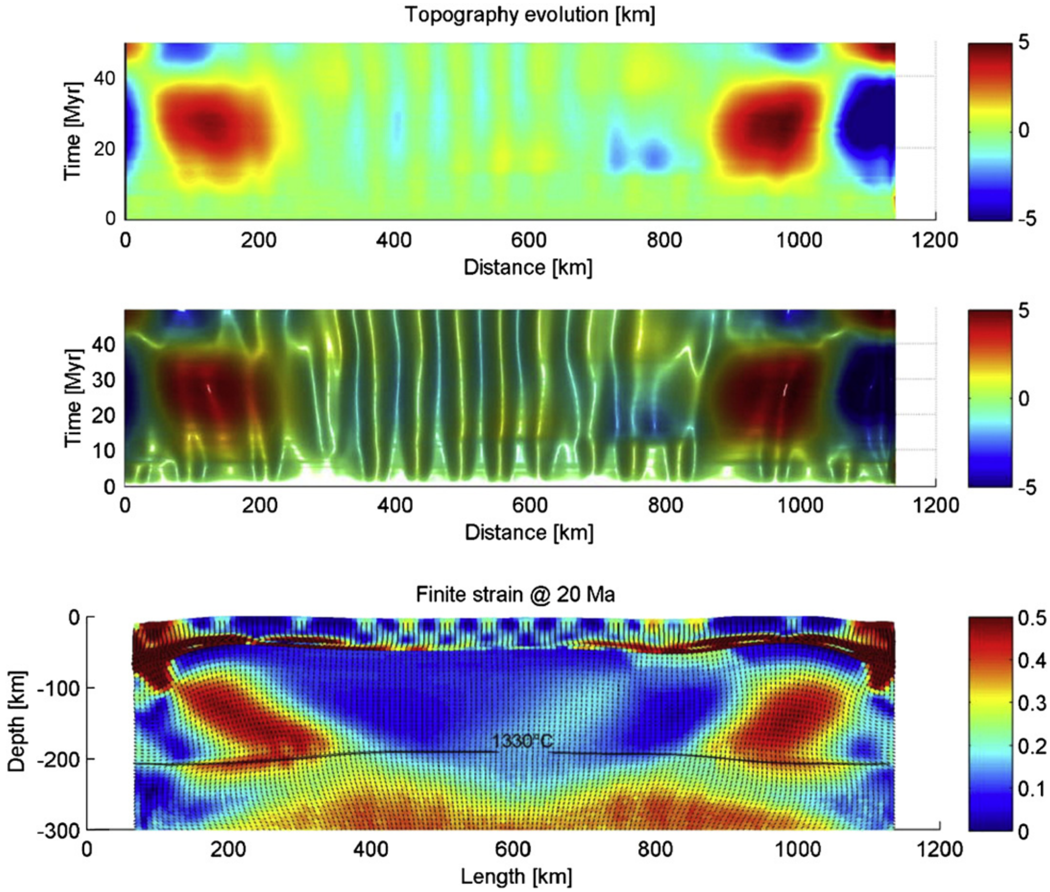


Fig. 6. Thermo-mechanical numerical model of folding of stratified 250 Ma old 250 km thick visco-elastic–plastic continental lithosphere showing development of short crustal wavelengths superimposed on large-scale mantle wavelengths. Shortening rate is 6 mm/yr. Dry olivine mantle, 40 km thick crust with granite upper crust, quartz-diorite lower crust. Bottom panel: finite strain distribution and the position of 1330 °C isotherm reflecting long-wavelength deformation of the bottom of the mantle lithosphere. Middle panel: topography evolution in 3D view. Upper panel: topography evolution in map view. Note also distributed brittle faulting in the upper crust with spacing controlled by the folding wavelength.
Modified after Smit et al., submitted for publication.

suggesting that the thermal (or compositional) anomaly has a depth extent to 250–400 km in the lunar mantle. The distribution of deep moonquakes shows a correlation with the seismic velocity variations in the deep lunar mantle, similar to the seismicity in the Earth. The presence of deep moonquakes and distinct seismic velocity heterogeneities in the mantle implies that the interior of the present Moon may be still thermally active.

The surface expression of deep-seated thermal anomalies and associated density distributions depends strongly on the mechanical structure and non-linear mechanical properties of the overlying lithosphere (Burov and Cloetingh, 2009). This is particularly true for continental lithosphere with its stratified rheology (Burov, 2011, Fig. 9). Indeed, rheological stratification and strain rate dependent rheology result in local strength drops and partial or full decoupling between competent rheological layers within the lithosphere leading to variations in the wavelength and amplitude of isostatic topographic response at surface and Moho level (Fig. 9). The lithosphere rheology also controls the wavelengths of the differential motions induced by a large variety of tectonic processes, including slab-detachment (Andrews and Billen, 2009; Duretz et al., 2011; Van Hunen and Allen, 2011), lithospheric folding (Cloetingh and Burov, 2011; Smit et al., submitted for publication, Fig. 6) and plume impingement (Burov et al., 2007; Guillou-Frottier et al., 2007; Cloetingh and Burov, 2011, Fig. 5). Particularly important in this context is the thermal state of the lithosphere and the nature of the lower crust (Burov, 2011, Fig. 9). Guillou-Frottier et al. (2012–this volume, see also Fig. 10) present models for plume-induced dynamic instabilities near cratonic blocks, demonstrating their major implications for P-T-t paths and metallogeny. Plume head — lithosphere interactions around cratonic blocks result in thermo-mechanical disturbances that lead to heating and burial phases of crustal rocks. The authors present results from numerical models of plume head — cratonic block interactions where a free upper surface condition and realistic rheologies are accounted for. These models include distinct cratonic blocks embedded within a continental lithosphere and separated by several hundreds of kilometres. Surface topography, thermal field and effective viscosity values are tracked for 20 Myr of interactions. The modelled dynamic interaction of a plume head around cratonic blocks results in two main types of instabilities, each of them resulting in a distinct P-T-t path. The "slab-like" instability, focused on cratonic edges when the plume head is away from the craton centre, shows a near-isothermal burial phase, while the "drip-like" instability occurring above plume head material results in a near-isobaric heating phase. Consequently, both clockwise and counter clockwise P-T-t paths can be expected around cratons, as actually observed around the Tanzanian craton and other cratonic areas. Metallogenic data from gemstone-bearing rocks in south-east Africa and data from ultrahigh temperature and ultrahigh pressure metamorphism are compatible with this model. It appears that vertical mantle dynamics around cratons may also explain thermobarometric signatures that are often attributed to horizontal tectonics.

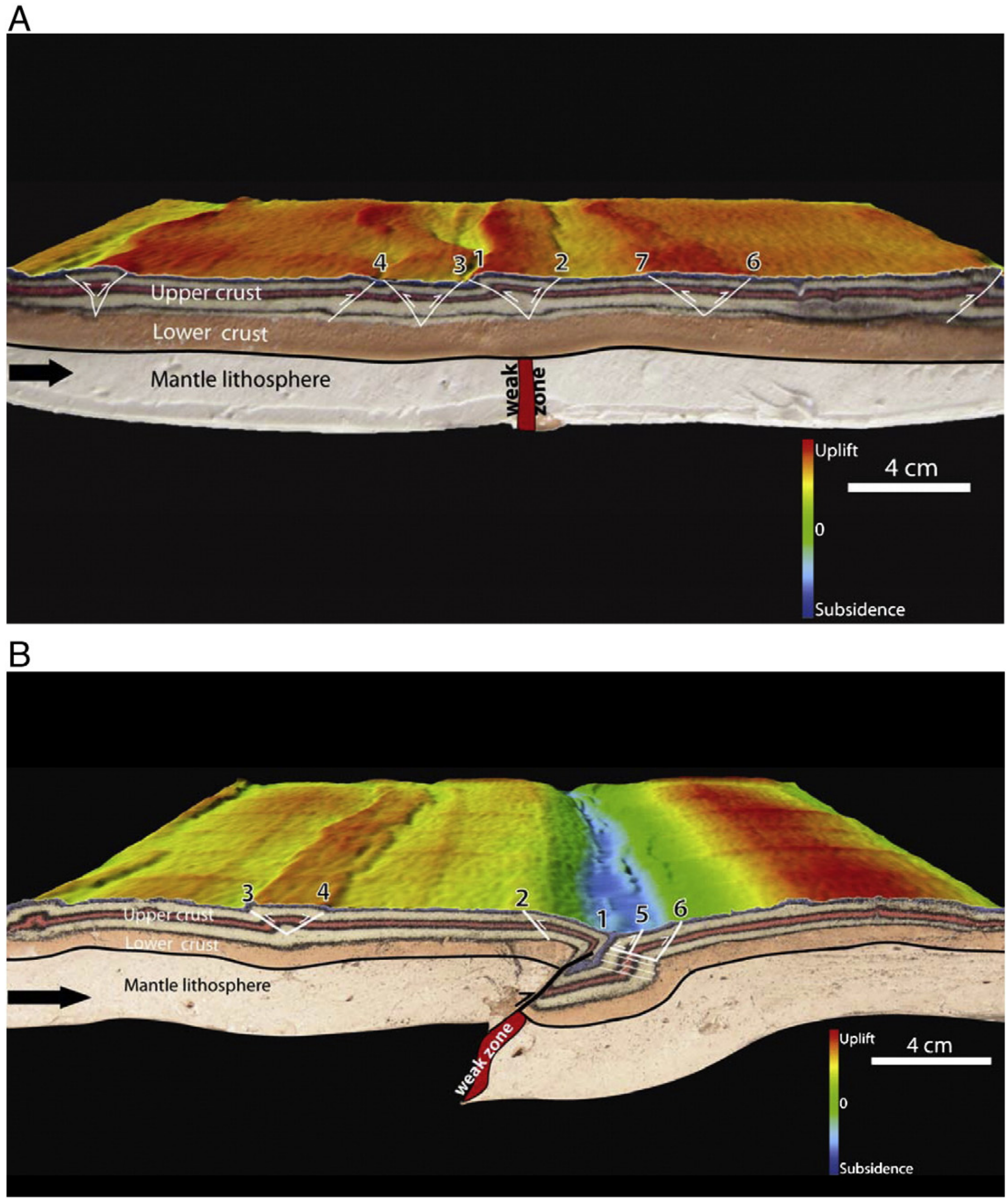


Fig. 7. Cross-sections and topography of analogue experiments with a vertical (Fig. 7A) versus an inclined (Fig. 7B) weak plate boundary (Luth et al., 2010). No displacement occurred along the vertical plate boundary, but the model deforms by lithospheric buckling and crustal thrusting of the plate interiors (Fig. 7A). With a 45° inclined plate boundary deformation initiated along the plate interface, but ceased after the consumption of weak material and propagated towards the plate interiors (Fig. 7B).

During the last few years, a number of studies have been carried out on the rheology of continental Europe (e.g. Pérez-Gussinyé and Watts, 2005; Tesauro et al., 2009b), benefitting from the availability of a large number of constraints on crustal and lithospheric structure and thermal state of Europe's lithosphere (e.g. Tesauro et al., 2008, 2009a,b) provided by several decades of intensive observational studies, in the context of programmes such as the European Geotraverse (EGT) (Blundell et al., 1992) and Europrobe (Gee and Stephenson, 2006). Following this up on a global scale, Tesauro et al. (2011, 2012–this volume) present models for global strength and elastic thickness of the lithosphere. The strength and effective elastic thickness (Te) of the lithosphere control its response to tectonic and surface processes. The authors present global strength and effective elastic thickness maps, which are determined using physical properties from recent crustal and lithospheric models. Pronounced strength contrasts appear to exist between old cratons and areas affected by Tertiary volcanism, which mostly coincide with the boundaries of seismogenic zones. The authors demonstrate that lithospheric strength is primarily controlled by the crust in young (Phanerozoic) geological provinces characterised by low Te (~25 km), high topography (>1000 m) and active seismicity. In contrast, the old (Achaean and Proterozoic) cratons of the continental plates show strength primarily in the lithospheric mantle, high Te (over 100 km), low topography (<1000 m) and very low seismicity.

During the last few years, the Carpathian mountains of Eastern Europe have been the domain of a large number of studies, integrating geology, thermochronology, geophysics and geomorphology to elucidate the causes of their recent differential motions. Their possible association with the dynamics of the downgoing slab in the bend zone, in particular in the context of geophysical and geological

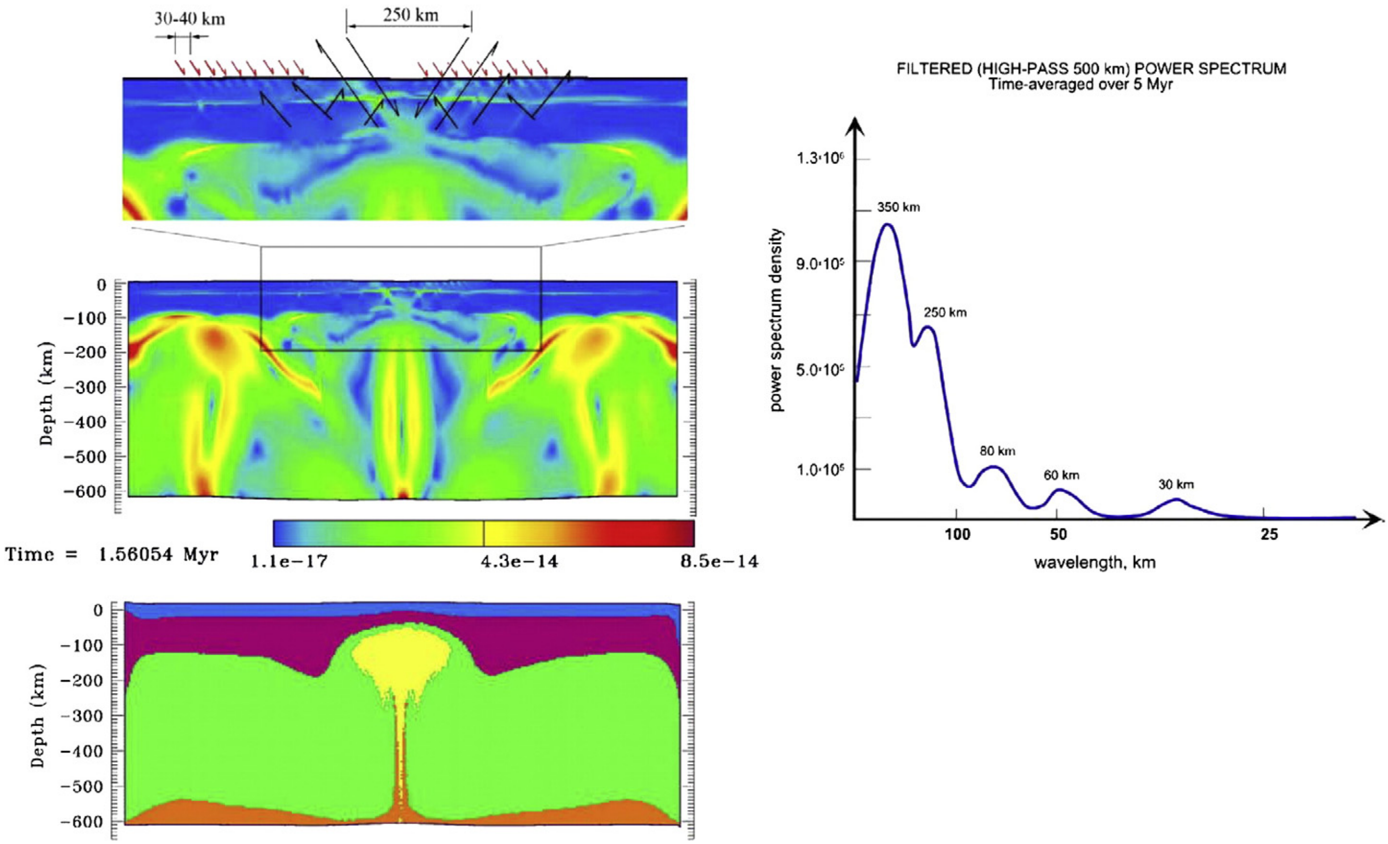


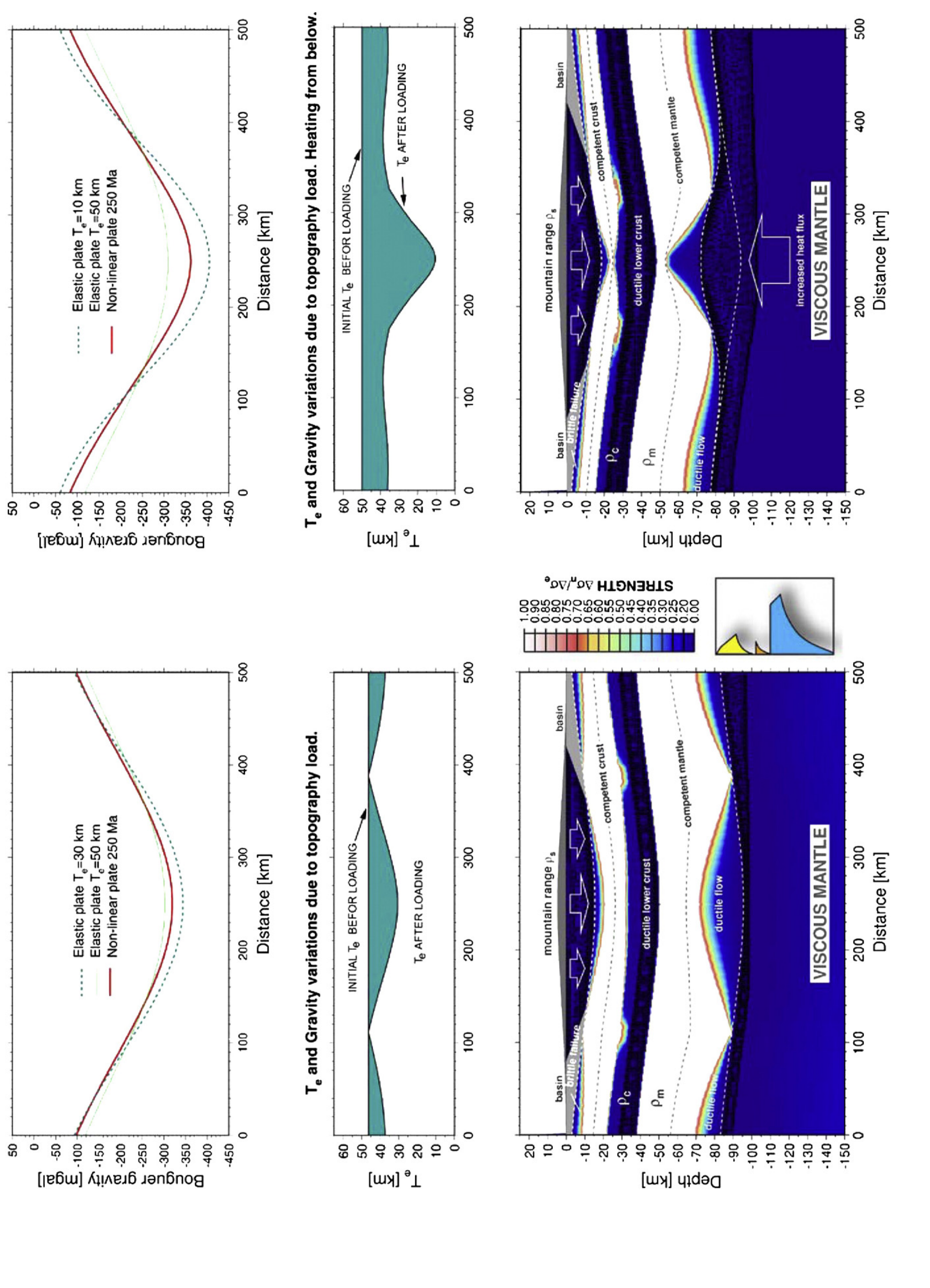
Fig. 8. Experiments on plume-lithosphere interactions with a heterogeneous viscous-elastic–plastic continental plate with stratified rheological structure. Colour code: purple — mantle lithosphere, blue — upper and lower crust, green — deep mantle, yellow — plume, orange — bottom marker layer (same as deep mantle). The heterogeneous plate includes 300 Ma old (strong) 300 km long, 200 km thick blocks embedded in thinner (150 km) and younger (150 Ma) lithosphere. Note strong localisation of interaction, with plume pushing on the borders of the lithospheric blocks producing subduction-like entrainment of the lithosphere.
Modified after Burov and Cloetingh (2010).

evidence for slab detachment (Wortel and Spakman, 2000; Martin et al., 2006) of the Romanian Carpathians, has been the subject of intensive investigation (e.g. Cloetingh et al., 2004; Matenco et al., 2010; Necea, 2010; Ismail-Zadeh et al., 2012; Merten et al., 2011).

Fig. 11 provides an example from the Transylvanian Basin/Apuseni Mountain system of Romania, illustrating the power of an integration of tectonics and state-of-the art geothermochronology, elucidating the connection between exhumation history and Present-day topography. As pointed out by Merten et al. (2011), a direct correlation between the topography and the exhumation ages demonstrates that the Apuseni Mountains were exhumed during the Cretaceous–Palaeogene orogenic build-up period. This demonstrates a rather stable topographic area during the Miocene roll-back of the Carpathians and the collapse of the associate neighbouring Pannonian basin.

Molin et al. (2012–this volume) further examine the interaction of mantle dynamics, crustal tectonics, and surface processes in the topography of the Romanian Carpathians through a geomorphological approach. Tectonic processes and dynamic mantle flow impart a unique imprint on topography and geomorphic responses over time scales of 10^4 to 10^6 yr. First-order topographic features in a tectonically active landscape represent ways to quantitatively characterise the interaction between crustal tectonics, mantle dynamics, and geomorphology, providing a basis for modelling landscape evolution. The authors analysed the topographic features of the Romanian Carpathians, a mountain range characterised by two straight segments connected by a narrow curvature zone. The deformation started in the Late Jurassic and includes two collisional phases during the Cretaceous and Miocene. They examined the tectonic geomorphology of the Romanian Carpathians focusing on regional and local topographic setting, drainage pattern, and river long profiles. The longitudinal profiles of rivers draining the southern Carpathians were found to be close to the equilibrium shape, in agreement with the older emersion of the chain. The longitudinal profiles of the rivers draining the eastern and south eastern Carpathians are reported to be in a transient state of disequilibrium as a consequence of a more recent emersion of the chain and of the Pliocene–Pleistocene tectonic activity in the Bend Zone. A relative topographic low is detected in the Carpathian Bend, where mantle seismicity and a high-velocity zone in tomography data are located and commonly interpreted as related to an almost inactive and dying subduction zone. In contrast, a topographic high exists in the Transylvanian basin, where tomography data show a low-velocity area, interpreted as upwelling of hot

Fig. 9. Effect of stratified viscous-elastic–plastic rheology on the integrated strength of the lithosphere and its flexural isostatic response to surface loading. On this example, a Gaussian-shaped mountain range of 3 km maximal height and 200 km wide provokes localized rheological weakening and noticeable modification (expressed in observable gravity anomaly due to Moho depression) of flexural response compared to common constant-strength models. The integrated strength is expressed in terms of T_e (middle panel). The strength distribution due to surface loading is shown in the bottom panel (ratio of actual, e.g. inelastic flexural stress to maximal elastic flexural stress). Left case: initially laterally homogeneous model. Right case: plate locally heated from below (e.g. due to mantle lithosphere interactions).
After Burov (2011).


Elastic plate Te=30 km
Elastic plate Te=50 km
Non-linear plate 250 Ma
Bouguer gravity [mgal]
Distance [km]
Te and Gravity variations due to topography load.
INITIAL Te BEFOR LOADING
Te AFTER LOADING
Te [km]
mountain range ρs
basin
brittle failure
competent crust
ductile lower crust
competent mantle
ductile flow
ρc
ρm
VISCOUS MANTLE
Depth [km]
STRENGTH Δσn/Δσe
Elastic plate Te=10 km
Elastic plate Te=50 km
Non-linear plate 250 Ma
Te and Gravity variations due to topography load. Heating from below.
increased heat flux

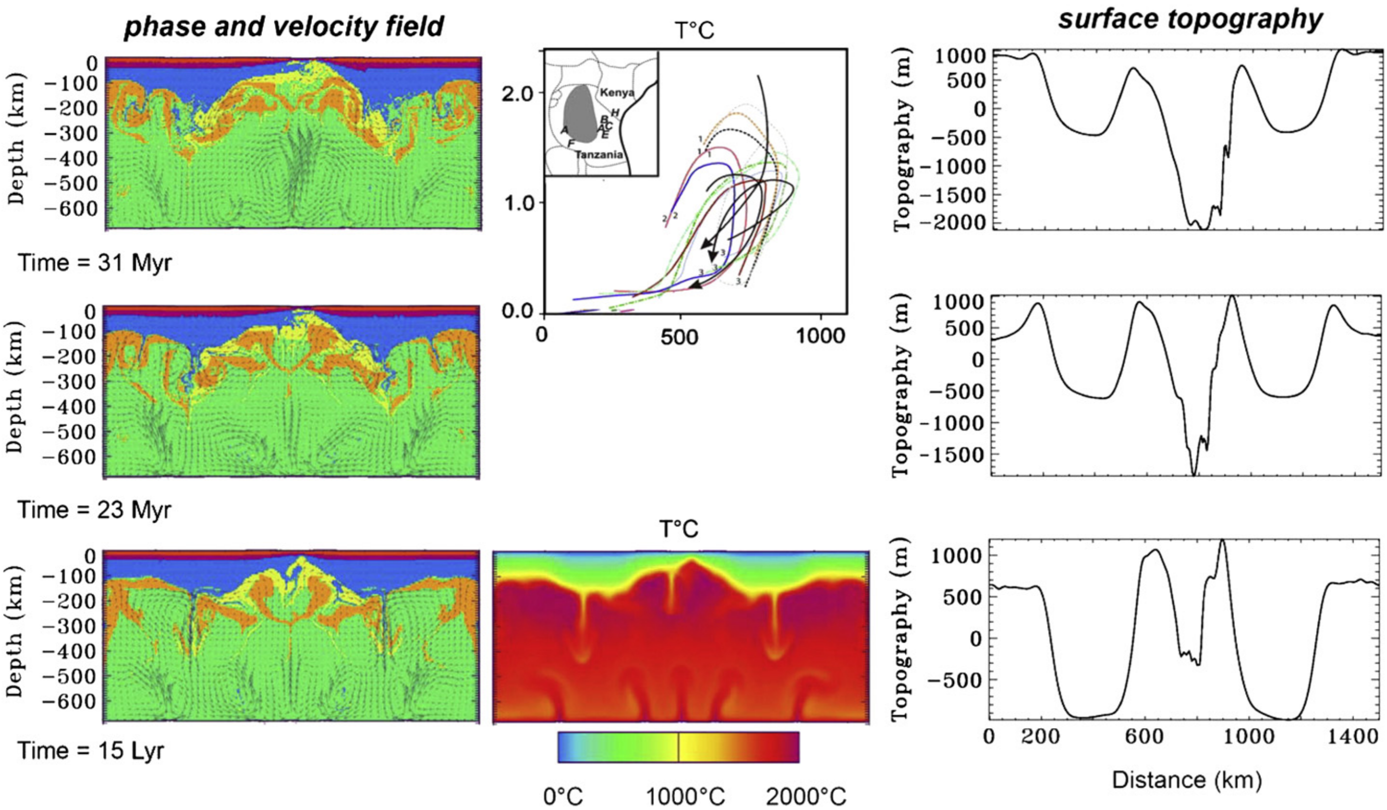


Fig. 10. Plume-lithosphere interaction below a heterogeneous viscous-elastic–plastic continental plate containing older cratonic blocks. Heterogenic structure of the lithosphere leads to almost complete overprinting of the long-wavelength dynamic topography by shorter scale topographic movements. Note also complex circulation of mantle and plume material near the bottom of the lithosphere leading to mélanges and cyclic burial and exhumation of mantle units. Left panel shows material phases (lithosphere mantle is blue, crust purple, plume material orange and yellow, asthenosphere and deep mantle — green). The top of the middle panel shows predicted (colour) and observed (black arrows) P-T-t paths (Kenia–Tanzania system). The bottom of the middle panel shows a snapshot of the thermal field. The right panel shows the predicted topography evolution. After Guillou-Frottier et al. (2012–this volume).

asthenospheric materials. Folded and tilted Middle Miocene–Upper Pliocene foredeep deposits suggest active compression beginning in the Lower Pleistocene. During the Middle-Late Pleistocene and Holocene, four terrace orders developed by the interaction between regional uplift and climate changes. According to the authors, the Carpathian topography results from a diachronous uplift superimposed on crustal tectonics. This diachronous uplift influenced the chain topography, the shape of river longitudinal profiles, and the formation of strath terraces. Crustal tectonics dominated the hydrographic net organisation. In the Carpathian Bend and the Transylvanian basin, mantle flow driven by slab pull produced negative and positive dynamic topography.

Rifted continental margins are the site of strong differential topography, connecting subsiding basins offshore and elevated topography onshore (Chalmers and Cloetingh, 2000). Early models of rifted continental margins were cast in terms of rapid vertical motions during continental break-up followed by gradual post-rift subsidence. As reviewed by Cloetingh and Ziegler (2007), rifted margins are often characterised by a polyphase evolution, often associated with a varying degree of duration of rifting and interplay of thermal processes, tectonic forces (see also Ziegler and Cloetingh, 2004) and compressional reactivation during their post-rift phase (Johnson et al., 2008; Gouiza et al., 2010; Munteanu et al., 2011). A striking example is the tectonic inversion of the Black Sea Basin during the orogenic collision recorded in the Pontides–Taurides domain (Fig. 12). The collision has gradually inverted the Black Sea Basin during the late Middle Eocene to Miocene times, demonstrating that orogenic stresses can be transmitted at far distances away from the plate boundary into rheologically weakened back-arc basins (Munteanu et al., 2011)

It also appears to be of vital importance to integrate observations from offshore segments of rifted margins with studies of vertical motions in the adjacent continent. The NW African rifted margin provides an example where such an integration (Gouiza, 2011; Gouiza et al., 2010), utilizing constraints from low-T geochronology data (Fig. 13), revealed the occurrence of pronounced regional 2–3 km magnitude of exhumation during the Late-Jurassic–Early Cretaceous post-rift phase of the margin evolution. The latter is characterised by the simultaneous occurrence of anomalously strong subsidence, deviating from predictions of classical models for extensional basin evolution (Fig. 14). As demonstrated by thermo-kinematic modelling, a thermal anomaly below the margin is required during the post-rift phase to account for the excess subsidence observed offshore (Gouiza et al., 2010).

The interaction between surface erosion at elevated rift shoulders and lower crustal flow in the relatively hot extending lithosphere (Burov and Cloetingh, 1997; Burov and Poliakov, 2001) provides another contributor to differential margin topography, deviating from predictions of early basin models (e.g. Lawrence et al., 1990), not incorporating insights on thermo-mechanical structure and stress regimes in the lithosphere. Japsen et al. (2012–this volume) argue that the morphology of elevated, passive continental margins is not related to rifting or continental breakup. Many studies of elevated, passive continental margins (EPCMs) assume that their characteristic, large-scale morphology with high-level plateaux and deeply incised valleys has persisted since rifting and crustal separation, and that

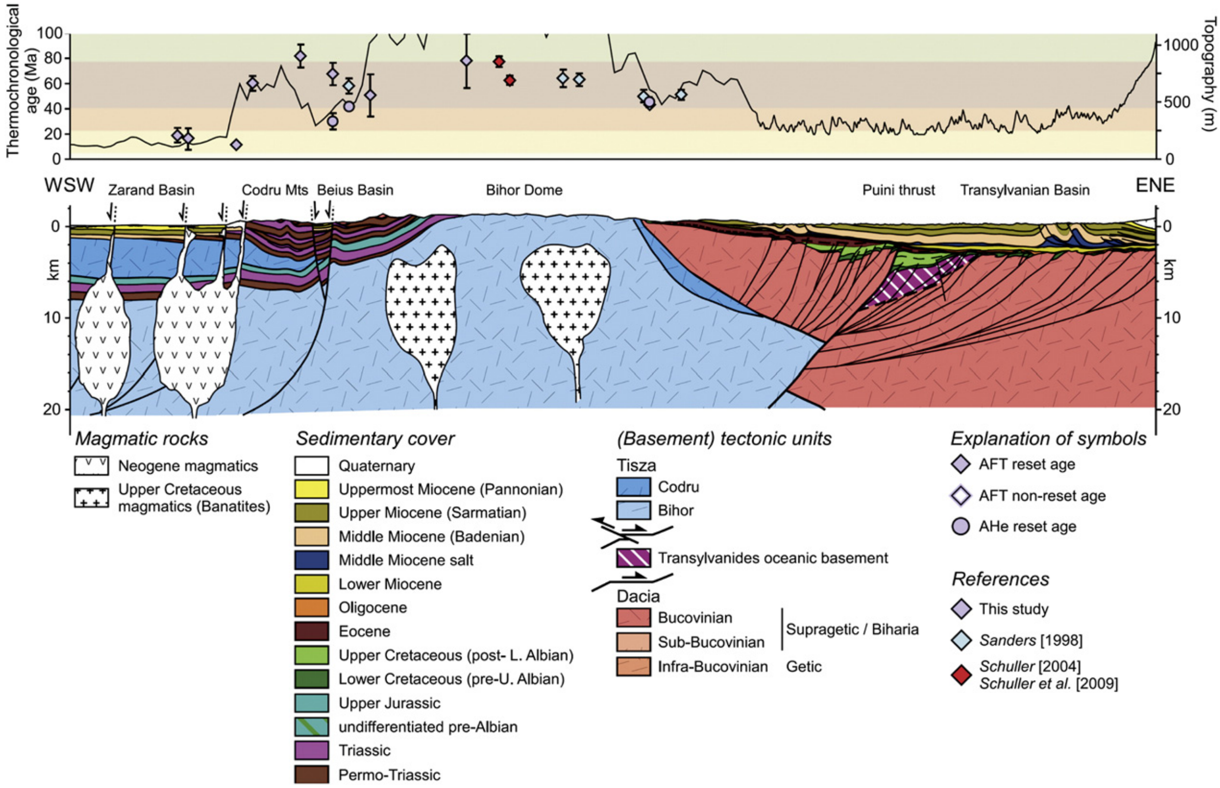


Fig. 11. Crustal-scale cross-sections across the Apuseni Mountains and neighbouring Transylvanian Basin (2X vertical exaggeration) with the topographic profile and thermochronological cooling ages Background colours in the thermochronological plots are evolutionary periods, i.e., from bottom to top: Miocene-Quaternary, middle Eocene–Oligocene, latest Cretaceous–early Eocene, late Albian–Santonian and Early Cretaceous. Solid lines represent topography (25× vertical exaggeration; scale-bar on the right side of the plots). After Merten et al., 2011.

the absence of post-rift sediments is evidence of non-deposition. The high mountains in West Greenland, however, expose evidence of km-scale, post-rift subsidence, and recent studies showed that typical EPCM morphology with elevated plateaux formed c. 50 Myr after breakup through a process of uplift and dissection of a regional, post-rift erosion surface. Since the West Greenland margin shares all the morphological characteristics of EPCMs, the results from West Greenland (Japsen et al., 2012-this volume) lead to question the common assumption that EPCMs have remained high since the onset of continental separation. They present published evidence of post-rift burial followed by uplift and exhumation from a number of EPCMs and their adjacent basins to support the notion that EPCMs are not permanent highs and that their morphology is unrelated to rifting and continental breakup. They present a conceptual model that accounts for a number of features observed along many EPCMs. In their model, post-rift burial followed by episodic km-scale uplift and erosion during at least two episodes; one to erode the region to produce a low-relief surface (a peneplain) near the level of the adjacent, opening ocean, and a second one to raise it to its present elevation. Their observations indicate that the abrupt change in crustal and lithospheric thickness may make the margins of cratons unstable a long time after rifting, and that changes in tectonic forces along the margin may initiate uplift.

3. Lithospheric stress fields and their controls on volcanism and geohazards

Lithospheric stress fields have been a topic of intensive research in the context of ILP for a long time (e.g. Zoback, 1992). Stress modelling has been an important component of these research efforts since the beginning (See Heidbach et al., 2010, for a recent review). These studies have addressed the relative roles of various factors affecting lithospheric stress, including the effects of plate-tectonic forces (Cloetingh and Wortel, 1985), forces set up by differential topography (Bada et al., 1998; Pascal and Cloetingh, 2009), effects of sediment loading (Cloetingh et al., 1982), and the role of magma forces (Jolly et al., 1994; Moran, 2003; Tibaldi and Lagmay, 2006; Roman and Heron, 2007). Fig. 15, for example, shows the orientation of the maximum horizontal shortening directions in Europe superimposed over topography and crustal thickness (Olaiz et al., 2009). The latter have been calculated from seismic and receiver functions studies.

Much ILP research has also been dedicated to the analyses of the relationships between stress and various types of geohazards, including seismic, hydrogeological and volcanic hazard. Fig. 16 provides an example of a field study dedicated to the recognition of late Quaternary faults affecting the Icelandic Rift (Gudmundsson, 2000). Landslide hazard studies can combine data from different sources, integrating field data, numerical data and analogue, scaled modelling, such as the ones conducted at Stromboli volcano (Fig. 17).

Stress fields are also of paramount importance to the understanding of differential vertical motions in the lithosphere and in the discrimination of tectonic and climatic controls on relative sea level variations (Cloetingh et al., 1985). In addition, stresses and their interaction with the geomechanics of the lithosphere (e.g. Zoback, 2007) are crucial in setting up conduits for fluid transport and melt movements inside the lithosphere. Feedback effects between tectonic stress and magma stress have also been put forward in a series of recent papers (e.g. Tibaldi and Pasquaré, 2008; Watt et al., 2009; Tibaldi et al., 2010; Bonali et al., 2011). These feedback effects may be represented by tectonic stresses that guide the processes of magma ascent and emplacement. In Fig. 18 a case is presented of tectonic control on the type and location of volcanoes in the central volcanic Andean Chain based on the tectonic style and state of stress (Tibaldi et al.,

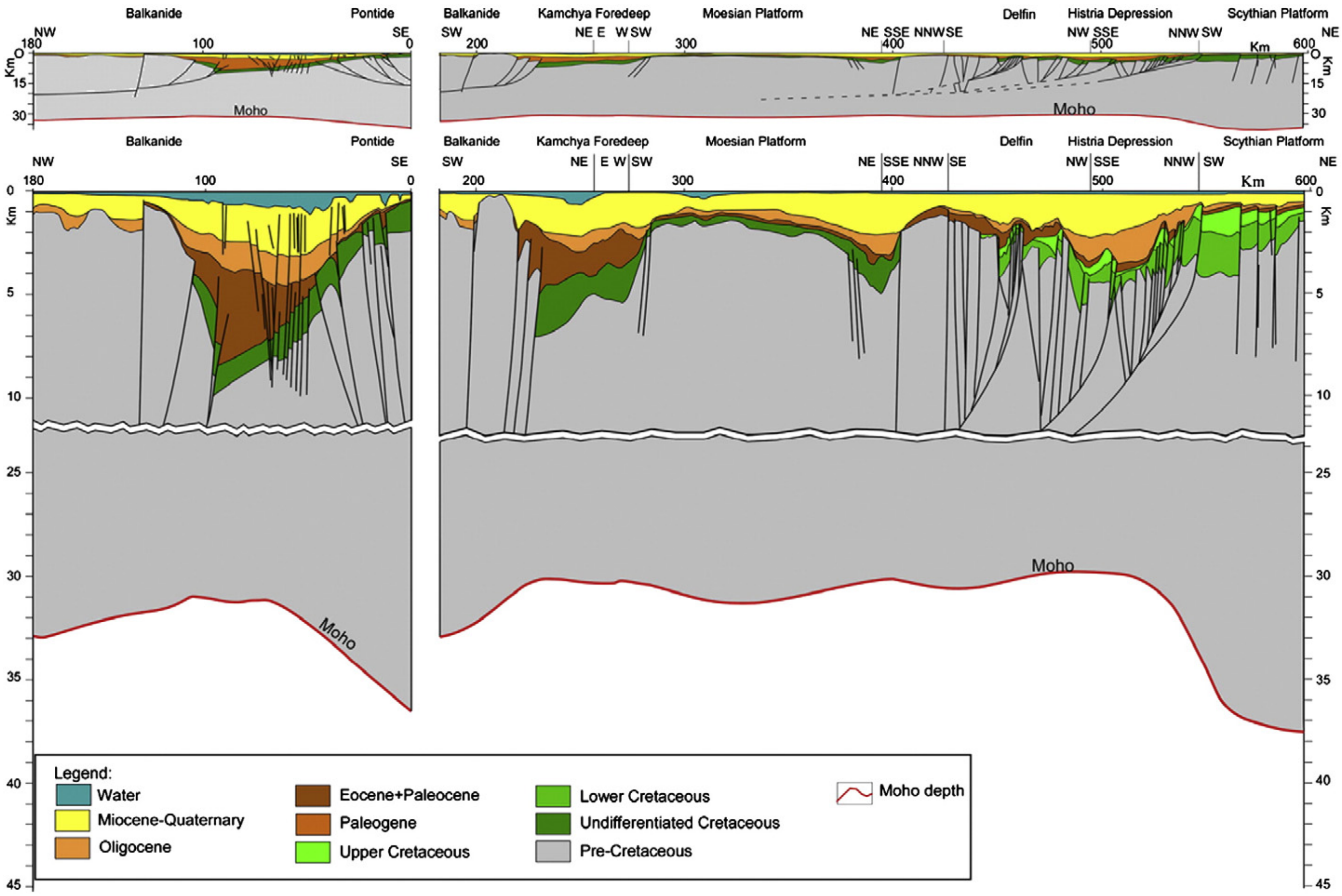


Fig. 12. Regional transect over the western part of the Black Sea starting from the Istanbul Zone (offshore western Turkey) to the Scythian Platform (Odessa Shelf, Ukraine), crossing the Strandja, the Balkanide, the Moesian Platform and the Nord Dobrogea Orogen. The cross section illustrates the gradual transfer of compressional deformation northwards during late Middle Eocene–Miocene times.
After Munteanu et al., 2011.

2009). At a more local scale, basement tectonics can control the development of deformations on volcanic edifices, also in the case of slope instability possibly leading to sector collapse development (Norini and Lagmay, 2005; Rovida and Tibaldi, 2005) (Fig. 19). These processes, in turns, might perturb the regional tectonic stress field through the magma forces exerted along the magma chamber and dyke walls. The resulting magma stress field can produce changes in the basement fault geometry and kinematics. Similarly, the anomalous heat flow in volcanic regions can contribute to modifying the dominant deformation style in the substratum.

Research carried out in the context of ILP (Tibaldi et al., 2008), through an integrated approach that combines field studies and analogue and numerical modelling, has resulted in a major progress in understanding the tectonic controls on volcanism exerted by a large extent through the interplay of thermal perturbations and stress fields. The following four papers in this volume follow up on this approach.

Fiorini and Tibaldi (2012–this volume) examine Quaternary tectonics in the central Interandean Valley (IV), Ecuador, with a focus on fault-propagation folds, transfer faults and the Cotopaxi Volcano. They present the results of a field geological-structural survey, analysis of seismicity, precise levelling of river terraces and numerical modelling. North of the volcano there are main Quaternary west-dipping reverse faults located along the western side of the valley. At the Cotopaxi foothills there are NNE–SSW-striking, vertical, right-lateral oblique strike-slip faults and E–W-striking normal faults, which offset Pleistocene deposits. South of the volcano, there are several folds showing Quaternary deformations, with the core of the folds sometimes affected by reverse faults. Most of the folds have a flexure geometry whereas the Guambalo fold shows a double flexure resembling a huge box fold. By numerical modelling, the authors computed the best solution that fits the observed geometry as fault-propagation folds. The fold system shows a double vergence linked to reverse faults dipping to the west along the western side of the IV and to the east along the eastern side. Stress tensors are calculated by striated fault inversion indicating pronounced spatial variations in the Quaternary stress regime. An increment in deformation along late Quaternary river deposits suggests a potentially very recent activity. These results are consistent with the distribution of crustal seismicity. Their research findings point to a larger Quaternary tectonic shortening south of the Cotopaxi volcano than north of it, with the transcurrent faults acting as transfer structures. Magma emplacement at Cotopaxi in this compressional setting has been favoured by the horizontal orientation of the least principal stress (σ_3) in connection to the transfer fault zone.

Bonali et al. (2012–this volume) investigate elastic stress interaction between faulting and volcanism in the Olacapato-San Antonio de Los Cobres area (Puna plateau, Argentina). These authors describe the relationships between Plio-Quaternary tectonics, palaeoseismicity and volcanism along the NW-trending Calama-Olacapato-El Toro (COT)

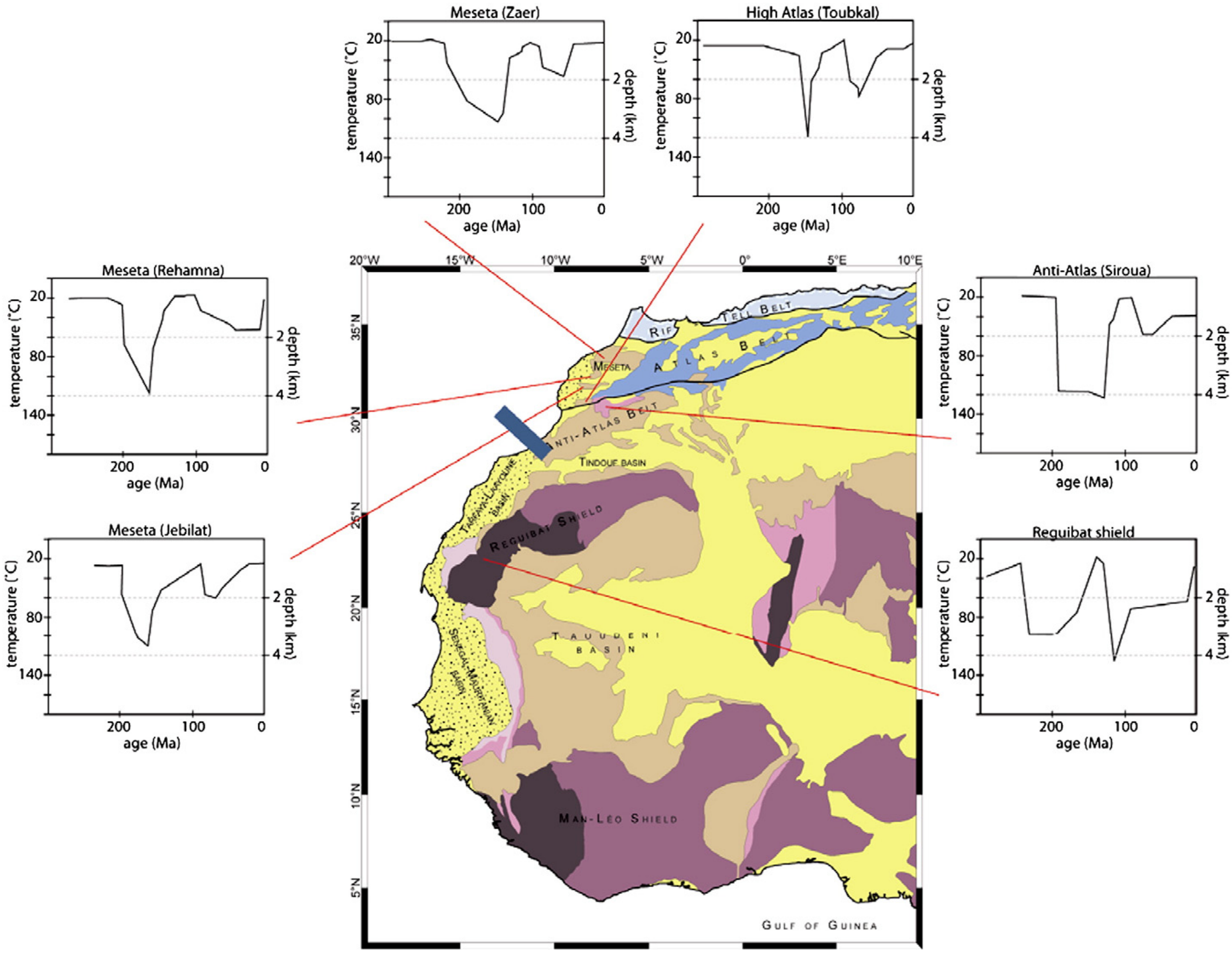


Fig. 13. Compilation (Gouiza, 2011) of the various low-T geochronology data available along the NW African rifted continental margin (Ghorbal et al., 2008; Ghorbal et al., 2009; Saddiqi et al., 2009; Ruiz et al., 2011), documenting a regional event of 2–3 km exhumation during the Late Jurassic–Early Cretaceous post-rift phase of the margin evolution.

lineament that crosses the Andean chain and the Puna Plateau and continues within the eastern Cordillera Satellite and field data reveal the presence of seven Quaternary NW-striking normal left-lateral fault segments in the south eastern part of the studied area and of a Plio-Quaternary N–S-striking graben structure in the north western part. The NW-striking Chorrillos fault (CF) segment shows the youngest motions, of late Pleistocene age, being marked by several fault scarps, sag ponds and offset Quaternary deposits and landforms. In the westernmost part of the examined area in Chile, at altitudes > 4000 m, recent N–S-striking normal fault scarps depict the 5-km-wide and 10-km-long graben structure. Locally, fault pitches indicate left-lateral normal kinematics. These faults affect deposits up to ignimbrites of Plio-Quaternary age. Although this area is located along the trace of the COT strike-slip fault system, no evidence of NW-striking Plio-Quaternary strike–slip structures appears to be present here. Numerical models were also developed in an elastic half-space with uniform isotropic elastic properties. The authors studied the stress changes caused by slip along the various Quaternary COT fault segments, showing that the last motions occurred along the CF might promote in the future further displacement along nearby fault segments located to the northwest. Furthermore, slip along the NW-striking fault segments imparts normal stress changes on the nearby Tuzgle volcano feeding system.

Milia et al. (2012–this volume) focus on a possible link between faulting, cryptodomes and lateral collapses at the Vesuvius volcano (Italy). The Vesuvius is an active volcano that has been affected by late Quaternary lateral collapses and tectonic faults. Cryptodomes and two debris avalanches, 18 ka-old (DA1) and 3.5 ka-old (DA2), were previously documented of the Vesuvius, and for the younger avalanche a link between onshore and offshore stratigraphy was reconstructed. The interpretation of seismic reflection profiles off Vesuvius, borehole stratigraphies, onshore and geomorphological data allowed the authors to recognise the relationships between debris avalanches, cryptodomes and faulting. Stratigraphic data reveal a remarkable difference between the architecture of the northern and southern volcano sectors that is compatible with the occurrence of the DA1 debris avalanche in the southern volcano sector. They present a new lateral collapse model of the Vesuvius volcano and document the relevance of inherited tectonic faults in guiding collapse geometry. It appears possible that the SW-directed collapse (DA1) was driven towards the hanging wall blocks of NW–SE normal faults, while the propagation of the W-directed collapse can be ascribed to the activity of the E–W-striking strike–slip fault. As pointed out by the authors, because of their distal location, a minor role of cryptodome intrusion on collapses of Vesuvius is likely. Their detailed analysis of substrate and edifice structure supports a

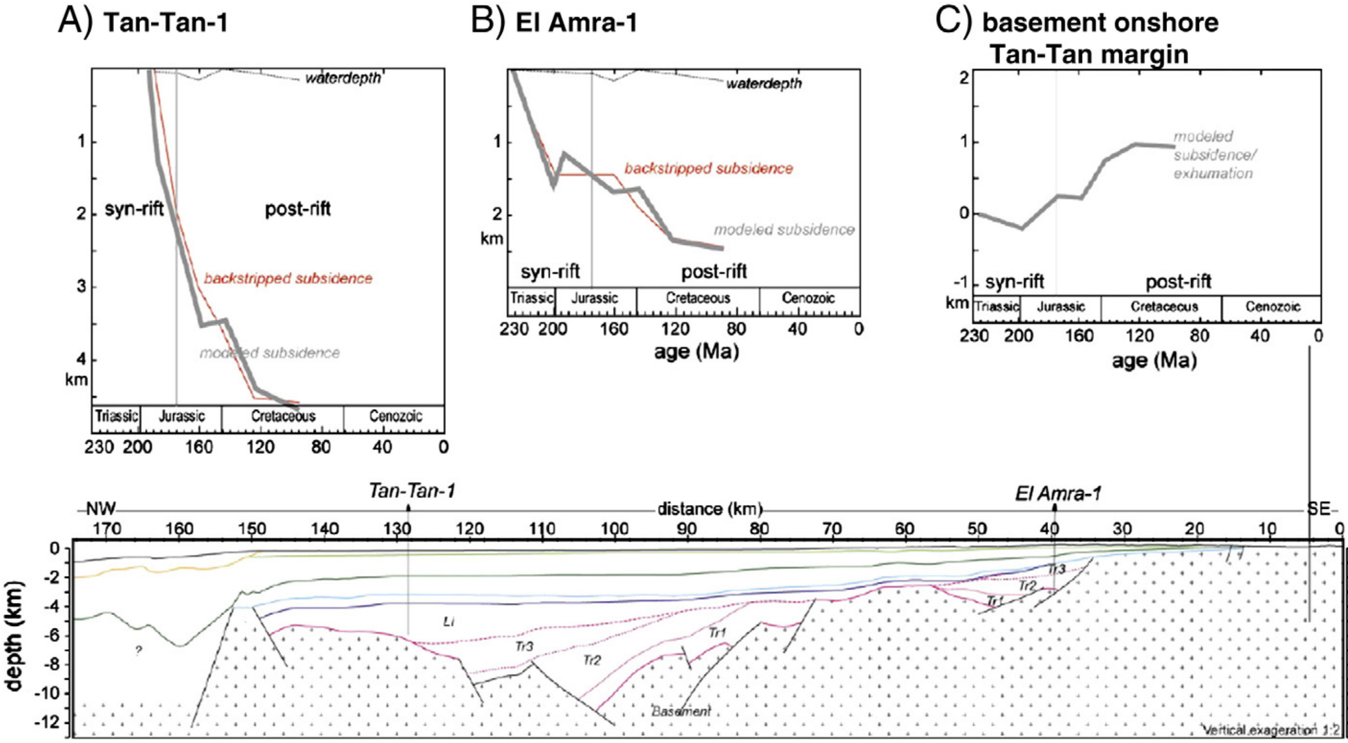


Fig. 14. Vertical motions along the southern segment of the continental margin of Morocco (see for location blue line in Fig. 13). The red curves show subsidence inferred by backstripping of industrial wells. The grey curves are predicted by thermo-kinematic modelling which imply a thermal anomaly below the margin during the post-rift phase to explain the anomalously strong subsidence observed offshore. This results in substantial exhumation in the onshore part of the margin and adjacent continental areas. Note that in the bottom figure the vertical depth scale is exaggerated and the faults are extremely flat.
Modified after Gouiza et al. (2010) and Gouiza (2011).

direct connection between substrate tectonics and lateral collapse. This approach broadens the horizons of volcanic hazard assessment of the Vesuvius.

Nomikou et al. (2012–this volume) present the results of a study of submarine cones in the Kolumbo Submarine Volcanic Zone of the Hellenic Arc (Aegean Sea, Greece). The seafloor northeast of the

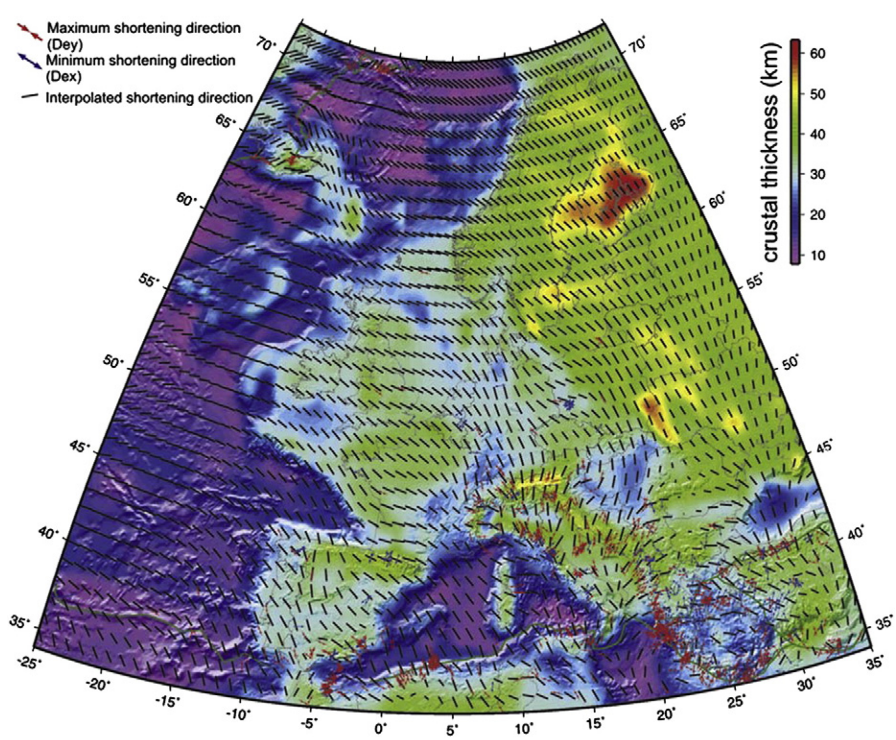


Fig. 15. Continuous maximum horizontal shortening map of Europe superimposed over topography and crustal thickness calculated from seismic and receiver functions studies. After Olaiz et al. (2009).

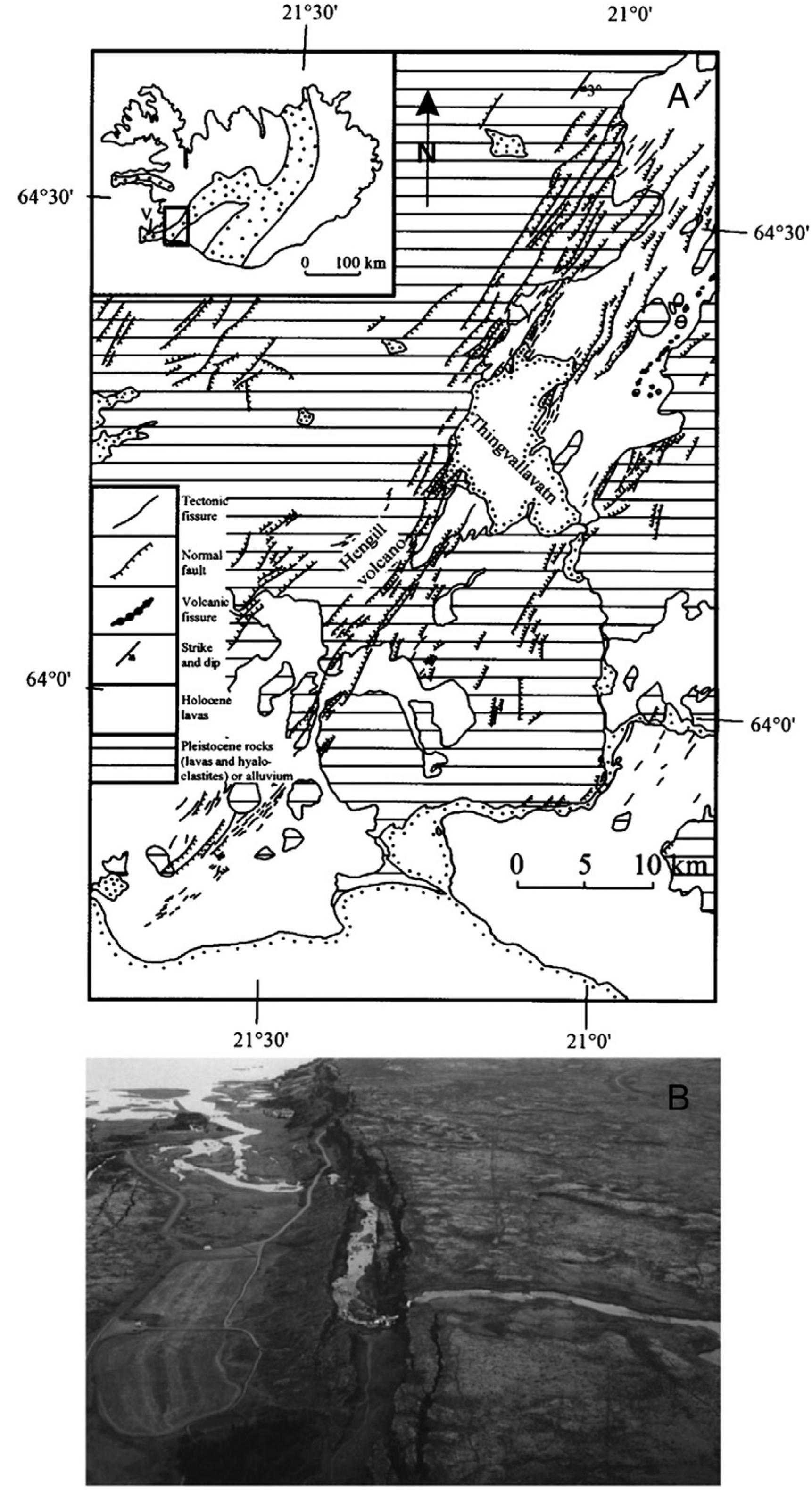


Fig. 16. Example of field study dedicated to the recognition of the late Quaternary faults affecting the south western Icelandic Rift. A. Here the deformation system consists of numerous tectonic fissures, normal faults, and volcanic fissures. The system is 80 km long and 10 km wide; the part located in the Holocene lava flow north of Lake Thingvallavatn is referred to as the Thingvellir Fissure Swarm, and its main western boundary fault is Almannagja. B. Aerial view of the Almannagja normal fault (centre) and associated tension fractures (left corner) in the Thingvellir Fissure Swarm. All the fractures developed in the 9000-year-old pahoehoe lava flow. Cars and houses (to the left of Almannagja) provide a scale. Modified after Gudmundsson (2000).

Santorini volcano consists of a small, elongated rifted basin that has been the site of recent submarine volcanism. This area lies within the Cyclades back-arc region of the present Hellenic subduction zone where the seafloor of the eastern Mediterranean Sea is descending beneath the Aegean microplate. Nineteen submarine volcanic cones occur within this small rift zone, with Kolumbo, the

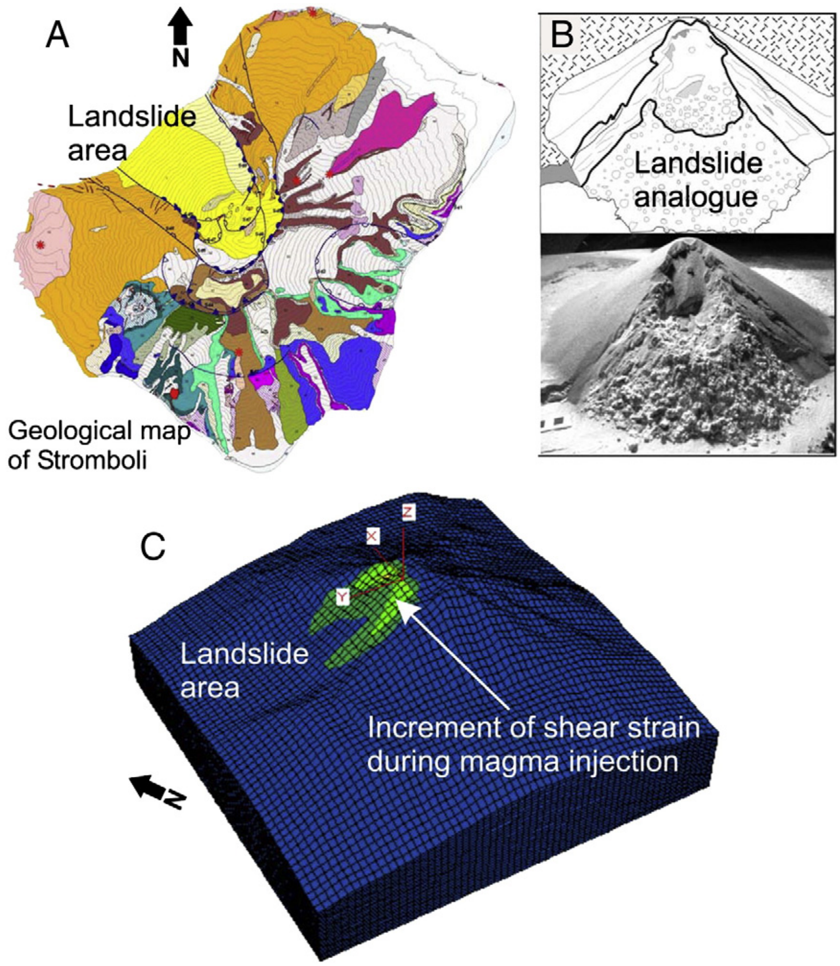


Fig. 17. Landslide hazard studies can combine data from different sources, integrating field data, numerical data and analogue scaled modelling, such as the ones conducted at Stromboli island (Italy). A. Geological map of the island; B. analogue, scaled simulation of landslide development triggered by magma intrusion; C. 3D numerical modelling showing the increment of shear strain in the landslide area due to magma injection in the volcanic cone.
After Casagli et al. (2009), Tibaldi (2010) and Tibaldi et al. (2010).

largest of these, which last erupted explosively in 1650 AD, causing significant damage and fatalities on the nearby island of Santorini. In general, the domes/craters northeast of Kolumbo were found to be sediment-covered and showed little evidence of recent volcanic activity. Another observation by the authors was that volcanic rocks were outcropping in the crater walls and slopes of some of the cones. However, they typically consist of volcanic fragments of pumice and lava that have been cemented together by biological activity, indicative of the lack of recent eruptions. Geochemical analysis of samples collected by Nomikou et al. (2012–this volume) on the northeast cones showed evidence of low temperature hydrothermal circulation on the summit and upper flanks in the form of stream-like manganese precipitates emanating from pits and fractures.

Pasquaré and Oppizzi (2012–this volume) discuss how the media appear to affect public perception of climate change and geohazards, presenting inferences from an Italian case study. Their paper uses a combination of a qualitative approach and a quantitative, software-based approach to explore the Italian print media construction of climate change and geohazards between 2007 and 2010. They have divided their analysis in two parts: the first one deals with the coverage of climate change; the second one focuses on the media representation of hydrogeological hazards and extreme events in Italy. It is evident that outreach to the public and the policy makers of research of natural hazards and the underlying solid earth processes remains a challenge. In that sense the research presented in this volume will provide a timely overview of recent advances made in integrated studies of coupled deep earth and surface processes.

Acknowledgements

Benjamin van Wyk de Vries is thanked for his dedicated efforts in hosting the ILP Conference in Clermont Ferrand. We acknowledge support from the International Lithosphere Programme (ILP), The Netherlands Research Centre for Integrated Solid Earth Science (ISES), and the NATO Science for Peace project 983142 “Geo-Environmental Security of the Toktogul Hydroelectric Power Station Region, Central Asia”. Elishevah van Kooten is thanked for editorial assistance. Francois Roure provided a thoughtful review.

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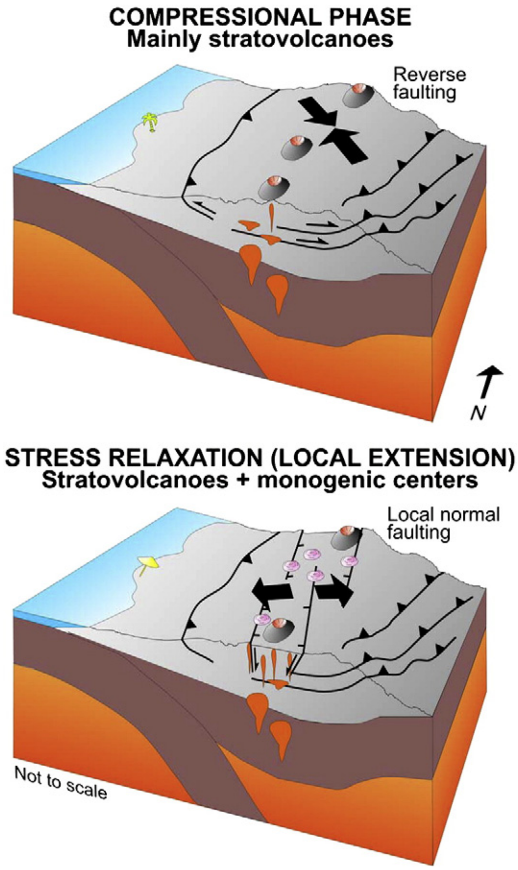

Fig. 18. Sketch of the relations between dominant crustal deformation mechanism and main type of volcanic centres developed in the central volcanic Andean Chain (South America).
After Tibaldi et al. (2009).

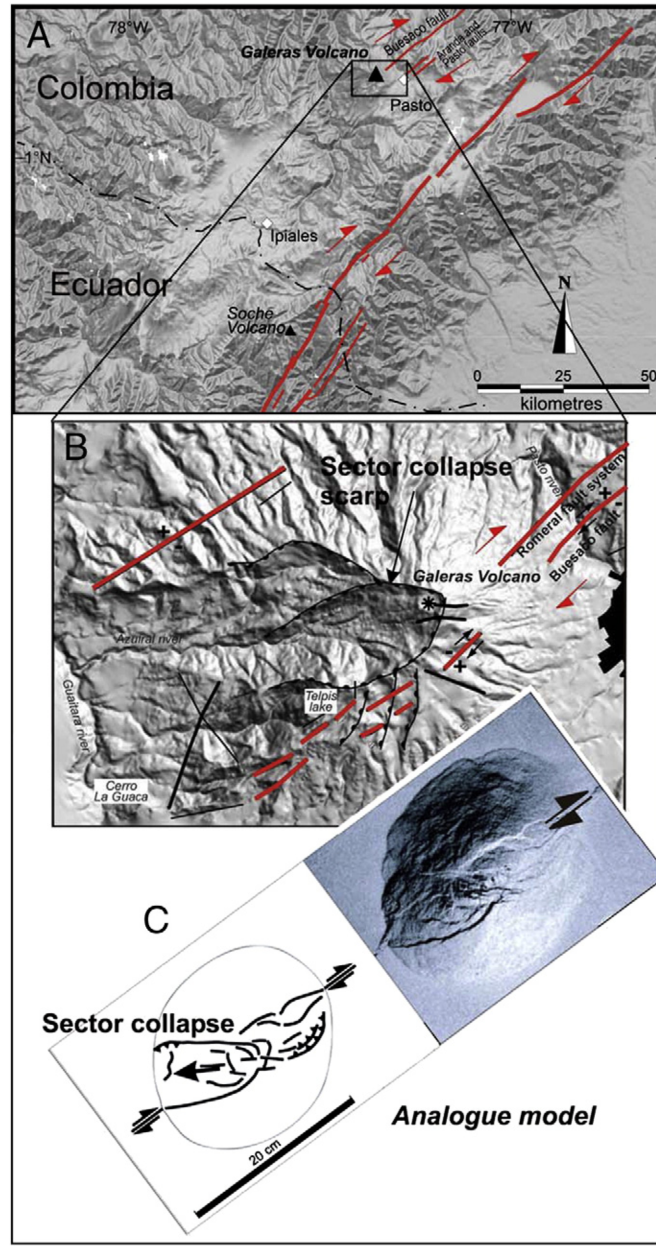

Fig. 19. A. Map of the main Quaternary faults affecting the Andean Chain at the border between Colombia and Ecuador. Note the right-lateral strike–slip faults (Buesaco and Aranda faults) along which the Quaternary-active Galeras volcano (Colombia) is located. B. Map of the main late Quaternary faults affecting the slopes of the Galeras volcano, representing the effects of the surface propagation of the Buesaco–Aranda faults. Note the orientation of the sector collapse developed on the western side of the volcano. C. Analogue model showing that the orientation of sector collapses on volcanoes lying above strike–slip faults is oblique to the fault strike. This experiment is in good agreement with the structures observed at the Galeras volcano.
A. is modified after Tibaldi et al. (2007); B. after Rovida and Tibaldi (2005); C. after Norini and Lagmay (2005).

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