

EUG XI



Theme RCM

Rifted Continental Margins

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Symposium RCM1

The Causes and Consequences of
Uplift at Continental Margins

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RCM1

Uplift at Continental Margins

Wednesday PO Session

RCM1 : WEpo01 : PO Uplift and 'Extension' (that isn't) at Young Continental Margins: A Result of Mantle Phase-Changes and Deep-Crust Metamorphism

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The upper crust of passive continental margins widely shows tectonic features characteristic of basement extension occurring at or soon after the time of ocean initiation. Whereas this evidence is largely offshore and obtained by seismic reflection, such margins also widely display coastal uplifts, sometimes with mysterious selectivity between crustal blocks. The generation of young oceanic crust and mantle emplaces lots of hot material laterally against the continental lithosphere. Hitherto the consequences of the resulting lateral heat-flush have been considered wholly in terms of thermal expansivity, which varies very little among silicates. However, the petrological effects of this lateral heat-flush into the middle and lower continental crust, and into the mantle below, are worthy of attention.

In general, at the crustal level, an upward displacement of the metamorphic facies boundaries is to be expected, implying some degree of dehydration and the upward migration of the resulting fluid. Received petrological wisdom asserts that the water 'escapes from the system', so a net increase in column density is inferred. If, on the contrary, the water merely migrates to higher in the column it is readily shown that a major overall volume increase (several tens of percent in the zone affected) and reduction of column density results. This volume increase, moreover, is achieved with a tiny fraction of the heat input that pure thermal expansion would require. This makes non-unroofed deep crustal metamorphism potentially a major and sensitive player, both in epeirogeny and in horizontal displacements in the basement (Osmaston, 1973; 2000). The dilatation will especially affect the mid-crust, which receives the water/fluids from below. In a straight passive margin, along-strike dilatation will be inhibited, so the total dilatation will be partitioned between vertical and oceanward directions. Thus the mid-crust may be expected to extrude laterally oceanward. The resulting upper-crust tectonics are therefore to be seen as 'dilatation tectonics', not requiring extensional forces. Importantly, the magnitude of this effect, and related uplift, will vary with the constitution of the continental crust involved.

Where the continental tectosphere is old and thick, lateral heat-flush will also promote phase changes (garnet-to-spinel-to-plagioclase peridotite) within its mantle. This process converts joules into dilatation even more efficiently than the crustal one (Osmaston, 1973). But here the heat input is at much greater depth, so will spread further inland, given time. It is also ultimately reversible as the heat dissipates whereas, for the crustal process, reversibility is limited if shallower recombination of fluid occurs.

Osmaston MF, In: *Tarling DH & Runcorn SK (Eds.), Implications of continental drift to the Earth Sciences. Academic Press, London, 2, 649-674, (1973).*

Osmaston MF, *Abstracts CD-ROM, 31st Int. Geol. Congr., Rio de Janeiro, General Symposium 4-2, (2000).*

RCM1 : WEpo02 : PO Thermo-Mechanical Modelling of Subsidence Effects Induced by Changing In-Plane Stresses at Passive Continental Margins and in Intra Cratonic Basins

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The timing of the Cenozoic uplift of the continental margins around the North Atlantic is still being debated. The evidence for the timing is indirect and results from studies of ages and structures of the sediments in the basins offshore. Further indirect evidence of tectonic activity is the observed late Cenozoic accelerated subsidence of basins on the North Atlantic continental margins and in the North Sea Basin. A possible history of the vertical

movements for the area is multiphase uplift with the initial uplift at the Paleocene/Eocene transition and the last important uplift in the Neogene.

During the Mesozoic breakup of Pangea the continental lithosphere on either side of the North Atlantic area experienced extension resulting in the formation of e.g. the Møre Basin and the Viking and Central Graben. With the opening of the North Atlantic the extensional tectonic regime gradually reversed to become compressional (ridge push). Further compressional pulses were produced by the Miocene reorganisation of North Atlantic spreading. The compression is evident in compressional structures such as the Ormen Lange and Helland Hansen domes on the Norwegian Shelf.

Thin elastic plate models have been used to quantify the vertical movements of passive margins induced by changing in-plane stresses. However, the amplitude and the sign of stress-induced vertical movements depend on the history of deformation and loading, as well as the thermal history, which is beyond the scope of thin elastic plate models.

In this paper we use a finite-element thermo-mechanical model of the lithosphere with a visco-elastic-plastic rheology (Braun & Beaumont, 1989). The model includes surface processes such as erosion, sediment transport, sedimentation, and sediment compaction, as well as sea level variations. A passive margin/intra cratonic basin is produced by extension, thermal subsidence and sediment loading. Thereafter the stress field is reversed and compressional pulses introduced, and the ensuing vertical movements of the model surface are recorded. Model tectonic subsidence histories are compared with observed tectonic subsidence histories in the Viking and Central Graben and on the Norwegian Shelf.

Braun J & Beaumont C, *Geology*, **17**, 760-764, (1989).

RCM1 : WEpo03 : PO Investigating the Causes of Uplift and Denudation by Seismic Imaging Technique: A Case History from the Irish Sea

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In recent years, a range of research has documented widespread Cenozoic epeirogenic uplift and denudation across the British Isles and surrounding areas. Despite that, little attention has been paid to possible mechanisms. This project aims at investigating and explaining causes of the well documented ~3 km of Tertiary denudation in the East Irish Sea basin (EISB). The study takes advantage of a wide range of geophysical datasets in an attempt to impose further geophysical constraints on the complex and uncertain geological processes involved in unroofing igneous material. A reinterpretation of the combined Caledonian Suture Seismic Project (CSSP) and Irish Caledonian Suture Seismic Project (ICSSP) wide-angle seismic profile form the main part of the project. The sea-to-land closely spaced wide-angle explosion line runs from the mid-North sea high, across northern England, the Irish Sea and Ireland with a total length of over 600 km. The interpretation is significantly improved by the detailed up-to-date near surface geology information. Whole-crustal and upper mantle seismic velocity models are obtained by two different seismic topographic imaging programs based on forward and inverse ray tracing method. The credibility of the outcome velocity models has been examined by means of direct model assessment approach and synthetic and amplitude modelling. The final velocity model shows detailed lateral velocity structure variation along the whole profile. This result will now be integrated with the denudation study in the area.

RCM1 : WEpo04 : PO Late Neogene Uplift of Britain – A Continental Margin Effect?

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There is good evidence to show that through most of the Neogene the landscape of Britain was mainly one of subdued relief and low elevation (Walsh et al., 1999). However, in the past two million years, much of the land surface has risen by various amounts between 150 and 500 m, particularly along the central zone and parts of the north and west, to create the present day upland areas (Clayton & Shamooin, 1999). Uplift was not uniform and differential movements were probably fault controlled. At the same time, subsidence occurred in the east of East Anglia and around the western coasts. Denudation and the isostatic response to denudational offloading have enhanced the topographic range (Watts et al., 2000). Similar uplift occurred across northern France (Lagarde et al., 2000). The mountains of Norway resulted mainly from late Neogene uplift and are deeply incised, with denudation accompanied by high sedimentation rates at the continental margin, where prograding fans are unstable. The full extent of these uplifts has yet to be established. There are complex interactions between landscape evolution, tectonics, climate, surface processes, sediment transport and deposition, and lithosphere response. The causes of these late Neogene uplifts are difficult to explain simply as continental margin uplift. This and possible alternative mechanisms are explored.

Clayton K & Shamooin N, *Geomorphology*, **27**, 173-189, (1999).

Lagarde J-L, Baize S, Amorese D, Delcaillau B, Font M & Volant P, *Quaternary Sci*, **15**, 745-758, (2000).

Walsh P, Boulter M & Morawiecka I, *Geol. Soc. Lond. Sp. Pub.*, **162**, 45-63, (1999).

Watts AB, McKerrow WS & Fielding E, *J. Geol. Soc. Lond.*, **157**, 1169-1177, (2000).

RCM1 : WEpo05 : PO Late Neogene Climatically-Forced Changes in River Activity: A Controlling Mechanism for Uplift and Subsidence in Southern and Midland Britain

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Examination of the sedimentary and lithological characteristics of the river systems that existed in southern and Midland Britain basin prior to glaciation (probably OIS 12, c. 450 ka) indicate a systematic change in sediment load over the period of the Early and early Middle Pleistocene (c. 2.6 Ma to 450 ka). Initially, the far-travelled load of these rivers consisted only of suspended sediment of which diagnostic microflora enabled the source of the material to be provenanced. Any saltation-load or bedload transported at this time was of local derivation. Subsequently, the rivers transported far-travelled saltation-load and bedload, often with an ice-floe transported fraction, and in this case diagnostic lithologies allowed the source of this sediment to be provenanced. Thus, it can be determined that the rivers changed from transporting clay and silt-size sediment to the southern North Sea basin to transporting sand and gravel, and a similar change can be determined round the coasts where coastal sediments changed from locally-derived to far-travelled sands and gravels. The river and coastal deposits contain plant, molluscan, and fauna remains that allow biostratigraphic comparison with the established Quaternary stratigraphy in the Netherlands, and this enables the change from very low energy fluvial activity to higher energy conditions to be dated to about OIS 65 (c. 1.77 Ma). This change in river activity is attributed to climate forcing in which the low energy conditions reflect the small changes of climate (c. 21 ka, precession driven) typical of the period prior to OIS 104 (c. 2.6 Ma), while the more energetic conditions reflect the more moderate amplitude climatic changes (c. 42 ka, obliquity driven) in which the effects of cold climate processes such as gelifraction, gelifluction and glaciation operated. These would have operated in the upper parts of the catchments and produced coarse-grained sediment load, that could in turn have been transported by seasonal snow melt, seasonal glacier melt and deglacial meltwater. It is proposed that the increased erosion rates would have stimulated isostatic uplift in the upper parts of the river catchments due to erosional unloading and increased subsidence in the

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offshore zones due to increased rates of sedimentation, and both of which can be demonstrated the elevation of river terraces and the position of coastal sediments. Changes in the rates of uplift in the interfluvial areas of British catchments and subsidence around some British coasts are therefore attributed to climatic forcing of river activity

RCM1 : WEpo06 : PO Neogene and Quaternary Flexural Activity, NW Paris Basin

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The dynamic of the Mesozoic Weald-Boulonnais, Somme and Bray have been partly controlled by the distribution of pre-existing variscan thrust faults. Jurassic to Cretaceous N-S extension gave the basins an asymmetric geometry with the greatest subsidence located along there N-E margins. From the late Cretaceous, the N-S Alpine compression initiated Cenozoic inversion with a major activity from the upper Eocene. The inversion process continued further mostly during the late Miocene and the Early Quaternary with a N150 transpressive compression, particularly evident at the level of the Somme. Most of the recorded movements is flexural, associated to drape folds formation in Cretaceous, above normal (Somme) or inverted (Bray, Boulonnais) deep faults. These movements are confined in a wedge-like zone (Manby et al., 2000), squeezed to the North into the Anglo-Brabant massif which well supported by new gravity data. This zone corresponds to the 'Picardie trans-anticline' described by Menessier. Neogene and Quaternary observations show an activity by steps of these flexures, supported by the sedimentary record and dating. No evident strike slip component is observed in this zone by the Late Cainozoic. Above the deep faults, evidence of surface rupture is lacking despite the record of co-seismic features, clustered by periods in the internal portion of the wedge-like zone or more continuous to its eastern or western boundaries. The rate of differential movement at the level of the various flexures is about 0.1 mm/year, since the Paleocene; this value does not integrate the temporary long wave length deformations. The studied zone is globally subsiding in agreement with the post-rift evolution of western Europe. Local adjustments are linked to the presence of basement blocks; since the Upper Paleocene (Landenian high stand, third order 2.1: +200 m), by reference with the eustatic curves (Haq et al., 1988; Hardenbol et al., 1989), only a slight uplift is recorded in the Bray only (+30 m by reference to the 2.1), these of the Boulonnais is limited (+10 m by reference to 2.1) compared to the Weald (+ about 50 m). The subsidence is maximal north of the Variscan front, below the Flemish coastal plain (-200-230 m by reference to the 2.1). This late range of subsidence is comparable to the sectors south of the South Armorican Shearing Zone, the other major Variscan boundary reactivated in Western Europe during the Cainozoic.

Manby, G, Mansy, JL, Everaerts, M, *J. Geol. Soc. London*, (submitted).

RCM1 : WEpo07 : PO New Insights on the Tectonic Reactivation of the North Ligurian Margin (SE France) Since 5 Ma

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The North Ligurian continental margin is located at the transition between the French-Italian southern Alps and the Ligurian sea which spreads from the east of Provence to the Gulf of Genoa.

After the rotation of the Corsica-Sardinia block (16-15 Ma) the margin underwent a major erosional phase linked to the Messinian sea-level drop (5.3 Ma) (Clauzon et al., 1995). This event was followed by a transgression characterised by a sedimentary succession consisting of a Late Messinian 'Upper Evaporite' unit (Late Messinian) overlain by Pliocene (up to 3.8 Ma) marls.

A preliminary study of Plio-Quaternary vertical motions along normal faults offshore from Antibes to Imperia showed that the upper part of the Ligurian margin underwent recent differential uplift, with amounts of uplift increasing from west to east. The uplift rate was estimated at 0.3-0.5 mm/yr (Chaumillon et al., 1994). Using more than 20 reflection seismic profiles collected from the same area and studying the geometrical relationships between the different reflectors overlying the Upper Evaporite (UE), we show here that differential vertical motions can be detected as early as 5.2 Ma, corresponding to the onset of the transgressive phase recorded by UE deposition on the margin.

Concurrently, apatite fission track thermochronology shows an acceleration of denudation at about 6 Ma of the NW, most elevated, part of the onshore Argentera massif, with estimated post-6 Ma denudation rates of 0.6-0.8 mm/yr (for geothermal gradients of 30-25°C/km). This acceleration was followed in the rest of the massif at about 3.5 Ma where denudation rates are estimated at 1.1-1.4 mm/yr (Bigot-Cormier et al., 2000).

Consequently, the results of both methods are in good agreement with accelerated vertical motions of the southern Alps and their margin since 5.2 Ma, with a probable acceleration of uplift since 3.5 Ma.

Geomorphological and drainage system analyses from the Argentera massif to the Ligurian margin allows us to model and discuss the causes of the vertical motions since 5.3 Ma observed throughout this zone : they may be due to an isostatic and erosional response triggered by sea level changes and/or to the acceleration of compressional deformation of the European margin-Apulia indenter contact zone that affected and was recorded by all of the western alpine External Crystalline Massifs.

Clauzon G, Rubino J-L & Savoye B, *Field Trip Guide Book, Pub. ASF, Paris*, **23**, 254 p., (1995).

Chaumillon E, Déverchère J, Rehault J-P & Gueguen E, *C. R. Acad. Sci. Paris*, **319**, 675-682, (1994).

Bigot-Cormier F, Poupeau G & Sosson M, *C. R. Acad. Sci. Paris*, **330**, 363-370, (2000).

RCM1 : WEpo08 : PO Denudationally-Driven Seismicity at the Western Indian Margin? Stratigraphical, Structural, and Geomorphological Constraints for Earthquakes in the Deccan Traps Region

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The object of this work is to explore the underlying causes of seismicity along the passive continental margin of western India, and the southern Deccan in particular. The preferred explanation is given in terms of a response to the long-term and ongoing morphotectonic development of this continental margin.

The Deccan Trap continental flood basalts were erupted 63 - 67 Ma ago at the Cretaceous-Tertiary (K-T) boundary. Study of the lava stratigraphy and its structure aids in the evaluation of the post-eruptive deformation and erosion effects and, therefore, is fundamental in aiding understanding of the causes of seismicity affecting the southern Deccan (Widdowson & Mitchell, 1999). This approach is timely since the recent Latur earthquake (30th September, 1993) of magnitude ~ 6.5 caused a disproportionately large number of human casualties (Gupta, 1994).

The structure of the lava pile is a broad anticline-monocline the origins of which were controlled partly by the pattern of volcanic eruption (Mitchell & Widdowson, 1991), and partly by subsequent long-term uplift that has affected the Indian continental margin (Widdowson, 1997). Crustal movement beneath the basalts continues today through the juxtaposition of fault-bounded pre-Deccan basement blocks. The orientations of structural and lineament fabrics in the south-west Deccan mimic those of the adjacent pre-Deccan basement terranes. Thus, the structural heterogeneity of the basement is transmitted through, and superimposed upon, the overlying basalts. The mechanism for this transmission probably involves basement block movement at depth, which then results in fracturing and small-scale faulting of the basalts above. It is argued here that one of the fundamental controls upon this continuing basement adjustment is an isostatic adjustment of the Indian margin resulting from regional denudation patterns and, in particular, the inland recession of the Western Ghats escarpment (Widdowson & Cox, 1996). In addition, 'far-field' stresses resulting from the India - Asia collision, together with those associated with evolving ocean floor stresses and loading patterns (Whiting et al., 1994), could potentially reactivate basement weaknesses beneath the Deccan basalt lavas. However, much more work is required to determine their contribution to the type of intra-continental seismicity occurring today in the Deccan region

Widdowson M, & Mitchell C, *Memoirs of the Geological Society of India (West Volume)*, **43**, 425-452, (1999).
Gupta, HK, *Memoirs of the Geological Society of India*, **35**, 1-5, (1994).

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Whiting, BM, Karner, GD & Driscoll, NW, *Journal of Geophysical Research*, **99**, 13791-13811, (1994).

RCM1 : WEpo09 : PO Cenozoic Uplift, Denudation and Drainage of India

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Sedimentary sequences on the eastern coast of India indirectly record discrete uplift events. These sequences have been used to investigate the relationship between uplift/denudation caused by regional tectonic events, such as Réunion hotspot activity, and the evolution of sedimentary systems and drainage patterns. The distribution of sediments in the basins throughout the Cenozoic has been measured by mapping of the sequences using grids of seismic lines tied with biostratigraphic information from well logs. Seismic reflection profiles and well log information from Krishna-Godavari and Cauvery basins have been studied in collaboration with the Oil and Natural Gas Corporation (ONGC), India.

Throughout the Late Cretaceous, these basins had been sediment-starved. Delta progradation began in the Maastrichtian and a shallowing of the basins around the K/T boundary points to regional uplift controlled by the Deccan Plume. Renewed subsidence through the Paleocene and Eocene led to a thick wedge of sediments developing in front of the Godavari river. Syn-sedimentary faults occur in discrete phases and cut through these sediments. A regional Oligocene unconformity is followed by faulting and a thick Miocene sequence. Uplift, with the development of vast submarine canyons in the latest Miocene and Pliocene is coupled with growth faulting and a massive increase in depositional rate which continues in pulses into Pleistocene and Recent times. These late Cenozoic events are probably controlled by the regional effects of the continuing Indo-Asian collision.

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RCM1 : WEpo10 : PO Neogene Morphotectonic Evolution in the Forearc of Chilean Central Andes, Copiapu-Region (261/4-271/4 South Latitude)

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The Andean forearc in the Atacama Desert (Northern Chile, between 26  and 27  South latitude) can be subdivided into four main, trench-parallel (North-South oriented) morphologic units, from West to East: The Coastal Cordillera, the Central Depression, Precordillera and the Altiplano or Puna. Two approximately North-South oriented fault systems are the most important tectonic features in this region: (1) the Atacama Fault System (AFS) along the axis of the Coastal Cordillera, which was active from the Jurassic to the late Tertiary (?) (Scheuber and Reutter, 1992; Brown et al., 1993), and (2) the Precordillera Fault-System (PFS), with evidence for activity during the Tertiary (Tomlinson et al., 1993). The major drainage systems cross-cut the mentioned trench-parallel morphologic and tectonic features from the western border of Altiplano-Puna, to the West, towards the Pacific coast.

The peripheral Neogene to Recent erosional and depositional landforms in the Copiapu-region, allow us to study the development and evolution of the main drainage system. To the east of the AFS, it is possible to recognize four episodes in the Neogene morphological evolution: (1) a first deep vertical incision, (2) aggradation and filling of the paleo-drainage system by Atacama Gravels, (3) a pedimentation, that is still well preserved in the Central Depression, and that is responsible for a particular hypsometric signature of drainage basins in the Precordillera, (4) reorganization of the new post-Atacama Gravels drainage system and its rejuvenation by vertical incision. The examination of both thalweg and crest profiles suggest the uplift of the Coastal Cordillera, west of the AFS. The corresponding activity of the AFS is posterior to the deposition of the Atacama Gravels, which is visible in aerial photographs (lineaments crossing alluvial fans), and in the field (deformation of the Atacama Gravels, deposition of evaporites trapped by the activity of the Fault). The quantification of the relative base movements, for each episode of the morphological evolution of this part of the Central Depression and Precordillera, is possible looking at the slope profiles of ignimbritic levels intercalated within the Atacama Gravels, of the pedimentation surface and of the present-day thalweg profiles.

Scheuber, Eand Reutter, K-J, *Tectonophysics*, **205**, 127-140, (1992).

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Tomlinson, A, Mpodozis, C, Cornejo, P, Ramirez, C, *Second International Symposium on Andean Geodynamics, Oxford, U. K.*, **1**, 259-262, (1993).

RCM1 : WEpo11 : PO Apatite and Zircon Fission Track Analysis of the Ecuadorian Sub-Andean Zone: A Record of the Cretaceous and Tertiary Andean Geodynamics

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The aim of the study is to investigate the evolution of the moderately evolved Ecuadorian Amazon Foreland Basin (AFB) with particular reference to the region of the Napo antiform (northern Sub-Andean Zone, SAZ) and its relationship to the adjacent Cordillera Real. This involves an attempt to establish the association between tectonic exhumation processes within the source areas and sediment dispersal and facies development in the bordering AFB. The timing and rate of the sedimentary processes and

exhumation of the source during Cretaceous and Tertiary times are poorly constrained even though the inception of the Ecuadorian AFB is assumed to have occurred during the Maastrichtian, when the main detrital supply from the Cordillera Real becomes evident.

A powerful approach to quantify the sedimentological and tectonic history of the Cordillera - Basin system is to examine the thermal history of the northern SAZ. Apatite and zircon fission track data are being acquired from volcanic/plutonic basement and sedimentary formations. The technique permits a quantification of the thermal history of the region over the temperature range of ~ 300 - 200 (zircon) and 110 - 60 C (apatite) and simultaneously constrains the thermal history of possible source areas using detrital ZFT and AFT from samples where no annealing has taken place due to burial in the basin. Preliminary results from both apatite and zircon within the basement indicate that important cooling occurred during the following periods: 140-125 Ma and 80-75 Ma. These periods can be correlated with known tectonic events that affected the northern Andean margin (Pelletetec and Pallatanga events). However, these cooling periods have not been identified in the Cordillera Real. We suggest that the rocks that held this history have been already removed by erosion or reset. These data and the sedimentary facies patterns indicate that the Napo structure was initiated during the Cretaceous.

Correlating detrital ZFT ages with stratigraphic ages allows us to estimate the timing of the exhumation of the potential source rocks. Possible syn-sedimentary volcanic sources are currently being discriminated by heavy mineral analyses. Generally, young detrital ZFT populations pre-date deposition in the order of 5 - 40 Ma. This implies that the source terranes were exhumed at mean rates with maximum range of ~ 0.2 - 1.6 km/My (assuming a geothermal gradient of 30 C/km and rapid transport). In comparison, similar rates were measured in the Cordillera Real for some periods of the Tertiary. In contrast, older detrital ZFT populations may represent sources in the Guyana Shield area.

RCM1 : WEpo12 : PO Variations in the Cooling and Denudation History of the Continental Ecuadorian Andes to Collision with Oceanic Crust: Evidence from ⁴⁰Ar/³⁹Ar and Fission-Track Thermochronology

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Oblique to strike geological segmentation (e.g. volcanic activity, topography, seismicity) in the Andean chain has been previously recognised at various scales and is commonly attributed to changes in the convergence vectors of the oceanic and continental plates, as well as the upper-plate expressions of differing along-strike subducted slab age, strength and composition. New white mica and biotite ⁴⁰Ar/³⁹Ar and zircon and apatite fission-track data from several traverses across the Cordillera Real of Ecuador in the Northern Andes reveal distinct along-strike differences in the timing of accelerated crustal cooling and denudation during the Cenozoic. The data record elevated cooling rates from temperatures of ~ 380 C during ~ 65 - 55 Ma and ~ 43 - 30 Ma from all sampled regions of the Cordillera Real and at ~15 Ma and since ~ 9 Ma in the northern Cordillera Real. Each cooling period was probably driven by denudation in response to the accretion and subduction of heterogeneous oceanic crust.

Elevated cooling rates of up to ~ 30 - 20 C/My were initiated during the Paleocene and Eocene-early Oligocene along the entire contemporaneous margin of Ecuador and were driven by the accretion of the oceanic Pallatanga Terrane and Macuchi-Pi-on Block respectively onto north-western South America. Both of these geological provinces originated at the southern parts of the leading and trailing boundaries of the Caribbean Plateau and accreted onto the margin during the approximately northeastward migration of the Plateau into its current position. Within Ecuador the development of higher topography and elevated cooling rates of up to 50 C/My at ~ 15 Ma and since ~ 9 Ma are restricted to the region north of 1 30'S and is situated above the postulated subducted flat-slab section of the aseismic Carnegie Ridge. Plate convergence rate calculations suggest the Carnegie Ridge collided with the Ecuador

Trench at ~ 15 Ma, which caused the pre-existing coastal provinces to displace to the northeast, subsequently driving extension and marine incursions in southern Ecuador and compression and uplift in northern Ecuador. Cooling at these times may be a result of increased denudation rates that were driven by an increase in compressive stress and buoyancy of the continental margin, which developed as a consequence of coupling between the continental crust and the subducting Carnegie Ridge flat-slab segment. Elevated topography in northern Ecuador swings seaward in the vicinity of the Gulf of Guayaquil and is approximately parallel with the Grijalva Fracture Zone and the location of proposed lithospheric tears, suggesting a deep crustal influence on the topography.

RCM1

Uplift at Continental Margins

Thursday AM Session

RCM1 : THam02 : F3

Causes of Large-Scale Continental Uplift

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I provide an overview of the causes of continental uplift with a particular focus on how mantle flow induces uplift on scales larger than ~1,000 km over times >1 Myr. The long wavelength geoid results from a combination of large-scale, mantle density differences and deflections of the Earth's surface induced by viscous flow driven by such density differences. Such deflection are called dynamic topography. A fundamental, but under appreciated, aspect of dynamic topography is that it is time-variable: The flow which drives the topography also causes the internal buoyancy forces to sink (or rise) within the mantle so that the amplitude of dynamic topography will decrease (or increase). The time-scale for substantial changes in dynamic topography are on the order of 10 Myr, over which time plates would have moved appreciably. In order to make quantitative predictions which can be connected to observations (such as the timing of uplift, or tectonic subsidence inferred from bore-holes) one must model flow within the mantle with plates moving on the surface. I illustrate how we have connected observations of continental vertical motion to dynamic models with examples from Australia and southern Africa since the Cretaceous.

The long-known, out-of-phase sea-level fluctuations experienced by the Australian continental platform during the Cretaceous may have been driven by the demise of subduction on the eastern margin of Australia. Three-D convection models with plates are tested with patterns of marine inundation, bore-hole tectonic subsidence, and uplift inferred from fission track analysis. Dynamic models are also consistent with seismic tomography showing the present position of the old slab in the lower mantle as well as predicting a cold spot along the mid-ocean ridge between Australia and Antarctica.

I show initial results on similar, but substantially more sophisticated, dynamic models of the breakup of Gondwanaland. The largest, coherent low seismic velocity anomaly in the lower mantle is found beneath the South Atlantic and southern Africa — the centroid of the former Gondwanaland supercontinent. The character of flow beneath Gondwanaland is reconstructed by integrating the convection equations backward in time. The driving force is estimated from observed tomography and the system is integrated backwards with Gondwanaland plates on the surface of a sphere. With initial conditions estimated at 130 Ma, the model is integrated forward and surface topography and uplift rate are predicted as a function of time. As of this writing, it is unclear if the dynamic uplift is more consistent with Cenozoic uplift of southern Africa (as implied by studies of landscape evolution) or high topography of Gondwanaland during supercontinent breakup (as implied by fission track analysis of samples collected from rifted margins).

RCM1 : THam03 : F3

Disentangling Transient and Permanent Uplift Caused by Mantle Plumes

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Many aspects of the development of the North Atlantic province have been influenced by the behaviour of the Iceland Plume whose striking dominance is manifest on the global gravity map. Magmatic underplating associated with the activity of this plume is an important mechanism for generating regional surface uplift and denudation of large portions of the adjacent margins. Surface uplift is rapid because substantial volumes of basaltic melt are added to the crust over geologically short periods of time (1-10 Myrs).

One consequence of this uplift is that large amounts of clastic sediment are shed into surrounding basins. A striking feature of these deposits is that in many places they are pulsed on timescales of 1-3 Myr. An intensively studied example is the Paleogene of the North Sea Basin. Here, discrete pulses of sand deposition by turbidity currents and by debris flows were triggered when previously eroded

sands were remobilised downslope from the shelf as a result of episodic lowstands of relative sea-level. We correlate the timing of these sediment pulses with the timing of surface uplift inferred to have been caused by episodic magmatic underplating on the northwest continental shelf of Europe.

A range of independent evidence suggests that time-dependent fluctuations in plume activity have occurred during the last 60 million years. These fluctuations have periodicities of 1-5 million years which are caused by temperature variations within the plume's stem. We suggest that the existence of discrete pulses of Paleogene submarine fan deposition can be linked to variations in plume activity. Multiple lines of research demonstrate that distinct episodes of uplift and subsidence are closely related to permanent and transient effects associated with plume activity. During the Paleocene, a hot sub-vertical sheet of asthenosphere was injected along the Iceland-Faroes Ridge, continuing as far south as the Irish Sea and Lundy Island. This sheet caused a welt of magmatic underplating to be injected into the crust. There is excellent evidence for substantial uplift and denudation at locations overlying this thickened welt which is straddled by the Faroe Islands.

RCM1 : THam04 : F3

Tectonic Structure of the Norwegian Margin (Vøring and Møre Basins): The Role of the Jan Mayen Fracture Zone

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The comparison of two crustal sections across the Vøring and Møre basins allow the understanding of the present tectonic structure as well as the Mesozoic and Cenozoic evolution of the Mid Norwegian Margin. These transects have been constructed by means of detailed inspection of multichannel seismic profiles and available 2D crustal models to give a more complete vision of this passive volcanic margin. The crustal structure of the Vøring Margin shows a SE to NW stepwise reduction in thickness from c. 43 km onshore to c. 30 km beneath the Trøndelag Platform and c. 20 km beneath the Vøring Basin. The Møre Margin shows a more abrupt transition from the Norwegian mainland (c. 43 km) to the Møre Basin (c. 20 km) lacking the intermediate region corresponding to the Trøndelag Platform. The Cretaceous infill of the Vøring Basin is thicker in its southeastermost part, coinciding with the axis of two synclines bounding an anticline that are interpreted as related to a major NW-dipping listric normal fault at depth, which limits the basin from the Trøndelag Platform. Towards the NW, the Cretaceous basin thins and is deformed by a shallower set of NW-dipping listric normal faults (Gjallar Ridge). On the contrary, the Cretaceous succession of the Møre Basin is thicker in its middle part and wedges towards both flanks, outlining a wide syncline bottomed by rotated blocks of basement limited by an array of similar NW-dipping normal faults. These faults show little displacement in contrast with the major normal fault described for the Vøring Basin. The absence of an area analogous to the Trøndelag Platform to the south, together with the different tectonic style of the Mesozoic across the Jan Mayen Fracture Zone suggests the active role of this lineament during the Mesozoic basin formation. Furthermore, the different geometry of the Mesozoic structure at the end of the Late Cretaceous controls the Cenozoic infill of the margins: narrow basins in the Vøring and a wide basin in the Møre. Since most of the Cenozoic tectonic inversion domes are confined between the Jan Mayen and Bivrost lineaments, we propose a transpressive contribution for their development, and thus, a long-lived activity for the Jan Mayen Lineament through many different tectonic regimes, from Mesozoic early synrift through Tertiary breakup and sea-floor spreading.

RCM1 : THam05 : F3

Compressional Reactivation of the Atlantic Margin, SE Brazil, and its Effects on Uplift, Exhumation and Sediment Transport

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We assemble and discuss evidence for compressional reactivation of the obliquely-rifted margin of SE Brazil, in Late Cretaceous and Cenozoic times, attributing the reactivation to plate-wide stresses and hot-spot activity. Our conclusions are based on current seismicity, digital topography, fission-track ages, gravity data, surface geology, fault-slip data, regional reflection seismic profiles and well data. Onshore, mountain ranges up to 2700 m high are underlain by a Moho that is 37 to 42 km deep. Crustal seismicity is widespread and focal mechanisms of earthquakes indicate a transpressional stress regime. Neotectonic fault-block tilting has resulted in extensive river capture. Based on fission-track data, the mountains underwent Cretaceous and Eocene phases of exhumation. These ages tend to be homogeneous within large fault blocks. The youngest ages are on the coast, at the foot of the Serra do Mar. Behind this range, a series of Tertiary continental pull-apart basins developed during Paleogene right-lateral transtension and became inverted during Neogene right-lateral transpression. A string of Alkaline mafic intrusions, attributable to the Trindade hotspot, were emplaced in Late Cretaceous to Paleogene times along reactivated strike-slip faults of the main Neocomian transfer zone, which reaches the coast at Cabo Frio. Offshore, current seismicity is restricted to the continental margin. The patterns and history of sedimentation are complex, because they respond mainly to onshore uplift and drainage reorganization. In Late Cretaceous and Paleocene times, the River Paraíba do Sul reached the sea in the Santos Basin, producing submarine canyons, clastic fans and large depocentres in areas of salt withdrawal. In Oligocene times, uplift of the Serra do Mar blocked this exit to the sea, forcing the River Paraíba do Sul to flow as far as the Campos Basin, where it formed a Neogene delta. Basement tectonics are also important. All along the shelf edge, Cretaceous sediments have been folded, tilted, eroded and unconformably overlapped above a reactivated Neocomian Moho uplift, to produce an accentuated nearshore hinge-line. In places, the hinge-line is a true reverse fault. In general, Neocomian transfer zones were reactivated as strike-slip faults. In the main Cabo Frio transfer zone, reactivation resulted in a large anticline and was accompanied by abundant volcanism. From a detailed comparison of fission-track ages and stratigraphic ages, we conclude that compressional reactivation occurred in at least three phases (Campanian, Eocene and Neogene), which we correlate with the Peruvian, Incaic and Quechua phases of deformation in the Andes and with paroxysms in the rate of convergence at the western margin of South America.

RCM1 : THam06 : F3

Erosion as the Main Cause of Uplift along Transform Continental Margins: The Côte d'Ivoire-Ghana Example

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The morphology of transform continental margins differs from the one of rifted (divergent) continental margins by a narrow shelf (few tens of km), and especially by a very steep continental slope (often more than 20° in average) associated to a very narrow continent - ocean transition. On transform margins, the shelf always shows traces of aerial erosion in relation with an uplift increasing toward the continent - ocean boundary. The main hypothesis proposed to explain this uplift is thermal expansion of the continental lithosphere, induced by heat transfer from a spreading axis sliding against the transform margin. This presentation will show that : 1) In the case of the best documented transform margin, the Côte d'Ivoire - Ghana margin, the uplift occurred prior to the contact between the continental lithosphere and the oceanic spreading center. Uplift began during the intracontinental stage, when the transform fault was located between Africa and South America, and increased at continental break-up time, i.e. when the active

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transform fault brought into contact Africa and an oceanic plate. Furthermore, there is no direct evidence of heating by the oceanic plate nor of uplift at the time of the contact with the oceanic accretion axis. These observations rule out an explanation of uplift based on thermal expansion only.

2) The transition from intracontinental transform fault (continent against continent) to continent-ocean transform fault brings into contact two plates with different elevations, and consequently creates a topographic step. The transform fault is vertical at depth, but the step can not stay vertical at surface: the highest plate has to be eroded, and products of erosion are deposited on the deepest plate. This erosion of the vertical transform border unloads the highest plate. Assuming uncoupling across the transform fault (i.e. free vertical motion), erosional unloading produces a flexural uplift of the transform border. Mechanical modeling of lithospheric flexure shows that the erosional unloading can explain alone both amplitude and timing of the uplift observed along the Côte d'Ivoire - Ghana margin, excluding all other mechanisms proposed for transform margins (heat transfer, underplating, tectonic unloading, tectonic thickening). The erosion of the vertical transform border then appears to be the main cause of uplift and subsequent erosion of the shelves of transform continental margins.

RCM1 : THam10 : F3 Deriving Surface Uplift Histories on Passive Continental Margins

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Since they reflect the magnitude, timing and spatial extent of surface uplift, changes in topography through time can potentially provide valuable constraints on crustal and mantle processes. Reconstructions of palaeotopography, based on a traditional denudation chronology approach, and involving the identification and correlation of erosion surfaces, have been used in a range of recent studies to infer surface uplift over geological time. In spite of the severe criticisms of traditional denudation chronology that have been advanced since the 1960s, such reconstructions are being regarded by some researchers as key evidence in the evaluation of geophysical models of mantle dynamics and continental rifting and break-up. The traditional denudation chronology approach is unfortunately severely limited by problems of chronology and correlation, as well as being crucially dependent on assumptions as to the nature of landscape evolution which are, at best, unproven. A range of other strategies have been used to document surface uplift but these are either limited in applicability (eg elevated shoreline or shallow marine deposits of appropriate age), or problematic (eg palaeoelevation estimates derived from basalt vesicle ratio data).

Tectonically-driven surface uplift has been widely regarded as an important process in passive margin development, but in the absence of clear evidence of surface elevation change it is difficult to confirm. The pulse of denudation and associated cooling of the shallow crust that, on the basis of inferences from low-temperature thermochronology, has characterized many passive margins during the rifting and break-up phase, has almost invariably been attributed to surface uplift. But a similar denudational pulse could also result from the fall in base level that would result from the rupture of an already elevated region of a supercontinent. An additional factor is the localised surface uplift that results from denudational unloading, a relevant effect on passive margins where a major discontinuity in topography and denudational regime typically runs parallel or sub-parallel to the coast. Such uplift needs to be accounted for before active tectonic uplift is inferred. These issues are explored with reference to southern Africa, a region which represents a 'type-locality' for the traditional denudation chronology approach, and for which there are quantitative estimates available for long-term denudation patterns based on both thermochronology and cosmogenic isotope data.

RCM1 : THam11 : F3 Late Neogene Passive Margin Denudation History - Cosmogenic Isotope Measurements from the Central Namib Desert

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In this paper we review ideas on the geomorphological history of the Southwest African passive margin, focusing on the Central Namib sector and presenting new evidence on the late Neogene landscape evolution of this region. The hyperarid Central Namib Desert occupies the 100 to 150 km wide pediment at the foot of the Great Escarpment and is part of the Southwest African passive margin which formed after breakup in the South Atlantic. We present new evidence from *in situ* cosmogenic ^{21}Ne dating of pediment surfaces, river terraces and river cut bedrock benches from this area. Our results generally confirm previous fission track and cosmogenic isotope studies in the same area and numerical models of coupled tectonic-surface processes. These studies concluded that, following a period of major post-rift denudation, long term denudation rates of this passive margin have been very low. Our results indicate that denudation rates during the late Neogene have been even lower (of the order of 0.5 to 1 m/my) than those estimated previously from samples taken from inselbergs on the pediment. Inselbergs appear to be located in or near areas of Plio/Pleistocene incision and badland erosion. We obtained a ^{21}Ne age of 5.18 ± 0.18 Ma from a resistant quartz vein projecting above pediment unaffected by recent incision, the oldest exposure age from the Namib so far. Calculating denudation rates from this quartz vein sample, we conclude that the pediment has undergone less than 10 m of surface lowering since the onset of arid conditions during the mid Miocene. Our results also indicate a late Neogene episode of accelerated denudation in the Central Namib Desert triggered by incision of deep canyons starting after ~2.75 million years ago. We interpret this as a signal of increasing wet conditions in this region, in response to Pliocene/Pleistocene global cooling. Evidence of, yet undated, earlier incision episodes suggests that the denudation history of this passive margin is one of slow long-term denudation - as other workers concluded on the basis of AFT and cosmogenic nuclide analyses - interrupted by pulses of rapid denudation.

RCM1 : THam12 : F3 Post-Breakup Evolution of High Elevation Passive Margins using Apatite (U-Th)/He Ages

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High elevation passive margins are common continental margins on the Earth's surface. They are grand-scale erosional features characterised by major escarpments, trending parallel to coastlines, that may reach 1200 meters in elevations. The escarpments commonly separate a highly dissected coastal plain from an inland plateau with subdued relief. On the basis of geomorphological observations, fission track-based thermochronometry and geophysical modeling, competing hypotheses for the post-break-up evolution of passive margins have been proposed: (i) lateral retreat of the escarpment from the continental edge to the present position at a constant rate until today, (ii) rapid lateral retreat reaching the present position in the first few millions years after continental break-up, and (iii) excavation of the escarpment in place, with no retreat. Quantitative constraints on the generation of first order topographic phenomena, such as the position of the escarpment through time, can be furnished by apatite (U-Th)/He thermochronology. This method has a closure temperature of 70°C and so it is a powerful tool for investigating changes in the thermal structure of the uppermost 2 - 3 kilometers of the Earth's crust over time. Apatite (U-Th)/He ages can provide a reconstruction of the thermal structure of the shallow crust imparted by the topographic position of the escarpment through time and so can be used to distinguish between the different proposed scenarios. The southeastern Australian coast is a classical example of high elevation passive margin: the Great Escarpment runs parallel to the coast for 3000 km, and the relief reaches elevations of 2000 meters. We are performing a study of apatite (U-Th)/He chronometry from coast-perpendicular

traverses across the coastal lowlands, escarpment and plateau of the southeast Australia in order to determine the evolution of the escarpment and elucidate its position through time. Preliminary apatite He age data are available from one transect completed to date. Apatite from the coastal plain have ages of between 80 and 90 Ma, suggesting that the coastal lowlands developed very rapidly after rifting and continental break-up at 95 Ma. Older ages on the plateau (> 200 Ma) indicate that the elevated plateau remained stable throughout continental break-up. The He data is inconsistent with a scenario of constant, lateral retreat of the escarpment across the coastal plain. Our working model, to be tested in future transects, involves in-place excavation of the escarpment. Local variations of the ages on the coastal plain suggest that embayments and promontories were present since the early stage of the escarpment evolution.

RCM1 : THam13 : F3 First Apatite Fission Track Study on Pan-African Basement in Ethiopia: Preliminary Results

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An apatite fission track (AFT) study has been carried out on Panafrican crystalline basement samples from Ethiopia. The aim was to assess the thermal evolution of the upper crust to constrain the age of the basement doming and to try to resolve whether passive or active rifting mechanisms prevailed in the Main Ethiopian Rift.

AFT central ages range from 422 ± 27 Ma to 65 ± 6 Ma and are older (> 325 Ma) in Northern Ethiopia than in Southwestern Ethiopia (<124 Ma), suggesting that samples from Southwestern Ethiopia have experienced temperatures > 110°C much more recently than samples from Northern Ethiopia. Mean track length (MTL) values vary between $12.66 \pm 0.37 \mu\text{m}$ and $11.38 \pm 0.17 \mu\text{m}$ and standard deviation ranges from $2.71 \mu\text{m}$ to $1.29 \mu\text{m}$. Most of track length distributions are unimodal and more or less negatively skewed, suggesting that samples have experienced progressive steady cooling. Although MTL are low, very short tracks were not common and so it seems most of the tracks should have been created in the upper part of the partial annealing zone (PAZ), where moderate temperature only allows slight annealing. Longer MTL and broader track length distributions are observed in Southwestern Ethiopia. This implies these samples experienced more significant annealing, possibly related to higher pre-cooling temperatures and that they crossed the lower temperature limit of the PAZ earlier than samples from Northern Ethiopia, which seem to have stayed within the PAZ until relatively recently. AFT data also display a 'boomerang'-shape distribution where longer MTL are related to younger age. This might suggest a cooling event younger than 65 Ma affected the samples from different paleo-temperatures (e.g. Fitzgerald et al., 1995).

Thermal histories were quantified using the Monte Trax approach (Gallagher, 1995) and Laslett et al. (1987) annealing algorithm. Preliminary results outline that samples from Northern Ethiopia remained a longer time within the PAZ and rapidly cooled across the 60°C isotherm within the last 16 Ma. In contrast, this recent rapid cooling is poorly constrained for other samples. Even though this recent cooling event has to be more discussed, it might be interpreted as denudation possibly related to doming and/or changes in drainage. This would imply that basement uplift postdated the main flood basalts (30 Ma; Hofmann et al., 1997) and was roughly coeval with extension (18-14 Ma; Ebinger et al., 1993). This inference thus appears to be in conflict with the usual rifting models.

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RCM1 : THam14 : F3 Exhumation and Uplift of Rocks in Extensional Regime: Results from Geotechnical Analyses and Comparison with Radiometric and Stratigraphic Data in Southern Tuscany

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Uplift of rocks is the displacement of rocks with respect to the geoid. Such displacement can be estimated knowing the amount of exhumation and the displacement of the Earth's surface with respect to the geoid (England & Molnar, 1990). The displacement of the Earth's surface results from topographic data or, in the case of sedimentary rocks, from topographic data and depth of deposition. Exhumation is the displacement of rocks with respect to the Earth's surface. It can be estimated through radiometric analyses: several cooling ages of the same mineral at different structural levels permit to compute exhumation, with the assumption of a thermal profile. Differently, in clay-filled extensional basins, exhumation and uplift of rocks are evaluated through the compressibility properties of the sediments. This paper focuses on evaluating the rate of exhumation by means of cooling ages and compressibility tests in two different areas of southern Tuscany (inner northern Apennines). Since early-middle Miocene, this region was affected by extensional tectonics and, since middle Pliocene, uplifting occurred. As a consequence, erosion deeply affected clayey Pliocene sediments.⁴⁰Ar/³⁹Ar incremental-release age determinations have been carried out on borehole samples of the eastern Larderello geothermal field, in order to constrain the timing of exhumation. Samples from different depths were examined (Dallmeyer & Liotta, 1998) and a rate of exhumation of 0.18 mm/yr was estimated. Compressibility tests were carried out in the clay-filled Pliocene Radicofani Basin analysing near surface undisturbed samples (Disperati & Liotta, 1998). Results lead us to construct the porosity-depth curve of the basin and, consequently, to estimate the amount of erosion (i.e., exhumation) which have been occurring since middle Pliocene. Such amount ranges between c. 1,200 m (0.40 mm/yr) and c. 300 m (0.10 mm/yr), in the western and eastern side of the basin, respectively. Considering the depth of deposition (Liotta & Salvadorini, 1994), the present altitude and the amount of exhumation, the uplift of rocks in the basin resulted ranging between c. 2,000 (0.66 mm/yr) and c. 900 m (0.30 mm/yr) in the western and eastern side of the basin, respectively. The altitude of the middle Pliocene coastal sediments of southern Tuscany (Bossio et al., 1995) is 700 m (0.22 mm/yr) in the eastern Radicofani Basin and 200 m (0.07 mm/yr) in the eastern Larderello region. Such values represent only the minimum possible uplift of rocks in the study areas. Compressibility analyses of clayey sediments in southern Tuscany resulted a powerful tool in order to compute uplift of rocks, while radiometric analyses permit to evaluate only exhumation and stratigraphic data suggest a minimum possible value of uplift of rocks.

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