EUG XI

Symposium LS04

Intraplate Strike-Slip Deformation Belts

Convenors

Francesco Salvini
Fabrizio Storti

Tuesday AM Session

LS04 : TUam02 : F2
Are Continental-Scale Strike-Slip Faults Rooted into the Mantle? Seismic Anisotropy Constraints and Thermo-Mechanical Implications

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A large body of geological and geophysical observations in active and fossil continental-scale transcurrent faults supports the idea that the entire lithosphere is coherently deformed. Geological observations in middle to lower crust shear zones evidence efficient strain localization, even in a partially molten crust. Synkinematic magmatism in wrench faults points toward partial melting of the mantle coeval with deformation. Gravity anomalies reveal a Moho topography associated with major continental shear zones. Seismic profiling and magneto-telluric soundings provide evidence that major transcurrent faults cross-cut the Moho. Seismic anisotropy measurements in orogenic belts characterized by large-scale transcurrent motions suggest that the lithospheric mantle deformed coherently with the crust and developed a crystallographic preferred orientation of olivine over its entire thickness. In active belts, shear waves splitting parameters even support that the fabric associated to major strike-slip faults is coherent with asthenospheric flow structure. Parallelism between crustal and upper mantle structure is also suggested by measurements of electrical conductivity anisotropy. All these observations lead to the concept of intra-continental lithospheric wrench faults rooted into the upper mantle and possibly continuing into the sub-lithospheric upper mantle. This concept has important tectonic implications. The crystallographic preferred orientation of mantle minerals is frozen at the end of a tectonic event and retained until a tectonic reactivation occurs. Numerical modeling of the deformation of an olivine polycrystal shows that a preferential orientation of olivine crystals inherited from strike-slip faulting induces a significant mechanical anisotropy in the lithospheric mantle. This directional weakening due to frozen-up crystallographic fabrics in the lithosphere may explain the long-lived nature and systematic reactivation of some major strike-slip faults. During continents breakup and ocean opening, major transform faults, such as the Newfoundland-Azores-Gibraltar TFZ in the Central Atlantic, are inherited from preexisting lithospheric wrench faults. Moreover, a transtensional reactivation of the inherited mantle fabric may explain the propagation of rifts and the opening of oceanic basins parallel to the old tectonic grain of the continent. Finally, there is a growing body of evidence that the exhumation of HP-metamorphic rocks may occur through the reactivation of a preexisting tectonic fabric either in a transtensional or a transpressional regime.

LS04 : TUam03 : F2
Kinematic and Mechanical Controls on the Formation and Evolution of Large Intracontinental Wrench Zones in Physical Models

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We present results from a series of scaled physical experiments on the role and mutual influence of kinematic and mechanical parameters that control the initiation and evolution of large-scale (>100-km-long) wrench zones in tectonic plates. The models had an initially isotropic brittle layer (upper continental crust) and viscous lower part (lower crust). Unlike in most of the previously published experiments, where strike-slip was imposed by a basal discontinuity, wrench zones in our models formed spontaneously in response to the presence of preexisting weak areas in the tectonic plate, where the upper, brittle crust was thinner (e.g., older extensional basins or areas of thermal anomalies). Experimental results indicate that the presence of such preexisting weak zones is enough to trigger the formation of strike-slip zones, even in the absence of preexisting structural fabric. Moreover, our results suggest that the lateral boundary conditions control the shape and evolution of the wrench zone. In models that were laterally confined (no possible movement normal to the strike-slip direction), the wrench zone was wide, made of an array of positive flower structures bounded by Riedel-R curved fault planes. Most fault planes were oblique to the direction of regional shear. Faults propagated from the weak zones toward each other. A lot of the shear was accomodated by distributed shear within the wide strike-slip zone. By contrast, the initial geometry and evolution of the wrench zone differed in models where the amount of lateral confinement was decreased (e.g., if a continental passive margin was parallel to the strike-slip direction). Regional shear was entirely accommodated by a single, narrow, linear strike-slip zone. The zone formed in the center of the plate and propagated toward each weak zone. The wrench zone comprised only two strike-slip faults trending parallel to the direction of regional shear, and along which no significant vertical displacement occured. We infer that the lower lateral confinement allowed a major reorientation of the direction of principal stresses, which allowed for the formation of slip planes parallel to the regional direction of wrenching to form and entirely accommodate the regional strike-slip motion.

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LS04 : TUam04 : F2
Constraining the Kinematics of a Major Intracontinental Transform Boundary: The Ailao Shan-Red River Shear Zone

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The Ailao-Shan - Red River shear zone (ASRR) plays a key role in the debate concerning the eastward extrusion of Indochina during the India - Eurasia collision. This 1000 km long belt of mid-crustal high-grade metamorphic ranges, extends from SE Tibet to the South China Sea (SCS). It has been interpreted to be the left-lateral transform boundary between the Indochina and South China blocks. New evidences from the northerwesternmost (XueLong Shan) and southeasternmost (DayNuiConVoi or DNCV) metamorphic ranges of the ASRR completing already abundant available data, better constrain the kinematics of the ASRR. U/Pb ages of granitoids within the shear zone range from 33 to 22 Ma suggesting that left-lateral shear took place during this entire span. Such an age range is confirmed by in situ Th-Pb ion microprobe dating of monazite inclusions in rotated garnets between ~ 31 and ~ 21 Ma. The cooling history of the whole shear zone, based on more than one hundred $^{40}Ar/^{39}Ar$ data, shows two main episodes of rapid cooling in the four main ASRR metamorphic ranges: (I) cooling from peak metamorphism during left-lateral shear, and (II) cooling from greenschist conditions during right-lateral reactivation of the ASRR. During the first cooling phase (I), denudation rates were ~ 0.4 mm/yr in the DianCang Shan and ~ 1.6 mm/yr in the Ailao Shan and DNCV. In the NW part of the ASRR (XueLong Shan, Diancang Shan) we link rapid cooling (I) to local denudation mechanisms in a transpressive environment. In the SW part (Ailao Shan, DNCV) the more rapid cooling (I) resulted from diachronic, regional denudation by zipper tectonics in a transtensive regime. The induced cooling diachronism visible along the Ailao Shan suggests that, from ~ 25 Ma until ~ 17 Ma, left-lateral deformation took place at a rate of 4 to 5 cm/yr. DNCV rocks, belonging to the South China block, always stayed in a transtensive regime and do not show cooling diachronism. The similarities of deformation kinematics onshore along the ASRR and offshore in the South China Sea (SCS) are striking even in detail, confirming the causal link between large-scale continental strike-slip faulting and marginal basin opening. A review of the Geological offsets indicates a minimum left-lateral offset of 500 km, while Paleomagnetic studies suggest more than 1000 km. The presence of this huge and rapid strike-slip fault in SE Asia during the collision, and its later reactivation in the oposite sense, is often neglected in models of Eurasia deformation. It is best accounted for by a two stage extrusion model.

LS04 : TUam05 : F2
Pull-Apart Basin History along the Eastern Indian Shear Zone from Eocene to Present

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An en-échelon pull apart basin system extends for more than 2000 km from the Eastern Himalayas in the North to the Andaman Sea in the South. The northern Andaman Sea was extensively surveyed during the recent Andaman cruise (May 2000 on board R/V Marion Dufresne II, the logistic vessel of the French Polar Institute; www.geologie.ens.fr/Andaman) using multibeam, gravity, magnetics and seismic reflection profiling. Oceanic spreading is active today along two main rift segments and has produced at least 100 km of oceanic crust. The present-day geometry of this rift system is young and followed a mid-Miocene intracontinental rifting marked by the emplacement of large volumes of volcanics (Alcock and Sewell seamounts). The northernmost rift segment connects to the active dextral Sagaing Fault in the Ayeyarwady Delta, which crosscuts northwards in Central Myanmar en-échelon Middle Eocene to Middle Miocene depocenters filled by more than 8 km of sediments. The age of extension of these Central Myanmar basins is constrained further by the age of metamorphic stretching lineations that affect the continental crust exhumed along the eastern margin, dated between 30 to 15 Ma (Ar/Ar) along the Shan plateau scarp. Consistent direction of normal faulting within the basins and direction of lineations in the exhumed metamorphic basement systematically indicate a NS to N160°E stretching, compatible with a pull apart origin in relation with the overall Eastern Indian shear zone. This pull apart basin system was inverted between 10 and 15 Ma during the initial stage of motion along the Sagaing Fault and initial opening of the Andaman Sea. Transfer zones in this basin system were then reactivated as NE or SW verging thrusts. We discuss the maximum amount of total extension within these basins versus the amount of shearing between India and Sundaland, as well as episodic stretching versus continuous extension and exhumation process. The present-day active structures, Andaman rift system and Sagaing Fault, are young and overprint older pull apart basins, suggesting a non steady-state mechanism of accommodation of hyper-oblique convergence.

LS04 : TUam06 : F2
The Role of Pseudotachylyte Formation in Active Strike-Slip and Extensional Deformation in the Altai Transpressional Belt in Central Asia

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The Altai fold-belt in Central Asia, bounded by major transpressional shear zones, is currently accommodating a part of the converging movements between the Indian and the Eurasian plates. The stresses, transferred northwards over 2500 km, starting from the active margin at the Himalayan collision zone, caused uplift along the transpression zones of the Altai, starting in the Pliocene. The southern parts of the belt (in Mongolia) are characterised by active seismicity, generally causing dextral movements on NW oriented transpressive faults and reverse movements on E-W trending thrusts, delimiting ramp-basins.

This paper presents the results of a tectonic study of the northern part of the Altai belt (in Siberia). Although historical earthquakes in this area are rare and of low magnitude, there are several indications of major seismic activity and important tectonic movements during the Quaternary. We studied the kinematic- and dynamic evolution of the Shapshal-Teletsk transpressional zone, situated along the boundary zone between the Altai and the Tuva-Mongolian plate. It is the most prominent strike-slip zone in the region, linking the seismically active Mongolian faults to the geologically active Teletsk extensional basin, more then 300 km to the north.

A field study of the fault kinematics in the region revealed a complex mechanism of reverse and dextral strike-slip and oblique movements with basin formation at releasing bends and contraction at restraining bends, fault bounded block rotations, and extensional basin development due to stress axes permutation. The formation of the Teletsk basin has occurred in a very short period of rapid subsidence in the late Quaternary, as evidenced by reflection-seismic profiles and by a micro-structural analysis of fault rock. Pseudotachylyte, forming at high slip-rate during seismic faulting, was found at several locations inside the basin delimiting border faults of the Teletsk graben. The relationship between the pseudotachylyte (with its closely associated micro-breccia, formed by abrasive wear) and the macroscopic metre-scale isolated breccia lenses outcropping at several levels in the currently normal border faults, indicates that the faults developed initially in a dextral seismic strike-slip setting with sidewall-ripout formation. In a later stage this strike-slip weakness zone was reactivated as a major listric normal fault with landslide geometry controlling the graben formation. A geochronological study of the pseudotachylyte using ^{40}Ar-^{39}Ar stepwise heating and laser ablation techniques provides insights in the distribution of ^{40}Ar and its migration relative to the associated micro-breccia and unaffected country rock. These data can provide temporal constraints for the tectonic evolution of the area and determine the role of the pseudotachylyte in the recent seismic faulting and basin formation.

LS04 : TUam07 : F2
Granulites in Karakoram: Crustal-Scale Folding Versus Strike-Slip Motion

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Granulitic assemblages (meionite scapolite - clinopyroxene - pargasite - plagioclase or orthoamphibole - rutile - spinel - pyrope) are found in the Karakorum Fault zone. Thermobarometry on the metabasites yield conditions of T ~ 800°C and P ~ 5.5 kbar. These conditions suggest that the Karakoram Fault, accommodating the lateral extrusion of Tibet, should be a lithosphere-scale shear zone, similar to the Red River fault. Ar-Ar data show that the granulitic metamorphism occurred before 32 Ma, and that retrogression in the amphibolite facies conditions occurred at c. 18 Ma. Granulitic assemblages (sillimanite - K-feldspar - garnet) also occur in the Karakorum margin itself. These granulites, associated with migmatitic layers, post-date the southwest vergent nappe piling and polyphased M1 metamorphic history (pre-37 Ma) in the Karakoram Metamorphic Complex. M2 metamorphic conditions are estimated at T = 750-800°C and P = 5-6 kbar. M2 granulitic isograds define an E-W thermal anomaly, also marked by migmatitic domes. Ar-Ar amphibole ages, obtained on a S-N transect from the Shyok Suture / MKT to the dome zone and a compilation of data from the literature are used to constrain the timing of tectonometamorphic events. Far from the dome zone, in the Shyok Suture zone, cooling ages range from 52 to 38 Ma. At the rim of the domes, ages decrease from 20 to 13 Ma, and at the core of the dome, young U-Pb monazite ages of 6-7 Ma date the M2 metamorphic peak. The chronological and metamorphic data, and the presence of young (9 Ma) mantellic derived plutons in domes area, clearly indicate that the EW domal lineament is related to a heat advection process from the mantle. We propose that this late M2 tectonometamorphic and magmatic evolution is due to Indian slab detachment, initiated at 20-25 Ma.

LS04 : TUam10 : F2
Fission-Track Constraints on Mesozoic and Cenozoic Tectonic History of the Northern Edge of the Tibetan Plateau

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Studying the kinematic of the deformation on the northern edge of the tibetan plateau is fundamental to understand the tectonic evolution of the whole Tibet. Several questions remain concerning the propagation of the deformation inside the asian lithosphere, the exhumation rates, the rates of formation of the main reliefs and the age of this topography.

Fission-track analysis on zircons and apatites yields new information about the timing of deformation of the northern tibetan plateau. Ages on zircons, ranging from 221 ±22 Ma to 96 ±4 Ma are indicative of a general late Triassic - early Jurassic cooling probably driven by the collision between the Qiantang and Kunlun blocks. Mid Jurassic slow cooling is recorded also in apatites, in regions not affected by later Cenozoic deformation. This Jurassic denudation was followed by a period of sedimentation during the Cretaceous, except along the Altyn Tagh fault zone, and in some restricted areas of the western and eastern Qilian Shan. This long and relatively quiet period ended at about 40 ±10 Ma along the major Altyn Tagh and Kunlun strike-slip fault zones which were activated by the India - Asia collision. This first movement along lithospheric faults resulted in the eastward extrusion of the Tibet plateau which was followed, in late Oligocene - Miocene times, by a major compression event, initiating the formation of the high relief of north Tibet. A final compressional event took place at 9 to 5 Ma and is well correlated with high sedimentation rates in the basins of this region. This compression induced continental subduction in the Kunlun ranges, the Altun Shan belt, and probably the Qilian Shan belt.

LS04 : TUam11 : F2
Partitionning along the Indo-Burmese Wedge: Onshore and Offshore Constraints

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Crustal velocity fields obtained by combining recent GPS measurements and Quaternary fault slip rates confirm N015° oblique convergence of India with respect to South East Asia in the Myanmar region, at a rate of about 40±5 mm/yr . Part of this motion is accommodated by dextral strike-slip on the Sagaing Fault, but finite offset of a young volcano cut by this fault indicates a maximum mean rate of slip of 25 mm/yr for the last 300.000 years. At least 1/3 of the total motion thus has to be distributed west of the Sagaing Fault, possibly along the western boundary of the Shan Plateau, in the Central Basin of Myanmar, and over the Arakan Yoma belt (Indo Burmese Wedge). We combine Landsat Imagery and onshore field data with multibeam and seismic reflection data recently collected at sea during the Andaman Cruise (May 2000) to propose a new structural map of the Arakan Yoma. In the southern part of the wedge, between 14°N to 17°30N, the front (more or less N020° trending) is transpressional with pure strike-slip motion on N040° oriented segments and wedge growth along NW-SE segments. This geometry is compatible with partial partitioning, the N015° convergence of India being resolved into a N040°, 20 mm/yr component (India-wedge motion) and a NS, 25 mm/yr component (wedge-Sundaland motion taken essentially on the southern portion of the Sagaing Fault). The central part of the wedge, between 17°30N and 20°N, is affected by N120° southward verging thrusts, both onshore and offshore. The wedge gradually bends to the west, and dextral shear faults oriented N020° and N160° develop onland with probably small displacement. North of this bend, the internal part of the wedge is cut by large N010° dextral strike slip faults, whereas the external part is marked by NS folds ending northward on the Shillong shear. This part of the wedge is best interpreted as full partitioning of the oblique motion, the total motion being resolved into a 15 mm/yr EW motion (frontal folds) and a 38 mm/yr NS strike-slip component. Gradual evolution from partial partitioning to the south to full partitioning to the north requires a corresponding increase in the amount of shear. If taken along the Sagaing Fault only, this would imply stretching of the Burma sliver, which is not observed. We thus conclude that shearing to the north is accommodated by several of the NS to N010° dextral faults within the wedge itself and at the boundary with the Central Basin.

LS04 : TUam12 : F2
Deformation Partitioning and Magmatic Activity at the Southern Termination of Intraplate Fault Systems in the Ross Sea Region, Antarctica

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The Ross Sea has been undergoing a long-lived E-W extension since Mesozoic times along mainly N-S to NNE-SSW trending faults. Crustal thinning in the Ross Sea caused block faulting and uplift of the Transantarctic Mountains, in Victoria Land. Starting in Eocene times, inherited, Paleozoic NW-SE trending crustal discontinuities in northern Victoria Land reactivated as the onshore dextral transcurrent continuations of the Tasman and Balleny fracture zones of the Southern Ocean. Right-lateral strike-slip tectonics affected Victoria Land and the western Ross Sea, interfering with the preexisting extension. The concomitance of strike-slip and extensional regimes induced transtension in the transition region between Victoria Land and the Ross Sea, where McMurdo effusive and intrusive rocks are located. We show that the Cenozoic NW-SE dextral shear in Victoria Land has been localized along the western shoulder of the Ross Sea, where the Mesozoic faulting provided a mechanically weakened region. Clockwise rotation of the Cenozoic stress field caused reactivation of the preexisting N-S extensional faults in an overall transtensional regime, that favoured magma ascent. Dyke injection occurred both along the regional NW-SE strike-slip faults and in the N-S transtensional arrays, but was strongly favoured in the latter, where the resulting extensional component is higher.

LS04 : TUam13 : F2
Anatomy of a Major Intraplate Fault System in Antarctica: The Lanterman Fault

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The Lanterman Fault is one of the NW-SE striking, intraplate strike-slip shear zones that bound the major Proterozoic to Early Paleozoic tectono-metamorphic blocks constituting the northern part of Victoria Land, Antarctica. In particular, the Lanterman Fault constitutes the boundary between the Bowers and Robertson Bay terranes and has been previously interpreted as a Early Paleozoic feature. This fault zone, several kilometres wide and with an onshore along strike length of about 400 kilometres from the Southern Ocean to the Ross Sea, records almost entirely brittle shear, producing complex, NW-SE to N-S trending, anastomosing dextral fault strands. Brittle faulting is subparallel to the regional subvertical schistosity, attesting that it was superimposed in a broad region that experienced earlier ductile-dominated deformation. The regional-scale brittle deformation fits into a general kinematic model involving progressive NW-SE dextral simple shear. Trend variations of the Lanterman Fault produced different deformation regimes along strike. Particularly, the eastern shoulder of the Rennick Graben constitutes a major releasing bend along the Lanterman Fault, rather than the boundary fault system of an extensional basin. The Lanterman Range corresponds to a major restraining area, possibly developed above a contractional step-over along the Lanterman Fault. Two major onshore age constraints exist for brittle faulting along the Lanterman Fault: (i) involvement of the Permo-Triassic Beacon and the Jurassic Ferrar rocks in faulting; (ii) intimate link between right-lateral faulting and Cenozoic magmatism along the southern onshore termination of the fault. Several lines of evidence thus indicate that final amalgamation and assembly of the Bowers and Robertson Bay terranes in northern Victoria Land was the response to large-scale Cenozoic right-lateral movements along NW-SE inherited weaker structures rather than the fossil picture derived from a mere early accretionary history commonly referred to the Early Paleozoic Ross Orogeny.

LS04 : TUam14 : F2
Regional Crustal Architecture of Intraplate Strike-Slip Belts over the Transantarctic Mountains and Adjacent Ross Sea Rift as Imaged by Potential Field Investigations

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The Transantarctic Mountains (TAM), the highest and longest rift-related mountain belt in the world, reach elevations over 4000 m and extend for over 3500 km across Antarctica. Uncertainties regarding magnitude, timing and kinematics of Mesozoic and Cenozoic extension between East Antarctica and West Antarctica still remain. However the rifted nature of the adjacent continental crust of the Ross Sea (RS) as part of the West Antarctic Rift System is fairly well documented from seismic, gravity and magnetic evidence (Behrendt, 1999). Crustal architecture of the TAM is much less well known. Salvini et al., (1997) proposed from offshore seismic data and TAM geology that the post-Eocene tectonic framework of the RS-TAM system is due to reactivation of Paleozoic-age terrane boundaries as major right-lateral strike slip faults linking to oceanic transform faults. Previously, Tessensohn (1994) instead suggested that the inherited fault system of the Ross Orogen accommodated the transform fault strain linked to Cretaceous Australia-Antarctica plate motions by left-lateral shear. Potential field investigations over the RS-TAM region are now fairly extensive and can furnish new data which can contribute towards: locating some of the strike-slip faults; evaluating kinematics and timing; imaging crustal segmentation; establishing relationships with the inherited fault systems; investigating their control on rift-related magmas. Ferraccioli & Bozzo (1999) interpreted aeromagnetic data to reveal the unexposed prosecution of the Ross-age Exiles Thrust and discussed more recent post-Jurassic segmentation of the TAM blocks linked to reactivation of this fundamental fault zone. Magnetic lineaments also clearly define the buried Campbell and Priestley strike-slip faults at the south-western edge of the Rennick Graben and show their control upon the location of the quiescent Mt Melbourne volcano (Ferraccioli et al., 2000). Prominent magnetic anomalies define partially buried Cenozoic alkaline intrusives at the intersection between NW-SE strike-slip and ENE off-splay faults in association with the highly uplifted Southern Cross Mountains Block. Offshore, the magnetic data clearly image the N-S clustering of rift related volcanic activity resulting from seismically imaged strike-slip motion along the NW-SE faults. Regional and high-resolution onshore-offshore aeromagnetic data favour NW-SE directed Cenozoic oblique rifting generated by intraplate strike-slip faulting. New aeromagnetic and gravity data collected over part of the extensively ice-covered Rennick Graben, a fundamental structure effectively linking the continental Ross Sea crust to the Pacific Ocean, is also presented and interpreted to contribute towards establishing regional crustal architecture of the strike-slip dominated region.

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Tuesday PM Session

LS04 : TUpm25 : F2
Stretching of an Inhomogeneous Lithosphere and its Response to the Brittle Upper Crust: The Western Mediterranean

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The Western Mediterranean Rift consists of several extensional basins, which formed during the Neogene. Strike-slip zones separate individual basins and compensate for differences in strain-rate. Paleomagnetic data document rotations about vertical axes of regional scale (microplates) and of local scale (rotations within strike-slip zones). In many cases the measured rotations could be dated as being Neogene or younger in age, and thus they can be assigned to Mediterranean extension.

The complex puzzle of Mediterranean extension has been explained due to superposition of alpine compressional structures and Neogene extension. In a new approach we propose a finite element model to simulate Mediterranean extension based on lithosphere thickness variation. In a first step the Alpine thrust belt was restored to its geometry before Mediterranean extension. Pre-Neogene crustal thickness was mapped by assigning normal crust C1, of the Alpine foreland, and thickened crust C2, of the Alpine thrust belt, to cells of a 50x50 km grid. In a second step the grid was stretched assuming a temperature-dependent rheology for the lithosphere. With progressive stretching, the lithosphere cools and increases its strength resulting in an effective limit on the degree of extension. The limit for the Mediterranean is deduced from a widespread type of crust of approximately 20 km thickness (C3). Under the assumption of a regional constant thermal gradient and the exponential dependency of strain-rate on temperature, it follows that thicker lithosphere undergoes larger strain.

The model matches well the actual structure of the Western Mediterranean. As test for the model, published paleomagnetic vectors, corrected for deviation between reference pole direction and grid, were plotted on the deformed grid. The good alignment of the paleomagnetic vectors with the grid lines confirms the above assumptions. Also, calculated strain-rates for individual basins agree well with modelled rates, and zones of increased horizontal shear coincide with observed strike-slip zones.

An embryonic stage of a strike-slip zone is observed in the Eastern Pyrenees. This area coincides with a bend of the Alps-Pyrenees mountain belt from a NE-SW strike - parallel to the Mediterranean extension axis - to E-W strike - oblique to the Mediterranean extension axis. Neogene deformation of the Eastern Pyrenees is documented by right-lateral pull-apart basins in the north, and left-lateral rotations above transpressive faults in the south. This configuration of the Eastern Pyrenees can be explained by eastward extension of the axial part with thickened crust, whereas its adjacent foreland with normal crust remained unaffected by Mediterranean extension.

The results of the finite element experiment explain strike-slip zones as being dependent on initial gradients in lithosphere thickness, which are oblique to the general extension axis, as in the Eastern Pyrenees. The model also shows the close relationship between ductile and brittle deformation behaviour.

LS04 : TUpm26 : F2
Deformation History and Architecture of Transpressional Inversion along the Intraforeland Mattinata Fault, Italy

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The Adriatic foreland of the Apennines thrust-and-fold belt is compartmentalised by E-W trending, strike-slip faults. The left-lateral Mattinata Fault, in Southern Italy, is one of the best expressed fault systems of the Adriatic foreland. The Gargano Promontory is a structural high along the Mattinata Fault. There, the transition from Mesozoic shallow-water carbonate rocks to deep-water carbonates is exposed. Synsedimentary extensional faults are preserved in the Gargano Promontory, along a WNW-trending zone of transitional carbonate rocks. Such extension is overprinted by a complex array of thrust and strike-slip deformations, that can be explained within a transpressional framework induced at a major restraining bend along the Mattinata Fault. Transpressional deformations caused the overall positive inversion of the former basin-boundary faults. This inversion is well evident in offshore seismic profiles and testifies for the key role played by the inherited fault network in the location and propagation of younger strike-slip and contractional deformations. Field data and progressive restoration of offshore reflection seismic profiles pointed out that the inversion tectonics along the Mattinata Fault has occurred since Miocene times and evolved during the Pliocene and the Quaternary.

LS04 : TUpm27 : F2
Polyphase Dextral Slip and Late-Stage Transpressive Deformation along the Eastern Periadriatic Line, Northern Slovenia

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The Periadriatic Line (PAL) is a major Neogene post-collisional fault system of the Alps, accommodating upper-crustal deformation due to northwestward indentation of the Adria microplate into the European plate. Structural history of easternmost outcrops of the PAL zone, located in northern Slovenia, reveals two principal stages of dextral movement, associated with transpressive strike-slip faulting, folding and rotation of tectonic blocks in shear zones.

In Early Miocene about 100 km of dextral displacement occurred along the eastern segment of the PAL, facilitating eastward extrusion of the Eastern Alps towards the retreating subduction zone in the Carpathians (Ratschbacher et al., 1991; Csontos et al., 1992). The first phase of movements terminated by Late Early Miocene due to major rotations of crustal blocks in the Pannonian Basin area, and the fault zone was sealed with sediments (Fodor et al., 1998).

In Pliocene and Quaternary, continuing NW to NNW directed movement and counterclockwise rotation of Adria caused dextral transpression and inversion of Miocene basins in a wide belt of deformation inside and south of the PAL zone. To the west, in the eastern Southern Alps, the deformation was mainly accommodated south of the PAL by SE directed thrusting and reactivation of older, S directed thrust systems (e.g. Castellarin & Cantelli, 2000). Towards the east the style of deformation gradually changed to oblique convergence, accommodated by dextral strike-slip faulting, rotations of large blocks in the shear zone, and minor transpressive thrusting north of the PAL. Already in Late Miocene the principal displacement zone started to shift southwards to adjoining shear zones subparallel to the PAL proper. The PAL itself was reactivated and rearranged by younger strike-slip faults, which are either adjoining or displacing it. Area south of the main strike-slip deformation zone was predominantly deformed by transpressive N-S shortening, producing basin inversion, basement pop-ups and folding.

Progressive stopping of strike-slip movements in the main zone caused gradual transfer of dextral slip towards the south, which was accompanied by transtensional opening of Quaternary basins of differing age in releasing oversteps between the fault zones. The present-day deformation appears to be concentrated well away from the PAL in Friuli area and along the Idrija dextral strike-slip fault system, as indicated by current rapid displacements and regional distribution of seismic activity.

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LS04 : TUpm28 : F2
The Southern Tyrrhenian Sea Margin: Example of a Lithospheric Scale Strike Slip Duplex

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The architecture of northern Sicily is currently interpreted as resulting from recent deformations related to the opening and evolution of the Tyrrhenian Sea, superimposed on older deformations related to development of the Apennine-Maghrebide fold-and-thrust belt. The nature of recent deformations, however, is poorly constrained, and models that have been proposed for their development are highly controversial, in that they imply N-S directed extension (PEPE et alii, 2000) or shortening (FACCENNA et alii, 1996), respectively. Analysis of the kinematic character of the main structures may be useful for unravelling the recent evolution of northern Sicily, thus providing additional constraints for geodynamic modelling. In this study, after a brief review of the tectonic history of the sicilian-tyrrhenian margin, we present the results of a structural analysis carried out along faults and shear zones exposed onshore northern Sicily and the Egadi Islands. At odds with extensional and contractional interpretations, but in general agreement with previous structural analyses (e.g. see GHISETTI & VEZZANI, 1981), our data reveal a dominant strike-slip or transtensional character for most investigated faults. Based on integration of these new data with available information on adjacent offshore structures, we propose that the southern Tyrrhenian Sea margin corresponds to a lithospheric-scale E-W trending dextral shear zone, namely to a strike-slip duplex, that was developed in response to a horizontal, NW-SE oriented contractional stress field.

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LS04 : TUpm29 : F2
Continental Collision, Extension, Lateral Extrusion and the Timing of Deformations in the Internal Domain of a Mountain Belt: An Example from the Eastern Central Alps (Bergell Area) during the Oligo-Miocene

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The Periadriatic Line and its related secondary faults is the most important fault system in the Alps. A detailed understanding of the kinematics, timing and magnitude of movements on this fault system is critical to any tectonic model of the late stages of Alpine collision. In order to understand the late deformation field in the internal domain of the Eastern Central Alps, we investigated the brittle-ductile fault systems in the Oligocene intrusions in the Bergell and Insubric areas. At map scale, we define the Bergell block as delimited by four main discontinuities of first order, with kinematics compatible with its late Oligocene-early Miocene northeast-directed lateral escape. The NW-SE oriented Forcola and Muretto normal faults, at the western and eastern block boundary respectively, are bounded in the north and in the south by two major strike-slip faults, the NE-SW oriented, sinistral-reverse Engadine Line and the dextral E-W oriented Insubric Line. In the Bergell block, the overall fault pattern includes strike-slip, oblique normal and normal faults. Because most sites revealed successive deformations, two paleostress tensors were computed, based on the observation of consistent relative chronology criteria, such as cross-cutting relationships between fault sets. These stress tensors correspond to an older extension regime and younger compressional strike-slip regime. During both events, the long axis of the strain ellipsoïd remained sub-horizontal and NE-SW to ENE-WSW directed. This fault pattern kinematically allowed the north-east-directed lateral escape of the Bergell block, the major discontinuities bounding the system accommodated most of the displacements. From their geometry and kinematics, both the Forcola and Muretto normal faults have to be seen in the context of late Oligocene-early Miocene dextral transpression, associated with an orogen-parallel stretch and coeval with conjugate dextral and sinistral strike-slip along the Insubric and Engadine Lines, respectively (Schmid and Froitzheim, 1993). Timing constraints on the Forcola line are given by the structural relationships between the 25 Ma old Novate intrusion (Gulson, 1973) and this normal fault. The study of shear zone patterns and deformation mechanisms in the Novate leucogranite, reveals SW-NE extension recorded from sub-magmatic to greenschist facies temperature conditions. A model of syn-extension emplacement of the Novate intrusion along the Forcola Line is proposed at 25 Ma. New zircon and apatite fission track ages from several profiles through both Forcola and Muretto normal faults show no age offset indicating that the activity of these faults is sealed at around 20 Ma. The activity of the main transtensive zones in the Bergell area can thus be bracketed between 25 Ma and 20 Ma. This period of exhumation of the Bergell block, assisted by normal faulting, was followed by dominant strike-slip movements during the final exhumation mainly controlled by erosion.

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LS04 : TUpm30 : F2
Block Rotations along the Southward Splining Branches of the North Anatolian Fault

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After the collision of the Arabian and Anatolian plates along the Zagros suture 11 Ma ago, the Anatolian plate started to escape westward along two transform faults, North and East Anatolian faults. GPS studies indicate that (McClusky et al., 2000) the Anatolian plate is rotating southwestward according to a pole around Sina peninsula. This escape and rotation tectonics caused internal deformation of the Anatolian plate and splining of the North Anatolian Fault. In the North Central Anatolia, there are a number of southward splaying branches of the North Anatolian Fault. These splays divide the Anatolian Plate into some fault-delimited blocks such as Tokat, Merzifon, Osmancik and Gümüs blocks. Eocene-Oligocene volcanic rocks cover large areas on these blocks. In this study, palaeomagnetic samples collected from these volcanics in 46 locations. 8 of them have been rejected because of the unreliable magnetisation. The palaeomagnetic results demonstrate that each fault-bounded block has affected by vertical block rotations clockwise or anticlockwise. The clockwise and anticlockwise rotations are 8-43°, 30-38°, respectively. The amount and direction of the block rotations were controlled by the geometry and type of fault delimiting each block.

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LS04 : TUpm31 : F2
Transpressional Deformation in the Neoproterozoic Mobile Belts of NW-Namibia

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Two Pan-African mobile belts, the Kaoko- and Damara belt, trend NW and NE respectively across NW-Namibia and intersect in an area known as the Ugab Terrain. This terrain is composed of siliciclastic metaturbidites with minor turbiditic and hemipelagic marbles, all of Neoproterozoic age, which have been strongly deformed and intruded by 5-10 km diameter syenite plutons in the latest Proterozoic. The Ugab Terrain is deformed by an early phase (D1-D2) of two sets of semi-orthogonal folds and associated foliations, an S1 homogeneous cleavage and an S2 crenulation cleavage. The cleavage intersection, foldaxes and a D1-D2 stretching lineation are strictly parallel throughout the investigated area. Most spectacular are km-scale N-S trending upright D1-folds that are visible from space and which indicate a major component of regional E-W shortening normal to the trend of the Kaoko Belt. However, the close association with D2 and the colinear nature of all D1-D2 structures suggest that the folds formed in transpression rather than in coaxial bulk shortening. After intrusion of the syenite plutons a later phase of deformation, D3, caused local km-scale refolding of D1-D2 and evidence for renewed or continued transpressional deformation. This evidence includes a dependence of S3 and D3 fold-orientation on finite strain; transected folds; asymmetric deformation of pre-D3 foliation boudins; and shear zones in upright carbonate beds in steep limbs of D1 folds. D3 folds trend from NE to N with increasing strain, which could correspond to a set of N-S trending 10 km wide transpressional D3- shear zones parallel to older D1-D2 structures. The most spectacular effect of D3 however, is a complex asymmetric defomation pattern around the syenite plutons. Two of the plutons have been mapped and are found to cut D1 folds. They are internally undeformed except from being cut by late NW-SE trending veins of biotite granite, and show 10-km scale D3 strain shadows in metasediments to the NE and SW. The shape of the strain shadows, the deflection of the transected D1 folds and the orientation of included panels of the wall rock suggest that the plutons themselves rotated as relatively rigid bodies over 40-90° with respect to the far-field D1 foliation. The complete pattern of D3 structures around both plutons is similar to that in and around porphyroblasts in thin sections of deformed metamorphic rocks. Although intense D3 deformation obscures the exact nature of D1-D2, this foliation-fold pair seems to be the product of transpressional deformation similar to that of D3. Work is in progress to establish the large-scale tectonic significance of the D1-D2 and D3 events in the transitional zone between the Kaoko and Damara Belts.

LS04 : TUpm34 : F2
Neotectonic Strike-Slip Movements in Western Hungary; Inferences from Field Study, Shallow High Resolution Seismics and Analogue Modelling

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The recent tectonic evolution of the Pannonian basin is identified by strike-slip basin inversion. Integration of structural geology, geomorphology and high resolution seismics formed the basis for an analogue model that helps to understand the process of strike-slip fault propagation. Paleostress analysis showed that although the present day setting of the Pannonian Basin is compressional, local extensional stresses occur. The stress conditions responsible for the recent tectonic movements in the study area are mainly strike slip. The geomorphology is the region is strongly influenced by recent tectonic movements. The outcomes of a high resolution seismic survey on Lake Balaton supports the field observations. A left lateral strike-slip zone is found underneath the lake. The structure shows signs of early Holocene activity. Based on the orientation of the faultzone, it could well be activated under the stress conditions calculated for the youngest movements of the faults studied in the field. However, large sinistral strike slip faults as observed on the seismics are not found in the field on the lake borders.In the region NE of the Lake, in the extend of the faultzone observed on seismics, lies a dense cluster of minor earthquake hypocentres. This led to the hypothesis that activation of the large sinistral faultzone could be related to seismicity and geomorphologic expressions in the region. To further study this relationship, an analogue model was build. The purpose of this modelling experiment was not to quantify the amount of tectonic movement, but to study the processes at active fault tips and the surface expressions of these processes. The outcome of the modelling experiment gives good explanations for the observed geomorphology. Furthermore the model gives insight in the architecture of prograding strike-slip faults.

LS04 : TUpm35 : F2
Strike-Slip Margins of the Greenland Plate Resulting from two Parallel Spreading Systems

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Greenland has been a separate plate for about 20 Ma in the Tertiary, when two parallel spreading systems on either side of the plate were active simultaneously. The northern continental margins of the Greenland plate are formed by two major strike-slip faults, the dextral de Geer Fault in the NE and the sinistral Wegener Fault in the NW. They are supposed to be the traces of transform faults crosscutting a barrier of continental crust between the opening Atlantic and Arctic Oceans. To complicate matters there is a, roughly co-eval, E-W trending compressional foldbelt (Eurekan) subparallel to the same margins which has also been genetically related to the transform system. This belt has been interpreted in Spitsbergen as transpressive mountain belt (Lowell, 1972), in Canada as compressional belt formed by rotation of the Greenland plate (Okulitch & Trettin, 1991). We have used published seafloor spreading data and results from five seasons of onshore fieldwork in an attempt to correlate the onshore and offshore features and events.

Seafloor spreading data from the Labrador Sea (Roest & Srivastava, 1989) document the first attempt of the North Atlantic system to break through the barrier of the linked North American and Eurasian plates. The actual onset of spreading is poorly documented (Chalmers, 1991), but there is agreement on the existence of anomalies 28 to 25. The orientation of these anomalies indicates a NE-ward movement of Greenland. At anomaly 24 time, the North Atlantic started to open between Greenland and Eurasia (Talwani & Eldholm, 1977), while the direction of the anomalies changed in the Labrador Sea (Roest & Srivastava, 1989). The data indicate now that Greenland moved to the N.

The NE-ward motion of Greenland would result in strike slip movement along Nares Strait, the N-ward motion in a transpressive or compressive component. We present field results from Judge Daly Peninsula on the shores of Nares Strait which show that there is indeed evidence onshore for the same relative sequence of events: A first period of sinsitral strike slip motion associated with the formation of elongated (Paleocene?) pull-apart basins, was followed in a second step by compression of the Eurekan system. When spreading seized to the west of Greenland in Oligocene time, the Greenland plate remained attached to North America. All the action now moved to the east side of Greenland, where the North Atlantic linked with the Arctic Ocean by means of a dextral transform. In Svalbard, the dextral strike slip motion must therefore be later than the Eurekan-age compressive West Spitsbergen Fold-and-Thrust Belt. One possibilty to accomodate at least a branch of this strike-slip fault lies in the graben system of Forland Sundet. Motion may have been initially transpressional but from anomaly 13 on mainly transtensional.

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LS04 : TUpm36 : F2
South America-Scotia Plate Boundary of Geophysic Modelling. In the Tierra del Fuego Island, Argentina

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Four geological and geophysical campaigns were carried out in the Argentinean onshore-offshore sector of the Tierra del Fuego Island (1998-2000) along the supposed trend of the Maggallanes Fagnano Fault System (MFFS). A survey of GPS-fixed gravimetric and magnetic data , reflexion multichannel seismic profiles and the execution of field structural geology transects permit to characterize the position, the kinematic evolution and produce a geophysical model of the area. The main structure of the Island are: 1) a system of ESE-WNW-trending asymmetric folds-and-thrusts, N-verging, originated by a mostly N-S Late Cretaceous to Tertiary shortening of the Magallanes foreland basin and the shallow marine sequences of the Rocas Verdes marginal basin. 2) a superposed Oligocene-Quaternary E-W left-lateral strike-slip faults runs from the Pacific entrance of the Magallanes Strait to the Atlantic coast of the Island, where significant deformation is to have been surveyed both in on-shore (Lago Fagnano, Cabo Leticia and Cabo Colorado) and off-shore (continental shelf), as well as in the remote-sensing maps. 3) a Quaternary system of N-S faults with right lateral strike slip attitude cross the previous structures. The magnetic map shows a significant susceptibility contrast at the south-eastern tip of Lago Fagnano, related to -the Cerro Hewhoepen alkaline intrusion. Its shape, as reflected by geophysical modelling, the location and petrographic nature, might suggest that the emplacement is due to a releasing bend of the faults. The Bouguer anomaly map shows a regional decreasing throught South indicating a major thicknnes of continental crust. A delimited maximun in the anomaly is related with higher density of the intrusion body. The sector to E of the Lago Fagnano to Atlantic coast present two minimum anomaly owing to the present of two pull apart basin. The W-E fault system present a stepped style of the boundary the plates as well the presence of the Bouguer minimun anomaly in the Cabo Colorado and the absence the minimun anomaly in the Cabo Leticia are indicating that the boundary plate in the Atlantic coast is shifted in the northern sector. In cross-section, this tectonic lineament is represented by sub-vertical faults and associated asymmetric basins, generated by simultaneous strike-slip motion and transform-normal extension, as imaged by seismic profiles acquired off the Atlantic coast of the Island.

LS04 : TUpm37 : F2
The Norfolk Basin (Southwest Pacific): A Back-Arc Basin Formed between two Transform Faults

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The Norfolk basin is located between New Caledonia in the north and New Zealand in the south. This basin is limited to the west by the Norfolk ridge and to the east by the Three King Rise. The franco-Australian FAUST 2 cruise on the Atalante has been carried out off Norfolk island with the classical system of acquisition used on this ship (multibeam, high speed seismic, gravity and magnetism). In addition three dredges have been perfomed. We surveyed the north Norfolk basin that is separated from the south basin by a saddle where several large volcanoes protrude. The general trend of the seamounts is east-west and normal faults with the same trend limit the saddle to the south. After a deep trough that trends north-south, the three Kings rise that has also a north-south orientation, bounds the south Fidgi basin, extends to the south and merges with the slope of Northland island of New Zeland. The top of the

Three Kings rise is punctuated by several volcanoes. This rise is interpreted as a small island arc placed above a Miocene subduction zone dipping to the west. In this hypothesis the Norfolk basin is a back arc basin that opened during the eastwards motion of the arc. However, the new identification of magnetic anomalies in the South Fidgi basin raises the question to know if a piece of the Oligocene oceanic crust of this basin has disappeared by subduction. The Norfolk basin is limited to the south by the right-lateral Vening Meinesz F.Z. and to the north by the Cook Fracture Zone. We surveyed this more than 400 km long fracture located between the north Norfolk basin and the South Fidgi basin from the Three Kings Rise to the Loyalty ridge and basin that are lying east and southeast of New Caledonia. The apparent motion of this strike-slip fault is left-lateral as indicated by the geometry of the structure at the two ends of the fracture zone. Moreover, a focal mechanism confirms this left-lateral strike-slip motion although the main motion should be Miocene if we relate the Cook F. Z. to the opening of the Norfolk basin. Nevertheless the three-D map shows that this feature is very young and an intra-plate deformation is suspected. The Norfolk basin is replaced in the framework of the tectonics of this region from the loyalty basin and the emplacement of the Poya ophiolite in New caledonia to the Northland of New Zealand with the emplacement of allochtonous ophiolitic terranes.

LS04 : TUpm38 : F2
Polyphase Metamorphism and Deformation along Romanche Transform: Results of Transpressional Shearing?

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We investigated a large collection of metabasite and meta-ultramafic mylonites dregded from the Romanche Transform, in the Equatorial mid-Atlantic. Based on detailed microstructural observations, electron microprobe, X-ray diffraction and bulk rock chemical analyses we identified amphibolite facies tectonites, upper greenschist and lower greenschist facies mylonites, and polyphase tectonites showing complex deformation and metamorphic histories. The amphibolite facies tectonites are represented by coarse grained well equilibrated amphibolite or banded amphibolite mylonites containing phenocrysts of idiomorphic zoned plagioclase. These textures are interpreted as the result of exceptionally high annealing affecting existing mylonitic fabric with/or without possible melt invasion. Brecciation of basic rocks locally preceeded high temperature recrystallization and amphibolite facies annealing. The upper greenschist facies tectonites (actinolite+albite+epidote+chlorite) range from weakly deformed, almost statically metamorphosed amphibolites, through augen and banded mylonites, to ultrafine grained ultramylonites. The lower greenschist facies mylonites and phyllonites (chlorite+quartz+albite+epidote) are ultrafine grained, strongly foliated rocks developed under high fluid influx associated with mylonitisation. All types of tectonites are affected by subsequent folding, crenulation cleavage development and/or brecciation that occurred under lower greenschist facies conditions. The distribution pattern of metamorphic conditions is roughly zoned with highest grade rocks occuring deepest in the lithospheric section. The lower greenschist facies refolding and fracturing does not correlate with depth. Such a metamorphic zonation reflects a conductive type of metamorphism similar to that recorded in a continental crustal environment. The deformation sequence and high strain intensities are consistent with a recently developed model of tectonic transpression for studied segments of Romanche Transform (Bonatti et al., 1994) based on the morphology of transverse ridges and the geometry of the transform valleys. We suggest that both metamorphism and deformation of the oceanic lithosphere along the Romanche transform boundary are associated with an exceptionally high thermal gradient which may be syntectonical with a polyphase transpressional shearing.

Bonatti et al, *J. Geophys. Research*, **99**, 21779-21802, (1994).

Tuesday PO Session

LS04 : TUpo01 : PO
New Geochronological Data from the Eastern Gangdese Batholith with Implications for the Dextral Movement of the Jiali Fault, SE Tibet

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The Gangdese Batholith represents the Andean type magmatic arc that was active along the southern Lhasa Block as a result of northward subduction of the Neo-Tethyan plate before the India-Asia collision. This study reports new geochronological results of granitoids from the easternmost part of the Gangdese Batholith near Chayu (N97ºE). Zircon separates dated by single grain method using TIMS yield concordant U-Pb ages of 135-110 Ma, constraining the main duration of the arc magmatism in this part of the Gangdese Batholith. Hornblende and biotite separates dated by Ar-Ar and K-Ar methods, however, reveal two groups of age data, i.e., a Cretaceous group broadly coeval with the U-Pb dates of zircons from the same samples and a Miocene (~25-12 Ma) group significantly younger than the associated zircon ages. The latter group is observed in and/or close to the Jiali fault zone which is generally considered as a major dextral strike-slip fault active in southern Tibet during the Quaternary. Samples that show strong foliations define a restricted Ar-Ar age span of ~18-12 Ma, which we suggest to constrain the main activity of the strike-slip movement. Thus, the Jiali fault was initiated and most active in the Miocene, but not in the Quaternary as previously thought. This age span is virtually identical to that of the dextral strike-slip movement along the north-south-trending Gaoligong shear zone, western Yunnan (~18-13 Ma, Hsu et al., 2000). These fault activities, moreover, were synchronous to the main stage of the dextral displacement along the Sagaing fault that could have accounted for opening of the Andaman Sea. Our geochronological data may therefore provide not only crucial constraints on the timing of the Jiali fault movement, but also new insights into the post-collisional intracontinental deformation in the right-lateral accommodation zone from the eastern Himalayan syntaxis all the way down to the Andaman Sea.

LS04 : TUpo02 : PO
^{40}Ar-^{39}Ar Thermochronology of Palaeozoic Intraplate Deformation and Exhumation, Central Australia

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The eastern Arunta Inlier of central Australia preserves a record of long-lived Palaeozoic intraplate tectonics, which includes the late Ordovician to Carboniferous Alice Springs Orogeny. Most of the major structures relating to this event are S-vergent; however two major shear zones near the northern margin are steeply N-vergent.These structures, the Entire Point Shear Zone (EPSZ) and the Delny Mt Sainthill Shear Zone(DMSZ) separate Ordovician granulites of the Harts Range Group (10 kbar, 800°C) in the south from Palaeoproterozoic basement overlain by unmetamorphosed Neoproterozoic sediments to the north. Movements on the EPSZ include an important strike-slip component. Exhumation of the Harts Range Group commenced at c.450 Ma, with juxtaposition of the Ordovician granulites against the Palaeoproterozoic Kanandra Granulite along the EPSZ (Scrimgeour & Raith, in press). The Kanandra Granulite and EPSZ were subsequently reworked by mylonites along the DMSZ that show a northwards decrease in grade.

Muscovite from the lowest grade mylonites (muscovite-chlorite-quartz phyllites) from the northern margin of the DMSZ yielded ^{40}Ar-^{39}Ar ages of 362 ±3 and 364 ±3 Ma and are interpreted to reflect the timing of deformation. Muscovite ^{40}Ar-^{39}Ar ages from higher grade mylonites in the DMSZ range between 366 ±2 and 349 ±2 Ma and the spectra commonly show excess Ar in the low-T steps; they are interpreted to reflect cooling through c.420°C during exhumation. Hornblendes within the shear zones typically preserve partially reset Mesoproterozoic cooling ages, except where the hornblende completely recrystallised in the Palaeozoic. An amphibolite from the EPSZ, which crystallised during the Ordovician, has a hornblende ^{40}Ar-^{39}Ar cooling age of 403 ±10 Ma. Hornblendes from Ordovician granulites in the Harts Range Group also give ^{40}Ar-^{39}Ar cooling ages of c.400 Ma. The preservation of Proterozoic cooling ages for hornblende in boudins within the EPSZ is interesting given the fact that the surrounding Ordovician mylonites preserve upper amphibolite facies assemblages that formed at 700°C. Biotite shows extreme incorporation of excess Ar. The availability of excess Ar is related to the tectonic setting in which exhumation and cooling are controlled by thrusting of Proterozoic crust rich in radiogenic Ar beneath the Harts Range Group along the EPSZ and DMSZ.

The DMSZ acted as a major retro-shear that accommodated exhumation at the rear of the south-vergent orogenic wedge during the Alice Springs Orogeny, and the ^{40}Ar-^{39}Ar data suggests that much of this exhumation occurred by c.360 Ma about 90 m.y. after the onset of compressional deformation in the region at a constant cooling rate of 4-5°C Ma^{-1}. Our data indicate that large-scale thick-skinned intraplate deformation in the Arunta Inlier may have ceased by the late Devonian, and that Carboniferous deformation may have resulted in less exhumation than was previously believed.

Scrimgeour I & Raith JG, *Geol. Soc. London Spec. Publ*, **in press**, (2001).

LS04 : TUpo03 : PO
The Neotectonic Features of the Southeast Marmara Region, Turkey

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The Sea of Marmara region is a transition zone between the E-W directed right lateral strike-slip of the North Anatolian fault (NAF) and the N-S directed extensional regime of western Anatolia. These two different stress regimes led to the formation of a complex tectonic pattern in the southern Marmara region. The approximately E-W trending rombohedral shaped horsts and grabens are found to be located between the Marmara depression to the north and Nilüfer-Karacabey depression to the south. The Bandirma Horst, the Mudanya Horst and Kursunlu Horst are the most prominent morphological features of the region. These horsts and grabens are bounded by oblique faults with prevalent directions of E-W, NE-SW and NW-SE. Neogene fluvial and lacustrine sequences cover the pre-Neogene basement rocks in the area. The data collected is this work show that the cover sediments are similar to the western Anatolian Neogene sediments and that the basins in this area formed before formation of the NAF. The role of the N-S extension on the development of structural features in the region is important as much as the E-W strike-slip.

LS04 : TUpo04 : PO
A New Seismic Data Set for Investigation of the Southern Rhine Graben Fault System

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The Upper Rhine Graben is part of the European Cenozoic rift system. It is characterised by a low seismicity level in comparison to other continental graben systems. Under the present day stressconditions the structure is reactivated in a left lateral strike slip sense. Due to variations in the orientation of the graben axis, the local stress field varies. The seismicity seems to be concentrated in the Southern part of the system, especially on the Eastern flank of the graben. However, while the Eastern side was covered by a semi-permanent seismic array, the Western side clearly lacks documentation. Within the framework of the

URGENT/ENTEC programmes, a dense array of 55 3-component mobile seismic stations was installed in the Upper Rhine Graben area. The outcomes of this field experiment have now been processed and form the basis for a detailed seismicity map of the region. Furthermore, the new data provide insight in the architecture of the strike slip reactivation of the Rhine graben and the present day crustal stress conditions in the region. In the near future these data will be completed with anisotropy studies and structural field study, leading to an integrated 3D kinematic model of the region.

LS04 : TUpo05 : PO
Magma Transport in a Transpressive Zone: The Tuolumne Intrusive Suite, Sierra Nevada, California

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The Tuolumne Intrusive Suite (TIS) is an upper-crustal, Late Cretaceous plutonic sequence in the Sierra Nevada batholith, California. Plutonism in the the Sierra Nevada magmatic arc resulted from oblique subduction of the Farallon oceanic plate below North-America. The TIS is characterized by magmatic textures, even along contacts between plutons within the suite, and except along its eastern margin where the late magmatic Cascade Lake dextral shear zone produced solid-state textures. The classic model for emplacement consist of massive injections of magma and instantaneously emplaced plutons (Bateman & Chappell, 1979). We propose a new model, with successive injections of magma pulses within a releasing bend separating en echelon strike slip faults during transpressive regional deformation.

Our field work argue for the existence of two feeding zones located at the end of each strike-slip faults. Numerical modelling of the thermal evolution of a pull-apart structure with spreading centres located at fault extremities, shows that a steady-state magma chamber is created with slip rate as slow as 20 km/Ma. These are similar to the average slip rate within the magmatic arc, based on plate motion analyses, expected during the Late Cretaceous transpressive event in the Sierra Nevada (Tikoff & St-Blanquat, 1997). The combination of this slip rate and other structural data suggests that about 10 Ma were necessary for the construction of the whole TIS, a duration compatible with avalaible geochronological data. At this scale, magma transport is a continuous phenomenon. However, it is not a steady-state process, as shown by the evidence of short forceful injections. These injections could be linked with variations in magma production and/or transport rates. The rate of magma transport in an arc context is then strongly time-dependent, and control the ascent/emplacement mechanisms if we consider a steady-state regional deformation rate at the scale of a few million years.

Bateman,P. C. & Chappell, B. W., *Geological Society of American Bulletin*, **90**, 465-482, (1979).
Tikoff, B & St Blanquat, M, *tectonics*, **16**, 442-459, (1997).

LS04 : TUpo06 : PO
Neogene Extensional Features and Quaternary Volcanism Associated with the Kunlun Fault

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On the northern edge of the Tibet plateau, the Kunlun fault zone is one of the largest left-lateral strike-slip systems allowing the eastward extrusion of the asian lithosphere. West of 91°E, the western end of this fault is a complex association of strike-slip fault segments connected by normal faults. The 1997 French - Chinese expedition to the western Kunlun range allows us to study the geology, thermochronology and tectonic evolution of the Jingyu basin. This basin is a key area to understand the late Cenozoic tectonic activity of the western termination of the Kunlun fault. A N-S compression period inducing the formation of both large anticlinal folds and thrust faults, is followed in mid-Miocene times by an E-W extension phase. This extension is marked by the eruption, from 15 Ma to 0.5 ±0.2 Ma, of shoshonitic lava containing xenoliths from the at least 50 km deep crust - mantle boundary. The extension is controlled by the individualisation of two segments of the left-lateral Kunlun fault, creating a pull-apart basin. The detailled thermochronological study of two late Triassic - early Jurassic granite plutons shows that a southward jump of a segment of the Kunlun fault induced, 3 Ma ago, the formation of a large normal fault connecting to the south, the main Kunlun fault with its new segment. Finally, Quaternary rhyolitic volcanism was implaced along the late normal fault. As a whole, these data highlight the intense tectonic activity affecting the west Kunlun area. Many researches are still to be carried on, but we clearly demonstrate that the widespread extension observed in this area of the tibetan plateau is recent and very active.