

EUG XI



Symposium OS10

Structural Geology and Tectonics

Convenor

Graham Potts

OS10 Structural Geology and Tectonics

Wednesday PM Session

OS10 : WEpm25 : G5 Centrifuge Modelling of Nested Diapirs

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Nested diapirs are a common igneous feature in different parts of the world (e.g. the Chinamora batholith in Zimbabwe, the Ardara pluton in Ireland, the Central Odenwald in Germany, and the Joshua Flat - Beer Creek pluton in California). They can be described as diapir-in-diapir structures, where still partially melt masses representing earlier plutonic diapirs are intruded by subsequent diapirs. These structures are important for the construction of entire batholith, since subsequent intrusions of diapirs into the same region or even magma chamber can extend the life time of an igneous system tremendously. Here, we present results of a centrifuge model to study the kinematics and dynamics of nested diapirs. The model consisted of three layers from bottom to the top; a 5 mm thick buoyant lower layer of (RG1) simulating a partially molten magma ($\rho = 2.45 \text{ g/cm}^3$ and $\mu = 8.5 \times 10^{18} \text{ Pa s}$), a 50 mm thick non-Newtonian overburden (DC+P) simulating a natural silicic overburden ($\rho = 2.7 \text{ g/cm}^3$ and $\mu_{\text{eff}} = 10^{22} \text{ Pa s}$); and a 10 mm thick layer of PDMS simulating a less dense overburden. The model was centrifuged for 9°30' at 700 g before a profile was cut for photographing. Two mushroom-shaped diapirs of the buoyant layer intruded the overburden to spread below the less-dense PDMS layer. During their rise, the diapirs deformed the overburden units and dragged them upward. A second buoyant layer of similar density and viscosity as the first buoyant layer, (differently stained, RG2) was attached to the bottom of the model. The model was then centrifuged for further 6°10' at 700 g. A profile of the model shows that the second-stage intrusion occurred along the stem of the preexisting diapirs, which was easier to intrude than producing new intrusion paths. The second intrusion was not diapiric, instead the second buoyant material rose passively (not diapiric) similar to a dike using the stem of the preexisting diapir as a mechanically weak pathway. Once reaching the level of neutral buoyancy, the intrusive material spread laterally resulting in extensive spreading and expansion of the overhang of the preexisting diapirs. Model results show that nested diapirs are not necessarily the result of multiple phases of diapirism. Instead, it can be the result of subsequent diking of buoyant material through the stem of preexisting diapirs. Multiple diapirs can form only when the overburden units deform ductilely during the different stages of diapirism.

OS10 : WEpm26 : G5 Emplacement of Gneiss Domes: An Integrated Study of Field Work (Variscan Pyrenees) and Analogue Modelling

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Elongated gneiss domes are common features of orogenic core zones. They are characterized by 1) alignment of their length axis parallel to the trend of the orogenic belt; 2) gneiss or migmatite core mantled by deformed metasediments; 3) discrete contact between gneiss and metasedimentary rocks; 4) steeply dipping foliation in marginal zones and shallowly dipping foliation in the core of the dome; and 5) increase in metamorphic grade towards the core.

Some gneiss domes were rigid bodies when they attained their present position in the structural framework of an orogen, but their origin is still a matter of conjecture. Models that attempt to explain the tectonic evolution of gneiss domes in the Variscan Pyrenees include diapirism (Soula, 1982), compression followed by extension (Zwart, 1986), and transpression (Carreras & Capella, 1994; Gleizes et al., 1998). In order to test existing or develop new models, we present results from field studies and analogue modelling.

Detailed structural field studies were undertaken in the Variscan core of the Pyrenees, the Axial zone, and concentrated on the Aston-Hospitalet and Bossost domes. The domes are core by a pre-Variscan (early Cambrian?) orthogneiss and Variscan migmatites, respectively. Their structural characteristics are similar: a) schistosity associated with the major D2 deformation wraps around the domes, forming a girdle around a subhorizontal E-trending fold axis; b) mineral lineation plunges gently, trending NW-SE to WNW-ESE. Complex geometries with mineral lineations oriented orthogonal to stretching direction are also observed. Orientation of gneiss foliation and quartz-rodging in the gneiss core of the Aston-Hospitalet dome are similar to schistosity and mineral lineation in the adjacent schist, implying coeval development. Kinematic indicators in the schist of the Aston-Hospitalet dome display complex sense of shear with predominant sinistral strike-slip component. Top to the east thrusting is also observed. These patterns are not concordant with dextral shearing in the late stage of D2 as proposed by Gleizes et al. (1998), and may imply an earlier (or later ?) phase with sinistral shear component.

Analogue modelling of dome structures are performed with a shear box apparatus that allows homogeneous deformation in general flow regimes (Piazzolo et al., in press). Experiments include deformation of viscoelastic fluid polymer (PDMS) with inserted rigid dome-shaped objects, and domes and layers of different viscosity (Rhodorsil Gomme) under various stress regimes. The resulting geometries of schistosity and lineation are compared to the observed natural orientations, and help constrain the deformational parameters that caused development of the gneiss domes of the Pyrenean Axial zone. Preliminary experiments under sinistral transpressional stress yielded orientation of lineations similar to what is observed in the field.

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Gleizes G, Leblanc D & Bouchez JL, *Geological Society London Special Publications*, **135**, 267-273, (1998).

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Zwart HJ, *Tectonophysics*, **129**, 9-27, (1986).

OS10 : WEpm27 : G5 Quantification of Grain Boundary Migration Microstructures in Quartz Veins of the Sambagawa Metamorphic Belt, Central Shikoku, Japan

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This contribution is part of a series of projects where microstructures of natural and experimental rock deformation are analyzed with the aim of correlating microstructure development and mechanical regimes both for natural and experimental strain rates and temperatures. For quartz, three experimental regimes of dislocation creep correspond approximately to three natural microstructure regimes. For increasing temperature, regime 1 corresponds approximately to bulging recrystallization (BLG), regime 2 to subgrain rotation recrystallization (SGR), and regime 3 to grain boundary migration recrystallization (GBM). The regime 1 - regime 2 boundary does not coincide exactly with the BLG - SGR boundary and the natural GBM regime extends to much higher conditions than can be realized experimentally for regime 3.

The Sambagawa metamorphic belt of central Shikoku, Japan, consists of multiply deformed pelitic schists, basic schists and quartz schists. Metamorphic conditions range from chlorite to oligoclase biotite grade. Along various transects, the crystallographic fabrics and microstructures of the metacherts have been studied in detail. The c-axis fabrics (clef girdles, type I crossed girdles and small circle girdles) show systematic changes with grain shape, but the correlation between microstructure type (P-type or S-type) and metamorphic grade is not unique. So far, the comparison with experimental studies has been difficult because in experiments pure quartzites are used.

In order to exclude the influence of secondary minerals (biotite), the Sambagawa was resampled. Along the Asemi River transect, pure quartz veins were collected. The microstructures show a beautiful transition from SGR to

GBM. In SGR, typically, a core of relict grains is surrounded by a mantle of smaller recrystallized grains. The shape of the recrystallized grains is usually equant, but flattening and preferred orientation have been observed. At very high temperatures, GBM produces very lobate grains which strongly interpenetrate each other.

Grain shape and grain size distributions are among the critical geometrical characteristics by which the dynamic recrystallization regimes can be differentiated. In this study we test and develop shape descriptors which reliably discriminate between increasing contributions of GBM to the deformed microstructures. We compare the performance of the so-called fractal analysis, classical shape factors, SURFOR, PAROR and PARIS factor analysis. For the very lobate grains we also define new measures of grain size.

The results confirm an increase of grain size with increasing temperature. They also demonstrate that the PARIS factor is a very sensitive tool for discriminating and classifying grains of varying lobateness and correlating them to varying contributions of the grain boundary migration process.

OS10 : WEpm28 : G5 Kinematics and Quartz Textures in the Pennine Mischabel Fold and Austro-Alpine Dent Blanche Thrust, Zermatt Switzerland

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At the basal thrust of the Austro-alpine Dent Blanche nappe and in the footwall Pennine rock units quartz fabric analyses indicate southward directed thrusting for the last stage of nappe emplacement in this part of the central Alps. Kinematic directions inferred by these quartz textures commonly do not coincide with those predicted by stretching lineations. In our particular case, orientations of stretching lineations are rather complex while principal axes of the quartz textures remain geographically constant in orientation and reveal perfect orthogonal arrangement with the regional Mischabel fold axis. These suggest that the development of quartz fabrics corresponds to the fold formation during last increments of deformation whereas the stretching lineations reflect rather the total accommodated (finite) strain. Quartz preferred orientations in the hinge zone of the Mischabel fold are similar to those at the thrust, with asymmetric single girdles to c-axes point maxima. Subgrain rotation recrystallization is the predominant deformation mechanism, suggesting steady state conditions in fabric development during progressive rotational deformation. In contrast, asymmetric cross girdles dominate the upper limb and uneven small circle c-axes distributions characterize the lower limb. Fabrics on both limbs are dominated by grain boundary migration recrystallization. The clear contrast in quartz textures and deformation mechanisms across the fold profile conflicts with common views on heterogeneous strain patterns, as the major component of rotational shear is expected in the fold limbs rather than in the hinge. Our study suggests that fabric development in the limbs of the recumbent Mischabel fold was controlled by local shear due to mechanically active fold amplification. However, quartz fabrics at the limbs were potentially reorganized, when fold-induced vorticity reached its maximum. In addition, the quartz textures of the inverted limb indicate a period of non-rotational deformation probably due to a reversal in sense of shear, when bulk shear became dominant over the former antithetic limb shear. The normal limb experienced always the same sense of shear and hence developed quartz textures reflecting a more advanced rotational deformation. In contrast, the fold hinge never experienced such a complexity in its deformation path and therefore reflects rather continuous bulk strain, which was caused by the southward displacement of the Dent Blanche nappe.

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OS10 : WEpm29 : G5 From Ductile Mass Flow to Discrete Shear Zones: Evolution of the Penninic Units of the Monte Rosa Region, Switzerland/Italy

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Incompetent layers play an important role during nappe stacking. The degree of strain partitioning within a ductile nappe stack strongly depends on the viscous strength contrast and the volume proportions of the constituting layers. Since the strength is primarily a function of temperature and metamorphic grade a nappe stack passes several stages of characteristic deformation style during exhumation. Within the Penninic nappe stack comprising the ophiolitic Zermatt-Saas and Antrona units, the continental Monte Rosa- and Siviez-Mischabel nappes and the continental Portjengrat and Stockhorn units, it was the Mesozoic sedimentary cover of these crystalline nappes derived from continental upper crust which acted as weak layers from greenschist facies conditions on.

These sediments were pinched during NW-directed detachment and nappe stacking, occurring contemporaneously with early exhumation from eclogite facies conditions (T=600°C, P=2.7 GPa, Barnicoat, 1995). In the absence of a marked competence contrast considering large scale deformation during this early stage, contraction was accompanied by pervasive symmylonitic isoclinal and sheath folding (D1+D2; Klein, 1978; Lacassin, 1985) involving all the units, regardless of lithology. Decreasing temperatures as well as low rates of mineral phase re-equilibration during successive exhumation stages down to greenschist facies conditions caused an increasing rheological differentiation, resulting in the boudinage of competent layers and, after equilibration of mineral phases, allowed for local reversal of competence enhanced by intense fluid circulation.

From the late Oligocene onwards (Escher, 1997) ongoing contraction led to a blocking of the further growth of the accretionary wedge which initiated SE- to S-verging folding (i.e. Mischabel backfold, Gabbio synform; D3) and dextral oblique thrusting. Parts of the Portjengrat unit served as a dextral shear zone south of the emerging Mischabel backfold, evidencing temperatures around 500°C during the penetrative augenmylonitic deformation of its granitoids. Subsequent cooling to greenschist facies and semi-ductile conditions enforced large scale strain partitioning: while the crystalline units eventually formed open folds dextral shearing was transmitted to the south and concentrated in the sedimentary horizons of the Portjengrat unit and in the "Furgg zone", respectively. There D3-deformation finally culminated in E- to SE-directed dextral oblique thrusting related to the formation of the Stockhorn and Trifhorn antiforms and pervasively overprinted older structures.

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Klein JA, *Leidse geologische medelingen*, **51**, 233-312, (1978).

Lacassin R, Mattauer M, *nature*, **316**, 739-742, (1985).

OS10 : WEpm30 : G5 Dynamic Recrystallization Microstructures of Quartz Indicate Fast Strain Rates in High Temperature Shear Zones of the Ivrea Zone

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The Ivrea Zone is part of the Southern Alpine basement consisting of lower crust and upper mantle rocks. This segment of the lithosphere was thinned during prealpine extensional tectonics. The high temperature shear zones are associated with the extension. Lower crustal rocks of the Ivrea Zone were retrogressed from granulite facies to lower amphibolite facies conditions. Lithosphere thinning proceeded after the formation of the high temperature shear zones and the deformational conditions changed to lower greenschist facies ductile shearing and to cataclastic faulting. The investigated sample comes from a high temperature shear zone at Forno in the Strona valley (Italy).

The granulite facies paragneiss has been deformed by amphibolite facies mylonitization and is cut by later cataclastic faults. The latest stage of amphibolite facies deformation is indicated by dynamic recrystallization microstructures of quartz displaying bulging recrystallization and by neocrystallized fine grained biotite. Applying garnet-biotite thermometry to newly formed biotite and garnet in mylonite layers a temperature of 530°C can be determined for this stage of mylonitization. Applying the paleopiezometer of Twiss (1980) to the recrystallized grain size data of quartz a flow stress of approximately 120 MPa can be derived. From the temperature and flow stress data the strain rate has been calculated using different flow laws of quartz. They all result in strain rates higher than 10^{10} sec^{-1} , which is clearly faster than the strain rate conditions usually assumed for mylonitic fault zones. Such fast strain rates can be reached in the intermediate and lower crust by localized shearing in narrow fault zones. It demonstrates that gneissic series of lower crustal levels are not only characterized by homogeneous penetrative deformation, but narrow mylonitic fault zones may accommodate localized deformation. The relatively rare occurrence of high temperature shear zones could be due to unusual fast strain rates, which could be a condition for their formation. The fact that strong localization of deformation occurs points to a mechanically strong lower to intermediate crust.

Twiss RJ, *Proc. Conf. IX, Magnitude of Deviatoric Stresses in the Earth's Crust and Upper Mantle*, Open File Report, 665-683, (1980).

OS10 : WEpm33 : G5 Slip Systems, Dislocation Generation, and Dynamic Recrystallization of Plagioclase in Nature and Experiments

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The deformation experiments were carried out on gem quality single crystals of labradorite at 900 C, 1.0 GPa confining pressure, strain rate = 10^{-6} sec^{-1} . One sample was deformed with the [001](010) slip system normal to the compression direction (no resolved shear stress on the dominant slip system), another sample with the (010) plane at 45 degrees to compression direction, and [001] down-dip (maximum resolved shear stress on [001](010)).

The results of the experiments, obtained by light microscopy and TEM, are: (1) There are 2 important slip systems for plagioclase: [001](010) and <110> in (111) or (001). (2) Dislocations loop out from fractures into dislocation-free regions of the crystals. Thus, fractures are important for the generation of dislocations, which if glissile can produce crystal plastic deformation. (3) Small (0.1 micron), dislocation-free fragments from the fracture process occur in a matrix with high defect density (the fracture zone) and may act as nuclei for recrystallization by grain boundary migration.

Recrystallization processes in plagioclase porphyroclasts were studied in naturally deformed samples from an anorthosite of the Jotun Complex (Norway). The deformation temperature was approximately 700°C at <90 MPa. Two populations of plagioclase porphyroclasts can be distinguished based on microstructural observations. The crystallographic orientation and grain shapes of the two populations are interpreted as "soft" and "hard" orientations of the dominant slip system (010)[001] with respect to the kinematic reference system. In the soft-orientation-porphyroclasts the misorientation (measured by U-stage) is dominated by subgrain rotation due to the activation of the (010)[001] slip system, whereas in hard-orientation-porphyroclasts no dominant misorientation relationship could be identified. TEM-analysis of the slip systems of dislocations in both types of clasts indicates that [001](010) and <110> in (111) or (001) are the main slip systems. Only in hard-orientation-porphyroclasts micro-fracturing was observed in the TEM. Micro-fracturing is likely to be the mechanism for nucleation of new grains (at small fragments) in these porphyroclasts resulting in a no-host control orientation relationship of new grains.

The samples of naturally and experimentally deformed plagioclase show activation of the same slip systems and similar recrystallization mechanisms. The following general conclusions can be made:

1. Plasticity at low to medium temperatures in feldspar deformation and perhaps in other silicates could depend on fracturing.
2. The recrystallization process may involve nucleation (at fragments) and is of great importance for the natural deformation of silicates because of plastic anisotropy, which is common in silicates.
3. The orientation of crystals with respect to the kinematic reference system may control the recrystallization mechanism but not so much the activation of different slip systems.

OS10 : WEpm34 : G5 Systematic Analysis of the Temporal Significance of Porphyroblast-Foliation Relationships in Deformed Rocks

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The relationships between porphyroblasts, foliation in the surrounding matrix and any inclusion fabrics provides valuable information on the relative timing and kinematics of natural deformations. In recent years attention has focussed on the kinematic significance of porphyroblast-matrix interactions and the temporal significance of such relationships has been neglected. By considering all of the possible deformation histories that a porphyroblast-matrix system may have we present a comprehensive and systematic analysis of the age relationships and deformation histories that can be extracted from porphyroblast-matrix systems. This information is used to contrast and formalise the interpretation of data from single sites, where exposure is continuous and no correlation is necessary, and multiple sites where correlation is required.

For a simple system involving one foliation and one continuous period of porphyroblast growth there are 11 possible deformation histories. These histories display various combinations of pre- syn- and post-foliation porphyroblast growth and they can be investigated by considering, (a) the patterns of age relationships associated with the various histories, (b) the morphology of the porphyroblasts (the presence or absence of a particular phase of growth) or, (c) the exact geometry of a porphyroblast, its inclusion fabric and the surrounding matrix foliation.

Analysis of the age relationships associated with the 11 possible histories indicates that the system is highly ambiguous with several histories sharing one or more porphyroblast-foliation relationships. The degree of ambiguity is reduced when porphyroblast morphologies rather than porphyroblast-foliation relationships are considered. The 11 possible histories generate six different porphyroblast morphologies. Three of these morphologies are unique but the remaining morphologies are common to one set of four and two sets of two possible deformation histories. In a single site individual porphyroblasts may have grown for only part of the history. This can lead to the presence of more than one type of porphyroblast. From knowledge of the systematics of the 11 histories, groups of compatible and incompatible porphyroblasts may be identified. Compatible porphyroblasts can form parts of one of the 11 deformation histories whereas incompatible porphyroblasts cannot. Incompatible porphyroblasts indicate that the deformation history is more complex involving either two foliations or two distinct periods of porphyroblast growth.

Where porphyroblasts have been observed in more than one site (e.g. in partially exposed regions) the correlation of structures may lead to further ambiguity. Using insights gained from the systematics of porphyroblast-foliation relationships in single sites the effects of correlating porphyroblast growth can be distinguished from those that arise from correlating foliations

This work establishes a clear and systematic framework for the temporal analysis of porphyroblast growth which can provide the basis for further detailed process based studies.

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OS10 : WEpm35 : G5 K-Ar Dating of Synkinematic Illite in Fault Gouge

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K-Ar age data obtained from synkinematic illite in gouge from two fault zones will be presented. The faults occur at Burwood Beach in the northern part of the Sydney Basin, eastern Australia and are hosted by siltstones and tuffs of the Lambton Subgroup, Newcastle Coal Measures. They are subparallel, approximately 1.5 m apart and trend N-S with steep easterly dips. A total displacement of 10 m is observed on the western fault, whilst 3 m of vertical displacement has occurred on the eastern fault. 1 cm wide foliated gouge zones are developed along both fault surfaces and represent the regions in which principal displacement has occurred.

11 samples were collected from the gouge zones and host siltstones and tuffs within and outside the damage zone. They were disaggregated using a gentle freeze-thaw technique to separate <2 and 2-6 micron fractions. The mineralogy of the fractions was determined by XRD analyses of air dried, glycolated and heated (550°C) samples indicate the presence of illite/smectite (I/S) and kaolinite in varying proportions in the fractions from the fault gouges and host rocks in the damage zone. In most samples, the I/S contains 70-90% illite. Twenty three K-Ar dates have been determined. The ages of samples in the gouge and damage zones range from 126.8 to 164.5 (n=9; x=148.3 Ma; σ =10.5) for the 2-6 micron fraction and 122.2 to 150.9 Ma (n=10; x=137.2 Ma; σ =7.8) for the <2 micron fraction. Older ages of 272 to 281.8 Ma and 237 to 244.9 Ma for the 2-6 and <2 micron fractions, have been obtained from undeformed host rock. Radiogenic ⁴⁰Ar ranges from 59.28 to 98.1% indicating negligible atmospheric Ar contamination. The reliability of the ages is confirmed by the agreement within 2 σ analytical limits for the duplicate analyses of the <2 micron fraction of some samples.

The 272-282 Ma K-Ar dates obtained from the 2-6 micron fractions of the host rocks are older than the age of the sequence in which the samples occur (245-252 Ma; Roberts et al., 1996). This suggests that detrital mica is present in these samples consistent with petrographic studies. The younger ages of 237-244.9 Ma are thought to reflect the time at which diagenetic formation of illite/smectite occurred. The <2 micron ages (122-150 Ma) obtained from the fault gouge is thought to reflect the last slip event occurring on the faults, which is possibly related to underplating and uplift of the Australian continent. This study highlights the potential and value of isotopic dating of synkinematic, diagenetic illite to determine upper crustal deformation events.

Roberts J, Cloué-Long JC & Foster CB, *Australian J. of Earth Sciences*, **43**, 401-421, (1996).

OS10 : WEpm36 : G5 ⁴⁰Ar/³⁹Ar Geochronology and Structural Evolution of the Québec Appalachians: Recurrent Tectonic Compression and Exhumation during the Paleozoic

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The Northern Appalachian Belt extends from New England (USA) to Newfoundland (Canada). It is attributed to multiple Paleozoic orogenic pulses with variable metamorphic conditions and structures; the Taconian (Middle-Late Ordovician), Acadian (Devonian) and Alleghanian (Permian) orogenies. In Québec, the Appalachians result from superposed metamorphism and deformation related to the Taconian and Acadian orogenies (Tremblay and Pinet, 1994). Taconian metamorphism occurs mainly in

Cambrian-Ordovician continental margin rocks of Laurentia. Acadian metamorphism is locally found in the Laurentian margin but is predominant in Ordovician rocks of Iapetus and in Silurian-Devonian sedimentary basins of the Gaspé Belt. Late- to post-orogenic extensional deformation characterizes both the Taconian and Acadian orogens. Crustal extension occurred at the end of each compressive orogenic cycles, and is linked to major basin-forming events. Brittle to ductile, retrogressive shear zones typify the extensional structures and feature the crustal denudation of medium to high-grade metamorphic rocks. In southern Québec, a regional geochronological study (Tremblay et al., 2000; Castonguay et al., 2001), based on the Ar isotopic dating of ~150 single-grains of amphiboles and micas, reveals the coexistence of four age groups; (1) Late Proterozoic (>945 Ma), (2) Middle Ordovician (465-456 Ma), (3) Late Silurian-Early Devonian (431-405 Ma), and (4) Middle Devonian (380-370 Ma). Groups 1 and 2 ages are preserved in the hanging wall of normal faults fringing the internal zone of the Laurentian margin. Group 1 ages are obtained from detrital micas in continental rock units that have escaped younger metamorphic events, and that have been brought down by extensional faulting following the Taconian orogeny. Group 2 ages record NW-verging crustal thickening of the Laurentian margin during the Taconian orogeny, which is mainly attributed to ophiolite obduction over Laurentia, and are found in fold-related structural windows attributed to Acadian deformation. Group 3 ages occur in metamorphic cores located in the footwall of SE-verging detachment (?) and normal faults fringing the Taconian internal zone, and are attributed to the tectonic exhumation of the Laurentian margin metamorphic terranes following the Ordovician crustal thickening. This event, referred to as the Salinian orogeny elsewhere in the Appalachians, has been coeval with crustal extension and the formation of major sedimentary basins in mainland Canada and New England. Group 4 ages occur mostly in oceanic rocks of Iapetus and in Silurian-Devonian rocks. It records a renewed NW-SE crustal compression in Devonian times, which has been followed by orogenic collapse and basin formation (i.e. Maritimes Basin) in Late Devonian-Carboniferous times (Lynch and Tremblay, 1994).

Tremblay, A. & Pinet, N., *Geological Society of America Bulletin*, **106**, 1171-1181, (1994).

Tremblay, A., Ruffet, G. & Castonguay, S., *Geological Society of America Bulletin*, **112**, 136-146, (2000).

Castonguay, S., Ruffet, G., Tremblay, A. & Féraud, G., *Geological Society of America Bulletin (in press)*, (2001).

Lynch, G. & Tremblay, C., *Tectonophysics*, **238**, 55-69, (1994).

OS10 : WEpm37 : G5 A Fission-Track Approach to the Timing of Exhumation of the Danubian Window (South Carpathians, Romania): Cretaceous and/or Tertiary?

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The Alpine evolution of the South Carpathians in terms of convergence/thrusting is well accepted and is characterized by three main stages. During the "Austrian" phase Getic nappes have been thrust onto the Severin nappe, this phase being sealed by Albian post-tectonic sediments. The late-Cretaceous "Laramide" phase caused thrusting of the Getic/Severin nappe pile onto the Danubian nappes. This phase is sealed by post-tectonic sediments of Maastrichtian age. Evidence for Miocene shortening, finally, can be found throughout the Carpathian loop. Yet timing and amount of extension leading to the exhumation of the Danubian nappes is still a matter of debate.

24 new zircon and apatite fission track ages from the Getic and Danubian nappes in the South Carpathians are discussed in the light of a compilation of previously published fission track data (Bojar et al., 1998; Sanders, 1998; Schmid et al., 1998; Willingshofer, 2000). Thus a three stage cooling history is proposed: 1) The Getic nappes are generally characterized by Cretaceous zircon (128-80 Ma) and Cretaceous/Tertiary apatite fission track ages (82-55 Ma) indicating cooling and exhumation of these units already at that time. 2) FT ages of the Danubian nappes, presently outcropping in the Danubian window below the Getic nappes depend on their position with respect to the Oligocene Cerna-Jiu fault. Southeast of this dextral strike-slip fault the Danubian nappes record Eocene

and Oligocene zircon and apatite cooling ages. Northwest of this fault zircon fission track data cover a range in ages from Cretaceous to Oligocene. Samples yielding apparent Cretaceous ages display a great range in single grain ages, the youngest single grains exhibiting Eocene/Oligocene age. The different cooling histories are attributed to the activity of the Cerna-Jiu fault and distinct exhumation histories to either side of this curved fault. 3) At a late stage the the Danubian/Getic nappe stack of the Parang mountains has additionally been affected by a N-S striking west-side-down normal fault.

Late Cretaceous extension shortly post-dating nappe stacking in the south Carpathians led to exhumation of the Getic nappes. Parts of the Danubian nappes must also have been exposed at the surface as evidenced by Danubian pebbles found in Maastrichtian sediments. However, all the presently exposed Danubian nappe units clearly witness a phase of accelerated cooling in Eocene/Oligocene times. Hence the Danubian window was exhumed as a core complex along the "Getic detachment" during that time.

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OS10 : WEpm38 : G5 Cooling and Exhumation History of the Oligocene Rieserferner Pluton: Constraints from Combined K/Ar-Mica and Apatite and Zircon Fission-Track Dating

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The small segment of Austroalpine basement between the western Tauern window and the Southern Alps comprises three different structural levels juxtaposed along two distinct crustal scale sinistral transpressive strike slip zones, the Defereggan-Antholz-Vals (DAV)-Line and the Kalkstein-Vallarga (KV)-Line. Little vertical displacement along the KV-Line implies similar structures and metamorphism to both sides, while the DAV-Line separates basement rocks deformed and metamorphosed during alpine and variscan cycle in the north from the variscan amphibolite facies structures to the south. The latter suffered minor brittle alpine overprint only.

Furthermore, the DAV-Line exhibits a close relationship to the Oligocene Rieserferner Pluton as indicated by sheared contact metamorphic andalusite porphyroblasts coeval with a mylonitic overprint of the granitoids in some marginal areas of the pluton (Steenken et al. 2000).

The existing data set of Rb/Sr-biotite cooling ages (Borsi et al. 1978) is supplemented with new K/Ar-data of biotites. The new data confirms the already established trend of eastwards continuously increasing cooling ages to the north of the DAV-Line from 16 Ma at the Rensen pluton in the West towards 30 Ma at the eastern end of the Rieserferner Pluton, while partly reset Rb/Sr-biotite ages further to the east provide insufficient information on the cooling history of the basement (Borsi et al. 1978).

Refining the postulated model of crustal scale rotation (Borsi et al. 1978) to the north of the DAV-Line the whole cooling history is revealed by zircon and apatite fission-track ages enlarging the existing data set (Grundmann & Morteani 1985, Coyle 1994, Stöckert et al. 1999) Both age-groups exhibits a similar trend from youngest ages in the west (19 Ma Zr-FT, 13 Ma Ap-FT) increasing towards the east (27 Ma Zr-FT, 16 Ma Ap-FT). Furthermore, apatite fission-track ages markedly younging towards the Tauern window. Since the data is still scattered it is not clear whether this trend is smooth or stepped.

Cooling rates ascertained from the mineral pair method are generally <20°C/Ma. They will directly be transferred into exhumation rates assuming an average geothermal gradient of 30°C/km. Resulting exhumation rates of less than 1 mm/a do not affect the depth of isotherms due to heat advection in a geological significant manner. Hence it is assumed that variable cooling rates within the basement north of the DAV-Line correspond to differential exhumation amounts.

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Highest exhumation rates are bracketed between the intrusion age of the Rieserferner Pluton at 31 ± 3 Ma (Müller et al. 2000) and the apatite PAZ range at 0.5 mm/a, while final exhumation takes place at reduced exhumation rates of 0.2 mm/a. E-W tilting as indicated by variations in exhumation rates strongly affects the western part of the area studied between the Rensen Pluton and the Central Rieserferner Pluton, while further east rotation becomes of minor importance. A total exhumation difference between the Western and Eastern Rieserferner of about 2.2 km (5° tilting) as indicated from K/Ar-biotite and zircon fission-track ages is mainly compensated before reaching the PAZ for apatite fission tracks.

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OS10 : WEpo01 : PO Simultaneous Extensional Tectonics and Calcareous Magmatism in the Lora Del Rio Area (Ossa-Morena Zone, Iberian Massif)

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The possibility of a time and space relationship of core complex structures and the intrusion of granitic bodies in shallow crust levels is a recent discussion point. On the one hand, a core complex structure has been defined in the SE of the Ossa-Morena Zone (Lora del Rio area). This structure is characterised by the occurrence of two low-angle normal shear-zones, which are perpendicular to each other. These shear-zones individualize three blocks that correspond to three structural levels, with different deformational structures and metamorphic paths (Apraiz, 1988).

The upper block, which is separated from the other two blocks by the main detachment, preserves structures of an early compressional deformation-phase and a metamorphic evolution, that is typical of the upper block of core complex structures. Extensional features predominate on the intermediate block, which is situated between both shear zones. This block shows a complex metamorphic evolution, i.e. in the early phase it acts as the lower block, with respect to the main shear-zone, whereas in the later phase, after the formation of the secondary shear-zone, it develops characteristics of the upper block. It shows a prograde LP-HT evolution, with very tight isogrades, which are parallel to the secondary shear-zone. The metamorphic path of the lower block shows a Barrovian type prograde metamorphism, that reaches 750°C and 10-12 kbar at its highest pressure point, followed by the decrease of the pressure and a slight increase on the temperature (800°C at 4-6 kbar). Finally a decrease on the pressure and temperature is observed until it reaches the green-schist facies.

On the other hand, the Ventas Quemadas calcalkaline granite intrudes on the intermediate block. There are evident data that indicate its simultaneous intrusion with respect to the extension. The blasts formed by contact metamorphism show clear evidence for being sinkynematic. The main low-angle fault is adapted to the geometry of the granite without cutting it. To finish with, the high-temperature metamorphism on the Lora del Rio core has been dated at 340 Ma and indirect datations made in similar granitoids offer equivalent results (330-340 Ma, Burguillos del Cerro). These few existing data suggest that in this sector there is a tight relationship between the extension and the intrusion of the Ventas Quemadas granite.

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OS10 : WEpo02 : PO Fabric of the Rio Ceará-Mirim Mafic Dyke Swarm (Northeastern Brazil), Determined by Anisotropy of Magnetic Susceptibility and Image Analysis

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Anisotropy of magnetic susceptibility (AMS) and petrofabric studies of the Mesozoic Rio Ceará-Mirim Dyke Swarm (Northeastern Brazil) indicate that its magnetic fabric originated by (re)crystallization of magnetic oxides in a post-emplacement stress field. The 350 km long swarm is characterized by relatively thick dykes, generally in the order of 20 m up to 150 m in width. The strong magnetic susceptibility of these rocks, around 5×10^{-2} SI, is attributed to magnetite with low Ti content. The magnetite usually show embayed contacts with the silicates and fine-grained ilmenite exsolution typical of high-temperature reaction textures. The resulting AMS has a large proportion of abnormal magnetic fabric types, as observed in 58% of the 48 dykes studied. The remaining 42% of the dykes show a "normal" magnetic fabric regionally characterized by steep magnetic foliation subparallel to the dyke as well as to subhorizontal lineations. In four adjacent dykes situated in the central-eastern part of the swarm, however, the lineation plunges down-dip suggesting a magmatic feeder zone. The shape alignment of the magmatic plagioclase supports the inferred regional flow pattern, indicating that

the origin of the "normal" magnetic fabric should occur by growth of magnetic oxides mimetizing the silicate fabric. Most abnormal magnetic fabrics are weakly anisotropic ($1.005 < P < 1.025$) and have lineations displayed at a high angle to the dyke wall. A "normal" plagioclase shape fabric occurs in the dykes bearing an inverse magnetic fabric, indicating that the AMS was formed in a stationary silicate framework. The alignment of magnetic particles may have originated by stress-induced anisotropies when the dykes cooled, with the lineation following the minimum regional stress direction.

OS10 : WEpo03 : PO Isotopic Mapping of the Western Himalayan Syntaxis: Tectonostratigraphic Correlations and Insights

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In common with many orogenic core regions, the Western Syntaxis of the Himalaya (the Nanga Parbat massif) is a complex mosaic of polymetamorphic tectonic units, where conventional tectonostratigraphic methods of mapping and correlation are so challenging as to be virtually ineffective. While the major tectonic units of the main Himalaya can generally be correlated along most of the rest of the 2000 km range, the units that dominate the syntaxis were until recently seen as obscure or entirely unique. Previously, the syntaxis gneisses were ascribed to the High Himalayan Crystalline Series (HHCS) on the basis of their high grade, but Whittington et al (1999) showed that their Nd isotopic signature was characteristic of another unit, the Lesser Himalaya Series (LHS). In detail, Lesser Himalayan rocks are distinguished by older model ages (2.3-2.8 Ga), as opposed to model ages of 1.6-1.8 Ga for the HHCS, a distinction originally made on the basis of Nd model age and zircon dates in the central Himalaya (Parrish & Hodges 1996) Rapid Neogene exhumation (e.g. Zeitler et al 1982) means that deeper crustal levels are exposed within the syntaxis than elsewhere in the orogen, providing a possible explanation for this occurrence of high-grade gneisses from the LHS, where metamorphism is typically very low grade.

This study extends the Nd isotopic dataset out to the eastern margin of the syntaxis, where a highly condensed section of gneisses and schists shows a progressively weaker imprint of Neogene metamorphism and melting associated with recent exhumation. Evidence for pre-Neogene, and indeed pre-Himalayan events, is preserved in this zone, and the model ages indicate that rock units with LHS and HHCS isotopic signatures are present, as in the main orogen. Other recognised components include ca. 1.4-1.6 Ga mafic dykes (Treloar et al 2000), an Ordovician granitoid gneiss (Foster et al 1999) at the basement/cover boundary within the HHCS section, Ky-bearing leucogranites with similar Nd signature to HHCS leucogranites in the central Himalaya, and a marginal unit of very low grade phyllites isotopically identical to the HHCS, which recent work suggests corresponds to the Tibetan Sedimentary Series at the top of the structural pile in the main orogen.

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OS10

Structural Geology and Tectonics

OS10 : WEpo04 : PO

The Investigation of Mineralogical-Petrographical and Structural Features of Sandikli Metavolcanites (Porphyroids) (SW Afyon, Turkey)

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The Acid Magmatics, located southwest of Sandikli (Afyon) town which are identified as Sandikli Porphyroid in the literature. The metamorphic rock groups are named as Sand_kl_Metamorphites in the investigated area. Sandikli Metamorphites are composed of Lower Metamorphites which are composed of Hüdai Quartzite and Sandikli Porphyroid (metarhyolite and metatuff). The Upper Metamorphites are composed of Kocakarakaya Metacglomerate and Kestel Metapelites. Sandikli Metamorphites are covered from Maymunkayasi polygenic conglomerate, which is relatively Triassic age. As a result of regression, Maymunkayasi polygenic conglomerate has developed with a sudden uplift in study area and this unit has various metamorphic gravel which has sharp edge and altered. At the top of this unit, there is Akdas Limestone with angular unconformity. Its age was founded Mesozoic with index fossils. This unit has various fractures that developed in Alpine Period.

Fault zones that were determined using remote sensing investigations, founded harmonious with the field study. The fault trend of Sandikli Metamorphites has been founded generally N30W, N45W and N35E. Akdas Limestone that is located south of investigated area was N40E. General characteristic of fault type is dip slip faults. The study area was affected by polyphase deformation and showing intense fracturing and folding. Sandikli Porphyroid, with faulting session that developed in Alpine Period, transformed into cataclastic rocks as mylonite protomylonite and blastomylonite. As result of mesoscopic structural studies and for the determine tectonic deformation stages, the investigated area was divided into four homogenous sub-areas. Sandikli Metamorphites was affected by polyphase folding periods and fracturing. It was found that the region had been affected by three folding phase (S1, S2, S3). At the end of the metamorphism, the investigated area had been affected by rigid deformation in probably Alpine Period. There have been 193 fracture locations measured in the study area. These results have been interpreted with the computer programs, fracture strike as NW-SE and dip as NE have been founded in the area.

OS10 : WEpo05 : PO

Textural Evolution of Deformed Carrara Marble over a Large Strain Range

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Experimental deformation of rocks enables the study of textural evolution with strain under well-defined deformation conditions and deformation regimes. With the torsion deformation technique used in this study high shear strains were achieved over strain ranges comparable with nature. This study extends previous high strain experiments on Carrara marble in the power law creep field to lower temperatures in the exponential creep field. Experiments were conducted in torsion at three different temperatures and strain rates up to shear strains between 1 and 30. The low temperature experiments (500 and 600°C) are characterized by the formation of large stretched calcite grains accompanied by relatively slow bulging recrystallization at grain and twin boundaries. At higher temperatures (727°C and higher) the deformed grains are progressively recrystallized due to sub-grain rotation and grain boundary migration and a completely recrystallized calcite mylonite is produced at high shear strains. These two different microstructural evolutions are accompanied by two different textural evolutions, measured with the Electron BackScatter Diffraction technique. The low temperature microstructure corresponds to two c-axes point maxima, one perpendicular to the shear plane and one oblique to the shear plane and opposite to the sense of shear. This texture type is commonly called the calcite deformation texture in simple shear (Schmid et al., 1987). At very high shear

strains ($\gamma > 10$) a third maximum developed oblique to the shear plane and with the sense of shear, resulting in orthorhombic texture symmetry. The high temperature recrystallization microstructure corresponds to a texture with the c-axes point maxima normal to the shear direction and a strong orientation component $\{r\langle a \rangle$, where the c-axes are inclined relative to the shear plane. This texture strengthens with strain, but no further changes in preferred orientations are observed. This texture is commonly called the calcite recrystallization texture (Pieri, 1999). This study shows that at constant deformation conditions textures change with increasing strain. At high shear strain the textures end up with an orthorhombic symmetry. Therefore the determination of shear sense and deformation path by using texture asymmetry has to be handled with great care, because textures may mask the actual deformation history, especially at high strain. On the other hand, the above texture types can be used as indicators for a certain range of deformation conditions in experiments and after appropriate scaling also in natural shear zones.

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OS10 : WEpo06 : PO

Interseismic Loading Behavior of the Himalayan Range in Nepal

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Various data pertaining to the seismic cycle and crustal structure of the Himalaya of Nepal are now available. They are consistent with a model in which ~23 mm/yr of horizontal shortening is accommodated by localised seismic slip along the Main Himalayan Thrust fault and aseismic flow in the lower crust beneath the high Himalaya and southern Tibet.

On the basis of this model, we analyse lateral variations along the Himalayan arc in order to assess the significance of 3D effects such as extension in Southern Tibet.

For this purpose, we have developed a simplified 3D model of interseismic deformation based on dislocation theory. We consider the geodetic measurements, GPS and levelling data; the pattern of microseismicity, assumed to represent zones of increased Coulomb stress; the slip vectors of the major Himalayan earthquakes and the structural position of the grabens. Our modelling suggests that the azimuth of horizontal shortening varies along the arc with zones of relatively abrupt changes.

These azimuths variations seem to control the distribution of the grabens in southern Tibet. Such a segmentation could be linked with a long term process such as lateral variation of the 'locked zone' characteristics. These characteristics may be induced by indentation of the arc by basement structures as the Faizabad or Munghir-Saharsa ridge.

OS10 : WEpo07 : PO

First Experimental Study of the Seismic Properties of Eastern Alps, Italy. A Case Study from Val Badia-Brunico-Vedrette di Ries-Valle Aurina Transect

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The Transalp 98 project combines deep seismic reflection profiling with a wide variety of other geological data, in order to better understand the structure of the Earth crust and the processes controlling the crustal evolution. It considers, in the Italian territory, a profile across the Eastern Alps, from the State border to the Dolomites, crossing NS the Penninic, the Austroalpine and the South Alpine units along the Aurina, Tures, and Badia valleys. In order to better constrain the interpretation and the nature of the reflectors, some experimental measurements at high confining pressure (from 10 to 300 MPa) and room temperature of the compressional wave velocity (V_p) have been performed. Ten rock types were selected for the experiments. These are: granites, tonalites, metapelites, paragneiss, orthogneiss, quartzite and amphibolites metamorphosed from greenschist to amphibolite facies conditions, which are representative of the most common lithologies of Valle di Tures area (Eastern Alps, northeastern Italy). In order to determine the directional dependence of the seismic wave velocities, three mutually perpendicular cores (26 mm in diameter and about 40 mm in length) were drilled from all samples, with respect to the fabric elements of the rock, i.e., foliation and lineation. The elastic wave velocities were measured at increasing confining pressures with approximately 20 MPa increments until the maximum pressure (around 300 MPa) was reached, then at decreasing confining pressure separated by 20 MPa decrements. The highest mean V_p were those of the amphibolites (6.908 km/s), the minimum those of granites (5.890 km/s). Metapelites and fine grained paragneisses were the most anisotropic lithology (19 to 27% anis.), while the tonalites were nearly isotropic. Metapelites and fine grained paragneisses mainly displayed an orthorhombic anisotropy, whilst amphibolites, orthogneisses and coarse grained paragneisses showed a transverse isotropy. The measured seismic properties of each of the oriented samples were used to constraints the seismic behaviour of the considered transect, also taking into account the volumetric abundance of the different rock types.

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OS10 : WEpo08 : PO

Field Constraints to the Mid-Tertiary Kinematics of the Ligurian Alps (Italy)

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In the eastern sector of the Ligurian Alps (part of the Western Alps, Italy), Early Miocene folds and thrust faults involve both the metamorphic units of the belt and the tertiary sedimentary cover. Sediments pertain to the Tertiary Piemontese Basin, which is a late to post-orogenic molassic basin spanning in age from the Late Eocene - Oligocene to the Late Miocene. This work summarizes the structural features and the kinematics of these Early Miocene deformations and discuss their role in the geodynamic evolution of the Ligurian Alps.

Folds are strong asymmetrical, large-wavelength (up to several km) open folds with axial planes medium to steeply dipping towards W-SW. Thrust faults have low-angle planes and km-wide fronts, accompanied by fault rocks and m-scale horses. Fault rocks are crush breccia, with minor crush microbreccia, protocataclastic and cataclastic. In places thrust planes are accompanied by zeolite re-crystallization; the concurrent re-crystallization of chlorite and carbonates on the slickensides suggests a temperature lower than 250°C and very low pressure for this stage. Fold symmetry and sense of movement deduced from thrust faults indicate a consistent top to E-NE sense of shear.

These deformations appear to be linked to the migration of the Ligurian Alps towards E-NE with the subsequent back-thrusting onto the Apennine units. This tectonic phase was powered by the anticlockwise rotation of the Corsica-Sardinia block, in turn caused by the NW displacement of the Adriatic indenter against Eurasia (Tapponier, 1977; Laubscher et al., 1992).

Seismic cross sections through the Ligurian Alps (Biella et al., 1988; Laubscher et al., 1992) suggest a present-day N-S to SE-NW direction of shortening, which does not match the Early Miocene kinematics. These contrasting data suggest a progressive rotation of the direction of shortening, during a continuous geodynamic evolution from Miocene to present, powered by the still active Europe-Africa convergence.

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OS10

Structural Geology and Tectonics

OS10 : WEpo09 : PO Optimization of a Control Network for Monitoring Possible Tectonic Displacements Using the GPS Methodology

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In this paper a research work carried out on a GPS control network in the 'Salentina Peninsula' (Southern Italy) is reported. The study area is located in the surroundings of the town of Taranto (Apulia region), between the southernmost margin of the 'Murge' hills and the Ionian sea. From a geological point of view, this area is characterised by a Mesozoic carbonate basement overlain by transgressive calcarenite clastic and Plio-pleistocene clay-silt-marly deposits belonging to the Bradano foredeep. Tectonically, the area must be seen within the broader frame of the Murge district: the Mesozoic carbonate substrate is to be ascribed to a large monocline dipping south-westward, upon which displacements structures have been formed. As the entire Ionian area is supposed to be continuously evolving, a GPS control network has been established in an area around the town of Taranto in order to verify possible tectonic displacements between the 'Murge' chain and the 'Salentina Peninsula' (Caprioli et al., 1998). The GPS methodology is particularly useful for measurements of geometric land deformations because it provides quantities - like spatial distances or rather some differences of point coordinates - which will change because of possible shifts among the points of the network. The measurement campaigns in the study area started in November, 1997. From the first results it appeared that for obtaining significant data about relative displacements of the tectonic structures it was necessary to extend the network to a larger area. Thereafter, the control network has been implemented and improved. This paper reports the results of the entire study.

Caprioli M., Costantino D., De Fazio P., Trizzino R.,
Proc. "FIG'98" Conf., Brighton, U.K., (1998).

OS10 : WEpo10 : PO Polyharmonic Buckle Folding Accommodates all the Shortening in a Thick, Shale Dominated Sedimentary Pile of the AntiAtlas of Morocco

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Middle to late Carboniferous continent-continent collision between north America and Africa lead to the closure of the Japetus ocean. The former passive margin sediments of up to 10 km thickness on the Moroccan side of this ocean are considerably shortened by 15 to 25% in this event. Shortening is accommodated by intense polyharmonic buckle folding, while thrusting is conspicuously absent. This rather unusual deformation style is explained by the omnipresence of thick shale/marl sequences interlayered with a series of more competent, but still well layered sandstone and carbonate beds. The absolute thickness of the latter seems to dictate the wavelength and amplitude of the major fold trains. Three different levels are distinguished from bottom to top: basement and Cambrian carbonates form large domes and basins with wavelengths on the order of 20 km and amplitudes of around 10 km. Ordovician sandstones of the 'Bani' have wavelengths of 5 to 10 km and amplitudes of 2 to 3 km. Devonian and lower Carboniferous limestones ("Rich") display comparatively small-scale folds with less than 500 m wavelengths and similar amplitudes. A detailed mapping of these structures in the SW AntiAtlas of Morocco reveals an extremely high cylindricity both within and among the different fold trains. The lateral endings of folds as seen on geologic maps, aerial and satellite imagery are mostly due erosion of slightly plunging, cylindrical folds, rather than true, conical terminations in 'en échelon' manner. Small scale observations of paleo-stress features and their inversion indicate a constant, SE oriented maximum shortening direction at a high, near 90° angle with axial planes of folds. A major, still open question regards the thin skinned / thick skinned nature of this fold belt. Cross section balancing together with detailed structural observations are in favour of a thick skinned interpretation, with shortening imposed 'from below', i.e. by the inversion of former extensional grabens or half-grabens rather than 'from behind' along a non-detected basal décollement horizon.

OS10 : WEpo11 : PO Progressive Duplex Development in the Miocene Foredeep Succession (Northern Apennines, Italy)

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The Neogene post-collisional evolution of the northern Apennines is characterized by the northeastward overthrusting of the Ligurian nappe (Jurassic ophiolites and Cretaceous-Eocene sedimentary sequences) onto the Adria continental margin units. These latter have been characterized by foredeep deposits since the Late Oligocene (Macigno, Cervarola and Marnoso-Arenacea formations). In the Romagna sector of the northern Apennines (south-east of Bologna) the Marnoso-Arenacea Formation (MAF; Late Burdigalian-Tortonian) crops out in a wide tectonic window originated by a gentle asymmetric antiformal (NE-SW axial trend). The Ligurian nappe, originally overlying the MAF, was eroded mainly after the Middle Pleistocene; the resulting clastic deposits form the alluvial terraces at the Apenninic margin with the Po Plain (Cerrina Feroni et al., in press). Structural and stratigraphical data on the MAF, associated with seismic and well data, allowed to build two 50 kilometers long and up to 7000 meters thick transverse geological cross-sections along the northwestern and southeastern boundaries of the Romagna tectonic window (Sillaro and Marecchia zones). The cross-sections indicate that the MAF structural setting is represented by a deformed hinterland-dipping duplex characterized by several imbricate slices ('horses'). The top of the MAF stratigraphic succession involved in the thrust system shows ages progressively younger toward the outer horses, ranging from Langhian to Late Tortonian. The link thrusts, trending NW-SE and dipping steeply to the SW, anastomose upward into the basal tectonic surface of the Ligurian nappe which represents the roof-thrust of the duplex, showing a smooth geometry (McClay, 1992). The floor thrust does not crop out; it can be located between 3000 and 6000 m of depth at the detachment surface between the MAF and the underlying marly-siltitic deposits (Schlier Formation). As the MAF duplex is not completely contained within one stratigraphic succession, its evolution is controlled by the timing of the Ligurian nappe overthrusting, whose emplacement shows syn-sedimentary features documented by the occurrence of Ligurian olistostromes into the MAF succession. Consequently the duplex piggy-back evolution is characterized by the progressive activation of the roof thrust after the Ligurian nappe emplacement throughout the time of duplex formation (Middle-Late Miocene).

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OS10 : WEpo12 : PO East Sea Opening and Tectonic History of the Yansan Fault, Southeastern Korean Peninsula

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The Yansan fault is one of the latest major faults developed in the Korean peninsula and the East Sea (Sea of Japan) is a back-arc basin in the western Pacific, where three plates which is Pacific, Philippine Sea and Eurasian plates. Since 1980 the identification of the activity of the Yansan fault, which is active or not, has been one of the most controversial problems in Korea with respect to siting of industrial facilities such as the nuclear power plants. In the final analysis, the tectonic history of the Yansan fault could be explained with reference to the spreading stage of the East Sea related to the tectonic stress regime in the region.

To interpret the tectonic history of the Yansan fault that is oriented NNE direction in southeastern Korean peninsula, the paleostresses were analyzed from about 1,000 striated small faults and 330 extension joints, which were measured from 37 sites near and along the strike of the Yansan fault. Six sequential tectonic events have been reconstructed as follows; (I) NW-SE extension, (II) ENE-WSW compression and NNW-SSE extension, (III) NW-SE compression, (IV) ENE-WSW extension, (V) E-W compression and N-S extension, and (VI) NNE-SSW compression and ESE-WNW extension.

The movement history of the Yansan fault running in NNE direction was interpreted based on these six sequential stress fields and opening of the East Sea. The initial feature of the Yansan fault was formed at the first stage with the development of extension fractures by tectonic event (I) of NW-SE extension. The fault was activated continuously with a right-lateral strike-slip movement by tectonic events (I) and (II). The movements had been continued until the Late Miocene. This age was the most active period in faulting. The left-lateral strike-slip movement was followed by subsequent tectonic events (III) and (IV). The faulting was suspended temporarily by compression of tectonic event (V) which was perpendicular to the strike of the fault. This period might be very short and the magnitude of the tectonic event was also small. In the last stage, the fault reactivated with slight extension or right-lateral movement by tectonic event (VI).

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OS10 : WEpo13 : PO Deformation and Fluid Flow in Normal Faults of Geological Formations with Low Permeability: Example of Toarcian Shales of Tournemire (Aveyron, France)

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Fractures are the privileged place for fluid flow in geological formations with extremely low intrinsic permeability. Fractures rarely consist of a simple plane, but usually of a group of microstructures which give an insight of the dynamic evolution of fracture planes. The geometry and the disposition (architecture) of the voids, created during the growth of fractures, may, according to their degree of connection, guide the fluid flow and lead to the acquisition of structural permeability inside the fractures. An example of relations between deformation and fluid flow is presented with conjugate normal faults. They are in a formation consisting of Toarcian shales, located in Causses basin near the town of Tournemire (Aveyron, France). Three microstructural units can be distinguished in the investigated fault zones. Dilated and sheared zones are at center. They are bordered and cross cut by crack-seal veins in pull apart. These two patterns are not always present together and form the core zone. The third unit is the damage zone. It is the most external and is composed mainly of microcracks distributed along the walls of fault planes. Microtectonic analysis showed that these faults were formed during N/S extension which occurred towards the end of upper Jurassic and which probably continued during Cretaceous. The voids are now filled with crystals of calcite. Dynamic analysis of twinning of these crystals showed that the infill was strained under the same tectonic event. Setting and strain of infill occurred under the same state of stress. Fluid pressure (Pf) is an important parameter involving in the mechanisms responsible of described microstructures that develop structural permeability inside these fault planes. Microstructural observations imply that distribution of Pf, in the shearing zones, was not homogeneous at the initiation fracturing. The fault zones were compartmented leading to variations of Pf. The mechanism responsible of formation of veins in pull apart occurred later in the development and goes with the destruction of the compartmentation which probably induced the homogenization of Pf inside the fault planes. The isotopic composition ($\delta^{18}O$, $\delta^{13}C$) of calcite infill is the same for all microstructures. The nature of fluid would not have changed during déformation.

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OS10 : WEpo14 : PO Late Orogenic Shear Zones in the Ultramafites of the Voltri Group (Western Alps): Relationships between Progressive Deformation and Syntectonic Fluids

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This work deals with the progressive deformation and the influence of fluids in brittle-ductile and brittle shear zones, developed in ultramafic rocks, during late orogenic events. The Voltri Group derives from oceanic units and slices of subcontinental mantle involved in the alpine tectonics, under metamorphic conditions evolving from eclogite facies to subgreenschist facies. Late orogenic events (late Eocene-Early Miocene) are characterized by widespread development of shear zones under greenschist to subgreenschist facies regional metamorphism.

Two systems of reverse shear zones (RSZ) are the most recurrent structures and this study is focused on RSZ developed in peridotite. In places RSZ are accompanied by gold-bearing quartz veins, exploited until the end of 1800. For both systems of RSZ, we analyse samples along profiles from the hanging wall to the footwall. We performed structural and microstructural study together with major and trace elements and REE geochemical analyses of bulk rock, in order to reconstruct the structural evolution and the relation between chemical metasomatic alteration and deformations. The two RSZ systems are characterized by opposite sense of shear, different thickness, fault rocks, veins and type of wallrock alteration.

The first system (RSZ) has a top to W-NW sense of shear and is characterized by mylonites, shear bands, asymmetric boudins and asymmetric porphyroclasts. Mylonites are cut by gold bearing Mg-carbonate-quartz veins and Fe-Mg-carbonate veins. Metasomatic alteration is generally very local and frequently restricted to the border of the veins. Veins can be classified as face and displacement controlled veins, syntaxial and stretched fibres. In the middle of the veins a late growth or replacement of quartz by chalcedony is common.

The second RSZ system (RSZ) has a top to E-NE sense of shear and often reactivate shear planes of the first RSZ system; it is characterized by huge metasomatic alteration, and by the development of hydraulic breccia, cataclastite and mylonite. Veins can be classified as parallel controlled veins (crustiform and colloform texture), non-directional controlled and replacement controlled veins.

In both RSZ systems, moving toward the middle of the shear zone, wallrock lherzolite is progressively deformed, increasingly affected by chemical alteration and transformed in serpentinite, talc-chlorite schist, Mg-carbonate and Mg-silicate rocks. Comparison between the two systems of RSZ reveal different relationships between deformation and alteration process. Related fault rocks and geochemical data of bulk rock point to a distinct composition of the syntectonic fluid during the two RSZ events.

OS10 : WEpo15 : PO Reaction Induced Weakening in Experimentally Deformed Plagioclase-Olivine Aggregates

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Phase equilibria in plagioclase, spinel and garnet peridotites can be important during deformation because they can result in strain localization in the upper mantle lithosphere during subduction or extension. In order to study the effect of chemical disequilibrium on the deformation of mantle rocks and other polyphase mineral mixtures, shear deformation experiments were carried out at 900°C and confining pressures of 1.0 and 1.5 GPa on plagioclase-olivine mixtures. The different pressures represent different degrees of overstepping of the mineral reactions $plg+ol=sp+px$ and $plg+ol=gt+px$. By varying the degree of overstepping, we were able to study the relationships of deformation and reaction in the transition of plagioclase peridotites to spinel and garnet peridotites.

The experiments were performed in a Tullis-modified Griggs apparatus using an all-NaCl confining medium. A 2-6 μm grain size fraction was prepared from Aheim olivine (Fo₉₂), Blumone gabbro anorthite (An₉₂) and Sonoran labradorite (An₆₀); olivine was mixed with anorthite or labradorite in a 2:1 ratio. The mixture was placed between Balsam Gap dunite pistons, which were cut at 45° to the compression direction. Prior to deformation, the samples were heated at 1000°C for 6 hours in a CO-CO₂ gas mixture and subsequently hot pressed for 24 hours at 0.8 GPa and 900°C. The samples were deformed at a strain rate of 5x10⁻⁶ sec⁻¹ and at P-T conditions of either 900°C-1.0 GPa or 900°C-1.5 GPa. Comparison experiments were performed with pure Fo₉₂, An₉₂ and An₆₀ at 900°C and 1.0 GPa.

An₆₀-Fo₉₂ samples deformed at 1.0 and 1.5 GPa both show strain hardening with no yield even at stress equal to the confining pressure. No reaction occurred at either pressure.

An An₉₂-Fo₉₂ sample deformed at 1.0 GPa is significantly weaker than pure olivine and shows strain weakening followed by steady state flow; it has a similar strength as the pure An₉₂ sample. Olivine grains appear undeformed whereas An₉₂ grains are elongated, implying crystal plastic flow. However, the fine grained (<2 μm) reaction products have coalesced and appear to have accommodated most of the deformation.

The An₉₂-Fo₉₂ sample deformed at 1.5 GPa has a higher yield strength, followed by more pronounced strain weakening. The starting material is fully transformed to a fine grained (<2 μm) ol-sp-gt-px assemblage. The strain in the fine grained reaction products is inferred to have been accommodated by granular flow.

Thus, in An₉₂-Fo₉₂ samples we observe an increase in reaction progress with increasing confining pressure while the reaction is associated with a switch in deformation mechanism. In regions of mineral reaction, we also observe shear localization. By applying the autocorrelation function (Panozzo Heilbronner, 1992), we are able to quantify the heterogeneous shear strain in the samples and correlate it with the associated plagioclase-olivine reaction.

Panozzo Heilbronner R, *Tectonophysics*, **212**, 351-370, (1992).

OS10 : WEpo16 : PO Transpressive Strike-Slip System of the Southern Part of the Polar Ural Mountains in Russia Derived from the Deformational Regime of Rigid, Ultramafic Bodies in the Area of the Main-Ural-Fault, MUF

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On the geological map of the Ural one can see an increase in the degree of differentiation of the ultramafic bodies located in the centre of the orogenic belt from north to south and a decrease in the length-width-ratio of the single geological complexes. Also the width of the northern part of the Ural Mountains is considerably smaller than that of the southern part, indicating a longer and more forceful compression in the north. The ultramafic Rai-Iz massif in the southern part of the Polar Ural and several, also ultramafic bodies further to the north adjoin inflexibly responding, prolonged units of variable composition, that line up like a string of pearls on a length of about 1000 km on the east and in the centre of the Main-Ural-Fault (MFU) in a north-south direction. Detailed mapping of small, representative areas and several profiles provided structural data that contributed to the understanding and interpretation of the deformational type and the tectonical structure within and in the vicinity of these geological units. Particular attention was paid to the structural and petrological construction of the borders of the studied ultramafic bodies. The lens-like prolonged ultramafic massifs are integrated into strongly deformed, partly intensively mylonitized petrological units that are medium to steeply inclined toward E to ESE. Especially the western contact of the rigidly responding bodies shows an intense deformation, reflected in a subhorizontal to horizontal, sinistral thrusting. Also vertical, torn off isoclinal folds (loops) display this sense of motion. Especially at the boundaries of the formations the deformation is strongest in the different materials, producing mylonites in the scale of 1 to 10 m. The ultramafic units themselves only show a deformation in a 1 to 2 m marginal zone. Internally they are mostly unaffected by the deformation, except at discrete thrusting zones. Located in the north of the Rai-Iz massif lies a complex of different,

steeply southwards inclined units that form a mélange zone. The ultramafic units along the Uralides have been squeezed into the orogen like cherry stones. Due to the converging strike-slip regime these units were boudinized and with increasing collisional energy during the collision tectonically pushed upwards into a high crustal zone that is not typical for ultramafic bodies. This explains the lack of contact zones in spite of the considerable high temperature these bodies had when they formed. Furthermore indicates the intense foliation in the close contact of the ultramafic massifs a tectonical positioning. The deformational type and the tectonical structure of the Polar Ural displays a sinistral, oblique up-thrusting and in wide areas subhorizontal to horizontal motion in the centre of the orogenic belt. A formerly, strongly favoured magmatic positioning for these ultramafic units can therefore be ruled out.

OS10 : WEpo17 : PO Detection of Active Compression Structures on SAR ERS Imagery: Example of the Central Japan Seismic Area

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Observations on Synthetic Aperture Radar (SAR) scenes of the European Remote Sensing (ERS) satellite permit a new mapping of active faults in Central Japan. The analysis gives a coherent pattern of active structures resulting from a stress regime where the maximum stress component σ_1 trends N110°E. This stress field is associated both with compression and with a strike-slip regime of deformation. Compression is characterized by ~N20°E-trending reverse faults and folds axis. Strike-slip tectonics is characterized by a system of ~N65°E dextral and ~N145°E sinistral conjugate strike-slip faults. The reverse faults act like frontal ramps that laterally end into strike-slip lateral ramps. We have evidenced new unknown tectonic structures associated to shearing, such as active folds, push-up hills and pull-apart or releasing bend basins filled with Plio-Quaternary sediments. Tension fractures generally form at the beginning of deformation.

The tectonic analysis explains the location of the Plio-Quaternary Ontake San volcano which is rooted on a vertical tension fracture related to a N110°E-trending σ_1 accounting for both compression and strike-slip regime of deformation. This open structure is able to have given way to the magma. Observation of geometric relationships between tectonics and the emplacement of the Ontake San volcano testifies that the active tectonics began in the Pliocene. This age is consistent with that of the sediments filling (1) the pull-apart basins along strike-slip faults and (2) the alluvial plains regarded as syncline drag folds associated to reverse faulting.

OS10 : WEpo18 : PO SIMS-Dating of Ductile Shearing in SW Finland

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Individual zircon grains from granite dykes in a prominent ductile shear zone in SW Finland have been dated using the Nordic high-resolution ion probe (NORDSIM). The shear zone is the southern boundary to a belt of ca 1830 Ma old migmatite granites with tentative extensions across the Baltic Sea into Sweden. The sense of shear is dextral and particularly well exposed in the archipelago of the Åland Islands where sampling and structural investigations have been carried out.

The shear zone cuts, and strongly deflects, early Svecofennian granitoid gneisses and abundant meta diabases intrusive in these gneisses. Based on comparative evidences, the age of these meta diabases would be about 1865 Ma. This figure also marks the maximum age for the earliest shearing along the shear zone.

The late-kinematic granite dykes range in width up to some tenths of metres and cut the previously developed deformation in the sheared gneisses. The granite dykes are gently folded and occasionally schistose thus recording the

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waning deformational stages along the ductile shear zone. Zircons of the dykes indicate a Concordia intercept age of 1789 ± 8 Ma while the individual lead 207/206 determinations form a mean at 1790 ± 6 Ma ($n=15$, 95% conf., MSWD=0.91). The granite intrusions in the shear zone are roughly coeval with bimodal ca 1800 Ma old diapiric intrusions in the area of SW Finland.

The new age for the very late displacements along this mega shear enables correlations with significant shear zones in central Sweden with reported activities at around 1800 Ma ago. The new 1789 Ma age also adds to the tectonic framework of SW Finland by depicting late movements concentrated along major vertical shear zones in a more or less consolidated crust.

OS10 : WEpo19 : PO Controversial Geochronological Data for the Tectonic Evolution of the Ireimo Region (Central Madagascar)

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The Precambrian basement of Madagascar consists predominantly of strongly deformed granulite facies rocks. The Ireimo region in central Madagascar, however, comprises deformed low grade (greenschist to lower amphibolite metamorphism) quartzites, metapelites and dolomitic carbonates (Ireimo Group). The finite strain pattern of the Ireimo region has been determined from remote sensing and field studies. Overprinting relationships and structural facing directions indicate at least two main orogenic events in the low-grade Ireimo Group metasediments, that are considered to be related to the final assembly of Gondwana. During a first deformation phase, W to SW-directed thrusting and associated major recumbent folding of Ireimo Group sediments (and possibly basement slices) occurred at low-grade (greenschist to lower amphibolite facies) metamorphic conditions. This deformation resulted in a penetrative axial plane foliation in suitable lithologies. A second phase of (probably transpressional) deformation affected the Ireimo Group and resulted in the formation of steep shear zones and large-scale roughly N-S trending folds with steeply dipping axial planes.

Spectral analysis of Landsat TM images allowed us to distinguish high-grade sillimanite-bearing quartzites from low-grade Ireimo Group quartzites in the western Ireimo region. The contact between these two units in the western, southern and northern part of the Ireimo Region is a thrust contact along which low-grade Ireimo Group sediments were transported west to southwestward on top of high-grade basement rocks. This tectonic contact is deformed by the second phase (with respect to deformation of the Ireimo Group) N-S trending folds and shear zones.

Ar/Ar dating of muscovite defining the first-phase schistosity in metapelites of the Ireimo Group yield Late Cambrian to Early Ordovician ages (492 ± 8 Ma; Huber, 2000). Chemical Th-U-Pb monazite dating confirms this age, however with a larger error: 484 ± 42 Ma (Huber, 2000). The Ar-Ar ages could be interpreted as indicating the timing of the first phase deformation event in the Ireimo Group. However, the post-tectonic Vohimavo intrusion in the Ireimo area has been dated by Handke et al., (1999) at 540 ± 8 Ma. This would imply that the muscovite Ar-Ar ages are at least 50 Ma younger than the greenschist facies event which produced them.

The second-phase N-S trending folds in the Ireimo Group metasediments can be correlated with similarly oriented folds and associated vertical shear zones in southern Madagascar, that have been dated at 520-500 Ma (chemical Th-U-Pb microprobe dating of monazite) by Martelat (1998). This also questions the age of 540 Ma for the post-tectonic Vohimavo intrusion (which cross-cuts second-phase structures in the Ireimo region). Further structural and geochronological studies are necessary to provide better constraints for the age of deformation in central Madagascar.

Handke MJ, Tucker RD & Ashwal LD, *Geology*, 27, 351-354, (1999).

Huber S, *MSc Thesis, University of Bern*, (2000).

Martelat J-E, *Thèse Université Blaise Pascal Clermont-Ferrand II*, (1998).

OS10 : WEpo20 : PO Significance of Late Shear Zones in the Internal Domain of Western Alps: Consequence of a Pure-Shear Deformation Regime?

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Late, ductile shear zones, of centimetre to kilometre scale, and functioning in the greenschist facies, occur in the Penninic nappes under greenschist facies conditions between Tignes and Val de Suse (France and Italy). The movement on the shear planes indicates a down-dip transport direction, underlined by a stretching lineations (minerals or fibres) whatever is the actual local dipping toward East or West. The ductile shear-zones belong to the last stages of a complex D2 event. This event corresponds to retrograde metamorphic conditions (epidote-glaucophane blueschist facies to greenschist facies) and develops a S2 flat-lying to gently dipping foliation and subsequent East and/or-West verging shear zones (SZ2). A study of the S2-related microfibrils and of the D2-related F2 folds showed that they were controlled by a pure-shear deformation regime. Earlier D1 structures (S1, SZ1), the initial steeply-dipping attitude being locally preserved, are often transposed by the S2 flat-lying foliation. The F2 folds apparent verging, alternatively toward East or West, does not provide any kinematic indication. Similarly, movement directions registered on the SZ2 plans, alternatively toward East or West, could correspond to a consequence at large-scale of the overall pure-shear deformation regime. Thus, at least since the Middle-Oligocene, the Penninic domain forms a finite structural entity, the latest deformation stage of which being characterised by flattening. Such a flattening is incompatible with the shortening mechanism which controls the building of the Alpine collision belt. Knowing that the External Alps are still compressional since Miocene times, this implies that a complete decoupling of the Penninic domain with respect to the on-going foreland extrusion. The Penninic domain is a remnant orogenic prism, consisting in geologic units of varied origin, which floats like a pop up at the roof of the orogenic pile. According to such a geometry, the escape of material is possible at the limits of the prism and should follow the direction of the small axis of the deformation ellipsoid, toward East or West. This pop-up model, actually, is very similar to the critical prism model proposed by Platt (1986). During the last stages of the overall flattening mechanism, large detachment faults occurring behind the main frontal thrust, accommodate the lateral escape in forming the most obvious nappes (actually "nappes of nappes") where "extension" and/or "flattening" deformation regime dominate.

Platt JP, *Geol. Soc. of Am. Bull.*, 97, 1037-1053, (1986).

OS10 : WEpo21 : PO Mesozoic Structural Evolution in the Southwestern Part of the Ogcheon Belt, Korea

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The Ogcheon belt with NE-SW trend is formed of metasediments deposited in an early Paleozoic rift and lower Paleozoic platform sequence, disconformably covered by middle Carboniferous to lower Triassic coal-bearing sequence. The belt has been intensely affected by Mesozoic tectonic movements and is significant in understanding the structural evolution in the Korean peninsula. Mesozoic movement in the southwestern part of the belt is discussed in the light of geometry, distribution, kinematics and age of associated structures. The non-coaxial, ductile shearing under low-grade metamorphic condition is corresponds to D1 deformational phase and is responsible for the establishment of the Honam (Soonchang) shear zone. The earliest recognizable structural element in the late

Paleozoic metasediments is a regionally penetrative foliation S1 subparallel to bedding plane in most places. S1 fabric consists of the syntectonic greenschist facies assemblages. Asymmetric microstructures consistently show a dextral or top-to-the northeast sense of movement. F1 fold are attributed to the layer-parallel shearing closely associated with the generation of mylonite and exhibit a pervasive axial-planar fabric and an intense stretching lineation parallel to fold axes. The ages of syntectonic granites indicate that the timing of ductile shearing is early Middle Jurassic. D2 phase is characterized by shallow-level, progressive compressional movement. The NE-SW-trending folding F2 and thrusting have occurred with top-to-the-southeast transport direction, subperpendicular to the trend of the belt. F2a-folds are asymmetric, open to tight, locally isoclinal and recumbent, and have an axial-surface foliation S2. In general, S2 is characterized by a spaced crenulation cleavage and do not contain any metamorphic minerals. Hence, F2a-folds developed post to the peak metamorphic condition. F2b-folds develop as large-scale open folds with subvertical axial planes. The mappable axial traces of F2b-fold are NE-SW direction. Regionally extensive sinistral strike-slip regime during Cretaceous time was coeval with D3 phase in the area. D3 is marked by high-level, NE-SW-trending extensional faulting and large to regional-scale, E-W-trending F3 folding. They are followed by WNW-ESE-trending oblique-slip faulting in the late stage of Cretaceous deformation. F3 folds show regionally SW-vergence, which implies a sinistral wrench tectonic movement. D3 induced the regional bending of the ductile shear zone and is genetically related to the formation of Cretaceous strike-slip basins along the margins of the Ogcheon belt.

OS10 : WEpo22 : PO New Kinematic and Ar-Ar Data on Strike-Slip Ductile Shear Zones around Junggar Basin, Xinjiang, NW China

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The Xinjiang is a key region for the geological understanding of central Asia. This area was mainly built during Palaeozoic accretion events and underwent subsequent strike-slip shearings. Structural studies and new Ar/Ar dating in the Tianshan and in the Chinese Altai mountains provide new information about Late Palaeozoic and Early Mesozoic strike-slip tectonic events. In the Tianshan, the main east-west ductile shear zones are dextral, as indicated by field evidence and quartz c-axis analysis in the central and east part of the orogen. It is associated with an eastward decreasing greenschist metamorphism as indicated by biotite recrystallization and typical quartz microfabric. Ar/Ar dating of biotite give an age of 250-245 Ma for this regional dextral shearing. Relics (few kinematic indicators, quartz c-axis LPO patterns showing high to medium temperature conditions) of an earlier sinistral N80 trending motion were locally recognised in eastern Tianshan. In the western part of the orogen, this stage is contemporaneous with a N110 trending dextral strike-slip shearing dated at 290 Ma by Ar/Ar on biotite. In the spur of Altai mountains, the north-eastern border of the Junggar basin is formed of several major ductile shear zones trending NW-SE. An earlier sinistral motion occurred in the Erqishi zone which is the Chinese extension of the Early Permian sinistral shear zone of Irtysh in Kazakhstan. Mylonitized volcano-clastic rocks with sinistral σ and δ -type porphyroclasts underline this strike-slip shear zone. A regional dextral shearing overprinted this earlier tectonic activity. New Ar/Ar dating indicate a complex cooling history related to this succession of sinistral and dextral shearing episodes. As in Kazakhstan (Melnikov et al., 1998), the first event occurred at about 280-290 Ma (Ar/Ar on biotites). Subsequent dextral shearing lead to the north-westward exhumation of a complex folded metamorphic zone affected by a north-westward shearing with development of NW-SE A-type folds and L-type tectonics. Ar/Ar datings on amphiboles and biotites from this zone give ages of 250-240 Ma related to its north-westward motion controlled by dextral strike-slip shearing. Those results are consistent with recent paleomagnetic reconstruction (Enkin, et al., 1992; Li, et al.,

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1991; Zhao, et al., 1990). Relative rotations of Tarim and Junggar blocks and the north-westward collision of Mongolia with Siberia induced several strike-slip motions in the area which divided up central Asia during the Palaeozoic-Mesozoic transition.

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OS10 : WEpo23 : PO Development of Composite Quartz C-Axis Texture Patterns during Exhumation of HP-LIT Rocks of MTU (Variscan Belt of Iberia)

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High pressure and low to intermediate temperature (HP-LIT) metamorphic mineral assemblages are found in the rocks of the Malpica-Tui Unit (MTU) either defining or being surrounded by a regional foliation mostly developed in amphibolite and greenschist facies conditions (Llana Fúnez, 1999). This regional tectonic foliation, tracking the exhumation path of the MTU in the context of the Variscan collision in SW Europe, is studied at regional scale through the microstructural record in quartz in different lithologies, but with special emphasis in orthogneisses. The quartz c-axis texture patterns in XZ planes are characterized by variably asymmetric crossed girdles of type I and type II. The unequal distribution of c-axis measurements in YZ planes with respect to the foliation plane in the projections defines another asymmetric pattern, named unusual monoclinic pattern (as it is better envisaged in sections perpendicular to the lineation).

As asymmetry in quartz c-axis textures is associated to the contribution of non-coaxial deformation to the flow regime, it is suggested that both asymmetries, seen in XZ and YZ planes, are associated to two different components of non-coaxial deformation (therefore to different flow regimes) accumulated in the finite fabric (i.e. regional foliation) at different stage during the exhumation process. The first deformation registered, seen in the old quartz grains and characterized by the unusual monoclinic pattern, presents the non-coaxial component of deformation perpendicular to the orientation of the maximum stretching defined by the lineation (oriented parallel to the orogenic trend). The youngest deformation overprints partially the previous one and presents a non-coaxial component parallel to the older maximum stretching. Placed in the tectonic setting, both stages have distinct meaning. It is inferred that the first event relates to the exhumation of the high pressure rocks with a "tectonic transport" perpendicular to the structural trend of the orogen and the second event relates to a late overprint of the previous fabric indicating transport parallel to the orogen, likely associated to tectonic escape.

According to the composite nature of the finite fabric in the rocks, and to the flow regime during the exhumation, the regional stretching lineations should not be used as tectonic transport direction in this particular tectonic setting.

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OS10 : WEpo24 : PO The Role of Strike-Slip Tectonics in the Neogene-Quaternary Evolution of the Plateau Ibleo (Suth East Sicily)

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The Hyblean carbonate plateau is located on the northern margin of the African Plate within the Central Mediterranean region. It represents a part of the foreland of the Upper Cenozoic Maghrebian thrust belt, that formed as a result of collision between the North African continental margin and the Calabrian arc. It is bounded to the south by the stable Saharan Platform, and to the north by the frontal part of the Sicilian segment of the Maghrebian thrust belt. In the east it is confined by the Malta Escarpment, to the west it terminates abruptly onshore in central Tunisia

against the North-South Axis. The present day structural configuration of the platform reflects a complicated tectonic history involving both intraplate extension and plate margin deformation. As a consequence the platform area has been characterized by a complex interplay between extensional, compressional and strike-slip tectonics. Fieldwork, integration of aerial photos and spot image, help us to produce a morphotectonic and structural model of the area. This region has been affected by extensional and strike-slip tectonic expressed by subvertical fault trending NE-SW, NNE-SSW, ESE-WSW and NNW-SSE. The NE-SW, ENE-WSW fault systems are mainly expressed to the West by the alignment Comiso-Chiaramonte and to the East a similar pattern is due to the graben systems of Marina di Ragusa and Pozzallo-Ispica-Rosolini. The NNE-SSW fault system Sicily-Ragusa-Giarratana is well exposed in the western part of the plateau (along the Ragusa Platform), this is an important structural feature which affects all the domains above described, it is characterized by vertical slip rates with a lateral component of motion, and was active over the entire platform during the Late Miocene to Early Pliocene time. Some authors (Ghiesetti e Vezzani, 1980; Grasso et al., 1990) interpret this lineament as a transform zone linked to the Pantelleria rift. The younger fault system is represented by the prominent NNW-SSE trending normal fault segment (M.Tauro-Siracusa-Penisola della Maddalena) which extends on the Ionian side of the Iblean . It is oriented parallel to the Malta Escarpment and affects formations as young as Pleistocene calcarenites and volcanics. The complex fault pattern which dissects the Iblean foreland is well reflected by the submarine structures of the Ionian sea and of the Sicily Channel. The main tectonic trends of the plateau are reflected by the principal morphological elements, and in particular by the hydrographic pattern, in the Ragusa area the NE-SW linear drainages are in fact dominant. The close relationship between the structural and morphological features put in evidence the recent activity of the main fault trends.

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OS10 : WEpo25 : PO Tichka-Granite (High Atlas, Morocco): Regional Tectonics vs Emplacement Related Structures

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The Variscan Tichka granodiorite of the High Atlas of Western Morocco forms an elliptical pluton with a long axis of around 25 km, apparently emplaced in a dextral wrenching regime at mid-crustal levels. Detailed structural mapping at the southwestern border of this pluton allows to place tight constraints on the relative timing between regional scale green schist facies folding deformation, emplacement related deformations both in the country rock and the pluton itself, contact metamorphism and a suite of dikes. The pluton displays a concentric banding of alternating layers of an increasingly differentiated calco-alcaline suite of diorites, granodiorites, granites (most abundant) and 'septa', i.e. contact metamorphic inclusions of thin sheets of country rock. The latter vary in size from meter to several hundred meters in length, with sedimentary layering subparallel to magmatic foliation, dipping steeply (80°) to the NE, E and SE, towards the center of the pluton. Magmatic lineations are dipping at shallow angles of less than 30° to the NW, N and NNE. The contacts between the different intrusives are often cusped-lobate and show evidence for magma mingling and multiple successive phases of injection. The latest, most felsic intrusives are found in the most external 'shells' of the pluton. Magmatic deformation intensity increases toward the border of the pluton, where mafic inclusions display strongly elongate cigar shapes with axial ratios in excess of 10:1. Country rocks are made up of a late Proterozoic - lower Cambrian sedimentary series including coarse grained conglomerates, meta-volcanics as well as abundant carbonate / marl series. Regional scale deformation is characterized by open to isoclinal folds with steeply south-eastward dipping axial planes and subhorizontal fold axes oriented SW-NE. Within a zone of about one kilometer width of the pluton contact, fold axes are progressively

steepened and deformation intensity increases dramatically. Very strong stretching lineations both regionally and within this contact zone are systematically subparallel to the local fold axes. Foliation trajectories within and outside of the pluton determine a triangular zone or 'triple point' at the extreme SW boarder of the pluton. Small scale fold vergences are coherently oriented in country rocks away from the contact, but increasingly chaotic toward the centre of the triple point and in the septa within the pluton. Overall maximum horizontal shortening is oriented 320°NW-SE. Contact metamorphism affects country rocks in an estimated 15 km wide zone. In agreement with previous studies, we interpret the Tichka pluton as emplaced as a diapir in a regional dextral strike slip regime at mid-crustal levels.

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OS10 : WEpo26 : PO Dynamic Recrystallized Carrara Marble – Field Relationships in Comparison to High Strain Deformation Experiments

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Recent structural studies performed in the Alpi Apuane, NW Tuscany (Italy) describe the occurrence of naturally deformed Carrara marble, which shows dynamically recrystallized microstructures (Molli & Heilbronner, 1999; Molli et al., 2000). In the present contribution, we are investigating in detail the occurrence of these dynamic microstructures in the western Alpi Apuane and their relationship to mesoscopic deformation structures. Recent high strain torsion experiments (Pieri, 1999) reveals similar calcite microstructures. Therefore an attempt in comparing nature and experiment can be made. The shape preferred orientation (SPO) as well as the volume weighted grain size distribution were analyzed in order to investigate the microstructures of naturally deformed marbles. Additionally we employed the U-stage and Computer Integrated Polarization Microscopy (CIP) to determine the crystallographic preferred orientation (CPO) of the deformed marbles. The dynamic recrystallized rocks are located in millimeter to decimeter wide shear zones, which were formed during the D2 exhumation history of the Alpi Apuane (Molli et al., 2000). Calcite/dolomite thermometry indicates that the shear zones developed at about 340° C, overprinting the preexisting D1 structures. Two different types of shear zone related microstructures can be observed: Type-1) This microstructure is characterized by an unimodal grain size distribution (modal grain diameter app. 100 µm) with a strong shape preferred orientation oblique to the shear zone boundary. Irregular and saturated grain boundaries suggest grain boundary migration processes to be the dominant recrystallization mechanism during deformation. Type-2) The second type of microstructure is characterized by a bimodal grain size distribution with small recrystallized calcite in the matrix grains (30-40 µm) and large porphyroclasts (150-200 µm). The matrix recrystallized grains and the sub-grains in the porphyroclasts have similar grain sizes. Additionally small-scale saturation of grain boundaries are indicative for bulging recrystallization. However sub-grain rotation recrystallization is the dominant recrystallization mechanism. The two different natural deformation structures can be related to different experimentally derived microstructures. In comparison to high strain torsion experiments by Pieri (1999) the Type-1 microstructure corresponds to experimental microstructures at γ values of 0.5 - 1.5 and constant temperature (727°C) and strain rate ($3 \times 10^{-4} s^{-1}$). Type-2 can be related to γ values of 4-5 and the same experimental conditions. Although the microstructures are very similar, it remains difficult to compare nature and experiments, because the individual shear zones show rarely the experimental low to high strain evolution. Therefore it is unclear if both natural microstructures belong to the same deformation conditions. Extrapolation of experimental conditions to natural ones further complicates the comparison.

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OS10 : WEpo27 : PO Mafic Dyke Swarms West of the Barberton Greenstone Belt, South Africa

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The Archaean granitic basement of the Kaapvaal craton west of the Barberton greenstone belt, South Africa, is intensely intruded by mafic dykes. Traditionally there is a local terminology used whereby the dykes have been subdivided into diabases and dolerites. The former are slightly altered and are considered to predate the Transvaal Supergroup, therefore being Archaean in age, while the latter, being very fresh dolerite, are correlated with Karoo igneous activity during the Jurassic. However the situation is actually far more complicated than this.

The results of this study show that the mafic dykes occur in swarms which, regionally, can be divided into 5 sets orientated NE-SSW, ENE-WSW, E-W, ESE-WNW and SE-NW. Locally, detailed field mapping accompanied by photo-geological interpretation, has shown that there are at least 8 generations of dyke swarms, with a wide variety of types of diabases and dolerites. Reactivated tectonic lineaments have been utilised on numerous occasions. Different dyke sets are observed hosting more than one generation of dyke, often with no or little difference in the strike despite an obvious difference in age. Such differences are revealed by relationships such as two parallel dykes, only a few tens of metres apart, one of which is intruded by while the other intrudes a dyke with a perpendicular strike direction.

By determining the relative ages of the dyke generations, and using a knowledge of the regional geology, it is possible to tentatively correlate the different generations with known periods of volcanism and mafic layered intrusions preserved in adjacent sequences. These include the Archaean Dominion and Nsuzé Groups, Usushwana Complex and Ventersdorp Supergroup, the Proterozoic Transvaal Supergroup, Bushveld Igneous Complex and Waterberg Group, and the Phanerozoic Karoo Supergroup.

These correlations are being tested by comparing the geochemistry of the dykes with those of the various volcanics. With such correlations confirmed, it is possible to establish the palaeo-stress patterns prevalent in these basement rocks during the time of deposition or extrusion of the various sequences. In addition, the analysis of petro-fabrics and AMS in the dykes will reveal the palaeoflow directions. Together with the palaeostress data, it will show the mechanism of intrusion of the different dykes and give a better understanding of the tectonic processes taking place underneath the various Archaean, Proterozoic and Phanerozoic basins of the Kaapvaal craton during their formation.

OS10 : WEpo28 : PO Late Stage Microstructural and Textural Evolution of Naturally Deformed Carrara Marble- A Comparison to Experimental Rock Deformation Data

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Carrara Marble is frequently used for experimental rock deformation, therefore a large number of mechanical and microstructural data have been published. At the same time microstructural and textural data for naturally deformed Carrara Marble are available. We are now able to compare experimental data with natural ones, verifying if experimental work is adequate to simulate natural deformation processes.

In this study we analysed the microstructural and textural evolution of a natural shear zone, which was formed during the second deformation event (D2) in the Alpi Apuane. The shear zone overprints a pre-existing S1 foliation, which is deflected into the shear zone and can be used to determine the shear direction and the shear strain (γ) at any distance from the center of the shear zone. For the analysis of the crystallographic preferred orientation (CPO) Computer Integrated Polarization Microscopy (CIP) as well as Electron BackScattered Diffraction (EBSD) were employed. At any given site, the bulk texture of the entire microstructure is a combination of the partial texture of the recrystallized grains and that of the relict grains, which can be measured separately. In addition to the CPO, the volume weighted grain size distribution, the shape and the preferred orientation of grains and grain boundary surfaces were determined. By combining CIP and EBSD data, microstructural features, such as serrations of grain boundaries are correlated to the complete crystallographic orientation of adjacent grains.

With increasing γ a decrease in grain size starting from a bimodal distribution (20 μm ; 100 μm) to a single peak at 20 μm can be detected. The CPO outside the shear zone are characterized by a double maximum of c-axis at 26° and 46° with respect to the shear zone normal, inclined towards the compression direction. Within the center of the shear zone a single maximum normal to the shear zone boundary is dominant. Grain size reduction and CPO variations can be explained by the formation of recrystallized grains, which show a new crystallographic orientation compared to the relict grains. The textural evolution can be interpreted in terms of a transition from dominant e-twinning with additionally r-slip to dominant basis <a> slip. In simple shear pre-cut experiments by Schmid et al. (1987) and torsion experiments by Pieri (1999) and Barnhoorn (unpublished), similar textural evolutions were reported. The surface and the particle fabric (Surfor, Paror) shows a stable oblique orientation with respect to the shear zone boundary, which is not affected by the shear zone. However, evaluation of shape factors (e.g. PARIS-factors) of individual relict grains documents qualitatively a clear trend, which can be explained by subgrain rotation to be the dominant recrystallization mechanism, because relict grains with lobate grain boundaries become progressively smaller and less lobate.

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OS10 : WEpo29 : PO Basement Deformation by Folding and Fracturing. Example of the Bielsa Thrust Sheet (Pyrenees)

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The Bielsa thrust sheet is a south-verging unit of the Axial Zone in the Central Pyrenees. It is located between the Gavarnie and Millares thrust sheets, located on top, and overlies the Guarga thrust sheet. The four nappes define a piggyback-sequenced imbricate thrust system developed during the Tertiary Pyrenean compression. Most part of the Bielsa thrust sheet consists of a Variscan two-mica granitoid, the Bielsa Massif, overlain by Triassic (Buntsandstein facies) and Cretaceous cover rocks. The geometry of the Triassic units allows the overall structure of the Bielsa thrust sheet to be reconstructed. The main structures are ENE-WSW folds that can be followed 10 km along strike. These folds show a northward vergence in the southernmost part of the Bielsa nappe, and southward vergence in the central and northern parts. They show wavelengths between 0.5 and 1 km and maximum amplitudes of more than 1 km. Some of these folds are associated with steeply-dipping thrusts. Since no important detachment exist between the Bielsa granite and the Triassic cover these folds are interpreted as basement-involved folds. Rotation of the granitic basement along E-W horizontal axes can be assessed by means of palaeomagnetic data and position of weathering profiles developed within the granite during Triassic times. NE-SW gentle folds involving the contact metamorphic aureole also appear in the northern part of the Bielsa thrust sheet, near the contact with the Millares unit.

Fracture analysis based on photo-geological study and field-work of the Bielsa Massif shows several orientation maxima. There are three vertical fracture sets: N-S, NE-SW and NW-SE, and two shallow-dipping fracture sets: southward-dipping WNW-ESE, and northward dipping WNW-ESE. Slickenside striations on these fractures show a shallow-plunging absolute maximum in NNE-SSW direction. Most faults show reverse or strike-slip movements, and are consistent with a NNE-SSW shortening direction. Movement along fractures was probably contemporary with Tertiary deformation of the granitic massif. Closely-spaced small-scale fracturing can be also the responsible for large-scale continuous folding of the granitic body. This conditioning can account for the opposite vergences of folds. The present-day geometry of the Bielsa thrust sheet can be interpreted as a result of Tertiary compressional deformation, with a first stage of folding, favoured by reactivation of previous fractures, and a second stage of southward-thrusting during the formation of the Pyrenean Axial Zone.

OS10 : WEpo30 : PO The Late Variscan Fracture Network in N Portugal (NW Iberia): A Re-Evaluation

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The fracture network in N Portugal has been used to help deduce the Variscan dynamics of Western Europe, especially the sinistral NNE-SSW fault system. This work shows that the late Variscan network has been in great part reactivated during the Alpine orogeny till present day. The most illustrative case is the N-S to NE-SW fracture system which was dextral during the late stages of the Variscan orogeny and sinistral during the Alpine. Fault rocks and intrusions are clearly different: muscovite, tourmaline, chlorite, high temperature quartz inclusions and apite dykes in Variscan times, and low temperature cataclastites, fault gouge and Mesozoic mafic dykes in younger Alpine times. We proceeded with the isotope dating of the NNE system using K-Ar in muscovite. The age of these faults is ca. 310 Ma, slightly younger than the enclosing porphiroid biotite granite, which is ca. 318 Ma old. The Variscan dextral NW-SE and N-S to NE-SW fracture systems are conjugates of the sinistral ENE-WSW to ESE-WNW fracture systems. During the Alpine (till present day), the dextral NW-SE system was still reactivated mainly as dextral, the NNE-SSW system as sinistral (opposite to Variscan kinematics), and moderately inclined sinistral ENE-WSW faults as thrusts. In places, the younger rejuvenation is mostly dip-slip with generation of well-developed modern grabens.

OS10 : WEpo31 : PO A New Perspective on the Paleoproterozoic Structure of Eastern Bergslagen, Central Sweden

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North-eastern Bergslagen is part of an Early Paleoproterozoic (1.90-1.87 Ga) magmatic arc in the Baltic Shield. The structural pattern is characterised by narrow, elongated synforms of supracrustal rocks within a composite "batholith" dominated by calc-alkaline granitoids. Foliations are generally steep and stretching lineations steep to moderate in plunge. Both the rock distribution and the structures have been interpreted to record a major component of syn-intrusive deformation, while subsequent, regional E-W folds and a NW-SE shear zone system (the Singö Shear Zone, SSZ) have been considered to affect mainly the coastal areas in the east. Recently, however, N-S splays from the SSZ with apparent dextral horizontal components have been indicated by integrated interpretations of topographic, geological and geophysical data.

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Our kinematic and structural results considerably modify the pre-existing interpretations. The N-S plays are the steep limbs of regional, east-vergent folds that are "foot-wall" structures to the SSZ. Fold interference patterns indicate that the shear folds are F2 or F3 and hence the structural pattern of north-eastern Bergslagen is more pervasively affected by post-magmatic deformation than previously understood. In addition, the shear folds fit into the framework of regional E-W folds that characterise a large part of east central Sweden, with the exception that fold axes and stretching lineations are steeper than in the higher grade areas to the north and south. To the north of Bergslagen, many of these folds have limbs truncated by NNW-SSE, ductile, steep 1.8-1.82 Ga shear zones which approximately date the folding.

In the Stockholm archipelago to the south, such regional E-W folds affect the Ormö Band Series (OBS) a spectacular sequence of banded rocks that can be traced at least 80 km. Previous studies have generally interpreted the OBS in primary terms (supracrustal sequence or magmatic differentiation). However, our results show that the OBS instead is the result of intense deformation of various plutonic and supracrustal rocks, and several generations of pegmatites. Kinematic indicators are obscured by recrystallisation and annealing and further complicated by folding, therefore its character (contracted or extensional) is not yet constrained. Relative timing (e.g. truncation by c. 1.81-1.82 Ga pegmatites and deformation by c. 1.8 Ga folds) shows that the OBS is older than the steep, regional NNW-SSE shear zones. It is also comparable in character and age to major (~200 m thick), partly shallow-dipping shear zones north of Bergslagen dated to ~1826 Ma. Possibly the OBS is part of a coherent, major structure that prior to the development of the regional folds defined a system of NW-SE, moderately dipping Svecofennian deformation zones trending approximately parallel to the Svecofennian-Archean boundary in the northern part of the Baltic Shield.

OS10 : WEpo32 : PO Major and Minor Sheath Folds in HP Granulites of the Bacariza Formation (Cabo Ortegal, NW Spain)

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The Cabo Ortegal Complex is a composite nappe pile that forms part of the so-called Allochthonous Complexes of the northwestern Iberian Peninsula. This allochthonous sheet, made of different units separated by thrust contacts, includes ultramafic rocks, metabasites and quartz-feldspathic gneisses metamorphosed under different conditions. High-pressure deformation and metamorphism occurred in this complex.

The HP granulite Bacariza Formation is included within the Cabo Ortegal Complex. Regarding its geochemical composition and outcrop distribution, this formation is considered to be quite heterogeneous. The main granulite types are the following: (1) ultramafic granulites, (2) mafic granulites that often alternate with layers of intermediate composition, (3) Mg-rich mafic granulites, (4) intermediate granulites and (5) acid granulites. All of them show mineral assemblages with Grt and Cpx in equilibrium. Other rock types, such as eclogites, calc-silicate rocks, Grt-Bt gneisses and gabbros can be occasionally found.

The main deformation phase recorded HP granulite facies conditions (up to 810°C, 15 kbar) and gave rise to the development of a compositional banding-parallel S1 foliation and L1 mineral and stretching lineations. The NNE-trending lineation is subhorizontal and it is defined by the preferred orientation of Cpx, Zo, Phg, Qtz ribbons and elongated Grt. A NNE-directed sense of movement of the hangingwall blocks is recognized. Folds deform the HP foliation and develop at places an axial planar foliation defined by the preferred orientation of HP mineral assemblages. Therefore they are considered to be coeval with a polyphase HP deformation. Eye and anvil fold structures in YZ structural sections have been also identified in several outcrops as well as on the map scale. They are interpreted as lineation-perpendicular geometries of sheath folds. The mapped foliation trajectories produce a variety of geometries defining dome, saddle, basin and inverted saddle configurations, likely related to culminations and depressions of secondary sheath folds within a major one. The

foliation traces in granulites indicate in some places that the granulites had already an internal organization before they were thrust by the ultramafic massifs. As a consequence, spectacular C-S shear zones developed. A posterior granulite/amphibolite facies mineral assemblage statically replaced the original granulite mineral assemblage, in such a way that the present Am-defined preferred orientation mimics that developed under HP granulite facies conditions.

OS10 : WEpo33 : PO Geological-Geochronological Model of the Lower Precambrian Structural Stage Formation in the Urals

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A new plate-tectonics-based model of the Uralian segment of the Earth's crust evolution is proposed for the first time. Two geodynamic cycles are recognised in the evolutionary history of the Lower Precambrian structural stage of the Urals, beginning with 2.6 Ga. The earlier, reduced cycle is manifested as granulite-grade metamorphism, which is thought to be associated with successive rifting and collision dated at ca. 2.6 Ga. The later, complete geodynamic cycle is distinguished by granulite- and amphibolite-grade metamorphism and associated phenomena. It includes the stages of continental rifting (ca. 2.3 Ga), oceanic spreading (ca. 2.1 Ga), subduction (ca. 1.9 Ga), collision (1.9-1.7 Ga) and platform development (after 1.7 Ga). Stabilisation and formation of the Lower Precambrian structural stage of the Urals, as a part of contemporary crystalline basement of the European Platform, was completed ca. 1.7 Ga.

OS10 : WEpo34 : PO Reconstruction of Paleostress Magnitudes by Calcite Twinning Inversion: A Review

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Calcite twinning analyses were conducted in order to estimate stresses direction and magnitudes of tectonic events in three different structural domains: (i) the presently active Taiwan orogen (e.g., Rocher et al., 1996), (ii) the Pyrenean foreland (Rocher et al., 2000), active during the Cenozoic, which recorded Oligocene extension and Alpine collision, (iii) Cambrian passive margin of Iapetus ocean, overlain by Paleozoic Appalachian foreland deposits, then opened during Mesozoic. Like fault slip analysis, calcite twinning inversion yields the principal stress axes σ_1 , σ_2 and σ_3 and a shape ratio of the stress ellipsoid ($\Phi = \sigma_2 - \sigma_3 / \sigma_1 - \sigma_3$), but also the stress differentials ($\sigma_2 - \sigma_3$) and ($\sigma_1 - \sigma_3$). In addition, the inversion method used here (Etchecopar, 1984) allows the separation of superimposed stress tensors corresponding to the successive tectonic events that have occurred in these three polyphase domains. 10's calcite samples were extracted in strata of various age in each region, in order to test the regional consistency of the results. For each region, the tectonic calendar inferred from calcite twinning analysis is consistent with that reconstructed from minor fault inversion; for each tectonic event, stress directions inferred from both methods are similar. Magnitude of the deviatoric stresses inferred from calcite twinning varies from one sample to another within 30%, a value which lies within the errors of the method (Rocher, 1999). Few modifications are proposed to improve these results. The stress magnitudes inferred from calcite twinning are similar to that obtained from in-situ stress measurement, from other methods of calcite twin inversion, or from other paleopiezometers. The σ_1 deviatoric stress ranges from 25 to 70 MPa for compressional events, and the σ_3 deviatoric stress ranges from -30 to -18 MPa ($\sigma_1 - \sigma_3$ -P and $\sigma_2 - \sigma_3$ -P) for extensional events. From these events. From these reconstructions, we also deduced that the stress magnitude decreases as a function of the distance to an orogen (Rocher et al., 2000a).

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OS10 : WEpo35 : PO Transpressional Emplacement of the Variscan Bielsa Granite (Pyrenees)

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The Variscan Bielsa granite is located in the Axial Zone of the Central Pyrenees and constitutes a part of the 'Gavarnie - Héas - Barroude - plan de Larri - Bielsa' WNW-ESE elongated structural-metamorphic dome. The pluton is intrusive into quartzites and quartz-pelites of Cambro-Ordovician age which crop out at the northern border. At the southern and eastern parts of the pluton non-metamorphic post-emplacement permo-triassic rocks crop out. The main deformational structures in this igneous body are: 1) magmatic foliation and lineation, defined by feldspar phenocrysts and biotite crystals, 2) S-C structures, with biotite concentrated on C planes and a strong stretching lineation on them, and 3) alpine brittle faults. Anisotropy of magnetic susceptibility (AMS) throughout the granite is consistent with field structures and indicates foliation striking WNW-ESE with variable dip, and subhorizontal WNW-ESE lineation. These foliations and lineations are parallel to the elongation of the massif in map view and to the major structural directions of the country rocks, attributed to the main Variscan phases. The zonation of bulk low-field susceptibility is related with mineral content and indicates a more basic composition at the northeastern and eastern parts of the pluton, where the border facies outcrops and a metamorphic aureole is developed in the country rock. The highest degree of magnetic anisotropy is observed in the northeastern border where S-C structures are more systematic. The zonation of shape of the magnetic ellipsoid shows prolate ellipsoids along a central band parallel to the elongation of the massif in map view, and oblate ellipsoids at the borders of the pluton where flattening is more important. Mapping of foliations and lineations of the Bielsa Massif shows a concentric pattern at the central part, suggesting a root zone. Structures within the granitoid body and the country rock allow to interpret this intrusion as contemporary to a dextral transpressional setting, syntectonic with the late stages of the Variscan orogeny. The Alpine orogeny seems to have imprinted the granite only with brittle faults and, possibly, reactivation of earlier shear zones.

OS10 : WEpo36 : PO Tectono-Metamorphic Evolution of the Simano Nappe at Alpe Sponda, Central Alps, Switzerland

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The Simano nappe belongs to the lower Penninic domain of the Central Alps. Barrovian-type metamorphism gradually increases from lower amphibolite facies conditions in the northern part to upper amphibolite facies conditions in the south. This study aims to discover whether this basement nappe shared also part of the > 25 kbar history of the adjacent Adula Nappe.

The field area is located in the frontal part of the Simano nappe at Alpe Sponda where the rock types are mainly metapelites and paragneisses, with some amphibolite layers and calc-silicate nodules. Three deformation phases are distinguished. S2 is the dominant regional planar fabric. It represents the axial-plane foliation to isoclinal D2-folds and dips gently to the SW. Fold axes FA2 are dispersed within this axial plane foliation, with directions varying between 145° and 360° reflecting both the strong non-coaxiality and heterogeneity of the D2 deformation, as well as the pre-structuring of the nappe prior to D2. Rare shear criteria indicate a movement top to N-NW during D2. Evidence of the early Alpine/pre-Alpine history is scarce and has been largely obliterated during the D2 Tertiary deformation phase. An S1-foliation folded during D2 can be observed in

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different outcrops, but in the absence of Mesozoic metasediments, it cannot be unequivocally established that D1 is of Alpine age. Ky and And-bearing veins related to D1 from north of Alpe Sponda may be evidence that D1 is pre-Alpine. The Campo Tencia-synform (Grujić & Mancktelow, 1996), an upright fold generated during D3, is well exposed in the western part of the field area. The axial-plane parallel foliation S3 developed only in micaschists and mica-rich gneisses. Axial planes dip steeply in a SW direction. The interference of S2 and S3 results in a large-scale undulation of the rocks. The last deformation phase visible in the field is correlated with D5 of Grujić & Mancktelow (1996). D5-fold axial planes and fold axes are gently dipping in a NW direction. Metapelites show the assemblage Ky-St-Gr-Ms-Bt-Pl-Qtz. Most garnets are pre-D2 and almost no new growth can be observed during D2 and D3. Crystallization of staurolite and kyanite prevailed during D2 and D3. Metapelites seem to have equilibrated at PT-conditions near 550-600°C and 5-7 kbars during D2 and D3.

The Simano nappe appears to have a very distinct tectono-metamorphic evolution prior to the main Alpine deformation phase D2 compared to the Adula nappe and its UHP-metamorphism.

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OS10 : WEpo37 : PO Rheology and Microstructures of Quartz Aggregates Deformed in Torsion

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Torsion tests were performed on quartz aggregates (Dover flint) in a gas-medium apparatus (Paterson rig). Tests were carried out at constant twist rate (corresponding to maximum shear strain rate of 10^{-4} s^{-1}) and three different temperatures (1250, 1300, 1400 K) under drained and undrained conditions. The samples were first pre-heated for different amounts of time (from 25 min up to 25 h). Increasing temperature has a strong softening effect on Dover flint deformed under drained conditions. At 1300 K, a volume increase of up to 15% was observed. According to Mohr-Coulomb theory, the pore pressure was around 100 MPa. At 1400 K, deformation localized in narrow zones, leading to local strains of up to $\gamma = 5$. The microstructure and LPO were strongly heterogeneous on a microscopic scale. The presence of melt could not be excluded. Deformation was mainly ductile, with little volume change and lower pore pressure. Undrained samples yielded at about 25-50% of the yield point of drained samples at both 1300 K and 1400 K. They showed tension fractures oriented normal to the tensional principal stress axis ($\gamma = 0.1$). In drained samples at 1300 K, the microstructure at low shear strain ($\gamma < 1$) was characterized by fluid trails at low angle (15-20°) to the shear zone boundary comparable to synthetic Riedel shears ("R" after Petit, 1987). At higher strains ($1 < \gamma < 2.5$), the trails inter-connected to form discrete fracture surfaces with no visible movement parallel to the surface of discontinuity ("shear joints" after Mandl, 2000). No stress drop associated with the formation of the shear joints was observed. Two samples were unloaded at a shear strain of $\gamma = 1.3$ and 2.5, respectively, and reloaded after 1/2 h annealing at the deformation T and P. Both of them yielded at a lower level of shear stress than during initial deformation and subsequently deformed by frictional sliding along the fracture surfaces with an associated drop in stress. The microstructure showed the evolution of the shear joints into proper faults with a clearly visible displacement. EBSD measurements and synchrotron experiments indicated a weak lattice preferred orientation in the matrix with an oblique c-axis girdle opposite to the sense of shear. In summary: Undrained samples with high pore fluid pressure deformed in the brittle field with a pore pressure close to the confining pressure. Drained samples deformed at 1300 K in the semibrittle field up to high shear strains without a tendency to localize the flow into faults. Shear joints developed during hardening. The deformation localized into faults by annealing and subsequent reloading. Weak but clearly developed textures in high strain samples are attributed to a minor component of intracrystalline plasticity in the bulk rock.

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OS10 : WEpo38 : PO Kinematic Model for the Argentine Precordillera from a Multidisciplinary Approach using Structural and Fault Striae Analyses and Cosmic Ray Exposure (CRE) Dating

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Along the Andean plate boundary (~28°S / ~32°S latitude), present day convergence is mainly accommodated within the Chile trench and in the foreland of western Argentina. The aim of this study is to elaborate a Quaternary kinematic model for the Argentine Precordillera, which is supported by (1) a quantitative inversion of earthquake and fault-slip data, (2) moment tensor sums analyses and, (3) cosmic ray exposure dating along active faults. Two main structural domains characterise this Andean region: the Argentine Precordillera (AP), a high-level thrust-and-fold belt located east of the Frontal Cordillera, and the Sierras Pampeanas (SP), an eastern province of thick-skinned basement uplift. The AP is separated from the Frontal Cordillera by a N-S piggyback basin, the Calingasta-Iglesia valley, which is affected on its eastern side by the active 110 km-long right-lateral El Tigre fault. CRE dating along the fault trace yield an horizontal slip-rate of ~1 mm/yr for the El Tigre Fault. Between 29°S and 31°S, the active deformation front of the AP is characterized by the interaction of thin-skinned, east-vergent structures of the Central Cordillera (CP) and thick-skinned west-vergent structures of the Eastern Precordillera (EP). The EP is bounded on its western side by the active Villicum-Pederal thrust system. CRE dating along a segment of this thrust system, the Las Tapias Fault, yield a vertical uplift of ~0.8 mm/yr and a shortening rate of ~1.4 mm/yr. To determine the state of stress in the AP a quantitative inversion of fault-slip data populations measured at individual sites has been computed. This analysis allow to establish the Quaternary stress field and contribute to provide evidence for temporal and spatial changes in the state of stress over the last 10 Ma. Indeed, the Quaternary stress field is not homogeneous through the AP and the westernmost SP. A stress partitioning model, supported by the stress field deduced from fault kinematics, between the AP and the El Tigre Fault, yields a shortening rate of about 2-3 mm/yr to be accommodated by the AP thrusts. In addition, earthquake moment tensor sums have been used to calculate shortening rates due to seismic deformation both along the Chile trench and in the Andean foreland basin at about 30°S. Even if the use of moment tensor sums is affected by the choice of volume of the deforming zone volume and by the too short time interval, it is striking that between ~28°S and ~32°S, the shortening rate due to seismic deformation is less than 5% of plate convergence. Moreover, the ~3 mm/yr shortening rate calculated in the Andean foreland basin (essentially Ms 7.4 Cauce event) is of the same order of magnitude than the slip rates calculated for the last 700 kyr using CRE dating.

OS10 : WEpo39 : PO Structural-Metamorphic Evolution of Cordierite-Bearing Gneisses from the Teletsk Region (Altai, Russia)

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High-temperature metamorphism accompanied by partial melting and plutonism is a common feature in collisional belts. The geodynamic processes responsible for such high T in medium/shallow crustal levels are not yet well understood (Bohlen, 1987). This paper presents a detailed analysis of metamorphism in pelitic metachists and gneisses from the Teletsk region. In the central Asian Paleozoic collision belt, the Teletskoye lake is a young extensional basin that formed along a structurally highly anisotropic Paleozoic basement. The basement consists mainly of metamorphic rocks (migmatites, crystalline schists and gneisses) what are related to granitoids. The HT-LP metamorphism is represented by assemblage of cordierite, andalusite, staurolite and garnet. The NW-trending shear zone crosscuts the basement and consists of

mylonites with garnet and sillimanite, and biotite schists. Two identifiable sets of ductile fabrics can be distinguished in the strongly foliated cordierite-bearing biotite gneisses, referred as deformation phases D0-1 and D2. As oldest remnant structures, isolated small scale intrafolial fold hinges depict an early stage deformation, outlined by S0-1 fabric, locally preserved in between the regional foliation fabric S2. S1 has been affected by D2 folds which are commonly tight and intrafolial. Biotite defines an axial planar fabric S2 schistose fabric. Cordierite overgrows the early very fine grained fabric (S0-1), outlined by thin and very regular oriented small biotite and fine ore minerals, and is itself stretched afterwards in the regional country rock shear fabric (S2). Greenschist facies retrograde metamorphism is evidenced by the S2-concordant and selective transformation of biotite into chlorite. The HT-LP association, possible partial melting needs the additional heat input. On base of structural data the extensional regime (detachment) can be suggested (Thompson and Connolly, 1995). Therefore the thermal evolution is a very important topic for extensional process reconstructions. For modeling the tectono-thermal evolution of crustal segments during orogenic event the mechanical behavior of the crust during metamorphism is important. Thereupon the behavior of HT minerals, especially cordierite is under great interest. Three morphological types of cordierite are distinguished in Teletsk gneisses: (1) cordierite in the core with numerical oriented biotite and opak inclusions, (2) rim zone free from inclusions, and (3) fine grained aggregates. The detailed study of mineral zoning pattern, textural observations, chemical data and geothermobarometric data (Kalt A. et al, 1999; and references therein) allow giving the P-T evolution of these metamorphic rocks.

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OS10 : WEpo40 : PO Dauphiné Twins in Quartz Tectonites: A Study from the Norwegian Caledonides

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Dauphiné twins are the most commonly observed twins in a-quartz crystals. It involves a 180 degrees rotation of the twin member around the c axis relative to the parent member. Dauphiné twins may form as a result of an applied stress, e.g. Thomas and Wooster (1951). Also other processes, such as the a-b quartz transition, heating and sudden cooling or the application of strong electrical fields, may result in Dauphiné twins. Tullis & Tullis (1972) developed a thermodynamic theory, which predicted that if an axial compression was applied, a r-rhombmaxima subparallel to the unique stress axis would be formed, due to a positive difference in elastic energy (at constant stress) between the twin and parent member. Thus, with time, one of the two orientations would remove the other totally. This theory is supported by the observation of r-rhomb fabrics in natural and experimental quartz tectonites, e.g. Tullis and Tullis (1972). Previously it was not possible to achieve direct information about the crystallographic nature of the grain boundaries, because information was inferred from orientation distributions of bulk samples. With application of the EBSD technique, it is possible to resolve the orientation of a mineral to the detail of its Laue group (-32m for quartz) (Olesen and Schmidt, 1990), to achieve discrete information about the twin boundaries, and the orientations of the members of the twins. There have been other EBSD studies on the occurrence of Dauphiné twins in natural quartz tectonites (Neumann, 1996; Heidelbach et al., 2000; Lloyd, 2000). The orientation of the twin members are commonly related to the unique stress system such as Tullis and Tullis (1972) predicted, but Neumann (1996) observed that the twin population decreased with increasing strain and concluded that the twins were formed either by growth or by passing through the a-b inversion. We have studied one sample from the Jotun Nappe Complex (JNK) and one sample from the Troms region. The latter was deformed under greenschist facies conditions and showed trigonal rhomb-fabrics but no significant number of Dauphiné twins. The former sample from JNK was deformed under high amphibolite facies conditions, possibly granulite facies conditions, and showed numerous Dauphiné twin boundaries, which was the only significant high angle boundary in the sample. Plastically deformed garnet (garnet "fish") suggest that the sample was deformed under very high-T

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conditions. This implies that the twins also could have formed as a result of the a-b inversion. Further investigations needs to be carried out in order to establish the origin of the twins. A third sample from the Troms region, which has been deformed under mid-amphibolite facies conditions is under investigation.

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OS10 : WEpo41 : PO Geometry and Kinematics of the Boltaña Anticline (Southern Pyrenees)

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The Boltaña anticline is located in the central sector of the Southern Pyrenees, southwest of the Cotiella thrust system. It separates the Jaca basin and the Graus-Trempt basin and it is one of the N-S fold characteristic of the Ainsa region. The Boltaña anticline has been interpreted as a thrust ramp anticline (Farrell et al., 1987), associated to the western termination of the South Pyrenean Central Unit. It grew simultaneously to the deposit of Middle and Upper Eocene (Soler and Puigdefàbregas, 1970), within a transitional environment between platform margin and slope (Puigdefàbregas, 1975). In this work we study the geometry and kinematics of the Boltaña anticline by means of three cross-sections perpendicular to the fold, based on seismic reflection profiles, field data and the Boltaña-1 borehole data.

The Boltaña anticline is a 30 km-long north-south trending anticline with a slight southward plunge. Its southern end presents a periclinal termination that describes a westward concave arc. The amplitude of the Boltaña anticline varies from 1.6 km in the north to 1.2 km in the south and its wavelength from 10 km in the north to 5 km in the south. The Boltaña anticline is underlain by a N-S striking west-verging thrust detached in the Triassic ductile beds, as indicated by seismic sections and field data. In the Ara river cross-section, the F'gols Alogroup, Early to Middle Ypresian (Mutti et al., 1988) in age, crops out in the core. Its entire geometry is defined by Boltaña limestones, Castigaleu Alogroup, Middle Ypresian (Mutti et al., 1988). Along strike changes in the geometry of the Boltaña anticline can be explained by geometry variations in the underlying thrust: its displacement varies from 2.2 km in the north to 0.2 km in the south, where the thrust ramp presents a shallower dip. Southward both the anticline and the associated thrust disappear, as indicated by seismic data.

The Boltaña anticline is a synsedimentary fold, with growth strata that allow to determine its evolution. The Castissent and Santa Liestra sequences represent the growth strata, only appearing in the western limb, because of a dramatical thinning in the syncline located eastward of the Boltaña anticline. The Boltaña anticline continued its growth during the deposition of the Banast-n and Jaca-Ainsa Alogroups as can be inferred from syntectonic sediment geometries appearing in its eastern limb. The Campodarbe Alogroup (Priabonian) represents the post-growth strata. The Boltaña anticline can be explained as an oblique ramp of the western termination of the Montsec Unit, formed as a consequence of E-W thickness variations in the pre-tectonic sedimentary cover. This origin has been checked by means of analogue models with thickness variation of the sedimentary cover.

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OS10 : WEpo42 : PO Oligo-Miocene WNW-Directed Thrusting in the Western Alps North and South of the Pelvoux Massif: A New Interpretation of the Briançonnais Front

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In the Alps, the contact between the Helvetic (or Dauphinois) paleogeographic domain and the internal Penninic domain is the result of a multistage tectonic evolution. N-S shortening in the Eocene led to collision between these two domains as well as the emplacement of detached and unmetamorphosed Pennic nappes. In the western Alps, the end of this collision phase is marked by the transgression of detrital flysch formations, the Priabonian flysch des Aiguilles d'Arves, sealing this contact. Starting in the Oligocene WNW directed movements of the Adriatic block with respect to stable Europe caused WNW directed thrusting, partly reactivating the earlier formed contact. In the area between the Mont Blanc and Pelvoux external massifs thrusting was accommodated along the Roselend thrust (RT). The RT carried in its hangingwall all the Penninic units, together with the Priabonian 'flysch des Aiguilles d'Arves' and its substratum (the so called Ultra-dauphinois) on top of more external units. South of the Pelvoux massif evidence for WNW directed thrusting as well as SW directed thrusting has been described. The relative timing and relationship of these two directions of transport was not yet fully understood. New data from the region south of the Pelvoux massif suggest that the Roselend thrust finds its continuation along the Briançonnais front, still indicating consistent WNW directed thrusting. In detail, immediately to the SE of the Pelvoux massif, the Roselend Thrust carries the Briançonnais units over the Dauphinois domain. Further to the South, this same structure brings Briançonnais units on top of the Embrunais Ubaye nappe stack. In both these areas stretching lineations and kinematic indicators show that the direction of displacement remains top to the WNW, as observed north of the Pelvoux massif. These data indicate that during late Oligo-early Miocene time, the entire Western Alps moved to the WNW and that this WNW directed thrusting phase clearly postdates the first 'mise en place' of the Embrunais Ubaye nappes. The SW-NE oriented lineations, observed by previous authors and mentioned above cannot be directly related to this large scale WNW oriented thrusting. Age and significance of SW directed thrusting remain enigmatic.

OS10 : WEpo43 : PO Large-Scale Folding in the Otago Schist Belt, New Zealand

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In the Otago Schist the main fold generation is described as large recumbent folds with sheared-out lower limbs representing thrust zones (Craw 1985, Cox 1991). These nappe folds are thought to verge towards the internal part of the orogen (Norris & Craw 1987), which appears to be unusual. Moreover sheath folding is assumed to be the dominant fold type (Gray et al. 1995). This theory of nappe folds is rejected in favour of a new model: Re-examination of the fold structure lead to the assumption of two successive fold generations forming km-scale folds that verge toward the orogenic foreland. Both fold generations have an almost identical fold style with an early stage of buckling and a late stage of flexural flow folding. The large-scale folds are assumed to be asymmetric with the parasitic folds mainly concentrated on the short limb. The parasitic folds grow in amplitude and wavelength (cm- to m-scale) forming asymmetric open to close folds on the long limb, to symmetric tight to isoclinal folds on the short limb. Type 2 interference

pattern is observed mainly on the long limbs of both fold generations. The folds of the first generation verge to the NE, while the second ones verge to the NW. The first generation is dominant in the eastern part of the Otago Belt. The second one grows in amplitude and decreases in wavelength from the eastern to the western part of the Otago Belt, but is always smaller than the first generation. If the hinges of both generations of large-scale folds meet, both fold axes rotate towards each other into an N-S direction. In the hinge zone of the second folds, only small-scale folds and lineations of the first generation are preserved, acting as passive markers. On the long limb of both folding phases beneath the hinge zone, crenulation lineations, which are parallel to one related fold axis elsewhere, rotate towards each other into an E-W direction. Extension normal to the second fold axis leads to boudinage on the long limb, while extension parallel to the second fold axis is restricted to the hinge zone of both fold generations.

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OS10 : WEpo44 : PO The Frontal Folds of the Jura Mountains Revisited: Subsequent Folding of Oligocene Extensional Structures during a Thick-Skinned Phase of Jura Folding?

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The Jura Mountains of northwestern Switzerland and adjacent France represent a thin-skinned fold-and-thrust belt formed as the result of far-field compression from the Alps in Mio- to Pliocene times. Along their northern termination (simultaneously representing the southern end of the Rhine Graben), compressional structures of this folding event interact with pre-existing, mainly Oligocene extensional structures linked to the formation of the Rhine Graben. The northernmost Mesozoic sediments form flexures which were previously regarded as extensional structures, being almost unaffected by compressive Jura tectonics (e.g. Laubscher, 1982).

A detailed fault plane analysis along these flexures reveals that they are affected by compression. Fault plane populations in inclined strata show a mix of conjugate strike-slip faults, reverse faults and oblique-slip normal faults. By back-rotating the data into a horizontal position, the oblique-slip normal faults become pure dip-slip normal faults which are interpreted to have formed during Eo- to Oligocene Rhine Graben formation (by ESE-WNW-directed extension) and prior to Mio- Pliocene folding. Strike-slip and conjugate reverse faults, however, appear to have formed during subsequent flexuring. They indicate N-S- to NW-SE-compression during folding of the frontal Jura. Permutation of σ_1 and σ_2 allows for the contemporaneous activity along both strike-slip- and reverse faults. This is deduced from the repeated formation of horizontal slickolites along strike-slip faults and their subsequent rotation during contemporaneous folding.

In order to constrain the geometry responsible for the formation of the flexures, reflection seismic lines were interpreted. The analysis reveals that the flexures nucleate along inverted normal faults, bordering Permo-Carboniferous troughs. This indicates thick-skinned reactivation of faults at depth. A timing constraint (post 3 Ma) for this shortening is provided by the age of the folded Pliocene Sundgau gravels (4.1 to 3.0 Ma old; Petit et al., 1996; Fejfar et al., 1997). This suggests that it post-dates the main phase of Jura folding related to thin-skinned décollement during Mio- to Pliocene times which was active between 11 and 3 Ma in the northern Jura mountains (Kälin, 1997).

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OS10 Structural Geology and Tectonics

OS10 : WEpo45 : PO Contrasting Structural Patterns of Granites Emplaced during Non-Coaxial Deformation, The Example of Mundão and Sátão Granites (Central Northern Portugal)

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The Mundão and Sátão plutons crop out in the Central Iberian Zone of the Iberian Variscan Belt as two small intrusive bodies (9 and 15 km², respectively) of syntectonic, S-type, two-mica granites. Both plutons were intruded into a pre-Ordovician psammitic-pelitic sequence affected by late-Variscan transcurrent deformation (D4). In the field area, the D4 folding event is related to a NW-SE major sinistral shear zone, the Douro-Beira shear zone (DBSZ), that also affects Upper Carboniferous sediments from the core of the Porto-Sátão Syncline. Structural constraints show that the Mundão and Sátão plutons were both emplaced during this sinistral regional setting event. However, the differences in the structural patterns of the Mundão and Sátão granites suggest that their emplacement was not exclusively controlled by the regional deformation. The two plutons crop out close to the hinge of two D4 kilometre-scale S-shaped folds with NW-SE to NNW-SSE vertical axial planes and sub-vertical axes and are roughly elliptical in section. The Mundão intrusion is elongated parallel to the fold axial plane whereas the Sátão massif is elongated more or less perpendicularly to this direction. In the Sátão granite, the foliation trajectories define a concentric zoned pattern, parallel to the contacts of the intrusion. The northern contact is marked by a mylonitic border plunging to the south and by a deformed aureole in the country rocks. The kinematic criteria indicate a reverse movement from south to north (i.e. the granite overthrusts the metasediments) with a horizontal component showing a sinistral sense of shear in the eastern part of the massif and a dextral sense of shear in the west. In the central part of the massif and along its southern contact, the foliation is sub-vertical and poorly developed. In the Mundão granite, the foliation is always sub-vertical with a mylonitic character along the borders of the intrusion. The strike of the foliation varies from strongly oblique to the elongation of the massif, in the centre, to parallel to the contacts in the more deformed border zones. Along the eastern contact, the mylonitic foliation is folded. These folds have a vertical axial plane parallel to the contacts and plunge to NNW. S-C dextral structures have also been recognized along this contact. In contrast, no folds were observed along the northern contact, although the S-C dextral structures are still present. The emplacement of the Mundão granite, unlike the Sátão granite, does not seem to have produced a deformation aureole in the country rocks. The differences in the structural patterns of two plutons suggest that the bulk morphology of these intrusions has been essentially determined by the near-field deformation, the rheological behaviour of the magma and the rheology of the adjacent country rocks, rather than by the regional deformation.

OS10 : WEpo46 : PO Lithostatic or Hydrostatic Fluid Pressure Conditions? A Fluid Inclusion Study in a Cataclastic Fault-Zone

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This contribution presents results from an ongoing investigation of a cataclastic fault zone, in the crystalline complex of Ruhla-Brotterode, NW Thuringian Forest, Germany. The fault zone, which juxtaposes Variscan orthogneiss to post-Variscan granite, consists of a central part of up to 10 m width, that is penetratively cataclastically deformed. Away from this central part deformation is concentrated in up to 1 cm width cataclastic shear zones. The number of small cataclastic shear zones increases towards the central part of the fault zone. Along these cataclastic shear zones, quartz veins with tourmaline and/or chlorite are sometimes developed. These veins were sampled for fluid inclusions investigations.

Some quartz veins have a pallasite vein filling structure, whereas others show features typical of cataclastic deformation. Most veins, however, have quartz grains that are anidiomorphic, not visibly zoned and without crystallographic or shape preferred orientation. Secondary fluid inclusion trails with very small inclusions occur in all veins, but only 2 samples of veins with 'ordinary' microstructures yielded single inclusions and inclusion clusters, that could be primary and were large enough to analyse in the microthermometry.

At room temperature these inclusions are two phased with a small vapour bubble. These inclusions can be divided in two groups. One that homogenizes in the fluid phase between temperatures of 150 and 220°C, and another that homogenizes in the fluid phase at temperatures between 260 and 320°C. For both groups melting of the last solid phase is observed at temperatures between -4 and -1.5°C, indicating that both inclusion groups contain an aqueous fluid phase of low salinity.

Composition, shape, arrangement and position in the sample are similar for inclusions of both groups and only their densities differ. As there are no indications that these inclusions changed their densities after their formation, the different densities must have originated during formation of the fluid inclusions. This implies that during growth of the vein quartz and formation of the fluid inclusions, temperature and/or pressure conditions of the fluid phase changed. The irregular distribution of both inclusion groups (no obvious zoning or grouping of the inclusions) in the sample indicates that temperature and/or pressure conditions changed in a regular way several times during growth of the vein quartz. These observations can be explained by assuming that quartz growth in the vein occurred under alternating almost lithostatic and almost hydrostatic pressure conditions in an active fault zone.

Thursday AM Session

OS10 : THam01 : G5 Structural and Metamorphic Evolution of the Timan-Kanin Region

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Two stages of tectono-metamorphic evolution are recognised in the Timan-Kanin region in the Precambrian, each being associated with formation of a structural stage. The lower structural stage exposed in Kanin Peninsula is composed of schists of the Low Proterozoic (?) Mikulkin Series. The schists underwent amphibolite-grade reworking at moderate pressures. The oldest structural elements are represented by recumbent isoclinal folds with subhorizontal hinges. To the same structural stage may belong garnet-staurolite schists of the Cheshskaya Suite, reached by a borehole in North Timan. The upper structural stage is composed of Upper Precambrian terrigenous and carbonate rocks forming a series of uplifts in Timan and Kanin. The metamorphic grade is from the epidote-amphibolite facies in the northwest to lower grades of the greenschist facies in the southeast. The rocks are compressed to asymmetric folds with steep axis surfaces. The deformation is less pronounced in the southeastern part of the area.

OS10 : THam02 : G5 Transregional Ore-Concentrating Activation Megazones of Ukraine

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The distinguishing of transblock through activated patterns - megazones of activation within the East European platform limits is of special interest at the present time. Megazones of activation represent planetarium belts, concentrating within their limits large ore deposits of different age. On the territory of Ukraine the authors select a system of three through latitudinal megapatterns. Almost all large ore deposits concentrate within their limits. These megazones are traced both the west and east far beyond the Ukraine's territory, cutting the whole European continent (L.Galetsky, T.Shevchenko 1998). The histogram of the deposits distribution of the coloured, rare and noble metals shows latitudinal concentration of the metals very distinctively. 87% of the deposits first of all large ones are concentrated, within these belts. Practically all deposits of gold, iron, manganese, uranium, coloured and rare metals of Ukraine; polymetallic fields of Sventokshyk mountains and Silezia, deposit of native copper in Volyn traps; Dubravin apatite deposit in carbonates, gold-nickeliferous fields of Kalach-Ertil zone, Perha rare metal ore field, deposit of fluorite etc. The high concentrations of metals within plutonic latitudinal belts can be primary, arisen before formation of the Earth crust, or secondary, formed as a result of migration of ore elements in the field of 'extreme parallels' (M.Stovas, 1959). As a result of stable vibration (precession etc.) of position of line of rotation, in zones exists high-gradient dynamic environment directing and focusing (due to the fluid-dynamic concept of ore and oil formation (V.Sokolov, 1997)) fluid streams and, probably, plutonic migration of ore elements to the zones. It is one of the defining factors of origin and forming of fluid systems. The external and internal factors interact by a principle of mutual complementary, as a result of which there is a self-organizing of ore forming systems. The external (cosmogeous, inner) factor here is periodic tectonic-magmatic activation of the Earth's plutonic shells. Analysis of plutonic lineaments with abnormal concentration of metals from positions of the new idealized concepts and constructing of the patterns of ore-formation systems opens new outlooks of both theoretical and applied significance. The confrontation of obtained data to other regions of the world has shown availability of same patterns within the limits of all large continents. It gives a base for distinguishing of all planetary geodynamic system of through transregional ore-concentrating megazones of activation - "Geotrance". Its further analysis opens new outlooks for eliciting large and unique fields, and also is necessary for the account of areas of heightened seismicity and exogeodynamic activity at building large plants and prevention of catastrophes.

OS10

Structural Geology and Tectonics

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OS10 : THam03 : G5 Embryonic Basins in a Border Fault Relay Zone, Significance for the Tectonic Evolution of Lake Baikal

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The segmented nature of Lake Baikal is well expressed by the different geometry of its three sub-basins. This is a result of the different orientation of the main border faults, changing their strike from a more or less SW-NE direction in the southern basin to an almost N-S direction in the northern part of Lake Baikal. The Zavarotny area, along the northwestern lake border, is one of the areas where such a change in orientation is observed. Within this area two different segments of the Baikalsky border fault partly overlap, revealing a linking relay structure. Here the southern fault segment dies out in the lake, allowing a western onshore fault to take over its displacement towards the north. The morphology of the offshore part in this relay zone was examined on digital terrain models, constructed from echo sounding data. This DTM revealed the presence of small basins and ridges within the area, striking obliquely to the border faults. Structural investigations on a detailed high-resolution seismic grid, allowed us to accurately determine the geometry of the faults delimiting these basins. The structure of the onshore part is less well studied because large parts of it are covered by coarse-grained sediments from the Baikalsky Range. Although the two Baikalsky fault segments strike – within the zone of overlap – almost parallelly and have the same dip direction, we observe structures that differ significantly from those well known from relay ramp studies. The ramp structure we observe dips towards the north east, but it is not cross-cut by faults striking more or less orthogonal to the main fault segments. Instead we observe only faults that are slightly oblique, and even smaller faults that are almost parallel. These smaller faults are interpreted as being a result of block rotations in some parts of the ramp along axes parallel to the major faults. The observed deviation from the ideal relay ramp picture is most probably a result of the interference between fault linking processes as well as others. Indeed other processes are to be expected as the border fault deflection systematically occurs on left overstepping relays or splay. This suggests that the main active fault is slightly 'rotated' in a clockwise direction, leaving earlier fault traces to become less important. Whether lateral movements on the major transfer zones, separating the different Baikal basins, could be the underlying mechanism is a topic of future research.

OS10 : THam04 : G5 Numerical Modelling of the Subsidence Mechanisms Controlling the Evolution of the Black and Caspian Seas

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The Black and Caspian Seas are two of the deepest basins in the world but the mechanisms that have controlled their subsidence histories remain poorly understood. Lithosphere-scale models have therefore been developed to investigate the interplay of geological and geodynamic processes that have controlled the complex subsidence histories of these basins. The main advantage of this modelling is that it can be used to investigate the effects of deep processes that are poorly constrained by geophysical and field data.

Modelling software has been developed to forward model extensional basin evolution through sequential time steps. It accounts for both discontinuous depth-dependant stretching and sequential tectonism – providing insights into basin development via multiple rift phases and

inversion. The model also accounts for temporal changes in the style and location of rifting and inversion, often associated with the evolution of complex basins. The lithosphere temperature field is initially defined by a pre-rift thermal state and, over time, perturbations occur due to tectonism and changes in the background field such as the migration, growth and decay of anomalous 'hot-spots.' Loading can be isostatically compensated for either locally or regionally and temporal change in the effective elastic thickness is also accommodated. Model results are visualised in the form of cross-sections showing basin geometry, stratigraphic architecture and underlying crustal structure.

Sensitivity tests have been performed to examine the dynamic control of a range of parameters on basin subsidence. The model shows that the detachment depth exerts a strong influence on basin morphology, such that as when detachment depth increases, basin configuration approaches that produced by a uniform lithosphere extension scenario. Both enhanced lower lithosphere extension and multiple rift / inversion phases exert a strong control on basin fill architecture. Varying the lithosphere thickness over time and simulating transient background temperature anomalies also exert strong controls in modifying the thickness of syn- and post-rift sequences. To date the model has mainly been applied to the eastern Black Sea and shows that the basin cannot be attributed entirely to either extensional or compressional tectonics. The uniform lithosphere extension mechanism cannot account for the thickness of sediment fill observed in the basin while the simulation of compressional deformation around the basin edges does not account for the enhanced subsidence in the central basin. Model results strongly suggest an influence of lower lithosphere processes in controlling the evolution of the Black Sea. Modelling is currently being applied to the southern Caspian Sea, which has a similar tectonic history to the Black Sea basin, but is much deeper with over 20 km of subsidence.

OS10 : THam05 : G5 A Variscan Suture Zone along Sheared SW Boundary of the Orlica-Snieznik Massif (The Sudetes, NE Bohemian Massif)?

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The Sudetes in southwestern Poland and northern Czech Republic expose a Palaeozoic collage of the northeasternmost extremity of the Variscan belt, including a number of probable suture zones. A Variscan suture separating the Saxothuringian zone (terrane) to the NW from the Tepla-Barrandian zone (terrane) to the SE, has been interpreted within the Rudawy Janowickie and south Karkonosze metamorphic complexes (Mazur & Aleksandrowski 2001; following earlier concepts of Pin et al. 1988 and Matte et al. 1990). The equivalent of the latter suture seems to be represented by a major shear zone in the Orlica Mts, occurring along the boundary between the Nove Mesto - Lewin Klodzki phyllite-greenstone complex (probably of Tepla-Barrandian affinities) in the SW and the gneissic Orlica-Snieznik and the mica schist Stronie complexes (presumably corresponding to the Moldanubian/Gföhl terrane) in the NE. Both crustal domains show different structural patterns (Fajst 1976) and their contact is occupied by 1.5 to 5 km wide amphibolite belt intruded by gabbroic and acid igneous rocks. The amphibolite displays MORB-like geochemical features (Opletal et al. 1990). The structural study performed by the present authors revealed that the continuous belt of the Stronie complex mica schists adjacent to the contact from the NE, define a 1-2 km wide shear zone overprinting and obliterating all earlier fabric elements. This shear zone shows evidence for predominantly dextral shearing along moderately westerly dipping foliation and shallow NW-plunging stretching lineation. The strain intensity decreases both to the NE and SW of the contact. Locally the rocks show record of younger top-to-SW semi-brittle shearing event associated with extensional collapse. These relationships partly correspond to recent results of Dumicz (1998), who interpreted the discussed contact as located along the ductile-to-brittle normal-displacement Olesnice-Uhrinov shear zone ('fault'). Our results point to a later reactivation in semi-brittle regime of an earlier, predominantly strike-slip, ductile shear zone along the Olesnice-Uhrinov 'fault'. The hypothetical Orlica Mts suture zone deserves further structural, petrological and geochronological study which is planned in near future by the present authors.

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OS10 : THam06 : G5 Plate Tectonic Nomenclature for Pre-Variscan Units in Central Europe: A Discussion

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Pre-Variscan units in Central Europe were strongly overprinted during Variscan and/or Alpine events, and nomenclature is largely dominated by their belonging to Variscan resp. Alpine tectonostratigraphic units. Considering pre-Variscan basement relicts preserved in the Variscan mountain chain, we tentatively propose a new nomenclature being the mirror of their Early Palaeozoic (von Raumer et al. 2000) resp. Variscan evolution (Stampfli et al. 2000).

We recognised tectono-stratigraphic units containing Cadomian basement, Neoproterozoic to Cambrian active margin settings, and Ordovician accretionary stages, which belong to the Hun superterrane, formerly situated at the eastern continuation of Avalonia along the Gondwanan border. These units represent the leading edge of the Hun super-terrane and include a Middle Ordovician suture of an aborted Rheic ocean. Units to the south of those are characterised by the opening of the Paleotethys which separated the Hun super-terrane from Gondwana in Late Silurian times. Belonging to this zone, we place the classical Saxothuringian domain and the southern part of Armorica s.l. This scheme was transformed during the Variscan orogeny with the addition of elements derived from Laurussia. This is the case for the classical Rhenohercynian zone, together with the Lizard, the South Portuguese and the Moravo-Silesian Zones. They represent a Devonian oceanic domain opened within the Laurussian southern margin, due to a Gondwana-directed slab pull. The leading edge of the Hun super-terrane is represented at that time by a Silurian-Devonian active margin (the mid-German Crystalline Rise). The accretionary prism consists of the Phyllite zone (Rheic prism) and the Harz-Giesens zone (Rhenohercynian prism).

A similar tectonic scheme is repeated south of these units, with the Ligerian-Moldanubian, Helvetic-Cetic and Penninic-Austroalpine (partly) units representing the leading active margin of the super-terrane, then the Noric-Bosnian, Aquitaine-Cantabrian units represent the same northern Paleotethys margin. Thus, it is obvious that major lateral translations of terranes took place during the Variscan orogeny.

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OS10 : THam09 : G5 Pull-Apart Formation during Post-Orogenic Faulting in the Norwegian Caledonides, Leka Ophiolite Complex, Norway

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The Leka Ophiolite Complex (LOC) is located on the island of Leka, Norway, and a few neighboring islands. Leka is on the Trøndelag Platform at ~65° N along the western coast of Norway. The rocks of the adjacent mainland and most of the surrounding islands are basement gneisses and supracrustal rocks unrelated to the ophiolite

complex. Paleostress inversions, gravity inversion, and tectonic reconstructions allow investigation of the post-emplacement history of the ophiolite complex. 670 fault orientation and movement directions were collected from mesoscopic faults at 25 locations. Faults were measured within both the mafic and ultramafic sections on Leka and the immediately adjacent island of Madsøya. We used paleostress inversion techniques to determine the principal stress axes and reduced stress tensors for each location. Statistical outliers in the fault populations were rejected. The paleostress inversions revealed two main types of tensor, interpreted as small strains: (1) Horizontal extension. The extension was generally E-W, but varied from NE-SW to WNW-ESE, and (2) Horizontal extension and contraction. In this case, extension was E-W to NE-SW with an added component of perpendicular horizontal contraction. Some localities exhibited both types of tensors, reflecting at least two different deformations. Overprinting relations of fault striae corresponding to the two deformational events was not observed. These paleostress data were corroborated by a prior gravity survey from Norsk Geologisk Undersøkelse. This survey indicates that Leka has a strong positive anomaly (30 mGal), due to the high density of the ophiolite complex relative to the surrounding gneisses. Gravity inversion suggests that the LOC is confined largely to the surface exposures in Leka. Moreover, the LOC has steep-sided walls and a flat bottom located at ~6 km depth. Together, the data suggest that the LOC fills a fault-bounded rhombochasm. The faults bounding the LOC probably initiated during the Devonian. The faults are regional in scale, agree with the orientation of other NE-SW trending en echelon faults on the Trøndelag Platform, and are inferred to record a sinistral component of shear. The paleostress directions from Leka support this sinistral component of shear: 1) The E-W extension is consistent with sinistral motion along the bounding faults; and 2) The combination of horizontal extension and horizontal contraction suggests strike-slip deformation. The gravity inversion geometry is consistent with a rhombochasm geometry. This geometry also explains the preservation of the LOC, which is part of the thrust sheets of the Norwegian Caledonides and structurally higher than the basement gneisses that currently surround it. The ultramafic rocks within the pull-apart are excellent recorders of fault motion and they also allow a three-dimensional look at a rhombochasm using gravity inversion techniques.

OS10 : THam10 : G5
Structural Analysis of the Husavik-Flatey Transform Fault (Northern Iceland) and its Relation to the Rift System: An Approach using Remote Sensing and Field Data

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The Husavik-Flatey fault (HFF) is a major feature of the Tjörnes Fracture Zone which accommodates the dextral transform movement between the northern Icelandic rift and the Kolbeinsey medio-atlantic ridge (Saemundsson, 1974). Considering the E-W trend of divergence, the WNW-striking HFF is a transtensive transform fault. The HFF is exposed on land in the Tjörnes Peninsula. A new structural pattern of the HFF in this area is presented, based on the mapping of tectonic features using high-resolution imagery, including Synthetic Aperture Radar (SAR) images of the European Remote Sensing (ERS) satellite, SPOT images, aerial photographs and complemented by structural analysis in the field.

We show that the HFF is not a single transform fault but is constituted of several N120°E-trending fault segments that localise strike-slip and normal movements. New local releasing bends or pull-apart basins as well as push-up and en-échelon structures and also normal faults have been identified along the HFF system. We describe two different types of connection between the transform segments and the rift structure. In the first case, the transform fault segment turns progressively from WNW-ESE to N-S trend to become part of the rift structure. In this case, the same fault evolves from a strike-slip type into a normal one. For instance, the main fault trace runs across the Husavik City

with a N120°E mean direction. Two pull-apart basins attest its dextral component. Eastward, the fault turns progressively toward a N170°E trending parallel to the rift system. Along the bending segment of this fault, the dextral movement, demonstrated by 4-5 meters high push-up structures, is associated with a normal component (tilted blocks and tension fractures). In the second case, the connection between the segment and the rift mimics an imbricate fan of normal faults. This is the case for another branch of the HFF located 3 km further north. This N120°E-striking segment bends rapidly southward close to the Gudfinnugja normal fault (one of the main structures of the rift). This transform segment ends as an N-S segment with normal component. A second bending fault with normal component runs parallel to the first one but without connecting the main transform segment.

These structural patterns prove that the HFF is a complex transform fault. Several types of transform-rift connections may occur. Deformation takes place in a broad area where dextral component of motion is associated with a minor normal one. This is consistent with a transtensional model of deformation related to the oblique transform type of the Tjörnes Fracture Zone.

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OS10 : THam11 : G5
Tectonic and Thermodynamic Development in the Permo-Triassic Cover on the Southern Rim of the Argentera Massif (Southern Alps, France)

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During the alpine orogeny, the basement of the Argentera external crystalline massif deformed together with its autochthonous permo-werfenian sedimentary cover, below and independently from the detached mesozoic and paleogene cover.

The purpose of the present study is to identify and characterize the successive stages of deformation that the permo-werfenian sequence experienced, in order to propose a model of deformation development.

2 aspects are addressed :

- the tectonic analysis of some key sectors, located in the Rimplas-Valdeblora area in the W to the Roya valley (Fontan-Bergue) in the E. Some of these sites having already been the subject of former works (Graham, 1978 ; Siddans et al., 1984 ; Guardia and Ivaldi, 1985) ;
- the thermobarometric study of the quartz veins associated with the slaty cleavage within the autochthon cover of the Argentera massif.

Tectonic study :

The phase of major ductile deformation is characterized by folds striking NW-SE (Valdeblora area) to E-W (Roya valley). The cleavage generally strikes N120 to N090 and dips to the north. Occasionally it locally strikes NW-SE or NE-SW. We suggest that these sharp changes in trend are controlled by structural inheritance as permo or younger syndepositional normal faults which are common in both the Tinée and Roya valleys. Actually, field observations clearly show that cleavage tends to strike parallel to such inherited faults.

The successive stages of deformation, from ductile to brittle types, occurred in a regional compressive field with σ_1 trending N-S to N030. Ductile deformation was produced under simple shear or pure shear-dominated regime depending on the sites.

Thermobarometric study :

The analysis was carried out on quartz veins associated with the alpine cleavage in the carboniferous and permo-werfenian autochthonous sequences. The study was dedicated to fluid inclusions trapped in quartz crystals for some samples, to chlorites crystals (ripidolites) associated with quartz (geothermometer Cathelineau) and to some alpine phengites cut by quartz veins (geobarometer Massone-Schreyer). Taking into account the data obtained together with the results from other workers (FT on zircon: Bigot-Cormier et al., 1999 ; ⁴⁰Ar-³⁹Ar on alpine phengites: Ruffet et al., in prep.) the following interpretation can be

proposed: the quartz veins were formed at temperatures ranging from 300 to 330°C, under pressures bracketed between 2 and 4 kb; this episode probably occurred very shortly after the peak of alpine metamorphism during which phengite crystallized, at temperatures of at least 300°C and minimum pressures of 3 kb; these first events occurred between 28 and 20 My (Upper Oligocene - Lower Miocene) when the permo-werfenian deposits were buried under approximately a 10 km thick overburden comprising both autochthonous series and allochthonous sheets (penninic and austro-alpine?).

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Siddans AWB et al, *Journal of Structural Geology*, **6**, 339-368, (1984).

Guardia P & Ivaldi JP, *Bull. Soc. Geol. Fr.*, **8**, 353-362, (1985).

Bigot-Cormier Fet al, *Workshop FT analysis : theory and application, Chatillon*, (1999).

Ruffet Get al, *In prep*

OS10 : THam12 : G5
Post-Nappe Folding Versus Backthrusting in the Western Alps

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The main schistosity along the ECORS-CROP profile changes from SE-dipping in the external part of the Briançonnais (Front Briançonnais) to a dominant dip to the NW in the southeastern part (Gran Paradiso). This change in the dip direction is associated with overturning of the whole nappe pile. The metamorphic grade is changing from subgreenschist facies in the Zone Houillère to eclogite conditions in the Schistes Lustrés and the Gran Paradiso. In the west the metamorphic grade increases towards the tectonically higher units, while in the east a decrease in the metamorphic grade towards the tectonically higher units is observed. Classically the change in dip, the so called fan-structure of the Briançonnais, was explained by outward directed thrusting followed by inward directed back-thrusting (Butler and Freeman, 1996).

New structural investigations carried out in this area show that the main foliation is affected by open folds on all scales with gently SE dipping (5°-20°) axial planes and NE-SW oriented fold axes. The strain intensity of these post-nappe folds increases from west to east. These late folds overprint isoclinal folds associated with older deformation phases as well as the following tectonic contacts: the contact between the Zone Houillère and the Rutor massif in the external part and the contact between the Schistes Lustrés and Zona interna in the internal part ('Entrelor shear zone'). The presently W-dipping stretching lineations along these contacts are refolded. Retrodeformation of these post-nappe folds suggests that the stretching lineations were originally SE-dipping. This implies that these contacts were originally top-to-the northwest thrusts formed during the nappe stacking.

These structural data show that the so called fan-structure is in fact due to large scale post-nappe folding (Cogne-Savaranche Fold, Rutor Antiform). They also indicate, as stated by Cabry (1996), that there is no evidence for back-thrusting during this late stage of deformation. In summary, we propose that post-nappe folding rather than back-thrusting along the "Entrelor shear zone" (Butler and Freeman, 1996) is responsible for the large scale structures. Nappe refolding may be explained by wedging of the Gran Paradiso massif into the nappe pile.

Cabry R, *Eclogae geol. Helv.*, **89**, 229-267, (1996).

Butler RWH & Freeman S, *Journal of Structural Geology*, **18**, 909-923, (1996).

OS10 Structural Geology and Tectonics

OS10 : THam13 : G5 Development of Folds with Vergence Opposite to the Sense of Shear during the Exhumation of Metamorphic Rocks: The Montagnola Senese Case (Inner Northern Apennines, Italy)

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The vergence of folds describes the sense of asymmetry of asymmetric folds, without any direct relation to the kinematics that determined those folds. However zones characterised by simple deformation patterns are geological examples where the sense of asymmetry is considered parallel to the sense of shear: examples are given in minor folds whose vergences are useful tools for localising the hinge: these minor folds show their vergence consistent with the sense of shear. In this case, the fold asymmetry assumes the meaning of kinematic indicator. Differently, areas affected by refolding can show folds with vergence opposite to the sense of shear (Ramsay et al., 1983; Froitzheim et al. 1994; Krabbendam and Leslie, 1996, among others), hereafter named as antivergent folds. This work deals with antivergent folds that derive from the deformation of pre-existing metamorphic foliations, dipping in the opposite sense of direction of the superimposed shear-strain. Strain partitioning and pressure solution processes are envisaged to obtain antivergent folds during exhumation of metamorphic rocks. The study area is the Montagnola senese zone where Mesozoic rocks in the green-schist facies crop out. These rocks were affected by deformation during the collisional stage (late Oligocene - early Miocene) of the northern Apennines (D1 event), and during the post-collisional extensional tectonics (D2 event) that affected the inner zone of the northern Apennines since early-middle Miocene. During the D1 event, SW dipping axial plane schistosity and sheath folds have been occurred while, during the D2 event, westward verging folds developed. The S2 foliation, which is well expressed in narrow and localised zones, is mainly a pressure solution cleavage with NE plunging stylolitic teeth, suggesting a contractional strain inclined respect to this foliation. North-eastward extensional shear bands are associated to this deformational event. It is proposed that the evolution of the folds related to the D2 event was controlled by the alternate position of high and low strain domains: in the high strain domains, the deformation resulted by the combined effects of volume loss and shear displacement while, contemporaneously, in the low strain domains, recrystallisation and flattening processes developed. In this framework, the pre-existing foliation resulted in folds with vergence opposite to the sense of shear (antivergent folds).

Ramsay JG, Casey M & Kligfield R, *Geology*, **11**, 439-442, (1983).

Froitzheim N, Schmid SM & Conti P, *Eclogae Geologicae Helveticae*, **87** (2), 559-612, (1994).

Krabbendam M & Leslie AG, *Journal of Structural Geology*, **18**, 777-781, (1996).

OS10 : THam14 : G5 The Pre-Orogenic Architecture of the Lagonegro Basin (Southern Apennines, Italy)

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In the southern Apennines of peninsular Italy, the role of rift basin architecture during thrust belt accretion has long been recognised owing to the complex relationships existing among the major structural and paleogeographic elements of the Apulian continental margin. Detailed geological mapping and structural field work carried out within the hydrocarbon province of the High Agri Valley in Lucania, allowed us to define the architecture and geometry of the Mesozoic Lagonegro domain, a Mesozoic pelagic basin placed on the southern continental margin of Neotethys and located between two peritidal carbonate units (the internal Apenninic and the external Apulian Platforms, Auct.). In this area, four distinct Lagonegro units can be recognised, on the basis on the facies and thickness variations concerning Lower Triassic to Jurassic successions. The lithostratigraphic differences characterizing these four Mesozoic Lagonegro units are mainly controlled by the original architecture of the basin, with fault-bounded highs and depressions hosting syn-rift sequences characterized by different facies and thickness. The structure of the Lagonegro units above consists of four major, roughly N-S

trending, faulted antiforms cored by the incompetent Lower-Middle Triassic Monte Facito Formation, constituting the basal unit of the Lagonegro sequence. This implies that a common decollement level, located within the Formation above, must exist for all the juxtaposed units characterizing the different types of the Lagonegro Basin successions. The attainment of a regional decollement level was favoured by an early mild inversion of the basin, producing a roughly similar structural elevation of both hanging wall and footwall successions to Mesozoic faults. The structures above appear to be truncated by the tectonically overlying Apenninic Platform carbonates, as shown by the occurrence of both up- and down-section thrust trajectories in the footwall rocks of the Lagonegro units, and by the occurrence of local younger-on-older thrust relationships. This observation suggests that early shortening of the Lagonegro Basin succession preceded the emplacement of the Apenninic Platform units and took place in the foreland, at some distance from the active thrust front. Further deformation of the Lagonegro units, leading to variable degrees of modification and distortion of pre-existing structures, was associated with major basement-cover decoupling and emplacement of the peritidal carbonate platform-pelagic basin assemblage as a single tectonic unit, onto the foreland carbonates of the Apulian Platform.

Thursday PM Session

OS10 : THpm21 : G5 Computer-Aided 3D Retro-Deformation of the Northern Calcareous Alps around the TRANSALP Reflection Seismic Profile

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To determine the amount of shortening, depth of detachment and the style of deformation, we three-dimensionally retro-deformed a ca. 40 x 40 km area (around the TRANSALP seismic section) of the Lechtal and Allgäu Nappes (LN and AN, respectively), the largest nappes within the Northern Calcareous Alps. A three-dimensional model was constructed by splining lines from eight N-S cross-sections, spaced E-W at ca. 4 km intervals, which define faults and seven stratigraphic layers within the Permo-Triassic to Cretaceous stratigraphy.

The LN has four main thrusts which link to a detachment at 2-5 km depth below sea level. 3D fault displacements and heaves were determined using 'Allen Maps'. The algorithms 'fault-parallel flow' and 'flexural-slip unfolding' were used to restore northward movement on the thrusts and folding of beds over thrust planes, respectively. Minimum shortening estimates vary, from east to west, from 25 to 42% (with a typical error 6%), but additional shortening in the west is due only to folding. Nearly all the structural features of the LN are controlled by the Triassic 'Hauptdolomit' (HD) layer: 1. Where it is less than 500 m thick, imbricate thrusts develop. 2. Sections where the HD is thicker than 1 km are not faulted. 3. Folding of an earlier detachment, back-thrusting and isoclinal fault-bend folds are the result of the thrust system jamming where the HD is thickest (2.5 km).

The AN consists of two fault units, the so-called 'Randschuppe' which contains only Jurassic and Cretaceous strata and a second which contains Raibler series to Cretaceous beds. The main detachment occurs within the former. To the east of the modelled area, the second fault unit is internally thickened by a minor thrust, folding the base of the LN. Shortening values are between 43 and 49% in the east, but western sections were shortened by a constant 32%.

This modelling demonstrates the use of three-dimensional techniques to determine along-strike fault geometry and displacement variation, and balancing a 3D model.

OS10 : THpm22 : G5 Continental Collision History between Arabian Platform and Central Iran

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The Zagros Orogen in western Iran is formed in Late Cretaceous during closure of Neo-Tethys when the Afro-Arabian continent collided with central Iran. From north-east to southwest, the Zagros Orogen consists of the Urumieh-Dokhtar Magmatic assemblage, the Sanandaj-Sirjan Zone (SSZ) and the Zagros Fold-Thrust Belt. The rocks of the Sanandaj-Sirjan Zone are mostly of Mesozoic rocks and characterized by metamorphic and complexly deformed rocks associated with abundant deformed and undeformed plutons in addition to widespread Mesozoic volcanic rocks. The major structure in the SSZ was the result of the collision between this zone and the Arabian platform in Late Cretaceous. Structures associated with this event are characterized by the development of intense folding with south-southwest vergence to produce exposure of the metamorphic core. Deformation of the Sanandaj-Sirjan Zone has also continued into the Cenozoic. The Zagros Fold-Thrust Belt is a tectonically active belt that is currently shortening and thickening due to the collision. In the Cenozoic there has been continuing convergence along the Zagros Orogen, particularly in the Zagros Fold-Thrust Belt, with presently active dextral faulting occurring in the SSZ reflecting movement between the Arabian plate and central Iran. Compression normal to Zagros Orogen is reflected by further collision and Neogene deformation. Deformation and uplift is documented by the synorogenic siliciclastics that consist mostly of conglomerate in the

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Zagros Fold-Thrust Belt and along the southwestern border of the SSZ. These rocks are of Late Miocene and recent age and indicate that uplift was synchronous with opening of the Red Sea and Gulf of Aden. Since collision, dextral transpression in the SSZ is documented by deformation partitioning to two different types of deformations including thrusts and related structures and, abundant strike slip shear zones. Dextral motion in the SSZ is also shown by transcurrent displacement along the Zagros suture as has been demonstrated for the 'main recent fault' in the north-western part of the zone. Oblique convergence is also shown by the development of dextral north-south trending faults that cut the Urumieh-Dokhtar Magmatic Assemblage and associated dextral transcurrent motion along all north-south trending faults between the Chaman fault and the Zagros suture. Ophiolites exposed along the Zagros suture indicate obduction of oceanic fragments. Compression during the neogene is demonstrated by the abundant thrusts involving Cenozoic successions in the southwestern border of the SSZ that transported different parts of the hinterland over the Zagros Fold-Thrust Belt.

OS10 : THpm23 : G5 Asymmetrical Fabrics in the Mesozoic Accretionary Complexes of North-East Asia as Possible Indicators of Plates Kinematics (Results from the INTAS Project 96-1880)

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The main object of study are Paleozoic and Mesozoic volcanic and sedimentary rocks of Beregovoi terrane (Taigonos Peninsula, NE Russia) metamorphosed up to greenschist and amphibolite stages and deformed during the late Mesozoic accretion event. Metamorphic rocks contain numerous asymmetrical structures with the following sequence of formation: 1) boudinage-like structures in layer-parallel quartz veins with back-rotated swells; 2) stiff inclusions with symmetrical and asymmetrical "wings"; 3) ductile shear zones with minor folds of S- and Z- shape and C-S structures; 4) small-scale conjugate brittle fractures. Most of the shear-sense indicators point to sinistral displacement along NE-trending zones, although some dextral displacements are reported as well. Geometry of most asymmetrical structures points to NW-SE orientation of compression axis that is approximately normal to the regional structural trend. However, some small-scale conjugated ductile shear zones were formed in the stress field with NE-SW orientation of compression axis that is approximately parallel to the regional structural trend and implies inversion of stress field.

Sequence of structural events in general corresponds with that described in NW Kamchatka approximately 250 km to the NE from the study area along the regional structural trend reflecting large-scale plates kinematics. Sinistral displacements are resulted from northward motion of Pacific and Izanagi plates, whereas dextral displacements reflect counter-clockwise rotation of plates located in northern Pacific Ocean. This interpretation is in a reasonable agreement with paleomagnetic-based reconstructions of Engebretson et al. (1985) and Bazhenov et al. (1999).

OS10 : THpm24 : G5 Himalayan High-Grade Core as a Large Orogenic Channel: Insight from the Kingdom of Bhutan

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The Bhutan Himalayas have two major tectonic features that have not been described from the rest of the Himalayas: (i) sedimentary rocks of Tethyan affinity lie above the Greater Himalayan Sequence (GHS) as klippen;

these are erosional remains of the South Tibetan Detachment (STD); and (ii) a major out-of-sequence thrust, the Kakhtang thrust, lies structurally above the klippen.

In this paper we present field observations and geochronological data that constrain the main kinematic events in the Bhutan Himalayas. Our data indicate that the Kakhtang thrust is an out-of-sequence structure post-dating the peak of metamorphism and the initial north-directed shearing beneath the Tethyan klippen. By correlating the position of the STD in the hanging wall and in the foot wall of the Kakhtang thrust, the throw of the thrust is estimated to be 10-20 km. The differences in metamorphic assemblages between the hanging wall and foot wall of the thrust contribute to the inverted metamorphic field gradient within the GHS. The existence of klippen, even if eroded, is indicated by locally lower grade, right-way up, metamorphic field gradient. The Tethyan klippen demonstrate the large surface extent of the ductile shear zone of the STD in Bhutan. The dip-parallel length of the STD surface (i.e. the juxtaposition of the Tethyan metasediments and the high-grade metamorphic rocks from the southern edge of the klippen to the northernmost outcrop of the STD) is in excess of 140 km.

These observations indicate that the reconstructed shape of the high-grade core of the Himalayas during the peak of metamorphism and magmatism was a shallowly north-dipping orogenic channel 10-15 thick extending over 200 km beneath Tibet. This contrasts with the conventional interpretation of the shape of the GHS as an orogenic wedge bounded below by the north-dipping MCT, and above by steeper north-dipping normal faults of the STD zone. All the rocks that show penetrative ductile deformation, including the MCT and the STD and the sheared rocks below and above these structures, define the orogenic channel. The boundaries of the channel are, therefore, fabric boundaries. If such an orogenic channel is confirmed for the rest of the Himalayan chain, it must be taken into account for geodynamic and thermal models of the Himalayas and of the Tibetan plateau.

OS10 : THpm25 : G5 Gravity Constraints on Palaeoproterozoic Thin-Skinned Tectonics at the Southern Margin of the Pilbara Craton, Western Australia

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The Hamersley Province in northwestern Australia is an Archaean-Palaeoproterozoic (~2800-2200 Ma) succession comprising several kilometres of volcanic rocks, banded iron formation and sediments that were deposited onto the granite-greenstone terrain of the Archaean Pilbara craton. The rocks of the Hamersley Province were deformed by south-to-north directed compression between about 2200 and 1800 Ma. Gravity data obtained along and around deep seismic reflection lines across the Hamersley Province have been used to constrain basement geometry and the geometry of thin-skinned tectonics.

Gravity data were obtained with a Scintrex CG3 M gravity meter and station locations were positioned using differential GPS. Data were obtained at 250 m intervals along the 100 km long seismic lines, and at ~400 points in a 50 by 20 km area surrounding the lines. Terrain corrections were applied using a digital elevation model with a resolution of about 50 m. Large-scale regional gravity variations are modelled based on lithospheric-scale profiles extending from the Pilbara craton in the north to the adjacent Yilgarn craton in the south. Isostatic equilibrium is maintained along these regional profiles.

Interpretation of the deep seismic reflection lines incorporates fold-dominated thin-skinned tectonics in a cover succession largely uninterrupted by major thrust offset. The seismic data do not provide precise constraints on the depth to the basement-cover contact, and stratigraphic constraints are poor in the region surrounding the seismic lines. A compilation of stratigraphic information for the entire Hamersley Province suggests that the basement-cover contact lies at a depth of 4-6 km under the seismic lines. The large density contrast between basement and cover (~200-400 kg/m³) means that gravity data provides additional constraints on the geometry of the basement-cover contact.

No major gradients are evident in the gravity data, which suggests that there is unlikely to be any major basement offset. Similarly, blind thrusts inferred to exist under

regional anticlines cannot be delineated in the gravity data as they do not juxtapose lithological units with sufficiently different densities. Forward modelling shows that gravity variations can largely be accounted for by near-surface lithological variations, particularly those associated with the exposure of high-density banded iron formation. Longer wavelength anomalies suggest that the Hamersley Province cover succession thickens from about 4 km in the north (towards the foreland) to around 6 km in the south. This thickening may reflect stratigraphic thickening, deformation induced thickening, or some combination of these two possibilities.

OS10 : THpm26 : G5 Are all 1000-1100 Ma old Rocks Related to Formation of the Supercontinent Rodinia? The View from Sri Lanka, Madagascar and Southeastern Africa

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Current models consider high-grade metamorphic rocks formed during the 1000-1100 Ma (Grenvillian) period to be the result of collisional events, leading to formation of the supercontinent Rodinia. In this amalgamation process, Peninsular India was probably sutured to East Antarctica along the Eastern Ghats belt, but whether Sri Lanka, Madagascar and East Africa had any part in Rodinia is in dispute. Sri Lanka contains abundant evidence for Grenvillian-age granulite rocks. The Vijayan Complex (VC) in the eastern part of the island predominantly consists of ~1000 Ma amphibolite facies calc-alkaline granulites that are in thrust contact with the older Highland Complex in the central part of the island. This, in turn, is bounded to the W with ill-defined contact by amphibolite- to granulite facies granulites and clastic metasediments of the Wann Complex (WC). The WC granulites are also predominantly calc-alkaline and intruded between ~755 and 1080 Ma, and detrital zircons of the sediments suggest a depositional age <1080 Ma. Available Nd-isotopic systematics support short mean crustal residence times for the VC and WC rocks, thus supporting models of their generation in magmatic arc systems. We suggest that both the VC and WC were part of an Andean-type active margin situated at the outer edge of Rodinia and resulted from subduction of oceanic crust under the evolving supercontinent.

Seemingly continuous magmatism from ~1080 to ~755 Ma in the WC either implies continuous subduction for >300 Ma and breakup of Rodinia thereafter or, alternatively, magmatism occurred in two events, the older (~1000-1080 Ma) associated with Rodinia margin magmatism, the younger (755-880 Ma) the result of arc magmatism after breakup of Rodinia and related to consumption of the Mozambique Ocean and formation of Gondwana.

In contrast, Madagascar has no proven Grenvillian-age magmatic or metamorphic rocks and probably played no role in Rodinia assembly. Its voluminous 720-820 Ma calc-alkaline granulites may be related to arc magmatism linked to Gondwana terrane accretion.

The East African Orogen (Mozambique belt) preserves local evidence of ~1000-1100 Ma (Kibaran) granulite and mafic magmatism (but not metamorphism) in northern Mozambique and southern Malawi whose significance is uncertain and does not seem to be related to orogenic activity as part of Rodinia formation. The majority of igneous rocks was generated in the ~600-840 Ma age bracket and probably signifies arc magmatism during terrane accretion as part of Gondwana assembly.

All segments discussed above underwent high-grade metamorphism between 640 and 550 Ma, associated with ductile deformation, and this is interpreted as reflecting final amalgamation of the Gondwana supercontinent. Considerable differences in metamorphic age favour as yet little understood terrane assembly over simple collision between East and West Gondwana.

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OS10 : THpm29 : G5 A Modern Structural Regime in the Paleoarchean (~3.65-3.62 Ga); Isua Greenstone Belt, Southern West Greenland

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The footwall gneisses beneath the western part of the Paleoproterozoic Isua Greenstone Belt, southern West Greenland, are interpreted here in terms of a stack of mylonitic crystalline thrust-nappes. In present coordinates, the kinematic history of the thrust-nappe stack is interpreted in terms of initial longitudinal (strike-parallel) thrusting towards the southwest, followed by transverse thrusting to the northwest, and subsequent extensional collapse of the thickened crust toward the southeast. The mylonitic nappes are intruded and by, and misoriented within, a 2991 ± 2 Ma tonalite complex that provides a minimum age for the thrust-nappe stack. Dated tonalite veins within the mylonites indicate that the nappes formed during the Paleoproterozoic at ~3.65-3.62 Ga and constitute the oldest thrust-nappe stack known on Earth. Diorite and tonalite that form the western margin of the central granitoids, structurally overlying the western Isua Greenstone Belt and its footwall, contain ~3.5 Ga mafic dykes, some of which are deformed and/or truncated at fault contacts within the granitoids. Accordingly, deformation structurally above the Isua Greenstone Belt occurred after ~3.5 Ga, and is significantly younger than the formation of the underlying mylonitic nappes; it may be Neoproterozoic in age. The structural regime of mylonitic thrust-nappe stacking is very similar to that found in modern mountain belts. Building on the kinematic history of the mylonitic nappes of the footwall, the arcuate Isua Greenstone Belt can be interpreted to be an early Archean, crustal-scale, recumbent interference structure, or a sheath fold. The kinematic history, deformation style and scale of structures suggests that the deformational behaviour, rheological constitution and overall strength of Paleoproterozoic continental crust were similar to those of modern continental crust.

OS10 : THpm30 : G5 Geometric Conditions Affecting the Shear-Sense Derivation at Stretched Lithotectonic Boundaries

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On horizontal length scales of 10-1000 km, many ductile deformation zones contain concordant lithotectonic boundaries (LTBs) which have been stretched during tangential shearing of the wall rocks. Structural geologists and tectonicists employ shear-sense indicators (deformation features with monoclinic symmetry) to study the paleokinematic process as well as the geometric net result of tangential shearing.

The monoclinic geometry of shear-sense indicators is commonly analysed in rock sections containing (1) the normal to a flattening foliation and (2) the direction of the coeval stretch lineation. In many LTB wall segments, such sections are approximately perpendicular to Y, the intermediate axis of a finite-strain ellipsoid. Unless the Y-axis lies in the LTB surface, however, monoclinic structural relationships discerned in the rock sections need not pertain to the tangential-shear sense. Using geological examples in which the LTB surface has been exposed by underground mining or imaged reliably by geophysical methods, we estimated the actual angle between the LTB normal and the

Y-axis in wall segments of the Brevard fault zone (Grandfather Mountain area, southern Appalachians) and of four structural discontinuities in the Canadian Shield. In all examples, the LTB surface originated prior to the wall-rock strain responsible for the foliation-lineation pairs considered by us. Therefore, one should not expect that the Y-axis be generally orthogonal to the LTB normal.

It turns out that the acute angle between the Y-axis and LTB normal is less than 80 degrees in all examples considered by us. Even an angular magnitude of 75 degrees can create large problems when attempting to determine the direction and sense of a tangential-shear strain in sections normal to the Y-axis. The same may apply to the analysis of large components of progressive simple shearing parallel to stretched LTBs.

OS10 : THpm31 : G5 Internal Patterns in Lava Domes Emplacement Analogical and Numerical Modelling

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Lava domes constitute a major volcanic risk, in particular because of destabilisation processes occurring during or after emplacement. Understanding the way in which they grow and evolve is critical. Moreover, previous studies have been essentially devoted to geometrical aspects or textures on domes carapaces and little work was made on overall strain pattern and kinematic evolution. To perform this subject analogue and numerical models were achieved and compared with field observations and data given in literature.

Scaled experiments were conducted at room temperature with silicon injected vertically on a planar base using a piston apparatus. Two kinds of experiments were carried out. The simplest, in three dimensions, enabled us to calibrate our apparatus. Analogue models evolve in a way similar to natural examples and in respect with equations given in literature. Then, in two-dimensional experiments, the viscous fluid is confined between two walls of glass allowing to study internal strain and motion. Models reveal the existence of two main zones in the dome: an injection field versus gravity one. Gravity field, located in dome periphery, behaves similarly to flows that are spreading at constant volume and submitted to their own weight (such as lava flows). The horizontal component of displacement is here the most important. In the dome centre, patterns are very different and the motion is governed by a vertical ascending movement, due to injection effect. Thus, we called this area "injection field". Spatial distribution between these two zones evolves with time. It allows to distinguish two stages in dome growth: mature and juvenile. A dome can be termed mature once the central domain has taken its definitive shape. Then, dome growth is only expressed by lateral gravity field growth and the geometry of injection field remains constant. Zones distribution is also dependent on injection rate. The higher injection rate the more developed the central domain. Concerning deformation patterns, models reveal the existence of a central zone with an inward shear sense surrounded by an external one with outward shear sense. Column above the piston aperture undergoes only pure shear.

Next, numerical models were carried out. To do so, I computed a precise deformation matrix working in three dimensions and combining pure and simple shear. The result allows to represent the three main axes of the final ellipsoid deformation in any imaginary or real cases. In this program all separated and incremental components of deformation are needed. Deformation patterns observed with models, especially stretching trajectories are confirmed and could be quantified.

Comparison with natural examples is also convergent with all the experimental data.

OS10 : THpm32 : G5 Displacements, Stresses, and Arrest of Hydrofractures

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Analytical models of hydrofractures in homogeneous, isotropic rocks indicate that, so long as there is any significant fluid overpressure in a hydrofracture, the crack-tip stresses are normally many orders of a magnitude greater than the host-rock tensile strength. It follows that, for such models, buoyant hydrofractures should normally not become arrested but rather reach the earth's surface. Nevertheless, field studies of many thousand dykes, inclined sheets, and mineral-filled veins indicate that most natural hydrofractures never reach the earth's surface but rather become arrested at various crustal depths. Similarly, thousands of hydraulic fractures, injected for the purpose of increasing the permeability and production rate of oil reservoirs (commonly at crustal depths of a few kilometres), are made so as to be confined to the reservoir and thus vertically arrested. The apparent paradox that most hydrofractures become arrested is here explained by the host rock not being homogeneous and isotropic, but rather heterogeneous and anisotropic, with layering that commonly includes sharp contacts and other discontinuities. Boundary-element models show that layers with low Young's moduli (soft layers) with sharp contacts, as well as stress barriers (layers with unusually high fracture-perpendicular compressive stresses), are very effective in arresting hydrofractures. Furthermore, the models indicate that the contrast (positive or negative) in Young's modulus at a contact affects the general shape of the hydrofracture. In particular, when a hydrofracture propagates into a stiff layer, its tip becomes thin and sharp but the rest of the modelled fracture relatively thick (with a large aperture). By contrast, on entering a soft layer, the tip becomes rounded and thick, whereas the rest of the modelled fracture becomes relatively thin (with a small aperture). Sharp contacts with stress barriers consisting of relatively soft rocks subject to high fracture-perpendicular compressive stresses are probably most effective for hydrofracture arrest.

OS10 : THpm33 : G5 Progressive Strain Localisation during a Normal-Fault System Evolution

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The kinematic analysis carried out in that study describes the growth of a syndimentary normal fault system of Timor Sea over the last 6 Ma from early growth to present day. Normal fault growth is most favourably analysed in syn-faulting sequences where sedimentation rates were higher than fault displacement rates. Then, horizon thickness and displacement variations allow the fault growth to be reconstructed using displacement backstripping. Using 3-D seismic reflection data, this study conducted to the following conclusions. Most of all faults in the array initiated within the first 1-2 million years of faulting, meanwhile the initial stage of fault system evolution was characterised by rapid growth in fault length, though fault reactivation of ancient major faults probably have emphasised the promptness of the nucleated fault propagation and influenced fault areal distribution. Fault maximum displacement rates were near constant through time, with larger faults usually moving faster than smaller. As displacement rates and fault lengths were both established rapidly, fault hierarchy in the array was also established early in the faulting history. Relationships between the maximum displacement and fault length change through time. Initially fault length increases more rapidly than maximum displacement, then fault propagation rates slowed significantly and the regional extension was mainly accommodated by displacement increasing. As the system evolved, fewer small faults remained active. High mortality rates for the smaller faults reduced the total number of active faults in the system and increased the relative proportion of extension accommodated onto larger faults.

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This later stage of strain concentration onto larger faults also appears to have been associated with an increase in the larger fault connectivity and a reduction in the length of the remaining active faults in the system. Together with the total fault number loss, this reduction reflects the regional rates of extension slowing. Strain localisation process could be the major reason for the frequent observed disparity of the fault dimension frequency cumulative power number. Indeed, if fault throw populations have constant slopes on each syn-faulting horizons, an up-sequence shallowing of the length and geometric moment population slopes, demonstrates this progressive strain localisation onto fewer and larger faults through time. If regional extension was to continue beyond the actual value, this strain concentration would result in the formation of a single through-going fault.

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Stress Permutations: 3-D Distinct Element Analysis Accounts for a Common Phenomenon in Brittle Tectonics

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Using 3-D distinct-element modeling, we explore a variety of situations to explain the stress permutations, an extremely common phenomenon observed in brittle tectonics. Stress inversions of fault slip data or earthquake focal mechanisms often reveal such permutations. The main aim of our study is to produce mechanically consistent 3-D models that account in a simple way for switches between principal stress axes s_1 - s_2 or s_2 - s_3 . Other phenomena, such as those related to elastic rebound, are beyond the scope of this work. It appears that the stress changes induced by variations in rheology are large enough to modify the local tectonic behavior and produce permutations of principal stress axes, despite the simplicity of far-field boundary conditions. Rather than simple directional changes, which exist but are limited, the relative variations in principal stress values are the major cause of permutations s_1 - s_2 and s_2 - s_3 . This is in good agreement with observations in nature, where despite permutations the orientations of axes often remain tightly clustered. Note that the most demonstrative experiments were done with a ratio F of 0.5, implying that s_2 is the arithmetic mean between s_1 and s_3 (low F ratios favor s_2/s_3 permutations, whereas high F ratios favor s_1/s_2 ones). In terms of geological significance, we conclude that the major causes of stress permutations are the heterogeneity of the brittle deformation (e.g., intact rock massifs between heavily faulted grabens of deformation zones) and the anisotropy of the mechanical properties that results from the fracturing and faulting (that is, a rock more resistant in the direction parallel to faults than in other directions). Our modeling effectively revealed that anisotropy in rock properties favors stress permutations. Of major importance seems to be the existence of relatively resistant zones at the tips of deformed ones, acting as channels where stress concentrates and switches occur. Because in nature such zones move in time and space, it is not surprising that stress permutations are so pervasive.

