EUG XI

Symposium LS06

Blueschist to UHP Metamorphism and Back Again

Convenors

John Schumacher
Simon Cuthbert
Tony Carswell

Wednesday PO Session

LS06 : WEpo01 : PO
Diversity of High Grade Metabasic Rocks from South Togo, West Africa: A Clue for a Regional Tectonic Imbrication of Pan-African Age

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The ultramafic-mafic (UMM) complexes from Ghana, Togo and Bénin are commonly considered as a particular lithotectonic units representing the suture zone of the Pan-African belt. In southern Togo, from Agou to Atakpamé, the UMM complexes outcrop as a linear trends, closely associated with various metasediments and orthogneisses. Field survey, petrological and geochemical data show evidences of striking dissimilarities amongst these complexes. With regard to their primary magmatic and subsequent metamorphic features, they might be discriminated into four mains. This paper deals with two very spectacular types : The Agou type occurs as intrusions within the pre-panafrican gneissic basement. Igneous protolites display LREE enriched tholeiites composition. Post-solidus recrystallizations lead to HT-HP granulites (925±50°C, 13 ±0.5 kb) and then to successive stages of retrogression under granulitic facies conditions (700-790°C, 11 ±0.5 kb), high to low grade amphibolitic assemblages (700-750°C, 8-10 kb to 650-600°C and 5-6 kb) and finally greenschists facies conditions (550-500°C, 3-4 kb). The inferred P-T path defines an anti-clockwise loop in the kyanite stability field. This suggests intrusion and equilibration of Agou type mafic magmas in the lower crust and progressive exhumation during the Pan-African orogeny. The Lato type where basic rocks are primary and/or tectonically intercalated within panafrican metasediments, are observed as variously retrogressed eclogites. The Lato eclogites derive from volcanic and sub-volcanic MORB. Eclogites occur in several tectonic units characterised by distinct P-T conditions. The North Lato unit corresponds to fresh eclogites (700 ±50°C, 19 ±4 kb) followed by a "cold" retrogressed path whereas the South Lato unit (630 ±50°C at 13 ±4 kb) evolved as the Toutouto unit, under retrogressed granulitic (8-10 kbar; 750-700°C) and amphibolitic amphibolites (4-6 kbar; 540-580°C) facies conditions with final common emplacement under greenschist facies conditions (2-4 kbar; 450-500°C). The related P-T paths display contrasted evolution compatible with subduction and collision processes during the Pan-African orogen. The UMM complexes of southern Togo probably emplaced in various geological settings (ocean, arc, subduction and collision zones) underwent contrasted P-T evolutions related to distinct tectonic levels in the crust during the subduction-collision processes. Pan African nappe stacking put all the UMM complexes together as suggested by the latest stages of evolution, under greenschist conditions.

LS06 : WEpo02 : PO
Episodic Retrograde-Prograde Metamorphism during Subduction of Oceanic Crust: An Example from High-P Blocks of a Serpentinite Melange, Cuba

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MORB-derived metamorphic blocks enclosed within the northern serpentinite melange from Cuba have followed clockwise P-T paths whose prograde sections intersected the epidote blueschists and amphibole-eclogite facies (450-600ºC; > 15 kbar), while their retrograde sections passed through the albite-epidote amphibolite and greenschists facies (<500ºC, <10 kbar). These paths can be related to a protracted geologic history with (southward ?) subduction of the proto-Caribbean oceanic lithosphere during pre-Albian times (> 103-118 Ma, Ar/Ar and Rb/Sr data), its accretion to the overriding plate mantle and the formation of blocks within the serpentinite melange, and the final exhumation during the Late-Cretaceous to Eocene collision of the Cretaceous volcanic arc with the North-American and Yucatán margins. Detailed chemical and XR mapping analyses of minerals have revealed,a complex metamorphic history during prograde metamorphism at high pressure. Garnet preserves oscillatory zoning, characterized by several retrograde zones within its prograde growth zoning. These oscillations formed through episodic garnet growth and dissolution events taking place previous to the formation of peak-T garnet rims. Similarly, prograde growth zoning of calcic to sodic-calcic amphibole is disturbed by retrograde concentric zones formed previous to the growth of peak P-T amphibole, at P above the eclogite-amphibolite transition. We interpret these types of zoning in high pressure minerals as the result of episodic changes in intensive variables P-T-mH_2O during subduction. The paired retrograde-prograde nature of the oscillations in prograde garnet and amphibole suggests that episodic cooling-heating events occurred during the downward travel of the subducting slab, probably accompanied by fluid infiltration. These retrograde/prograde episodes are considered to be caused by "oscillatory kinematics" during the subduction/accretion history of the blocks. These oscillations cannot be explained within the framework of a steady-state distribution of isotherms for a subduction. Instead, they can be explained if the plate-contact movement is distributed within a thick fracture zone, where differential movement of slices of the lower and upper plates are possible. Another possible mechanism is episodic retreat-advance events of the subduction zone, with episodic extension-contraction of the fracture zone and decrease-increase in T and P of the tectonic slices. If applicable to the ancient Caribbean subduction system, these events may have been caused by the onset of development of an opposite-facing (northward?) subduction zone below the Cretaceous volcanic arc of Cuba during the early Cretaceous.

LS06 : WEpo03 : PO
Exhumation of HP Rocks in a Serpentinized Mantle Channel: Evidence from Geochemical Study of Serpentinites (Tso Morari Dome, E Ladakh)

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The processes of exhumation of high to ultrahigh pressure rocks remain a major geodynamical problem. The Tso Morari eclogitic dome in Ladakh (NW Himalaya) as many other eclogitic massifs is underlined on its eastern border by a normal detachment zone where serpentinite lenses and partially hydrated peridotites have been founded. The association of high-pressure rocks and serpentinites suggests the possible role of serpentinites in the exhumation of ultra-high pressure rocks. In order to evaluate this role, geochemical analysis were carried out on these serpentinites. Bulk rock composition, chromite chemistry and platinoid group elements show that the serpentinites have a dunite or harzburgite origin from mantle residue. This refractory nature indicates their derivation from mantle wedge (Guillot et al., 2000). The present day isotopic Nd composition on five out of six samples show a strong linear correlation (r=0.985) with the inverse Nd concentration (1/Nd ppm), which suggests a two component mixing as REE source. The low concentration mixing end member (<0.04 ppm Nd) is superchondritic (positive eps(0)), in line with LREE depleted mantle characteristics. The higher concentration end member shows Nd isotopic compositions typical for Precambrian continental crust (eps(0) below -19). However its concentration (ca. 0.15 ppm Nd, still very low compared to continental crust with 30-40 ppm) as well the chemistry of these rocks are at odds with a simple bulk addition of continental material. Rather, the high water-rock ratios allowed for sufficient Nd (i.e. REE) transport to overprint the original mantle signatures of these rocks. The dewatering fluid origin could be either the sediments lying on the oceanic slab or the continental slab. Whether this overprinting took place at depth in the subduction zone or through later fluid circulation during the exhumation cannot be resolved from the Nd data. The occurrence of metamorphic forsterite associated with talc and antigorite without diopside and antophyllite in serpentinites suggests that the serpentinization and eclogitization took place under similar conditions (580°C - 20 kbar) at great depth. Thus, we propose that the serpentinites were formed by hydration of the mantle wedge as a result of dewatering during the subduction of the Tethys oceanic slab and the Indian slab. This process may well have produced the observed Nd characteristics, but additional later fluid interaction, during the exhumation of the Tso Morari cannot be excluded. The geochemical, isotopical and petrological studies of these serpentinites suggest the existence of an hydrated mantle above the subduction during the exhumation of the Tso Morari massif. The serpentinites could have provided a mechanically weak zone at the interface between the subduction plane and the rigid mantle wedge and then facilitated exhumation of the HP rocks by acting as a lubricant.

LS06 : WEpo04 : PO
Eo-Alpine Andalusite in the Schneeberg Complex (Eastern Alps, Italy/Austria): Constraining the P-T-t-D Path during Cretaceous Metamorphism

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The metamorphic evolution of the Upper Austroalpine Schneeberg Complex (SC) in the southern Oetztal basement comprises high-pressure metamorphism with subsequent static (re)crystallization (Konzett & Hoinkes, 1996). This metamorphic event is correlated with eclogite facies metamorpism in the SE Oetztal crystalline basement S of the SC. New findings of andalusite in the 'Monotone Serie' (garnet micaschists forming the core of the SC synform) allow to constrain the metamorphic evolution after the pressure peak. An interdisciplinary (petrological, geochronological and structural) investigation was performed to determine the tectonometamorphic evolution of the SC.

A continuous succession of three mineral (re)crystallisation phases (K1, K2, K3) is recorded by (micro)structures and compositional zoning of minerals. K1: Idioblastic grt1 is relatively Ca-rich, with slightly increasing X_{Mg} (=Mg/(Mg+Fe^{2+})) from core to rim. Grt1 grew synkinematically to D1 (mylonitisation and penetrative microfolding). Inclusions are fine-grained Qtz, Ilm, Mt and rare Ab1 and St1. The matrix contains phengitic Wm1, Pg, Qtz, Bt1, Ab1, Chl, Ky1 and Ilm. K2: All K2 mineral phases grew synkinematically to D2, a penetrative folding event with NW to WSW dipping fold axes. Grt2 formed idioblastic rims around Grt1, with decreasing Ca-content and X_{Mg}-ratio. A second Mn maximum reflects Chl-breakdown. The matrix consists of Ms2 (pure muscovite), Qtz, Bt2, Pg, Pl2 (with increasing Ca-content) and Ilm. Coarse-grained Ky2 and St2 grew due to Pg-breakdown. K3: K3-minerals formed syn- to postkinematically to D3. Large-scale tight upright S-vergent D3-folds have E-W-striking axes and an intense axial plane cleavage S3. Idioblastic Grt3 rims display again increasing X_{Mg}, decreasing Ca-content. Coarse-grained Bt and Pl as well as medium grained St3 and Chl crystallized in the matrix. Contemporaneously cm-sized andalusite grew by Pg-breakdown, as indicated by reaction rims of Pl between andalusite and matrix.

New data concerning the pressure peak correlate with the results of Konzett & Hoinkes (1996), who gave 580-600°C/0.8-1 GPa. Mineral zonations indicate decreasing pressure during K2. The coexistence of St, Bt, Grt and andalusite during K3 requires temperature conditions higher than 540°C at low pressure.

0.5 - 1 cm sized garnet grains were used for Sm-Nd geochronology. The Fe-poorer fraction (=Grt1) yielded 94.1 ±2.2 Ma, the Fe-richer fraction (= Grt 2 and 3) 92.7 ±1.2 Ma. The period of garnet growth therefore ranges between 96.3 and 91.5 Ma, constraining an eo-Alpine age for the metamorphic peak and the major deformation phases. Eo-Alpine cooling below 300°C is indicated by a Bt-whole rock Rb-Sr age at 79.5 ±0.8 Ma, derived from the same sample.

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LS06
Blueschist to UHP Metamorphism and Back Again

LS06 : WEpo05 : PO
Exhumation of Alpine Eclogites of the Eastern Alps: Constraints from Structural and Metamorphic Geology

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Alpine eclogites within the Eastern Alps are generally associated with rocks of continental lithosphere, while eclogites that are associated with oceanic assemblages are restricted to minor exposures. Such eclogites are exposed within the Penninic units of the Tauern Window (TW) and The Austroalpine Nappe Complex (ANC). (1) In the Eclogite Zone (EZ) of the central southern TW eclogites and associated high pressure metasediments are intercalated between Penninic basement units (Venediger Nappe (VN) in the footwall and the Rote Wand-Modereck Nappe (RWN) in the hangingwall). The EZ experienced a polyphase metamorphic evolution, described by a b-shaped P-T path. The EZ and external parts of the RWN were affected by eclogite facies metamorphism (20-22 kbar, 600-620°C) (M1). However, pressures of only 12 kbar are documented within the VN. The Penninic nappe complex was subsequently affected by high pressure blueschist facies metamorphism (7-12 kbar, ca. 450° C) (M2), and by upper greenschist to lower amphibolite facies metamorphism (M3). Nappe stacking postdated subduction-related M1, and was contemporaneous to M2. M2 overprint of the eclogites indicates refrigeration by a cold subducted lithospheric slab during exhumation in order to avoid re-equilibration during prolonged periods of static heating. Long-term preservation of high-pressure/low-temperature assemblages requires such a mechanism. This evolution is compatible with an emplacement model similar to corner flow. However, the EZ behaved as a coherent unit during its emplacement, which suggests thrusting as emplacement mechanism. Anyhow, the M2 overprint requires the emplacement of the eclogite facies assemblages while heating was delayed within an active subduction channel. (2) Within the Koralm/Saualm unit of the ANC most eclogites are eclogitic mylonites documenting plastic deformation of omphacite and garnet. The meso- and macroscale structures indicate an overall extensional regime, possibly related to a large-scale SE-directed ductile low-angle normal shear zone. The eclogites are associated with migmatite-like structures and are intruded by pegmatites. This indicates decreasing pressure, but isothermal or even increasing temperature conditions during exhumation.

LS06 : WEpo06 : PO
Neoproterozoic Metagranite did not Experience Ultrahigh-Pressure Metamorphism from Bixiling, Dabie Shan, Central China

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There has been much debate on whether or not the coarse-grained granitic gneisses closely associated with eclogites have experienced ultrahigh-pressure metamorphism in the Dabie Shan, central China (Liu et al., 1999). The recent discovery of petrographical and mineralogical evidences reveal that a metagranite with weak gneissosity, 100 m west of the Bixiling coesite-bearing eclogite (Chavagnac & Jahn, 1996), well preserves the primary igneous assemblage of biotite (Ti>0.13) + zoned plagioclase (An=12-16) + microcline (Ab>4) + quartz + allanite, which were followed by overprint of epidote-amphibolite facies metamorphism characterized by biotite (Ti<0.1) + phengitic mica (Si=3.16-3.30) + epidote (Ps=0.16-0.28) + albite (An<10) + K-feldspar (Ab<0.1) + quartz + amphibole assemblage. The most important feature of the granite is a large amounts of relics of euhedral plagioclase phencryst up to 3-10 mm, in which have partly transformed into unoriented fine-grained aggregate of epidote + white mica + albite, rather than jadeite + zoisite + quartz assemblage, as it occurring in the high-pressure metagranite from the Western Alps (Compagnoni & Brunello, 1973; Oberhansli et al., 1985; Koons et al., 1987; Fruh-Green, 1994). This implies that this rock has never experienced ultrahigh-pressure metamorphism. A single zircon U-Pb dating gives a concordia age of 725 Ma, in acord with that (712 Ma) of other granitic gneisses from the Dabie Shan, representing the crystallization age of the granite. According to the development of intense mylonitization between metagranite and its country rocks, it is considered that a large scale tectonic juxtaposition of ultrahigh-pressure rocks and the Yangtze continental crust mainly composed of granitoids occurred at high crustal level during exhumation.

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LS06 : WEpo07 : PO
Ultrahigh-Pressure Metamorphism from the Rhodope Metamorphic Province, Northeastern Greece: A Preliminary Report on a New Discovery

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The Rhodope Metamorphic Province (RMP) is one of the major geotectonic units of northern Greece that also extends northwards into eastern former Yugoslavia and southern Bulgaria. It mainly comprises amphibolites, often enclosing eclogite bodies, amphibolite-facies para- and orthogneisses and schists, in places migmatitic, and marbles, all invariably intruded by large granitic masses. The RMP has traditionally been viewed as a stable continental block, consolidated in Precambrian to Palaeozoic times. Recent structural and petrologic work has nevertheless shown the RMP in fact to be a complex of Cretaceous synmetamorphic nappes characterized by south- to south-westward stacking and associated with both coeval and subsequent extension in an Alpine active margin setting (Ricou et al., 1998, Dinter, 1998, Barr et al., 1999).

Mposkos and Krohe (2000) have further subdivided the RMP into discrete entities on the basis of exhumation age criteria for the various metamorphic rocks. Thus, the earliest exhumed and structurally uppermost entity is the Kimi Complex (65-48 Ma), followed by the Sidironeron Complex (42-30 Ma), and then by the Pangaeon Complex (26-8 Ma) which also forms the well-defined Rhodope metamorphic core complex.

We report here for the first time UHP indicators discovered in crustal rocks belonging to the Kimi and Sidironeron Complexes as exemplified above. With regard to the former, UHP indicators include: i) polycrystalline quartz (PCQ) aggregates included in garnet from amphibolitized eclogites, ii) needles of rutile exsolved inside sodic garnet porphyroblasts in metapelites, iii) relicts of high-Al titanite, rutile, zoisite and quartz inclusions preserved in garnet from highly retrogressed eclogite, and iv) minute carbon cubes and octahedra included in garnet porphyroblasts from metapelites. The presence of PCQ is attributed to the breakdown of pre-existing coesite and constrains metamorphic pressures to a minimum of 2.7 GPa at 700°C, whereas the exsolution of rutile needles from garnet has been interpreted - for similar to the Rhodope rocks - to reflect a high-Ti garnet precursor that was stable at pressures greater than 7 GPa (Ye et al., 2000). Thermodynamic calculations for the reaction: Grs+Rt+Qtz+W=Ttn+Zo furthermore suggest original pressures in the vicinity of 3.5 GPa at 700°C for the retrogressed eclogite.

As for the Sidironeron Complex, UHP indicators include PCQ aggregates included in garnet from garnet amphibolites and, most importantly, minute carbon octahedra included in garnet porphyroblasts in metapelites. Graphitized diamonds have previously been documented from crustal rocks forming the westernmost extension of Rhodope thrust units in central Macedonia, northern Greece (Kostopoulos et al., 2000). The mere presence of former diamonds dictates metamorphic pressures in excess of 3.4 GPa at 700°C for the host rocks. We conclude that the crustal protoliths of the RMP were subducted to depths ranging from 80 to over 200 km.

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LS06 : WEpo08 : PO
Exhumation of UHP Rocks in SW Norway – Allochthonous Western Gneiss Region Models

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Restoration of the Neoproterozoic to early Palaeozoic rocks in the external imbricate zone (Osen-Røa Nappe Complex) of the Scandinavian Caledonides in SW Norway, in combination with sediments (Gjevilvatnet Group) of similar age lying unconformably on the Western Gneiss Region (WGR) basement shows that the WGR has been laterally displaced by several hundred kilometres. In pre-orogenic times, the WGR formed a topographic high (Møre Plateau) on the Baltoscandian passive margin between the Hedmark Basin and the Vågåmo Sea. Basement rocks in external part of the Valdres Nappe formed the internal part of the Møre High and the Beito-Vang-Atnsjoen-Spekedalen Window Basement the external part. The Jotun Nappe came from Jotunøya, a Baltica affinity micro-continent, separated from the Møre Plateau by oceanic crust of the Vågåmo Sea. Burial (subduction) and exhumation of the UHP rocks in the WGR can be compared with the Chemenda et al. type model, although channel-flow (body forces) may have added to the buoyancy forces in exhuming the rocks. W-directed subduction of the Vågåmo Sea pulled the WGR down; at UHP conditions the WGR detached from its lithospheric mantle substrate and began to exhume, initiating the Mode I top-to-hinterland shear zone at the roof of the WGR. The difference in Caledonian metamorphic grade between the coastal parts of the WGR and the Beito-Vang-Atnsjøen-Spekedalen Window Basement, when compared to the geometry of the Chemenda et al. modeled continental subduction zone suggests c. 50 km shortening between the coastal WGR and the Beito-Vang-Atnsjøen-Spekedalen Window Basement; this is used to constrain the minimum original size of the Møre Plateau. Peridotites downtruded into the WGR from Baltica affinity crust during subduction and exhumation were derived from Jotunøya; there is no need to invoke a double continental subduction. During exhumation, the WGR over-rode the trailing edge of the Hedmark Basin, initiating imbrication of the Osen-Røa Nappe Complex. Autochthonous relicts of the Hedmark have been seismically imaged below the WGR. During this essentially horizontal transport, the hot and relatively weak WGR may have been squeezed between cold, relatively strong hanging- and footwall units and extruded towards the foreland, allowing the later part of Mode I top-to-hinterland faulting to be contemporary with footwall imbrication. The 50 km shortening between the WGR and the Beito-Vang-Atnsjøen-Spekedalen Window Basement may have occurred at this time or earlier, during exhumation. During this Mode I extension, movement was more 'bottom-to-east' than 'top-to-west', as Laurentia continued to converge on Baltica. Subsequent Mode II, relatively high-angle, extensional shear-zones may have been related to absolute plate divergence, with both synthetic and antithetic shears forming within and around the WGR.

LS06 : WEpo09 : PO
Metamorphic Rates Attending Continental Collision, Bergen Arcs, Norwegian Caledonides

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Metamorphic P-T path is used in combination with patterns of compositional zonation of eclogitic garnet to evaluate the metamorphic rates experienced by the Bergen Arc's eclogites during continental collision. Calculated metamorphic rates are used in turn with available radiometric Ar-Ar dates to constrain the age of the HP metamorphism event.

The eclogitic samples studied (courtesy of M. Erambert and H. Austheim) are composed of garnet + omphacite + kyanite + quartz + phengite (Na-rich) + amphibole + clinozoisite + rutile. Garnet shows strong compositional heterogeneities characterized by a marked concentric growth zoning (granulitic core and eclogitic rim) together with thin (100 µm large) linear zoning patterns (stringers) that formed during HP metamorphism (see Erambert and Austhreim, 1993). Detailed petrologic study indicates that the eclogitic rocks equilibrated at a pressure of 1.9 GPa for a temperature of about 730°C and were subsequently retrogressed under PT conditions of 0.6 GPa and 500°C.

Calculated paragonite = jadeite+kyanite+H_2O and dolomite+quartz = diopside+CO_2 reactions indicate that the concentration of water in the metamorphic fluid must have been of about $XH_2O = 0.5$ to prevent partial melting of the rock. Diffusion modeling of the stringer zoning patterns using the mathematical treatment of Perchuk and Philippot (2000) indicates that the timescale of retrogression from 730 to 500°C is less than 0.5 Ma. Assuming that decompression and cooling occurred regularly along the retrograde path allows calculating exhumation and cooling rates of the order of 20 cm/y and 1000°C/Ma, respectively.

The age of the eclogitic event remains controversial. Available dates for the eclogitic stage range between 450-462 Ma (U-Pb), 421-442 Ma (Sm-Nd) and 507 Ma (Rb-Sr). With regards to the early cooling stage, hornblende yielded consistent Ar/Ar plateau ages of 448 to 455 Ma (Boundy et al., 1996). Information on closure temperature (Tc) of isotopic systems can be extracted from the analytical solution of Dodson (1973) using appropriate sets of experimentally-determined diffusion data and calculated cooling rates. For example, calculated Tc for Ar in hornblende is about 570-650°C. Considering the extreme rates of cooling between 730 to 500°C, it implies that the Ar-Ar dates should be similar to the age of eclogitic metamorphism. This interpretation is in agreement with the U-Pb ages.

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LS06 : WEpo10 : PO
High-Pressure Conditions in the Quartzo-Feldspathic Gneisses Hosting the Mafic Eclogites of the Lanterman Range (Antarctica): Evidence for a Common P-T Evolution

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In the Lanterman Range, northern Victoria Land, three metamorphic complexes have been distinguished (Talarico et al., 1998): the Edixon Metamorphic Complex (EMC), the Bernstein Metamorphic Complex (BMC) and the Gateway Hills Metamorphic Complex (GHMC). The main feature of the GHMC is the presence of mafic eclogites occurring as metric to centimetric boudins within a sequence of quartzo-felspathic gneisses and minor quartzites. As is typical of high-pressure terrains, in the host gneisses the evidence of high pressure minerals are often lacking. However, detailed microstructural, mineralogical, petrological and geochronological investigations reveal a complex metamorphic evolution for the GHMC host gneisses, whereas a simple amphibolite facies evolution was detected in both adjoined BMC and EMC. Macro and microtextural observations in the GHMC reveal, on centimetre scale, the even rare presence of interlayering of mafic eclogite and gneisses with sharp contacts suggesting a pristine contact. Garnet from GHMC shows three contrasting textural and compositional features: i) large prograde poikiloblast with high Fe/Mg ratios (24 - 5.6 from core to rim) and carrying plagioclase, muscovite and biotite inclusions; ii) small euhedral prograde grains (Fe/Mg from 2.39 to 1.98) with the highest XCa content (0.35-0.24) and rare paragonite inclusions; iii) anhedral retrograde grains (Fe/Mg from 1.33 to 3.22) partly replaced by a symplectitic association consisting of plagioclase + biotite. White mica in GHMC is present with two microtextural and compositional features: i) large flakes of 3T phengite (Si δ3.3-3.4) partly replaced by a symplectitic association of plagioclase + biotite; ii) thin 2 M muscovite (Si δ3.1-3.2) along the main foliation associated with biotite. In situ laserprobe $^{40}Ar/^{39}Ar$ data on white micas and biotite show that the oldest age (up to δ496 Ma) are only preserved within the 3T phengite, whereas ages around 480 Ma have been detected in biotite from the GHMC and in both biotite and 2 M muscovites of the BMC and EMC. It is worth of note that the oldest muscovite ages overlap with the estimated age of the eclogite stage in the mafic eclogites (δ500 Ma - Di Vincenzo et al., 1997). These data suggest that the GHMC host gneisses and the associated mafic eclogites shared a common metamorphic evolution. Petrological data together with conventional geothermobarometry and experimental petrogenetic grid, indicate for the GHMC gneisses a clockwise P-T loop with an initial stage at 450-550° C and 6-8 kbar; an eclogite stage at 750-850°C and pressure between 15 and 25 kbar; finally conditions of 650-750° C and 5-9 kbar resulted for the retrograde amphibolite stage. In contrast, a medium - pressure evolution (metamorphic peak at 730°C and 8-9 kbar) and a low - pressure evolution (metamorphic peak at 700°C and 5 kbar) was reconstructed for the BMC and EMC, respectively.

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LS06 : WEpo11 : PO
Alpine Metamorphic Evolution of Corio and Monastero Metagabbros (Sesia-Lanzo Zone): An Example of Prograde Evolution and Development of Chloritoid-Bearing Eclogitic Assemblages in Basic Rocks

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In most metamorphic conditions intrusive rocks tend to deform along discrete high-strain zones within wich little-deformed domains reequilibrate, depending on the velocity of tectonic processes compared to that of metamorphic re-equilibration. The Corio and Monastero matagabbros outcrop in the southern part of the Sesia-Lanzo zone. After a complex pre-alpine metamorphic evolution (Rebay and Spalla, submitted, Lithos) these rocks extensively re-equilibrated under high-pressure conditions (glaucophane garnet epidote chloritoid omphacite) during Alpine orogeny.

A series of corona textured samples displaying an increasing percentage of alpine high pressure metamorphic transformation, allowed the study of the different steps leading to the formation of a sequence of different high pressure assemblages. The assemblages developed successively at increasing pressures and vary according to the microdomain in which they develop (original mafic mineral or plagioclase). Mafic minerals are commonly transformed into amphibole, with a high glaucophanic substitution. Zoned amphiboles composition records continuously the changes of metamorphic conditions: horneblendic cores display a first tremolitic rim followed by Na-Ca amphibole and finally by a glaucophanic rim. In plagioclase microdomain paragonite epidote and then jadeite epidote, glaucophane and chloritoid develop. Mg-garnet grows after pre-alpine chlorite veins. A zoned-garnet corona develops between relic anortitic plagioclase and pre-Alpine chlorite veins.

In the same microdomains (original igneous minerals) different high pressure assemblages develop depending on the different type of pre-eclogitic transformations undergone by adjacent gabbro portions. The chemical domains where re-omogeneisation during prealpine hydration was achieved are the ones where chloritoid-bearing assemblages develop. On the contrary, samples where pre-eclogitic hydration did not occur, develop classic garnet corona between adjacent microdomains still preserving igneous-minerals relics, or develop omphacite-bearing assemblages.

Thermobarometric calculations and mineral assemblages stability allowed the reconstruction of a prograde path, from low greenschist-facies (T<400°C, P<4 kb) to eclogite-facies conditions (T 500-600°C, P 1.8-2.1 GPa). This prograde evolution was followed by a retrograde evolution, in which part of the metagabbros re-equilibrated under greenschist-facies conditions during their exhumation.

Rebay, G. & Spalla, M.I., *submitted, Lithos*

LS06 : WEpo12 : PO
Recognizing and Mapping a UHP Metamorphic Terrain: The Southern Dora-Maira Massif (Western Alps)

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In the southern Dora Maira Massif, Western Italian Alps (Chopin, 1984), a stack of crustal slices with the same lithologic association recrystallized at different high-pressure conditions during the Alpine orogeny (Compagnoni et al., 1995). However, since the high-pressure mineral assemblages are largely obliterated by greenschist-facies minerals, it is very difficult to distinguish and map the different units.

By combining field work and data from a detailed petrographic and petrologic study in a key area of about 40 sq km, a new 1:10.000 scale geological map and a 1:50.000 scale interpretative map were carried out. Four tectonic units were distinguished, which are characterized by different early-Alpine metamorphic peak.

• The Brossasco-Isasca Unit (BIU), characterized by early-Alpine coesite eclogite-facies (UHP) recrystallization, and composed of two lithostratigraphic complexes. The monometamorphic complex mainly consists of orthogneiss with relics of late-Variscan granitoids and layers of pyrope-bearing whiteschist. The polymetamorphic complex consists of paraschist with relics of Variscan amphibolite-facies mineral assemblages, marble, eclogite, and phengite orthogneiss. Relics of metagranitoids with xenoliths of paraschist indicate that the BIU is a coherent portion of continental crust.
• The San Chiaffredo Unit, a small tectonic slice composed of a Variscan continental crust similar to that of the BIU, which suffered quartz eclogite-facies (HP) early-Alpine recrystallization.
• The Rocca Solei Unit, a tectonic slice composed of Variscan continental crust similar to that of the BIU, which suffered early-Alpine quartz eclogite-facies recrystallization. The polymetamorphic basement, which includes garnet-chloritoid micaschist with relics of pre-Alpine staurolite and minor eclogites, was intruded by granitoids converted to augen gneiss during the Alpine orogeny.
• The Pinerolo Unit, mainly consisting of graphitic micaschists which locally contain chloritoid and garnet with a peculiar compositional zoning. The interlayered metabasics indicate an epidote-blueschist facies early-Alpine recrystallization.

Among the criteria used to distinguish the UHP unit from the juxtaposed HP units, the most important ones are the following (Compagnoni and Rolfo, 1999):

• presence of index minerals: coesite instead of quartz (as inclusions in garnet, clinopyroxene, kyanite and zoisite); pyrope-rich garnet with composition close to the pure Mg end-member; ellenbergerite as inclusions in garnet; nearly pure glaucophane in rocks compositionally close to NMASH system (Kienast et al., 1991); absence of magmatic quartz in the less deformed metagranites;
• peculiar paragenesis: pyrope + quartz/coesite in whiteschist; kyanite + jadeite in orthogneiss; Ca-rich garnet + rutile + phengite in orthogneiss; kyanite in eclogite; Fe-rich garnet + kyanite in metapelite;
• minerals composition and nanostructure: high celadonite (Si > 3.50 a.p.f.u.) and low paragonite (< 10 mol%) contents in phengite; talc + quartz exsolution lamellae in 3T-phengite.

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LS06 : WEpo13 : PO
Exhumation of High Pressure Rocks in Greece: Preliminary Results

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Termination of high pressure metamorphism in the Aegean is diachronous and shows a temporal shift of exhumation from ~54 Ma in the Pelagonian Zone to ~ 40 Ma in the Cyclades and ~20 Ma in Crete (Lips et al. 1999). Late orogenic ductile extension contributing to exhumation of high pressure rocks occurred in the Aegean since the Lower Miocene (Gautier et al. 1993). Structural data from a transect parallel to the dominant tectonic transport is correlated to the metamorphic history and will be temporally constrained by argon geochronology to constrain the exhumation history. Along this transect in the Hellenides, high pressure rocks are characterised in the western part (e.g. the Peloponnese) by minerals as glaucophane, Mg-chloritoid and Mg-carpholite while in the eastern part (the northern Cycladic islands) these are characterised by lawsonite (pseudomorphs), glaucophane, epidote and garnet. Peak metamorphic conditions experienced by the exposed basement rocks are in the order of >15 kbar and >450°C (Schliestedt, et al. 1987; Bröckner, et al. 1993)with extensive retrogression under greenschist conditions occurring in both regions.

Ductile to semi-brittle tectonic transport direction varies in strike from 070-130 on the Peloponnese to 010-100 in the Cyclades and is indicated with stretching and mineral lineations of mainly quartz and glaucophane. Kinematic indicators such as shearbands, minor rotated clasts and asymmetrically stretched quartz veins show that the tectonic transport direction changes from dominantly top to the W-SW in the Peloponnese, Kea and Syros to dominantly top to the NE in Andros and Tinos.

Late conjugate brittle faults trending 340-350 have crosscut the Peloponnese most likely causing minor rotations. Brittle indicators as tension gashes, faults and fractures are trending ±320 subvertically in the Cyclades overprinted by a later trend. This marks a change in direction of extension from ENE-WSW to N-S.

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LS06 : WEpo14 : PO
Evolution of an Orthogneiss Suite during UHP Metamorphism and Exhumation (Dabie Shan, E-China): Petrological and Geochronological Constraints

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In the Dabie Shan and Sulu Complex and in many other UHP metamorphic terranes, peak metamorphic conditions are only preserved in boudins of mafic eclogites or calcsilicate rocks, whereas the enclosing gneisses generally record lower PT conditions. Such rocks recording substantially different maximum P-T conditions (i) could be juxtaposed by tectonic processes during the exhumation or (ii) might result from a different degree of overprinting during exhumation. However, to establish a dated PT-path from a rock volume, that was subducted to extreme depths and exhumed again, it is crucial to investigate rocks that evidently experienced a common history of subduction and exhumation. We investigate such rock samples from an orthogneiss suite located near Yehe ranging from a jadeitic cpx-bearing UHP dioritic gneiss to adjacent retrogressed medium grade gneisses by means of microstructural, petrological, and isotope analyses. We aim at dating minerals from different stages of the PT-path in order to reconstruct the tectonic-metamorphic evolution during exhumation of UHP terranes. This gneiss suite depicts a large segment of the PTtd history, from the UHP stage to juxtaposition into a mid-crustal level. The dioritic gneisses preserve UHP mineral assemblages exceptionally well. Zoisite-clinopyroxene(jadeite)-quartz forming pseudomorphs after plagioclase sigma-clasts reflect peak PT conditions. Using the garnet-omphacite-phengite geobarometer and the garnet-clinopyroxene geothermometer 33-35 kbar at 680°C were estimated. Various mineral reactions record successive exhumation episodes. A late deformation event during decompression and emplacement of rocks to mid crustal level is recorded by the syn-mylonitic assemblage biotite-epidote-albite-rich feldspar-quartz(±white mica) of a biotite gneiss. There are distinct variations of geochronological data that appear to depend on the degree of overprinting during the syn-decompression deformation. Rb-Sr geochronology from mineral phases (cpx, phg) and whole rock samples of the dioritic UHP gneiss yields 220 to 218 (±3) Ma, interpreted as a minimum age for the UHP stage. A second sample of the UHP gneiss yields 243±12 Ma (phg Si content 3.4 p.f.u.), matching already published data (e.g. Hacker at al. 1998). Data from the orthogneiss suite equilibrated during deformation at lower pressure show a Rb-Sr white mica age of 213±2 Ma interpreted as the approximate age of the medium pressure mylonitisation. The Rb-Sr white mica system has the potential to date various stages of the PT evolution of rocks, if (i) the dated materials can be clearly connected to a structural event defined by microstructural analysis and (ii) there is evidence for initial isotopic homogeneity among the phases used for age determination.

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LS06 : WEpo15 : PO
Blueschist-Facies Metamorphic Overprint in the Continental Crust Rocks from the Bocca di Tenda Gabbroic Complex (Northern Corsica)

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The post-Variscan gabbroic complex of Bocca di Tenda crops out in the southern portion of the Tenda crystalline massif, which is a wide basement fragment of the paleo-European continental margin. The gabbroic complex is enclosed by coarse-grained granitoids displaying a gneissic fabric developed in response to the Alpine orogenic event. Little is known about the Alpine metamorphic transformations in the Tenda crystalline massif. Gibbons and Horak (1984) showed that deformed granitoid rocks from the north-eastern portion of the Tenda crystalline massif, at the contact with adjacent high-pressure ophiolite nappes (Schistes Lustrés), are characterized by blueschist-facies metamorphic assemblages.

The primary features of the Bocca di Tenda gabbroic complex are well preserved, as the Alpine recrystallization is mainly restricted to ductile-shear zones (metre- to decametre-scale width). The gabbroic complex includes undeformed granitoid bodies, interpreted to be remnants of the original country rocks (Ohnenstetter and Rossi, 1985), and is crosscut by dykes of basaltic dolerite and porphyritic rhyolite. In the Alpine shear zones, rocks display gneissic to mylonitic fabrics and substantial metamorphic recrystallization.

Granitoids and Fe-rich mafic rocks show the metamorphic growth of crossite + epidote + phengite + albite + titanite (±chlorite ±quartz ±K-feldspar ±andradite-rich garnet). The metamorphic assemblages of Mg-rich mafic rocks are characterized by the absence of crossite and the occurrence of actinolite. Deformed rhyolites develop Na-clinopyroxene + Fe-riebeckite + quartz + albite + K-feldspar + phengite + titanite. In particular, Na-clinopyroxene, Fe-riebeckite and phengite commonly occur as coronas around igneous aegirine and arfevdsonite. The unusual metamorphic assemblage observed in the ryholites reflects the peralkaline composition of these rocks, which are characterized by anomalously high contents of Na_2O, K_2O and SiO_2, and negligible CaO and MgO.

The development of Na-clinopyroxene (up to Jd50), quartz and albite in the rhyolites suggests that the metamorphic crystallization occurred under pressure conditions of 0.9-1.0 GPa. Such pressure estimates are consistent with the high contents of celadonite substitution in the phengites (Si up to 3.6 apfu). The stability of epidote, chlorite and albite in mafic rocks constrains crystallization temperatures in the range 350-500°C. Such pressure/temperature values are similar to those estimated for the metamorphic event that affected the deformed granitoids cropping out at the north-eastern edge of the Tenda crystalline massif (Gibbons and Horak, 1984). The high-pressure metamorphic recrystallization is most likely widespread in the Tenda crystalline massif, thus implying that such a fragment of the paleo-European upper continental crust was involved in the Alpine subduction system.

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LS06 : WEpo16 : PO
Identification of the Tectono-Metamorphic Units: Deformation Gradients and Rate of Metamorphic Transformation, an Example from the Formazione di Pietra Rossa and Formazione di Cima Rovaia (Austroalpine Units, Central Alps, Italy)

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Tectonic events consequent to ancient changes of crustal thickness and to thermal perturbations imprinted signatures on metamorphic tectonites. At the mountain belt scale, thickness variations are envisaged to result from mechanically discontinuous translations of discrete crustal elements (i.e. tectono-metamorphic units) accompanied by large scale partitioning of deformation. In many metamorphic belts, extent, degree and timing of metamorphic re-equilibrations and fabric changes are only sporadically known and consequently the understanding of the thermo-mechanical record and the tectonic subdivisions persist highly interpretative, and mainly based on lithostratigraphic grounds or on “metamorphic field gradients” (England & Richardson 1977; Spear et al. 1984). It has been shown that the regional distribution of dominant metamorphic imprints does not necessarily correspond to the “metamorphic field gradient” and therefore this concept cannot be used to distinguish tectono-metamorphic units in terrains that underwent polyphase deformation and metamorphism without considering the effect of strain heterogeneity (Spalla et al., 2000). Different metamorphic imprints can dominate within a unique tectono-metamorphic unit, or the same dominant metamorphic imprint can occur in different tectono-metamorphic units, characterised by contrasted P-T-d-t evolutions. The structural correlation criteria (Johnson & Duncan, 1992; Williams, 1985), supported by microstructural analysis devoted to reconstruction of P-T-d-t paths (Johnson & Vernon, 1995), have been applied to Alpine polymetamorphic teconites. The resulting map, structurally and petrologically oriented, includes graphical representation of: i) rotation, dislocation, and superposition of structures, ii) incompatibilities of metamorphic assemblages related to planar fabrics, iii) strain variations (coronites, normal S/L tectonites, mylonites) imposed under the same metamorphic stage.

The application of this method to the central Austroalpine demonstrates that, during Alpine metamorphism, this basement was a single tectono-metamorphic unit, in which a deformation gradient controlled the distribution of metamorphic transformations. This single tectono-metamorphic unit includes two stratigraphic units of the literature (Formazione di Pietra Rossa and Formazione di Cima Rovaia), which correspond respectively to two diachronous dominant structural, and therefore metamorphic, imprints.

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Thursday AM Session

LS06 : THam01 : G0
The Garnet Isograd in the Blueschist-Facies Metapelites of the Ile de Groix (Armorican Massif, France): A Record of Ductile Thrusting during Exhumation

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In the Variscan belt (western Europe), the best exposure of blueschists is the Ile de Groix (Armorican Massif, France). A regional-scale zonation of the blueschist-facies metamorphism has been described, with the identification of a garnet isograd. Its petrologic and tectonic significance is the main topic of this work. Mineral assemblages in the metapelites from the Ile de Groix allow to distinguish two main units, an upper unit characterized by (i) high modal proportions of garnet, (ii) higher grain size, (iii) rarity of graphite-bearing layers and (iv) one single, although composite, foliation S1 and a lower unit defined by (i) low modal proportions of garnet, (ii) smaller grain size, (iii) abundance of graphite-bearing layers and (iv) a pervasive crenulation cleavage S2. In both units, garnet zonation record the prograde part of a single metamorphic cycle. In the upper unit, coexisting garnet and chloritoid are more magnesian and less manganiferous than in the lower unit. The upper unit is also distinguished from the lower unit by the presence of garnet-chloritoid-glaucophane assemblages. Bulk-rock chemical analyses of the metapelites from both units show no systematic differences, thus indicating that the differences in modal proportions and chemistry of coexisting minerals is due to a difference in P-T conditions. The P-T history of the blueschist-facies metapelites is estimated using a simplified petrogenetic grid in the NFMASH system, which suggests peak P-T conditions at about 16-20 kbar, 500°C and 12-16 kbar, 450°C in the upper and lower units, respectively. Peak P-T conditions are followed by a nearly-isothermal decompression for both units at slightly different temperatures (of the order of 50°C). P-T calculations using the TWQ method are in good agreement with the qualitative approach, but they indicate slightly lower temperatures compared to those estimated using the petrogenetic grid. The contact between the two units, i.e. the garnet isograd in both mafic and pelitic rock, coincides with a zone of high strain at greenschist-facies conditions. No progressive change in mineral compositions (for similar buffering assemblages) is observed towards the garnet isograd. The contact between the upper and lower units is thus interpreted as a greenschist-facies ductile thrust rather than a true reaction-isograd in an undisturbed metamorphic sequence. Thrusting of the higher-grade unit, i. e. the upper unit, over the lower unit occurred after the HP event (D1-M1), i.e. during the exhumation of both units (D2-M2). The contact has been later deformed by an open antiformal fold (D3). The observed superposition of higher-grade rocks over lower-grade ones argues against models where the exhumation history is entirely controlled by crustal-scale vertical shortening (i.e. extension).

LS06 : THam02 : G0
Closure Mechanism of the Ar-Ar System in Blueschists Constrained by P-T Paths and Rb-Sr Systematics (Ile de Groix, Variscan Belt, France)

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New Rb-Sr and ^{40}Ar-^{39}Ar data have been obtained on phengite from the HP/LT rocks from the Ile de Groix (Armorican Massif, France) in order to constrain their P-T-time path. The Ile de Groix is located 10 km from Lorient (southern coast of Brittany) and represents, with the Bois de Cené, one of the few occurences of Variscan blueschists. Two units recording distinct peak P-T conditions are distinguished. The high-pressure event, estimated at about 16-20 kbar, 500°C and 12-16 kbar, 450°C in the upper and lower units, respectively, was followed by a nearly-isothermal decompression. The contact between the upper (higher grade) and the lower (lower grade) units coincides with a greenschist-facies ductile thrust which occurred after the HP event (D1-M1), i.e. during the exhumation of both units (D2-M2). Rb-Sr and ^{40}Ar-^{39}Ar ages obtained on phengites in the blueschist-facies rocks from the Ile de Groix range from 348 ±5 to 356 ±10 and from 348.4 ±1.4 to 370.4 ±2.2 Ma, respectively. The Rb-Sr and Ar-Ar data obtained in the same sample are concordant whatever their metamorphic grade. Existence of excess argon is unlikely. Older ages are found in rocks with well-preserved blueschist-facies parageneses, while younger ages are obtained in samples with a strong greenschist-facies overprint. Relationships between ^{40}Ar-^{39}Ar ages and the greenschist-facies deformation suggest that the closure of the K-Ar clock occurs at around 450-500°C in rocks left nearly undeformed after the blueschist-facies metamorphism and at lower temperature in the samples overprinted by the greenschist-facies event. Later closure of the K-Ar clock is interpreted as due to continuing ductile deformation at decreasing pressure. Thus we propose that the closure temperature of the K-Ar system in phengite is higher than generally assumed.

LS06 : THam03 : G0
The Entrelor Melange: A key to Understand the Relations between Blueschists and Eclogites in the Piemontese Zone of the Western Alps

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The Piemontese zone in the northwestern Alps is traditionally divided into two units based on different metamorphic histories of these units. The first unit, the Zermatt zone, is well known for its high-pressure mineral assemblages (more than 20 kbar, 600°C, Reinecke, 1991). The second and tectonically high unit, the Combin zone, was metamorphosed under lower conditions (8-10 kbar, 400°C, Ballèvre and Merle, 1993). The Piemontese zone, found in the footwall of the “Entrelor shear zone” was considered as part of the Zermatt zone comprised between eclogitic rocks of the Gran Paradiso massif below and blueschist rocks of the internal Briançonnais (13 kbar, 500°C, Cigolini, 1995) above. The “Entrelor shear zone” was interpreted as resulting from a backthrust of the Briançonnais domain over the Schistes Lustrés acting between 34 and 37 My (Freeman and al., 1997). A study of the metamorphism in this area, carried out on the metapelites, reveals that these rocks do not contain mineral assemblages indicating very high pressure conditions. The mineral assemblage for pressure peak is formed by the association of Ctd, Pg and phengites included in alamandine-rich garnets (Alm 60%, Gros 30%). The pressure peak is estimated from this assemblage at around 13-14 kbar for temperatures between 400 and 450°C. Additionnally a detailed study of the metabasites shows that these rocks can be divided in two groups. The first is composed of rocks, which contain mineralogical assemblages, well preserved or as relic, which indicate HP metamorphic conditions (18-20 kbar, 500-550°C). The second type of rocks is formed by metabasites, which were never submitted to eclogitic conditions. These rocks contain mineralogical assemblages with glaucophane and tremolite as inclusion in albite. A preliminary estimate of the metamorphic conditions gives a pressure around 10 kbar for temperatures between 400 and 450°C. Such assemblages and conditions have been described for the Combin zone (Ballèvre and Merle, 1993). As a consequence of this result there is no metamorphic jump between the Zermatt zone and the internal Briançonnais (Zona Interna). Rather, the Piemontese zone represents a melange, we refer to as the Entrelor melange in this area, consisting of eclogites facies mafic knockers embedded in a blueschist facies matrix consisting of metapelites and prasinites. Structural data indicate that the Entrelor shear zone is not a backthrust (movement top-to-the-west!), which confirms the idea that there is no metamorphic jump between the metapelites of the Zermatt zone and the Zona Interna.

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LS06
Blueschist to UHP Metamorphism and Back Again

LS06 : THam04 : G0
Blueschists and Eclogites from the Western Alps: A Record of two Wedges in the Development of a Subduction Zone

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In the last years significant progress has been made in understanding the evolution of high-pressure rocks from the Alpine Piemontese zone in the framework of the Geofrance 3D Scientific Program. Integrated petrologic, tectonic and chronologic studies of the meta-ophiolites from southern part of the Piemontese zone, allow two subduction complexes to be distinguished: -The Queyras blueschist domain ("Schistes lustrés"), composed mainly of oceanic meta-sediments and small lenses of ophiolites show contrasted P-T paths under blueschist facies conditions related to a progressive evolution under paleo-thermal gradients between 25 to 30°C/km. Petrological and chronological investigations show that these rocks were exhumed from depths of 25 to 35 km with low exhumation rates (<mm/y). -The eclogitic Piemontese zone composed mainly of remnants of oceanic lithosphere, metamorphosed under paleo-thermal gradient of 4 to 5°C/km. The P-T conditions of eclogitic metamorphism is strongly heterogeneous with significant pressure gaps. The calculated exhumation rates are higher than 1 cm/y. These two domains are interpreted as the remnants of different structural levels of an intra-oceanic subduction zone. The Queyras blueschist domain, with an important meta-sedimentary component and ocean-derived detritism, is regarded as a crustal accretionary wedge, while the eclogitic units corresponds to a deep-seated wedge composed by a matrix of serpentinized peridotites ("serpentinized channel") and corresponds to crustal slices sampled at different depths along the Benioff zone. The exhumation of the blueschists and eclogites is diachronous, and mainly achieved while subduction was still active, throught contrasted mechanisms related to the internal dynamic of the two wedges. The tectonic pile of the Piemontese zone was created at 30 Ma and its exhumation achieved by the combination of erosion and extension mechanisms. The intimate association of serpentinites and eclogites suggests that serpentines may have played an important role in the exhumation of eclogites. We discuss by numerical modelling the role of serpentinites in the exhumation of the eclogites using the physical parameters deduced from the Monviso ophiolitic massif. This 2D numerical modellisation is realized by solving the Navier-Stokes equation coupled with a mass conservation equation.

LS06 : THam05 : G0
Magmatic, Metamorphic, and Exhumation History of Syros, Greece

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The Attic-Cycladic Massif is one of few localities in Europe where blueschist-eclogite assemblages have survived exhumation to the surface. On Syros, the type locality for glaucophane, both emplacement, prograde metamorphism, and exhumation are well preserved. To summarize the P-T-t history, we relate mineral reactions to available magmatic and metamorphic ages.

The main volcano-sedimentary sequence on Syros corresponds to a profile through an oceanic crust in a fossil arc splitting or back-arc environment. Despite ductile deformation and peak metamorphism to 1.5 GPa and 500°C, the lithostratigraphy is well preserved: a basal metabasite unit with eclogite-metagabbro-pillow "knockers" in a mafic glc schist to serpentinite matrix is followed by mafic-felsic tuffites, graywackes, carbonate-rich schists, matrix-supported carbonate conglomerates, and by thick calcite-dolomite marbles with intercalated quartzites.

Magmatic emplacement ages, dated with SHRIMP U/Pb on magmatic zircons from meta-acidites, fall around 240 Ma. In places, there is a zircon generation with U/Pb ages around 315 to 330 Ma, notably in the Vari granitoid and felsic gneisses in the south. The 240 Ma ages may correspond to incipient rifting of older variscan (~ 330 Ma) continental crust. The sediments have not been dated directly; however, hydrothermal Mn precipitation, by implication a short-lived phenomenon on hydrothermally active oceanic crust, crosscuts all important lithostratigraphic contacts, suggesting that the sediments are coeval with the magmatic units.

Metamorphic overprint commences with ocean floor metamorphism of unknown age, characterized by intense sodic metasomatism. The prograde path is represented by rare czo pseudomorphs after law that deformed in the glc-czo stability field, only preserved in hinge zones of early-generation isoclinal folds. Peak metamorphism is characterized by jd-qz in meta-acidites and was partly static. The peak overprint seems constrained to around 80 Ma with U/Pb SHRIMP dating on metamorphic zircons and a $176Lu/^{176}Hf$ equilibration age in a metavolcanic breccia that experienced fluid metasomatism, possibly near peak conditions. Exhumation was static and is reflected by undeformed cc paramorphs after aragonite, static scelettal law overgrowing older glc-czo-omph-pg foliation, as well as static discordant law-czo, law-pg, and omph-cc-ab veins. Initial decompression is shown to have been accompanied by a distinct cooling event at high ambient pressure, around 100°C relative to peak temperature. The preferred mechanism of initial exhumation is by slab delamination and underthrusting of a cooler slab segment in an oceanic accretionary wedge. Subsequent greenschist overprint, around the Miocene, is largely confined to the south of the island. It is accompanied by extensive tourmaline impregnation along brittle fractures, perhaps because it was triggered by granitoid intrusion at depth. The pervasive greenschist overprint in the south may be unrelated to the exhumation path.

LS06 : THam06 : G0
Evolution of Glaucophane Marbles and associated High-Pressure Rocks on the Island of Syros, Cyclades, Greece

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The rocks of the island of Syros are part of the Attic-Cycladic blueschist belt that formed during Eurasia-Africa subduction, which began in the Mesozoic. The rocks of Syros, as presently understood, can be broadly divided into three tectono-stratigraphic units: (I) metasedimentary and metavolcanic rocks, (II) remnants of oceanic crust, and (III) the Vari gneiss. With the exception of the Vari gneiss in the southeast, the rocks contain high pressure mineral assemblages reflecting conditions of at least 15 kbar and 500ºC. Peak metamorphism is probably Late Cretaceous (Broecker & Enders, 1999; Cheney et al., 2000) rather than Eocene as earlier studies suggested. Unit I is a sequence of volcano-sedimentary rock types. The lowermost rocks of Unit I consist of metamorphosed felsic tuffs that may contain felsic clasts, mafic schists), marbles, and finely-laminated manganese cherts. These rocks give way upwards to a section dominated by marble horizons. The two main lower marble horizons are typically dolomitic, in part, and are separated by glaucophane-schists, greenschists (retrograde), and minor quartzites and manganese cherts.

Relatively pure layers of calcite in the marble commonly display a columnar structure that is interpreted as calcite pseudomorphs of aragonite. At many localities, thin layers bearing silicate minerals define the foliation in the marbles. In addition to carbonates and quartz, the assemblages contain various combinations of Na-amphibole, Na-pyroxene, epidote, garnet and white mica. The mineral assemblages and compositions in marbles and associated rocks tightly constrain the metamorphic P, T and the fluid composition attained by the marbles. For example, the common occurrences of both Na-amphibole + $CaCO_3$ and dolomite + quartz suggest that the P-T trajectory crossed a reaction like: albite/Na-pyroxene + dolomite + quartz + $H_2O \Rightarrow$ Na-amphibole + $CaCO_3$ + CO_2, but did not cross dolomite + quartz + $H_2O \Rightarrow$ tremolite + CO_2. The P-T locations of these types reactions, both prograde and retrograde, are very sensitive to fluid composition. Assemblages suggest fluid compositions with $X(CO_2)$ in the range of only 0.03-0.01 in the marbles throughout much of the metamorphism.

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LS06 : THam07 : G0
Element Partitioning in Natural and Synthetic Carbonate Eclogites

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Both natural occurrences and experimental studies suggest that magnesite and dolomite can be stable in mafic systems at high pressure conditions. In this work, the stability of carbonates and Fe-Mg and Ca-Mg partitioning between carbonates and the coexisting silicates are discussed as a function of fluid composition and oxygen fugacity. Phase relationships and carbonate composition from coesite eclogites from Dabie-Shan (China), Bergen Arcs and Western Gneiss Region (Norway) are compared to synthetic high-pressure mafic assemblages. High-pressure experiments were performed on seeded gels, in the model system Na-Ca-Fe-Mg-Al-Si-C-O-H (NCFMAS-COH) using a piston-cylinder apparatus, at pressures ranging from 12 to 32 kbar and temperatures from 665 to 800ºC, at fH_2 buffered by NNO, via a double capsule technique. Fluid phase is generated from oxalic acid dihydrate. Three mafic composition ranging from Fe-basalt to Mg-basalt were employed in the experiments. In all compositions, a large amphibole-carbonate phase field is found below 22 kbar. At higher pressures talc and epidote represent the stable hydrous phases. A single carbonate (calcite or dolomite) occurs at low pressure. At P > 16-18 kbar, magnesite and dolomite coexist. As a result of progressive displacement of the graphite boundary in C-O-H toward H_2O at increasing pressure, graphite was detected by Raman spectroscopy in runs performed in the highest pressure range. Garnets from natural and synthetic assemblages consistently show composition ranging from 36 to 73 mole% of almandine and from 14 to 40 mole% grossular. The composition of natural dolomite and synthetic dolomite coexisting with magnesite lies very close to the dolomite-ankerite join. However, magnesite composition in natural assemblages lies very close to the magnesite-siderite join, whereas synthetic magnesites are substantially richer in calcium (up to 11 mole% calcite component). Dolomite/garnet Ca/Mg partition coefficients, $Kd(Dol/Gar)^{Ca/Mg}$, are similar in natural and synthetic assemblages, whereas $Kd(Dol/Gar)^{Fe/Mg}$ are significantly higher in synthetic assemblages. Regarding magnesite-garnet partitioning, $Kd(Mag/Gar)^{Ca/Mg}$ and $Kd(Mag/Gar)^{Fe/Mg}$ are higher in synthetic assemblages. Such a behaviour in experimental products is consistent to data presented by Yaxley and Green (1994). These data may suggest that natural magnesites and dolomites tend to re-equilibrate during decompression. $FeMg_{-1}$ exchange between garnet and dolomite, and between garnet and magnesite is strongly affected by exhumation of natural eclogites, as well as Ca/Mg exchange between magnesite and garnet.

Yaxley GM & Green DH, *Earth Planet. Sci. Lett.*, **128**, 313-325, (1994).

LS06 : THam10 : G0
Modelling Equilibrium Phase Diagrams for White Schists: New Insights on Metamorphic Evolution in the Western Penninic Alps

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Magnesium-rich rocks at high-pressure (whiteschists) are crucial for understanding subduction and exhumation mechanisms. A qualitative and quantitative approach to pressure-temperature-composition equilibrium phase diagrams for whiteschists has been carried out in the KFMASH system, between 0 and 30 kbar and 200 and 800°C, with the thermodynamic software DOMINO.

At high-pressure with increasing temperature, the following mineralogical sequence will evolve (with H_2O and SiO_2 in excess and associated phengite): Car-Chl / Chl-Cld / Cld-Tc / Tc-Grt-Ky / Grt-Ky. The water activity has a major influence on the stability of mineral assemblages concerned. To assess the effect of variable water activity, theoretical P-a(H_2O) sections have been generated for different temperatures. These sections show that the natural assemblage Cld-Tc only appears for a reduced water activity between 0.4 and 0.8 at 25 kbar and 500°C. To illustrate dependence on composition of the stability fields of the mineral, isothermal P-X sections were constructed. The assemblage Ky-Tc only appears at high-pressure in iron-free rocks. The stability field of the assemblage Chl-Ky increases towards low-pressures at the expense of the assemblages Chl and Chl-Bt for increasingly Al-rich bulk compositions. In contrast, with constant content in Fe and Mg and at high-pressure conditions, Cld-Tc is stable for large variations of the rock aluminium content.

Calculated equilibrium phase diagrams serve as a tool for the interpretation of natural rocks. The application of the new P-T grid to the Monte Rosa whiteschists leads to the conclusion that the characteristic assemblage talc-magnesiochloritoid, with a water activity of 0.6, was stable at approximately 23 kbar and 520°C. This is considered to be the peak of eclogite facies metamorphism in this area. Chloritoid has a complex XMg zonation pattern. Moving from the centre of a crystal to the edge, two increases in XMg, separated by a decrease are observed. The XMg pattern was established during the late stages of increasing P on the prograde path in the Monte Rosa Massif. The two increases are attributed to coeval growth in equilibrium, first with chlorite, and then with talc. The decrease, in-between, resulted from chloritoid growth in a metastable assemblage with chlorite and talc. Similar P-T conditions for the peak of metamorphism have been calculated from whiteschists for the Gran Paradiso Massif and for the "cold eclogite" unit of the Dora Maira Massif. This high-pressure event is followed at first by a near-isothermal decompression to approximately 9 kbar-480°C and afterwards by a slower decompression with concomitant cooling during a later stage of exhumation.

LS06 : THam11 : G0
Biotite Stability Conditions and the Formation of Eclogitic Assemblages in Subducted Continental Crust: An Experimental Approach

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Some high-pressure metamorphic rocks from the continental crust involved in orogenic collision (e.g. Monte Mucrone - Sesia-Lanzo zone - Italian Alps) display coronitic textures with an eclogitic high-pressure assemblage clinopyroxene + phengite + garnet growing at expense of biotite + plagioclase ±quartz. A series of experiments were carried out to locate this mineralogical transition in the pressure-temperature space and characterise these transformations. A natural metagreywacke with 1.43 wt% H_2O was used as a starting material, and experiments were performed in the pressure-temperature range 5 to 30 kbar and 800 to 950°C.

In the range 5 to 23 kbar, the assemblage biotite + plagioclase + garnet + quartz ±melt is stable. Towards high temperatures, orthopyroxene appears while biotite progressively disappears upon melting. In this pressure range, the grossular content increases progressively with pressure from 4% to 16%. In the range 25 to 30 kbar, the assemblage phengite + omphacite + garnet + quartz ±melt is stable. At temperatures higher than 920°C, phengite disappears and the melt becomes the only hydrated phase. These preliminary results suggest that in this pressure range the grossular content decreases with increasing pressure from 16% to 10%. So far, we did not observe any pressure-temperature field where the phengite and biotite stability fields overlap. The limit between the biotite and the phengite domains is subhorizontal in the pressure-temperature space and located between 23 and 25 kbar for temperatures ranging from 800 to 920°C. These experimental data are consistent with the overall reaction Bt + Plg ±Qtz = Phg + Cpx + Grt. Additional experiments in the range 23 to 25 kbar are in progress to determine precisely the width of the reaction field in which the change in mica and the transformation from albitic plagioclase to jadeitic clinopyroxene are combined. The systematic determination of the composition of the solid-solutions below 23 and above 25 kbar is used to identify the multivariant equilibria that control proportions and compositions of the phases in these multivariant domains. We demonstrate that the reaction Bt + Pl + Qtz = Grt ± Kfs + Melt plays an important role below 23 kbar. This experimental study is the first precise determination of the relative stability fields of black and white micas in metasediments. Our results show that, in metasediment, an eclogitic assemblage does not form below 23 kbar (850°C) and it is thus very likely that rocks displaying the mineralogical changes described above reached pressures as high as 23 kbar.

LS06 : THam12 : G0
Rb/Sr Geochronological Record of Fluid-Mediated Reactions in High-Pressure Rocks

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Isotopic data can be used to derive mass transfer velocities in subduction zones, if precise and accurate ages can be attributed in a reliable way to particular stages or events in the reaction history of high-pressure rocks. The potential of Rb/Sr mineral systematics for providing event ages is widely underestimated. The key question in interpreting Rb/Sr mineral systematics is whether the data reflect crystallisation, or cooling through a specific closure temperature. The classical concept of closure temperature implies solid-state diffusion of Sr in a mineral. The matrix of this mineral is modelled as an infinite Sr reservoir characterised by fast diffusion. In the absence of an intergranular fluid, this assumption is generally not fulfilled. Recent studies show that exchange of Sr is dependent on the modal proportions and on the diffusion kinetics of all minerals in an assemblage. Phengite-bearing high-pressure rocks provide assemblages favourable for preservation of crystallisation ages. It is proposed that information on complete high-pressure reaction histories may be preserved in Rb/Sr mineral systematics. In order to test this hypothesis, eclogites from the Marun-Keu complex (Urals, Russia) were studied. Field observations show that eclogitisation is fluid-mediated. In the absence of fluids, reaction kinetics may be slow, and pre-metamorphic relic assemblages are preserved. Rb/Sr mineral ages from relics predate eclogite-facies metamorphism. Fluids at eclogite facies conditions are often channelised in veins. The vein assemblages in most cases are dominated by quartz, with other phases as accessories. Such quartzitic assemblages preserve Sr-isotopic signatures of phases like omphacite and phengite as soon as the rock dries out. Postcrystallizational diffusional isotopic exchange between white mica and other phases must be negligible up to high temperatures because of the diffusion lengths involved and the low diffusivities of Sr in the quartz lattice. Eclogites are made up by omphacite, garnet, phengite, epidote/zoisite and accessories, with omphacite, epidote/zoisite and phengite as the main Sr-bearing minerals. It will be shown that phengite in such an assemblage remains as closed system up to temperatures far above the "commonly accepted" mica closure temperature, as there are no partners for Sr exchange: Omphacite has a very high blocking temperature due to its high lattice energy. Epidote commonly shows zoning patterns, indicating insignificant postcrystallisational diffusion. The Rb/Sr ages obtained from these assemblages are identical to ages for fluid activity in quartzitic veins. Post-eclogite-facies retrogression requires fluids as well. Assemblages from retrogression-related fluid pathways provide a time marker for the passage of the rock through the stability field of the retrogression assemblages. In the Marun-Keu complex, amphibolite facies retrogression immediately postdates eclogitisation. The approach allows to constrain metamorphic reaction rates and offers new insights on velocity of processes at depth.

LS06 : THam13 : G0
The Role of Micro-Inclusions in Garnet and Sm-Nd Disequilibrium of Low-Temperature Eclogites

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Dating high-pressure metamorphic rocks is critical to understand the dynamic of exhumation. However, in many low-temperature eclogites, Sm-Nd ages cannot be obtained: garnet is in disequilibrium with whole-rock (WR) and cpx, because of its unusual unradiogenic $^{143}Nd/^{144}Nd$ ratio. In order to decipher the causes of this disequilibrium, Sm-Nd isotopic analyses were carried out on minerals from Himalayan and Alpine eclogitic rocks, of different lithologies and/or variable intensity of post-eclogitic metamorphism.

Himalayan samples: (Tso-Morari unit, East-Ladakh): Fresh eclogite (Ts34) and eclogite retrogressed under blueschist facies (Ts51) exhibit a large range in $^{147}Sm/^{144}Nd$ ratios in minerals varying from 0.139-0.123 in muscovite-omphacite, respectively and 0.307-0.407 in garnet. $^{143}Nd/^{144}Nd$ ratios range from 0.512767 for WR to 0.512203 for garnet (Ts34), or show no significant variations (0.512883-0.512904) (Ts51). Garnet has the highest $^{147}Sm/^{144}Nd$ and the lowest $^{143}Nd/^{144}Nd$ ratios, the resulting negative slope cannot define an isochron. For the eclogite recrystallized under amphibolite facies (Ts45), WR, amphibole and garnet exhibit a large range in $^{147}Sm/^{144}Nd$ (0.145 to 0.406) and a significant range in $^{143}Nd/^{144}Nd$ (0.512847-0.512928), with garnet having the highest $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios. Thus the defined isochron gives an age of 47±11 Ma (DeSigoyer et al., 2000). Sm-Nd disequilibrium is all the more pronounced that the eclogite is fresh, and that the $^{143}Nd/^{144}Nd$ ratio is low for the whole-rock.

Alpine eclogites: Data for Sesia felsic sample (Li6) are strongly scattered: cpx and phengite have high $^{143}Nd/^{144}Nd$ ratios (0.513154-0.513198); WR and pure garnet have lower values (0.512093-0.510662) with impurified garnet plotting on the line WR-garnet, and close to WR composition. Garnet has the highest Sm/Nd and the lowest $^{143}Nd/^{144}Nd$. Cpx and phengite compositions define a regression line with a positive slope, giving an age of 63±7 Ma (Duchêne et al., 1997). By contrast, WR, unpurified and pure garnet compositions define a regression line with a negative slope. Minerals from Dora Maira felsic (DM) and Sesia Lanzo mafic (QU) eclogites are in strong disequilibrium: garnet has lower $^{147}Sm/^{144}Nd$ (0.089) and $^{143}Nd/^{144}Nd$ (0.511738) than WR (in DM), or than cpx and glaucophane (in QU), defining a negative slope.

Knowing the Lu-Hf eclogitization ages[1,2], two hypotheses have been numerically tested in order to explain the low $^{143}Nd/^{144}Nd$ ratios in garnet (i) the preservation of the isotopic signature of the plagioclase from which garnet grew up. However, the calculated plagioclase/whole-rock age is geologically meaningless, (ii) the occurrence of inherited sub-microscopic inclusions with low $^{147}Sm/^{144}Nd$ ratio in the garnet. The $^{143}Nd/^{144}Nd$ ratio of these inclusions is calculated considering that the garnet separate is a mixing between allanite/monazite inclusions with appropriate $^{147}Sm/^{144}Nd$ ratio (<0.05) and pure garnet with $^{147}Sm/^{144}Nd$ of 0.2. The calculated inclusion/whole-rock ages suggest that inclusions have an old, Precambrian, crustal origin. These inclusions were probably inherited from crustal contamination of the magmatic protolith.

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Thursday PO Session

LS06 : THam14 : G0
The Origin of Excess Argon in Ultrahigh-P Rocks from Qinglongshan (Sulu Terrain, China): A Combined Argon and Oxygen Isotope Investigation

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Neoproterozoic eclogite, quartzite, para-, and orthogneisses from Qinglongshan (Sulu terrain, eastern China) were metamorphosed to coesite-eclogite facies UHP conditions during Triassic (220-240 Ma) continental collision and subduction. The rocks exhibit unusually low and heterogeneous $\delta^{18}O$ values together with significant amounts of excess argon, interpreted to have originated from a pre-UHP protolith (Giorgis et al., 2000). For the present study, electron microprobe, $^{40}Ar/^{39}Ar$ and oxygen isotope data are presented from different lithologies from Qinglongshan. Phengite step heating of samples from quartzite, eclogite and gneiss yielded variable $^{40}Ar/^{39}Ar$ total gas ages (no plateau ages) between 280 Ma and 950 Ma, indicating a variable extraneous argon content. Four biotites and three K-feldspars from gneisses yield total gas ages between 200-202 Ma and 190-198 Ma, respectively. White micas of nearly muscovite composition (Si^{4+} content varying from 3.1 to 3.2 p.f.u.) from samples of gneiss and quartzite yield apparent ages of 200-205 Ma, corresponding to either the time of chemical re-equilibration or to metamorphic cooling. In addition, large phengite crystals (10 cm) interpreted as a late stage crystallization phase under high fluid activities yield relatively small amounts of excess argon ($^{40}Ar/^{39}Ar$ total gas ages of 250-280 Ma), suggesting that excess argon originating from late fluids is of minor importance. Furthermore, comparison between the phengite $\delta^{18}O$ values and $^{40}Ar/^{39}Ar$ total gas ages yields a correlation between the lowest (-9.7‰) and the highest (-1.2‰) $\delta^{18}O$ values and the oldest (950 Ma) and the youngest (260 Ma) $^{40}Ar/^{39}Ar$ total gas ages, respectively. This correlation is interpreted to reflect pre-metamorphic heterogeneities in the different protoliths of these samples. Moreover, the observed variation and correlation between the oxygen and $^{40}Ar/^{39}Ar$ data could record a later partial isotopic exchange between the protolith and more typical meteoric or metamorphic water in a downgoing accretionary prism during the Permian and before the HP-UHP metamorphic event. The distribution of excess argon in these rocks is controlled by a combination of different parameters including the following: 1) Closed (at a centimeter scale) isotopic system; 2) Proportion of phengite and epidote (which contains significant amounts of ^{40}Ar); 3) Degree of chemical re-equilibration during decompression; and 4) Argon closure temperatures of the minerals examined.

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LS06 : THpm21 : G0
The Kumdy-Kol Diamandiferous Rocks of Kokchetav (North Kazakhstan): Containers of Ultrahigh-Pressure Stage Deformation?

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The mid-crustal exhumation setting of the UHP Kokchetav massif consists of two different UHP petrotectonic domains (Theunissen et al., 2000), the Kumdy-Kol (diamond-bearing) and the Kulet (coesite-bearing) domain. Poorly outcropping, the structure of the Kumdy-Kol domain is less well known than the Kulet domain. Whether or not these different UHP domains rised along a common structure, mainly evidenced in the better outcropping Kulet domain, and with a common mechanism, is not clear (Maruyama et al., 2000; Theunissen et al., 2000). In the Kumdy-Kol domain the formerly mined Kumdy-Kol diamond-bearing unit is well exposed in a mine gallery. Based on the available mineralogical and petrological information of its diamond-bearing levels (Shatsky et al., 1995; 1999), the structural investigation of the Kumdy-Kol unit exposed in this gallery is performed and first results are given. This well exposed UHP unit consists of a structural concordant succession of four sequences: diamond-bearing metacarbonate rocks (I), metasomatic gneiss (II), diamond-bearing garnet-biotite-pyroxene gneiss (III) and migmatite gneiss (IV). In all exposed sequences, the steeply inclined layering is parallel to the metamorphic foliation (S), with a generally poorly developed mineral lineation (L). Thin sections along the lineation reflect predominant pure shear fabrics. Only in the biotite-garnet-pyroxene gneisses of sequence III mesoscopic folding was observed. The meaning of the folding in the evolution of the diamond-bearing rocks is investigated on oriented samples. One fold style is best described as ptygmatic folding with a well expressed 'layering' outlined by different contents of biotite and pyroxene. This layering is continuous and gradational in the hinge zone with cuspate shaped boundaries. In the fold limb position this layering changes in a fine 'lamination' texture, which is parallel with the outcrop-scale foliation fabric (S). A second fold style is an intrafolial and Z shaped similar fold apparently associated with the deformation at the origin of the metamorphic foliation in the unit and also parallel with the outcrop-scale foliation Garnets from the biotite gneisses have unusual chemical compositions and are generally intensely fractured. The chemical composition of garnets starting to form in diamond-stability UHP conditions is traced across the different fabrics (layering, lamination, metamorphic foliation) in the hinge- and limb-zone of the folds. The granulite facies metamorphic conditions of the folding in the UHP are constrained by comparing garnet and pyroxene chemical compositions across the different fabrics. Discussing these results in order to constrain processes acting during the fast rise of the Kumdy-Kol UHP unit to its mid-crustal level, needs additional information on the sporadic occurrence of tourmaline in sequence III and its widespread participation in the main foliation fabric (S) of sequence II.

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LS06 : THpm22 : G0
Mineral Inclusions in Kokchetav Diamonds: Direct Thermometry of Diamond Formation

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The ultra-high pressure metamorphic rocks of the Kokchetav massif, Kazakhstan represent a Cambrian suture zone, where supracrustal rocks were buried to great depth. The presence of micro-diamonds (Sobolev and Shatsky, 1990) is a clear indication for the ultra-high pressure. However, in the lack of reliable diamond thermometers, the peak conditions are commonly determined using equilibria between silicate and carbonate minerals. Current estimates are in the range of 4-7 GPa and 900-1000°C.

Here we report the finding of microscopic garnet and clinopyroxene inclusions within the micro-diamonds and use them to calculate the temperature of formation of the diamonds. Examination of 20 micro-diamonds from a single garnet-clinopyroxene rock from the Kumdy-Kol area led to identification of two garnet inclusions in one diamond and three clinopyroxenes in another. The inclusions are located at shallow depth below the surface of the diamond and are less than 1 micrometer in size. They are similar in composition to the garnet and clinopyroxene of the rock sample, but have all lower Mg#. The Ca# of the garnet inclusions is also lower than that of the matrix garnets. The Ca# of two of the pyroxenes is above 0.5; they also have excess silica. The third have normal silica and Ca# number that is lower than that of matrix pyroxenes.

Both diamonds originate from a single rock sample and share similar morphology. Assuming that they were formed in the same event, garnet-clinopyroxene thermometry yields an average temperature of 965±65°C. The full range spanned by the six combinations of garnet-clinopyroxene pairs is 880-1060°C. Matrix garnets and clinopyroxenes from the same rock sample yielded an average temperature of 885±68°C. These lower temperatures may reflect later equilibration at lower temperatures.

The temperature determined for the diamond inclusions is similar to peak temperatures of 900-1000°C estimated using coexisting silicate mineral inclusions in zircons (Maruyama and Parkinson, 2000) and garnet-pyroxene thermometry of eclogites form Kokchetav (Shatsky et al. 1995; Okamoto et al., 2000). It is also in agreement with the mantle-residence temperature of 900-940°C estimated by DeCorte et al. (1998), based on the low aggregation state of nitrogen atoms in the Kokchetav diamonds. The recorded temperatures indicate that diamond growth took place during peak metamorphic conditions when the rocks reached pressures and temperatures of the diamond stability field.

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LS06
Blueschist to UHP Metamorphism and Back Again

LS06 : THpm23 : G0
A Continental Rift in UHP-Facies: The Dabie Shan

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The geologic setting of the Dabie Shan prior to Triassic ultra-high-pressure (UHP) metamorphism is hitherto not well documented. Fieldwork within the UHP unit of the Dabie Shan combined with petrologic and geochemical studies allow definition of two basement-cover sequences. Two distinct sedimentary series, a volcano-clastic sequence (Ganghe Unit) and a clastic-carbonatic sequence (Changpu Unit), occur on top of basement ortho-gneisses within a (Precambrian) rift setting affecting the Yangtze craton. Portions of the felsic basement and the metasedimentary cover rocks as well as enclosed metabasites clearly record UHP conditions, as documented by the occurrence of coesite and P-T estimates. Furthermore, two different types of metabasites can be distinguished. The first type is derived from gabbroic rocks and is confined to the basement, whereas the second type originates from mafic volcanic rocks (lavas, dykes or tuffs) and occurs in both the basement and the cover units. a.) basement - The felsic basement gneisses contain UHP-facies eclogitic lenses or bodies, but dominantly display greenschist-facies assemblages. However, portions which can be classified as gneissic eclogite (i.e., plagioclase free but omphacite-bearing) are also recognised. Petrographic evidence indicates that ab-rich feldspar bearing gneisses are strongly retrogressed gneissic eclogite. Such a silicic basement in UHP-facies bears considerable amounts of coesite. Volume changes associated with crossing the quartz-coesite phase boundary influence the buoyancy, create fluid pathways, and enhance recrystallisation, thus resolving the enigma of lower grade gneisses hosting UHP eclogites b.) cover - The clastic-carbonatic Changpu Unit displays an original stratigraphic contact to its basement, as interpreted from occurrence of a thin layer of strongly deformed conglomerate on top of isoclinally folded gneisses. Intercalated metabasites and calc-silicate rocks preserve UHP indicators best. A basement relative to the volcano-clastic Ganghe Unit was not observed, but the top of the unit is in tectonic contact to the basement of the Changpu unit. This contact is manifested in a greenschist-facies mylonite, with cm-sized albite-blasts (showing an older foliation) in a micaceous matrix. Felsic volcanics in this unit preserve no indications of UHP or HP metamorphism, whereas metabasites preserve UHP conditions. These new findings suggest (i) generation of basement-cover units with distinct metabasite along a passive margin during a rifting stage (ii) subduction, UHP metamorphism and exhumation of such coherent units, (iii) lithologically controlled retrogression, and (iv) reactivation of tectonic contacts between lithologic units during late stages of the exhumation of the Dabie Shan.

LS06 : THpm24 : G0
Eclogite Evolution and the Timing of Ultra-High Pressure Metamorphism in Western Norway

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The Western Gneiss Region (WGR) of the Norwegian Caledonides exposes a SSE to NNW sequence of glaucophane/quartz-bearing to omphacite/coesite-bearing eclogites related to progressively deeper levels of subduction of the mostly Proterozoic continental crust lithologies of the Baltic Plate margin beneath the Laurentian Plate, down a ca. 5°C/km gradient (Cuthbert et al, 2000).

A transition from HP (quartz-stable with prograde zoned garnets) to UHP (coesite-stable with homogenised garnets) has been reported to the north of Nordfjord across what has been previously interpreted as a 10-15 km wide tectonically-mixed transition zone (Wain et al, 2000).

New petrographic observations and garnet grain X-ray elemental maps demonstrate, however, that UHP eclogites within the transition zone have evolved from HP eclogites and that some still retain earlier generation prograde growth zoned garnets with early stage inclusions of quartz and taramitic amphibole. Hence the intimately associated samples of UHP and HP eclogites within the transition zone are considered to be the product of variable degrees of reactivity response during the imposed UHP conditions appropriate for coesite stability and not of tectonic mixing.

Griffin & Brueckner (1985) indicated a ca.425 Ma age for eclogite metamorphism based on an average of their determined Sm-Nd isochron ages for garnet-clinopyroxene pairs from five high-T eclogite samples, whereas determined U-Pb zircon ages for certain WGR eclogites are closer to 400 Ma (Krogh et al, 1974: Gebauer et al, 1985). These previous dating studies did not attempt to distinguish between UHP and HP eclogites or indeed even consider the possibility of significant age differences between them.

Our identification by laser micro-raman spectroscopy of coesite inclusions within metamorphic zircons with a refined U-Pb age of 402±2 Ma from the large eclogite body at Ulsteinvik-Dimnøy on Hareidlandet indicates that UHP eclogites formed rather later in the Caledonian orogenic cycle than previously thought and were rapidly exhumed to the mid-crust (ca. 15 km) in about 25 Ma, corresponding to an average exhumation rate of 3-4 mm/year. The somewhat older Sm-Nd garnet-clinopyroxene isochron ages of Griffin & Brueckner (1985) for WGR eclogites and also their wide range of determined ages (407-447 Ma) may well be a consequence of their dated bulk garnet separates including variable proportions of garnet grains with older growth generation cores which grew under earlier amphibolite-facies and/or quartz-stable eclogite-facies conditions.

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LS06 : THpm25 : G0
Kinematics of HP and UHP Metamorphism in the Western Gneiss Region, Møre og Romsdal, Norway

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Evidence for HP and UHP metamorphism and deformation is found only by painstaking efforts to "see through" the effects of strong granulite- and amphibolite-facies overprinting and ductile deformation. Evidence for UHP metamorphism includes quantitative phase petrology in relict assemblages in kyanite±phengite eclogites suggesting 30-40 kbar at ~800ºC, polycrystalline quartz pseudomorphs after coesite, coesite inclusions in zircon, microdiamonds, quartz±hornblende rods in omphacite, and Na content in some garnet. Monazite geochronology by ion and electron probe in a UHP upper tectonic plate above normal HP rocks in Nordøyane indicates UHP metamorphism was 407 Ma or later, whereas amphibolite-facies overprint occurred at 395 Ma. Emplacement of the UHP plate (125 km) above the HP plate (60 km) involved 65 km of thrust exhumation over ~6 m. y. at 10.9 mm/yr. Other geochronology points to early Devonian HP and UHP recrystallization of Baltica basement and associated rocks of the WGR. This contrasts sharply with higher thrust slices of the Seve Nappe that show deformed ~430 Ma pegmatites cutting an older metamorphic fabric, and volcanic and intrusive assemblages of the still higher Støren Nappe that lack evidence for strong metamorphism since Ordovician to earliest Silurian igneous emplacement. The present assemblage of thrust slices with widely differing tectonostratigraphy, metamorphism and geochronology is thought to result from two processes: 1) A thrust imbrication system related to northwestward subduction of Baltica, in which faulting stepped toward the Baltica foreland, progressively involving more forward rocks in the processes of subduction. 2) A contemporaneous system of extensional faults gravitationally induced in the rising thrust stack which carried materials from early higher thrust sheets away from cooler positions near the foreland and emplaced them against warmer and deeper rocks in the hinterland, subsequently allowing all these levels together to receive a similar late ductile fabric in a field of sinistral transtension. Slabs and pods of garnet peridotite, interpreted to be Baltica mantle lithosphere, occur widely associated with WGR basement. Some contain ~1% of pyroxene exsolution in garnet indicating a former majorite component. In our opinion, this was unrelated to Devonian metamorphism, but developed in a Mid-Proterozoic mantle plume at ~1450ºC and ~35 kbar to form subcontinental mantle beneath what later became Proterozoic Baltica. This mantle moved close to the surface during continental thinning related to formation of the Baltica margin of Iapetus at the end of Proterozoic, and because of this proximity, became imbricated with Baltica crust during Devonian subduction, then receiving a secondary garnet-peridotite assemblage.

LS06 : THpm26 : G0
A HP-UHP Transition in the Western Gneiss Region, Norwegian Caledonides

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Boundaries between high pressure (HP, quartz stable) and ultrahigh pressure (UHP, coesite stable) zones in the Western Gneiss Region (WGR) are of two types. In the Nordøyane area (Terry et al., 2000) the boundary is characterised by a well-defined tectonic junction between allochthonous units (the microdiamond-bearing Blåhø nappe and a "basement" slice of migmatitic and augen gneisses). In contrast, the HP-UHP boundary in the Nordfjord-Stadlandet area is not associated with a particular lithotectonic contact or clear tectonic disjunction. HP eclogites and relics of HP gneisses are found extensively to the south of Nordfjord in a variety of lithological associations. UHP eclogites and UHP gneiss relics are found northwards in a broad coastal strip through Stadlandet to the Sørøyane, in similar lithological associations to those in the HP eclogite terrain (Cuthbert et al., 2000). HP eclogites are characterised by idioblastic, prograde-zoned garnets with amphibolite-facies mineral inclusion assemblages preserved in their cores. UHP eclogites tend to contain more xenoblastic garnets and generally lack prominent compositional zoning or relict inclusion suites. The HP-UHP transition zone is a 10-15 km wide strip of country in which both HP and UHP eclogites are found. This has previously been interpreted as a zone of tectonic mixing, juxtaposing HP and UHP eclogites from different structural levels (Wain et al., 2000).

New petrographic observations, combined with high-resolution X-ray compositional maps of garnets, demonstrate that some "UHP" eclogites within the transition zone contain at least two generations of garnet. Relics of prograde zoned, HP garnets constitute an early generation, sometimes including inclusions of monocrystalline quartz and taramitic amphibole. Intimately associated with the latter is a later generation of poorly zoned, xenoblastic garnet sometimes containing inclusions of polycrystalline quartz after coesite. The later, UHP generation appears to have developed by break-up and recrystallisation of the earlier, HP generation. We conclude that at least some UHP eclogites have developed by recrystallisation of HP eclogites, and that the transformation was variable in its efficiency due to differing degrees of reactivity. We therefore infer that the HP-UHP transition in Nordfjord is not simply a result of tectonic mixing, nor is it a simple tectonic boundary as seen in Nordøyane. Rather, it represents a zone analogous to a complex isograd in which the subducting Baltic continental crust underwent some important mineralogical and textural transformations. Our current investigations are focused on evaluating the processes responsible

for these transformations and their implications for the way in which continental crust may be processed during subduction. The presence of multiple generations of garnet may have implications for the interpretation of previously published isotopic ages for eclogites in the Western Gneiss Region.

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LS06 : THpm27 : G0
Local Origin of High Pressure Vein Material in Eclogite Facies Rocks of the Zermatt-Saas Zone

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Prograde dehydration reactions within metabasalts at the blueschist-eclogite facies transition produce kyanite-quartz-veins, sometimes with omphacite or chloritoid, of up to several meters length and 0.2 m width. Bulk rock analyses show clear depletion haloes for Al_2O_3 and SiO_2 near to the veins. Mass balance calculations suggest that the vein material must have been derived from the immediate surroundings, by gradients in Al_2O_3 and SiO_2 through a stagnant pore fluid without the need for fluid advection. The veins seem to have first formed in low stress regimes to accomodate H_2O-rich fluids released from blueschist to eclogite dehydration localised by regimes of brittle failure. For assumed values of porosity, $\phi = 0.01$, and Al_2O_3 concentration difference, $\Delta c = 10^{-5}$ mol cm^{-3}, calculations show the range of diffusion coefficients ($D = 10^{-9}$ to $10^{-10} m^2 s^{-1}$), and reaction rate constants (k(= 2 x 10^{-7} to 2 x 10^{-8} s^{-1}), that are consistent with the compositional data profiles and the assumed model. These values lead to a second Damköhler number, Da_{II} (=kL^2/D) of about 8 (for L = 0.2 m). This supports the idea that rates of reaction kinetics for mineral/fluid chemical exchange are of similar magnitude to molecular diffusion over the characteristic distance (L = 0.2 m). The veins are thus interpreted as local segregation phenomena and not as fluid dehydration channels of the subduction zone.

LS06 : THpm30 : G0
The Metamorphic Field Gradient in the Eclogite Type Locality

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The eclogite type locality in the Eastern Alps (Koralpe region) is the largest region of the Alps preserving high grade metamorphic rocks from the early part of the Alpine orogenic cycle: the Eoalpine event in the Cretaceous. The principal characteristics of the region are: (1) The gradient of Eoalpine metamorphism in the Koralpe is inverted. It increases from North to South over a distance of 50 km from greenschist to amphibolite and eclogite facies conditions along a structurally south-dipping sequence. This sequence consists of predominately metapelitic rocks containing metre to kilometre sized mafic bodies that are amphibolites in the north and eclogites in the south. (2) South of the highest grade rocks, the gradient drops symmetrically to the north, back down to lower grade conditions. (3) The structure is controlled by the flat-lying Plattengneiss shear zone, which is the largest shear zone in the Eastern Alps and covers the central 40 km of the transsect, where the metamorphic grade is the highest. (4) Eoalpine deformation occurred synchronous with the metamorphic peak and age of metamorphism decreases with increasing grade. (5) Despite the high grade, Eoalpine parageneses show relics of previous metamorphic events, indicating very heterogeneous equilibration and possibly short duration of the event. We show that, in the northern half of the profile, both pressure and temperature increase constantly from north to south across all boundaries that have been assigned tectonic significance by previous authors over a length of about 60 km. However, while pressure increases from 6 kbar to at least 15 kbar, temperatures increase only from 600°C to 700°C over the same distance. A comparable continuous decrease of the PT conditions can be seen in the southern part of the profile where pressure decreases from 15 kbar to 6 kbar over about 40 km. These results indicate that the metamorphic conditions of the eclogite type locality are not very perturbed from the stable geotherm, while the lower grade rocks to the north and south indicate a significant departure from thermally normal conditions at this time. These results are not completely consistent with traditional interpretations of the region. We discuss alternative interpretations to explain these features of this classic area. (This study is supported by FWF P12846-GEO and and by Large Scale Geochemical Facility in Bristol.)

LS06 : THpm31 : G0
Comparison of Kinematic Forward-Modelling and Field Evidence of Exhuming High Pressure Rocks (Schobergruppe, Austria)

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The Schobergruppe eclogites, lying between the Tauern Window to the N and the Periadriatic Lineament to the S, are part of the Austroalpine basement units, and are part of an eo-Alpine high-pressure belt (Thöni & Jagoutz, 1993, Thöni 1999). The high-pressure rocks were brought to depth at about 150 Ma, reaching their PT-peak at >97 Ma at conditions of 1.6-1.8 GPa and 630-690°C (Linner, 1999).

Detailed structural mapping of the eclogites and their contact to the host rocks was based on rectified aerial photographs, supported by microstructural analyses on thin-sections. The aerial photograph was combined with a digital elevation model, resulting in a 3D-map of the eclogite body.

The kinematic 3D-modeling software Noddy(r) (Jessel & Valenta 1996) was used to support interpretations of very complicated small-scale fold interference patterns and to allow modeling of the eclogite body itself on a larger scale. The resulting block model for the latter was combined with the local DEM, to compare the modeling with the mapping approach.

The high-pressure rocks were affected by five distinct but continuous deformation phases. The oldest structural record, Dn+1, is a rare oblique internal foliation locally preserved within some eclogite boudins. Dn+2 comprises a sequence of heterogeneous deformation events in space and time under eclogite facies conditions, resulting in a rather complex pattern of anastomosing shear zones alternating with folded and boudinaged metamorphic layering. Dn+2 is interpreted as recording the beginning of the exhumation under high-pressure conditions, within a top-to-NW general-shear flow.

A strong mylonitic and compositional foliation Sn+2 as well as a stretching lineation Ln+2a acted as marker planes and lines during all the following deformation phases. Important and obvious structural elements are several large-scale Dn+2b shear zones that probably formed within axial planes of large Dn+2a isoclinal folds. Dn+2a and b developed within the same kinematic frame.

At the base of the high-pressure rocks, tight Dn+3 folds developed preferentially in the host rocks producing a rather complicated interference pattern between Type 2 and 3 (Ramsay & Huber, 1987).

All ductile structures were overprinted by Dn+4, an extensional top-to-SE deformation. An upright, open folding and crenulation in the host rock (Dn+5) is considered to be linked to the exhumation of the Tauern Window further north of the investigated area (Wallis & Behrmann, 1996).

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Origin and P,T,t Path from Eclogites of the Escambray Massif (Cuba) Exhumed in a Subduction Context

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The understanding of the exhumation mechanisms of high pressure rocks is still a matter of debate. One of the motor generally invoked is the collision, but outcrops of blueschists and eclogites are also found in some actual subduction zones. Three eclogitic samples from the eastern part of the Escambray massif (Cuba) have been studied in order to obtain contraints on this problematic.

The Escambray massif is one of the three metamorphic complexes of the southwestern Cuban terranes, separated from the northern Maburjina amphibolitic massif by a strike-slip fault. The massif is constituted by two metamorphic domes. Each dome consists of three distinct nappe units and shows a reverse distribution of the metamorphic isograde from eclogites on top to greenschists in the lower structural unit. The studied samples have been collected in eclogitic lenses included in serpentinite or metasediments.

Geochemical analyses (major, traces elements and isotopes) of high pressure rocks from the eastern part of the Escambray massif show that some of them derived from a calc-alkaline arc similar to the one that was active during Cretaceous along the north-east subduction of Pacific under the proto-Caraibbean plate. The HP metamorphism therefore can be linked to this subduction.

The petrological study of a metabasite shows a prograd path from the epidote-amphibolite facies to the barroisite-eclogitic facies (T=560±80°C, P>12kbar). Other samples recorded the same peak conditions. These metabasites show evidences of a retromorphosis starting in the field of the glaucophane bearing eclogite till the lawsonite bearing blueschist facies. The metamorphic history of these eclogites recorded an anti-clockwise P/T path.

Concordant geochronological data (Rb/Sr and Ar/Ar) suggest that the eclogitic peak of these rocks has been reached before 70 Ma. A previous study (Goncalves, 1998) on diffrent eclogites from the Escambray massif show a similar but colder P/T history (400±60°C). The exhumation in the blueschist facies is dated at 86±2 Ma (Rb/Sr). The presence of eclogites exhumed at different moments during subduction and before any collisional events (the first event is dated around 55 Ma), substantiates that exhumation was related to the subduction processes. Moreover, the arrival of an oceanic plateau near the subduction zone between 86 and 70 Ma could be responsible for the decrease of the subduction velocity. This variation of the subduction velocity induced a heating in the slab area which is recorded in eclogites from the eastern part of the Escambray massif. These observations are in good agreement with proposed geodynamical models of the Caraibbean evolution.

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P-T Paths of the Mesozoic Raspas Eclogites, Andean Belt (Ecuador): Possible Constraints on Exhumation

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The Raspas Metamorphic Complex (SW Ecuador) derives from an oceanic lithosphere subducted during the latest Jurassic-early Cretaceous. The HP rocks are composed of an ophiolitic sequence consisting of metaperidotites, eclogite-facies mafic rocks (former gabbros and/or basalts) and metapelites. The mafic rocks comprise eclogites, garnet amphibolites and blueschists. The eclogites display the assemblage garnet+omphacite+barroisite±clinozoisite+ rutile. Phengite is also sometimes present. Garnet record a growth zoning (decreasing MnO and increasing MgO from core to rim). The garnet amphibolites are characterized by the assemblage garnet+barroisite+clinozoisite+quartz. Rare blueschists are amphibole- and mica-rich foliated rocks displaying a garnet + amphibole + epidote + mica + quartz + rutile paragenesis. Garnet also preserves growth zoning. Amphiboles show a barroisitic core overgrown by a glaucophanitic rim. Retrograde phases in the blueschists include abundant chlorite, albite, titanite and calcite. Field relations and bulk-rock chemical analyses show systematic differences between eclogites, garnet amphibolites and blueschists, suggesting that the three main mafic lithologies observed correspond to three different protoliths. On the contrary, the observed parageneses of the three lithological groups indicate that they experienced the same P-T conditions. Associated metapelites are mainly graphite- and garnet-bearing micaschists. Peak assemblages include the rare association garnet-chloritoid-kyanite, stable in a narrow P-T field in the KFMASH system. Garnet zonation and changes in chemistry of chloritoid record increasing T during the prograde path. Estimated peak PT conditions for the Raspas metapelites are at about 600°C, 15-20 kbar.The replacement of garnet and kyanite by chloritoid-quartz aggregates in the metapelites indicate decreasing temperature during the early stages of the decompression. This is well illustrated by the particular, and well-constrained, shape of the P-T path recorded by the metapelites, where the retrograde path is close to the prograde one, at least during the early stages of the exhumation history. Field data and microstructural analyses show that the regional deformation developed during the eclogite facies, and is significantly overprinted by lower-temperature parageneses only along the bounding shear zones. The latter are presently est-west trending dextral faults. The excellent preservation of the high-pressure parageneses, including the growth zoning in garnet and overprinting relations in the amphiboles, and the temperature decrease during the early stages of the decompression suggest high exhumation rates.

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Himalayan Subduction of the Indian Plate in NW Pakistan: Good, Bad and Indifferent Eye-Witnesses

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The recent discovery of coesite eclogites, in the parts of the subducted Indian Plate returned to the surface during the Himalayan Orogeny in Kaghan Valley, N Pakistan, has rejuvenated interest in the study of the geodynamic evolution of this most spectacular of all Earth's collision belts. The dominant rock series exposed south of the Indus Suture (Main Mantle Thrust) are meta-granitic basement gneisses and two series of meta-sedimentary cover rocks. The main amphibolite facies metamorphism evident in the series is strongly overprinted by a greenshist-facies event reflected in widespread growth of albite porphyroblasts. These themselves have been stretched and folded during a final extension-related exhumation. Metabasites, some with well preserved eclogite-facies assemblages, occur as boudins and sheets of various sizes in all units and have been interpreted as metamorphosed Panjal Trap basalts and their feeder dykes. If this hypothesis is true, as backed up by SHRIMP dating of eclogite zircon, then the presence of coesite-eclogite in this rock series means that the whole basement sequence and its cover units must also have been subducted to depths of 90 km or more. This would be spectacular alone if it were not for the amazing preservation of primary textural information in the baement gneisses. Although often strongly deformed, there are places where the granitic basement gneisses exhibit schlieren structures and textures strongly reminiscent of migmatitic, garnet-bearing leucosomes. Such features are typical for rocks that experienced temperatures of 1000K or more - values not attained during the Himalayan event if the multi-stage metamorphic evolution of the metabasites is taken as a guide - and thus these textures inform us about conditions of pre-Himalayan, perhaps even Precambrian, metamorphism. Further south from the suture zone, around Naran, widespread meta-granites are noted for their conspicuous coronas of garnet around magmatic biotite - again evidence for a restricted amount of reaction at high pressure conditions. In such relatively dry rocks the sluggishness of reaction at high pressure conditions means that the average density of the subducted segment would have been much lower that that predicted assuming equilibrium mineral assemblages, and would thus have added a significant buoyancy component to drive the required very rapid exhumation of these rocks.