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REPORT

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Summary:
This report contains the scientific program and abstract volume for the lectures and posters presented during the Alice Wain Memorial West Norway Eclogite Field Symposium. The lecture and field symposium, held in Selje from June 21st-28th, 2003, focuses on the dynamic processes of high- and ultrahigh- pressure metamorphism and exhumation of eclogites and associated rock types. The Symposium commemorates the outstanding contributions to west Norway eclogite research by the late Dr. Alice Wain, whose life was tragically ended by a fatal field vehicle accident in Scotland early in 2000. The main symposium themes cover micro- through macro-scale processes and include topics of mineralogy, geochemistry, microstructures, geochronology, field relationships and exhumation mechanisms, and kinetic and thermodynamic considerations of HP-UHPM rocks. The organising committee for the symposium, headed by Prof. Tony Carswell (Sheffield University) with logistical support from the Geological Survey of Norway in Trondheim, is held under the auspices of the Task Group for ILP Project III-8 on "Processes and Geodynamics in the formation and Exhumation of Ultra-High Pressure Metamorphic Terranes" and the International Eclogite Conference Committee. The abstracts presented in this volume exemplify the international interest in and broad spectrum of these HP-UHPM rocks and their roles in understanding lithosphere dynamics.

Keywords: Eclogite	West Norway	Eclogite facies
Metamorphism	Ultra-high pressure	Structure
Exhumation	Geochronology	Thermodynamics

The Alice Wain Memorial West Norway Eclogite Field Symposium

June 21st–28th, 2003, Selje, western Norway

Abstract volume and scientific program

Scientific program committee:
Tony A. Carswell
Hannes Brueckner
Simon Cuthbert

Volume editor:
Elizabeth A. Eide

Lecture Programme for the Alice Wain Memorial West Norway Eclogite Field Symposium 2003 in Selje, West Norway

	Sunday 22nd June	Monday 23rd June	Tuesday 24th June	Thursday 26th June
Themes:	*UHPM mineralogy & petrology*	*Geochemistry; geochronology*	*Metastability / reactivity; Tectonics & deformation*	*Geodynamic models; Orogenic garnet peridotites /pyroxenites*
Chairpersons	**Krogh-Ravna & Brueckner**	**Hacker & Terry**	**Robinson & Eide**	**Medaris and Andersen**
08.30 – 08.50	Dobrzhinetskaya	John	Langenhorst **(Terry, speaker)**	Brandon
08.50 – 09.10	Massonne	To be announced	Perchuk	Stockhert
09.10 – 09.30	Godard	Zheng Yong-Fei	Engvik	Indares
09.30 – 09.50	Xu Shutong	Zhang Zeming **(Liou, speaker)**	Lund	Ring
09.50 – 10.10	Zhang, R.Y.	Gilotti	Boundy	Brouwer
10.10 – 10.30	Schertl	Bingen	Cuthbert	Krabbendam
Coffee Break				
10.50 – 11.10	Bromiley	Root	Lombardo	**Bakun-Czubarow**
11.10 – 11.30	**Masago**	**T. Krogh**	Ravna	Green
11.30 – 11.50	Skjerlie	**Walsh**	Terry	Medaris
11.50 – 12.10	Nakamura	Robinson	Young	Spengler
12.10 – 12.30	Carswell **(Cuthbert, speaker)**	Hacker	Labrousse	Brueckner

Program Comments:
We have had to make changes in the program, and there may be other changes yet to come. Several people will not be able to attend the meeting including our coordinating chairman and guiding spirit, Tony Carswell, who has worked so hard to make this meeting a success. In addition, the oubreak of SARS has caused some of the Chinese scientists cancel. We are saddened by the prospect of not seeing so many of our colleagues and friends. Nevertheless the show must go on! The changes are shown in **bold type** in the schedule above. **Please let us know if you cannot come and yet are still listed on the program.** Note also the names of people who have agreed to chair the sessions.

Hannes Brueckner, Tony Carswell and Simon Cuthbert
1 June 2003

Volume Comments:
The abstracts were accepted as they were received and have undergone no significant editing for the purpose of this abstract volume. Changes to individual abstracts were almost exclusively of a formatting nature. In cases where the first author is not the person presenting the abstract as a lecture or poster, the presenting co-author's name has been underlined.

Elizabeth Eide
9 June 2003

Origin of eclogitic metagabbro mass in the Sambagawa belt: mantle wedge vs. ocean floor

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Eclogite-bearing metagabbro masses in the Sambagawa belt, a high-*P/T* metamorphic belt in SW Japan, have long been regarded as tectonic blocks derived from the mantle wedge of the former Sambagawa subduction zone. In order to assess this hypothesis, one of the metagabbro masses (the Seba metagabbro) was selected for structural and geochemical studies focusing on the relationship between this body and the surrounding schists that have an ocean-floor origin. These studies reveal the following characteristics for the Seba mass: i) the metagabbro is completely enclosed within the surrounding schists; ii) the marginal shear zone located between the enveloping pelitic schist and the central metagabbro has an intermediate bulk chemical composition between the two; and iii) the marginal shear zone displays prominent 10cm-scale chemical banding. These features can be readily explained in a model where the metagabbro originated on the ocean floor as an olistolith. The same feature would be difficult to account for if the metagabbro were derived from the mantle-wedge. The olistolith hypothesis also requires: i) the marginal shear zone originated as a sedimentary rock; and ii) the Seba metagabbro is a part of an olistostrome complex. Both these features are confirmed by field studies outside the Seba metagabbro. Based on these results, the Seba metagabbro is concluded to have originated on the ocean floor as an olistolith complex. The other eclogitic metagabbro masses in the Sambagawa belt show similarities with the Seba metagabbro, suggesting that most of these masses originated as blocks on the ocean floor, which were subsequently subducted together with their surrounding lithologies.

Keywords: bulk chemistry, mega-structure, metagabbro, olistolith, Sambagawa belt

An unusual mantle mineral group in ophiolite, Tibet

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An unusual mantle mineral group consisting of more than 80 species (or subspecies) minerals was discovered in chromitite from the Yarlungzangbo ophiolite belt, Tibet. It includes native element minerals, alloys, oxides, sulfide (arsenides) and silicates.

Pressure indicative minerals: Diamond, Moissanite, Si-rutile, Si-spinel, FeO(Wustite), native iron, free SiO_2, coesite.

Native element minerals: The native element minerals determined by the energy and wave spectrum analyses (some determined by X-ray diffraction, Native element minerals are: native Si, Fe, Zn, Pb, Al, Cr, Sn, Ni, Os, Ir, Ru, Rh, Pd, Au, Ag, W, Cu and Ti minerals, and graphite (diamond).

Alloys: Numerous alloy minerals have been identified. They are made by mixing different elements in different element proportions. Many of them are unnamed. The species of the alloys are as follows: Fe_3Si7, Si_3Fe_2, FeSi, Fe_7Si_3, Fe_3Si_2, $Fe_4Ti_3Si_2P$, Ni_3Fe, Ni_7Fe_3, $Ni_5Fe_3Cr_2$, Fe_9Cr, Fe_2Ni, Ni(Fe,Ir), Ni_4FeIr, Ir_2Ni_3Fe, Ir_3Fe_2, Ir_7Fe_3, Pt_5Fe_2, NiIr, Ir_2O_5, Ir_3Os_2, OsRu, Ru_3O_5, Os_3RuIr, Pt_7Fe_3, $Pt_5Fe_3Pd_2$, Os_3Ir_2, Fe_2Ru, NiC, FeC, TiC, WC, (W,Co)C, FeCo, SiC, Al_2Fe_2La, W_4Co, Cr_3C_2, CrC, Cr_4C, Cr_3C, Cr_7C_3, Fe_3MN, Ag_6Au, Ag_8SN_2, Ir_5Fe_4Ni, Si_2TiFe, NiFeSi, Ti_6W_4, Cu_3Zn, Fe_8CrNi, Fe_4CrC_3, Fe_6C_3Cr, Ni_6C_4, $Si_6CaAlFe$, $Si_7(Fe,Al)_3$, Si_7Ca_2Fe, Si_7Ca_3, Ti_2N_3, Si_2Ca, $Si_5Fe_2Al_2Ca$, $Si_5Fe_{2.5}Ti_{2.5}$, Si_6CaCu etc.

Oxides: Most of the identified oxides occur as inclusions in chrome spinel, alloy and native element minerals. The known oxides are : FeO, Fe_2O_3, Fe_3O_4, MgO, (Mg,Fe)O, SiO_2, CaO, Al_2O_3, $MgAl_2O_4$, $Mg(Al,Si)_{2-X}O_4$, TiO_2, $(Ti,Si)O_2$, $(Si,Ca)O_2$, $(Mg,Fe)_2(Cr,Al,Si)_4O_8$, $(Zr,Si)O_2$, CuO, ZnO, PbO, $(Fe,Ni,Si)_{1-X}O$, and $(Fe,Si,Mn,Ti)_{1-X}O$. Most of them are non-stoichiometric in chemical compositions.

Sulphides and arsenides: The following sulphides and arsenides have been identified: FeS, Pd_3Te, $(Pd,Fe,Cu)_2S$, Ag_4S, $(N(,Fe)_3S_2$, IrSAs, $(Os, Ru)S_2$,FeSAs, Ni_2S,MoS_2, Ag_8S_2, Pb_6S_2, Pd_6As_4, $(Ni,Fe)_4S_3$, (Fe,Ni,Co)S, Ni_3S_2, Sb_3S_5, Sb_3S_2, FeS_2, $(Fe,Cu)S_2$, PbS, RuS_2, $(Os, Ru)S_2$, $(Ru,Os)_3S_4$, MnS, Ti_yS_3 and PtAs.

Disussion: Some pressure indicative minerals, e.g., diamond and coesite, reveal that the formational activities of paleo-oceanic crust and mantle) may at least have reached a depth below 150km, whereas other minerals, such as silicon-rutile $(Ti_{0.82}\ Si_{0.18})O_2$, silicon-spinel and FeO(wustite), suggest that they were formed at even deeper. Laboratory experiments performed by Knittle and Jeanloz (1991) under temperature-pressures of the Earth's outer core and the base of the lower mantle, have demonstrated the formation of the FeO, SiO_2, Si_xFe_y, Fe and silicate assemblage. The mineral assemblage of Luobusa is similar to that from experiment, suggesting that the minerals of Luobusa were products of the chemical reactions at the core-mantle boundary. Mantle plume may originate at the boundary, during their upwelling, they carry small quantities of ultrahigh pressure minerals upwards to the upper mantle.

Non-silicates of the Chijiadian garnet lherzolite in the Sulu UHP metamorphic terrane, eastern central China

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The Chijiadian garnet lherzolite with coesite eclogite pod forms 0.12 km^2 big body, within quartzofeldspathic gneisses, 10 km southwest from Rongcheng, in northeastern part of the Sulu UHP terrane. The massive equigranular rock consists of olivine, orthopyroxene, clinopyroxene, garnet, late pargasitic amphibole and non-silicates: spinels, ilmenites and sulphides. The whole rock chemical composition and mineral chemistry of silicates as well point to the origin of the rock from the upper mantle peridotite depleted by partial melting. Mg-rich olivine (Fo_{90}), enstatite (*mg* = 0.91) poor in Al_2O_3, CaO and TiO_2 as well as Cr-diopside are typical for the mantle rocks of the garnet peridotite facies. Relatively homogenous garnets show an average composition $Pyr_{66}Alm_{22}Ca\text{-}mol_{12}$ (*mg* = 0.75; Cr_2O_3= 4.1 wt %) and sporadically only, in garnet cores with exsolutions of pyroxene and Cr-spinel, spots richer in Cr_2O_3 and CaO ($Pyr_{61}Alm_{23}Ca\text{-}mol_{17}$) can be found. The lherzolite in question underwent four stages (protolith, eclogite, granulite-amphibolite and greenschist facies) metamorphic evolution (Zhang et al. 1994, 2000).

The omnipresent spinels display diversified mineral chemistry troughout metamorphic history. The biggest euhedral spinel grains up to 50 µm in diameter or their relics belong most likely to the oldest generation (protolith or eclogite facies stage). They often show compositional zoning from $(Al_{0.93}Cr_{0.96}Fe^{3+}_{0.11})$ $(Mg_{0.45}Fe^{2+}_{0.55})O_4$ in core to $(Al_{1.38}Cr_{0.60}Fe^{3+}_{0.02})$ $(Mg_{0.60}Fe^{2+}_{0.40})O_4$ in rim, thus their *cr number* decreases (0.51 – 0.31), while *mg number* increases (0.45 – 0.60) rimwards. Unusual, tiny (below 2.5 µm in diameter) spinel grains, included in cores of some garnets, belong probably to the eclogite facies generation and range within the limit from $(Al_{1.04}Cr_{0.92}Fe^{3+}_{0.04})$ $(Mg_{0.63}Fe^{2+}_{0.37})O_4$ to $(Al_{0.50}Cr_{1.19}Fe^{3+}_{0.31})$ $(Mg_{0.43}Fe^{2+}_{0.57})O_4$, thus their *cr* value varies from 0.47 to 0.70, while *mg* changes within the range 0.63 - 0.43. These small spinels can be often found in the vicinity of exsolved orthopyroxenes or forming with orthopyroxene the two-phase inclusions within the garnet cores. Very fine chromite platelets can be also found in olivine grains with abundant exsolutions of ilmenite needles. The chromite inclusions are oriented along [100] direction of olivine. Next generation, granulite facies spinels are intergrown with orthopyroxene and clinopyroxene in kelyphitic radial rims around garnets. Being distinctly poor in chromium and ferric ion, they show the following average composition $(Al_{1.91}Cr_{0.06}Fe^{3+}_{0.03})$ $(Mg_{0.80}Fe^{2+}_{0.20})O_4$, with *cr* = 0.03 & *mg* = 0.80. The latest generation spinels are pure magnetites formed during serpentinization of olivine and orthopyroxene.

Ilmenites occur in the two different microstructural varieties. First of them represents relatively pure ilmenite forming tiny, less than 1 µm in diameter, and up to 90 µm long needles exsolved in olivines parallel to [010] direction, while the second variety forms coarser, symplectitic intergrowths with olivines replacing former titanian clinohumite. The second type of ilmenites include from 17 to 29 mol. % of geikielite and, complementarly, from 14 to less than 1 mol. % of pyrophanite.

From among sulphides Co-bearing pentlandite, forming grains near microfractures, has been recognized. The chemical composition of pentlandite ranges from $(Fe_{4.0}Ni_{4.8}Co_{0.2})S_8$ to $(Fe_{5.3}Ni_{3.3}Co_{0.4})S_8$. As the maximum thermal stability of pentlandite is close to 610 ^oC, this sulphide should be considered as belonging to the amphibolite facies paragenesis.
The P-T conditions of extreme metamorphism for the Chijiadian garnet peridotites were estimated for 4-5 GPa at 820^0C or 5-6 GPa at 780^0C, depending on the conventional geothermobarometers chosen (Hiramatsu et al. 1995) as well as for 4-6 GPa at $820\text{-}920^0C$ (Zhang et al. 2000) thus the rocks underwent UHPM under conditions of forbidden zone, with the geothermal gradient $<5\ ^0C\ km^{-1}$. In the present paper, on one hand, the ultradeep origin of the Chijiadian garnet lherzolite has been confirmed by the two microstructural features: 1) abundant exsolutions of $FeTiO_3$ needles within old olivine grains (cf the ultradeep Alpe Arami peridotite according to Dobrzhinetskaya et al. 1996, and TiO_2 solubility in olivine, Dobrzhinetskaya et al. 2000; Liou et al. 1998), as well as 2) exsolutions of fine orthopyroxene and subordinate clinopyroxene within garnet cores pointing to the pre-existance of majoritic garnets (cf Van Roermund et al. 2000; Haggerty, Sautter 1990). On the other hand, the presence of ilmenite–olivine symplectites being the product of titanian clinohumite breakdown points to the fertilization of the Chijiadian lherzolite within the supra-subduction zone of the mantle wedge (cf Wirth et al. 2001; Liou et al. op. cit.).

Thus, the Chijiadian garnet lherzolite represents, most likely, a depleted garnet peridotite from the supra-subduction mantle wedge, that underwent metasomatic enrichment and incorporation into the subducting cold lithospheric plate, then, during Triassic collision between the Sino-Korean and Yangtze cratons the rock was subjected to ultradeep submergence and to the final exhumation.

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Coesite-graphite facies eclogites in the eastern termination of the West Sudetes, SW Poland

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The UHP metamorphic rocks are being recognized recently by the presence of index minerals (coesite, diamond) or their pseudomorphs, by diagnostic chemical composition of the other minerals (supersilicic clinopyroxenes and garnets) or products of their breakdown with the exsolution microstructures, as well as by equilibration conditions of HP mineral assemblages, e.g. Grt-Omp-Phe±Qtz/Cs±Ky or Grt-Qtz/Cs-Rt-Ttn-Zo.

In the Bohemian Massif within the Central European Variscides neither coesite relicts nor diamonds were found in metamorphic rocks until quite recently when Massonne recognized diamonds (1999) and coesite relicts (Massonne 2001) in UHP rocks of Central Erzgebirge. In UHPM rocks of the West Sudetes, in the northwestern Bohemian Massif, only pseudomorphed coesite and quartz exsolutions within clinopyroxenes have been found so far (Bakun-Czubarow 1992).

In the eastern termination of the West Sudetes, the eclogites and eclogite-granulite rocks that underwent UHPM outcrop within orthogneisses, in the core of the Orlica-Snieznik Dome in the hanging wall of the Moldanubian thrust zone. Four types of UHPM eclogitic rocks can be distinguished on the basis of geochemical provenance, the extreme metamorphism parageneses and structures: 1) laminated eclogites of MORB provenance displaying peak metamorphism assemblage Omp-Grt-Qtz-Phe-Ky-Rt±Amp±Zo±Dol, 2) the MORB provenance porphyroblastic eclogites devoid of kyanite Omp-Grt-Qtz-Phe-Rt-Amp-Zo, 3) the massive eclogites of calc-alkaline affinity devoid of kyanite and phengite Omp-Grt-Qtz-Rt±Amp±Zo, as well as 4) eclogites from granulites devoid of phengite, with peak metamorphism assemblage Omp-Grt-Qtz-Rt-Ilm±Ky±Amp±Pl. In the present study particular attention has been paid to phengite eclogites (types 1 & 2) suitable for determination peak metamorphism conditions. The samples displaying textural equilibrium of phengites with the garnet-omphacite pairs and devoid of phengite-rich veins were selected for detailed study. In the investigated eclogites the X_{Ca} value of garnets varies within the limit 0.20 - 0.34, the jadeite component in omphacites ranges from 0.22 to 0.42, while Si content in phengites changes from 3.34 to 3.48 pfu.

In order to estimate the peak metamorphism conditions for phengite-bearing eclogites we used geothermometers based on Fe^{2+}-Mg exchange equilibria between Grt-Cpx (Powell 1985) and/or Grt-Phe (Green, Hellman 1982) as well as new geothermobarometric formulations for net transfer reactions in Grt-Cpx-Phe-Ky-Qtz/Cs assemblages (Ravna, Terry 2001). For estimation of peak metamorphism conditions there were used assemblages of omphacite with the highest jadeite content, garnet with the highest X_{Ca} value, and phengite with the maximum Si content. On one hand, the results obtained on Grt-Cpx-Phe equilibria for peak conditions of the type 1 eclogites range from 2.8 to 3.3 GPa at temperature varying from 750 to 810 ^{0}C. On the other hand the appropriate estimates obtained for the type 2 eclogites cluster around 2.8±0.1 GPa at 750±30 ^{0}C. Thus, all the peak condition estimates for the both eclogite types in question fall into coesite and graphite stability field. However, the question whether the obtained estimates correspond to the *real* peak pressures of the Sudetic UHP eclogites

remains open, and the alternative interpretation of the results as describing the conditions of incipient isothermal decompression of eclogitic rocks cannot be excluded.

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Origin of Western Gneiss Region garnet peridotites: refertilisation of Archean lithosphere? Evidence from the Almklovdalen peridotite body

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Previous work on the Almklovdalen peridotite body in the southern Western Gneiss Region (WGR) has had a tendency to focus on the garnet peridotites rather than the dunites despite the latter being the most volumetrically significant rock type. This is partly due to the fact that the dunites have been long interpreted as simply representing retrograded garnet peridotite. However, this study has revealed that the bulk of the dunites at Almklovdalen are highly refractory and may in fact represent primary lithospheric mantle material residual from strong melt depletion.

The Almklovdalen peridotites have whole-rock compositions that are depleted relative to estimates for primitive mantle. The garnet peridotites are less depleted with lower whole-rock Mg# and much higher whole-rock Ca and Al contents than the dunites. The dunites have extremely depleted compositions with Mg# in the range 92-93.6 and are very poor in Al and other magmaphile elements. Comparison of the Almklovdalen dunite compositions with experimentally derived melt suggests that the dunites can be modelled as residues after very high degrees (60%?) of melt extraction at high-pressure (5-7 GPa). In contrast the Almklovdalen garnet peridotites are consistent with being residues after ~20-35% partial melting at low pressure (2 GPa). On a SiO_2 vs MgO/SiO_2 diagram the dunites fall along the olivine-orthopyroxene mixing trend typical of low-temperature cratonic peridotites whereas the garnet peridotites lie on the residual melting trend for pyrolite suggesting that they more closely resemble high-T than low-T peridotite. This is supported by rare-earth element patterns for the Almklovdalen garnets which show high HREE but depleted LREE similar to garnets from high-T sheared peridotite xenoliths.

The differences in the pressure estimates for the garnet peridotites and dunites suggests that these rock types are not related by a simple progressive melt-depletion process. The key may lie in the mineralogical and compositional similarity between the garnet peridotites and high-T sheared peridotite xenoliths in kimberlites that represent refertilisation of a depleted precursor. The close spatial relationship between the fertile garnet peridotites and the highly depleted dunites at Almklovdalen are consistent with the garnet peridotite bodies representing zones of refertilised dunite. This is supported by the common association of the garnet peridotites with bands of eclogite and garnet pyroxenite, which might represent the crystallisation of percolating mafic melts.

Recent work by Griffin *et al*. (2002) has concluded that at least some Proterozoic lithosphere may represent strongly reworked Archean lithospheric mantle. If this is the case for the garnet peridotite bodies from the WGR, which are generally considered to be Proterozoic in age, then it might be expected that Archean isotopic signatures may be preserved in the reworked peridotite. To investigate this, Re-Os isotopes were measured *in situ* by multi-collector-laser ablation-ICPMS for sulfides from both the garnet peridotites and dunites. Re-Os T_{RD} model ages for the sulfides from the garnet-bearing peridotites define a strong peak at ~1.7 Ga which falls within the age range for the Gothian orogeny and matches previous age estimates for the peridotites. However, peaks at 2.8 and 3.2 Ga do not correspond with any known event in the WGR crust and suggest that the peridotites experienced an Archean partial melting event. The dunites have also yielded Archean whole-rock Re-Os T_{RD} ages (~2.7 Ga) which further

strengthens the case that they are the original depleted precursor to the garnet peridotites. The timing of refertilisation is harder to constrain but the Proterozoic age recorded in the garnet peridotites is close to the age of intrusion (Sm-Nd mineral age of ~1.82 Ga) for the pyroxenites at Almklovdalen (Brueckner and Medaris, 1998).

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Geochronology of the Bergen Arcs eclogites, W Norway: new SIMS zircon data and implications for Caledonian tectonic evolution

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Published ages on eclogite-facies metamorphism in the Bergen Arcs, Caledonides of W Norway, encompass the entire Silurian and Ordovician periods. Controversy over the timing of metamorphism and exhumation largely reflects problems in analyzing appropriate products and in interpreting data from occurrences showing incomplete achievement of eclogite-facies equilibrium. An improved dating and characterization of eclogite-facies metamorphism is derived from new SIMS U-Pb and trace element data on zircon from samples analyzed by Bingen et al. (2001 a, b).

Eclogite occurs in the crystalline Lindås nappe, which contains a Proterozoic (ca. 1237 to 951 Ma) anorthosite complex affected by penetrative granulite-facies Sveconorwegian metamorphism at ca. 931 Ma. Zircon grains in three granulite samples display magmatic cores ($1.03 \leq Th/U \leq 1.48$) and Sveconorwegian metamorphic rims ($0.40 \leq Th/U \leq 0.74$). Chondrite-normalized REE patterns of these two types of zircon are characterized by HREE enrichment ($223 \leq Lu_N \leq 2480$), positive Ce anomaly and negative Eu anomaly ($0.38 \leq Eu/Eu^* \leq 0.64$). Caledonian eclogite-facies overprint at 1.8–2.1 Gpa and 700°C was initiated along fractures in the meta-anorthosite complex and was kinetically controlled by introduction of a H_2O dominated metamorphic fluid. Eclogitization developed into 0.1 to 100 m thick eclogite-facies shear zones. Zircon grains in one unsheared eclogite sample generally display a Proterozoic core, which may be microscopic (~10 µm), and Caledonian rims. The Proterozoic cores have trace element signatures identical to the ones of zircon in the granulite samples. Seven SIMS U-Pb analyses of zircon core have $^{206}Pb/^{238}U$ apparent ages ranging from 934 ±37 to 777 ±33 Ma. The youngest apparent ages are obtained from poorly zoned zircon and probably affected by post-Sveconorwegian Pb loss. Caledonian rims are either weakly zoned or oscillatory zoned. The oscillatory zoned rims are the most peripheral, they are euhedral, and they attest to fluid-present condition during growth. The Caledonian rims are characterized by a Th/U ratio lower than 0.13. Their REE patterns display low LREE contents, enrichment in HREE with large spread in HREE contents, and a positive Ce anomaly. Some spectra display a decrease in abundance between Tb and Lu ($0.71 \leq Dy_N/Yb_N \leq 2.6$). The large spread in HREE content is attributed to coeval precipitation of zircon with garnet, and the lack of Eu anomaly to the absence of feldspar in the assemblage. The low LREE and Th contents are tentatively explained by comparatively low temperature for eclogite-facies metamorphism (700°C) and to coeval precipitation of zoïzite. Trace element signatures comfort the petrographic evidence that the Caledonian rims formed during eclogite-facies overprint, either by replacement of Proterozoic zircon or from liberation of ZrO_2 and SiO_2 during sub-solidus breakdown of the two-pyroxene +garnet +plagioclase +ilmenite assemblage to form the garnet +omphacite +rutile assemblage. 31 SIMS U-Pb analyses of the rims provide a statistically single age group with a mean $^{206}Pb/^{238}U$ age of 424 ±6 Ma (MSWD =2.9). This age is interpreted as the crystallization age of the rims. The SIMS data allow reinterpretation of ID-TIMS multigrain fractions data of Bingen et al. (2001b). Five fractions of the eclogite sample characterized by euhedral rims and six fraction of the sample of the enclosing granulite define a discordia line

with intercept ages at 931 ±2 and 422 ±3 Ma (MSWD =1.1). This discordia is interpreted as a mixing line, and the lower intercept reflects formation of the euhedral rims. Five additional fractions with varied habit plot above this discordia. They include Proterozoic cores presumably affected by Pb loss after the Sveconorwegian orogeny.

The 424 ±6 or 422 ±3 Ma age reflects eclogite-facies overprint during subduction of the crystalline basement of Baltica at the onset of the Scandian collision between Laurentia and Baltica. The Lindås nappe was exhumed to middle or upper crustal level probably by an extrusion process, by 408 ±8 Ma (Rb-Sr mineral isochron age in an amphibolite shear zone). It was incorporated into the orogenic wedge during convergence of the orogen and associated with the Upper Allochthon Hardangerfjord nappe, containing low grade Ashgill to Llandovery metasediments, an Ordovician ophiolite complex and a 430 ± 6 Ma granite pluton.

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U-Pb geochronology of metamorphism in Mid-Norway, and implications for the duration of the Scandian orogenic phase in the Scandinavian Caledonides

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In the mid-Scandinavian Caldeonides, a set of prominent extensional and strike-slip shear zones separate windows of high-grade rocks from nappes of the Upper and Uppermost Allochthons containing low to medium grade rocks. The extensional shear zones have been recently regarded as the location of major attenuation of middle crust during a late stage of the Scandian collision between Baltica and Laurentia. To test this interpretation, and to constrain the timing of the main metamorphic phases in the middle transect of the Caledonian orogen, new zircon, monazite and titanite ID-TIMS and SIMS data were acquired across the two extensional shear zones limiting the Central Norway Basement Window (CNBW). The CNBW is a core complex-like culmination trending ENE-WSW, made of high-pressure amphibolite-facies, locally granulite-facies, Proterozoic gneisses of Baltica ancestry and in-folded supracrustal rocks tentatively attributed to the Seve Nappes. The CNBW is similar to the Western Gneiss Region in W Norway, except for the absence of eclogite-facies rocks and peridotite bodies. The CNBW is limited to the SW by the Høybakken detachment zone and to the NE by the Kollstraumen detachment zone. SHRIMP analyses of monazite in three samples of high-pressure amphibolite-facies metapelite in the CNBW demonstrate homogeneous monazite populations, with unimodal age distribution. ID-TIMS analyses of single-grain or small fractions give reliable and precise estimates for the timing of monazite growth. Monazite from a garnet-kyanite gneiss yields an age of 426 ±1 Ma reflecting conspicuous migmatization in the rock and probably folding with ENE-WSW fold axis. Monazite in two garnet ±kyanite gneisses with minor staurolite yields ages of 420 ±2 and 403 ±5 Ma. A deformed garnet-bearing granitic dyke yields a zircon intrusion age of 417 ±5 Ma. Titanite in four samples of calc-silicate gneiss and marble define a tight cluster between 403 and 401 ±2 Ma. Titanite in the footwall of the Høybakken detachment pre-dates top-WSW ductile extensional shearing along the shear zone and consequently constrains final exhumation of the window along this detachment zone to be younger than 401 Ma. The nappes of the Upper Allochthon (Köli nappes) and Uppermost Allochthon (Helgeland nappes) overlying the CNBW are made of greenshist to amphibolite-facies supracrustal rocks and magmatic complexes. The magmatic complexes include ophiolite complexes and diorite to granite plutonic complexes intruded during several pulses peaking at ca. 495, 480, 460, 445 and 428 Ma. Scandian translation of these outboard nappes onto Baltica occurred after the last magmatic pulse specific to these nappes, i.e. after 428 Ma. In the eastern part of the Helgeland nappes, to the NE of the CNBW, monazite in mica gneiss and titanite in amphibole gneiss and marble range from 431 ±1 to 429 ±2 Ma. On the island of Hitra, to the SW of the CNBW, titanite in a marble yields an age of 443 ±4 Ma. Analyzed monazite and titanite in these nappes are coeval with the last pulse of local plutonism. This implies that high grade meta-morphism in these nappes relates to the pre-Scandian orogenic evolution. Monazite, titanite and zircon U-Pb data constrain the duration of high-grade Scandian metamorphism to be 25 m.y. in the middle part of the Caledonian orogen (426-401 Ma). The data underscore the importance of late-Scandian detachment shear zones as tectono-metamorphic breaks between the CNBW, affected by Scandian high-grade metamorphism and tight folding, and overlying nappes of the Upper and Uppermost Allochthons, which remained at high crustal level during the Scandian event. Orogen parallel

attenuation of middle crust along these detachment shear zones partly contributed to exhumation of high-pressure amphibolite- to granulite-facies rocks exposed in the windows around 400 Ma. Titanite U-Pb data suggests that exhumation of the CNBW (403 – 401 ±2 Ma) occurred slightly before the one in the Western Gneiss Region (395 ±2 Ma).

Olivine platelette (pseudo spinifex texture)formation in sagvandite (enstatite–olivine–magnesite–talc) of the Svartisen Nappe, Norway

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Granulite facies alpine-type ultramafic bodies (up to 400 m long) occur in garnet-mica schists in the Svartisen Nappe of the Norwegian Caledonides. Ultramafic protoliths experienced intense CO_2-and SiO_2- metasomatism, producing a characteristic assemblage of enstatite, olivine, magnesite and talc. The rocks are named sagvandites (Pettersen 1883).

The meta-ultramafic bodies are zoned. The serpentinite–ophicarbonate cores contain relic olivine and enstatite. Talc is stable in the ophicarbonate further out from the core. The outer rims consist of sagvandite. Olivine-platelettes (up to 20 cm long,+/- 2.5 cm thick and /-5 cm wide, Fo_{91}) occur in the outermost rim of the body, the so called "needle olivine" sagvandite. Moreover they occur in veins in sagvandite. Metamorphic olivine platelettes, which look like needles in 2 dimensions in thin section and outcrop, were first described from Nordvernes, Norway, as producing a “Jack-straw-texture” or “pseudospinifex texture“ (Bakke & Korneliussen, 1986).

The following metamorphic evolution is interpreted for meta-ultramafic rocks of the Svartisen Nappe:

1) An early metasomatic event under greenschist facies conditions causes serpentinisation (sometimes with carbonate formation) of precursor dunites and harzburgites. Hydration may have occurred along deep faults in the subcontinental lithosphere because geologically the Svartisen area represents a zone of continent–continent collision during the Caledonian orogeny (Bucher-Nurminen 1991).
2) Talc + carbonate formation towards the rim is a result of a prograde P-T overprint and CO_2 influx.
3) At peak temperature conditions (650-700 °C) olivine (Fo_{96}) and enstatite (En_{96}) bearing sagvandite is produced at the rim of the bodies.
4) Olivine-platelette formation: retrograde metamorphism, SiO_2- and CO_2-rich fluids produce platelette-olivine in veins and sagvandite at the rim of the bodies. Field observations, thin-section textures and modelling of fluid composition suggest olivine-platelettes are formed in a fluid-rich reaction zone. This is in agreement with Trommsdorff et al. (1998), who suggest that abundant fluid is required to produce a magmatic spinifex olivine, as well as metamorphic pseudospinifex texture olivine.
5) Further retrograde evolution produces tremolite from talc and Ca-rich fluid. The abundance of tremolite and hornblende at some localities (e.g. Grønøy) record evidence of high fluid-flow and water-rock interaction during retrograde conditions.

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Paleo-earthquake faults and eclogite metamorphism in the Lofoten Islands, northern Norway

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Exposures of deep crustal paleo-earthquake faults rocks (pseudotachylytes) have been discovered in the Lofoten Islands, northern Norway. Fault plane generated pseudotachylytes are products of localized deformation at high slip rates (≥ 0.1 ms^{-1}) along faults resulting in frictional melting. They are considered to represent fossil earthquakes. The exposures of pseudotachylyte fault rocks occur within partially eclogitized mafic granulite facies rocks on Flakstadøy in Lofoten. Eclogite metamorphism in the area reflects localized fluid infiltration along fracture and shear zones within predominantly mafic rocks as they were subducted to depths of ca. 50 km. The Lofoten area thus offers a rare opportunity to garner field-based evidence bearing on the possible connection between eclogite metamorphism and the initiation of intermediate depth earthquakes in the subducting lithosphere. Based on initial field and petrologic observations of similar deep crustal pseudotachylytes in the Bergen area of western Norway, it has been proposed that the deep crustal earthquake faulting in the area resulted from the metamorphic phase transition of anhydrous granulite rocks to high-pressure eclogite rocks as an indirect results of volume reduction. The Lofoten area provides a second field locality to test the ideas developed based on the exposures in the Bergen area.

The spectacular exposures of fault rocks from the Flakstadøy area in Lofoten enable direct observations of deep crustal earthquake fault systems on a variety of scales. Most of the pseudotachylyte fault rocks studied occur in the granulites at the border to the localized eclogite facies shear zones, although some occur in granulites away from the eclogitized areas. Displacements of up to 0.5 m have been observed along mm-cm thick pseudotachylyte fault veins. The majority of the pseudotachylyte fault veins mapped are discontinuous along strike over scale of 20 m. However, some individual fault zones are continuous along strike over > 100 m. Orientations of the pseudotachylyte fault veins within the relatively homogenous mafic granulites appear to define two distinct trends, one of which is sub-parallel to the consistent orientation of the eclogite shear zones in the area. Detailed electron microprobe studies reveal that the fault vein pseudotachylytes contain fine-scale delicate quenched textures, thus confirming the former presence of a melt. Moreover, the 10-100 micron scale microlites crystallized from this melt include high-pressure minerals, such as garnet and omphacite. The texture and mineralogy indicate that the earthquake fault rocks did indeed form under high-pressure eclogite facies conditions. Within the areas of localized eclogite formation in the granulites there is a consistent, close spatial association of the eclogites and pseudotachylyte fault rocks. Some areas of pseudotachylyte that occur away from any apparent eclogite are currently being investigated. For the area of pseudotachylyte fault veins near the localized eclogite shear zones, the field relations are consistent with an intimate interaction between fluid infiltration, metamorphic transition to eclogite and earthquake faulting.

Moreover, our recent field research also reveals that the eclogite metamorphism in the Lofoten Islands are much more extensive than has previously been recognized. Several new eclogite localities were discovered including a previously unrecognized area of eclogite that extends over 2 kilometers on Flakstadøy. This area is comprised of a series 1-3m wide anastomosing eclogite and retrograded eclogite shear zones. Relic lenses of granulite protolith occur within the shear zones. In general the more leucocratic eclogites are much

more retrograded than the mafic eclogites. The eclogites and retrograded eclogites are intercalated with minor sub-parallel garnet amphibolites. Ultramylonites occur within the relic granulite protlith, however thus far no unambiguous pseudotachylyte faults rocks have been found in this area of extensive eclogite metamorphism. We hypothesize that the Lofoten eclogites and related pseudotachylyte fault rocks formed during the Caledonian orogeny based on the age of other eclogites at similar structural levels in Norway and Greenland. On-going research is aimed at quantitatively documenting the timing of eclogite metamorphism and pseudotachylytes formation in the Lofoten area.

Geodynamic analysis of the role of lithospheric mantle in the formation and exhumation of UHP metamorphic rocks

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UHP metamorphism of continental crust is commonly explained in terms of plate subduction, with the continental crust subducted to great depths and then returned within a subduction channel or as an extruding slice. We consider here an alterative model where UHP metamorphism occurs within a thickened mantle root beneath a collisional orogen. Our model is different from the plate subduction model in that we envision little or no subduction of mantle during the initial phase of continent-continent collision. UHP metamorphism starts by underthrusting of continental crust and imbrication of that crust within lithospheric mantle in the hangingwall of the orogen. The involvement of the mantle in thrusting indicates thickening of the mantle, which should ultimately lead to density-driven underflow of the mantle root, either by a drip or detachment instability. UHP metamorphism continues as the crustal rocks are entrained with the descending lithospheric mantle. Given suitable viscosity and density contrasts, some of the slices will rise within the underflow, and ultimately come to rest at the base of the overlying orogen.

This model has several favorable features: 1) The plate subduction model implies that UHP metamorphism would be occurring in the asthenosphere, yet the relatively cool temperatures (~800 C) needed for UHP metamorphism indicates that the surrounding mantle should be lithospheric, not asthenospheric. 2) UHP metamorphic terranes commonly include both crustal rocks and garnet peridotites. Early imbrication of crust and lithospheric mantle accounts for how these rocks became intermixed. 3) The collisional setting in which UHP metamorphic rocks are found generally lack mantle-derived magmatism. This observation is consistent with convergence by shortening of lithospheric mantle, rather than by subduction of a plate.

We have analyzed this conceptual model using a full thermomechanical model to represent the evolution of the crust-mantle system during continent-continent collision. The numerical experiments show that in the early stages of collision, slices of lower continental crust are entrained to depth into a thickened lithospheric mantle root beneath the young model orogen. Subsequently, the mantle lithosphere root "drips" into the mantle as a Rayleigh-Taylor-type gravitational instability. This results in partial uplift of the buried crust, as the buoyant material separates from the descending root and rises. Late stage exhumation of the crust to the surface occurs more slowly, related to exhumational processes operating within the still active collisional orogen. The P-T evolution of the buried crust is tracked in the experiments and we find its history is consistent with those observed for UHP metamorphism. Extrusion-style behavior, as predicted by Chemenda and others, does not occur, primarily because the crustal slices become too soft to allow coherent motion of an extruding slice. The two-stage history observed in our numerical modeling is remarkable similar to real UHP metamorphism terranes, which commonly show an early history of rapid decompression (~10 km/m.y.) to depths of about 30 to 20 km, followed by much slower decompression (1 to 0.1 km/m.y.) on return to the surface.

An experimental investigation of water contents in UHP pyroxenes: insights into the role of omphacite as a repository for water during subduction

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Nominally anhydrous minerals (NAMs) may play an important role as repositories for water in subducting oceanic lithosphere. Examination of UHP metamorphic terrains that have undergone subduction to upper-mantle depths can provide us with important constraints on the solubility and speciation of water in NAMs under UHP conditions. Previous investigations have demonstrated that the pyroxene omphacite can contain several thousand ppm H_2O, in the form of structurally-bound hydrogen, at high pressure. However, despite the possible importance of omphacite there has been, to date, no comprehensive experimental investigation of water incorporation. This is largely due to the complex crystal chemistry of omphacite at high pressure and difficulties with sample synthesis. Therefore in this study we have developed a method for conducting long duration annealing experiments to investigate water solubility in natural samples under upper-mantle conditions. Initial experiments have been conducted using gem-quality diopside and performed in the piston-cylinder apparatus. The technique uses a semi-permeable platinum membrane that allows free diffusion of hydrogen whilst simultaneously protecting samples from reaction with buffering agents. Experiments are performed for up to several weeks, and samples are saturated with water in a tightly controlled chemical environment. Samples are recovered, and water incorporation investigated using polarised FTIR spectroscopy.

Experiments were conducted over a range of pressures from 5 to 40 kbars, 1000 to 1100°C. A number of experiments have also been performed at 15 kbars for varying amounts of time. Results indicate that water incorporation in the diopside sample is largley controlled by the existing defect structure. Initially large amounts of hydrogen can be incorporated in the samples, possibly associated with Fe^{3+} in octahedral sites in the diopside structure. With increasing time, FTIR spectra reveal that changes in the mode of hydrogen incorporation occur, and the amount of water incorporated in the diopside decreases. This appears to be due to reduction of Fe^{3+} to Fe^{2+} under the reducing conditions under which the experiments are performed. This assertion has been tested by performing additional experiments under more oxidising conditions. Final equilibrium water contents of annealed samples are approximately 200 ppm H_2O, with a slight increase in solubility with increasing pressure. The interpretation of results given here suggests that oxidation state plays an important role in water solubility in diopside. However, results also suggest that the existing defect structure is largely unchanged, even in experiments performed for over 300 hours. Previously, annealing experiments have only been performed for less than 50 hours due to problems with sample degradation. Therefore, the results from such short-duration experiments should be viewed with some skepticism

Results from the present study have important implications for consideration of water solubility in clinopyroxenes from UHP eclogites. Measured water contents for omphacites from eclogitic terrains vary from 100s to 1000s ppm H_2O. Previous experimental investigations of water solubility in jadeite have demonstrated that hydrogen is incorporated in the omphacite structure along the edges of cation octahedra, and is usually associated with cation vacancies. This is in accordance with the observed correlation of water content with Ca-Eskola content for natural omphacite. In the long duration diopside experiments, only

Fe^{2+}/Fe^{3+} content of the samples is stabilised under high-pressure conditions, and water content is still a function of the original defect structure of the sample. This suggests that the results of high-pressure annealing experiments using omphacites are unlikely to be generally applicable because of the excessive time-scales required to equilibriate cation vacancies. However, in short duration experiments using diopside samples, hydrogen is incorporated into the structure associated with existing defects. This suggests the intriguing possibility that water incorporation can be used to investigate equilibrium defect structures in omphacite from UHP terrains. Therefore, even though current water contents in such omphacite may not be representative of contents under upper-mantle conditions, short duration annealing experiments could be used to provide information about the role of omphacite as a repository for water during subduction. Furthermore, experiments at different oxygen fugacity could be used to estimate the oxygen fugacity experienced by samples under UHP conditions. The results of such experiments could prove useful insight into determining water contents and conditions in subducting lithosphere.

Towards complete PTt paths: Unravelling Alpine eclogite relics

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High-pressure (and ultrahigh-pressure?) relics in collision zones, such as the Central Alps, occur as fragments of various sizes. This poses questions of regional and fundamental geodynamic significance. We view the HP fragments in terms of the evolution of a TAC (tectonic accretion channel; Engi et al., 2001). Fragmentation started during the subduction stage, after which the mass flow slowed down as fragments were accreted in the root of the accretionary wedge. A reversal in the flow apparently triggered further fragmentation within the TAC, subsequent extrusion of (portions of) the TAC, and emplacement of several mélange sheets into the nappe stack at mid-crustal level. This gave rise to the thin mélange units of highly variable lithologies we find in the central and southern Lepontine Alps today. Important questions that arise are: How much of this scenario is reflected by the PTt-histories of individual fragments? How independent were the PTt-evolutions of now neighbouring fragments? Are different segments of individual PTt-paths interpretable as part of a coherent flow pattern in the TAC? What caused the transitions from one PT-segment to the next?

Currently we are investigating the PTt paths of single fragments in the Southern Steep Belt of the Alps, and especially within the Mergoscia-Arbedo zone (MAZ). The MAZ is a strongly flattened composite of ortho- and paragneisses, with minor calcsilicates; intercalated mafic and ultramafic fragments, which include the enigmatic Alpe Arami garnet peridotite body, in part preserve relics of HP metamorphism. We apply a various tools to document complete PTt paths for some fragments and to investigate their significance.

Thermodynamic modelling (using *Domino*, de Capitani, 1994) of equilibrium assemblages yields estimates of the PT conditions reflected by the preserved HP relics. We find a range in pressure from 8 to 21 kbar recorded for the HP stage in mafic fragments from the MAZ; this may be extended to at least 30 kbar if the Alpe Arami garnet peridotite is included. *Domino*-modelling also allows us to interpret observed grain-scale zoning patterns in terms of relative changes in pressure and temperature during the growth (and/or resorption) of porphyroblasts. Symplectites in many high-pressure fragments record isothermal decompression to mid-crustal depth, while some carry evidence of a stage of re-heating at pressures between 9 and 6 kbar. Other fragments within the MA zone do not show any evidence of high-pressure metamorphism. We are investigating whether they never reached corresponding depths or whether this is due to resetting – the MAZ hosts migmatites with up to 30-35% leucosome. Unravelling the decompressional history is essential to determine whether the disparity in recorded PT paths reflects an actual disparity in PT trajectories for different fragments, or simply variable amounts of metamorphic overprint.

Geochronology: Lu-Hf dating is applied to high-pressure assemblages of fresh eclogites, but also to garnet cores (whose rims were resorbed) from garnet amphibolites, in an attempt to date the early stages of garnet growth. Preliminary results indicate a roughly 30 My range in ages for the high-pressure metamorphism for different high-pressure fragments within the MAZ, i.e. in a single tectonic unit of the Alps. Monazite crystallisation ages and zircon fission track data constrain the timing of parts of the decompression history of some other fragments.

The results of our PTt studies reflect a protracted history of subduction, accretion and extrusion, and likely also a variety of residence times within the TAC.

We have used forward thermal models of subduction/collision zones, in which the PT evolution of fragments within the Tectonic Accretion Channel can be tracked, to relate PTt paths and geodynamic scenarios (Roselle et al., 2002). The reported characteristics and variety in PTt paths would be expected in case the high-pressure rocks in the Central Alps were exhumed as part of a Tectonic Accretion Channel.

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Mantle and crustal re-equilibration and metasomatism of garnet-bearing assemblages in peridotites of the Western Gneiss Region, Norwegian Caledonides

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The trace element and isotopic geochemistry and Sm-Nd mineral ages of garnet-peridotites and pyroxenites within several orogenic peridotite bodies in the Western Gneiss Region (WGR), Norwegian Caledonides indicate that at least two episodes of metasomatism changed the chemistry and mineralogy of dunites and harzburgites that trace their origins to a melting depletion event in the Archean. The first metasomatism was caused by the passage of melts through the host peridotites during the mid-Proterozoic while the peridotites were still part of the sub-Baltic Shield mantle. Crystal accumulation during the passage of these melts resulted in the formation of a variety of pyroxenites that either crystallized garnet directly from the melts, or formed the garnet during a subsequent mantle recrystallization event. Sm-Nd mineral ages (usually clinopyroxene-garnet-whole rock ± orthopyroxene) from the garnet-bearing assemblages range from 1.7 to 1.0 Ga. The oldest ages are considered a minimum age for recrystallization in the garnet stability field, which in turn sets a minimum age for the intrusion of the pyroxenites. The spread towards younger ages may reflect continuous, but variable, re-equilibration of the Sm-Nd systems between phases during the residence of the peridotites in mantle during most of the late Proterozoic and early Paleozoic. Or it may reflect episodic re-equilibration events that affected the sub-Baltic mantle during the evolution of the overlying Baltic crust, such as the Sveconorwegian Orogeny (0.95-1.3 Ga) or a major intrusion event that occurred at around 1.5 Ga.

The melts interacted with the host peridotite in a complex fashion, scavenging some major elements from the immediately adjacent peridotite while enriching it in other elements, particularly trace elements. Clinopyroxene from contiguous peridotite and pyroxenite show parallel trace element patterns that are enriched in LREE and some LIL elements, and relatively depleted in the HFSE. The concentrations of all elements are greater in the pyroxenite than the adjacent peridotite suggesting the melts were the source of the enriched fluids. Sr and Nd clinopyroxene isotope ratios from several localities occupy separate areas on a $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ covariance diagram. They define a regional trend characterized by large variation in $^{143}Nd/^{144}Nd$ but a relatively small increase in $^{87}Sr/^{86}Sr$ as $^{143}Nd/^{144}Nd$ decreases. Individual garnet-bearing localities define the same trend, but with less dispersion. These variations are diminished, but not eliminated, by correcting isotopic values to ca. 1.65 Ga.

The second metasomatism was heterogeneous and apparently restricted to peridotite bodies on Otrøy, Flemsøy and Fjørtoft along the northwest coast of the WGR. It was associated with

the development of an exsolved assemblage that includes clinopyroxene, orthopyroxene, spinel and garnet and, locally, microdiamonds. Sm-Nd analyses of the exsolved assemblages indicate recrystallization and metasomatism occurred during the closure of Iapetus in the Paleozoic, probably during the Scandian phase of the Caledonian Orogeny when the WGR was subducted deeply into the mantle where it was invaded by the peridotite bodies from the overlyingmantle wedge. Clinopyroxene trace element patterns between mineralogically similar orthopyroxenites show some to have depleted patterns (i.e. chondritic to sub-chondritic values for most elements) whereas others are enriched in LREE and some LILE, while the HFSE retain chondritic or sub-chondritic values. Similarly, clinopyroxene from some garnet peridotites and pyroxenites display the distinct Proterozoic isotopic patterns described above (variable $^{143}Nd/^{144}Nd$, relatively constant $^{87}Sr/^{86}Sr$) while others show a striking increase to very high (>0.715) $^{87}Sr/^{86}Sr$ ratios. The trace element patterns and high $^{87}Sr/^{86}Sr$ ratios of the most enriched samples are consistent with metasomatism in the mantle wedge above subducting ocean crust during the closure of Iapetus. However, this interpretation conflicts with textural evidence that indicates metasomatism occurred during the development of the exsolved assemblage. We believe this assemblage formed when the WGR region, with its cargo of introduced peridotite bodies, was subducted still further into the mantle, to the diamond stability field with the northwest corner of the WGR subducted to the deepest levels. Fluids, derived by dehydration reactions from the host gneisses and metasediments, invaded the peridotite bodies along local access zones causing the metasomatism to be heterogeneous. The peridotite bodies in the less deeply subducted portions of the WGR, to the east and south, were either unaffected or only slightly influenced by this crustal metasomatism, allowing them to retain their older mid-Proterozoic signatures.

New insights on the petrological evolution of high-ultrahigh pressure eclogites in the Stadlandet-Nordfjord area of western Norway

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The mineralogical and microstructural evolution of certain of the spectacular eclogite occurrences that outcrop within gneisses in the Stadlandet-Nordfjord area of the Western Gneiss Region of Norway will be reviewed and expounded from the early work of Pentti Eskola through to the more recent studies of David Smith, Alice Wain and beyond. Eskola (1921) drew attention to the impressive pegmatitic Opx-bearing eclogite lens at Grytting near Selje. Over 50 years later, Smith (1984) reported the first discovery of relict coesite from within a near-adjacent pod of finer-grained, Opx-free, eclogite. This and further discoveries, led Smith (1988) to propose the existence of a UHP, coesite-stable, eclogite province in this part of western Norway. Our more recent studies have confirmed evidence for the stability of coesite (now mostly indicated by distinctive poly-crystalline quartz (PCQ) pseudomorphs) in other pods of fine-grained eclogite (including at Liset) exposed along the foreshore to the NW of Grytting. Moreover, the low Al_2O_3 contents (0.28-0.39 wt. %) of Opx grain cores in the pegmatitic eclogite at Grytting, that lacks a free silica phase, is also consistent with formation at pressures within the coesite stability field. In addition, the field and petrographic studies of Wain (1997) have contributed hugely to the more widespread recognition of UHP eclogites within the Stadlandet-Nordfjord area.

The Opx eclogite at Grytting in fact shows an intimate association with a darker, more Fe-rich, finer-grained Opx-free eclogite within the confines of the exposed pod. Field relations show the fine-grained bimineralic eclogite to occur as impersistent layers and patches within the pegmatitic Opx eclogite or its replacement amphibolite. This lithological association, coupled with the presence of both carbonate and phlogopitic mica within the Opx eclogite, suggest that an influx of aqueous and CO_2-bearing fluid under UHP conditions has led to extensive replacement of the fine-grained, essentially bimineralic, eclogite by the pegmatitic Opx eclogite. This interpretation is further supported by the high $^{87}Sr/^{86}Sr$ ratios in all consistent minerals in a sample of this Opx eclogite (Brueckner, 1977; Brueckner & Griffin, 1985), indicative of infiltration by crustal-derived fluid during UHP metamorphism. Petrographic evidences for two distinct generations of garnet growth in some samples of this Opx eclogite are also significant.

Comparable textural features and isotopic data support a similar petrological evolution for the Opx-bearing eclogite body at Årsheimneset on the opposite side of Stadlandet. Here older, essentially bimineralic, eclogite with obvious prograde zoned garnets comprising the core of this eclogite pod has been replaced towards the pod margins by a coarser-grained Opx-, phlogopite- and carbonate-bearing eclogite that contains good petrographic evidence for coesite stability. Thus importantly this eclogite locality confirms that UHP eclogite formation constituted a separate younger event triggered by an influx of crustal-derived fluid superimposed on the previously formed HP (quartz-stable) eclogite.

The importance of fluid infiltration in promoting UHP eclogite mineral growth is also demonstrated by the spectacularly layered eclogite body at Saltaneset (ca. 3 km south of

Selje) that displays discordant garnet-quartz veins in which abundant PCQ inclusions within large idioblastic garnets indicate that the veins originally crystallised as garnet coesitites. UHP eclogite occurrences at Vetrhuset and Flister, about 7 km further south, within the HP-UHP Eclogite Transition zone as recognised by Krabbendam & Wain (1997) and Wain et al (2000), provide further important petrographic evidences within individual pods that UHP eclogite mineral growth followed on from earlier garnet growth initiated under amphibolite-facies conditions and continued under HP eclogite-facies conditions. At the Flister occurrence UHP garnet growth was demonstrably associated with a deformation event that led to the development of an obvious flaser texture. These eclogite occurrences, as also at Årsheimneset, clearly demonstrate the sequential formation of firstly HP then UHP eclogite-facies mineral growth that is contrary to the previous interpretation of tectonic mixing of separate HP and UHP eclogite bodies within the HP-UHP transition zone.

The remarkably fresh kyanite-bearing eclogite some 8 km further south at Verpeneset on the northern shore of Nordfjord is effectively the type example of a HP (quartz-stable) eclogite with distinctive prograde zoned garnets (Krogh, 1982). Contrary to previous expectations, we have recently discovered that a nearby flaser-textured eclogite pod contains PCQ inclusions in neoblastic garnets thereby extending the southern limit of coesite stability further south than previously thought.

Silica exsolution in eclogite from Altyn Tagh, NW China

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The confirmation of Altyn-north margin of Qiadum Basin HP-UHPM belt is one of important progresses in Chinese geologic research recently(Liu et al., 2002; Yang et al., 2001; Zhang et al., 2001).This study focus on the exsolution SiO_2 lamella in omphacite in eclogite from Jianggagesayi creek, Altyn Tagh.

The studied eclogite crops out as varies size of lenses in the garnet-bearing felsic gneiss of Altun Group of Proterozoic age (Regional geology of Xinjiang Province, 1993) and extends along the trend of gneissosity. The rock is a fresh eclogite, appears as grayish green and shows a coarse- to medium-grained granoblasic texture, and mainly consists of garnet (40-50%), omphacite (35-45%), rutile (5%) and quartz (5%) with minor apatite and amphibole. Abundant exsolution rods have been observed in omphacite of the eclogite, which were identified as quartz by laser Raman spectrometer and electron microprobe analysis. The strongly oriented quartz rods, up to 30μm long and 1-3μm wide, occur mostly in omphacite cores and rarely in the rims; These quartz rods have a consistent optical orientation parallel to the [010] omphacites plane. The bulk composition of omphacite existing prior to exsolution was obtained by two ways. One is estimating the proportion of exsolved SiO_2 rods in omphacite on the backscatters electron images (it is 1.3%± in our samples), analyzing the current composition of host omphacite, and then calculating with thermodynamic data (Holland et al., 2001); The other is using “broad-beam" electeron microprobe analysis (enlarge the electron beam to 20-30μm diameter) in regions containing SiO_2 rods. The reintegrated precursor omphacite compositions from two ways are very alike. All clearly show a feature of supersilicic, i. e.,Si>2 per formula , (Si+Ti)>(Ca+Mg+Fe+Mn+Ni-2Na) and fewer than 4.0 cations per 6 oxygens(Tsai et al., 2000; Smith and Cheeney, 1980), which implies existence of octahedrally coordinated silicon (Angel et al., 1988) and cation vacancies in M-site (Smyth, 1980) of precursor omphacite. Using the methods of Smyth (1980), Angel et al., (1988), Katayama et al., (2000) and Tsai and Liou (2000), we calculated 10-13mol% Ca-Eskola component ($Ca_{0.5}ž_{0.5}AlSi_2O_6$) and 10%± Na $(Mg_{0.5}Si_{0.5})Si_2O_6$ component contained in the omphacite.

Omphacite with exsolved SiO_2 rods is well know from eclogite xenoliths in kimberlite pipes (Smyth, 1980) and coesite-bearing eclogites (Smith1984; Bakun-Chubarow, 1992; Grak et al., 1995). Experiments have demonstrated that supersilicic omphasite requires high pressure and high temperature, and pressure is the most important factor(Smith, 1988; Mao, 1971; Zharikov et al., 1984), and Dobrzhinetskaya(2002) suggested that the pressure at which SiO_2-rich clinopyroxene is stabilized probably not less than 4 GPa, especially, in an experiment synthesizing silica-rich Na-Mg pryroxene at 100-150kbar, 1600ºC (Angel et al., 1998).

Using several calibrations of the Fe^{2+}-Mg exchange thermometer based upon assumed pressure of 3.0 and 4.0 GPa, and the composition of core part of garnet and reintegrated omphacite, we estimated the peak metamorphic temperature is about 1100-1200ºC. According to this temperature, the reintegrated composition of precursor omphacites and the experiments mentioned above, as well as the discovery of coesite pseudomorphs in eclogite in this area, the peak metamorphic condition of the studied eclogite is T >1100ºC, P>4GPa, and it may be higher if we considering the existence of 10%± Na $(Mg_{0.5}Si_{0.5})Si_2O_6$ end-member.

Multi-isotopic System Geochronology and cooling of Huangzheng Cold Eclogite From Southern Dabieshan HP-UHP Terrane, Eastern Central China

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Dabie-Sulu terrane is eastern termination and extension of the Qinling-Dabie orogen formed by collision between Northern China Block and Yantze Block. Southern Dabie Terrane (SDT) is the only locality which UHP mineral diamond occurred. At its southern end between SDT UHP and Shusong HP metamorphic complex there is exposure of so-called cold (low temperature) eclogite without coecite (Okay 1993, Wang et al, 1992). Calculated P, T condition is 580-610□ and 20-24kar. The correlation between hot and cold eclogites is not clear. Its distribution and age of cold eclogite is important for tectonic model and evolution of Dabieshan orogen. Until now no any age has been obtained yet due probably complicated prograde and retrograde metamorphism and not reaching isotopic re-equilibrium, and all published geochronology data are concentrated in to UHP hot eclogite in SDT.

We deal with multi-isotopic system dating of cold eclogite from Huangzheng and country gneiss, including U-Pb, Ar-Ar, and Sm-Nd. Micro-scale oxygen isotope compositions of zircons and garnet diffusion zoning in eclogite are also determined for understanding its protolith character and cooling history.

U-Pb SIMS ages of zircon and ^{40}Ar-^{39}Ar isochron ages of mica for one eclogite give coincident ages of 232-234Ma. U-Pb SIMS ages of country gneiss zircon and TIMS age of another eclogite zircon gave 221-223Ma. Retrograde amphibole has ^{40}Ar-^{39}Ar isochron ages of 200-206Ma. All the ages are correlated with its HP metamorphism representing peak- and retrograde-stages, respectively. Evidence of mineral inclusions in eclogite zircons confirmed this deduction. It is indicated that Huangzheng cold eclogite shares a same collision-related orogen with hot eclogite of SDT, and differs from those of Northern Dabieshan cold eclogite, which has pre-Triassic in age.

Sixteen oxygen isotopic analyses obtained by CAMECA 1270 show that they have δ^{18}O values of 4.55-7.52, with slight lower in protolith than metamorphic domain of zircons. Garnets from cold eclogite also have complicated prograde compositional zonations in different size of grains. Based on Fe and Mg diffusion exchange dynamics, we made diffusion modeling to match its existed zoning. Combining all age, geochemical and geothermal-dynamic data, we infer that the cooling and exhumation rates dramatic decrease from 30-40º to 6-8ºC /Ma and from 10-12km to 1.5km/Ma from eclogite to amphibolite face metamorphism. These values are comparable to other Dabieshan eclogites, but lower with those of Dora Maria of Alps and Kokchetav of Kazakhstan.

The discovery of native titanium, iron and TiFe alloy in coesite eclogite from China

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Native titanium, iron and TiTe alloy are found in a sample of eclogite from Dabie Shan, Hubei province, eastern China, all occur as inclusions in the garnet of coesite eclogite. This is the first reported occurrence of the native metals and alloy (Ti^0, Fe^0 and TiFe) in metamorphic rock. Native titanium and iron are very rare, especially native titanium. Native iron is often found in meteorites. However native titanium has only been found in granite and carbonatites (Frikh-khar D.I. et al. 1986., Trunilina V.A. et al. 1988.). The eclogite samples in this study were collected from an ultrahigh pressure (UHP) metamorphic complex about 3km northeast of Yingshan County in Dabieshan, China, the Central China Orogenic Belt. The metamorphic complex of the area is composed of feldspathic gneiss; with minor part of lenses of coesite-bearing eclogite and amphibolite. The coesite-bearing eclogites occur as lenses several centimeters to tens of meters in size surrounded by gneiss. The common mineral assemblage of the eclogite is garnet + omphacite + phengite + rutile + zoisite + coesite/quartz. Inclusions of coesite and quartz pseudomorphs after coesite have been found in garnet and omphacite in eclogite (Chen J.et al. 1995).

Native titanium, iron and TiFe alloy were identified by a transmission electron microscope (TEM) using a Hitachi H-9000NAR with 300KV accelerating voltage. An attached energy dispersive X-ray spectroscope (EDS) with an ultra-thin-window detector, which can identify all elements ranging from B (atomic number 5) to U (atomic number 92), was used to determine the chemical composition. The structures of the native titanium and iron in this area differ from both that of industrial titanium and iron, which are cubic or hexagonal, and also that of native titanium found in granites, which is hexagonal. The crystal structures and lattice parameters were identified by transmission electron microscopy (TEM). (1) Ti^D is tetragonal system, a=b=0.426nm, c=0.273nm, $\alpha=\beta=\gamma=90^o$; (2) Fe^D is face centered cubic, a=b=c=0.784nm, $\alpha=\beta=\gamma=90^o$.; (3) TiFe alloy is face centered cubic, a=b=c=0.739nm, $\alpha=\beta=\gamma=90^o$. Titanium is a very active element, which is easy to combine with other elements, such as O, H, N, and C. So far, it's the first discovery of native titanium in ultrahigh pressure metamorphic rock. It gives rise a series of new questions. Native Titanium and native iron occurred as inclusions in garnets, does it probably illustrate that before reached the eclogite metamorphic faces, the rocks went through much higher pressure or in a more reducing environment? On the other hand, the preservation of metals in ultrahigh pressure metamorphic rock would contribute to explain the dynamical process of continent-continent collision.

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Amphibole exsolution texture in diopside from Hujialing garnet-pyroxenite

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Exsolution texture, formed during exhumation of the subducted slab, is an indicator for ultrahigh pressure (UHP) metamorphism. Exsolution lamellae of quartz (e.g. Smith 1984), garnet (e.g., Smyth et al. 1989), quartz + oligoclase + K-white mica lamellae (Schmadicke and Muller, 2000), and phlogopite + SiO_2 phase (quartz/coesite lamellae (Zhu and Ogasawara, 2002a) in clinopyroxenes are well documented in UHP rocks. All these exsolution textures were formed at pressure >3GPa as a result of Ca-Eskola decomposition in super-silicic clinopyroxene.

We report here the first discovery of amphibole exsolution texture from Hujialing garnet-pyroxnite rocks, which exhumated from deep mantle together with coesite eclogites in Su-Lu UHP metamorphic belt. This garnet-pyroxenite rock consists mainly of garnet and diopside with minor amounts of amphibole (pargasite), ilmenite, Mg-Al spinel, magnetite, Opx, and olivine. Diopside contains abundant garnet inclusions as well as pargasite and ilmenite lammellae. Abundant parallel pargasite lamellae with variable width (1~10μm) occur in diopside. The pargasite lamellae were cut through by ilmenite needles in many cases. Such ilmenite needles also paralell to each other and show exsolution natures. TEM observations show that (020) in pargasite parallel to (020) of its host mineral diopside, which strongly suggests their exsolution origin.

The characteristics of the mineral assemblages observed in Hujialing garnet-pyroxenites (diopside + pargasite + ilmenite + garnet) indicate that the parental mineral of the reported exsolution texture should have composition of the mixture between pargasite + ilmenite and diopside. The prevailing exsolution of pargasite (stage I) and ilmenite (stage II) suggesting at least two-stages of exsolution processes, which implies that the exhumation histories of Hujialing garnet-pyroxenite rocks were complex.

Another important significance of the above described exsolution is the parental materials of Hujialing garnet-pyroxenite rocks. It is widely believed that the UHP clinopyroxene is Si-excess (super-silicic) with Si contents greater than 2.0 (at O=6 atoms) as for examples, in clinopyroxene both from Kokchetav eclogites (Katayama et al., 2000) and dolomite marble (Zhu and Ogasawara, 2002b). The low Si contents (mostly <1.97) in diopside with exsolution lamellae of pargasite and ilmenite in Hujialing garnet-pyroxenite rocks apparently suggested that such diopside do not belongs to super-silicic clinopyroxene, and therefore contradicts its apparent UHP natures. This paradox could be explained by the parental rocks of Hujialing garnet-pyroxenite rocks. We consider their parental rocks were ultra-mafic rocks, these Si-depleted rocks were subducted to the mantle during subduction, experienced UHP metamorphism (probably >200 km, Ye et al., 2000). Formed at the peak metamorphism, the clinopyroxene contains alkaline (Na, K), H2O, and Ti. These components are unfavorable in low-pressure clinopyroxene and will exsolve from their host phases during exhumation. Thus the pargasite and ilmenite lamellae formed in diopside at the exhumation stage of Hujialing garnet-pyroxenite rocks. These exsolution textures also suggested that clinopyroxene is an important mineral phase to carry H2O and alkaline elements to deep mantle, which could act

as key factors to generate a serious geological events such as magma, earthquake, the mantle convection, even to make the Earth differs from other planets and thus suitable for life (e.g., Ernst, 2001; Zhu and Ogasawara, 2002b).

Such complex exsolution textures also have very important implications for tectonic evolution of the Su-Lu subduction – collision system. With detailed study of these exsolution, it is possible to rebuild the tectonic scenario of the Su-Lu orogenic event. The mantle-origin ultra-mafic rocks was subducted to deep mantle, experienced UHP metamorphism, and finally exhumated to surface. It is necessary to emphasize the two-stage exsolutions observed in these rocks. The pargasite lamellae apparently formed earlier than the ilmenite lamellae in same diopside, this indicated that the exhumation of such UHP metamorphic rocks happened in two steps, one probably occurs at ~3GPa, another occurs at much low-pressure environment (at crust levels).

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Triassic high-pressure metamorphism in western Gyeonggi Massif, Korea: Correlation with the Dabie-Sulu Belt in China

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Triassic high-pressure metamorphism in Korea has been the focus of many previous studies dealing with the possible continuation of the Chinese continental collision belt into the Korean Peninsula. In particular, Permo-Triassic garnet amphibolites were reported from the Imjingang Belt, and considered to be correlative with those of the Dabie-Sulu Belt, China. High-pressure amphibolites also occur in the Gyeonggi Massif, but their tectono-metamorphic relationship with Triassic continental collision is yet equivocal. In this study, I report on high-pressure metamorphic complex recently identified in the Hongseong area, western Gyeonggi Massif, which could be correlative with the Dabie-Sulu Belt.

The Hongseong metamorphic complex consists of garnet amphibolite, quartz garnetite, marble, and hornblende gneiss, together with Paleoproterozoic basement gneisses such as porphyroblastic and augen gneisses. Tonalite and granodiorite showing magmatic foliations are widespread in this complex, and they apparently convert to tonalitic gneisses near the amphibolite-marble unit. Representative assemblages of amphibolites are hornblende + plagioclase ± garnet ± clinopyroxene + quartz ± biotite. Rutile, titanite and ilmenite occur as accessory phases. Transitions from garnet amphibolites to garnet-free amphibolites are well preserved on the outcrop scale, and hornblende-plagioclase symplectites are ubiquitous around the garnet porphyroblast. Both observations suggest a decompressional P–T evolution of the Hongseong metamorphic complex. Metamorphic pressures and temperatures were estimated using the garnet-hornblende (or clinopyroxene)-plagioclase-quartz assemblage of garnet amphibolites. They are in the range of ca. 10–14 kbar and 700–800°C. These results suggest that the Hongseong metamorphic complex has experienced a clockwise P–T evolution passing through the high-pressure condition close to that of the eclogite facies.

Zircon grains from tonalite-granodiorite and hornblende gneiss were dated using the Sensitive High-Resolution Ion Microprobe (SHRIMP). The U–Pb zircon ages suggest that tonalite and granodiorite were emplaced at ca. 820 Ma. Exceptionally, a zircon crystal from tonalite shows thin overgrowth rim with an apparent U–Pb zircon age of ca. 230 Ma. On the other hand, the U–Pb zircon ages of hornblende gneiss distinctly differ from those of tonalites. Low Th/U (< 0.01) rims define a concordant age group with the weighted mean U–Pb age of 223±5 Ma, in contrast to the apparent core ages ranging from 473 Ma to 335 Ma. The age of zircon rims is interpreted to represent the metamorphic age because their Th/U ratios are mostly less than 0.01. High-temperature metamorphism at 223±5 Ma, accompanying local anatexis of amphibolites, is interpreted to be coeval with the amalgamation of separate metamorphic units including hornblende gneiss, tonalitic gneiss and amphibolite-marble. The Triassic age of high-temperature and -pressure metamorphism in the Hongseong metamorphic complex is consistent with that of ultrahigh-pressure metamorphism in China. Furthermore, the predominance of Triassic high-pressure metamorphism in both the Imjingang Belt and the Gyeonggi Massif suggests that both terranes were actively involved in or significantly affected by continental collision process between the Sino-Korea and Yangtze cratons.

First finding of jadeite in the serpentinite melange of Monviso meta-ophiolite, Western Alps

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From the early Neolithic to the Bronze Age, i.e. in western Europe from the sixth millennium BC to the second millennium, prehistoric peasants used axes and chisels made of polished stones, collectively known as "green stones". The "green stones" mainly consist of serpentinite, fine-grained eclogite and Na-pyroxenite (omphacitite and jadeitite). Long since it has been established that "green stones" derive from the meta-ophiolites of the Piemonte Zone of the western Alps (Damour, 1881). However, though primary outcrops of serpentinite and fine-grained eclogite are well known in the Piemonte Zone, so far jadeitites have been found only as pebbles or boulders from "secondary" deposits, such as the alluvial post-orogenic Oligocene to Quaternary conglomerates. A search of jadeitite in the alluvial deposits, at the mouths of the main alpine valleys, shown that the most promising area was that of the Monviso. A systematic field survey in the area lead to discovery of a jadeitite outcrop, in a small cirque on the northern side of Punta Rasciassa (Po valley). The jadeitite occurs as a boudin about one m^3 in volume, embedded in a serpentinised lherzolite belonging to the basal serpentinite unit of the Monviso meta-ophiolite (cf.: Lombardo et al. 2002). On hand specimen, the jadeitite is a very pale grass green and fine-grained massive rock with sporadic bright green and whitish spots. At the selvages, the jadeitite boudin is surrounded by a darker retrogression margin 10 to 20 cm thick. Locally, a coarse portion with gabbroic structure is found.

Under the microscope, the jadeite appear to be heterogeneous, being formed of three main portions: 1) portions mainly consisting of clear jadeite; 2) portions where jadeite is associated to up to 10 vol% of rutile; and 3) portions of dusty jadeite. The jadeite occurs as aggregates of interlocked stumpy prismatic crystals, which systematically show a sharp compositional zoning. In the matrix, cloudy larger clinopyroxenes locally occur, probably deriving from original igneous phenocrysts. Typical accessory minerals are very small zircons. Metamorphic veins and pockets occur everywhere, and consist of randomly oriented jadeite nematoblasts surrounded by xenoblastic feldspar or sheet silicates (white mica, phlogopite and Mg-chlorite). A light purple allanitic epidote locally occurs as porphyroblasts both in the rock matrix and the veins. The gabbro-looking portion consists of greenish clinopyroxene and sheet silicates domains, which may include jadeite needles. A single garnet porhyroblast was observed: it exhibits a two-stage growth and contains inclusions of ilmenite and minor apatite. The compositional heterogeneity of the jadeitite, its association with serpentinised lherzolite and the presence of relict portions, the occurrence of metamorphic veins and pockets, the sharp compositional zoning of jadeite suggest that the jadeitite formed at the expense of a oligoporphyritic basaltic dyke, originally intrusive into the upper mantle, through a metasomatic process connected to the peridotite serpentinisation.

A comparison between the studied rock and the Neolithic implements made of polished stones from different archaeological sites of Mediterranean France (Ricq-de-Bouard et al., 1990) and Northern Italy (Compagnoni et al., 1995; D'Amico et al., 1995) shows that at least the rutile-bearing jadeitites derive from the internal portion of the meta-ophiolitic Piemonte zone, which is characterised by an early-Alpine eclogite-facies metamorphic overprint.

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The HP – UHP transition in the Nordfjord-Stadlandet region, Western Gneiss Complex, Norway

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Key achievements of Alice Wain's work in the Western Gneiss Region (WGR) were the mapping of a regional ultra-high pressure terrane, and the delineation of a transition zone between high pressure eclogites and ultra-high pressure eclogites. They recognised two petrographic types of eclogite; a group characterised by idioblastic, prograde-zoned garnets with amphibolite-facies mineral inclusion suites in the cores and lacking any evidence for coesite (HP eclogites), and a group with more xenoblastic garnets lacking prograde zoning and relict inclusion suites and containing coesite or polycrystalline quartz inclusions (UHP eclogites). Eclogite bodies were considered to be exclusively of one type, and where eclogite-facies schists and gneisses were associated with eclogites they were found to share similar characteristics in their garnets. The first appearance of UHP eclogites lay approximately along the line of Nordfjord, and to the north of this a "mixed" zone was delineated containing both HP and UHP eclogite bodies, extending as far as the southern end of the Stad peninsula. Based upon the close juxtaposition of HP and UHP eclogites and apparent non-lithostatic pressure gradients derived from thermobarometry, the mixed zone was interpreted as a zone of tectonic imbrication in which HP and UHP rocks were juxtaposed within a complex shear zone. This model has interesting implications for the subduction and exhumation kinematics of the WGR.

A number of problems are presented by this tectonic model for the HP-UHP transition. First, the mixed zone is not the locus of a significantly higher strain state in the country-rock gneisses. Secondly, recognisable, individual lithotectonic units in the mixed zone contain both types of eclogites. Thirdly, prograde-zoned garnets have been recognised in eclogites well into the northern UHP zone in Stad (e.g. Arsheimneset). Our detailed sampling, combined with a regional survey of compositional zoning in garnets, has shown that individual eclogite bodies in the mixed zone do, indeed, contain both HP and UHP eclogite types, even within samples of less than litre-size. Rare samples of both eclogite and pelite contain prograde-zoned garnets with good evidence for coesite in the rims, and more common examples exhibit two distinct textural and compositional types of garnet, with only the younger type having coesite. Some of the more southerly "classic" HP eclogites now turn out to display good evidence for coesite. This makes the tectonic juxtaposition hypothesis for the HP-UPH transition difficult to sustain (although it may have contributed to relative movements of eclogite bodies during the later stages of exhumation). Instead, these observations suggest that the mixed zone is, at least partly, a zone of limited efficiency in the "processing" of continental crust as it was subducted into the stability field of coesite.

Detailed analysis of garnet textures in these rocks provides valuable information about the nature of the transformation processes. They include the operation of continuous solid-solid reactions during increasing pressure, resulting in an increase in modal garnet; cracking and re-sealing of garnet; crystal-plastic strain with recrystallisation of older garnet and its matrix, and infiltration of fluids or melts that catalysed or participated in reactions. Relics of pre-UHP phases occasionally survive, and the crust appears to have remained refractory to change unless reaction rates were accelerated by fluid ingress

and/or deformation. Hence while tectonism may well have played some part in modifying the macroscopic distribution of HP and UHP rock masses near the coesite-in boundary, recognition of HP-UHP transitions on the mesoscopic and microscopic scales has the potential to provide valuable information about the processes that transformed the mineralogy and petrophysical properties of the descending crustal slab. Such variables are important to consider in models continental subduction.

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Diamond synthesis in a laboratory: an implication to microdiamond formations from ultra-high pressure metamorphic terranes

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The recognition of microdiamonds within ultra-high pressure metamorphic rocks a decade ago initiated a revolution in the understanding of continental collision terranes. There are now six known diamond-bearing regions: Kazakhstan (Sobolev and Shatsky, 1990); China (Xu et al., 1994); Norway (Dobrzhinetskaya et al.,1995; Van Roermund et al., 2002); Germany (Massonne, 1999; Nasdala and Massonne, 2000); Greece (Mposkos and Kostopoulos, 2001) and Russia (Bostik et al., 2002). The study of diamonds *in situ* in garnets and zircons shows that in Kokchetav (Kazakhstan) and Erzgebirge (Germany) terranes, diamond inclusions are frequently accompanied by hydrous phases (e.g. Dobrzhinetskaya et al., 2000, 2001, Stöckhert et al., 2001). Molecular water and carbonate radical have been detected in some diamonds from Kokchetav massive by FTIR (De Corte et al., 1998). Dobrzhinetskaya et al. (2001, 2003) using focused ion beam technique and transmission electron microscopy have discovered nanometric inclusions of oxides of Si, Fe, Ti, Th, Cr, and other cations associated with cavities of former fluid phases.

Two concepts are known to explain the origin of such diamonds: (1) crystallization from a supercritical COH fluid (e.g. De Corte et al., 1998; Dobrzhinetskaya et al., 2000, 2001; 2003; Ogasawara, 2000; Stöckhert et al., 20010 and (2) crystallization from fluid-bearing silicate or alkaline-carbonate melt e.g. Shatsky et al., 2001; Polyanov et al., 2002). Decades of study of kimberlitic diamonds also have suggested two primary avenues of their formation. COH-rich fluid (e.g. Melton and Giardini, 1981, Haggerty, 1986, Navon et al., 1988, Taylor, 1990) has been suggested, as well as crystallization from silicate or sulfide melt (e.g. Robinson, 1978; Sunagawa, 1994; Bulanova et al., 1998).

Traditionally, experimental attempts to replicate natural diamond formation have been based on synthesis in metal-carbon systems in a highly reduced environment (e.g. Bundy et al., 1961; Wenfort, 1974). Only recently has experimental modeling of natural diamonds at high P and T conditions been extended to the alkaline-carbonate-carbon system in the presence of H_2O (e. g. Akaishi et al., 1990; Tanigushi et al., 1996, Yamaoka et al., 2000). The latter ideas have been stimulated by results of fluid-inclusion studies in natural diamonds (mostly of kimberlitic origin).

I present here our experimental results of high P and T diamond synthesis from graphite in the presence of H_2O and in combinations with different minerals so that its bulk composition would be as close as possible to that of natural diamond-bearing rocks from ultra-high pressure terranes. Experiments were performed in a high-pressure multianvil apparatus using a double capsule of Pt with an enclosed smaller graphite capsule containing starting material at P=7-8.8 GPa and T=1200-1500°C for time periods ranging 1 to 138 hours. I have explored the following systems:

(1) graphite-brucite, (2) graphite-calcite-talc and graphite-dolomite-talc, (3) graphite quartz-muscovite and (4) graphite-quartz-H_2O.

Diamonds were found in all run products indicating that they crystallized from a supercritical COH fluid formed from the breakdown of water-bearing minerals and subsequent dissolution of graphite into liberated water. One of the notable features of diamond crystallization in most of the COH fluid environments investigated here is the considerable induction time that exists

prior to diamond nucleation. This incubation period increases dramatically with decreasing temperature and also depends on the bulk composition of the starting material. No diamond was crystallized from graphite in SiO_2-rich system after 43 hours experiment at 8 GPa and 1500°C, while carbonate and brucite systems contained diamonds formed after 10-20 hours at similar P and T conditions. Instead of diamonds in our SiO_2-rich experiment we have found fine-grained spherical graphite polycrystalline aggregates nucleated around newly crystallized coesite. This suggests that SiO_2 promote nucleation of metastable graphite on its surface in the diamond stability field. It is also expected that SiO_2 has a high solubility in supercritical fluid at such PT conditions. Therefore, the retardation of diamond nucleation from COH fluid saturated in SiO_2 allows us to conclude that SiO_2 somehow hampers diamond nucleation. It is important to more fully understand the kinetics of this process and the induction time required for diamond nucleation in SiO_2-bearing systems because this system is closest to the dominant rock type hosting natural UHP metamorphic diamonds.

Pressure contrast among eclogites in the Sanbagawa metamorphic belt, Japan

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Coarse-grained basic, pelitic and ultramafic lithologies of the eclogite facies, which have been subsequently re-equilibrated under the epidote-amphibolite facies conditions, are scattered in the highest-grade zone of the Sanbagawa metamorphic belt, central Shikoku. Equilibrium conditions of the eclogite facies stage were compared among three eclogitic lithologies of the Gongen, Western Iratsu and Eastern Iratsu masses.

The Gongen mass is a distinct quartz-rich lithology and occurs as a small (< 100 m in width) unit along the boundary between the Higashi-akaishi ultramafic mass and the Western Iratsu mass. This mass locally contains mafic clots and layers, which may represent original sedimentary features of a predominantly pelitic rock with intercalations of basic volcaniclastic materials. A typical eclogitic paragenesis of the Gongen mass is garnet ($Alm_{48-57}Sps_{1-4}Prp_{6-15}Grs_{13-24}$), omphacite ($Jd_{42-53}$), kyanite, epidote, phengite, quartz and rutile. Paragonite aggregates around kyanite and phengite are possibly decompressional products after the eclogite facies stage at which paragonite was unstable. The protoliths of the Western Iratsu mass are possibly oceanic materials consisting mainly of basic volcanic rocks, siliceous sediments and limestones, which are considered to be members of an oceanic island or oceanic plateau (Kugimiya and Takasu, 2002). A typical mineral assemblage of the eclogite facies stage is garnet ($Alm_{39-62}Sps_{1-18}Prp_{22-34}Grs_{20-39}$), omphacite ($Jd_{36-44}$), epidote, phengite, paragonite, quartz and rutile. Coexisting kyanite and omphacite are not exhibited and paragonite was possibly equilibrium with other eclogitic assemblages. The Eastern Iratsu mass are metamorphosed layered gabbro-peridotite sequence (Yokoyama, 1980). Typical mineral assemblages of eclogitic facies stage are clinopyroxene + orthopyroxene + garnet ($Alm_{37-41}Sps_{1-2}Prp_{40-46}Grs_{14-20}$) + corundum, and garnet ($Alm_{41-44}Sps_{0-1}Prp_{34-37}Grs_{20-21}$) + omphacite ($Jd_{32-43}$) + kyanite + zoisite + quartz for mafic and felsic layers of metagabbro, respectively. Peridotites have spinel lherzolite facies assemblages.

Combinations of garnet-omphacite geothermometers and phengite-bearing geobarometers give P-T estimates of 700-970 °C and 2.3-3.7 GPa for the eclogitic assemblages of the Gongen mass. The Gongen mass lies adjacent to the Higashi-akaishi ultramafic mass that contains lenses of garnet peridotite. Peak metamorphic conditions of the garnet peridotite are estimated at 650-900 °C and 2.0-4.5 GPa (Enami and Mizukami, 2001) and are similar to those of the Gongen mass. Pressure conditions of the Western Iratsu eclogites are probably lower than that of the Gongen eclogite judging from the presence of stable paragonite. A combination of kyanite eclogite and spinel lherzolite assemblages gives equilibrium P-T conditions of 650-750 °C and 1.8-2.0 GPa for the Eastern Iratsu mass. Two or more types of eclogitic rocks formed under different pressure conditions possibly occur in the higher-grade zone of the Sanbagawa belt. SHRIMP U-Pb ages of zircon in the Gongen eclogites are 110-120 Ma (Okamoto et al., 1999), and thus the eclogites and peridotites are considered to represent the deepest constituents of the Sanbagawa subduction zone.

Evidence for brittle behaviour and fluid-induced rapid transformation during eclogitisation. A dynamic process exemplified by eclogites in the Sunnfjord area, Western Gneiss Region, Norway.

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In Sunnfjord, Western Gneiss Region of South Norway, Proterozoic granulites and layered metagabbro display various degrees of transformation to eclogite during the Caledonian orogeny. The granulite complex consists of alternating mafic two-pyroxene granulite and felsic orthopyroxene + garnet bearing layers on a scale from 1 cm to 10 m. Layering in the Proterozoic gabbro is defined by modal variations of plagioclase, olivine, pyroxenes and minor Fe-Ti-oxide and spinel. Initial transformation under eclogite facies (T=510-620°C, P>12 kbar) occurred as hydration reactions along fractures, causing a density increase of c. 13%. Coronitic eclogite formed statically from the gabbro as the mafic magmatic phases were replaced by aggregates of omphacite, barroisite, tremolite, talc and rutile, whereas the plagioclase domains were pseudomorphed by omphacite, barroisite, clinozoisite, kyanite, paragonite and garnet. The felsic and mafic domains are separated by a garnet rim up to 5 mm thick. Garnet also formed along dilational veins radiating out of and connecting coronas, and includes the same eclogite facies minerals. In addition, microfractures filled by amphibole and omphacite cut through the corona and vein garnet, oriented perpendicular to the garnet.

Mineral chemical variations occur across corona and vein garnet. The characteristic patterns show both longer scale variations and abrupt short-scale variations in FeO of 19-27 wt%, MgO and CaO of 3-12 wt%, MnO of 0-0.5 wt% and FeO/(FeO+MgO) of 0.7-0.9. The garnet chemistry and zonation patterns are interpreted to be controlled by the chemistry of the growth location, the fluid influx and element supply. Abrupt chemical variations in corona and vein garnet reflect interaction between subgrain garnet growth and transport along microfractures from/to plagioclase and mafic domains. The coronitic eclogite transformation is regarded as a rapid process, as indicated by dendritic textures and coalescence of smaller subgrains in corona garnet, that was facilitated by transport along microfractures through garnet coronas.

The transformation of dry granulites and gabbro to eclogite with hydrous minerals requires supply of water. The timing of metamorphic reactions is therefore dependent on the timing of fluid introduction. The inclusion pattern in garnet from the metagabbro indicates that transformation started under eclogite facies conditions. Brittle deformation, in form of fractures allowing fluid infiltration and mobilisation of elements, is shown to be the most important process initiating transformation. Brittle deformation is thereby active in deep crustal levels corresponding to eclogite facies conditions. Fracturing is interpreted caused by a combination of high fluid pressure, volume changes during mineral transformations and external stresses.

Later ductile deformation occurs in both granulite and gabbro and cause complete transformation to eclogites. The granulite complex is converted to a melange-like lithology of eclogite and quartz+phengite-schists, and the metagabbro to an eclogite mylonite. Garnet porphyroblasts in the mylonite eclogite display the characteristic chemical variations as the corona garnet, indicating that they can be relics of the corona stage. Preservation of corona

fragments and textures of flattened coronas in eclogite tectonites indicate that deformation started after the initiation of corona growth. The alternation between Proterozoic protoliths, coronitic eclogites and eclogite tectonites demonstrate that ductile deformation in the deep crust was localised.

The examples where Proterozoic granulites and gabbro transforms under Caledonian eclogite facies conditions, show that the transformation of the deep crust to eclogite can be viewed as a dynamic process where fluid infiltration, brittle and ductile deformation are important parameters in addition to pressure and temperature.

Evolutionary model for exhumation of the Meliata blueschists, Western Carpathians (Slovakia)

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Convergence of the African related continental blocks with southern margin of the European plate resulted in closure of the Tethyan Triassic oceanic basins and formation of suture zone with occurrences of high-pressure rocks that can be traced from the Western Carpathians through Rhodopian to Taurid in West and Central Turkey. Structural analyses and paleogeographic reconstructions from most of these high-pressure terrains indicate an eastward motion of the Apulian promontory and subduction of oceanic basins beneath the European related continental blocks. Based on the present nappe structure in the Western Carpathians, subduction of the Meliata oceanic basin and subsequent exhumation of blueschists have been interpreted to occur along the south-dipping thrusts plans that are coincident with main convergence direction of Cretaceous collision. In this contribution we present new data on a westward exhumation mechanism for the Jurassic blueschists that were overprinted by northward Cretaceous collisional processes in the Western Carpathians.
The Eastern boundary of the Meliata accretionary wedge is situated along the southern margin of the West Carpathians in Slovakia and northern Hungary. It is a thrust over the crystalline basement consolidated during Variscan orogeny. The Meliata accretionary wedge is a complex stack of crustal and oceanic units, which is formed from bottom to top by: (1) Lower Thrust Sheet composed of sub-blueschist facies (8-10 kbar 350-400 ^{o}C) quartz phyllite and conglomerate of Permian age. (2) Upper Thrust Sheet consisting of blueschist facies (10-13 kbar 400-450 ^{o}C) marbles with metabasites and phyllites, which are derived from Triassic oceanic materials, but some Variscan amphibolite-facies basement rocks with blueschist overprint are also part of this sheet. According to geochronological dating, the blueschist facies rocks, formed during Middle Jurassic time (156 Ma) were exhumed in time space of 125-145 Ma. (3) Very low-grade (4-6 kbar 300-350 ^{o}C) Meliata Mélange composed of Permian evaporates and Jurassic shells, marls and sandstones that contain blocks (olistoliths) of Triassic radiolarites, cherts, limestones, serpentinites, gabbros and blueschists. (4) Very low-grade to non-metamorphosed Turna and Silica nappes derived from Apulian shelf and formed by Upper Permian - Jurassic limestones, shales, sandstones and some volcanic rocks.
Structural and metamorphic evolution of the Meliata accretionary wedge is characterized by fabrics and mineral assemblages testifying HP stage, retrogression during exhumation and emplacement of thrust sheets and late shortening of whole wedge during buttressing stage. The HP deformation stage D_{1-2} in the Lower and Upper Thrust Sheets is manifested by development of penetrative SE dipping metamorphic fabric, bearing intense stretching lineation plunging to the southeast. The S_{1-2} metamorphic fabric in the Meliata mélange that related to accretionary metamorphism (Upper Jurassic/Lower Cretaceous) is only preserved within competent Triassic marbles forming olistostromes. D_3 deformation stage – buttressing is developed in all thrust units of the Meliata wedge as well as in the underlying parautochtonous Paleozoic basement. It is characterized by N-S trending buckle and striking folds and steep ESE dipping slaty or spaced axial plane cleavage. The Cretaceous overprint was a polyphase process controlled by indentation of southern block actively moving to the north. The new structural data in combination with petrologic and geochronoloogic results allow to constraint a tectonic model for exhumation that is good agreement with paleogeographic reconstructions considered for the suture zones in the Rhodop massif, Aegean Sea and in West Turkey. Our new results fit well with paleomagnetic record of Jurassic drifting and subsequent anticlockwise rotation of African plate during Cretaceous.

Field characteristics and deformation features of eclogite facies folds: a case study from the Western Gneiss Region

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Exhumation of the deep crust during orogenic collapse is an accepted geological phenomenon, but structures formed during the earliest stages of exhumation are often overprinted by shallower deformation events. Large volumes of eclogite-bearing lower crustal rocks have been juxtaposed with allochthonous mid- to upper-crustal units, including several Devonian basins across the main extensional Nordfjord-Sogn Detachment Zone, Western Gneiss Region (WGR). The Drøsdal body, in Sunnfjord, southwestern Norway, is one of the largest mafic eclogites in the WGR, and provides the focus for this study.

The Drøsdal body displays a wealth of structures which were formed during deformation at a minimum depth of 50km and at peak temperatures of c. 700°C. Large volumes of mylonites with the eclogite facies assemblage garnet + clinopyroxene ± quartz ± amphibole ± zoisite/clinozoisite ± phengite ± kyanite ± rutile are preserved. E-W trending isoclinal folds, boudinage, hinge-parallel lineations and meter scale kyanite veins are among the eclogite facies structures found within the body. However, problems remain with regard to the kinematic details of eclogite deformation. For example, shear sense indicators are ambiguous at the field scale.

Helmsteadt et al. (1972) used outcrop scale observations of foliation and lineation to link the development of S-type and L-type omphacite fabrics to conditions of flattening and constrictional strain respectively. However, according to Brenker et al. (2002) the development of S-type or L-type fabrics is determined by cation ordering in omphacite. They observe that S-type fabrics develop in cases where the deforming omphacite has the C2/c ordering state, and L-type fabrics develop in cases where the deforming omphacite has the P2/n ordering state. Since the ordering state of omphacite is dependent on XNa content and on temperature, the development of S-type or L-type fabrics appears to be independent of strain, but further studies are required.

EBSD analysis has been carried out using samples from opposing fold limbs within the Drøsdal eclogite. All samples were cut perpendicular to foliation and parallel to lineation. Since foliation is deflected around the fold hinge between the samples, they have different orientations with respect to the geographic reference frame. The analysis yielded fabrics with a strong LPO but no asymmetry, indicating that the limbs may have been passively rotated subsequently to development of the LPO. The fabrics are classified as S-type, in which b[010] is parallel to Z and the fabric is rotationally symmetric around this direction. The omphacite has XNa 0.40-0.55, and prolate grain shapes are observed in hand specimens. According Helmsteadt et al. (1972), the fabrics indicate flattening strain rather than constrictional strain. However, using the XNa content of omphacite and the observed fabrics, the disorder-order rule of Brenker et al. (2002) implies temperatures of 700-800°C for the deformation recorded as an LPO. We are presented with an S-type LPO but a prolate shape fabric. Which one tells us more about the strain?

Accessory and rare minerals of diamond bearing eclogites from the Udachnaya pipe, Yakutia

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Presented results of optical microscopic and electron microprobe study of 46 samples of diamondferous eclogites of Udachnaya pipe point to a crystallization of eclogite melts in mantle conditions at T = 900 – 1300ºC. By peculiarities of chemical compounds and presence of groups of accessory minerals the given collection of garnet-clinopyroxene rocks can be divided into three types: magnesian, magnesian-ferrous and high-alumina varieties. The most detailed investigation made for accessory and rare minerals, such as diamond, ilmenite, rutile, corundum, kyanite and sulfides which permit to receive important information about conditions of evolution and differentiation of eclogite systems.

In the magnesian-ferrous and high-alumina series of eclogites the grains of rutile with spinel exsolution structures (14 – 15 wt.% FeO, 7 – 13 wt.% MgO, 32 – 44 wt.% Al_2O_3) were established. The origin of such formations is problematic. Probably, these structures were formed at disintegration of solid solution system (Mg, Fe)TiO_3 – Al_2O_3. The rutile grains have rims of secondary ilmenite (6 – 8 wt.% MgO), enriched by manganese (0,75 – 1,08 wt.% MnO).

Symplectitic intergrowths begin to form in the high-alumina eclogites at high potential of aluminum. In comparison with corundum inclusions in a diamond the corundum from eclogites is characterized by high contents of total iron (0,26 – 0,51 wt% FeO+Fe_2O_3). The weak zones of corundum and garnet intergrowths in most cases have undergone metasomatism transforming. However, the induction surfaces of growth are tracked in the non-altered parts of these intergrowths. The kyanite has no trace elements by electron-microprobe date. This mineral as corundum is typical for high-alumina eclogite xenoliths only.

Abundance of sulfide minerals in eclogites from the Udachnaya kimberlite pipe is higher in compare with xenoliths of ultrabasic rocks. Sulfide minerals in eclogites are situated as inclusions in rock-forming minerals, also in zones of their fractional melting on boundary of minerals, in veinlets and fractures. As contrasted to ultrabasic rocks, where a typical element in sulfides is the nickel, and a mineral is pentlandite, in sulfides of eclogites the defining element is the iron, and mineral is pyrrotine, and in same eclogite samples pyrite presents. Most widely sulfide aggregates in eclogites are situated in intergranular space, and the majority of them is referred to pyrrotine (or $M_{SS\mathit{Fe}}$) + pentlandite (Pn) + chalcopyrite (Cp)/cubanite (Cb) association or to pyrrotine (or $M_{SS\mathit{Fe}}$) + pentlandite (Pn) + djerfisherite (Dj) association. Most of sulfide grains consist of several minerals. Usually they are characterized by zonal structure. Cores of such sulfide aggregates are composed by pyrrotine (Po) with pentlandite lamellae, and rims are presented by chalcopyrite, cubanite and djerfisherite.

Sulfides with zonal structure of Po+Pn+Cp, Po+Pn+Cb, Po+Pn+Dj and $M_{SS\mathit{Fe}}$+Po+Pn+Cp+Py+Dj-associations dominate in eclogite xenoliths from diamond bearing kimberlite pipes. Sometimes pyrite, ore iron and magnetite are present in these associations. Separate grains of Py, Cp, and Dj with blocking constitution and in association with

secondary silicates are present in veinlets. Wide abundance of djerfisherite is indicator of mantel metasomatism alteration of eclogites in diamond bearing kimberlite pipes.
The detected regularities in variation of garnet, clinopyroxenes compositions, the features of accessory and rare minerals at transferring from magnesian eclogites to magnesian-ferrous ones and further to alumina eclogites definitely point out on their formation in uniform process of ultrabasic-basic mantle rocks with differentiation of primary mantle melt under affecting of fluids enriched with hydrogen, and further crystallization of melts at decreasing of pressure and temperature conditions with consequent affecting of large scale metasomatism on the formed rocks, and completion of final rock consolidation at a hydrothermal stage.

Rapid exhumation of UHP rocks related to slab break-off: insights from 2D numerical experiments

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Rapid (within a few Myr) exhumation of UHP complexes — including diamond-bearing rocks formed at a depth exceeding 100 km — requires a satisfactory geodynamic explanation. We used coupled 2D thermo-mechanical numerical experiments to demonstrate that extremely rapid (1-10 cm/a) exhumation of UHP complexes of crustal origin can be related to the process of slab break-off under a collisional orogen. The onset of the break-off process is due to a gradual increase of the pulling force associated with the hydration and rheological weakening of the mantle lithosphere under the overriding plate during subduction. Our experiments suggest that the formation of large coherent UHP complexes in continental collision zones can result from the temporary expansion of the subduction channel during incipient continental collision, when it can form a wider and deep-reaching (> 150 km) wedge of subducted crustal material. In our simulations, this crustal wedge decays within a few million years by upward extrusion, as a consequence of necking and subsequent separation ("slab break-off") of the subducted lithosphere, and related creation of an asthenospheric window. Further slower exhumation of the ultrahigh-pressure complexes from lower crustal depths toward the surface can take place during regional doming caused by the extension and heating of the crust above the asthenospheric window. Numerically modeled P-T-t paths for UHP rocks agree well with the petrological record available from several UHP regions.

Modeling the thermodynamic phase relationships and geophysical properties of eclogitic mantle lithosphere

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The presence of eclogite bears directly on processes of craton stabilization, the thermal state of the mantle lithosphere, mantle processes since the time of stabilization, and the current geophysical properties of the lithosphere. The mineral assemblages, modes, and mineral compositions of eclogite contain important information on their origin and physical-chemical conditions of formation. We have calculated how mineral assemblage, abundance, and composition vary with bulk composition as well as with temperature (T) and pressure (P) using the pseudosection option of the program PERPLEX. The chemical system used was: SiO_2-TiO_2-Al_2O_3-FeO-MgO-CaO-Na_2O. Fe_2O_3 was converted to FeO. Phase components considered were: quartz, coesite, pyrope, almandine, grossular, diopside, hedenbergite, jadeite, Ca- Fe- and Mg-tschermak, forsterite, fayalite, enstatite, ferrosilite, ilmenite, and rutile. We used as input bulk compositions a variety of fresh and altered basalts and eclogites, including those from the Jericho, N.W.T., kimberlite pipe. Thermodynamic data for the phase components and activity models are contained in the program PERPLEX. Stable mineral assemblages were calculated along a Slave cratonic geotherm. We have used these calculated compositions to set constraints on the protolith and the P-T conditions of eclogite formation. In addition, we have computed densities, heat capacities, and P and S wave velocities for these different mineral assemblages. The velocity calculations were done at room T and P and linearly extrapolated to mantle P-T conditions. Kyanite is stable in relatively aluminous bulk compositions and occurs only in the stability field of graphite along the Slave geotherm. The quartz-coesite transition produces sharp changes in both P and S wave velocities at depths of about 90 km, but an SiO_2 polymorph is generally lacking in mantle ecogites. We also explored an igneous crystal residue origin for eclogite by using P-MELTS to model the crystallization of basaltic magma under mantle conditions. For these calculations we used the activity models in P-MELTS. To produce Grt-Cpx eclogites a cumulate residue of $\geq$55% is necessary for all bulk compositions except ankaramite. We modeled metasomatism by computing relative %Si loss and using PERPLEX to calculate the resulting mineralogy at P/T. For Si losses of $\leq$30% relative, Grt-Cpx-Coesite eclogites can be produced from all of the model basalts except for ankaramites.

Devonian collision and HP/UHP metamorphism along the northeastern margin of Laurentia, Greenland Caledonides

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Caledonian collision between Baltica and Laurentia is generally taken to be Silurian or "Scandian" in age based on stratigraphic relationships at the thrust fronts of Scandinavia and Greenland. Our growing data set of U-Pb and Sm-Nd ages for HP metamorphism of Laurentian basement in the Greenland Caledonides indicates that collision persisted well into the Devonian. In contrast to Scandinavia, no exotic terranes are present in Greenland, and the structurally highest thrust sheet in North-East Greenland consists of Early Proterozoic Laurentian basement that was metamorphosed to eclogite facies during Caledonian collision.

Eight of nine Sm-Nd mineral isochron ages from eclogites between 76.5°-79°N fall in the range of 410-360 Ma. Zircons with metamorphic rims were recovered from six of the same samples; U-Pb SHRIMP ages of the rims corroborate the Sm-Nd data. The youngest ages are found in the eastern part of the eclogite province, which is also the locus of the ultrahigh-pressure metamorphism, i.e. P = 3.6 GPa, T = 970°C. Zircons from a kyanite-bearing ultrahigh-pressure eclogite have inclusions of garnet, omphacite, alumino-silicate, and quartz (or coesite), and give a weighted mean $^{206}Pb/^{238}U$ age of 360 ± 5 Ma. This age is intermediate to ages obtained for retrograde metamorphism in the Danmarkshavn area (McClelland and Gilotti, this volume), suggesting that this young age may be recording zircon growth events associated with fluid infiltration during retrograde metamorphism as well. Additional analytical work will address this issue. Since our results from Danmarkshavn show that the Sm-Nd system and U-Pb ages on zircon rims are recording the age of amphibolite facies metamorphism at some stage on the exhumation path, we caution that the same problem is probably lurking in the similar geochronology data sets of other eclogite terranes, and most notably the Western Gneiss Complex of Norway.

Additional evidence of Devonian metamorphism comes from high temperature - high pressure granulite facies metapsammites and anatectic metapelites of the Payer Land gneiss complex, located approximately 250 km SW of the main eclogite province. U-Pb SHRIMP analyses of zircon rims from two samples yield weighted mean $^{206}Pb/^{238}U$ ages of 403 ± 5 Ma and 404 ± 4 Ma. We consider this to be the best age for HP metamorphism so far obtained in the Greenland Caledonides, because new zircon growth in kyanite + garnet + K-feldspar + plagioclase + quartz melts can be directly linked to peak-P. If HP metamorphism in Payer Land is broadly coeval with that in the main eclogite province to the north, then exhumation takes place after 405 Ma up to 380-370 Ma, the age of amphibolite facies metamorphism at Danmarkshavn.

Ages for HP metamorphism spanning 500 km of Laurentian margin are consistently younger than the oft-cited Scandian climax, suggesting that the Baltica-Laurentia collision persisted

through the Devonian. Significant continental subduction or crustal thickening continued during the late stages of collision.

Microdiamond within zircon in thin section in the Straumen coesite-kyanite-eclogite pod, Norway

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The Straumen eclogite pod (n° 62/62 in Lappin, 1966), near Maalöy (Vestlandet), was the second eclogite pod in Norway in which definite coesite was discovered (Smith, 1985, 1988; Smith and Lappin, 1989). This pod, an ultra-"fresh" rutile-calcite-dolomite-amphibole-zoisite-phengite-kyanite eclogite with relict coesite + quartz, shows no trace of amphibolitisation. Like many other Norwegian eclogites, it contains a number of small zircons (~5-50 µm). Many of these zircons contain minute inclusions ~0.2-2 µm in size, equant or rounded in shape and of high relief. Given the difficulty to find such small and scarce zircons, it was decided to look for them in the thin section 62/62A by SEM, which revealed about fifty zircons. The carbon coating was subsequently removed with soapy water and then by ultrasonic vibrations in acetone. In order to identify the nature of the mineral inclusions, a Raman Microscope was employed with a green 514.5 nm Ar^+ laser. The spectra from two inclusions of one zircon (n° C3-1) yielded no trace of diamond, graphite or carbon, and hence only revealed the Raman spectrum of the zircon host. In contrast, another nearby inclusion yielded a sharp peak at 1332 cm^{-1}, which is diagnostic of normal diamond; its intensity was stronger than the most intense bands of the host zircon. This spectrum also showed a double-humped spectral massif (~1335 cm^{-1} & ~1580 cm^{-1}) typical of amorphous carbon; the latter wide band was about as intense as the strong zircon bands. This was deduced to prove the existence of microdiamond coexisting with carbon, but there remained some doubt if the carbon was relict coating and if the microdiamond was a relict contaminant trapped during polishing. This inclusion is just visible at the surface of the slide, but the inclusion below is much larger than its surface expression; this leads us to conclude that this microdiamond really belongs to the rock. A Raman spectrum from a slide coated with carbon displayed a wide band at ~1520 cm^{-1} rather than the typical double-humped massif; this suggests that the carbon coexisting with the diamond is not coating. The question is posed why amorphous carbon was observed rather than graphite. Another microdiamond, but with more amorphous carbon, was found in another zircon (n° C5-1) in the same slide.

Despite some scepticism, at least initially, microdiamond was reported in Kazakhstan by Sobolev & Shatsky (1987, 1990), in eclogite in China by Xu *et al.* (1992), in gneiss in the Erzgebirge in Germany (Massonne, 1998; Nasdala & Massonne, 2000) and in metasediments in Greece (Mposkos & Kostopoulos, 2001). These reports provided potentially compelling evidence of UHPM. In the Western Gneiss Region of Norway, the microdiamonds discovered previously were found in gneiss on Fjörtoft Island (Dobrezhinetskaya *et al.*, 1993, 1995) and in garnet-websterite also from Fjörtoft (Van Roermund *et al.*, 2002). The Straumen eclogite is the southernmost known microdiamond locality and is taken as evidence for peak pressure in the upper part of the 30-45 kbar range deduced by Smith (1976) and Lappin & Smith (1978), for the "Eclogite Suite" in Sunnmöre and Nordfjord, on the basis of other petrological criteria (notably low-Al orthopyroxene coexisting with garnet).

Garnet Peridotites in the Saxonian Granulitgebirge, Bohemian Massif

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Garnet-bearing ultramafic rocks, including garnet peridotite and garnet pyroxenite, occur in the Saxonian Granulitgebirge. The Granulitgebirge, being part of the Variscan orogenic belt in Central Europe, is situated at the northern margin of the Bohemian Massif. It forms a dome structure with granulite-facies rocks in the core that are in tectonic contact with lower-grade rocks in the schist envelope. This is interpreted as a metamorphic core complex (Reinhard & Kleemann 1994). The core consists of quartzo-feldspatic granulite with minor intercalations of intermediate and mafic granulite, metamorphic peak conditions of which were estimated at 1000-1050ºC and 22 kbar (Rötzler & Romer 2001).

Lenses of more or less serpentinised garnet and spinel peridotite with subordinate layers of garnet pyroxenite occur in the eastern and southern part of the Granulitgebirge. Textural relations in garnet peridotite reveal different equilibration stages:
stage I: garnet-clinopyroxene-orthopyroxene-olivine,
stage II: garnet-pargasite-clinopyroxene-orthopyroxene-olivine,
stage III: spinel-garnet-pargasite-clinopyroxene-orthopyroxene-olivine,
stage IV: spinel-clinopyroxene-orthopyroxene-olivine (kelyphite stage).

Preliminary PT estimates yield some 1000-1100ºC and 28 kbar for the early equilibration stage. A later stage at nearly the same temperature but distinctly lower pressure of 20-22 kbar is inferred from increased Al contents at orthopyroxene rims. These conditions are comparable to those in the host rock granulite implying a shared metamorphic history of mantle and crustal rocks from this stage on. Subsequent decomposition of garnet to spinel+orthopyroxene+clinopyroxene (in kelyphite) occurred due to decompression to ≤18-20 kbar (spinel peridotite stability field). Based on Al-contents in orthopyroxene II (in kelyphite) in stable coexistence with spinel (Schmädicke 2000), the kelyphite stage is attributed to unchanged high temperatures of ≥1000ºC. Hence, the garnet peridotite experienced nearly isothermal decompression from about 28 kbar to ≤18-20 kbar. In addition, cm-large crystals of clinopyroxene with mm-wide exsolution lamellae of garnet point to very high temperature conditions (>1200ºC) prior to stage I.

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Garnet peridotites: Wanderers of the mantle

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It is known from the xenolith suite and seismology that the shallow upper mantle (depth < 400km) consists predominantly, perhaps entirely, of peridotite and eclogite and the evidence is strong that the remainder of the mantle is made up of similar chemistry but with different, high-pressure, phases. It also is know that the mantle has been convecting for billions of years and that there is at least sporadic mixing between the upper and lower mantles. Only a small fraction of the circulating mantle material undergoes significant partial melting at midocean ridges, oceanic islands, and island arcs, hence large volumes of peridotite (and lesser volumes of eclogite) must have traveled extensively throughout Earth with little or no change in chemistry, at least over the last billion years or so. In particular, the probability must be high that material currently located in the shallow upper mantle has previously resided in the transition zone (400-700 km) or deeper. It follows, therefore, that there is a reasonable likelihood that mantle rocks transported to the surface of Earth under conditions that they remain in the garnet facies (ie. rapidly as xenoliths in explosive volcanic rocks or along a "cold" trajectory as in ultra-high-pressure [UHP] metamorphic belts) have traveled through the mantle transition zone or even the lower mantle. The temperatures in those regions of Earth are such that it is a virtual certainty that any rocks entering or leaving those regions would recrystallize to the stable mineral assemblage, potentially preserving within the rocks a microstructural "memory" in the spatial relations between the new mineral species. Whether they preserve such evidence of their travels in a form that can be recognized are questions critical to UHP metamorphic studies, as are questions concerning the mechanisms by which such rocks may have been exhumed.

Microstructures suggestive of depths greater than 200 km have now been reported from kimberlite pipes from several parts of the world and at least 3 continental collision zones (Western Gneiss Region, Norway; Western Alps; SuLu terrane, China). For the latter case, interpretations fall into two fundamental categories (i) single-stage hypotheses that propose that the mantle rocks have been rafted to the surface by continental material subducted to the maximum depths inferred from the microstructures; (ii) multiple-stage hypotheses that invoke one or more intermediate stages of convection that carried the very deep rocks to a shallower location where they were stored until brought to the surface up a later subduction zone.

In this presentation, we will review several microstructures suggestive of great depth and the processes by which these memories are progressively stripped away with time and deformation. We also will show examples of experimental simulations in which hypothesized reactions are investigated to allow comparison of their microstructures with potential natural counterparts.

Exhumation of Norwegian UHP rocks: What's come up?

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We have been working to understand the genesis and exhumation of UHP and HP rocks in Norway using a combination of geochronology, petrology, and structural geology. Our principal findings to date include:

• The UHP metamorphic rocks of the Western Gneiss Region were at peak pressures at ~410 Ma, still at eclogite-facies conditions at 395–400 Ma and then exhumed to upper crustal levels by 390 Ma. The Peclet number for such an exhumation rate and the apparent >10 km length scale of the UHP domains is >1.6–3.3, suggesting that conductive heating was overshadowed by rapid advection; moreover, the fact that the HP rocks appear to have cooled during exhumation implies that some cooling boundary condition, such as deeper level subduction, caused a greater-than-adiabatic cooling. Modeling of K-feldspar $^{40}Ar/^{39}Ar$ spectra shows that, following exhumation to upper crustal levels, the HP–UHP rocks subsequently underwent very slow cooling for 100–150 Myr.

There is a clear gap of ~20 Myr between the inferred age of the initiation of continental collision and the time of UHP recrystallization. Such a large interregnum between the first stages of collision and the attainment of peak pressure would almost certainly have resulted in thermal erasure of the UHP metamorphism if the profound continental subduction occurred at the start of collision (the characteristic diffusion distance for 20 Myr is ~25 km). Thus, the UHP metamorphism was a late-orogenic event that just preceded large-scale exhumation within the orogen.

• The entire UHP–HP slab rose from mantle depths and stalled at ~40 km depth where it underwent a "Barrovian" overprint at ~1.2 GPa. Significantly, the UHP–HP slab was exhumed through the crust diachronously, reaching muscovite closure to Ar diffusion in the east at ~400 Ma and in the west at ~390 Ma. The overlying 40-km thick "lid" to the UHP slab could have been continental or intraoceanic arc crust. Late-stage Barrovian metamorphic overprints are common to UHP terranes, suggesting that UHP terranes typically stall at the continental Moho because the buoyancy force approaches zero. We hypothesize that many UHP terranes never underwent their final stage of exhumation and now constitute significant portions of the lower crust worldwide.

• The UHP rocks are allochthonous with respect to Baltica basement and separated from the Baltica basement by a top-W, amphibolite-facies extensional shear zone, the Nordfjord–Sogn Detachment Zone (NSDZ). This overturns earlier ideas that the HP–UHP rocks were exhumed in the footwall of the normal-sense NSDZ and shows instead that the UHP rocks moved structurally downward with respect to Baltica in their latest stage of movement. The juxtaposition of UHP rocks in the hanging wall with Baltica basement in the footwall demands that this fault—or a related structure—had an earlier contractional history that thrust the UHP rocks over Baltica basement.

• The history of the Nordfjord–Sogn Detachment Zone in the Solund area is now well known. Intraoceanic arc rocks were thrust over the Baltica margin after 434 Ma, burying a stack of

three intervening continental margin units to depths of 30, 50, and 80 km, beginning at 428 Ma and finishing by ~410–400 Ma. Within <5–10 Myr, all these units were exhumed to ~25 km depth along an amphibolite-facies top-W normal-sense shear zone. This exhumation corresponds to a normal displacement of 70–110 km and shear strains >100.

• The size and shape of the UHP terrane have been redefined. New coesite and coesite pseudomorph localities have been found as far SW as Verpeneset, as far east as Hellesylt, and throughout the Sorøyane. Moreover, areas without coesite and coesite pseudomorphs suggest that there are three distinct UHP domains within a larger HP province. This conclusion is bolstered by the distribution of muscovite $^{40}Ar/^{39}Ar$ chrontours, which wrap around the two southern UHP domains. These two observations imply that previously unrecognized large-scale folding about E-plunging axes controls the distribution of HP and UHP rocks; differences in $^{40}Ar/^{39}Ar$ muscovite and K-feldspar ages across these folds require that the folding is as young as 335 Ma. The high-pressure area is now known to extend over 40,000 km^2 and the three UHP domains collectively cover ~2500 km^2.

Building the Pamirs: The view from the eclogitic underside

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The Pamir Mountains of central Asia are an outstanding example of extreme shortening during continental collision. Surface geology requires >650 km of Cenozoic shortening, which could have been accommodated through the formation of a much thicker crust than currently thought (~75 km, roughly twice the normal thickness of continental crust), by continental subduction, or by a combination of both. Widespread, though volumetrically minor potassic volcanism accompanying the India–Asia collision has received much attention because it may help explain the evolution of the Tibetan plateau, but there is no consensus as to whether it was derived from melting of the sub-orogenic mantle lithosphere or from progressive heating and partial melting of over-thickened or subducted crust. In addition, the development of the Pamir–Tibet collisional plateau is controversial. New petrologic and geochronologic data on xenoliths erupted during Miocene volcanism in the southeastern Pamir Mountains show that Late Cretaceous quartz monzonites and Paleocene sedimentary rocks with affinities to Gondwana were underthrust northward, buried to >50–80 km during the early stages of the India–Asia collision, heated and partially melted during subsequent thermal relaxation, and then blasted to the surface. These xenoliths provide direct evidence for the early Cenozoic thickening of the Southeastern Pamir Mountains and suggest that the present mountain range was a lofty plateau for most of the Cenozoic.

Evolution of the Trondheim Nappes

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We have completed a thermobarometry and geochronology study in the Trondheim–Tännfors–Røros–Oppdal area to assess the relationship between UHP metamorphism and emplacement of the exotic continental and oceanic nappes of the Uppermost and Upper Allochthons. We calculated pressures and temperatures with Thermocalc using equilibria between garnet, biotite, muscovite, plagioclase, kyanite, staurolite, hornblende, and quartz, and determined PT paths by applying the Gibbs method of Spear et al. $^{40}Ar/^{39}Ar$ ages were determined for a broad suite of hornblende, muscovite, biotite, and K-feldspars, and monazite ages were measured with secondary ion mass spectrometry.

Following crystallization of the Bindal Batholith at ~447–437 Ma , emplacement of the Uppermost Allochthon at ~435 Ma produced sudden burial of recent intrusions in the Upper Allochthon (e.g., Råna) and Vestranden gneiss (e.g., Roan) to 12–15 kb (Nordgulen et al., 1993; Northrup, 1997). This was echoed in the Seve/Blåhø, Gula, and Köli Nappes, where 434–456 Ma plutons intruded at depths of ~4 kb were rapidly buried to 12, 9, and <8 kb, respectively. PT paths for the Seve/Blåhø and Gula Nappes reveal compression during heating, implying that these two units were buried together in the footwall of a west-dipping contractional fault beneath structurally higher units such as the Köli Nappe. All of these units have hornblende ages of ~435 Ma along the eastern edge of the nappe stack, indicating that imbrication of the stack—as well as significant subsequent extension—was finished by that time. Another 20 Myr was required for muscovite to cool through Ar closure (415 Ma), suggesting minimal tectonic exhumation in that timeframe.

This development stands in stark contrast to the western edge of the Trondheim nappe stack, where temperatures remained elevated for an additional 20 Myr, with hornblende and muscovite closure being reached at ~417 and 400 Ma, respectively. The muscovite ages of the western edge of the nappe stack represent the oldest part of a broad gradient in muscovite ages that extends across the entire Western Gneiss Complex, “bottoming out” at ~375 Ma along the coastline.

Thus, the history of the eastern Trondheim nappes is clearly linked to the emplacement of the Uppermost Allochthon, whereas at least the younger history of the western Trondheim nappes is closely linked to that of the Western Gneiss Complex. The genesis of the Norwegian UHP rocks at 410–400 Ma probably has no causal relationship with the eastern Trondheim nappes, which had stabilized at shallow crustal levels long before, and, by implication, no direct relationship to continent collision or ophiolite emplacement.

Extrusion of lower crustal rocks in continental collision settings: an example from the Grenville Province

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Belts of high-P rocks in continental collision orogens commonly represent crust that has been subducted to mantle depths. However, high-P belts also occur in intracontinental settings where there is no evidence of prior subduction. A prime example is the high-P belt of the Grenville province, for which extrusion of lower levels of thickened crust can be invoked.

The Grenville Province consists of Laurentian basement with accreted arc material, involved in continental collision that culminated with the Ottawan orogeny (~1.07-0.99 Ga). This was a major NW-directed imbrication episode, responsible for the final configuration of the orogen. In the Grenville Province, high-P granulites and eclogites occur along a discontinuous belt stacked between parautochthonous units, that display Barrovian metamorphic signatures, and mid to low-P units of the hinterland. The best documented part of this high-P belt is the Manicouagan Imbricate Zone (MIZ).

The MIZ consists of shallowly SE-dipping tectonic slices of 1.65-1.45 Ga igneous rocks that were pervasively deformed and metamorphosed under 1400-1800 MPa and 800-900°C at ~1.05-1.03 Ga. Kinematic characteristics of high-strain zones depend upon the structural position. The lower levels are characterized by thrust-sense S/L shear zones (NW- directed transport) and L-dominant tectonic domains with fabrics consistent with channel flow in the same direction. The middle levels display evidence of lateral escape to the SW. The highest levels are transected by normal-sense shear zones (top to the SE). Thrust-related shear zones are intruded by late tectonic Fe-Ti gabbro with tholeiitic within-plate signatures and high-P mineral assemblages, indicating emplacement of mantle-derived melts within thick crust. On the hinterland side, MIZ is overlain by units that escaped Grenvillian-age deformation and metamorphism (Hart Jaune terrane; HJT), and represent high levels of Ottawan crust. Farther south high-P rocks typical of the MIZ occur as tectonic inclusions in an antiformal culmination of high-strain mid-P granulites (Gabriel high-strain zone: GHSZ), that were metamorphosed at the same time (~1.05-1.04 Ga) and under similar high-T conditions (800-900°C) as the MIZ, but under markedly different pressures (~900-1100 MPa).

Overall structural configuration is consistent with NW-directed extrusion of the MIZ over the Parautochthonous belt shortly after the metamorphic peak. Key factors that controlled extrusion of such a deep crustal segment include thermal weakening due to the high-T metamorphism; and the presence of a crustal scale ramp in the underlying Parautochthonous belt. The presence of broadly synmetamorphic mafic intrusions in shear zones related to the early stages of exhumation of the MIZ suggests that magmatic underplating may have occurred while the crust was still thick, and that advective heat from the mantle may have played an important role in the thermal evolution and the development of high ductility in the high-T units. This is consistent with synchronous achievement of peak Ts throughout the pile. Part of the hangingwall of MIZ during extrusion is represented by the mid-P GHSZ. Similar metamorphic ages in the MIZ and the GHSZ imply that high-P metamorphism in the former and juxtaposition of high and mid-P rocks along the latter occurred within a few My only. Following extrusion, the hinterland units structurally above MIZ apparently experienced NW-directed shortening (linked to extensional collapse of the orogen's interior and transport of

high-level units towards the foreland), and final normal-sense displacement along major shear zones.

Disregarding the difference in levels of exposure, the tectonic configuration of the Manicouagan area bears some interesting similarities with the Himalaya-southern Tibet system. Key elements in a generalized section across the latter, towards the hinterland's interior, include high-grade gneisses of the Higher Himalayas, synforms with low-grade rocks and gneissic domes, in a pattern similar to that of the MIZ-HJT-GHSZ. In the case of the Himalayas this pattern has been modeled with channel flow of ductile crust underneath a plateau and surface denudation at the plateau's rims as controlling factors for the extrusion of the Higher Himalayas (Beaumont et al. 2001). However in these models development of high ductility is limited to the middle crust and is attributed to heat produced by radioactive decay only whereas in the Manicouagan section deeper levels of crust are extruded and there is evidence for mantle-derived extra heat. Steeper contacts between units above the MIZ, relative to equivalent contacts in Himalayan sections is consistent with late shortening achieved during the waning stages of the Ottawan orogeny, a stage that is not reached yet in the Himalayas.

LREE fractionation in MORB-type eclogites due to fluid induced eclogitisation of gabbroic rocks: evidence from trace element, Lu-Hf, and Sm-Nd isotope systematics

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Isolated outcrops (10-100 m hills) of deformed and undeformed eclogite occur closely associated with metagabbros, gabbros, and rare ultramafic rocks in a 200 km long by up to 40 km wide zone in central Zambia. Contacts with the country rocks and between the eclogites and the other mafic rocks are not exposed. Gradual stages of prograde transformation from gabbro to eclogite are preserved by disequilibrium textures of incomplete reactions. The undeformed eclogites often display a relict gabbroic texture, in which plagioclase and pyroxene have been pseudomorphically replaced by eclogite facies minerals. In contrast, the deformed eclogites have sheared to porphyroblastic textures. Relics of magmatic pyroxene are common in both deformed and undeformed varieties. No evidence for prograde blueschist or amphibolite facies mineral assemblages was found in the eclogites. Instead, fine-grained intergrowths of omphacite, garnet, kyanite, and quartz have replaced plagioclase or formed in the pressure shadows of magmatic pyroxene relics, indicating the direct eclogitisation of gabbroic precursors without stepping through intermediate metamorphic reactions. Eclogitisation took place ~600 Ma ago (Sm-Nd and Lu-Hf ages) at 630-690°C and 26-28 kbar and was accompanied by a channelised fluid flow that produced veins of the peak metamorphic assemblage. Textural evidence of incomplete reactions suggests that either (1) the eclogites did not remain at great depth long enough for reactions to complete, or (2) the fluids, which acted as catalysts for the reactions, left the system.

Based on trace element patterns, the mafic rocks studied here can be subdivided into three groups: (1) light REE (LREE) enriched, (2) LREE depleted, and (3) those having unusual REE patterns with a strong LREE variability. Most of the mafic rocks resemble very depleted to slightly enriched mid-ocean ridge basalts (MORB) in their Nb/La vs. $(La/Sm)_N$ and Hf/Yb vs. Nb/Zr ratios. In addition, their initial Nd and Hf isotope compositions indicate that, like MORB, they were derived from a mantle source characterized by long term depletion. Thus, their protoliths were probably subducted oceanic crust. However, group 3 samples display a significant fractionation of the LREE from the HFSE (high field strength elements, e.g., Nb and Hf), an effect that cannot be of magmatic origin but must have occurred during metamorphic reactions. To determine whether this LREE fractionation occurred during eclogitisation or later during retrogression, we dated peak metamorphism using Sm-Nd (relatively mobile elements) and Lu-Hf (relatively immobile elements). For all dated samples, the Sm-Nd and Lu-Hf ages are identical within error and we conclude that the LREE were fractionated during eclogitisation and that there has been no significant disturbance of the LREE since. The eclogitisation process was limited by fluid availability, and the flow of fluids through the rock is the most likely mechanism of open-system behaviour and LREE fractionation in the group 3 rocks. Trace element modelling of fluid-rock interactions under eclogite facies conditions reveals that the group 3 rocks must have reacted with an amount of fluid equal to 25 to 80% of their mass to create the most fractionated REE patterns. It is unlikely that such large volumes of fluid were derived from the lower gabbroic part of the oceanic crust, and therefore we postulate that serpentinised lithospheric mantle was the fluid source.

In summary, the LREE enrichment and depletion in groups 1 and 2, respectively, are apparently magmatic in origin. Eclogitisation of these rocks was limited to areas of fluid infiltration. However, the fluid flux was probably very small, because these rocks do not show decoupling between LREE and HFSE, which would have indicated open system behavior. In contrast, the group 3 rocks seem to have been affected by a larger fluid flux that redistributed the LREE, thereby decoupling the LREE and HFSE. Though all of the mafic rocks from our study area were subducted, only those gabbros that were infiltrated by fluid under eclogite facies conditions were eclogitised. Thus, Zambian eclogites and their veins represent relict fluid pathways through subducted oceanic crust and provide direct evidence for channelised fluid flow and element transport within a slab.

Evolution of the Nordfjord-Sogn Detachment Zone, Hornelen Region, Norway

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The Nordfjord-Sogn Detachment Zone (NSDZ) can be followed along strike as a major ductile shear zone for several hundred km, and is presumably responsible for the exhumation of the Norwegian UHP province (Milnes et al, 1997). However, the kinematic evolution of the NSDZ is incompletely understood. The hanging wall of the NSDZ consists of several large low-grade Devonian sedimentary basins placed via normal-sense detachments structurally above a thin series of allochthonous amphibolite-grade basement–cover sequences. The footwall is primarily composed of autochthonous Baltic Shield basement gneisses. Most of the current literature suggests that the Norwegian UHP provinces were brought to the surface in the footwall of the NSDZ. However, there is some debate over the exact location of the UHP rocks with respect to the NSDZ and whether they reside in its footwall or its hanging wall (Young, 2002). The resolution of this debate has profound implications for the mechanics of UHP exhumation: if the UHP rocks are in the footwall, the normal-fault hypothesis remains valid, but if the UHP rocks are in the hanging wall, the NSDZ must actually be a major thrust fault that was subsequently overprinted by a relatively minor extensional event.

To better understand the mechanics and evolution of the NSDZ immediately south and east of the Hornelen basin, we are employing i) field and laboratory structural geology to understand the deformation histories of the various units; ii) thermobarometry to assess the P–T evolution of garnet-bearing lithologies; iii) $^{40}Ar/^{39}Ar$ thermochronology to characterize the thermal histories of the allochthons; iv) U/Pb geochronology to assess igneous crystallization ages; and v) detrital zircon geochronology of the myriad sedimentary basins. The Hornelen Basin was emplaced structurally above the allochthonous basement–cover sequences via normal-sense shear along a greenschist-facies detachment. Preliminary ion microprobe results show that the oldest deposits in the Hornelen Basin were derived from Precambrian crystalline rocks and 443 Ma metamorphic rocks. The structurally highest unit within the allochthon is composed of greenschist-facies metavolcanics overlain by meta-arkoses and schists and can be correlated to the Solund–Stavfjord Ophiolite Complex (Andersen, 1996). Felsic granitoids intruding the base of this unit yield ion microprobe U/Pb ages of 480 Ma, while detrital zircons from overlying meta-arkoses yield Precambrian ages. Structurally lower allochthonous units are composed of amphibolite-grade orthogneisses, paragneisses, quartzites and schists correlative with the Dalsfjord Suite and the Høyvik Group (Andersen, 1996). Shear bands and S–C structures observed in this unit in the field and in thin section are dominantly top–W. Preliminary thermobaromety and thermochronology on garnet-biotite-muscovite-plagioclase assemblages indicate maximum P–T conditions of 550°C and 8 kbar. A revised pseudostratigraphy for these higher grade allochthons suggests that large areas previously mapped as paragneiss are orthogneiss.

Elastic modeling for metastable minerals under UHP conditions

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Low-pressure minerals, such as quartz, occur as inclusions in zircon and garnet cores of the UHP metamorphic rocks. This implies that the host minerals can buffer the pressure of the rock, and inclusions can metastably survive within the refractory minerals at different P-T conditions. We examined an elastic model to explain the occurrence of metastable phases within refractory minerals. The model discussed the difference of compressibility between host minerals and inclusions.

Quartz shows obviously lower compressibility than garnet and zircon. If the inclusions were controlled by the compression of host minerals of garnet and zircon, the significant differences of the bulk modulus lead to the distinct pressures of each inclusion minerals. In the Kokchetav UHP massif, the diamond-bearing rocks were recrystallized at pressures of 60 kbar and temperatures of about 1000°C, and contained quartz inclusions in zircon and garnet cores. The volume of garnet and zircon decrease to 99.1% and 98.4%, respectively, at the UHP conditions compared to those of ambient conditions. The quartz inclusions compressed by same values of the host minerals require pressures of 19.6 kbar in garnet and 22.3 kbar in zircon. These conditions is apparently lower than that of the quartz-coesite transformation (< 29.5 kbar at 1000°C), whereas matrix minerals were experienced the conditions of diamond stability field. Thus, theory of equation of state can explain the presence of metastable minerals in refractory minerals of garnet and zircon during UHP metamorphism, because of the significant difference of their compressibility. On the other hand, the transformation to coesite within the refractory minerals requires bulk pressure of 104.8 kbar in garnet and 102.9 kbar in zircon, respectively, at a temperature of 1000°C. The inclusion pressure however has been easily released if plastic deformation was significant in the host minerals, so that the values represent maximum pressures to preserve the quartz inclusion.

The very resistant character of garnet and zircon based on their bulk modulus suggested to be potential capsule of metastable minerals, and can record the prograde metamorphic history of the ultrahigh-pressure metamorphic rocks.

Extreme continental thickening as a burial mechanism for UHP rocks in the Scandinavian Caledonides

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Continental ultrahigh pressure metamorphic (z > 90 km) terranes like the Western Gneiss Region in West Norway are generally thought to be buried by continental subduction, whereby continental crust is pulled deep down into the mantle by dense oceanic lithosphere. Subsequent exhumation is thought to occur by some sort of slab break-off or buoyant wedge-extrusion ('Chemenda-style') so that buoyant continental crust moves towards the surface. These mechanisms require that a) the UHP terrane in question was part of a passive margin just prior to UHP metamorphism and b) that the resultant orogen should display a strong assymetry.

Such an evolution is impossible for the WGR for the following reasons:
1) The North Atlantic Caledonides is doubly vergent, with Scandian HP and UHP eclogites occurring in both East Greenland and Norway. Thrusting was to the west and east respectively and late-orogenic extensional detachments top-to-east and west respectively.
2) Exhumation by buoyant wedge extrusion is unlikely as the WGR has no basal thrust to the east that could have put Scandian HP rocks over structurally lower low-pressure units. Also, HP/UHP detritus is absent from exhumation basins.
3) The Baltic Margin was not an Atlantic-type passive margin prior to Scandian UHP metamorphism. In Atløy, Mid-Ordovician metamorphism has been recorded in the Høyvik group of Baltic provenance. On Bømlo, the Geitung island Arc accreted to the Baltic Margin The Vågåmo Ophiolite, was obducted onto Baltic margin rocks prior to the Silurian. In the Seve Nappes – of Baltic provenance – eclogites metamorphism occurred at ~ 505 Ma and cooled prior to the Silurian.

It can thus be assumed that the Baltic margin lost its passive margin character sometime during the Ordovician, well before Silurian UHP metamorphism. Instead, we believe the WGR and the East Greenland Eclogite Province were buried by extreme crustal thickening (z >100 km) as a result of Baltica – Laurentia collision. Extreme crustal thickening by the growth of a substantial orogenic root requires that buoyancy is reduced in the system, otherwise, extreme topography will generate 'mountain push' forces which will arrest convergence, or result in horizontal spreading, rather than vertical thickening of the orogen. Buoyancy is reduced by thickening of the sub-continental lithospheric mantle and by a pronounced density increase (eclogitisation) of the orogenic root below ~ 40 – 50 km. The WGR experienced density changes of 5 – 10%. Thermal modelling suggests that extreme crustal thickening during a short lived orogen (< 30 Ma, depending on strain rate and initial crustal thickness) produces a mean geotherm of around $7^{o}C.km^{-1}$, sufficiently low to allow UHP metamorphism. The increase in density of the root and consequent buffering of the topography causes the base of the crust to accelerate downwards to a vertical velocity of ~ $4mm.a^{-1}$ as the orogen progressively thickens, producing this low, 'subduction type' geotherm.

UHP metamorphism does not, therefore, a priori require continental subduction – extreme crustal thickening is a feasible burial mechanism that may also have caused UHP metamorphism in other terranes.

Reaction-hardening and dehydration as an explanation of pervasive transformation of felsic eclogite during exhumation

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In many (U)HP terranes of continental affinity, including the Western Gneiss Region, pods of mafic eclogite occur within strongly deformed quartzo-feldspathic "country" gneisses with amphibolite-facies assemblages. Metamorphic and structural evidence shows that these assemblages developed during exhumation. This contribution examines the question why exhumation-related deformation and decompression reactions are pervasive in quartzo-feldspathic gneisses but not in mafic rocks, and why eclogites of felsic composition ('felsic eclogites' hereafter) are so rarely preserved. The answer to this conundrum lies in some peculiar properties of felsic eclogites.

Firstly, the typical assemblage of felsic eclogite (Phen + Cpx + Qtz (or coesite) + Zo ± Ky) is more hydrous than amphibolite-facies quartzo-feldspathic gneiss (Plag + K-fsp + Qtz + Hbl + Biot ± Zo) (1). Thus, the decompression reaction of felsic eclogite to quartzo-feldspathic gneiss is a dehydration reaction that is self-catalytic and easier to proceed than the hydration reaction of mafic eclogite to amphibolite, which requires fluid infiltration. A similar situation has been described concerning decompression of eclogitic rocks of pelitic composition (2). Secondly, the typical assemblage of felsic eclogite, dominated by phengite and quartz, is expected to be mechanically weaker than its amphibolite-facies equivalent, the rheology of which is dominated by feldspar. The decompression of felsic eclogite is, therefore, characterised by *reaction-hardening* - although a phase of temporary softening may occur due to the release of fluids and transient small grain size. Deformation enhances metamorphic reactions during both reaction hardening and reaction softening. The difference between the two processes is that during reaction hardening subsequent increments of strain will *preferentially occur in the reactant*, rather than the reaction product. Given sufficient deformation (and much strain is required if exhumation is tectonic!) each and every domain of felsic eclogite will receive its share of strain, sufficient to transform each and every domain into quartzo-feldspathic gneiss. Thus, reaction hardening would result in homogenisation of strain and transformation, especially when operating together with dehydration reactions.
In the Caledonian HP/UHP terrane of the Western Gneiss Region in Norway the following field observations were made. A) Exhumation-related deformation of the quartzo-feldspathic amphibolite-facies gneisses is strong but fairly homogenous (that is: poorly partitioned) over vast tracts (>40 000 of km^2) of the terrane. B) Felsic eclogite is preserved, but only in low strain zones, shielded from deformation during exhumation, commonly adjacent to mafic eclogite or granulite bodies. C) Extreme competency contrasts occur between felsic and mafic eclogite where these rocks occur together in larger domains.

Thus, deformation appears to have played a key role during decompression metamorphism. The last point suggests that the mechanical strength of felsic eclogite, controlled by phengite or zoisite, is lower than the strength of its amphibolite-facies equivalent, which is controlled by feldspar.

The combination of dehydration and reaction-hardening provides a credible explanation for the pervasive deformation and decompression reactions that are typical of quartzo-feldspathic

gneisses in which many mafic eclogite-boudins occur. The tectonic implication of this process is that continental terranes that experienced (U)HP conditions – like the Western Gneiss Region – may have experienced profound density changes during their orogenic cycle.

References

Bousquet et al. (1997): *Tectonophys.*, 231, 105-127.
Heinrich (1982): *Contrib. Minera. Petrol.*, 81, 30-38.

Note: this is an abstract accompanying a poster that Alice Wain and I presented at the 'Exhumation of Metamorphic Terranes" MSG Meeting in Rennes, in 1999, less than a year before Alice died. I have added some parts to the abstract, but all points made were on the poster. This work has not been written up yet, so it is appropriate to present the poster again at the Alice Wain Memorial Eclogite Symposium.

Precise U-Pb zircon ages define 18 and 19 m.y. subduction to uplift intervals in the Averøya-Nordøyane area, Western Gneiss Region

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The interval between subduction and uplift using eclogite-facies transformation zircons and those formed in extensional boudin-neck pegmatites has been determined with samples from Averøya and Nordøyane. Eclogite zircons are typically small, rounded, low U with concordant U-Pb systems. Precise analyses require multi-grain fractions (1-25 grains) and multiple analyses are needed to test for inheritance and discordance. Boudin-neck pegmatites contain abundant new zircons with ubiquitous cores hence multiple tips are analysed. Discordia, where defined, have zero lower intercepts, hence mean 207/206 ages are used where no line is defined, even though 206/238 ages are inherently more precise.

Eclogite at Averøya (old ferry dock) is unique in having two stages of metamorphic zircon growth. Three concordant fractions of the older, small rounded grains have a mean 207/206 age of 418 Ma (413,420,422 Ma) and a mean 206/238 age of 415±2 Ma (415, 415 ,415 Ma), whereas tips from two large euhedral grains have a mean 207/206 age of 410 Ma (408, 411 Ma) with 206/238 ages of 410 and 411Ma. The precise mean 206/238 age is the best for the first eclogitization because none of the five analyses here exhibit discordance and the 207/206 age has a large 2 sigma error of +/- 5 Ma. At this outcrop a post-eclogite pegmatite gave 5 concordant analyses with 3 giving a mean 207/206 age of 395.9 and a mean 206/238 age of 395.2 +-1 Ma. A second pegmatite collected from an eclogite boudin neck 26 km to the east (stop 4-12, 1997 Copena Field Guide) gave an identical mean 207/206 age of 395.6 (5 points 0.2,0.2,0.9.1.1,and 0.9 % discordant). Near Averøya an interval of 14 million years between final eclogitization (410 Ma) and extension-related ductile flow (395.5 Ma) is defined, with first eclogitization at least 5 million years earlier.

Only the second eclogitization is present in Nordøyane to the west-southwest. A sample of the contorted totally eclogitized north margin of the Flem Gabbro in the northern structural segment provided only a small amount of small rounded zircons. Data for two concordant analyses gave a mean 207/206 age of 412 (411,412 Ma) and a mean 206/238 age of 409 Ma (408, 410 Ma). At Lepsoya a sample of fresh omphacite eclogite from a small islet near Seth in the southern structural segment, provided a small yield of small rounded grains. Data for two concordant fractions of these gave a mean 207/206 age of 414 Ma (414 and 413 ma) and a mean 206/238 age of 412 ma (412 and 412 Ma.) Extension in Nordøyane was dated using a boudin-neck pegmatite from a kyanite eclogite at the north shore of Fjortoft and an eclogite raft south west of Kjellholmen on the north coast of Flemsøya. For the kyanite eclogite pegmatite, 5 single grain fractions of brown zircons yield a discordia line with points 0.6, 0.6, 1.4, 1.5 and 7.7 % discordant (unabraided grain) that define an age of 394.5 +/- 2 (83 % probability of fit) and a lower intercept near zero. Data for 4 colourless grains of a type commonly overgrown by brown zircon are 1.4 to 5.5 % discordant but using the known zero intercept, project to single or composite ages of 399, 401, 405 and 412 Ma as if they grew over an interval preceeding the final major growth stage. Hybrid boudin-neck pegmatite on Flemsøya contained abundant cored grains. Data for 4 tips from these yield data that are 1.3, 1.5, 2.3 and 3.2 % discordant with a mean 207/206 age of 397 Ma. The two most concordant analyses are the youngest and hence are least likely to contain older growth components.

These have a mean 207/206 age of 395 Ma (394, 395 Ma).

The combined data for two eclogites (414 and 412 Ma) and two extensional pegmatites (394.5 and 395 Ma) for Nordøyane indicate an 18 million year interval between subduction and extension, analytically identical to the 19 million years defined at and near Averøya. The first and second eclogitizations at Averøya (415 and 410 Ma) analytically overlap those at Nordøyane (414 and 412 Ma) but are 13 and 8 m.y. older than that at Ulsteinvik (402+/-2 Ma).

Pressure-temperature–time-deformation history of the exhumation of ultra-high pressure rocks in the Western Gneiss Region, Norway

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The Nordfjord area, north to the Hornelen Devonian basin, is the southernmost part of the Ultra-high Province defined in Western Norway by occurrences of coesite-bearing eclogites. The compilation of structural, petrological and geochronological data on the area allows to propose a model for the behaviour of the continental crust during its exhumation from mantle depths. The Nordfjord area appears as a 100 x 50 km boudin structured by at least two deformation stages. Three gneissic envelopes (Stadlandet, Vanylven and `Volda), limited by narrow high strain zones were constrictively stretched in the E-W direction and sheared to the west over a core preserving the granulite protolith in Flatraket. Post-eclogitic and syn-kinematic partial melting is wide-spread in the upper parts of this structure. A later stage of mylonization and dextral shear affected the region during its exhumation along the Nordfjord-Sogn Detachment Zone. The resulting Nordfjord Mylonitic Shear Band (NMSZ) is now the southern limit for the regional structural sketch. The first stage of deformation is coeval with reequilibration from the maximum pressure conditions (2.8 GPa, 650°C according to thermobarometric calculation using the THERMOCALC multiequilibrium method) in the coesite stability field to higher temperature and lower pressure conditions (1.8 GPa, 780°C), both stages recorded by the scattered eclogite lenses and subsequent retrogression in the amphibolite facies conditions (0.7 GPa, 580°C) recorded by the migmatized surrounding gneiss and the destabilisation symplectitic textures in the eclogites. Pegmatites indicate late crystallization in the green schist facies at 0.4 GPa x 420°C. U-Pb ages at 400 ± 5 Ma from zircons for the UHP stage, 389 ± 4 Ma from rutiles for the maximum temperatures, and 375 ± 5 Ma from titanites for the partial melt allow to calculate velocities higher than 2 mm/a for the different exhumation stages. Ar-Ar ages in the area, compared to a spectrum of cooling ages along a profile from the southernmost part of the WGC to the Vestranden Gneiss north to the Møre-Trondelag Fault Zone (MTFZ), show that cooling of the WGC between NMSZ and MTFZ is at least 20 Ma younger than cooling in the northernmost and southernmost areas. The WGC would therefore be the result of the late juxtaposition of two different compartments, a Northwestern Gneiss Complex (NWGC), characterized by UHP relics, constrictive stretching, boudinage and partial melting during an exhumation in several stages from the deeper parts of the orogen and a Southwestern Gneiss Complex (SWGC) with devonian basins, a well developped west-verging detachment system and HP to MP metamorphism recorded by disctinct tectonic units stacked together during a single and rapid exhumation stage from shallower levels of the crustal wedge. Those two different complexes could be respectively representative of deep subduction channel dynamics and shallower wedge circulation in the Caledonian orogen. The NMSZ appears then as a major tectonic limit between those two blocks responsible for vertical movement as much as strike-slip. Partial melting in the NWGC may have favoured its late exhumation and juxtaposition to the SWGC.

Exhumation-related deformation and retrogression of caledonian high-grade metamorphic rocks in NW and Central Svalbard

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The poster presents the first results of a joint project between the French Research Polar Institute (IPEV, programm ECLOCAL) and the Norsk Polar Institut in the Biscayarhalvøya and Motalafjella areas (NW Spitsberg and central west Spitsbergen, respectively).We present a reappraisal of lithological units and a preliminary structural model for the exhumation of Caledonian high-grade rocks.

In the Motalafjella area, phyllites from the lower metamorphic unit place constraints on the thermal exhumation conditions of the blueschist-eclogite rocks preserved in the upper levels of the Vestgøtabreen metamorphic complex. Low grade associations with carpholite to chloritoid destabilisation textures are indicative of relatively cold exhumation gradients. Lawsonite breakdown reactions and chlorite-phengite±chloritoid assemblages allow to precise the exhumation path for this early accretionnary wedge dynamics, at around 460-470 Ma according to geochronology data. This exhumation was achieved before the unconformable deposition of the Bulltinden group in Caradocian times (455 Ma).

Caledonian thrust units in Biscayarhalvøya, structured during the Siluro-Devonian Scandian phase, comprise rocks of contrasting deformation pattern and metamorphic grade. In fact, high pressure (HP) granulite facies gneisses and metaigneous rocks make up the core of a kilometre-scale structure, which is stretched along the N-S direction. Relicts of an early eclogite facies event are found in mafic lenses within the HP granulites. This high grade core is enveloped by the Biscayerhuken and Montblanc metapelitic formations, equilibrated in amphibolite to green schist facies conditions and showing coeval N-S stretching. The intensity of ductile deformation is increasing toward the rims of the structure, grading from preserved igneous textures in the Richarddalen gabbro boudins, only affected by discrete conjugate shear-bands in the amphibolite facies conditions, to L-tectonite structures in the Richarddalen gneiss and, finally, penetrative shearing in the metapelitic rims compatible with an overall coaxial deformation pattern. Intense folding of the schistosity along the N-S stretching direction and L-tectonites structures indicate a regional constrictive deformaton regime. Index of syn-tectonic partial melting are observed in the inner part of the Richarddalen granulitic gneiss. The occurrence of these different lithologies as coarse pebbles in the Lilleborgfjellet conglomeratic basal formation indicates that the exhumation of this elongated structure, possibly built in several stages according to geochronological data, was achieved before the Siluro-Devonian boundary, between 420 and 415 Ma.

These HP rocks, among the earliest exhumed in the N-Atlantic Caledonian orogen, show that various thermal conditions prevailed early in the evolution of the crustal wedge dynamics.

Mass-balance modeling of initial eclogite-forming reactions in the Sanddal mafic-ultramafic complex, North-East Greenland eclogite province

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The Sanddal mafic-ultramafic complex (SMUK) is a cluster of variably eclogitized mafic and ultramafic bodies that comprise the westernmost known eclogite facies locality in the North-East Greenland eclogite province (NEGEP). Although there are no true eclogites at SMUK, we have documented three distinct textural types of plagioclase replacement that record sequential stages in adjustment of SMUK olivine gabbro-norites to eclogite facies conditions (Lang & Gilotti, 2001, Journal of Metamorphic Geology, **19**, 495-515). The earliest stage, in which plagioclase was replaced by omphacite/spinel symplectite before nucleation of garnet (Type 1A and 1B) had not previously been described. Documentation of this texture provides clear evidence that, at least in some cases, garnet nucleation is delayed relative to nucleation of omphacite and is a rate-limiting step for eclogitization. Type 1C domains were produced by scattered nucleation of garnet in the same sample. In Type 2 domains of other samples, plagioclase was replaced by a layered corona with an outer layer of garnet, an inner layer of omphacite and an interior of inclusion-rich plagioclase. In Type 3 domains, the omphacite layer was overgrown by the garnet rim, and omphacite is preserved only as inclusions in garnet. In more coarse grained Group III leucogabbros, recrystallization was more complete; plagioclase replacement textures were less localized, and could not be divided into distinct stages. Plagioclase replacement in SMUK samples was not isochemical, and required diffusion of at least Mg and Fe from replacement of mafic phases in the surroundings. Strong compositional gradients in garnet reflect disequilibrium and were controlled by the different diffusion rates of Mg/Fe and Ca, different local chemical environments, and progress of the plagioclase breakdown reaction. The presence of small amounts of hydrous minerals (amphibole, phlogopite and clinozoisite) in local equilibrium in plagioclase domains of most SMUK samples indicates that a small amount of H_2O was present during high pressure metamorphism.

We have modeled mass balance reactions that describe changes at various stages in the partial eclogitization of these samples from SMUK in an attempt to better understand the very early stages of the eclogitization process; particularly what phases are involved in eclogite forming reactions, the proportions of reactants and products, the extent of exchange between spatially separated plagioclase and mafic mineral domains and the role of H_2O. Mass balance reactions have been calculated using the computer program CSpace (Torres-Roldan, et al., 2000, Computers & Geosciences, **26**, 779-793) and evaluated using Singular Value Decomposition (SVD). Choosing minerals to be included in model reactions was a trial and error process based on observed textures and mineralogy. Model reactions for the two earliest stages of eclogitization observed in sample 434462 were relatively successful with low residuals and reactants and products inferred from observed textures showing up on the correct sides of the reactions. The best model reaction (in moles) for the initial stage, before nucleation of garnet (igneous minerals to Type 1B), is:

$$8.8 \text{ Olivine} + 4.8 \text{ Plagioclase} + 1.0\ H_2O = 5.6 \text{ Opx} + 1.9 \text{ Omp} + 1.6 \text{ Spl} + 1.0 \text{ Amp}$$

Alternative models show that relict igneous biotite is not significantly involved in this reaction and addition of H_2O fluid is necessary. The best model for the net reaction in sample 434462 (igneous minerals to Type 1C garnet + omphacite assemblage) is

6.5 Olivine + 4.8 Plagioclase + 1.0 H_2O = 2.5 Opx + 1.7 Omp + 1.0 Amp + 1.5 Grt

Slight inconsistencies between these two reactions may relate to minor reaction of relict clino- and orthopyroxenes that is observed in the sample. A satisfactory model for reaction in Type 2 domains of sample 434351a required involvement of relict igneous clinopyroxene as follows:

31.4 Olivine + 34.8 Plag + 11.3 relict Cpx = 30.3 Opx + 45.8 Omp + 1.0 Grt

We have not yet been successful in modeling mass balance reactions in Group III sample 434464, which preserves relict igneous minerals and reaction textures. Preliminary model reactions like:

5.6 Opx + 3.8 Plag = 8.9 Jd-Cpx + 1.0 Grt and

16.2 Opx + 9.9 Plag + 1.5 H_2O = 26.0 Jd-Cpx + 1.0 Amp

are consistent with textural relationships, but result in large residuals in CaO in several minerals. These preliminary reactions demonstrate that introduction of H_2O was necessary to account for the presence of amphibole in early stages of eclogitization, and limited availability of H_2O may explain the fact that rocks at SMUK did not become true eclogites. Olivine, where present, reacted readily with plagioclase; however, in the absence of olivine, Opx and Cpx reacted with plagioclase to form garnet and omphacitic clinopyroxene.

Microstructure of rutile inclusions in garnet of kyanite-garnet gneiss from Fjørtoft, Western Norway: hints concerning metamorphic evolution

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The northeastern belt of rocks on Fjørtoft island, assigned to the Blåhø Nappe, is a heterogeneous group dominated by metamorphosed sedimentary rocks, mafic igneous rocks, and rare ultramafic rocks. They underwent ultra-high-pressure metamorphism as shown by recovery of microdiamonds by total rock digestion of a prominent kyanite-garnet gneiss, and by the occurrence of polycrystalline quartz after coesite in a kyanite-zoisite eclogite. Phase barometry in the eclogite suggests equilibration pressures up to approximately 4 GPa. Here, we focus on the kyanite-garnet gneiss, consisting mainly of quartz, kyanite, garnet, biotite, plagioclase and K-feldspar with accessory rutile, graphite and monazite (see also Robinson, Langenhorst and Terry, this volume).

In this study, we used transmission electron microscopy (TEM) to study the microstructural characteristics of rutile, which occurs in three varieties included in garnet. The aim of the TEM study was to test whether the three generations of rutile crystals would provide microstructural records of various stages of the metamorphic history from subduction to exhumation. The three varieties are: (a) relatively coarse, equant-sized, reddish-brown rutile, about 100 µm in diameter, which occurs also in the matrix; (b) small, droplet-like rutile with smoky-brown colour, 10-20 µm in diameter inside garnet , and (c) thin rutile needles, a few µm wide, occuring in oriented arrays in the outer parts of zoned garnets.

Under TEM, the coarse-grained reddish-brown rutile (a) contains numerous tangled dislocations, commonly forming nodes. This microstructure indicates that the rutile has been deformed, probably before incorporation into the garnet on the prograde path. This “early” rutile is regarded as an early breakdown product of ilmenite. The smoky-coloured rutile (b) apparently formed during a later stage of metamorphism because there is no indication of deformation. Energy-dispersive X-ray (EDX) microanalysis reveals a very high Nb content. This Nb-rich rutile is devoid of dislocations but contains two other defects: □-recoil tracks resulting probably from a considerable U content, and not yet fully characterized planar defects similar to stacking faults or microtwins. Finally, the rutile needles (c) have an epitaxial relationship to garnet and are absolutely devoid of lattice defects. They occur preferentially in the outer parts of garnet inferred to have grown at peak metamorphic conditions. Therefore the needles might have nucleated by exsolution from garnet during cooling from the highest temperatures, i.e. already on a retrograde path during exhumation. Altogether, our TEM observations substantiate that the microstructure of various metamorphic minerals have the potential to conserve a record of different episodes and conditions of the metamorphic evolution of UHP rocks.

UHP mineral inclusions hidden in zircons from metamorphic rocks in Sulu Terrane

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Laser Raman spectroscopy, cathodoluminescence (CL) image reveal that zircons separated from orthogneiss, paragneisses, amphibolites, kyanite quartzites and marbles in southwesten Sulu terrane preserve multi-stage mineral assemblages in different domains. Most zircons retain inherited cores with abundant low-pressure mineral inclusions and impurities. The metamorphic overgrowth mantles of these zircons preserve UHP mineral, whereas the outmost rims contain quartz and other low-pressure mineral inclusions. In general, the UHP mineral inclusion assemblages are characterized by Coesite ± phengite in granitic gneisses, coesite + garnet + omphacite, coesite ± garnet + jadeite + phengite + apatite and coesite + phengite ± apatite in paragneisses, coesite + garnet + omphacite ± rutile in amphibolites, coesite + kyanite + rutile + apatite and coesite + kyanite + phengite + rutile in kyanite quartzites, and coesite + diopside and coesite + olivine in marbles. These evidences suggest that the volumetrically continental materials, mainly consisting of protolithes of eclogite and country rocks in Sulu terrane, commonly occurred deep-subduction, experienced ultrahigh-pressure metamorphism, and then rapidly returned to middle crustal levels. The delicate micro-textures including irregular boundaries and various thickness of cores, mantles, and rims of zoned zircons revealed by cathodoluminescence images indicate that conventional U-Pb ages of zircons have led to mixing ages. This explains why many inconsistent U-Pb ages have been reported in the Sulu-Dabie UHP terrane. Thus SHRIMP U-Pb microspot dating of zircon cores, mantles and rims is essential to resolve such controversies.

The Fe^{2+}/Mg partition among amphibole, omphacite and garnet among epidote amphibolite, garnet amphibolite and amphibole eclogite and its implications for metamorphic reactions

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Epidote-albite amphibolite, garnet amphibolite, eclogitized amphibolite and amphibole eclogite as lenses are exposed in the west-east extending high-pressure belt of the Hong'an area, the Dabie Mountains, China, which consists of a part of high-pressure metamorphic facies series. These rocks have been studied for determination of metamorphic reactions of eclogitization.

The mineral assemblages in metabasic rocks changed from amphibole + epidote + albite + chlorite + quartz + ilmenite ± paragonite in epidote-albite amphibolite, via garnet + amphibole + epidote + albite + quartz + rutile±chlorite± ilmenite ±paragonite in garnet amphibolite, to garnet + omphacite + amphibole + epidote + quartz + rutile±paragonite in amphibole eclogite. The observation reveals that the volume content of chlorite, ilmenite, epidote, amphibole decreases with formation and growth of garnet and rutile from epidote-albite amphibolite to garnet amphibolite. Chlorite finally disappears in some of garnet amphibolite, meanwhile, ilmenite also decreases as minor phase. It is evident that garnet was predominantly formed in the garnet amphibolite stage. Eclogite was prograded from garnet amphibolite with formation and growth of omphacite and demise of albite. In this process, amphibole content dramatically decreases, and garnet keeps relatively constant.

The garnet-in reaction from epidote-albite amphibolite to garnet amphibolite is Ch + Ep / Czo + Ilm + Qtz = Grt + Ru + H_2O, which result in the decrease of chlorite, ilmenite and epidote and increase of garnet and rutile. The Fe^{2+}-Mg ratio of amphiboles is consistent between epidote-albite amphibolite and garnet amphibolite, implying that amphibole doesn't take part in the reaction. The Fe^{2+}-Mg ratio of amphiboles in epidote-albite amphibolite and garnet amphibolite are higher than that in amphiboles of eclogitized amphibolite and amphibole eclogite.

The chemographic relation between amphibole and omphacite in eclogite reveals that Fe^{2+}-Mg partitioning $K_{dAmp/Cpx}^{Fe/Mg}$ =$(Fe^{2+}/Mg)_{Amp}/(Fe^{2+}/Mg)_{Omp}$ between amphibole and omphacite is >=1 for 19 samples. Four samples of eclogitized amphibolite have $K_{dAmp/Cpx}^{Fe/Mg}$ <1, =1 and >1 due to great compositional range of amphibole in the samples. The observation and chemographic relation suggests that $K_{dAmp/Cpx}^{Fe/Mg}$ <1 and =1 results in two reactions of Grt + Amp + Ab = Omp and Amp + Ab = Omp, respectively in eclogitized amphibolite. The two reactions are responsible for formation of eclogite.

The chemographic relation of Fe^{2+}-Mg among garnet, omphacite and amphibole in other nineteen eclogite samples have been checked in order to interpret the role of the reactions determined from four eclogitized amphibolites for eclogite formation. The results of $K_{dAmp/Cpx}^{Fe/Mg}$ >=1 in nineteen samples support that it is above-determined two reactions for formation of eclogite. The two reactions result in the amphibole decomposition with

$K_{dAmp/Cpx}^{Fe/Mg}$ <1 and =1 to form omphacite, whereas the amphibole with $K_{dAmp/Cpx}^{Fe/Mg}$ >1 is still stable in eclogitization process.

The Fe^{2+}-Mg ratio of amphiboles of epidote-albite amphibolite and garnet amphibolite is observed to change from core to rim with the increase of Fe and decrease of Mg in some samples with progressive metamorphism. The relatively higher Fe^{2+}-Mg ratio of amphiboles in epidote-albite amphibolite and garnet amphibolite than eclogitized amphibolite and amphibole eclogite leads an interpretation that eclogitized amphibolite and amphibole eclogite were transformed from garnet amphibolite with amphiboles of low Fe^{2+}-Mg ratio, which corresponds to lower temperature than that shown by present epidote-albite amphibolite and garnet amphibolite.

Molina and Poli (1998) have constructed the topology for reactions Grt + Ab + Amp= Omp (1), Ab + Amp= Omp (2), and Ab + Amp= Grt + Omp (3) under conditions of saturation of quartz, paragonite, clinozoisite and water in the seven-component model system Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O (NCFMASH). Reactions 1 and 3 are conjugate univariant equilibriums due to garnet moves from one side to another side of reaction with the change of $K_{dAmp/Cpx}^{Fe/Mg}$, therefore reaction 2 is a univariant singular equilibrium. These reactions have moderate dP/dT slope. Reactions 1 and 2 occur below the temperature of singular point, and reaction 3 will proceeds above the temperature of singular point. Reaction 1 with lower pressure conditions and reaction 2 with higher conditions will occur in turn with increase of pressure along progressive metamorphic path. The topology for three reactions can be used to explain well the coronas observed in eclogitized amphibolite

References

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Ultrahigh-P evidence for the country rocks of garnet-bearing lherzolite in Altyn Tagh -exsolution of clinopyroxene in the garnet of retrograde eclogite

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Ultra-high pressure garnet-bearing lherzolite is recently discovered in Yinggelisayi area, Altyn Tagh (Liu et al 2002), which occur as interbeds together with retrograde eclogite and garnet-bearing granitoid gneiss. In some of outcrops, dark retrograde eclogite and light-colored granitoid gneiss occur as banded layers, or the dark retrograde eclogite appears as lens which are included in the light-colored granitoid gneiss. The recent investigation of the retrograde eclogite based on petrography and mineral chemistry show that the exsolution of clinopyroxene+rutile in the core of coarse-grained garnets, and the long-axises of euhedral rods clinopyroxenes are intersectant as an angle of 60º/120º and parallel to the long-axises of rutiles, and the corresponding crystal edges of individual clinopyroxenes are also parallel with each other. This phenomenon is similar to those of eclogite in Yangkou, China (Ye et al., 2000), suggesting that coupling replacements of Si^{VI}+ Mg→ 2 Al^{VI} or Na+ Si^{VI} → Ca + Al^{VI}, and Mg + Ti^{VI} → 2 Al^{VI} or Na+ Ti → Ca + Al^{VI} exist in the garnet before exsolution (Moore et al,1985; Ye et al, 2000), which means that the precursor garnet contain octahedrally coordinated silicon, is of a supersilicic garnet or majoritic garnet. The exsolution area of the clinopyroxene in the garnet is statistically about 3-5%, thus, the Si in the garnet is estimated to be 3.059-3.075 and Al 1.80-1.85 before the exsolution. Based on data of experimental petrology (Ringwood et al, 1971; Irifune et al, 1986) and recently calibrated Si-in-majorite and (Al+Cr)-in-majorite barometers (Collerson et al, 2000), the peak P-T conditions are calculated to be 7GPa and 1100ºC. The protolith of the retrograde eclogite is assumed to be derived from mafic magma of the subcontinental lithospheric mantle. The ultra-high pressure evidence discovered in the eclogite and associated garnet-bearing lherzolite and garnet-bearing granitoid gneiss suggests that the ultra-high pressure metamorphic rocks in the Altyn Tagh formed by continental subduction and the subduction depth might be over 220 km in deep mantle. This conclusion will help to understand the geodynamic mechanism of the Altyn Tagh orogenic belt in SW China.

Discovery of relic majoritic garnet in felsic metamorphic rocks of Qinling complex, north Qinling orogenic belt, China

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Qinling-Dabie-Sulu orogenic belt connect the south and north China continent. Shangxian-Danfeng fault, resulted from the closing of the Paleozoic Qinling ocean (Meng et al., 1999), subdivide Qinling into south and north Qinling orogenic belt. Recently, Yang et al.,(2002) discovered micro-diamond inclusions in eclogites and gneisses in north Qinling Mountain(Yang et al.,2002), suggesting the existence of utrahigh-pressure metamorphism in this area during Pleozonic. We report here is the first discovery of ultrahigh-pressure felsic rocks in Qinling group next to north boundary of Shangxian-Danfeng fault.

The studied rocks mainly consist of porphyroblastic garnet(15-25%), kyanite(5%), alkali-feldspar(25-30%) and quartz(45%±). Abundant fine-grained euhedral exsolved rutile + apatite + quartz needles have been observed in the core part of the garnet. Rutile long needles, is about 0.5-1.0μm wide and 10-100μm long distributing parallel distinctly to each other in three directions which oriented at 60º/ 120º and along four cubic <111> directions of garnet; Apatite (0.5 to 1.0μm in width and 5 to 10μm in length) and quartz needles (0.5 to 1.0μm in width and 10 to 40μm in length) parallel to each other or to the exsolved rutile in three directions. This phenomenon is similar to those of garnet in UHP metapelite from Rhodope region of Greek (Evripidis et al., 2002). Interestingly, a few of the oriented exsolution needles compose of two minerals of quartz + rutile or plagioclase + quartz, and the latter exhibit the pseudomorph of clinopyroxene, may resulted from the breakdown of exsolved clinopyroxene. The exsolutions of quartz, rutile and apatite in garnet indicate that the precursor garnet contain excess Si, Ti, Na and P, that is, of a majoritic garnet.

Majoritic garnet and garnet contain exsolved Cpx or Cpx +Ru or Cpx+Ru+Ap or Ru+Ap+Qz needles have approved to be a credible indicator of UHP metamorphism by experimental petrology(Ringwood et al., 1971; Irifune et al., 1986; Ono et al., 1998) and geological discoveries (Ye et al., 2000; Evripidis et al., 2002). Cpx+Ru+Ap and Qz+Ru+Ap exsolutions in garnet discovered from Yangkou eclogites, China and Rhodope metapelite, Greek, respectively, all suggesting the peak metamorphic pressure exceeding 7GPa (Ye et al., 2000; Evripidis et al., 2002).
The exsolution needles is too fine for us to analysis its composition by normal electeron microprobe analysis accurately, so we obstain the precursor garnet component by using “broad-beam" (enlarge the electron beam to 20-30μm diameter) in regions containing exsolution needles, that is Si =3.037-3.051, Al=1.843-1.864, Na=0.035- 0.055 per formula. Based on the recently calibrated Si-in-majorite and (Al+Cr) -in-majorite barometers, the peak pressure of Qinling UHP felsic rock is caculated to be 7 GPa±.

Considering the protolith of the studied metamorphic rock is greywacke, the forming conditions of the rock we estimated above suggest that the UHPM rocks in north Qinling orogenic belt formed by continental subducted into mantle depth, and the depth might be greater than 200 km. This conclusion provide not only further evidence of the existence of UHP metamorphism in Qinling orogenic belt, but a new evidence to discus the regional structure relationship and dynamics mechanism between the two UHP metamorphic belt of Dabie-Sulu in east China and Altyn-north margin of Qiadam Basin in west China.

The tectonic implications of Maobei eclogites, Eastern China: Petrologic and geochemical constraints

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The Dabei-Sulu ultra-high pressure (UHP) metamorphic terrane in eastern China is typically considered as a surface manifestation of collision between the Yangtze and Sino-Korean cratons. Most eclogitic bodies within this belt are associated with gneisses, marbles and ultramafic rocks. Although these UHP eclogites have been intensively investigated, documents on the mechanism for forming rutile and kynite (5-10 % for both phases) bearing eclogites are rare. In this study, rutile and kynite eclogites from Maobei village in Sulu region were analyzed for their mineral compositions and to establish the metamorphic history. Also, bulk trace element abundances were determined to evaluate the nature of their protoliths, which is critical in understanding the tectonic evolution forming this UHP terrane.

Rutile and kyanite eclogites from Maobei show distinct petrographic textures. The rutile eclogites consist of fine-grained garnet and clinopyroxenes with cavities and prevailing amphibolitic veins, while the kyanite eclogites display bands of coarse garnet and omphacite grains. Sometimes the coarse garnets are rimmed by small recrystallized garnet grains. Based on the petrological features, the rutile eclogites might have been deformed under semi-brittle environment but the kyanite eclogites were formed under more ductile condition. In other words, they are deforming under different level structures. Garnets in rutile eclogites and kyanite eclogites are almandine and pyrope-rich respectively. In rutile eclogites, the clinopyroxenes are classified into omphacite to aegirine-augite because of the increase in acmite content. The clinopyroxenes in kyanite eclogites are categorized as omphacite for their extremely low acmite content. Amphiboles are mainly magnesio-hornblende to tschermakite in both eclogites. The core compositions of garnet and clinopyroxene in rutile eclogites indicate equilibrations at 750-830□ and 14-15 kb, whereas those for kynite eclogites were equilibrated at higher P-T conditions ranging from 770 to 880□ and from 15 to 18 kb. These high-pressure garnet-clinopyroxene assemblages were then retrograded to amphibolite facies; approximately 400-590□under 8-9 kb, based on the garnet-hornblende geothermometer and the garnet-hornblende-plagioclase- quartz geobarometer. Evidently, the kyanite eclogites were derived from higher P-T conditions than rutile eclogites. In a P-T diagram, the exhumation paths for both rutile and kynite eclogites plot between the fields for subduction zone and continental geotherms. Consequently, it is inferred that Maobei eclogites were exhumated during the transition from a subduction environment to a continental collision environment. The most significant geochemical features for Maobei eclogites are the strong depletions in Ta and Hf relative to their neighboring elements in a primitive mantle normalized diagram. Although Ta and Hf depletions can be explained as features for continental materials, the absence of associated Nb and Zr depletions making the continental origin suspicious. Furthermore, Maobei eclogites show variable rare earth elements (REE) variation patterns of which the most important are the light rare earth elements (LREE) depletions in three of the six analyzed samples. Although eclogites might experience interaction with fluids, such process is unlikely to cause LREE depletions because LREE are preferentially enriched in fluids relative to heavy rare earth elements (HREE). Therefore, we infer that the depletions of LREE, which are characteristics of oceanic lithosphere, in these eclogites represent the nature of their protoliths and the depletions in Ta and Hf might be caused by fractionation of rutile or

other mineral phases during subduction. In summary, the results from this study show that Maobei eclogites might represent oceanic lithosphere existed between the Yangtze and Sino-Korean cratons. Following the continuous northward subduction of the oceanic slab, the tectonic environment of this area finally entered into the continental collision period, and the Maobei eclogites uplifted during this stage.

Two eclogite lineages in Himalayan thrust sheets and Alpine analogues

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Eclogites were first reported in the Himalaya from the Tso Morari Dome of the NW Himalaya (Berthelsen, 1953) and subsequently in the Upper Kaghan Nappe (Chaudry & Ghazanfar, 1987; Spencer et al., 1990) and in the nearby Neelum valley (Fontan et al., 2000), again in the NW Himalaya. All these eclogites are hosted in relatively thin thrust sheets that occupy a high tectonic level in the Himalayan nappe stack, just below the Tibetan sedimentary sequence (Tso Morari) or the Indus suture (Upper Kaghan).

Petrologic study of the eclogites from the NW Himalaya (Pognante & Spencer, 1991; Guillot et al., 1995; De Sigoyer et al., 1997; Lombardo et al., 2000) records peak metamorphic temperatures of 580°-600°C at metamorphic pressures in excess of 2.3-2.4 GPa. The NW Himalayan eclogites have glaucophane as a retrograde phase and followed a nearly isothermal decompression path into the field of epidote amphibolite facies. Coesite was recently discovered in some of the Upper Kaghan and Tso Morari eclogites, suggesting these tectonic units may have been subjected to metamorphic pressures in excess of 2.7 GPa (O'Brien et al., 2001; Sachan et al., 2001).

A garnet-omphacite Sm/Nd isochron dates the growth of the eclogite paragenesis at 49 ± 6 Ma in the Upper Kaghan nappe, and ages of 43 ± 1 Ma and of 39-40 Ma were obtained on phengite and on rutile, respectively (Tonarini et al., 1993). Eclogitization is dated at 55 ± 12 Ma in the Tso Morari Dome by a Lu-Hf isochron (De Sigoyer et al., 1999). The Tso Morari eclogites were exhumed rapidly between 55 Ma and 48-45 Ma in a subductional context, more slowly between 48-45 Ma and 30 Ma during continental collision.

Eclogites were recently found also in the E Himalaya, in the Kharta region of S Tibet 30 km E of Mt. Everest (Lombardo et al., 1998; Lombardo and Rolfo, 2000). The Kharta eclogites occur in the Lesser Himalayan Ama Drime Orthogneiss exposed at the core of the Arun antiform.

The Kharta eclogites are black, dense rocks, with discernable red garnets several mm in size, set in a matrix of amphibole and surrounded by a white plagioclase rim. Garnet is homogeneous but has a wide intersample range in composition ($Alm_{41-61}Prp_{10-16}Sps_{0-3}$ $Grs+Adr_{25-35}$). Primary omphacite is not preserved, but is replaced by a symplectite of plagioclase and diopside (Jd_{5-6}) ± orthopyroxene. Garnet crystals are surrounded by plagioclase (An_{40}) and orthopyroxene (En_{37-47}) ± clinopyroxene ($Wo_{47}En_{33}Fs_{20}$) where garnet abutted matrix quartz. The pale milky green patches that are conspicuous in hand specimen are comprised of plagioclase-biotite intergrowths probably replacing phengite, no relics of which have survived. The amphibole matrix is a brown hornblende $(Na_{0.3-0.4}K_{0.1-0.2})(Na_{0.1-0.2}Ca_{1.8-1.9})(Mg_{1.5-2.2}Fe^{2}_{2.0-2.5}Fe^{3}_{0.1-0.3}Al_{0.4-0.5}Ti_{0.2-0.3})(Al_{1.3-1.5}Si_{6.5-6.7})O_{23}$ that replaces garnet and orthopyroxene, and also grows on the diopside-plagioclase symplectite.

Pressures, and especially temperatures, of the eclogite-forming event (M1) remain largely conjectural, as garnet is the only eclogitic mineral which has survived a subsequent overprint

of granulite facies. On the other hand, P-T conditions of the granulite event (M2) in the Kharta eclogites can be estimated by phase compositions and thermobarometry. Intersection of the Grt ± Pl ± Opx ± Qtz, Grt ± Pl ± Cpx ± Qtz and Grt ± Opx equilibria indicates equilibration temperatures of about 750°C -790°C at metamorphic pressures around 0.7-1.0 GPa. Equilibration temperatures lower by about 100°C are indicated by the Grt ± Hbl and Hbl ± Pl equilibria. M2 was followed by a later static recrystallisation (M3) under low P and high T, which produced pervasive amphibolitization of the eclogites. The age of eclogitization is assumed to be Himalayan, probably Oligocene, and that of amphibolitization Miocene (Lombardo and Rolfo, 2000).

At the scale of the Himalayan orogen, a duality is apparent between the NW- and E Himalayan eclogites. The NW Himalayan eclogites, now sitting at high tectonic levels, formed earlier and reached shallow crustal levels essentially unaltered. In contrast, in the E Himalaya, eclogites exposed at deeper tectonic levels, formed later and have a strong HT overprint that erased almost completely the eclogitic mineral assemblages. Such a duality is evident also in the Alps, between the Austroalpine and Lower Pennidic eclogites, and has important implications for exhumation models of HP and UHP terrains.

Earthquakes in the deep continental crust: Insights from studies on exhumed high-pressure rocks

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A growing body of evidence now challenges current petrophysical models of the continental lithosphere by demonstrating that the assumptions of steady state deformation and thermodynamically controlled metamorphism may not be universally valid. Exhumed high-pressure rocks in the Bergen Arcs and Western Gneiss Region of western Norway, as well as occurrences elsewhere, exemplify that lower-crustal rocks may resist metamorphic reequilibration for geologically significant periods of time (i.e. several hundred Ma). Evidence from the peridotite-bearing Lindås Nappe anorthosite complex (Bergen Arcs) and the Kråkeneset gabbro (Western Gneiss Region) in western Norway further indicate that such extended metastability exercised a profound control on the mechanical properties of these rocks, which retained high strength and brittle properties at depths exceeding 60 km. Initial eclogite facies reactivation occurred as deep-crustal earthquake events and led to extensive fracturing, cataclasis, and generation of pseudotachylyte (i.e. the product of frictional melting). Brittle failure of these rocks at high-grade metamorphic conditions was followed by fluid infiltration and partial eclogitisation, ultimately leading to a drastic reduction in rock strength. Our field observations indicate that the brittle rheological state of some deep-crustal rocks, and their propensity to remain metamorphically metastable despite prevailing conditions of high temperature and pressure, is largely controlled by their very low fluid contents. The occurrence of deep-crustal earthquakes in continental collision zone settings is supported by a recent reassessment of earthquake focal depth distributions on the continents, showing that near-Moho earthquakes previously thought to have formed in the lithospheric upper mantle instead are likely to have occurred in the lowermost, possibly dry, continental crust. These new results have far-reaching implications for continental geodynamics and emphasise the need for an improved understanding of the nature of the deep continental crust. The combined knowledge from field-based and geophysical studies suggest that extensive coupled metamorphic and rheological metastability of the lower continental crust may not be as uncommon as previously assumed, wherefore current petrophysical models of the continental lithosphere may need to be modified accordingly.

High-pressure metamorphism and deep-crustal seismicity: Evidence from contemporaneous formation of pseudotachylytes and eclogite-facies coronas

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The Kråkeneset gabbro, located on the island of Vågsøy in the mixed HP/UHP zone of the Western Gneiss Region, display extensive metastability through the entire prograde and retrograde P-T histories. Eclogite constitutes less than a few percent of the total volume of the body and high-pressure assemblages typically form thin coronas around magmatic phases or occur along localized zones of brittle deformation and fluid infiltration. The gabbro displays pseudotachylyte vein networks that define subparallel brittle fault zones, <50 cm wide, transecting the gabbro body. The pseudotachylytes contain µm- to mm-scale amoeboid and dendrite-like textures of garnet and plagioclase with inclusions of the eclogite facies minerals orthopyroxene, omphacite, amphibole, and dolomite, suggesting rapid disequilibrium growth of minerals during high-pressure conditions. Textural and petrological evidence from pseudotachylytes and corona structures show that the growth of these unusual textures occurred shortly after pseudotachylyte crystallization by a process of rapid solid-state alteration of a microcrystalline pseudotachylyte matrix. The pseudotachylyte-lined fault zones are in close spatial association with numerous amphibole ± carbonate-filled hydrofractures with conspicuous fracture-parallel alteration zones defined by hydrous eclogite facies assemblages. These eclogite facies hydrofractures testify to the existence of high fluid pressures and to fluid infiltration following brittle failure during high-grade metamorphic conditions. Geothermobarometric estimates (c. T=650-700°C, P=~20 kbar) and petrological data imply that hydrofracturing, pseudotachylyte crystallization and the subsequent pseudotachylyte alteration process must have occurred during high-pressure metamorphism. Our observations are suggestive of a deep-crustal earthquake scenario where a high-pressurized fluid phase plays a double role by causing both seismic failure through the embrittlement effect and facilitating eclogitization of the metastable anhydrous gabbro. Metamorphic reaction along hydrofractures and fault planes led to the development of eclogite facies foliation fabrics and illustrate the rheological change from brittle to plastic behavior associated with the gabbro to eclogite transition.

Prograde *P–T–t* path deduced from compositionally zoned garnet in a whiteschist from the Kokchetav HP–UHP massif, northern Kazakhstan

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It has long been a centre of interest of metamorphic petrology to estimate pressure–temperature–time (*P–T–t*) paths for individual rocks. Garnet is a common mineral in metapelites over a wide *P–T* range. Garnet in metapelite generally has a distinctive compositional zonation, and many metamorphic petrologists have drawn *P–T* path using zoned garnet. In this paper, *P–T–t* path was estimated for whiteschists from the Kokchetav massif using compositional zoning and mineral inclusions in garnet.

Kokchetav highpressure–ultrahighpressure (HP–UHP) massif in northern Kazakhstan is the deepest subducted metamorphic belt of the world. The studied whiteschist samples were collected from the Kulet region, located at the middle part of the Kokchetav massif. Geology of this region is characterized by a block-in-matrix structure consists of eclogite block and metasedimentary schist matrix. Whiteschist is often associated with eclogite blocks on their periphery and in embayment. The whiteschist consists of coarse-grained matrix of quartz, phengite and talc with porphyroblastic garnet and kyanite and minor amount of rutile.
The garnet porphyroblast is generally coarse-grained (up to 3 mm) and contains abundant mineral inclusions. The garnet is generally almandine-rich, and has a distinctive compositional zoning. Almandine component shows a rim-ward increase. Pyrope component is generally low and shows a slight increase towards rim. Grossular component shows the most distinctive zoning pattern. It shows a slight rim-ward increase in the core domain, which is followed by large decreases in the mantle and the rim domains. The zoning pattern of spessartine component is more irregular especially in the core domain, but generally decreases towards rim, which characterizes a prograde zoning. These zoning patterns are commonly observed in every analysed garnet.

Mineral inclusions in the garnet are abundant in the core domain, and relatively rare in the mantle and rim domains. The dominant inclusion mineral is SiO_2 polymorph. It displays a clear zonal distribution in garnet porphyroblast. In the core domain, all SiO_2 phase is monomineralic quartz, which occupies the most population of inclusions in the core domain, whereas coesite and its pseudomorph are found in the outermost mantle domain. Next to quartz, Ti-phase inclusions are abundant throughout the core and mantle domains. They also display a zonal distribution. Ilmenite occurs relatively inner part of core domain, and most of which makes a composite inclusion with rutile, whereas monomineralic rutile occurs relatively outer part of core to mantle domains. In the rim region, both of ilmenite and rutile are present, although their population is low. Zircon, apatite, monazite are commonly observed throughout the porphyroblast, and minor kyanite and phengite are observed in the outer-core to mantle domains.

Inclusion thermometry was carried out using ilmenite–garnet thermometer of Pownceby *et al.* (1991). The results range from 500 to 750 °C, and show a systematic increase from core to rim in each porphyroblast. In the kyanite-bearing domain, the following pressure-sensitive

reaction can be used for barometry: 3Fe-Ilm (in Ilm) + Ky + 2Qtz = 3Rt + Alm (in Grt). This barometry yielded pressures of 12–13 kbar for outer-core inclusions at given temperatures. A petrogenetic grid drawn in K_2O–CaO–FeO–MgO–Al_2O_3–SiO_2–H_2O (KCFMASH) model system using a UniEQ computer program of Omori & Ogasawara (1998) enables forward modeling of the compositional zonation in garnet. The change of grossular component along the model *P–T* path expected from the forward modeling is close to the observed grossular profile of outer-core to rim domains. No *P–T* constraint is available from thermobarometry in inner-core domain, however, the forward modeling of garnet zoning makes up for the early stage *P–T* path of garnet growth.

The estimated prograde *P–T* path is counter-clockwise which bents steeply at around 700 °C, 12–15 kbar. This is similar to the metamorphic *P–T* gradient of the Kokchetav massif deduced from the metabasites of various grade. This result is highly different from the traditionally drawn clockwise *P–T* path in many metamorphic terranes.

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$\delta^{13}C$-Signature of Microdiamonds from the Saxonian Erzgebirge, Germany

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Microdiamonds were detected in quartzofeldspathic rocks from the Gneiss-Eclogite-Unit of the Erzgebirge (Massonne, 1999) situated in the northwestern edge of the Bohemian Massif in Middle Europe. They occur as inclusions in garnet, kyanite and zircon. Microdiamonds are ubiquitous in zircon showing the highest diamond concentration compared to the other host minerals. In addition, the largest diamond grains (diameter ~ 30 µm) appear in zircon. Moreover, the transformation of diamond to graphite, frequently observed in garnet, is very limited in zircon. Thus, microdiamonds enclosed in zircon are the best candidates for a study of their $\delta^{13}C$-signature to elucidate the origin of the carbon.

At first, a zircon concentrate was prepared from sample St6100. This sample had been taken from a lens of diamondiferous quartzofeldspathic rock embedded in ordinary migmatitic gneisses. This lens, being several hundreds of metre long, is located close to the Saidenbach reservoir, 1.5 km NW of the village of Forchheim. A portion of the zircon concentrate was embedded in araldite epoxy and polished so that the obtained surface intersected the middle of the zircon grains. U-Pb age dating with a SHRIMP was applied to this specimen (Massonne et al., 2001). In addition, the inclusion assembly in zircon was carefully studied (see Massonne & Nasdala, 2003). No carbonates were detected in the zircons. Graphite is only a very rare constituent of the inclusion assembly. Thus, it was estimated that clearly more than 95 % of the carbon in our specimen is stored in enclosed microdiamonds. Another portion of the concentrate was taken for the determination of the $\delta^{13}C$. For that purpose, ca. 5 milligrams of the zircon concentrate were crushed to release the microdiamonds. The crushed material was oxidised at temperatures above 1000°C and the produced CO_2 was studied by a mass spectrometer. The subsequent results were obtained after calibrating the instrument with several standards (e.g., USGS24): carbon content = 0.46 wt.%, $\delta^{13}C$(PDB) = -25.5 ‰. We interpret this result as an indication for an organic source of the carbon. Because bulk rock analyses of the diamondiferous quartzofeldspathic rocks are very similar to those of clastic sediments (Massonne, 2003), organic material could have been already part of a sedimentary protolith. After sedimentation in Devonian times, according to the age of rare zircon cores with magmatic zonation features (Massonne et al., 2001), these rocks submerged to depths of more than 200 km (~ 340 Ma ago) where they were broadly molten at temperatures close to 1200°C (Massonne, 2003). It is assumed that the organic carbon became part of the silicate melt and that no external C-bearing fluid contributed to the melting process. Thus, the original carbon isotope signature could be preserved. Afterwards, during uplift and cooling, the magma began to crystallise still in the stability field of diamond (P > 45 kbar). Diamonds were among the early phases of crystallisation as garnet, kyanite, and zircon, which could enclose the magmatic microdiamonds. A similar process is suggested for the diamondiferous rocks of crustal origin from the Kokchetav Massif. In fact, $\delta^{13}C$ values of only -10 to -11 ‰ were observed in garnet-clinopyroxene rocks and silicate marbles (Cartigny et al., 2001) but these together with relatively high $\delta^{15}N$ values were taken as a hint to a metasedimentary source of the carbon in the ultrahigh-pressure rocks from the Kokchetav Massif.

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Protoliths of Eclogites from the Variscan Erzgebirge

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Abundant metre to km-sized eclogite bodies are known from the Variscan crystalline complex of the Erzgebirge being part of the Bohemian Massif in Middle Europe. They occur in two of the three major units of this complex, which are the Mica Schist - Eclogite - Unit (MEU) and the Gneiss - Eclogite - Unit (GEU). Previous studies of the trace element signature of these eclogites (Klapova, 1990; Schmidt et al., 1990) have related the protoliths of the eclogites to N-, P-, and E-MORBs as well as to within-plate basalts. We have tried to find out if there is any geochemical systematics among the different eclogite occurrences. In particular, we were interested in the protoliths of coesite-bearing eclogites (Massonne, 2001) from the ultrahigh pressure metamorphic area close to the Saidenbach reservoir where diamondiferous quartzofeldspathic rocks occur as well.

Bulk rock analyses of about 40 eclogite samples (15 taken close to the Saidenbach reservoir) were obtained by XRF spectroscopy. In addition, the concentration of specific trace elements (REE and others) was also determined by HR-ICP-MS. The obtained results allow a clear discrimination of three types of eclogites which correlate well with their occurrence in specific areas of the Erzgebirge: 1) Eclogites (SiO_2 = 49-52.5 wt.%) from a southwestern portion of the MEU are, for instance, characterised by $(Nb)_N$ and $(Sr)_N$ values (normalised to chondrite) between 3-6 and 3-12, respectively. Ta/Yb ratios are ≤0.08. The REE patterns are characterised by $(La/Sm)_N < 0.7$ and $(Sm/Yb)_N$ around 1. These values and other characteristics point to N-MORBs as protoliths. The strong scatter of the metallogenetically relevant elements Cu, Sn, and Pb in the eclogites could be the result of an interaction of the rocks with a hydrous fluid in a subduction zone environment. However, a hydrothermal process in the oceanic crust before subduction, leading to similar results, cannot be excluded. 2) Eclogites from the Saidenbach reservoir are basaltic to andesitic in composition (SiO_2 = 47.5-58.5 wt.%). The above geochemical parameters, being significantly larger than those of group 1), are: $(Nb)_N > 20$, $(Sr)_N > 10$, Ta/Yb > 0.14, $(La/Sm)_N$ = 1.2 - 3, and $(Sm/Yb)_N > 1.4$. Moreover, they scatter relatively strongly. A further typical pattern is the clear negative Eu-anomaly found, at least, for all five samples from the eastern shore of the Saidenbach reservoir. Again the concentrations of Cu, Sn, and Pb but also of Ba and Th scatter unsystematically. We cannot derive the protoliths of these eclogites from MORBs. Instead, magmatic protoliths related to oceanic islands, active continental margins or intraplate magmatism are conceivable. A context of some of the eclogites from the Saidenbach reservoir with sedimentary protoliths (marls) cannot be excluded, as well, although the Sc, V, Cr, and Ni contents are relatively high being at least above 20, 130, 50, and 10 ppm, respectively. 3) Eclogites (SiO_2 = 48-52 wt.%) from areas surrounding the region of the Saidenbach reservoir are characterised by $(Nb)_N$ = 5-36, $(Sr)_N$ = 5-17, Ta/Yb = 0.07-0.25, $(La/Sm)_N$ = 0.5-1.5, and $(Sm/Yb)_N < 1.8$. We refer these data to original MORBs. However, in addition to N-MORBs a trend to P-MORBs is discernable. Because the geochemical characteristics of group 3) eclogites are independent on their location in the MEU or GEU, the boundaries of these units must be called in question.

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Coexisting jadeite and omphacite in an eclogite-facies metaquartz diorite from the southern Sesia Zone, Western Alps, Italy

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Jadeite and omphacite association is newly found from an eclogite-facies metaquartz diorite collected in the Orco Valley, southern part of the eclogitic micaschist complex of the Sesia Zone, Western Alps, Italy. The mineral paragenesis of the sample is jadeite, omphacite, garnet, phengite, zoisite/clinozoisite and quartz with minor amount of paragonite, glaucophane, titanite, rutile, apatite and zircon. Both jadeite and omphacite occur as idiomorphic to subidiomorphic grains in the matrix, and some of them are in contact with each other with sharp grain boundary. Most of jadeite is homogeneous in each grain, but compositions of jadeite are scattered from a grain to another (X_{jd} = 0.75-0.90). The half of the omphacite grains is homogeneous and the other shows various zoning patterns. Some grains show prograde zoning with an increase of X_{jd} (from 0.31 to 0.56) and decrease of X_{aeg} (= Fe^{3+}/(Na+Ca)) (from 0.15 to 0.06) from the core to the rim. The rim composition of zoned omphacite is similar to that of homogeneous omphacite (X_{jd} = 0.40-0.56). The rim compositions of jadeite-omphacite pair in direct contact show an apparent miscibility gap between X_{jd} = 0.50±0.03, X_{aeg} = 0.10±0.02 and X_{aug} (= (Ca-Al^{IV})/(Ca+Na)) = 0.40±0.02 in omphacite and X_{jd} = 0.78±0.02, X_{aeg} = 0.09±0.01 and X_{aug} = 0.13±0.02 in jadeite. The application of garnet-clinopyroxene geothermometer of Powell (1985) yields 410-490 ^{o}C at P = 12 kbar and the garnet-omphacite-phengite geobarometer of Waters & Martin (1993) yields 13.6 kbar at 410 ^{o}C and 12.5 kbar at 490 ^{o}C. Several authors have considered solid-solution properties of omphacite for constructing phase diagram or calculating activity of phase components (e.g., Carpenter, 1980b; Carpenter 1983; Banno, 1986; Davidson & Burton, 1987; Holland, 1990; Carpenter et al., 1994; Holland & Powell, 1996; Nakamura & Banno, 1997). The position of the miscibility gap has been also discussed with observations of natural metamorphic rocks: e.g., for diopside-omphacite join by Brown et al. (1978), Carpenter (1980a), Enami & Tokonami (1984) and Tsujimori (1997), and for jadeite-omphacite join by Carpenter (1979), Yokoyama & Sameshima (1982), Harlow (1994), Compagnoni et al. (1995) and D'Amico et al. (1995). However, positions of miscibility gaps have no yet been confirmed in spite of the presence of many studies. We assess the theoretically proposed phase diagram using available data from natural samples. The available pyroxene compositions both in the present study and in the literatures are well concordant with the jadeite-diopside-aegirine ternary diagram of Carpenter (1983).

Epidote-rich kyanite-talc-phengite eclogites, Sulu terrane, E. China

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Recent highway construction across the Qinglongshan in Donghai, eastern China has exposed a 660 m section of interlayered gneiss, eclogite, and minor quartzite. Eclogites are characterized by unusually abundant (15-40%) hydrous phases including talc, phengite, and epidote; many also contain kyanite. Several samples contain two stages of epidote: large poikiloblasts aligned with the foliation and contain coesite pseudomorphs; later-stage prisms with few inclusions cut the foliation. The compositions of these two stages are similar: X_{Fe} = 0.15-0.18. Extensively amphibolitized samples contain epidote with up to X_{Fe} = 0.25, associated with retrograde pargasite and albite. Omphacite is characterized by 5-15 mol% aegerine, and cores contain exsolved quartz (?) rods. Garnet is pyrope- and almandine-rich, with 12-15 mol% grossular, and hosts both prograde (paragonite, amphibole) and peak stage (omphacite, epidote, talc, phengite, kyanite) mineral inclusions. Phengite cores contain up to 3.6 Si p.f.u. (11 oxygen basis), and rims contain 3.2-3.4 Si p.f.u. Several samples contain talc rimmed by barroisite; optically and compositionally identical coarse-grained amphibole present in other samples is pseudomorphic after talc, and indicates that the reaction Omp + Tlc + Grt + Ky = Amp + Qtz has completely consumed talc. Estimated peak conditions of 30-35 kbar, 550-650°C, are consistent with coesite and polycrystalline quartz inclusions in garnet, epidote, kyanite, and omphacite. High oxygen fugacities required to stabilize the epidote-bearing assemblage suggest that the protolith reacted with oxidizing, near-surface water prior to ultrahigh-pressure (UHP) metamorphism, and behaved as a closed system thereafter. This is consistent with the preservation of negative $\delta^{18}O$ values (-14 to -16 per mil) in UHP minerals from this region (Rumble and Yui 2001). The high oxygen fugacity and negative oxygen isotope values recorded by these rocks may both reflect the "snowball earth" hydrothermal system postulated by Rumble et al. (2002). Oxidized conditions during peak metamorphism may explain the absence of microdiamond in this area (e.g. Liou et al. 2002).

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Bracketing the age of HP metamorphism in the Greenland Caledonides: New U-Pb SHRIMP-RG age determinations on retrograde amphibolite facies metamorphism

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The North-East Greenland eclogite province (NEGEP) represents Laurentian crust subjected to high pressure (HP) and ultra-high pressure (UHP) metamorphism during evolution of the Caledonian orogen. The eclogite facies rocks include eclogites *ss,* garnet clinopyroxenites, garnet websterites, websterites, and coronitic metagabbros that occur as mafic pods. The majority of the mafic pods are boudinaged layers interpreted as intrusions emplaced into the surrounding wall rocks in the Early Proterozoic, prior to involvement in Caledonian orogenesis. This study focuses on establishing timing relationships for the HP terrane in the southeastern part of the NEGEP near the Danmarkshavn weather station (76°46'N, 18°40'W). Danmarkshavn area garnet websterites record peak P-T conditions of 2.35 GPa and 790°C; and yielded a Sm-Nd mineral isochron age of 370±12 Ma, and a $^{206}Pb/^{238}U$ SHRIMP age of 364±24 Ma based on three zircon rim analyses (Brueckner et al., 1998). In order to test whether these ages reflect the timing of peak metamorphic pressure or record retrograde metamorphism, zircons from the freshest HP assemblage and the amphibolitized margins of two pods were compared and analyzed by SHRIMP-RG at the SUMAC Lab, Stanford University, Palo Alto, U.S.A. Zircons from pegmatitic material in boudin necks adjacent to the individual pods were also analyzed.

Zircons were extracted from an eclogite pod and the same garnet websterite studied by Brueckner et al. (1998). All the zircons were imaged by cathodoluminescence to distinguish rims from inherited cores, and to compare the amount of new rim material between the HP sample and its amphibolite facies equivalent. Rims on zircon from the center of the eclogite pod and amphibolitized eclogite at its margin yielded weighted mean $^{206}Pb/^{238}U$ ages of 374 ± 8 Ma and 373 ± 11 Ma, respectively. Rims on zircon from fresh, partially amphibolitized, and strongly amphibolitized garnet websterite yielded weighted mean $^{206}Pb/^{238}U$ ages of 372 ± 10, 389 ± 5 Ma, and 378 ± 8 Ma respectively. Zircon from a pegmatite emplaced within the neck of the boudinaged websterite pod above yielded a weighted mean $^{206}Pb/^{238}U$ age of 374 ± 3 Ma. Th/U ratios, with values ranging from 0.02 to 0.2 for all samples, are indicative of zircon growth from metamorphic fluids. The similarity in ages between zircon rims at the center of the mafic pods, the amphibolitized rims of the same pods, and pegmatitic material adjacent to them indicates that zircon rim growth between 380 and 370 Ma represents fluid influx during retrograde amphibolite facies metamorphism and deformation rather than metamorphism at peak P conditions.

In addition to zircon rim growth at 370-380 Ma in the Danmarkshavn region, a small subset of rim ages from the eclogite pod and its margin yield weighted mean $^{206}Pb/^{238}U$ ages of 333 ± 5 Ma and 342 ± 9 Ma, respectively. Oscillatory zoned zircons from pegmatitic material adjacent to the eclogite pod yielded a weighted mean $^{206}Pb/^{238}U$ age of 337 ± 7 Ma. These ages are consistent with age determinations on pegmatites that cross cut strike-slip structures associated with the Germania Land deformation zone (see Sartini-Rideout et al., this volume).

The age of HP metamorphism in East Greenland is best defined as ca. 405 Ma on the basis of $^{206}Pb/^{238}U$ SHRIMP data on zircon growing in HP granulite facies melts in the Payer Land

gneiss complex (McClelland and Gilotti, 2003). However, Payer Land is located approximately 250 km SW of the NEGEP. HP and UHP metamorphism may be diachronous along strike, as well as across strike within the NEGEP. Most of the Sm-Nd and zircon rim ages from the NEGEP are in the range of 410-360 Ma (Gilotti et al., this volume). Current brackets on the age of HP metamorphism in the NEGEP are taken as post- 410 Ma (from the combined Payer Land and NEGEP data) and pre-380 Ma on the basis of the ages reported above. Future geochronological studies will concentrate on identifying and dating zircons with HP/UHP inclusions and metamorphic zoning to ascertain the age of peak-P conditions.

Multistage mineral assemblages and P-T evolution of the Sandvik peridotite, Gurskøy

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Introduction A small outcrop of Mg-Cr garnet peridotite and associated garnet pyroxenite occurs at Sandvik on the island of Gurskøy. This outcrop is important because it contains several of the numerous mineral assemblages that have been identified in peridotites of the Western Gneiss Region (WGR), and it provides additional information on the long and complex P-T evolution of WGR peridotites.

Mineral assemblages From oldest to youngest, the sequence of assemblages in Sandvik peridotite, based on textural relations, is:

Stage 1) olivine + garnet + orthopyroxene + clinopyroxene (now exsolved; formerly low-Ca, high-Al and high-Cr)

Stage 2) olivine + garnet + orthopyroxene (low-Al) + clinopyroxene; all four phases occur as porphyroclasts; this is the prevalent garnetiferous assemblage at Sandvik and in at least twelve other peridotite bodies in the WGR

Stage 3) olivine + garnet + spinel + orthopyroxene + clinopyroxene; a five-phase assemblage, which occurs as fine-grained kelyphite around garnet porphyroclasts of Stage 2

Stage 4) spinel + orthopyroxene + clinopyroxene + rutile; oriented inclusions within Stage 2 garnet porphyroclasts and perhaps contemporaneous with Stage 3

Stage 5) olivine + spinel + orthopyroxene + pargasitic amphibole; a granoblastic assemblage that constitutes the matrix for Stage 2 porphyroclasts

Stage 6) olivine + chlorite + orthopyroxene + tremolitic amphibole; this assemblage occurs in a separate, nearby outcrop of peridotite and represents the most common and widespread assemblage in WGR peridotites.

The mineral assemblages of Stages 1 and 2 are Proterozoic in age, Stages 3, 4, and 5 are thought to be Caledonian, and Stage 6 is Caledonian.

Temperature-pressure estimates Geothermobarometric calculations, based on the Al content of orthopyroxene and Fe-Mg exchange between olivine and garnet (for peridotite), or orthopyroxene and garnet (for pyroxenite), yield an estimate of 1000 ^{o}C, 51.5 kbar for the Stage 2 assemblage in peridotite and a closely similar result for associated pyroxenite. This value is in accord with, but at the high end of, P-T estimates for the comparable assemblage in other WGR peridotites. Using the reconstructed composition of Stage 1 clinopyroxene, $Wo_{40.5}En_{56.0}Fs_{3.5}$ (reconstructed) *vs*. $Wo_{47.6}En_{50.3}Fs_{2.0}$ (exsolved host), two-pyroxene geothermometry yields 1220 ^{o}C, which, when combined with the Al content of orthopyroxene, gives 67.9 kbar. Such elevated P-T conditions approach those that have been proposed for pre-Stage 2 assemblages in peridotite bodies elsewhere in the WGR.

Stage 4 "pseudomajorite" The Stage 4 assemblage, which consists of tiny, oriented grains of orthopyroxene, clinopyroxene, spinel, and rutile within Stage 2 garnet porphyroclasts, is particularly interesting, because it resembles majoritic garnet that has been described from peridotites on Otrøy, Fjørtoft, and Flemsøy. However, the Stage 4 assemblage differs from majoritic garnet in two important respects: spinel is a prominent member of the mineral suite, and the reconstructed garnet composition, rather than being supersilicic, contains 2.99-3.00 atoms of Si, based on 12 oxygen atoms per formula unit. Rutile is a relatively common exsolution feature in garnet in other WGR peridotites, and the Sandvik Stage 4 rutile may also be an exsolution feature (reconstructed garnet contains 0.28 to 0.58 wt% TiO_2). The remaining members of the Stage 4 association, orthopyroxene, clinopyroxene, and spinel,

most likely result from decompression, analogous to the Stage 3 kelyphite, but their confinement to the interior of garnet grains is unusual and deserves further investigation.

P-T evolution of the Sandvik peridotite Mineral assemblages and compositions in the Sandvik peridotite reveal a complex metamorphic history, beginning with an early, cryptic, garnet-bearing stage at ~1200 ^{o}C and 65-70 kbar, followed by re-equilibration at ~1000 ^{o}C and 50 kbar. During later deformation at lower temperatures and pressures, additional garnet grew in kelyphite, which surrounds garnet porphyroclasts. Further cooling, decompression, and deformation resulted in development of amphibole- and spinel-bearing assemblages and, ultimately, the common chlorite peridotite of the WGR.

Work in progress Analyses of Sr, Nd, and Hf isotopes in garnet, clinopyroxene, and whole rock samples from Sandvik are underway to establish the ages of different mineral assemblages and to assess the chemical provenance and evolution of these interesting and important rocks.

Evolution of garnet peridotites and iron eclogites in the almklovdalen body, Western Gneiss Region, Norwegian Caledonides

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Garnet-bearing assemblages (peridotites, pyroxenites and eclogites) occur at several localities within the Almklovdalen body as well as within other orogenic peridotite lenses within the Western Gneiss Region of the Norwegian Caledonides. The classic interpretation is that the primary garnet ± clinopyroxene ± orthopyroxene ± olivine assemblages formed in the mantle during the mid-Proterozoic, based on the oldest of 0.5 to 1.7 Ga. Sm-Nd mineral ages. The younger dates tend to cluster at 1.0 – 1.2 Ga and 1.3 – 1.55 Ga and may match similar ages in the basement crustal rocks of the WGR that evolved during the Gothian (1.6-1.75 Ga) and Sveconorwegian (0.95-1.3 Ga) orogenies and an intrusion event at 1.5 Ga. If so, the peridotites represent sub-Baltic mantle that was coupled with the Baltic crust since at least the mid-Proterozoic. However, the younger events did not significantly perturb the mineral chemistries of the primary minerals in the garnet peridotites, which show only exsolution textures related to decompression and minor retrograde zoning at their outermost rims (for example decreasing Mg/Fe in the Mg-rich garnets). Therefore, the scattered younger dates can also be interpreted as mixed ages caused by partial re-equilibration of the 1.6 to 1.7 Ga assemblages through continuous diffusion while still sequestered in the mantle or during an episodic loss related to the Caledonian Orogeny.

External eclogites in the high-grade metamorphic rocks enclosing the orogenic peridotite bodies recrystallized during the Caledonian Orogeny at around 400-415 Ma during the closure of the Iapetus ocean basin when a western continent, Laurentia, collided with an eastern continent, Baltica. The collision involved the subduction of the WGR into the mantle where it was metamorphosed under HP/UHP conditions. This model is supported by textural and chemical observations that show prograde zoning of the garnets and clinopyroxenes within the eclogites. The subduction event also allowed the garnet-bearing orogenic peridotites and the external eclogites to be brought together, or juxtaposed, as the peridotite intruded the subducted WGR from the overlying mantle wedge.

A major complication with this juxtaposition model is the discovery of superferrian eclogites within the Almklovdalen body. These "internal" eclogites also show a prograde pattern within garnet grains that indicate initial recrystallization in the amphibolite facies changing to recrystallization in the eclogite facies. This prograde texture is characteristic of the external eclogites but not of the garnet peridotites. If the superferrian eclogites formed at ca. 400-415 Ma, it would indicate a Caledonian origin identical to that of the external eclogites. The mystery then is how these Caledonian eclogites became entrained within peridotites that show a largely Proterozoic history? Alternatively, if the superferrian eclogites formed during the mid-Proterozoic, then why don't the garnet peridotites and pyroxenites of the Almklovdalen body also record a prograde history?

A Fe-rich eclogite was collected from Rødkleiva, near the Grubse quarry, Almklovdalen, to date by the Sm-Nd mineral method. Garnet, clinopyroxene, symplectite after clinopyroxene, secondary amphibole, and the whole rock do not define an isochron due in large part to the off-line position of the amphibole. Excluding amphibole and considering only clinopyroxene

– symplectite – whole rock – garnet gives a scatterchron age of 574 +/- 38 Ma (MSWD = 11.4). The symplectite is clearly secondary after clinopyroxene and should not be regressed with it. If only clinopyroxene and garnet are considered the age becomes 581.5 +/- 6.2 Ma. A significantly younger age results if symplectite-whole rock and garnet are considered (568 ± 5.8 Ma, MSWD = 0.56). The change in "age" is attributed to contamination by fluids during the development of the symplectite, which raised the $^{143}Nd/^{144}Nd$ ratio of both the symplectite and the bulk rock. None of these combinations define either a mid-Proterozoic or Caledonian age, but in fact deepen the mystery. An apparently similar superferrian eclogite from the Gurskebotn peridotite defines an age of 599 ± 42 Ma that is within error of the ages described above. These ages need to be verified by further work in order to understand the complicated evolution of superferrian eclogites and garnet peridotites, but if the ca. 580 Ma age is supported by further dates, it would suggest another event affected the peridotites of the WGR, perhaps one related to the opening of Iapetus.

TEM investigation on fine structure of phase interface between coesite and retrograde metamorphic quartz

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Coesite is the high pressure allomorph of SiO_2 under the condition of P= 2.6 Gpa, T=700°. Differing from quartz, it has some distinguishing features, such as higher protuberance, lower index of double refraction, poorer cleavage and giving out blue light under the electron beam (Chopin, et al., 1995). SiO_2 inclusions in garnet and omphacite in UHP eclogite from Shima, Anhui Province, Dabie Shan, China are often between several micrometer and some dozens of micrometer, and the bigger one can reach a few hundred micrometer. Observed by optical microscope, most of the coesite monocrystal(50μm - 210μm) appear in the retrogressive metamorphic α-quartz by the form of residue (You and Han et al., 1996). A coesite inclusion within garnet is surrounded only by a thin corona of polycrystalline quartz. The host garnet shows well-developed radial fracture. Most of the coesite inclusions in omphacite have transformed into polycrystalline quartz, the omphacite has symplectitic corona. The host omphacite has radial and concentric fracture. Recently we have performed a transmission electron microscopy (TEM) and energy-dispersive X-ray spectrometer (EDS) investigation on the fine structure of the phase interface between coesite and retrogressive metamorphic quartz in UHP coesite-bearing eclogite from Shima, Anhui Province, Dabie Shan, China. The EDS and TEM studies indicate that the ultra-microstructures of interface between coesite and retrogressive metamorphic quartz has three forms: Firstly, in most of the cases, the unsmoothed interface, which is directly associated by atom between coesite andα-quartz, is interface of complete syntaxy, partial syntaxy or non-syntaxy. The interface phase doesn't exist. Secondly, sometimes it can be observed that there is a interface of SiO_2, which is an amorphous layer about 2nm – 6nm between coesite andα-quartz. Thirdly, the EDS analyses confirm that the interface between coesite andα-quartz contains Al- and Fe- oxide, etc. It is probably due to the bias agglomeration on the interface between coesite andα-quartz of some elements, such as Al and Fe, etc. which react with Si, O and other trace elements and become mixed heterogeneous texture of continuous interface layer. TEM studies indicate that the fine structure of interface between coesite andα-quartz is a little complex. Different interface layer shows different dynamical mechanism during the transition process from coesite to α-quartz, and the detail of both composition and structure of interface layer also has something to do with their transition process. This study was supported by the NNSFC grant 40172019 and HBNSFC grant 2002AB020.

Spinel-pyroxene symplectite in the Horoman Peridotite Complex, Japan: implications for phase transition from garnet- to spinel-peridotite and P-T history

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The Horoman Peridotite Complex, Japan, ascended from garnet-lherzolite stability field (Ozawa & Takahashi, 1995; Takazawa et al., 1996). Furthermore, Ozawa & Takahashi (1995) suggested that the higher part of the complex follows a higher temperature decompression path than the lower part of the complex. Symplectites, intergrowth of irregular fine-grained minerals, are an important feature of the Horoman peridotites, and are interpreted to be pyropic garnet origin (e.g., Kushiro & Yoder, 1966). Textural and chemical variations of symplectite in the Horoman have been found in a whole complex (Takahashi & Arai, 1989; Ozawa & Takahashi, 1995; Takahashi, 1997, 2001). A combination of textural and geochemical variations among the symplectites will, therefore, provide an opportunity to understand phase transition of peridotites from garnet- to spinel-lherzolite stability fields as a function of the differences in thermal history during exhumation (Morishita & Arai, 2003). Symplectite in the Horoman complex is divided into two types based on mineral assemblages: (1) spinel-pyroxene symplectite consisting of orthopyroxene, clinopyroxene and spinel, and (2) plagioclase symplectite characterized by presence of plagioclase around spinel. Here we studied spinel-pyroxene symplectite only because the plagioclase-symplectite is affected by chemical modification due to the further formation of plagioclase with pyroxene porphyroclasts after formation of spinel-pyroxene symplectite during later P-T conditions (Ozawa & Takahashi, 1995). We present the textural and geochemical characteristics of spinel-pyroxene symplectites from the lowest, middle and upper parts of the complex (LZ, MZ and UZ, respectively). All symplectites are included in lenticular fine-grained mineral aggregates consisting of orthopyroxene, clinopyroxene and spinel. Note that the minerals in a two-dimensional section are coarser grained and more rounded in the fine-grained aggregate than in the symplectite. The modal proportion of the minerals in the symplectite is almost the same, opx : cpx : spl = 2 : 1 : 1. The size of symplectite minerals increases from the lowest (LZ) through to the middle (MZ) to the upper parts (UZ). Three-dimensional (3-D) microstructure of symplectite minerals in UZ were obtained from > 1000 slices of X-ray computerized tomography (CT) taken by a high-resolution X-ray CT system at SPring-8, Japan (Morishita et al., 2003). Although mineral grains in symplectites are usually recognized as separate grains in a two-dimensional section, some of them are connected to each three dimensionally. The predominant elongation axis of the symplectite spinel might be related to spatial distribution of the symplectite clinopyroxene. These characteristics of the 3-D microstructure are almost the same as those estimated from MZ (Morishita, 2000). The reconstructed major element composition of the bulk symplectite of the LZ satisfies garnet stoichiometry whereas those of MZ and UZ are not consistent with garnet stoichiometry. The primitive mantle normalized pattern in trace elements for the LZ symplectite is similar to that of pyrope-rich garnet from fertile peridotites, which is characterized by enrichment of HREE and a positive Zr anomaly. The LZ symplectite has inherited both major and trace element signatures from pre-existing garnet whereas the compositions of the MZ and UZ were modified during exhumation of the complex. The basal part of the complex (LZ) experienced the lowest temperature decompression in the complex, resulting in less textural and chemical modification. On the other hand, the higher part of the complex (UZ) experienced a relatively higher temperature decompression path than other parts of the complex, resulting in chemical equilibration among the constituent minerals. No essential difference in 3-D microstructures

of symplectites between the UZ and MZ in spite of variation in size of symplectite minerals indicates a possibility that there had been already thermal gradients in the whole complex as symplectites were formed. The preservation of the high-pressure geochemical heterogeneity might imply that the phase transition from garnet- to spinel-lherzolite facies occurred within a geologically short time.

Characteristics of biotite- or orthopyroxene-bearing eclogites from the Caledonides – thermodynamic evaluation on stability of phengite and biotite in eclogites

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Stability of phengite and biotite in eclogite is discussed using petrological data of natural eclogites, and the observational data are examined by thermodynamic calculations. Generally, phengite is a major K phase in natural eclogite and is stable in wide range of bulk composition. However, in eclogites from several localities of the Caledonides, biotite occurs as a stable eclogite-facies mineral, and is often associated with orthopyroxene. Bulk compositions of such biotite- or orthopyroxene-bearing eclogites are compared with those of eclogites from the Dabie–Sulu region, China, where phengite is a major K phase in eclogite. The biotite- or orthopyroxene-bearing eclogites from the Western Gneiss Region (WGR) of the Caledonides are rich in MgO (= 10–15wt%) and relatively poor in CaO (= 7–8wt%) and Al_2O_3 (= 12–16wt%). The CaO/MgO ratios of the biotite- or orthopyroxene-bearing eclogites are clearly lower than those of eclogites from the Dabie–Sulu region, indicating that MgO-rich and CaO-poor environments should be important for stabilizing of biotite and orthopyroxene in eclogite. Biotite-bearing eclogite from the North-East Greenland Eclogite Province is rich in MgO (≈ 16wt%) and CaO (≈ 15.5wt%) and extremely poor in Al_2O_3 (≈ 8wt%). To stabilize biotite in eclogite, Al_2O_3-poor environments are also important. Bulk compositions of these biotite- or orthopyroxene-bearing eclogites are similar to picrite basaltic compositions. To examine these observational data, thermodynamic calculations were carried out in 7-component system $KH_2O_{1.5}$-Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2 that includes garnet, kyanite, phengite, biotite, quartz, omphacite, orthopyroxene and olivine in conjunction with mass-balance calculations. Firstly, calculations were performed on the average bulk composition of eclogites from the Dabie–Sulu region to lherzolite composition (KLB-1). The calculation results confirmed that phengite should be stable in eclogite with “ordinary” basaltic composition, whereas biotite and orthopyroxene should be stable in picrite basaltic compositions (MgO > 11.0wt%, CaO < 9.8wt%, Al_2O_3 < 15.2wt% at 700°C, 2.5GPa). Further calculations in basaltic system revealed that increase of MgO content and decrease of CaO and Al_2O_3 contents were important to stabilize biotite and orthopyroxene in eclogite. Thus, mineral assemblage in picrite basalt system should be completely different from that in normal basaltic system.

The first finding of eclogite relict in the Korean Peninsula and its tectonic meaning

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In the southwestern part of the Gyeonggi Massif in Korea, garnet granulite occurs as individual lens or lens mixed with marble or ultramafic rocks and contacts with the surrounding Precambrian Complex as a fault. The Precambrian Complex is divided into Duckjeongri granitic gneiss and Walhyunri Formation consisting of biotite or amphibole schist. Most garnet granulite lenses are found in the Duckjonri granitic gneisses but at Bibong garnet granulite lens occurs within Walhyunri Formation. Garnet granulite at Bibong shows three stages of metamorphism. The first stage is eclogite facies (EG) metamorphism recognized by the inclusion assemblage within garnet, Grt + Omphacitic Cpx + Pl + Qtz + Rutile. The second stage mineral assemblage, Grt + Sodic Aug + Pl + Qtz + Rutile + Rutile or Tnt ± Amp, is recognized from the matrix and represents the high-pressure granulite facies (HG). The third stage is amphibolite facies(AM) metamorphism which is recognized from the strongly retrograded part where Grt + Amp + Pl + Qtz assemblage is stable. Due to the retrograde metamorphism from the first to third metamorphic stages, garnet shows a compositional zoning where X_{Pyp} and X_{Grs} decrease and X_{Fe}, X_{Alm} and X_{Sps} increase towards rim; X_{Fe}, X_{Pyp}, X_{Alm}, X_{Sps} and X_{Grs} are 0.66, 0.22, 0.43, 0.01 and 0.34 for the typical core and are 0.75, 0.18, 0.55, 0.03 and 0.24 for the strongly retrograded rim. Most Cpx are sodic augite or augite but some Cpx inclusions are omphacitic($X_{Di\text{-}Hed}$, 0.68; X_{Jd}, 0.23; X_{Ac}, 0.02; X_{CaTsch}, 0.07). Cpx also shows a compositional zoning in which X_{Jd+Ac} and X_{CaTsch} decrease towards rim. The P-T conditions of the first, second and third stages are 750-880°, 17.1 – 21.2 kb, 705-885°, 10.3 – 14.7 kb and 540 - 730°, 9.0 – 12.4 kb, respectively. These data indicate that Bibong garnet granulite had experienced a retrograde P-T path from the EG to the AM through HG.. The garnet-whole rock Sm/Nd age of Bibong garnet granulite is 224.8 ± 6.6 Ma which represents the metamorphic age of the HG or EG metamorphism. The P-T path and metamorphic age of Bibong garnet granulite are similar to those of the retrograded eclogite in the Sulu Collision Belt in China, which indicates that the southwestern part of the Gyeonggi Massif in Korea may be a possible extension of the Sulu Collision Belt in China.

Ultrahigh-pressure metamorphism and continental subduction to depths of 200 km: Implications for intra-continental ultrapotassic magmatism

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Conventional plate tectonic concepts require that oceanic lithosphere is continuously consumed at convergent margins, whereas continental lithosphere generally does not suffer the same fate. However, recent petrological data for exhumed relicts (of both mantle and crustal parentage) of continental subduction from the Kokchetav massif of Kazakhstan, the Sulu and Dabie terranes of China, the Western Gneiss Region of Norway and the Saxonian Erzgebirge indicate that at least some sections of continental lithosphere were recovered from depths up to 200 km. The relationships between oceanic subduction and arc magma petrogenesis have been studied for several decades, and are relatively well understood. The magmatic legacy of continental subduction, however, is far less clear. Correlation of spatial and temporal associations of continental subduction-collision orogens containing ultrahigh-pressure metamorphic (UHPM) relicts with broadly coeval or younger, high-K and/or ultrapotassic lavas, may indicate a direct petrogenetic relationship between UHPM and potassic magmatism. Slab break-off at depths around 200 km may provide a simple mechanism for the generation of small degrees of partial melts of the leading edge of the slab, and ultrapotassic magmatic products located at ~ 200-300 km lateral distance from the collisional suture. Derivation of an apparent, interpolated geotherm for continental subduction from petrological data indicates that at depths of around 200 km P-T conditions of crustal rocks will approach the solidus, and require only a small thermal perturbation (< 100 ˚C) for them to undergo partial melting. This can be provided by slab break-off and consequent asthenospheric circulation. Partial melts resulting from elimination of K-feldspar and K-wadeite in recrystallized continental crust ± sediments may have surface expressions as ultrapotassic lavas, and/or hybridization and metasomatism of the overlying lithospheric mantle. At least some ultrapotassic lavas, including lamproites and possibly some group II kimberlite occurrences, disposed in relative proximity to collisional orogens containing UHPM relicts may have been generated in such a way. Isotopic signatures have indicated continental crust source components in some lamproites and other ultrapotassic rocks spatially and temporally related to UHPM-bearing collisional orogens. Kimberlites are generally considered to be derived from partial melting of Phl-Mgs garnet lherzolite at pressures of > 50 kbar; carbonate may be generated in mantle rocks by the carbonation reactions Ol + Dol + CO_2 = Opx + Mgs or Ol + Cpx + CO_2 = Opx + Dol. The Kokchetav massif contains highly diamondiferous marbles which have yielded peak pressures of *c.* 70 kbar, and clearly suffered decarbonation reactions at great depth in the collision zone. This demonstrates, at least, that supracrustal platform carbonates *could* be subducted to depths of *c.* 200 km in the Proterozoic. and the metasomatised mantle above the collision zone could constitute a source region for kimberlite magmatism.

Eclogitization and fluid evolution during fast exhumation of granulites

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Eclogite-facies rocks are highest in the pressure hierarchy of metamorphic facies. However, on the basis of our study we argue that eclogites within the Bergen Arcs, Norway, formed at lower pressures than those experienced by the granulites from which they are derived. The granulites equilibrated at T=800-900°C and P<10 kbar in Grenvillian time and were preserved metastably in dry undeformed zones under eclogite facies conditions in Caledonian time (Austrheim & Griffin, 1985 Chemical Geol 50: 267-281). The granulite to eclogite transformation can be regionally observed in zones of fluid infiltration and deformation (e.g. Austrheim, 1987 EPSL 81:221-232). Pressure-temperature estimates indicate that the eclogitic rocks equilibrated at 1.9 GPa/ 730°C, with water activity (*a*H2O) less than 0.4, and were subsequently retrogressed under P-T conditions of 0.6 GPa and 500 °C (Perchuk, Petrology 10: 99-118, 2002). H_2O-CO_2-NaCl phase relations quantified for the peak P-T conditions show that (i) a single-phase homogeneous H_2O-CO_2-NaCl fluid exists for *a*H2O higher than 0.25, (ii) *a*H2O ranges between 0.25 and 0.50 for brines coexisting with excess salt. Similar calculations for the P-T conditions of the retrograde stage show that the compositional field for single-phase fluid decreases dramatically. Accordingly, it is to be expected that segregation of eclogite-stage fluid to CO_2-rich phase and brine ± salt should occur during decompression. Fluid immiscibility on the decompression path can explain the observation of coeval hydration vs carbonation reactions attending eclogitic metamorphism of anhydrous granulites (e.g. Boundy et al., 2002 JMG 20: 649-667).

Calculated extreme rates of exhumation and cooling of the eclogite-granulite continental block of about 30 km/Ma and 160 ^{o}C/Ma (Perchuk, 2002, *ibid*) can be accounted for by the mechanism of Chemenda et al (1996 EPSL 143: 173-182). According to this model, subduction of continental lithosphere into the mantle can lead to the failure of the upper crustal layer near the base of the overriding plate. The detached buoyant crustal slice then intrudes the interplate zone. Buoyancy-driven rapid exhumation of the detached slab leads to juxtaposition of anhydrous rocks forming the lower continental crust (granulites) over the top of relatively hydrated upper crustal rocks. Dehydration of the underlying slab and infiltration into the overriding anhydrous lower crust can cause eclogitization of the overriding unit along faults or fractures. This scenario has two important consequences: 1) eclogitization should occur on the exhumation path, and 2) the granulite facies rocks experienced higher pressure then the eclogites. The pressure difference between granulite-and eclogite-facies rocks is likely to be dependent on a variety of, as yet unknown, kinetic and kinematic parameters. Interestingly, if such a scenario proved to be viable, it implies that granulitic rather than eclogitic rocks should retain information on the ultra-high-pressure history.

Microstructures caused by melting of metamorphic garnets

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Proof of melting in eclogite-facies rocks is crucial for understanding their origin and exhumation mechanism(s). Indeed, the magmatic versus metamorphic origin of diamond and other ultra-high-pressure minerals (e.g. K-Cpx) in the Kokchetav massif is a subject of long-standing geological discussion. Partial melting of crustal rocks dramatically changes their rheological properties, significantly increases their mobility and thus their exhumation rates.

Former melts in eclogite-facies rocks are difficult to recognize, since they are normally obscured by subsequent metamorphic recrystallization. However, refractory garnet inherited from the melt or affected by melting could preserve the original magmatic composition stable under metamorphic P-T conditions. Accordingly, garnet could retain information about both the magmatic and metamorphic episodes experienced by the rock.

Melting experiments on metamorphic garnets from eclogites were carried out in a piston-cylinder apparatus at 1300°C and 27 kbar. Euhedral garnets from the Yukon-Tanana terrain, Canada (Perchuk et al 1999 Geology 27: 531–534), served as starting material. These show concentric chemical zoning characterized by a marked increase in Mg, decrease in Fe and, to a lesser extent, Mn from core to rim. Garnet rims are almost inclusion free (only rare crystals of omphacite and quartz are found). However, core regions contain numerous inclusions of clinozoisite, quartz, rutile, clinopyroxene, paragonite and titanite. Both the distribution of inclusions and the compositional heterogeneity of the garnet lead to different melting temperatures: the rim remains refractory, in contrast to the fusible core. In the run products, the cores of the starting material consist of quenched melt of Ti-rich basaltic composition and recrystallized irregular Mg-rich garnets, some of which show euhedral shapes. Most of the crystals, however, still contain relics of the former Fe-rich garnet. Where the rim is relatively thick and the initial amount of inclusions relatively low, most of the melt is retained in the core. In most cases, however, the melt penetrated through the garnet rim, producing stringers and/or very patchy structures which are easy to detect in back-scattered images of the electron microprobe.

The composition of the observed melt is close to the Grt-Czo tie-line of the ACFM projection, slightly shifted towards omphacite. Accordingly, sub-solidus recrystallization of the melt under eclogite-facies conditions is likely to lead to the growth of Fe-rich garnet, clinozoisite, quartz and rutile, with minor clinopyroxene. This mineral assemblage is very common in (ultra-) high-pressure metamorphic terrains and therefore can be interpreted in terms of both metamorphic and magmatic origins.

We argue that the observed experimental modification of garnet resulting from “interior” melting (originating from reactions between (hydrous) inclusions and the host garnet) can also be produced by melting from the outside. Such an “exterior” modification of garnet can be facilitated by partial melting of matrix minerals. The wet solidus of basaltic rocks (~650-750°C, in e.g. Grt-, Ep-bearing gneisses or schists) falls in the range of peak metamorphic temperatures of eclogites-facies conditions (~600-1000°C). Accordingly, partial melting of basic (and also more acid) lithologies is likely to be a common feature in nature. Detailed

studies on garnets from high-pressure terrains are necessary to prove whether the structures described above can be used as a key indicator of partial melting.

A detailed P-T path for eclogites in the Tromsø Nappe – tectonic implications for the uplift of HP units

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The Tromsø Nappe is the uppermost tectonic unit within the northern Scandinavian Caledonides. It contains eclogites, garnet peridotites and related HP rocks, variously retrograded and recrystallized to lower grade assemblages. Post eclogite partial melting of the mafic rocks yielding trondhjemitic/tonalitic leucosomes is a common feature. The Tromsø Nappe is separated from the underlying Skattøra migmatite complex (formed at ca 950 ^{o}C, 1.0 GPa; Selbekk) by a mylonitic thrust fault.

Micro-textures of metabasites within the Tromsø Nappe give detailed information about the P-T evolution. Inclusions of hornblende + plagioclase (An_{12}) + quartz apparently coexisted with the enclosing garnet in eclogite at 600-650 ^{o}C/1.45 GPa. Rare inclusions of omphacite (Jd_{53}) + albite in outer rim of garnet give slightly higher conditions (660 ^{o}C/1.6 GPa). Maximum P conditions based on coexisting garnet + omphacite + phengite + kyanite + quartz + $CaCO_3$ (arag?) are calculated to 2.8 ± 0.3 GPa at 725 ± 60 ^{o}C. Parallel needles of quartz in omphacite are observed in a few samples.

Post eclogite decomposition of high-P phases includes formation of symplectites of Na-augite + oligoclase after omphacite, and biotite + plagioclase after phengite. Three successive stages of symplectite formation – S1, S2 and S3 – after omphacite have been found. They are distinctly different in both size and composition of clinopyroxene and plagioclase lamellae. The width of the symplectite lamellae varies in the order S1 > S3 > S2, suggesting that $T_{S1}>T_{S3}>T_{S2}$. There is also a systematic decrease of X_{Jd} in the lamellae: $X_{JdS1}> X_{JdS2}> X_{JdS3}$ indicating a continuous pressure decrease. Composition of the corresponding plagioclase lamellae is fairly constant (An_{15}). A combination of the symplectite geothermometer of Joanny et al. (1991) and the clinopyroxene-plagioclase-quartz geobarometer of Holland (1979) yield T/P_{S1} = 840 ^{o}C/1.68GPa, T/P_{S2} = 700 ^{o}C/1.34GPa, and T/P_{S3} = 740 ^{o}C/1.19GPa, respectively.

Reaction rims of diopside + plagioclase between garnet and quartz are common, while corresponding rims of orthopyroxene + plagioclase are found in a couple of samples.
The post-symplectite stages included local hydration to hornblende + plagioclase ± epidote ± quartz assemblages, succeeded by neo-growth of garnet between hornblende and plagioclase and finally recrystallization to a mosaic textured assemblage of garnet + hornblende + plagioclase ± diopside ± epidote + quartz at ca. 650 ^{o}C, 1.0 GPa.

The inferred P-T path indicates an early subduction of continental crust to depths of ca. 90 – 95 km with temperatures around 725 ^{o}C, succeeded by initial uplift to about 55 km with a moderate temperature increase of ca. 100 ^{o}C. Partial melting of the eclogites was most probably associated this stage. Subsequent cooling towards a more normal geothermal gradient to ca. 700 ^{o}C at 45 km was succeeded by a new thermal pulse at a depth of about 40 km. The heat source most probably was the still very hot Skattøra migmatite complex, upon which the Tromsø nappe has been thrust. Later cooling and uplift accompanied with hydration to amphibolite facies assemblages preceded a new event of pressure increase and deformation resulting in total recrystallization at high amphibolite/HP granulite facies conditions. This

event may, speculatively, be attributed to a now totally removed tectonic unit being emplaced on top of the Tromsø nappe.

Prograde and retrograde evolution of garnet-bearing ultrabasites from the Tromsø Nappe, Northern Scandianvian Caledonides

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The Tromsø Nappe is the uppermost tectonic unit within the northern Scandinavian Caledonides. It contains eclogites, garnet peridotites and related HP rocks, variously retrograded and recrystallized to lower grade assemblages. Post eclogite partial melting of the mafic rocks yielding trondhjemitic/tonalitic leucosomes is a common feature. The Tromsø Nappe is separated from the underlying Skattøra migmatite complex by a mylonitic thrust fault.

Micro-textures of garnet-bearing ultrabasites within the Tromsø Nappe give detailed information about the P-T evolution. Large (up to 3 cm) porphyroblasts of garnet invariably contain inclusions of chlorite + pargasite. Additional inclusions comprise diopside and spinel. Spinel appears to change composition related to its position within garnet, showing an increase in $Fe^{2+}/(Fe^{2+}+Mg)$ and X_{Cr}, and a complementary decrease in X_{Al}, going from the central to the marginal parts of garnet. The variation in spinel composition during garnet growth thus indicates increasing T and P. Garnet is low in Cr, and vaguely zoned.
The apparent stable matrix assemblage was garnet + diopside + pargasite + olivine + enstatite? ± Cr-spinel. However, no orthopyroxene has so far been found in any samples. Diopside and pargasite included in garnet has a higher XMg# compared to matrix diopside. Post HP decomposition includes formation of hornblende + spinel symplectites after garnet, and radial growth of chlorite on garnet margins. Olivine is finally altered to talc and then serpentine + magnetite.

Preliminary T estimates are c 600 ^{o}C/1.6 GPa for inclusions of clinopyroxene and spinel in central parts of garnet, while a combination of garnet rim with matrix clinopyroxene and spinel in outermost rims of garnet indicate c. 760 ^{o}C/2.5 GPa.

The inferred mineralogical evolution of the garnet-bearing ultrabasic rocks show a close agreement to the P-T path deduced from eclogites within the Tromsø Nappe, pointing to an early subduction of continental crust to depths of ca. 90 – 95 km with temperatures around 700 - 750 ^{o}C, succeeded by uplift and decompression/hydration.

Exhumation processes: Normal faulting, ductile flow and erosion

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Deep-seated metamorphic rocks are found in the interior of many divergent and convergent orogens. Plate tectonics can account for high-pressure metamorphism by subduction and crustal thickening, but the return of metamorphosed crustal rocks back to the surface is a more complicated problem. In particular, we seek to know how various processes, such as normal faulting, ductile thinning, and erosion, contribute to the exhumation of metamorphic rocks, and what evidence can be used to distinguish between these different exhumation processes.

We review the characteristics of exhumation and exhumation processes in different tectonic settings. Continental rifts, such as the severely extended Basin-and-Range province, appear to exhume middle and upper crustal rocks, whereas continental collision zones are capable of exposing rocks from >125 km. An important distinction has to be made between settings in which metamorphic rocks were formed and exhumed early during the orogenic history when thermal gradients are on the order of 10-15°C km^{-1} (early exhumation) and settings in which exhumation mechanisms operate at high-T/P ratios during the late stages of an orogeny (late exhumation). Most of the exhumation of high-pressure rocks occurs during the early stages of orogeny, especially at the transition from subduction to continental collision. However, the processes that accomplish early exhumation are largely unknown. Extrusion in so-called Chemenda-type wedges has been invoked, but this is mechanism can probably operate only at depths of up to 40-50 km. Rheologic constraints make extrusion wedges in the deep crust at temperatures >600°C unlikely and therefore this mechanism is not capable for exhuming ultrahigh-pressure rocks. Late exhumation is easier to quantify and usually does not appear to result in >25 km of exhumation.

Rates of exhumation are widely used to distinguish between different exhumation processes for early and late exhumation. This approach is not diagnostic since erosion and normal faulting show the same range of exhumation rates, reaching maximum rates of 5-10 km Ma^{-1} for both processes. Low-angle normal faults are very problematic for exhuming metamorphic rocks efficiently because they have to slip at rates >20 km Ma^{-1}. Nonetheless, such great rates have been proposed for the Cretan detachment in the Aegean. In contrast, ductile thinning generally appears to operate at slower rates. The pattern of cooling ages can be used to distinguish between different exhumation processes. Normal faulting generally shows an asymmetric distribution of cooling ages, with an abrupt discontinuity at the causative fault, whereas erosional exhumation is characterised by a broad symmetric cooling-age pattern with few to no structural breaks.

We also consider the challenging problem of ultrahigh-pressure crustal rocks. Understanding the exhumation of these rocks requires that we first know where and how they were formed. One explanation is that metamorphism occurred within a thickened crustal root, but it does seem unlikely that the crust, including an eclogitised mafic lower crust, could get much greater than ~110 km while maintaining a reasonable Moho depth (≤70 km, assuming that the seismic Moho would be observed to lie above the eclogitised lower crust). Diamond-bearing crustal rocks cannot be explained by this scheme. The alternative is to accrete the upper 10-40 km of lithospheric mantle into the root. This scenario will provide sufficient pressures for

both coesite- and diamond-bearing eclogite-facies metamorphism, while maintaining a reasonable Moho depth (≤70 km) and reasonable mean topography (≤3 km). We speculate that the detachment and foundering of the mantle root may contribute to the exhumation of any crustal rocks contained within the mantle root. The most spectacular exposure of dense peridotite from depth >185 km as reported from Norway and density considerations strongly suggest that buoyancy does not appear to play an important role for the exhumation of regionally coherent belts of deeply buried rocks.

Tectono-stratigraphic and geochronologic keys to the kinematics of HP and UHP metamorphism in the Western Gneiss Region, Møre og Romsdal and Trondelag, Norway

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HP and UHP metamorphism and deformation in the region must be understood in terms of a great thrust orogen with allochthonous sheets transported 100's of kilometers onto the Fennoscandian continental margin. Allochthons differ in character, from fossilferous Cambro-Silurian cover and basement of proximal Fennoscandia, through Ordovician arc and ophiolite assemblages of Iapetus Ocean or its Laurentian margin, to clastic and carbonate assemblages from the Cambro-Ordovician passive margin of Laurentia. The assemblages are thickest and best characterized in foreland or tectonically high positions, but can be traced deep into the ductilely deformed hinterland where they may be only meters thick but provide key markers for kinematic analysis. Evidence for HP/UHP metamorphism is found only by "seeing through" effects of strong granulite- and amphibolite-facies overprinting and ductile deformation. UHP evidence includes quantitative phase petrology in relict assemblages in kyanite±phengite eclogites suggesting 30-40 kbar at ~800C, polycrystalline quartz pseudomorphs after coesite, coesite inclusions in zircon, microdiamonds, and quartz±hornblende rods in omphacite indicating former supersilicic vacancy pyroxene.

Precise U-Pb isotope dilution analyses of metamorphic zircon containing coesite inclusions at 402±2 Ma and zircon overgrowths on Proterozoic igneous baddeleyite at 401 ±2 Ma, all from mafic rocks, point to early Devonian HP/UHP recrystallization in the WGR. Surrounding and enclosing gneisses contain unreset to slightly reset Proterozoic igneous zircon and mildly to 100% reset titanite on a chord with lower intercept at 395±2 Ma, indicating contemporaneous termination of diffusional Pb loss over an enormous region. The ~400 Ma ages contrast with higher slices of the Seve Nappe with deformed pegmatites at 431.0 ±2.9 Ma and 422.7 ±1.8 Ma, cutting an older metamorphic fabric, and Iapetus arc volcanics and intrusives of the still higher Støren Nappe, lacking evidence for strong metamorphism since Ordovician to earliest Silurian (482-441 Ma) igneous emplacement . On Nordøyane, monazite geochronology by ion and electron probe in aluminous gneiss of a UHP upper tectonic plate above normal HP rocks indicates UHP metamorphism was 407 Ma or later, and amphibolite-facies overprint was active at 395 Ma. Emplacement of the UHP plate (125km) above the HP plate (60km) involved 65km of thrusting over ~6 m. y. at 10.9 mm/yr.

The present assemblage of slices with differing tectonostratigraphy, metamorphism and geochronology resulted from two processes: 1) Thrust imbrication related to northwestward subduction of Fennoscandia, in which faulting stepped toward the foreland, progressively involving more forward rocks in subduction. In the northeast (Trollheimen) part of the WGR, relatively late thrust doubling of Fennoscandian basement and Late Proterozoic cover occurred over a minimum distance of 40 km across strike. 2) Contemporaneous extensional faults gravitationally induced in the rising thrust stack, carrying materials from early higher thrust sheets away from cooler positions near the foreland and emplacing them against warmer deeper rocks in the hinterland, subsequently allowing these levels together to gain a

late ductile fabric in a field of sinistral transtension. Such relationships occur west of Trondheimsfjord where basement rocks with titanite 100% recrystallized at high T just before 395 Ma are now against Ordovician plutons, now gneisses, with nearly unreset Ordovician igneous titanite. Early on these faults were associated with deposition in extensional basins, where the best fossil age is Late Emsian (403-394 Ma), essentially overlapping times at greater depth of the last eclogite metamorphism and amphibolite-facies overprint.

Slabs and pods of garnet peridotite and pyroxenite, interpreted as Fennoscandian mantle lithosphere, occur widely associated with WGR basement. Some contain contain ~1-3% of pyroxene exsolution in garnet indicating a former majorite component and large exsolved aluminous orthopyroxene megacrysts. One contains microdiamond inclusions in spinel. We think these features are unrelated to Devonian metamorphism, but developed in a rising Mid-Proterozoic mantle plume at 1500-1400°C and 65 to 25 kbar that produced part of the subcontinental mantle of Proterozoic Fennoscandia. This mantle was brought near the surface during continental thinning related to the late Proterozoic formation of the Fennoscandian margin of Iapetus, and then was imbricated with Fennoscandian crust during Devonian subduction, locally receiving a secondary garnet-peridotite assemblage.

Interpretation of inclusions in kyanite-garnet gneiss: Fjørtoft, Western Norway

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A decade ago microdiamonds were discovered in kyanite-garnet-graphite gneiss, at Fjørtoft, using a total rock digestion process. More recently the island was mapped and geothermobarometry on a kyanite eclogite, containing polycrystalline pseudomorphs of coesite, yielded T = 820°C and P= 34-39 kbar, on the edge of the diamond stability field. Nevertheless there has been no record of microdiamonds in situ in a mineral host. We used the special rock polishing techniques employed at Bayreuth to test a number of specimens for the occurrence of microdiamonds. This permits location of microdiamonds over relative large areas on specially polished surfaces. At the same time attention was focused on some samples with garnets up to 5 cm in diameter, in the hopes that these would contain mineralogical relics from the UHP conditions under which these rocks were presumed to have equilibrated, despite a strong amphibolite-facies metamorphic overprint. Based on the present assemblage of quartz-kyanite-garnet-biotite-plagioclase-K-feldspar-rutile-graphite, it was postulated that under UHP conditions the rocks would have consisted of coesite-kyanite-garnet-phengite-jadeite-rutile± diamond. Unfortunately we could not obtain additional material from the samples digested earlier, though some of our samples do come from the same outcrop.

Despite careful work on 6-8 polished surfaces, covering both large garnets and fine-grained matrix, no traces of microdiamonds were found. Transmitted- and reflected-light examination of polished thin sections, including both large and small garnets, and qualitative SEM analyses, showed the following: 1) Numerous monocrystalline quartz grains inside garnet, but no recognizable polycrystlline quartz aggregates after coesite as found in the nearby kyanite eclogite; 2) Abundant inclusions of graphite plates; 3) Inclusions of colorless mica (still to be analyzed), commonly associated with kyanite and coarse rutile; 4) Fine colorless, low birefringent needles, suspected as jadeite, are kyanite; 5) Rounded high-relief, high-birefringent inclusions with white internal reflections suspected as titanite are Nb-rich rutile. This is distinct from coarse polycrystalline rutile as inclusions in garnet and in matrix, and monocrystalline rutile rods apparently exsolved from outer parts of garnet (see Langenhorst et al., this volume).

Accepting the correctness of the earlier reports of scarce microdiamond in these outcrops, we now would interpret the large garnets as having grown and included monocrystalline quartz, graphite, kyanite, white mica, and rutile in an amphibolite-facies prograde path well before reaching UHP conditions. Garnet zoning in a polished thin section remaining from the microdiamond-bearing sample shows an increase in Fe/(Fe+Mg) from core (0.65) to rim (0.77) that is consistent with diffusional exchange with biotite during cooling. The grossular (Xgr) content is flat in the cores (0.025) and increases toward the rims (0.10). This is interpreted as prograde growth zoning preserved as a result of slow diffusion of calcium. There is a slight decrease in grossular at extreme rims (0.055) that reflects slight diffusional modification of the profile during retrograde metamorphism. This information can be combined with previously reported U-Th-Pb ages of monazite in this sample. 407 Ma is the maximum age when monazite was included in garnet at the point where Xgr begins to increase, and 395 Ma was the time of partial retrograde equilibration at about 700°C, 11kbar. If correct, then the postulated UHP mineralogy would have appeared late and in the matrix

where most susceptible to later amphibolite-facies retrograding. We are currently examining the pattern of chemical zoning in the garnets with respect to the distribution of the three types of rutile, to learn more about metamorphic evolution.

U/Pb zircon ages from eclogites and ca. 400 Ma ultrahigh-pressure metamorphism in the Western Gneiss Region

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Understanding the formation and exhumation of the ultrahigh-pressure (UHP) rocks of western Norway hinges on precise determination of the time of eclogite recrystallization. Our study consists of SHRIMP analysis, in conjunction with cathodoluminescence (CL), of zircon from four UHP and high-pressure (HP) eclogites; and detailed TIMS analysis of zircon from two samples subjected to combined thermal annealing and multi-step chemical abrasion (CA). Zircon from the Flatraket eclogite yielded a 437–395 Ma range of apparently concordant SHRIMP ages, but without the necessary precision to discriminate between i) ongoing concordant growth; and ii) discordance due to a minor inherited component and metamorphism at the younger end of the age range. The observation of cores with distinctly stronger CL response in unanalyzed grains argues for the latter. CA/TIMS of two fractions yielded moderate Pb loss from the first (lowest T; "*A*") steps; possible minor Pb loss or minor growth at 400 Ma from the *B* steps; and a 407–404 Ma cluster of slightly discordant $^{238}U/^{206}Pb$ ages, most likely free from Pb loss, from the remaining steps. We interpret the latter to reflect incomplete recrystallization of inherited zircon, with possible new growth, at ca. 400–395 Ma. Alternatively, these ages may represent concordant growth at a mean age of 405 Ma, with apparent discordance due to intermediate daughter product effects. Zircon recrystallization under HP/UHP conditions is inferred from three lines of evidence: i) zircon occurs as inclusions in garnet, omphacite, phengite, breunnerite, dolomite, and quartz; ii) garnet included in zircon and matrix UHP garnet have similar compositions; and iii) chondrite-normalized ICP–MS analyses of the CA steps reveal small Eu anomalies and shallow HREE profiles, indicating zircon recrystallization in the presence of garnet and not plagioclase.
Zircon from the UHP Verpeneset eclogite contains ~10 ppm U, severely compromising SHRIMP precision. A weighted mean $^{238}U/^{206}Pb$ age of 403±21 Ma (95% confidence; MSWD=0.92; n=5) is geologically meaningful only if the data represent a single episode of concordant growth. In contrast, CL imagery reveals incomplete recrystallization of inherited zircon, CA/TIMS ages are Caledonian yet distinctly discordant, and steep HREE profiles indicate a component of inherited igneous zircon. Importantly, the Verpeneset CA/TIMS results are consistent with incomplete recrystallization at 400–395 Ma, but not with concordant growth at 405 Ma.

SHRIMP analysis of zircon from a coesite-bearing eclogite at Otnheim reveals considerable inheritance of *ca.* 950 Ma and 1.6 Ga components. Rare rims yield Caledonian ages, with one statistically concordant analysis at 410±11 Ma (1-sigma).

CL imagery and Th/U ratios show that zircon rims from a HP eclogite at Langenes formed by recrystallization of inherited zircon. Isotopic resetting was incomplete, yielding a poorly constrained SHRIMP lower intercept age of ~400 Ma.

Our preferred age of 400–395 Ma for the Flatraket eclogite is consistent with results from all our samples, and with previously reported U/Pb zircon ages from WGR eclogites. Four TIMS fractions from the Ulsteinvik eclogite yield ~400 Ma $^{238}U/^{206}Pb$ ages. Three of these fractions overlap concordia within error, and all four overlap our Flatraket *B* step results. Two TIMS fractions from the Sandviknaes eclogite are slightly discordant with a poorly constrained

lower intercept age of ~400 Ma. Additionally, monazite from a microdiamond-bearing gneiss at Fjørtoft yields a prograde age of ~407 Ma. In contrast, Sm/Nd mineral isochrons of HP and UHP eclogites of the WGR yield a range of apparent recrystallization ages from 447–407 Ma, indicating either prolonged metamorphism or variable isotopic disequilibrium. Of these, only two ages, 410±16 and 408±7 Ma, are derived from three-point isochrons (garnet–clinopyroxene–whole-rock). As at least three points are necessary to assess isotopic equilibrium, these ages must be considered more robust than the 425 Ma mean of multiple two-point isochrons. The discrepancy between the U/Pb and Sm/Nd ages may be explained by either the 1–2 % uncertainty in the ^{147}Sm decay constant, or recrystallization of garnet and clinopyroxene prior to zircon.

Our zircon age of ca. 400–395 Ma is significantly younger than the 425 Ma age often cited for western Norway eclogite recrystallization, implying faster rates of exhumation (~15 km/m.y.) and weakening the link between UHP metamorphism and ophiolite emplacement at 430–425 Ma.

Eclogite formation of felsic and mafic granulites from the southern part of the Western Gneiss Region

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Work in progress focuses on the partial eclogitization of felsic and mafic granulites on the island of Hisarøyna, in Gulen, Sogn & Fjordane. The island is situated in the gneiss culmination north of the Bergen Arcs Shear Zone (BASZ) and south of the Devonian Solund Basin. The northern part of the island is strongly affected by deformation and retrograde metamorphism related to top-to-the-west shearing along the Nordfjord Sogn Detachment Zone (NSDZ). The central part of the island is less affected by mylonitization along the NSDZ. Here we find a coarse- to medium grained granite, which is variably stretched in the east-west direction. This part of the island is also characterized by a complex of banded amphibolites, coarse-grained rutile-bearing kyanite-garnet-micaschist and quartzite. The complex locally contains pods of massive eclogite. These rocks are folded into a large-scale sheath-like structure forming the low-topography across the island. The southern part of the island is dominated by a banded, granulite facies complex in which felsic and mafic rocks alternate on a scale of centimetres to 10`s of meters. The granulite complex also includes a massive granite with characteristic blue quartz. The mafic protolith contain two pyroxenes (opx: $\approx En_{0.6}$; cpx: $\approx Wo_{0.44}En_{0.36}$), plagioclase, biotite and Fe-Ti oxides, while the felsic rocks consist of quartz, K-feldspar, plagioclase, biotite, garnet, oxides and locally ortho- and clinopyroxene. These rocks are fully, or for the most part partially eclogitizised. The granulites and eclogites are cut and retrograded by east-west trending amphibolite facies shear zones. The best-preserved eclogites and granulites are found in lenses between the shear zones. The partial eclogitization of the mafic rocks results in a metamorphic breakdown and clouding of plagioclase. Coronas of Na-rich pyroxene and garnet form around oxides and granulite facies pyroxenes. Some samples have a set of parallel micro-cracks that transect the granulite cpx. These cracks are decorated with eclogite facies minerals exemplified by extensive formation of atoll garnets and omphacite (Jd_{37}). We suggest that fracturing of the original minerals played an important part for enhancement of the eclogitization processes in these rocks. P-T estimates (cpx-gar) of eclogitization along the cracks give temperatures of ca 510°C and pressures (min) of ca 14 kbar. Fully eclogitizised samples of mafic rocks are dominated by common eclogite facies minerals such as omphasite, garnet and rutile, and they show an eclogite facies foliation. The felsic rocks on southern Hisarøy include both granites and gneisses of uncertain, but possibly metasedimentary origin. This rock is dominated by quartz, and also contains K-feldspar, garnet, biotite, muscovite and commonly zircons, in addition to remains of opx. At the scale of outcrop, pegmatite segregations are common and back-vein the mafic layers in the gneiss. The work demonstrates that the rocks on Hisarøy were metamorphosed at granulites facies prior to the Caledonian eclogitization. Similar granulites have been found in Sunnfjord and North of Sognesjøen. The Hisarøy granulites may thus be part of a larger granulite terrain, possibly of Svekonorvegian age. The granulite complex on Hisarøy was partly eclogitizised during the Caledonian event and addition of fluid along fracture appears to assist the reactions.

Metamorphic and fluid evolution of Ultra-high metamorphosed (UHP) crust of Tso-Morari region, Ladakh, Himalaya (India): Constraints from mineral chemistry and fluid inclusions

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The Tso-morari crystalline Complex(TMC) in eastern Ladakh ,India preserves the signature of ultrahigh-pressure metamorphism in the form of coesite-bearing eclogites. These eclogites occur as boudinns and lances in the kyanite-sillimanite grade of rocks.

The TMC eclogite contains essential mineral assemblage of garnet, omphacite, phengite, rutile , epidote. Coesite, talc,dolomite, magnesite, aragonite and Mg-calcite are also present as inclusion in the zoned garnet.Coesite-bearingg garnet has alamandine rich composition.Core has high Mn and low Mg whereas rim has the highest Mg. The UHP eclogite has undergone three stages of metamorphism, viz. prograde,peak and retrograde. The prograde assemblage is characterized by the presence of magnesite and quartz.At the ultrahigh pressure(27 Kbar) and temperature of 650^0C,this quartz transform into coesite. This is very well constrained by the presence of quartz,calcite and glauophane in the core to mantle part of coesite-bearing garnet.The peak metamorphism is characterized by the formation of coesite in garnet in co-existence of high Si-phengite, omphacite, magnesite, aragonite, dolomite, zoisite/clinozoisite, talc at a pressure of >40 Kbar and temperature of $>750^0$C. This is in agreement with the estimated peak pressure-temperature from phengite,jadeite barometry and garnet-clinopyroxene and garnet-phengite thermometry.The retrograde metamorphism is marked by the development of chlorite and chloritoid around garnet at a minimum pressure of 4-5 Kbar and temperature of $>500^0$C.

The five major types of fluid are identified by microthermometry. (1) N_2 rich (2) High salinie aqueous inclusion occur as primary inclusions in peak metamorphic mineral assemblages.(3) CH_4 rich,(4) CO_2 rich and (5) Low saline aqueous inclusions. N_2 rich and high salinity aqueous inclusions occur as primary inclusions in peak metamorphic mineral assemblages. CH_4 rich,CO_2 and low saline aqueous fluid inclusions , appear to be related to late structural features or traces of micro fractures accompanied by widespread retrogression. The syn-metamorphic fluid (N_2 and High-saline aqueous) could be remnants of pre-metamorphic fluid, which become modified through small-scale fluid-rock interaction. The source for N_2 from feldspar, which become unstable at the onset of eclogite facies metamorphism. The source high –saline fluid may be recycled sea-water because, it is Na-rich not Ca –rich. it can be envisaged that these fluids are inherited from pore fluid at the earth's surface, but with drastic modification through complicated small-scale fluid-rock interaction processes through prograde and peak metamorphic stages. CO_2 , CH_4 and low-saline fluids may have been introduced from external sources. These external sources were not present at a distant. The striking relation between CO_2 and CH_4 and carbonates shows that the scale of fluid movements may not be more than a few meters. This might also be the case for low saline fluid derived from enclosing gneisses as well as from other sources as the low-saline fluid is common in the rocks of upper continental crust.

The mineral assemblage in the UHP rocks reveals that prograde metamorphism started with the greenschist facies condition pass and finally reached to the coesite-eclogite facies passing through intermediate blueschist facies. The presence of these mineral assemblage indicate

deep subduction of Indian continental crust along with circulation of N_2 and high saline fluids in UHP condition and later on the introduction of carbonic and less saline fluid took place in the system during exhumation process of UHP rocks. The occurrence of such exotic mineral assemblage along with carbonic fluids indicates low-temperature subduction in the Himalaya.

Timing of dextral strike-slip shear zones in Danmarkshavn, North-East Greenland – implications for the exhumation of eclogites

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The North-East Greenland Eclogite Province (NEGEP) consists of mafic pods metamorphosed at eclogite facies conditions encased within orthogneiss that records retrograde amphibolite facies metamorphism. In the central portion of the NEGEP, the province is divided into 3 blocks by two N-S strike-slip deformation zones: the sinistral Storstrømmen shear zone and the dextral Germania Land deformation zone. The role of these major shear zones in the formation and exhumation of the eclogite province, if any, is not well understood. The present study attempts to establish the timing of the strike-slip deformation relative to the timing of eclogite facies metamorphism.

Mafic pods in the Danmarkshavn area (76°46'N, 18°40'W) typically occur as boudinaged layers, with the boudins stretched both vertically and parallel to the strike of the gneissosity in the adjacent wall rocks. Both the margins of the pods and the surrounding quartzofeldspathic gneisses experienced amphibolite facies metamorphism that presumably occurred during or after exhumation of the eclogite terrane. Pegmatites spatially associated with the mafic pods vary from 50 cm to 5 m wide and 1 to 7-10 m long. They are interpreted as syn-deformation melts that filled necks of individual boudins.

The gneisses are cut by NNW-striking strike-slip shear zones that are related to the Germania Land deformation zone. Individual shear zones vary from several centimeters to 5-6 meters in thickness and typically have strike lengths of more than 200 meters. A dextral sense of shear is defined by δ and σ porphyroclast asymmetry and the deflection of pre-existing foliation. The shear zones are formed by protomylonites and mylonites recording amphibolite to greenshist facies assemblages with recrystallized biotite, amphibole, feldspar, and quartz. Mineral stretching lineations are defined by feldspar and less commonly, horneblende. The lineations trend NNW-SSE, and plunge 5-10^0 both to the N and to the S, but predominantly to the N.

The shear zones are cross cut by E-W deformed and undeformed pegmatite bodies that vary from 5 to 100 m in width and 1 to 10 m in length. The E-W pegmatites are either associated with a new set of minor deformation zones cutting the earlier ones at an angle of almost 90^0, or the dextral shear zones are simply deflected by the emplacement of the pegmatites in flanking structures. U/Pb SHRIMP analyses on zircons from 2 separate pegmatites yield weighted mean $^{206}Pb/^{238}U$ ages of 345 +/- 5 and 332 +/- 6 Ma. This is distinctly younger than ages determined for amphibolite facies retrograde metamorphism of eclogite pod rims and pegmatite emplacement within boudin necks at approximately 370-380 Ma (McClelland and Gilotti, this volume).

On the basis of these results, dextral shear zones in the Danmarkshaven region, and by association the GLDZ, evolved between 370 and 330 Ma. The strike-slip deformation is then either related to a possible transpressive event responsible for the pervasive deformation of the gneisses and pre-dates the Carboniferous E-W extension and basin formation, or occurred some time between the pervasive deformation and the emplacement of the latest swarm of pegmatites. This implies that either the shear zones are unrelated to the exhumation of the HP

and UHP provinces, or that exhumation started during the transpressive event as vertical extrusion. In fact, although lineations in the shear zones are mostly sub-horizontal, 20% of the measured lineations show a plunge greater than 30^0. Sub-vertical stretching of garnet and kyanite was also observed within some of the eclogite pods in the area, and the boudins are flattened within the vertical gneissosity. Further analysis of the structural data combined with the new geochronological information presented here is necessary to resolve this conundrum.

Uplift history of Paleoproterozoic kyanite-eclogites from Yalumba Hill, Tanzania: Late-stage sapphirine and orthopyroxene bearing symplectites

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Yalumba Hill in the Usagaran Belt, adjoining the Tanzania Craton at its SE side, forms a spectacular outcrop of the oldest known eclogites (2 Ga) exposed in an orogenic belt [1]. Beside MORB-type eclogites, Ky + Opx bearing eclogites, Opx + Cpx bearing cumulate-type rocks and Ky + Kfs bearing metapelites occur which allow a detailed reconstruction of the P-T path in this old subduction zone.

In the Opx-Ky-eclogite, Spr-Spl-Crn-Pl-Mag bearing symplectites replace in part Ky and Opx-Pl ± Hbl symplectites and coronas were formed at the expense of Grt and Cpx. Both textures are commonly used to infer high, granulite-facies temperatures during decompression. However, both textures in a single rock seem to be very rare.

The earliest relics of the prograde evolution are preserved in the cumulate rock type in the form of Opx (and Cpx) inclusions in Grt. The low Al_2O_3 content (1.4 wt%) of this Opx in conjunction with Fe-Mg thermometry [2] point to 18 - 20kbar at 780 - 800°C during maximum subduction depth. The abundant Opx porphyroblasts of this rock type showing higher Al_2O_3 contents, obviously re-equilibrated subsequently during uplift and/or at higher temperatures. In the ky-eclogite the further uplift history is documented by the formation of an Opx corona and subsequent development of Opx-Pl ± Hbl symplectites around Grt in which the Al_2O_3 content of Opx continously increases from the outer corona with c. 2 wt% to about 3 wt% in the symplectitic Opx close to the relic Grt porphyroblast. Al-in-Opx barometry points to decompression from about 15 kbar to about 8 kbar, whereas one obtains with Grt-Opx-Pl-Qtz barometry [3] decompression from only 12 to 8 kbar during corona and symplectite formation. The temperature obtained for the latest Opx, formed near the present Grt rim, is still 630 - 670°C but must be regarded as a minimum temperature due to the possibility of cation exchange after its formation during further cooling.

The high Opx-Grt temperatures during uplift of the subduction zone rocks are in accordance with the formation of the slightly peraluminous Spr in symplectites replacing Ky. The high temperatures required for the formation of Spr + H_2O (c. 750°C at 8 kbar) may not have been attained by the Yalumba eclogites since a reduced a_{H2O} is indicated by the formation of late-stage Cl-SO_4 bearing Scp.

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Cathodoluminescence Petrography of UHP-metamorphic Rocks from Dora Maira/Western Alps, Kokchetav/Kazakhstan and Sulu/China

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Thin sections of ultrahigh pressure (UHP) metamorphic rocks from the Dora Maira Massif/Italy, Kokchetav Massif/Kazakhstan, and the Sulu region/China were investigated using a hot cathode cathodoluminescence (CL) technique. Coloured images of important but otherwise invisible growth features could be easily achieved within seconds. These features are correlated with chemical variations of minerals revealed by electron microprobe (EMP). In general, CL is induced by activator-elements (e.g. Mn^{2+} and REE) and lattice defects whereas so-called quencher-elements (mainly Fe^{2+}) reduce or even extinct luminescence. Since X-ray-intensity mapping images of minerals using the electron microprobe takes to 50 hours, the CL-method represents an ideal and rapid approach prior to chemical characterization.

Rock samples studied from Parigi, Dora Maira are pyrope quartzites and jadeite quartzites. Features observed in bluish luminescent garnets include small-scale oscillatory zoning patterns, changes in morphology during growth, and an increase in brightness from core to rim with an outermost late garnet generation lacking luminescence. Even kyanite (blue to red luminescence colours) reveals distinct growth zones. Due to mineral inclusion studies in combination with EMP-analyses it is possible to detect different kyanite-forming reactions, important for deriving a more accurate PT-path. Different crystallographical orientations of twinned kyanite result in various luminescence colours. Jadeite crystals (yellowish green luminescence) partly show a very irregular zonation which is not or only weakly developed using a polarizing microscope. SiO_2 phases are easily distinguished due to their different CL-colours (coesite: bluish-green, quartz: dark red to violet, chalcedony: yellow). Accessory zircon shows complex zonations with bright to dark blue and partly orange luminescent colours.

Diamondiferous carbonate-bearing garnet-pyroxene rocks from the Kokchetav Massiv contain brownish luminescent garnet crystals which reveal complex and irregular growth structures. In addition, some garnets contain different sytems of cracks which were partly annealed by a later garnet generation which lacks luminescence. Exsolution textures of dolomite within Mg-bearing calcite are detected by their different CL-colours (dolomite: dark red, Mg-calcite: orange). Microprobe analyses proved yellow luminescent carbonates in talc-bearing pseudomorphs after forsterite to be nearly Mg-free $CaCO_3$. Pyroxene displays complex zonation patterns (green to blue luminescence) and - to some extent - exsolution-textures of K-feldspar (blue). Accessory luminescent minerals like diamond (greenish blue and partly zoned), zircon (blue), and apatite (green) are easily identified in thin section even if they occur in very small abundances.

Jadeite-kyanite-quartz rocks from Maobei near the CCSD drill site contain red to blue luminescent kyanites some of which display twinning features. Each twin individual, like

those from Dora Maira, is characterized by a different luminescence colour. Various kyanites show a concentric zonation with bluish-red luminescent cores fading into red rims. Jadeitic pyroxenes are partly zoned; they typically reveal yellowish green luminescence colours similar to those from Dora Maira. Apatite (orange CL) and zircon (bright bluish CL) are accessories.

The present results demonstrate the advantages using a “hot cathode” CL microscope, in particular in conjunction with EMP-studies for petrography of UHP metamorphic rocks. Internal structures of minerals like small-scale growth zoning, inhomogeneities, exsolution lamellae, dissolution and deformational effects can be made visible within seconds. Many of those specific features could easily have become overlooked without applying CL microscopy.

Although being mainly descriptive, the conclusions drawn above open new avenues for petrological applications. The knowledge of detailed structural characteristics of rock-forming minerals has an invaluable impact to the more precise and detailed derivation of PT-paths and thus to the evolution of geodynamic processes with any metamorphic rocks involved. Thus, we propose that the CL-technique should be used more intensively for routine investigations of thin sections as a pathfinder prior to chemical characterization by EMP.

Subduction-driven model of thickening and synconvergent exhumation of HP rocks: Andean hot type orogeny in Variscan belt

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New geodynamic model is presented demonstrating that the Devonian subduction generates thermal softening of continetal crust in arc and back arc region and is a prerequisite for the formation of an exceptionally thick and hot orogenic root during Carboniferous times. Thermal weakening by continuous magmatic underplating in arc/.back arc regions permits burial to 70 - 80 km in time periods of about 20 – 30 Myr and exhumation from these depths in less than 10 Myr. Example from the eastern Variscan Belt, Bohemian Massif, Czech Republic, is based on field geology, petrology of metamorphic rocks and detailed U-Pb, Pb-Pb zircon geochronology. It describes an evolution from (I) Devonian subduction/obduction metamorphism, sedimentation and magmatism in the arc region and back arc extension, (II) Carboniferous compression leading to deformation at both supracrustal and lower crustal levels, thickening of the crust and eclogite to HP granulite-facies metamorphism, followed by (III) syn-convergent but localised exhumation associated with widespread dehydration melting. The existing U-Pb data constrain this evolution to no more than 40-30 Myr. Thermorheological 2D modelling starts from a hot thinned to standard crust forming a wide orogenic root within 20 Myr at a maximum of 70 – 80 km depth, and subsequent exhumation by synconvergent extrusion to depths of about 30 km within 10 Myr. The model explains formation of orogenic root as a thermorheological process linked to dynamics of subduction and without needing to involve an external heat source from the mantle during late stages of thickening. It presents a new explanation of the high-temperature high-pressure and low-pressure conditions typical of the Variscan orogeny. Finaly, the late exhumation stages are related by slab pull, leading toroll-back effect in thickened domain, which generates heterogeneous extension. This tectonic switching from compression to extension is associated with activation of lithospheric transfer faults along which deepest mantle and lower crustal rocks were exhumed at along 330-320 Ma.

The first example of Neoproterozoic eclogites from the Central Asiatic belt

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We report the first finding of neoproterozoic eclogites from the Central Asiatic belt (Northern Muyia Block, Eastern Siberia). The eclogites occur in the form of numerous bodies up to 20 meters in size within garnet-biotite gneisses. The whole block occupies the area approximately 300 km^2. Primary phases observed in eclogites are garnet, omphacite, quartz, amphibole, phengite and zoisite. Garnets (Xprp = 0,11-0,29) in eclogites are weekly zoned with decreasing of Ca and increasing of Mg/Fe ratio from core to rim. Garnets may contain minute inclusions of rutile, titanite, amphibole, zoisite, and phengite. Omphacite (Xjd = 0,3-0,45) is replaced by amphibole and pyroxene-plagioclase symplectite. According to our data equilibrium temperature of the studied eclogites varies within 670-740^{0}C. Taking into account that we can estimate only lower pressure limit of pressure using jadeite component in omphacite (14 kbar) the upper limit is unknown. Based on the major elements contents we can conclude that of basic composition relating to tholeiite series were the eclogites protoliths. Trace and REE elements data suggest that oceanic basalt of P-and T- types can be considered the protholits of eclogites. Fluid inclusions were studied by Raman-spectroscopy and microthermometry in minerals from eclogites and country rocks. Single-phase inclusions of liquid N_2 (density 0,77 to 0,81 g/cm^3) are typical of garnet and quartz from eclogites, they occur more seldom in the gneisses. Raman data confirm that early inclusions contain typically pure nitrogen, sometimes mixed with minor quantities of methane (up to 4,9 mole%). Single phase inclusions of liquid CO_2 are most typical of the quartz in the gneisses. Lowest homogenization temperature (-36 to -46^{0}C) corresponding to highest densities (1,11 to 1,17 g/cm^3) are observed in early inclusions. For a reference temperature of 740^{0}C, pressure deduced from isochors corresponding to maximum density N_2 isochors in the eclogites and CO_2 in gneisses are in fair agreement: 9,0-9,5 kbar for the eclogites, 8-8,5 kbar for the host rocks. Eclogites samples that underwent retrograde metamorphism to the lesser degree as well as host gneisses were taken for isotopic study. Sm-Nd method is used to date eclogites and country gneisses. The whole rock –garnet-omphacite Sm-Nd isochron for the eclogite yields the age of 631 ± 17 Ma (MSWD= 0,04). The garnet-biotite gneisses yields the whole rock-garnet and magnetite age of 636 ± 8,9 Ma (MSWD = 1,42). Initial ε_{Nd} values for eclogite and gneisses are +7,2 and -0,18 respectevely.

Experimental modeling of diamond formation in dolomite marbles of Kumdy-Kol diamond deposit

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Kokchetav massif (Northern Kazakhstan) is the type locality of ultra-high pressure (UHP) diamond-bearing metamorphic rocks. Four types of diamond-bearing rocks have been recognized in the Kumdy-Kol microdiamond locality of the Kokchetav massif: garnet-biotite-gneiss, garnet-pyroxene-quartz rock, garnet-pyroxene rock, and garnet-pyroxene-carbonate rock (dolomite marble).

Although investigators have obtained a lot of data, several questions have not been solved yet, such as: 1) At which stage of metamorphism the diamonds crystallized?; 2) Does the composition of the rock correspond to that of diamond crystallization medium?; 3) Why the microdiamonds are unevenly distributed in the metamorphic rocks? To solve these questions the authors have performed traditional mineralogical and petrographic studies and experimental modeling of microdiamond crystallization processes in dolomite marbles. A specific feature of dolomite marble is an extremely high content of microdiamonds – up to several thousand carats per metric ton. Experiments were performed using a high-pressure apparatus of a “split –sphere” type.

After the experiment at P = 5.7 GPa and T = 1420 C, dolomite, clinopyroxene, garnet, graphite, and diamond were recognized in the specimen by means of X-ray analysis. The phase composition drastically differs from the initial one. The major part of specimen is a fine-crystalline aggregate composed of quenched phases, dolomite and clinopyroxene. The garnet crystals contain inclusions of two types: numerous black platy crystals of graphite up to 50 micrometers in size (identified by Raman spectroscopy) and single melt inclusions up to 80-100 micrometers in size. Melt inclusions have been also discovered in pyroxene and newly-formed coesite. The melt inclusions represent a crystallized carbonatite melt, and their composition varies from point to point within inclusions. Compared to the initial composition the melt has low Si and high Fe/Mg and K. Besides, the melt has a higher Ca/Mg compared to the dolomite from the rock. The Mg-poorest melt inclusions have been found in newly formed coesite, where the influence of the Mg-rich matrix was minimal. Newly formed diamond crystals (up to 100 micrometers in size) were observed exclusively in the form of octahedrons on the walls of the PT ampoule and immediately in the carbonate-silicate fine-crystalline aggregate at the contact with graphite.

According to X-ray data, the specimen after the experiment at P =7 GPa and T=1700°C mainly consists of dolomite and also contains clinopyroxene, garnet and diamond On close examination, abundant inclusions of octahedral diamond crystals about 5-10 micrometers in size and their intergrowths were found in the garnets. Also some garnets contained single melt inclusions as well as melt inclusions with diamond.

The performed experiments, investigations of microdiamonds and mineralogical studies of garnet-pyroxene and dolomite marble allowed several conclusions.

The bulk content of K_2O in pyroxene from carbonate rocks ranges from 0.5 to 1.5 wt.%. The pyroxene used in the experiment contains 0.5 wt.% in K_2O. Newly formed pyroxene contain less 0.07 wt.% K_2O. Carbonatite melt inclusions contain about 0.7 wt.% K_2O. The

melt/pyroxene partition coefficient for K exceeds 10 and therefore explains the low K_2O content of the synthesized pyroxene. As mentioned above, the carbonatite melt contains about 0.7 wt.% K_2O. Pyroxene in equilibrium with such a melt should contain less than 0.07 wt.% K_2O, that accords well with the obtained results. Therefore, we assume that the composition of the rock used in the experiment may be not absolutely the same as that of the medium of pyroxene crystallization under UHP conditions. We suggest that hydrous fluid was removed from carbonate and garnet-pyroxene rocks.

The natural garnets from Kumdy-Kol diamond-bearing rocks and eclogites contain no majorite. The synthesized garnet in association with carbonate contains 3% majorite and that in association with coesite contains 4% majorite. The experimental constrains show that the pressure of metamorphism was less than 50 kbar.

Thus, based on the obtained data we suggest that diamond in the dolomite marble crystallized from a carbonatite melt in equilibrium with K-rich fluid. The occurrence of diamond-bearing carbonate rocks supports a possibility of carbonate subduction to mantle depths in the diamond stability field. Those deeply subducted carbonate rocks can be a potential source of high-K fluids similar to those found in fluid inclusions in diamonds from kimberlites.

Carbon minerals at ultrahigh- and high-pressure metamorphic localities

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For understanding of high and ultrahigh metamorphism processes it is important to study not only microdiamonds but also carbon mineralization in whole. Carbon (graphite) substance is spreaded much wider and it gains typomorphic singularities under action of ultrahigh and high P and T.

We have investigated graphite-containing eclogite-like rocks (Ural, Russia), granulite and amphibolite (Kola peninsula, Russia), carbon-containing dynamoshales (Ural, Russia). The metamorphic rocks in these objects have undergone action of high and ultrahigh pressure and some of them at high temperature, which have reduced morphological, structural and phase transformations of carbon substance to formation of microdiamonds and graphite mineralization with typomorphic singularities likely the graphite of diamond association in the Kumdikol deposit of microdiamonds, Kazakhstan (Shumilova T.G., 1996).

At the zone of eclogitization except for microdiamonds the carbyne-like carbon and its pseudomorphes after diamond were found out at first in the all world. One of singularities of graphite transformation is the formation of current forms of graphite, wire and fibrous-like forms of graphite isolations. The some hedgehog-like forms of graphite were detected which testified to microlocal thermal explosions with separation of a gas phase. The realization of X-ray researches by the monocrystalline and powder analyses has allowed to reveal the following tendency - for the high stages of metamorphism at increasing of modification degree of rocks, graphite exhibits the tendency to an essential modification of basic interplanar distance (002), emerging of additional carbon phases.

As for graphites of amphibolite-granulite stage of metamorphism, despite of large graphite selections, their polycrystalline structure with the crystallite sizes about 10 mkm is observed; diminution of the basic distance accords up to 0,331 nm and its magnification – up to 0,343 nm; and also turns of graphite monocrystalline blocks are usual on an angle up to 25^0. Presence of lonsdaleite, chaoite, carbyne and monocrystal of cubic graphite were found out in graphite of the same rocks (Shumilova et.al., 2002). According to the data of X-ray method chaoite occurs within graphite particles as different oriented crystallites with the dimensionality about 10 mkm.

At the zone of boundinage carbon-containing dynamoshales indications of the carbyne forms presence in carbon and disordered graphite were found out. Thus, the obtained mineralogical testimonies show indications of processes of graphite flow with its partial melting in the intensively metamorphosed rocks. The earlier theoretical and experimental synthesis researches had shown, that in similar conditions at outcome of local thermal explosions in graphite the pressure could be created up to 60 kBar, and nanodispersive diamonds and diamond-like carbon could be formed. The find of cubic graphite confirms a real possibility of local ultrahigh pressure in graphite of granulite can up to 150-300 kBar (Shumilova et.al., 2002).

Research of phase transformations and typomorphic singularities of carbon mineralization, suffered action of ultrahigh pressure metamorphism, can be used for prediction of microdiamonds (Shumilova T.G., 1997) and for geological-structural reconstructions.

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Experimental studies of the Verpeneset eclogite from 10-35 kbar with emphasis on the supersolidus phase relations to zoisite

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Major crustal thickening during orogeny is generally followed by catastrophic collaps of the orogen and exhumation of high and ultra-high pressure (UHP) rocks. During exhumation, the UHP rocks may follow P-T-t paths that overstep the solidus in the presence of a hydrous fluid phase, and in some cases probably the zoisite dehydration-melting solidus. Evidence for this is given by geothermometry, modelling and the actual presence of syn-exhumation felsic leucosomes and pegmatite dykes in some exhumed terrains (e.g. Western gneisss region, Tromsø nappe). The formation of partial melts may significantly lower the rheological strength of the crust and may thus help to explain the very fast exhumation of many UHP terrains.

In order to better understand partial melting of eclogite during UHP conditions and during subsequent exhumation, piston cylinder experiments under fluid-absent conditions and with variable amounts of added water (1, 2, 4, 6, 8, 10 wt%) have been performed on the zoisite-bearing Verpenesset eclogite at 35, 27, 21, 15 and 10 kbar. Partial melting occurs at temperatures that can be reached during exhumation if small amounts of water are present (4 wt%). The composition of the partial melts (tonalite-trondhjemite-granodiorite) and the solid residues vary significantly with pressure. Based on the residual assemblages produced in the melting experiments (35 kbar: work in progress, 27 and 21 kbar: cpx-zoi-gt, 15 kbar: cpx-hbl-zoi-gt, 10 kbar: cpx-hbl-zoi-pl), melts formed by melting of mafic rocks rocks during an exhumation event should show a range of major and trace element compositions.

The experiments at and below 27 kbar show that zoisite is an important residual phase at relevant temperatures, and its thermal stability increases with decreasing amount of added water. Experiments at 35 kbar are currently being performed. The highest thermal stability is 950°C at 21 kbar, 2% added water. The widespread crystallization of zoisite suggests that melts formed during exhumation of eclogite should generally be Sr-poor, despite the absence of residual plagioclase. In the present bulk composition, zoisite is stable to higher pressures than amphibole, confirming that the formation of zoisite is an important way of transporting water to deep crustal levels and also in subduction zones.

Microdiamond and exsolved structures in garnet-peridotite in the North Qaidam, Northern Tibet: implications for ultra-deep origination (>200 km)

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The North Qaidam is a newly identified Paleozoic coesite-bearing UHP belt in the northern Tibet, NW China (Yang et al., 2001; Song et al., 2003). The Luliangshan garnet peridotite massif was first reported by Yang and Deng (1994) in this UHP Belt. It occurs as lensoid block in quartzo-feldspathic gneisses and occupies an area of about 500 m × 800 m. Three types of rocks have been recognized in the field; this includes garnet lherzolite, garnet or garnet-free dunite and garnet pyroxenite. The former two types display clear interlayering structure in different scales determined by variations in content of olivine and pyroxene. Garnet pyroxenite occurs as vein-like block and is unconformable with the layer of garnet peridotite. No eclogite was found to intercalate in or interlayer with the peridotite. Exsolved structures have been observed in garnet and olivine within the garnet-lherzolite. Exsolutions in garnets are densely packed rods of rutile, two pyroxenes and two kinds of sodic amphiboles, and in olivines, ilmenite and chromian spinel. The two pyroxene exsolutions suggest the existence of original majoritic (or supersilicic) garnets that are only stable at depths greater than 150 km. The rutile and sodic amphibole rods, on the other hand, reveal that the original garnet contains high concentrations of Ti, Na and hydroxyl. On the basis of estimation of Ti and Na content, we interpret that the original garnet formed at the pressure of above 7 GPa. This interpretation is also supported by the occurrence of high concentrations of ilmenite and Cr-spinel precipitates in olivines in the same garnet lherzolite, although the ultra-deep origin (> 300 km) remains controversy, and by microdiamond in zircon separates from garnet lherzolite. Furthermore, the geotheromobarometric calculation (O'Neill and Wood 1979; Brey and Köhler 1990) yields P-T conditions of T = 920-1040 ºC and P = 5.5-6.7 GPa, which is consistent with our estimation based on the exsolved structures. Therefore, it is reasonable to conclude that the garnet peridotite body in the North Qaidam UHP belt is originated at mantle depths of greater than 200 km.

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On microstructural methods to obtain pressure-temperature estimates from relic majoritic garnet microstructures

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Within orogenic garnet peridotites from Otrøy, W Norway, centimeter-sized garnets have been reported containing relic majoritic garnet microstructures within residual peridotite (Van Roermund & Drury, 1998). Similar garnet microstructures have been reported from garnet websterites (Terry et al., 1999) and garnet (clino-)pyroxenites (Spengler et al., 2002). The latter occur as cm-scale layers within the Raudhaugene garnet peridotite body, Otrøy, have sharp contacts with their surroundings and interpreted to reflect HP basic melts refertilising the residual harzburgites and dunites during Proterozoic times (Brueckner & Medaris, 2000). In addition these garnet pyroxenites contain microstructural evidence of the existence of former (though late) Ti-clinohumite. Here we report the results of a LM, SEM, EMPA (including wide beam mappings), LA-ICP-MS and 2D digital image analysis on exsolved pyroxene from garnet microstructures from the Raudhaugene garnet-pyroxenites. The aim was to develop and test two independent microstructural methods that can be used to determine metamorphic pressure at the time of majoritic garnet formation.

The garnet pyroxenite has a characteristic porphyroclastic texture in which M_1 garnet- and pyroxene clasts float in a M_2 matrix of garnet, clinopyroxene, amphibole ± olivine (containing symplectic intergrowths of olivine and ilmenite/rutile). M_1 garnets contain oriented precipitates of two pyroxenes - predominantly clinopyroxene. No detectable chemical differences were found between M_1 and M_2 garnets, however M_2 garnets close to M_2 olivines are enriched in Cr. M_1 clinopyroxene has low Ca (0.836 c.p.f.u) and 0.119 Al. M_2 Cpx has 0.880 c.p.f.u. and 0.047 Al. EMP and LA-ICP-MS line-scans across M1 and M2 garnets are uniformly flat.

Garnet 1 core areas, covering several pyroxene-precipitates and up to 32400μm^2 in size, were selected for EMP mapping (15-20kV, 5-10µm beam size, counting times between 20-50sec, spacing 6-12µm). The results, after integrating 225-900 measurements plus a statistical accuracy correction, indicate that the former majoritic garnet had a silicon-component between 3.010±0.004 and 3.019±0.007 c.p.f.u.

Alternatively 2D image analysis of the same M_1 garnet core areas revealed 1.04±0.13 to 1.80±0.23 vol% of precipitated pyroxene. This corresponds to a recalculated garnet-silicon component between 3.009±0.001 and 3.015±0.002 c.p.f.u. In addition the 2D spatial distribution analysis was extended to garnet core areas that were as large as 16 times the size of the former, resulting in a mean garnet-silicon component of 0.8±0.2 vol% of precipitated pyroxene corresponding to 3.007±0.002 c.p.f.u..

PT estimates of 1160-1290°C and 3.5-4.0GPa were obtained, using the thermodynamic model for the CMAS system of Gasparik (2000) in combination with the lowest garnet Si value (3.007 c.p.f.u.) and M_1 Cpx-core compositions. M_1 clinopyroxene cores have continuous Ca and Al zoning, indicating that temperature estimates are likely to be minimum values. Increasing Ca contents, from core to rim, within larger M_1 clinopyroxenes is consistent with a temperature drop to about 1000-900°C (Gasparik, 2000). In contrast temperature estimates, using Harley (1984) and Krogh Ravna (2000) grt-pyr Fe-Mg exchange thermometers, range

between 550 and 750°C indicating prolonged Fe-Mg diffusional exchange between these two phases.

PT estimates for the M2 assemblage are in the range of 1.0-2.5GPa and 550-750°C and interpreted to be Caledonian.

To summarize: Two different methods have been used to calculate the Si-content of the majoritic garnet. Both methods gave similar and overlapping results (within the limits of each method). The 2D image analysis technique is however much preferred. It is very simple and more reliable due to smaller errors involved and the capability to take the spatial precipitate distribution into consideration.

If the minimum temperature estimates, derived from the garnet pyroxenites, represents "true" metamorphic conditions it can be concluded that the Raudhaugene garnet peridotite experienced, after initial refertilisation, UHP conditions at 3.5-4.0GPa and 1160-1290°C. The age of this metamorphic event is however not known.

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A mechanism for syn-convergent exhumation of HP granulites in the Bohemian Massif, Czech Republic: Geochronological, structural and petrological constraints

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The exhumation of omphacite bearing granulites at the eastern margin of the Bohemian Massif occurred in two phases. The first event is characterized by elevation of HP rocks due to vertical channel flow driven by lateral compression. This vertical extrusion is documented by structural data namely by homogeneous vertical fabric developed in the 2 km wide belt of intermediate HP granulite belt (peak conditions ~18kb/800°C). The vertical fabric was later reworked by shear zones, which make a positive fan–like structure in migmatitic orthogneiss rimming the granulite belt. The assemblages associated to the formation of structural fan and indicate its formation in the middle crust under amphibolite facies conditions (10kbar/700°C). These data document vertical ascent of HP rocks from a depth of 65 km to 35 km along viscous channel only few km wide. We assume that U-Pb and Pb-Pb single zircon age of 345 to 341 Ma date peak metamorphic conditions. The second phase of exhumation was associated with activation of transpressional shear zones along boundary of adjacent rigid indenting plate at a depth of 35 – 30 km. This event was associated with syntectonic intrusion, at 339-345 Ma, of tonalite sill emplaced at crustal depth of 25 km. The time required for cooling of the sill as well as for heating of country rocks brackets this evolution into max. 25000 years. Therefore, similar ages of crystallization for the tonalite magma and of the peak of granulite metamorphism suggest a very short exhumation period, limited by the analytical errors of dating methods. Our calculation and numerical modelling suggest that the initial exhumation rate during vertical extrusion was 7 mm/yr, followed by exhumation rate of 24-40mm/yr during subsequent uplift along transpressional shear zone. This work also document transition from deep pure shear regime to strong deformation partitioning at mid crustal levels during compression driven exhumation of HP granulites.

Pre-collisional high pressure metamorphism and nappe tectonics at active continental margins: a numerical simulation

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Studies on HP and UHP metamorphic rocks exposed in collisional belts have shown that these units (1) are derived from both continental and oceanic crust, being intermingled on the length scale of nappes, (2) are frequently associated with hydrated peridotites, (3) reveal a variable P-T-t record, with (4) narrow time constraints indicating that exhumation rates can be on the order of plate velocity. Their (micro)structural record indicates that the deformation inherent in their burial and exhumation must have been highly localized in low-viscosity shear zones, for which some kind of dissolution precipitation creep or fluid assisted granular flow and Newtonian behaviour is anticipated. The P-T-paths, the restricted size of the UHP metamorphic slices, and the narrow time constraints favour tectonic models that involve exhumation by forced flow in a subduction channel. Using a set of appropriate flow laws for different crustal and mantle materials, and including progressive hydration of the mantle wedge, we have extended our previous model of a subduction channel (Gerya et al. 2002, Tectonics) to an active continental margin.

Our 2D-simulation shows the following characteristics. Within a few million years from the onset of subduction, subduction erosion starts to remove continental crust from the front of the upper plate. Most of this material is transferred to beneath the frontal part of the forearc, where former upper and lower continental crust becomes wound up in a marble-cake like fashion forming a wide wedge reaching a depth of about 50 to 70 km. Minor amounts of continental crust are carried further down, to depths of 100 km and more, into the narrowing subduction channel and partly return by forced flow, mixing up with material derived from the subducted oceanic crust and the hydrated mantle at the hanging wall. These returning HP or UHP metamorphic slices become extruded from the subduction channel at the landward side of the marble cake wedge. Controlled by the strength of the overlying continental lid, both the wedge and the landward HP and UHP metamorphic megascale melange progressively warp up and eventually become exposed by erosion. After 30 million years of subduction with a rate of 2 cm/year an active continental margin structure with four distict zones has developed, which are (landwards from the trench):

A) Accretionary complex of low grade metamorphic sedimentary material
B) Wedge of deformed continental crust, with medium grade HP metamorphic overprint, wound up and stretched in a marble cake fashion to appear as nappes with alternating upper and lower crustal provenience
C) Megascale melange composed of HP and UHP metamorphic oceanic and continental crust, and hydrated mantle, all extruded from the subduction channel
D) Upward tilted frontal part of the remaining lid, with exposed deeper levels of the overriding continental crust juxtaposed against zone C.

Comparing the width and spatial arrangement of these zones, the provenience and the inferred structural and petrologic record of the respective rocks, and the simulated P-T-paths, with the Alps yields a remarkable similarity. Hence, if the assumptions underlying the setup of the numerical experiment and the specific choice of parameters are realistic, the results would lead to the following conclusions:

(1) High pressure metamorphic continental crust in orogenic belts needs not be ascribed to the downgoing plate, but can be derived by subduction erosion from the active continental margin; hence, (U)HP metamorphism of continental material needs not indicate collision.
(2) Large parts of the material removed by subduction erosion become wound up in a marble cake fashion in a broad wedge beneath the forearc, forming alternating nappes of lower and upper crustal provenience.
(3) Material carried further down into the subduction channel mixes up with oceanic and hydrated mantle material and partly returns by forced flow. It becomes extruded on the landward side of the marble cake wedge, forming a megascale melange of HP and UHP nappes with contrasting P-T-paths.
(4) The kinematic patterns arising in our simulations suggest that paleogeographic reconstructions based on the vertical sequence of nappes in orogenic belts may need critical reevaluation.
(5) Finally, the internal nappe structure of an orogenic belt - like the Alps - may develop largely prior to collision, with overprint during collision largely restricted to the foremost forearc and a region of backthrusting.

Microstructures of coesite

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Coesite is the index mineral of ultrahigh pressure metamorphism (UHPM). In natural UHPM rocks it has been identified as single crystal inclusions in various host minerals. Rarely it has been observed in contact with more than one other mineral phase or grain, in the so-called "matrix" of the UHPM rock. The preserved coesite crystals reveal partial transformation to fine-grained quartz along their original interphase boundaries and along intragranular cracks. So far, neither preserved interphase boundaries between coesite and other minerals stable at UHPM, nor coesite grain boundaries (apart from rare twin boundaries) have been observed in natural rocks. Here we illustrate characteristic microstructures of coesite developed in laboratory experiments by optical micrographs, SEM, and TEM images. The experiments (carried out at our institute over the last decade) comprise synthesis of coesite aggregates from a silica glass precursor, static annealing of aggregates, deformation of single-phase coesite polycrystalline aggregates in the plasticity and dislocation creep regimes, and crystallization of coesite in partially molten polyphase aggregates of natural rock composition.We expect that – on principle - the microstructures attained in our experiments correspond to those developed in natural coesitite and coesite-bearing rocks at UHPM at comparable conditions. Although the chance to find preserved polycrystalline coesite in exhumed UHPM rocks in nature is rated very low, due to the favourable kinetics of the coesite to quartz transformation, original coesite microstructures may be reflected by certain microstructural features of quartz formed after coesite.

Coesite is monoclinic (point group 2/m; space group B2/b) with a structure characterized by rings of four tetrahedra. The optical data are $n_{\square}$ = 1.5967, $n_{\square}$ = 1.5974, $n_{\square}$ = 1.6012, with $n_{\square}$ // b, and angles between $n_{\square}$ and c of 4 to 6°, and between $n_{\square}$ and a of 24 to 26°. Predominant crystal faces are (010), {130}, and (001), with a tabular shape parallel (010). In annealed aggregates the shape of the coesite grains is largely controlled by unilaterally rational high angle grain boundaries, with grain shapes from isometric to tabular after (010). A foam structure with simply curved or plane high angle grain boundaries meeting at angles of about 120° at grain edges only develops at temperatures above 1100°C, when the anisotropy of interfacial free energy becomes insignificant [1]. As this effect is not time-dependent, normal grain growth driven by the reduction of the interfacial free energy for coesite is predicted to be restricted to very high temperatures. Microstructures reflecting a foam structure of coesite, notwithstanding its later transformation to quartz, would thus imply very high temperatures. Deformation experiments on coesite aggregates at strain rates of 10^{-4} to 10^{-7} s^{-1} and temperatures of 800 to 1100°C [2] produced microstructures similar to those of quartz, apart from the effects of the marked anisotropy of interfacial free energy. At low temperatures and high flow stress in the regime of plasticity, the crystals are inhomogeneously deformed by glide on (010) and show deformation lamellae. At higher temperatures and lower stresses, in the regime of dislocation creep, migration recrystallization causes bulging of the high angle grain boundaries and recovery leads to formation of subgrains. A pronounced crystallographic preferred orientation (CPO) consistent with the predominant glide system (010)[001] is well developed in experiments at 1000°C. Anisotropic growth during recrystallization enhances the shape preferred orientation (SPO) of the tabular grains with (010) normal to the direction of shortening. In coesitite experimentally deformed at temperatures of 1100°C, these characteristic CPO and SPO are less well developed, which may be caused by the activation

of additional glide systems and/or the vanishing anisotropy of interfacial free energy with diminishing tendency of tabular growth. We do not know whether the dislocation creep microstructures are typically ever developed in subducted rocks in nature, as stresses at the respective depth in subduction zones may be generally too low to activate this deformation mechanism [3,4]. Coesite in partially molten UHPM rocks [5] tends to be idiomorphic, with rational interfaces, and tabular shape as observed in the subsolidus synthesis and deformation experiments. Such grain shapes are thus expected for inclusions of coesite in UHP mineral phases grown from a melt (or supercritical fluid) at temperatures of up to 1100°C.

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Disequilibrium phase assemblages including microdiamond or graphite in original COH + silicate fluid inclusions trapped in garnet at UHP metamorphism, Erzgebirge

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Minute polyphase inclusions in garnet of UHP-metamorphic gneisses (Erzgebirge, Germany) contain either microdiamond [1] or graphite associated with phlogopite, quartz, paragonite, phengite, kyanite, plagioclase, apatite, and rutile. They are interpreted to represent original inclusions of a dense supercritical COH fluid rich in K, Na and SiO_2, from which the mineral assemblage has crystallized upon cooling and reaction with the garnet host [2,3].
The inclusions (as seen in the SEM) can be subdivided into five classes: (A) diamond plus silicates, apatite, and rutile; (B) graphite aggregate pseudomorphs after diamond plus silicates, apatite, and rutile; (C) single graphite flakes plus silicates, apatite, and rutile; (D) silicates, apatite, and rutile without a carbon phase visible in the given section, and (E) retrograded inclusions with micas partly transformed to chlorite. For all inclusion types, eventual brittle failure of the garnet host due to internal overpressure built up during release of confining pressure at still high temperatures is demonstrated by healed radial cracks. This implies that the internal pressure of the inclusions as a function of temperature followed variable paths, depending on the instant of decrepitation. The fact that the five classes of inclusions are randomly distributed in the garnet host indicates, that the variable phase assemblage does probably not reflect a evolution in the composition of the fluid phase trapped during progressive growth of the garnet. The diversity can instead be related (apart from the position of the cut surface) to variable P-T-conditions at the stage of the nucleation of the carbon phase, and during subsequent precipitation of the other minerals. If this is true, the phase assemblage of the individual inclusion reflects its distinct P-T-history dependent on its shape, size, and position within the host, as these parameters control the pressure difference required for decrepitation and thus the individual internal P-T-history of the inclusion.

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Tectonic framework of post-collisional crustal ductile extension in UHPM and HPM belts in the Tongbai-Dabie-Sulu region, central China

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The present-day observable tectonic framework of ultrahigh pressure (>2.7 GPa) metamorphic (UHPM) and high pressure metamorphic (HPM) belts in the Tongbai-Dabie-Sulu region, central China was dominantly formed by an extensional process, mostly between 200 Ma and 170 Ma, following the Triassic (250-220Ma) collision between the Sino-Korean and Yangtze cratons and initial exhumation (220-200Ma) of UHPM rocks. The structures that control the present spatial distribution of the UHPM and HPM rocks in particular the typical features of a Cordilleran-type metamorphic core complex, in which at least four regional-scale, shallow –dipping, ductile detachment zones are recognized. Each of these detachment zones that are named here, from base to top, the lower detachment zone, the middle detachment zone, the upper detachment zone and the top detachment zone, respectively, corresponds to a pressure gap of 0.5 to 2.0 GPa. The detachment zones separate the rocks exposed in the Tongbai-Dabie-Sulu region into several petrotectonic units with different P-T metamorphic conditions. To the south of the Balifan-Mozitan-Xiaotian fault (BMXF), four petrotectonic units can be distinguished, including, from bottom to top, the core complex unit, the ultrahigh pressure unit, the high pressure unit and the epidote–blueschist unit. The overlying sedimentary cover was generally unaffected by ultrahigh pressure and high-pressure metamorphism. The geometry and the kinematics of both the detachment zones and petrotectonic units show that the exhumation of UHPM and HPM rocks in the Tongbai-Dabie-Sulu region was achieved, at least in part, by non-coaxial ductile flow related to the multi-layered detachment zones, and by coaxial vertical shortening (>50-80%) and ductile thinning in the metamorphic units, under amphibolite- to greenschist-facies conditions, and in an extensional regime. All ductile extensional deformations are mainly limited to depths greater than 10 to 15 km, i.e. the depth of brittle/ductile detachment transition, It is concluded that the UHPM and HPM rocks were exhumed, probably, from the mantle depth to the surface during a multistage history, including wedge intrusion (220-200Ma), crustal ductile thinning and extension flow (200-170Ma), and late-orogenic collapse and unroofing (140Ma to present). A new tectonic evolution model is proposed for the UHPM and HPM belts in a crustal scale.

Significance of Dauphné twins in Quartz tectonites- an EBSD study from the Norwegian Caledonides

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Three samples, MJØLLFJELLST1, NØO837 and NØO573, from the Norwegian Caledonides, belonging to different metamorphic deformation conditions, were investigated via EBSD for the occurrence of Dauphiné twins, D.t.s.. Results were to be compared with microstructure and crystallographic fabrics of the samples. Investigations were done as part of my Masters project at Department of Geosciences, University of Aarhus. The project was initiated by my supervisor assoc. Professor Niels Østerby Olesen Department of Geosciences, University of Aarhus.

All samples (normal cylindrical polished samples with a diameter of 3 cm) were SYTON polished. Because of the pseudo symmetry between EBSP's of adjacent grains with Dauphiné twin relation, indexing was carried out in semi automatic mode, where I chose the right pseudo symmetric solution manually. Data were collected along traverses in stage scan mode to optimize the geometry of the experimental setup in accordance with the calibration. Hence a high reliability and accuracy can be expected from the data. To minimize time span EBSP's were only indexed when a change in orientation was observed. All EBSD work and EBSD data analysis was done with the CHANNEL4.2 software from HKL Technology. The results from the samples are different, both in terms of microstructure, crystallographic fabric and occurrence of Dauphiné twins.

MJØLLFJELLST1 has a conspicuous GBM microstructure, Y0 c-axis fabric, trigonal "comet" distribution of the rhombs, and numerous D.t.s. (35% of high angle boundaries). Grains with D.t.s. in MJØLLFJELLST1 have a hexagonal rhomb distribution, with maximums where the "comets" of r- and z-rhombs meet. The main deformation of MJØLLFJELLST1 probably to took place under upper amphibolite facies conditions, deduced from mineral assemblages and the c-axis fabrics, though ductile deformed garnets testifies to an earlier granulite facies event. The penetrative character of the amphibolite facies event has overprinted all evidence of the granulite facies event in the quartz fabric. NØO837 has a both GBM and SGR type microstructure, some D.t.s., an asymmetric type 2 relic, and a trigonal cleft girdle distribution of the rhombs. From mineral assemblages in surrounding rocks it is inferred that deformation took place during mid-amphibolite facies conditions (Olesen 1971).

NØO573 has a SGR microstructure, an asymmetric type 2 girdle, uniform rhomb distribution and almost no Dauphiné twins. From mineral assemblages in surrounding rocks it is inferred that deformation took place during greenshist facies conditions.

The further faith of the D.t.s. was investigated by calculating and plotting the misorientation angles of transformed D.t.s. and axes in the hexagonal "super lattice" 6mmm of α-quartz.Grains that were very close to perfect D.t.s. have hexagonal axes away from the <001> twin axis, whereas at higher angles the axes move closer to <001>. Since the trigonal misorientation axes of grains without D.t..s. plots very close to <001>, the lack of hexagonal misorientation axes of transformed D.t.s at <001> may represent some structural resistance for newly formed perfect twins to be rotated around <001>.

The different crystallographic fabrics of grain with and without twins indicate that the occurrence of D.t.s. is affected by deformation, and that D.t.s. influence the crystallographic fabrics. Inverse polefigures of supposed paleostress axes fits well with the piezocrescense theory of Tullis & Tullis 1972. Furthermore grains with D.t.s. for these supposed stress axes lie as close as it is a loved by the c-axis fabrics of the samples to the minimums and maximums of uniaxial compliance. Therefore it is likely that the process responsible for the D.t.s. is "piezocrescense. Although MJØLLFJELLST1 probably has experienced high temperature deformation it is not likely that the D.t.s. originate from the □ □ inversion since they would have been destroyed by the penetrative amphibolite facies deformation. Furthermore they would have had a completely different microstructure if they were inversion twins. D.t.s. might serve as a tool to estimate the orientation of paleostress.

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Boundary conditions of deformation related to the production and exhumation of HP and UHP rocks in the hinterland of the Scandinavian Caledonides, Western Gneiss Region, Norway

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Geologic mapping, structural analysis, quantitative strain analysis, and modeling are integrated with a well constrained P-T-t path from microdiamond-bearing rocks and associated kyanite eclogite on Fjørtoft, in order to determine the boundary conditions of deformation. Extensive preservation of eclogite-facies structural features in metamorphosed gabbro and diorite gneiss in Baltica crust allow refinement of processes taking place at a minimum depth of 65 km in the Scandinavian Caledonides. These features, formed during continental collision, allow direct inferences to be made regarding the geometry of folds, kinematics and original structural orientations related to production and exhumation of HP rocks. The geometry of folds associated with eclogite-facies fabrics is isoclinal to tubular with axes parallel to the trend of a stretching lineation. Results from strain estimates and the presence of L>S or L>>S fabrics indicate that these structures were formed in a constrictional strain field. Locally, these structures are well preserved in eclogite-facies mylonite zones up to at least 40 m thick cutting Proterozoic gabbro and adjacent gneiss. Results of this study indicate that coherent Baltica crust at 60-70 km depth was experiencing sub-vertical and horizontal shortening while extending toward the foreland during tops-southeast (140º) shearing that is geometrically consistent with thrusting parallel to plate motion. This relative motion resulted in progressive imbrication of high-pressure rocks associated with the development of eclogite-facies mylonite zones and stacking of high-pressure and ultra-high pressure rocks, with the youngest imbrications in contact with the deforming zone separating coherent Baltica crust below from imbricated basement above. At higher structural levels the allochthons show orogen-normal transport, assuming that the erosional front of the Caledonide nappes and the regional metamorphic isotherms give a reasonable approximation for the trend of the orogen. The oblique nature of the collision, combined with the inferred change in strike of the orogen, is interpreted to have allowed different degrees of thickening along its length. The constrictional strains under eclogite-facies conditions may have been in response to extension or by sinking of dense mantle lithosphere or channel flow.

The late exhumation history along the PTt-path, which begins at depths between 45 and 65 km at ~750 °C, is also well preserved by strain partitioning. Linear and planar structural elements appear to show a progressive change from NW (normal to the strike of the orogen) for the earliest to NE (parallel to the strike of the orogen) for the youngest. On Nordøyane, the earliest mylonite zones, interpreted as originally subhorizontal, range in strike through a 20° angle from 110° to 90°. Later steeply dipping mylonite zones, formed under lower amphibolite-facies conditions, strike 75° and locally truncate earlier structures. The youngest mylonite zones, formed under lowest amphibolite conditions, strike 50° and truncate all earlier structures. Folds developed during this progression show the range in orientation from WNW to ENE reflected in the orientations of the mylonite zones that is interpreted to represent progressive evolution during top-west shearing. These changes in orientation of the late structural features are interpreted to have been caused by changes in boundary conditions related to transtensional deformation during exhumation.

L>S fabrics, absence of axial planar foliation, and chaotic orientations of axial surfaces of granulite to amphibolite-facies folds indicate formation in a constrictional strain field. This is also supported by estimates of the finite strain accumulated at ~780 °C and 45 km and similar observations by previous workers. Assuming a simple monoclinic deformation for transtension, strain estimates and structural measurements indicate apparent transtensional angles of 9-11° that increased to greater than 20° and then decreased to less than 20°. These changes in transtensional angle agree with changes in the orientation of the X-Y plane of strain during exhumation from 45 km to less than ~20 km depth, and appear to reflect changes in the boundary conditions of deformation. This upper crustal transtension is interpreted to have occurred during continued sinistral oblique convergence and provides a mechanism for syn-collisional exhumation of HP and UHP metamorphic rocks.

Microstructures and textures in synkinematic garnet from eclogite-facies shear zones in the Haram Gabbro, Haramsøya, Norway

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Shear zones in the Haram Gabbro, produced during the Scandian Orogeny, allow characterization of metamorphism, microstructures, textures, and deformation mechanisms with increasing strain. The Haram Gabbro is a metamorphosed Proterozoic intrusive complex that has an exposed length of 1.3 km and width of 0.3 km. It shows well preserved primary igneous textures that underwent partial transformation to eclogite. The shear zones range in width from a few centimeters up to tens of meters and are characterized by grain-size reduction of all phases and an increase in modal garnet. They have a steeply dipping foliation associated with a steeply plunging stretching lineation. Asymmetric porphyroclasts, deformed cumulate layers, and asymmetric shear fabrics indicate a north side-up-sense of shear. All shear zones show similar mineralogical associations and show no evidence of being different in age. The shear zones are interpreted to be segments of a crustal scale high strain zone produced during top-SE shearing.

Metamorphism, previously estimated at 780 °C and 1.8 Gpa, in weakly deformed gabbro is associated with classic garnet corona textures. There are two major types of corona textures containing the following phases from core to rim 1) omphacite-plagioclase-garnet, or Opx or Cpx-omphacite-plagioclase-garnet and 2) ilmenite/rutile-plagioclase- garnet. Textures among the minerals indicate that coronas form by the general reactions: 1) Ca plag + Opx/Cpx + spinel = omphacite + garnet + kyanite + Na plag. 2) Ca plag + ilmenite + spinel = rutile + garnet + kyanite + Na plag.

Linkages between deformation and metamorphism were determined using petrographic analysis, orientation contrast (OC) imaging, compositional mapping, and mapping of lattice-preferred orientations (LPO) using electron backscattering diffraction (EBSD) in the SEM. The reaction products plagioclase and kyanite show a strong preferred grain-shape orientation related to deformation in the shear zones. Garnet occurs in layers up to a few hundred microns in thickness as well as isolated grains down to just a few microns in diameter. Omphacite forms polycrystalline layers in strain shadows around orthopyroxene porphyroclasts. The LPOs of plagioclase, ilmenite, and omphacite are all related to the deformation in the shear zone.

Garnet in weakly deformed areas shows classic corona structures that are indicative of having formed at nearly static conditions. Radiating growth patterns seen in fine-grained areas of garnet coronas are similar to patterns seen in other phases like omphacite that replaces igneous orthopyroxene. This radiating pattern is interpreted to be a result of the original diffusion controlled growth. In deformed samples, garnet displays weak LPOs locally (i.e. on a scale of tens of micrometers) but the overall LPO is random. OC images of garnet from deformed and undeformed samples have similar grain sizes ranging from ~1-150 µm. However, deformed samples typically display a gradation of grain size with fine grains (~ 1-15) in the interior and coarse grains (~50-100) in the outer parts of one garnet layer. Garnet grains also show deformation structures such as subgrains, grain-shape-preferred orientations and, at high strains, granoblastic features. Grain boundaries are curved and locally show pinning and bulging indicating that grain boundaries were migrating. Microstructures and LPOs in garnet indicate grain-boundary sliding as the dominant deformation mechanism. The

fine grained part garnet layers in deformed samples deformed relatively easily with necking or breaking. These features are also characteristic of superplasticity.

Local partial melting and retrograde metamorphism of eclogites in northeastern Hong'an, central China

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We report new occurrence of eclogites with possible partial melting structures, and propose a genetic relation between partial melting and retrograde metamorphism of eclogites and their country rocks in the northeastern Hong'an block of the Dabie orogen, central China. In contrast to the Dabie terrane, the Hong'an block preserves better outcrops of quartz- and coesite-bearing eclogites with little or no post-collision (Cretaceous) regional magmatic/structural overprinting. Hence, the Hong'an region is a key place to document tectono-metamorphic evolution of the Dabie orogenic belt. In Huatugang locality (N31°23'44", E115°04'15"), a kyanite-bearing quartz eclogite outcrop shows widely distributed, subparallel, deformed veinlets and seams, which include quartz, plagioclase, biotite, and epidote. This may indicate partial melting with probable fluid-melt-solid chemical interaction during exhumation of the eclogite and surrounding rocks. In Sidaohe locality (N31°20'50", E115°03'04"), lenticular sheared eclogite boudins (meters wide) occur within foliated biotite-hornblende tonalitic orthogneiss. In the domain of eclogite boudins, felsic patches and veinlets intrude the eclogite core or surround the strongly retrogressed eclogite rim with sharp contact, and clearly indicate a magmatic origin. In Futienhe locality (N31°28'17", E115°03'51"), phengite-bearing foliated eclogite bands interlayered (in sharp contact) with epidote-bearing quartz-mica schist of probable granitic protolith and garnet-bearing quartz-mica schist. An interesting finding is that all of the three rock types of Futienhe contain epidote grains showing chemical zoning. In the case of eclogite, epidote shows REE enrichment coreward and iron enrichment rimward. Field and petrographic observations imply that deformation and retrograde metamorphism (after peak eclogite-facies metamorphism) might have postdated partial melting of eclogites and country rocks. Field occurrences, mineral compositions, and textural relations indicate that partial melting, probably caused by near-isothermal decompression of eclogite, may have played a key role in early stage of exhumation history of the very high pressure metamorphic rocks.

A structural, metamorphic and geochronological study of eclogites and country rock gneisses from Otrøy (Moldefjord), WGR, Norway

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Garnet peridotites on Otrøy, WGR, Norway, have conceived considerable attention due to the spectacular discovery of "majoritic garnet". In order to constrain the Caledonidian exhumation history of these garnet peridotites we have performed a preliminary study on the surrounding country rock gneisses and eclogites. Our aim was to map out the main geological units, to reconstruct their PTt path and to constrain their exhumation.

Detailed mapping showed that the various gneissic lithologies form steeply dipping east-west running belts of about 0.2-1.5 km wide. The main gneissic lithologies consist of quartzofeldspathic 'augen' gneisses and 'grey gneisses'. The latter are variable in composition, but amphibole, biotite gneisses predominate, often with a migmatitic texture. Eclogites (and garnet peridotites) occur enclosed within the gneisses.

Selected samples were taken from all lithologies and subsequently studied by LM, SEM and EMP. Peak metamorphic conditions were established for the following eclogite bodies: (1) Raknestangen opx eclogite (first described by Carswell et al (1983), northern coast), (2) a small bi-mineralic eclogite body along the north coast, (3) a coarse opx eclogite near the island of Magerøy and (4) Midsund eclogite (found along the west coast, north of the village centre). Composition and mineral chemistry of these bodies vary significantly. The opx-eclogites consist of grt+cpx+opx±phl, with average opx composition: (3) En_{82}, (1) En_{66-78}, cpx: (3) Jd_{75}, (1) max Jd_{85} and grt: (3) Py_{55} and (1) Py_{35-47}. The 'normal' eclogites contain grt+omph±phl, with average cpx: (2) max Jd_{85}, (4) Jd_{32} and grt: (2) Py_{38}, (4) Py_{52}. EMP line scans across all these minerals revealed flat profiles, except for the outermost rims. However in one eclogite body, in between the two major garnet peridotite bodies, euhedral ~1cm large prograde zoned garnets were found.

PT estimates were made using Brey and Kohler (1990), Ellis and Green (1979), Harley (1984), Carswell & Harley (1990), Krogh (2000) and Powell (1985), and resulted for opx eclogites in: (1) 780°C, 20 kbar (cpx-grt assemblages, minimum pressure) and 750°C, 25 kbar (opx-grt assemblages), (3) 810°C, 26 kbar. For normal eclogites (minimum pressure): (2) 800-850°C, 20 kbar and for (4) 735±50°C, 15.3±0.5 kbar. The conditions for the opx eclogites are substantially higher than previously reported (Cuthbert et al 2000). Moreover the conditions are close to the UHP stability field. However ongoing research has to clearify whether these (near) UHP conditions are also found in the southern part.

Pressure-temperature estimates on post-eclogite mineral assemblages and/or post-eclogite migmatites (pl+amp+grt) gave 695 °C, 12 kbar. Sillimanite needles overgrowing the foliation indicate that near isothermal decompression continued into the sillimanite field.

A granulite pod and an early migmatitic vein recorded conditions of about 870±60°C and 10.5±0.7 kbar. As these conditions are inconsistent with the decompression path, we have tentatively interpreted the latter as reflecting pre-Caledonian metamorphic conditions.

In addition, gneisses with kfs+pl+qtz±bt or ±ms leucosomes are quite common. At two localities they host considerable amounts of monazite. Application of EMP Th-U-Pb

geochronology on these monazites resulted in a well-constrained age of 377 Ma. In one case a core of Proterozoic age (>900 Ma) was found (currently under research).

The steeply dipping amphibolite facies foliation in the gneisses runs east-west and is accompanied by a well-developed east-west subhorizontal stretching lineation. Most material objects are symmetrical (feldspar augen, eclogite bodies), but sinistral extensional shear bands and rotated rigid objects have been found. Most eclogite and peridotite bodies are boudin-shaped, with their long axis approximately east-west, in line with the foliation and lineation trend. In addition fine-grained, late, greenschist to amphibolite facies shearzones were found. In contrary to the dominant non-coaxial sinistral shear found on the Northern Islands and Moldefjordsyncline (Robinson and Terry 1998), the fabrics on Otrøy also indicate substantial coaxial deformation.

Finally detailed mapping around the Raudhaugene-and Ugelvik peridotite bodies suggests that both bodies could have been one single sheet, before being subjected to extensive shearing accompanying uplift.

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Archean eclogites from the Belomorian Mobile Belt in the Fennoscandian/Baltic Shield, Russia

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Eclogites have been found (Volodichev, 1990) in the central part of the Belomorian Mobile Belt (Gridino area, Karelia) located in the Fennoscandian / Baltic Shield. Detailed petrological and geochronological studies have shown that there are two age generations of eclogites in this area: an Archean generation (> 2.7 Ga) and a Palaeoproterozoic generation (2416.1±1.3 Ma).

Archean eclogites are common in the tectonic melange zone. Its fragmental constituent is dominated by eclogite-like rocks (Gt-Cpx-Pl composition), eclogites, Gt-Cpx, Gt and Fsp amphibolites, as well as ultrabasic rocks, gabbro, zoisitic rocks (presumably after anorthosites) and alumina gneisses. The matrix of the melange, which accounts for not less than 50% of total rock volume, is represented by gneisses of quartz diorite-trondhjemite composition and enderbites. The eclogite-bearing tectonic melange is cut by small trondhjemite intrusions and dykes. The U-Pb zircon age of the dyke sampled on Stolbikha Island is 2701.3±8.1 Ma. In addition, the melange zone is cut by Palaeoproterozoic gabbronorite dykes (Stepanov, 1990) that have an age of 2.43-2.44 Ga (Lobach-Zhuchenko et al., 1998; Slabunov et al., 1999).

The protolith of the eclogites is mafic rocks. They can be correlated petrogeochemically with the metabasalts occurring in the ophiolite-like complex of the Central Belomorian mafic zone (Slabunov & Stepanov, 1998; Bibikova et al., 1999).

The eclogites consist of garnet (21-28% pyrope) and omphacite (25-38% jadeite). Geothermobarometric data (Gasparik, Lindsley, 1980; Powell, 1985) show that they were generated at a pressure range of 14.5-17.5 kbar and a temperature range of 770-880° C. The prograde evolution path of the eclogitization process coincides closely with the geothermal gradient of «warm» subduction (Peacock, 1993).

The eclogites that have survived as relicts were greatly transformed by intense decompression. The PT-conditions of this decompression agree with the sub-isothermal decompression path, pressure decreasing from 14 to 6 kbar in the temperature range of 850-675° C. The decompression transformation falls into several stages: a) eclogite facies (Gt (24-30% Prp) – Omp-Di (19-23% Jd) – Pl (17-20% An), b) high- to moderate-pressure granulite and amphibolite facies (the formation of symplektitic eclogite-like rocks with the paragenesis Gt (23-25% Prp) – Di (5-13% Jd) – Pl (18-24% An), Gt-Cpx and Gt amphibolites).

Petrological and geochronological data thus point to the existence of eclogites that formed in Archean time. This shows that geodynamic processes, at least those in Late Archean time, did not differ considerably from Phanerozoic geodynamic processes.

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Arrest of the Norwegian ultrahigh-pressure/high-pressure slab in the lower crust during exhumation

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We studied the P–T and deformation histories of a 220 x 100 km swath across the Western Gneiss Region—from the ultrahigh-pressure domain in the west to the edge of the Trondheim nappes in the east—to shed more light on the mechanisms of exhumation of the ultrahigh- and high-pressure rocks. Western Gneiss Complex crystalline rocks are structurally overlain by a succession of allochthonous sheets correlated with the Blåhø, Saetra and Risberget nappes. High-temperature structures are fairly consistent across the swath: foliations dip gently S or N where not locally folded, and stretching lineations plunge shallowly E or NE; sense of shear indicators are generally absent. Electron back-scatter diffraction of quartzites and mylonites shows amphibolite-facies <a>-prism slip during coaxial to top-W noncoaxial deformation. These fabrics are statically overprinted by amphibolite-facies metamorphism; in the west this overprint caused visible symplectization of coarse high-pressure minerals. Late-stage, top-E brittle/ductile normal faults produced minor thinning of the section in the east, while the Nordfjord–Sogn Detachment Zone along the western edge of the study area shows pervasive top-W sense of shear in delta and sigma clasts, asymmetric boudins and shear bands.

Eclogites span the entire E–W extent of the study area but are generally strongly retrogressed to amphibolite-facies. Eclogites from the basement and allochthons record minimum pressures of ~1.1–1.5 GPa and temperatures of ~600 °C; one orthopyroxene eclogite yields maximum temperature conditions of ~831 °C and 2.8 GPa. Evidence of coesite—palisade-textured, polycrystalline quartz in garnet—has been found >50 km farther east than previously known, north of Hellesylt on Geirangerfjord. Despite the widespread evidence of ultrahigh to high pressure, thermobarometry of pelite and garnet amphibolite samples reveals surprisingly similar maximum temperature conditions of ~650–750 °C and 1.1 GPa across the entire area. Garnet zoning analysis shows that garnets across the swath grew while temperature was increasing and pressure decreasing.

In situ monazite dating by secondary ion mass spectrometry yields ages ranging from 1.5 Ga to 340 Ma. Pre-Caledonian ages were found only in the Western Gneiss Complex, supporting a distinctly different provenance for the allochthons, which record Caledonian ages of ≤405 Ma. $^{40}Ar/^{39}Ar$ dating of muscovite shows a clear age gradient in the Western Gneiss Region from ~385 Ma in the west to ~395 Ma in the east, adjacent to the Trondheim nappes. The Trondheim nappes show distinctly older ages: ~405 Ma from the Blåhø Nappe and ~417 Ma from the Köli Nappe.

These data show that the Norwegian ultrahigh-pressure (UHP)/high-pressure (HP) terrane was exhumed in two stages. Initial buoyancy(?)-driven exhumation carried the rocks from mantle depths of > 100 km to lower crustal depths (35–40 km), where the rocks stalled and re-equilibrated at 650–750 °C under relatively static conditions; monazite ages of ~395–405 Ma presumably relate to this event. The older cooling ages from the Trondheim nappes suggest that the intraoceanic arc of the Upper Allochthon may have constituted the overlying crustal section. Late-stage slip on the Nordfjord–Sogn Detachment Zone, combined with limited extension farther east, then exhumed the rocks through the crust at 395–385 Ma, bringing up deeper rocks to the west.

No sharp boundary between “hot” and “cold” eclogite terrains in the Dabie Mts., China

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To answer the question whether the boundary between “hot eclogite terrain” and “cold eclogite terrain” is tectonic or transitional, we investigated the key area near the Hualiangting Reservoir in the Dabie Mountains, China. Petrologically, three types of eclogite could be recognized. They are, from north to south, the Jinheqiao Eclogite (JE) enclosed in epidote-biotite gneiss, the Dam Eclogite (DE) enclosed in biotite gneiss and granitic gneiss, and the Zhujiachong Eclogite (ZE) enclosed in biotite gneiss and biotite-muscovite schist. The so-called boundary between the “hot” and “cold” eclogite terrains separates DE on the north and ZE on the south. Coesite was found only in JE and coesite pseudomorph in both JE and DE, while no coesite at all in ZE. Garnets show the highest grossular component (0.29) in JE and the lowest pyrope component (0.21) in ZE. Jadeite components decrease systematically from JE (0.45) through DE (0.39) to ZE (0.36). Si contents in Phengite from all eclogite are higher than 3.4 pfu.

More than two hundreds of eclogite samples were collected and checked and peak metamorphic P-T conditions were estimated by using the garnet-omphacite-phengtie thermobarometer. The average peak metamorphic P-T values are: 3.8 GPa and 679 ^{o}C for JE, 2.4 GPa and 590 ^{o}C for DE, and 2.2 GPa and 510 ^{o}C for ZE. In order to recognize the actual feature that is always masked by mathematic average, we designed a P-T-G diagram to plot the P-T values of peak metamorphism against the geographic positions (G) of the analyzed eclogites. The P-T-G plots display following features. (1) P-T values of all eclogites vary in a certain ranges, P = 2.9-4.5 GPa and T = 440-940 ^{o}C for JE, P = 1.8-3.1 GPa and T = 480-830 ^{o}C for DE, and P = 1.7-2.6 GPa and T = 410-620 ^{o}C for ZE. (2) P-T values straddling the boundary between “hot eclogite terrain” and “cold eclogite terrain” show neither abrupt gap nor sharp contrast. In addition, recent SHRIMP age dating indicated that the peak metamorphic age of JE is around 222 Ma and that of ZE is 222-236 Ma. Therefore, we conclude that there is no sharp boundary between the so-called “hot eclogite terrain” and “cold eclogite terrain” near the Hualiangting Reservoir. Both DE and ZE belong to a coherent terrain once subducted down to depth of quartz-coesite transition zone.

Distribution of hydrous component in jadeite of the Dabie Mountains

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There are two kinds of jadeite in the jadeite-quartzite from the Dabie Mountains, Eastern China: the jadeite of weak and strong deformation. The former shows uniform composition and the latter shows both uniform and zonal composition. These jadeites were examined with infrared spectroscopy. Nearly all jadeites display hydroxyl stretching bands, implying that hydrous component commonly exists in most jadeites. The concentration of hydrous component in the jadeites with weak deformation is consistent, whereas the concentration of hydrous component in strongly deformed samples are variable. These observations indicate that crystal chemical factors not only control the hydrous component incorporated during crystallization, but also affect the post-crystallization changes in jadeite during subduction and exhumation of continental crustal rocks.

A TEM study on fluid inclusions in quartz and symplectitic minerals from jadeite quartzite

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Coesite-bearing jadeite quartzite has been known at Shuanghe, Dabie Mountains, China. The geological setting and mineral assemblages of the jadeite quartzite have been reported (Cong *et al*., 1995; You *et al*., 1996; Dong *et al*., 1996 and Liou *et al*., 1997). It contains jadeite, quartz and subordinate garnet. Retrogressive textures are developed as symplectites or coronas replacing or surrounding jadeite and garnet. Studies on fluid inclusions in the jadeite quartzite have been made by Han *et al*.(1996, 1999) and Fu *et al*.(2001). Fluid inclusions in quartz are post-UHP metamorphic CO_2-rich or low-salinity aqueous fluids as well as mixed CO_2-H_2O fluids. No evidence of decrepitation was observed at the resolution of optical microscope. Recently we have performed a transmission electron microscope (TEM) and energy-dispersive X-ray spectrometer (EDS) investigation on the fluid inclusions in quartz and in symplectite. TEM studies indicate that fluid inclusions less than 0.3μm (0.01-0.3μm) in diameter in quartz have negative crystal morphology, other large inclusions are irregular or oval. Fluid inclusions in sympletitic albite and magnetite are anhedral, generally less than 0.1μm (0.003-0.1μm), and arranged along trails on regular distance. Most of them are connected to dislocation arrays. Negative crystals in quartz connected to dislocations have also been observed. The above microstructures are undetected at the scale of the optical microscope, representing a possible path for leakage of the fluid phase. The EDS TEM analyses confirm that the fluid inclusions in quartz contain CO_2, KCl, NaCl and Fe sulfide, whereas fluid inclusions in magnetite have CO_2, F, Mn-, Al-, and Si-oxide. Therefore, the nano-structures may modify the original composition and density of the fluid inclusions, with significant implications for the correct petrological interpretation.

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New findings of micro-diamonds in eclogites from the Dabie Shan and Su-Lu region, central eastern China

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Several grains of micro-diamonds were found from the localities near Donghai (Sulu region), and Dabie Shan. Micro-diamonds from Dabie Sahan are found in the ultrahigh pressure terrane (eclogite belt) and the ultramafic rock belt (or the northern Dabie) where a lot of eclogite bodies were reported since 1999. Most the new findings of micro-diamonds are found in polished thin sections of eclogites except one from artificial heavy sands extracted from eclogite. Micro-diamonds in thin sections are occurred as inclusions in garnet from eclogites except two larger crystals appeared as interstitial. All the reported micro-diamonds are fairly confirmed by using the Raman Spectrum with the Raman peak around 1330cm^{-1}. A largest one is found at Xindian village where the present authors found the first occurrence of micro-diamond in 1992. The new finding of micro-diamond is as large as 180 μm across, and is interstitial among eclogitic minerals rather than an inclusion in garnet. Smaller inclusions of micro-diamonds and graphite in, and the zonal structure of the host micro-diamond, exclude the possibility of any exotic origin of this micro-diamond. Three grains of micro-diamonds from Sulu region are 160, 60 and 30 μm across respectively. The grains sized 60 and 30 μm are enveloped in a fluid bubble, the composition of which remain to test. Crystals of the micro-diamonds mentioned above are mainly octahedron or the composite of octahedron and hexahedron. An aggregate and a single crystal of micro-diamonds are found in eclogites in the ultramafic rock belt or the northern Dabie Shan. The aggregate of micro-diamonds is found in a polished thin-section of Baizhangyan eclogite enveloped by banded gneiss. It is sized in 70 × 60 μm, and looks like to be composed of 3 or 4 grains of micro-diamonds. The crystal form is obscured due to graphitization and the thin film of garnet covering the micro-diamonds. A free grain of micro-diamond was discerned from the artificial zircon sands extracted from Huangweihe eclogite enveloped in foliated garnet peridotite. The micro-diamond is 50 × 50 μm in size and tetrahedral in form. It is an isotropic crystal with adamantine luster and is easy to be discerned from the zircon crystals extracted for dating. The new findings of micro-diamonds indicate that not only the traditional ultrahigh pressure terrane or the hot eclogite belt but also the ultramafic rock belt or northern Dabie Shan terrane suffered ultrahigh pressure metamorphism.

Some geologists take a skeptical attitude about the existence of the first occurrence of micro-diamonds from the Dabie Shan because no one found it after the first occurrence of it. The peculiar properties “larger in size and lower frequency” of Dabie Shan micro-diamonds obstruct most the geologists to discover them. It means that you have to make more rock thin-sections with sufficient and suitable thickness and watch them carefully, if you want to find the micro-diamonds in eclogites from the Dabie-Sulu region.

Deep subduction of a great quantity of materials in the Sulu UHP metamorphic belt

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Coesite inclusions were discovered by the Laser Raman analysis on zircons in the granitic gneiss at depths of 1103.04m and 1352.40m and in retrograde eclogites at depths of 1979, 2020 and 2037.99m in the main hole of the China Continental Scientific Drilling (CCSD) located in the southern part of the Sulu UHP metamorphic belt. In Cpx inclusions of the mega-phenocrysts of garnet in the garnet peridotite of the pre-pilot hole(PP1) of the CCSD, exsolution lamellae of titanium clinohumite, titanium chondrodite, chromite and phlogopite were found, that provides new evidence for the deep subduction of a great quantity of materials in the Sulu UHP metamorphic belt.

(1) The discoveries of coesites at a depth of 2000m in the main hole of CCSD
It is a critical scientific topic whether the outcropped country rocks covering hundreds of square kilometers in the Sulu UHP metamorphic belt have been subjected to UHP metamorphism with a deep subduction of great quantities. The study of Liu et al (2001) shows that a host of materials in 3-D space above 1000m in the Sulu area hare been subjected to UHP metamorphism (>2.8Gpa, >650°C).

The CCSD has revealed that the 2000m long cores mostly consists of 1000m rutile-bearing eclogite, 80m garnet peridotite and pyroxenite, 400m granitic gneiss and over 500m other paragneiss and vein rocks (Xu et al., 2002).

The cores from the main hole can be divided into several segments from top to bottom: rutile eclogite, ultrabasic rocks, paragneiss with ecologite, granitic gneiss and phengite eclogite. No repeated lithology is seen over the 2000m.

Five samples were collected: 2 felsic gneiss samples (at 1103.04 and 1352.40m) and 3 amphibolized phengite eclogite samples (at 1979.31, 2020.32 and 2037.99m). In these samples, 15 coesite inclusions were obtained from 536 zircon grains.

The discovery of coesite inclusions as deep as 2000m in the Sulu area implies that coesite in the Sulu UHP metamorphic belt can occur at depths below 2000m. According to these evidences that the lithology is not repeated and the subducted continental slab was in a extension setting during its exhumation, it can be thought that the subducted slab is far thicker than 2km, that further proves the existence of which a great quantity of materials from the Yangtze plate was deeply sublucted beneath the North China plate during 220-240Ma.

(2) Exsolution lamellae in Cpx and Opx inclusions from Garnet peridotite and deep subduction

Dobrizhinetskaya (1996) discovered abundant ilmenite rods exsolved from olivine in a subduction zone periditite and argued that the implied high solubility of TiO_2 suggested an origin at very great depth. The maximum depth of subduction >200 km was determined for Yankou eclogites (Ye et al., 2000), that are situated in the same Sulu UHPM terrane as the area of Donhgai drilling site.

We found inclusions of Cpx and Opx inside Garnet crystal of Garnet peridotite from about 180m depth of PP1 at the south Donghai, in which exsolution lamellae or small inclusions of Titanium clinohumite, Titanium chondroite, chromite and phlogopite have been discovered.

a) Sample PP1-141-Garnet Peridotite:

There are 3 types exsolution lamellae of Titanium clinohumite and Titanium chondroite in Cpx: exsolution rods, exsolution platy and small exsolution. Their elongated directions are parallels to the cleavage of Cpx. Exsolution lamellae of Phlogopite and chromite in Cpx are also parallels to Ti-Clh lamellae.

b) Sample PP1-151 and PP1-152 Grt-peridotite:

Exsolution lamellae of phlogopite and chromite found in OPx (enstatite) of Grt. They are also parallels to the cleavage of Opx. K_2O content of phlogopite is about 10 %.

The study for exsolution lamellae in Cpx and Opx inclusions of Grt from Grt-peridotite indicates that precursor Cpx should be a Cpx phase enriched in TiO_2, K_2O and H_2O, and precursor Opx should be a Opx phase enriched in CrO_2, K_2O and H_2O.

According to K_2O solubility in Cpx is a function of pressure (Harlow, 1997) and K and Ti enrichments of subduction zone environments arising from both fluid and solid inclusions incorporated in microdiamonds from UHPM terranes (Dobrzhinetskaya et al., 2001, 2002). We suggest that precursor Cpx and Opx should be UHP phases.

Timing and mechanism of formation and exhumation of the Northern Qaidam Ultrahigh-Pressure Metamorphic Belt

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Lying in the northeastern Qinghai-Tibet Plateau, the Qilian Caledonides form a WNW-ESE trending belt about 800 km long and 400 km wide. It is considered to be the product of convergence and collision of the Alxa plate (west segment of the northern China plate), the Qilian microplate and the Qaidam-East Kunlun plate (west segment of the Yangtze plate) during the Caledonian. Subduction complexes along both sides of the Qilian terrane separate the three microplates (Xu et al., 2000). Late Devonian molasse deposits rest unconformable on the Lower Palaeozoic folded metamorphic rocks and Caledonian granites, indicating the end of the Caledonian orogeny.

The 350-km-long, WNW-ESE-trending North Qaidam ultrahigh-pressure (UHP) metamorphic belt, lying between the Qilian and Qaidam-East Kunlun microplates was formed by subduction of both oceanic and continental crust between 495 and 440 Ma. The UHP belt was exhumed by a process of "oblique extrusion" during transformation from "normal" to "oblique" subduction. Exhumation began at 470-460 Ma and was completed by 406-400 Ma. Exhumation structures are well preserved in the UHP rocks and record extensive retrograde metamorphism.

The northern Qaidam UHP belt was formed when the South Qilian ocean basin was subducted northward beneath the Qilian microplate beginning about 507-490 Ma. Deep subduction of oceanic crust produced UHP belt (495 Ma) while a volcanic island arc, I-type granites (507–480 Ma) and a fore-arc accretionary wedge (pyroclastic rocks + marble) formed along the southern margin of the Qilian microplate. Later (495-470 Ma) deep subduction (> 100 km) of continental crustal rocks (including 900–1100 Ma metamorphosed basement) of the Qaidam-Kunlun microplate produced coesite-bearing gneisses and schists.

The overturned anticline in the north Qaidam terrane dips to the southeast and east and sinistral and dextral transpression structures occur on both limbs. The occurrence of the transpression structures indicates that the driving force during exhumation was oblique convergence. Thus, the combination of oblique collision and subduction results in both "vertical extrusion" and "transpression". We call this combined mechanism "oblique extrusion". Based on the isotopic age data (400–406 Ma), which show that the eastward slip and the dextral transpression structures are coeval, we suggest that exhumation involved a combination of vertical extrusion and transpression. Final exhumation of the UHP metamorphic terrane accompanied by retrograde metamorphism and intrusion of voluminous S-type collision granites between 470 and 400 Ma.

During a change from normal to oblique subduction, the subducted slab ruptured and the eclogites were fragmented and mixed with the UHP gneisses and schists. During the next 60-70 Ma, the two were exhumed together by "oblique extrusion". Driven by buoyancy forces, the UHP block was indented into the volcanic island-arc and fore-arc belt and was juxtaposed against the island arc. As a result of upward oblique extrusion of soft material within rigid walls, the foliation in the upper part of the subducting slice is arched and a horizontal

stretching lineation forms. This process is distinguished from simple horizontal compression in that the latter usually produces a vertical foliation and vertical stretching lineation.

Newly discovered coesite – kyanite aggregates in the Luobusa ophiolite, southern Tibet, China originated from exhumed mantle?

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The Indus-Yarlunzangbu suture extends for over 1500 km in southern Tibet and marks the collision between the Indian and Eurasian plates. Cretaceous ophiolites in the suture were emplaced at about 50Ma. The Luobusa ophiolite at about 200 km southeast of Lhasa extends for 43 km in an EW direction along the southern bank of the Yarlunzangbu River. Many podiform chromite ore bodies occur in the ophiolite; diamond and many other UHP minerals, such as Si-rutile and Si-Mg spinel have been discovered and considered as lower mantle origin. This paper reports a new discovery of coesite and kyanite from chromite ores.

Coesite and kyanite occur as aggregates in an outer rim of a native Ti mineral with a narrow zone of TiSi alloy in between. A concentric structure from native Ti core about 700 x 500 µm in size through a TiSi alloy zone of about 20~70 µm wide to rim of coesite-kyanite aggregates about 30~50 µm in width is apparent. These minerals were identified by laser Raman Spectroscopy (LRS) and energy dispersive spectrometer (EDS). Coesite occurs as acicular to elongated crystal aggregates, 20~30 x 2 µm in size. The EDS analyses show that the coesite is pure SiO2, and LRS yields a typical Raman band of 521cm^{-1} and small bands of 271 cm^{-1}, 178 cm^{-1} and 151 cm^{-1}. Kyanite occurs as acicular crystals, 20 x 2µm in size, and are randomly distributed. Kyanite contains small amount of Ti, and has typical Raman peaks of 949 cm^{-1}, 896 cm^{-1} and 485 cm^{-1}. Some fine-grained Ti-Mg-K-Na-Ca oxide crystals are found as interstitial materials within the coesite and kyanite aggregates. The native Ti core contains almost pure Ti and minor amount of Si whereas the TiSi alloy has an average formula of Ti_7Si3. Such rimward in the decrease of the amounts of Ti probably suggests a chemical reaction of native Ti with silicate to form a symplektic texture.

Kyanite is known to be stable up to 13-18 GPa (420-450 km), and over this pressure it decomposes to stishovite and corundum (Schmidt et al., 1997); coesite is replaced by stishovite at P > 9 GPa (Yagi and Akimoto, 1976). These experimental data suggest that the coesite-kyanite assemblage formed at 100-270 km depth. However, the regular variation from native Ti through Ti_7Si_3 to coesite-kyanite and oxide aggregates suggests a series of chemical reaction between Ti metal and silicate under high pressure and temperature. Similar reactions between liquid iron and silicates at high pressures (□24 GPa) and temperatures documented by experiments of Knittle and Jeanloz (1991) yield metallic alloys (FeO and FeSi) and nonmetallic silicates (SiO2, stishovite and MgSiO3, perovskite) at the pressures of the core-mantle boundary, 140 GPa.

Several other HP minerals, such as Si-rutile, Si-Mg spinel, diamond, and intergrowth of SiO2 and FeO phases, have been identified in the Luobusha podiform chromitite. They were considered to have originated from the transition zone or the lower mantle. The coesite-kyanite aggregates at the rim of native Ti probably formed during the upwelling stage when a superplume brought chromitite from lower mantle to shallow levels beneath an oceanic spreading ridge. During such ascending process, a series of relatively lower pressure minerals, such as coesite-kyanite described in this report were formed.

Garnet peridotite and garnet pyroxenite in the North Qaidam Ultrahigh-pressure Metamorphic Belt, NW China

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The North Qaidam UHP metamorphic belt in NW China extends eastward to East Qinling where microdiamonds were recently discovered as inclusions in zircons from both eclogite and its gneissic country rocks. SHRIMP age data indicate that both North Qaidam and East Qinling UHP metamorphism occurred in Early Paleozoic time (about 500 Ma). Together with the Dabie-Sulu UHPM belt in eastern China, the UHPM rocks occur in a giant region of over 4000 km long across the central China. Since the Dabie-Sulu UHP metamorphism occurred in the Triassic, two separated UHPM belts exist in the central China Orogen. Garnet peridotites have been extensively reported from the Dabie-Sulu UHPM belt, but less known from the North Qaidam UHPM belt.

Garnet peridotite massif is less common in North Qaidam. The investigated Luliang Shan massif, about 200 x 50 m in size, occurs banded garnet peridotite and dunite with garnet pyroxenite veins. Individual layer varies from less than 0.1 to over 5 m with a sharp boundary. Garnet peridotites contain 70-80 vol% olivine, 5-15% orthopyroxene, 5 % clinopyroxene, 5-10 % garnet and few spinel. The garnet peridotites have an average Mg# of 92 and are characterized by low CaO (< 1 wt.%), total alkalis (Na_2O + K_2O average 0.17 wt.%) and Al_2O_3 (1.18 wt.%). Garnet peridotites with low pyroxene content exhibit LREE enriched patterns ($[Ce/Yb]_N$=4); these may be due to metasomatism or crustal contamination. Comparing to primitive mantle rocks, the Luliang Shan garnet peridotites are enriched in LILE's (K, Rb and Ba) but depleted in Nb, Zr and Ti. These characteristics suggesting that the mantle-derived peridotites have been subjected to metasomatism and continental crust contamination; this is consistent with presence of phlogopite.

The garnet peridotite shows porpyroblastic texture; coarse-grained garnets (up to 2-3 cm) set in the relative fine-grained matrix of forsterite, diopside, enstatite and garnet. Some coarse-grained garnets contain mineral inclusions of olivine and spinel and some fine minerals. Olivine ranges in composition from $Fo_{91.4 \text{ to } 96.7}$; Cr-rich garnet ($Cr_2O_3$ 1.2 to 1.9 wt%) is characterized by low TiO_2 (0.04-0.05 wt%) and high pyrope component (68-73 mole%); enstatite (En_{91}) by low Al_2O_3 content (< 0.6 wt%); diopside contains 0.9-1.4 wt% (Cr_2O_3). Peak metamorphic temperatures of 773 ± 50°C and 797 ± 50°C are obtained by Fe-Mg partitioning of Grt-Ol and Grt-Cpx at 35 kbar, and 914±15°C at 30 kbar based on Ca partitioning between two pyroxenes. Peak pressure of 36 ± 2.2 kbar at 773°C and 45 ± 2.2 kbar at 914 ^{o}C estimated by the barometer of Bery and Köhler (1990) indicated the garnet lherzolite has been subjected to subduction zone UHP metamorphism.

Zircon separates from both garnet peridotite and garnet pyroxenite are subrounded with poorly developed prism and pyramidal faces. Cathodoluminescence images of the zircons show no compositional/morphological zoning but some grains contain garnet and pyroxene inclusions identified by laser Raman Spectrum. These features and low Th/U ratio (0.01-0.03) indicate a metamorphic origin of zircon. SHRIMP U-Pb dating at Stanford University on 14

zircon grains from a garnet peridotite sample yields an age range of 497-436 Ma, which is consistent with SHRIMP ages of 495-443 Ma of zircons from adjacent eclogite.

Exhumational dehydration of zoisite in ultrahigh-pressure (UHP) eclogite from northeastern Sulu UHP terrane, eastern China: catalytic effect on granulite overprint

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Ultrahigh-pressure (UHP) eclogite from the northeastern Sulu UHP terrane in eastern China suffered various extents of granulite-facies overprint predating the pervasive amphibolite-facies retrogression (Wang et al., 1993; Banno et al., 2000; Nakamura and Hirajima. 2000), and their country gneisses show migmatization. Isothermal decompression P-T path had been deciphered from distinctive coesite-eclogite with diagnostic granulite-facies mineral assemblages and reaction textures (Banno et al., 2000; Nakamura and Hirajima. 2000), however, such indicative reaction textures are lack in other rock types from the same region, or even from the same outcrop, which suffered similar tectonometamorphic evolution.
The zoisite-bearing eclogite and the vicinity quartz-bearing eclogite commonly develop medium-pressure granulite-facies minerals (770-850 ^{o}C, 6.5-8.5 kbar) predating the pervasive regional amphibolite-facies retrogression, which is typically documented by the growth of orthopyroxene, clinopyroxene and plagioclase at the expense of garnet and quartz. However, such granulite-facies overprint is lack in the zoisite-absent eclogite away from the zoisite-bearing eclogite at the same outcrop. Several types of reaction textures associated with the dehydration of zoisite were recognized in zoisite-bearing eclogite. Zoisite reacted with nearby kyanite and produced corundum and anorthite in the quartz-absent domain ($2Zo + 2Ky = 4An + Crn + H_2O$). Zoisite reacted with nearby kyanite and quartz and produced anorthite in the quartz-present domain ($2Zo + Ky + Qtz = 4An + H_2O$). The estimated P-T conditions of the granulite-facies reactions echoed well with the P-T conditions required for the zoisite dehydration reactions.

It is known that mineral reaction rates are strongly influenced by the presence or absence of an aqueous fluid phase. The crystallization of the granulite-facies minerals in the studied eclogites requires the existence of an aqueous fluid phase at relevant P-T conditions. We therefore conclude that the fluid induced by dehydration of zoisite plays a catalytic role for the granulite-facies mineral reactions, and the extent of granulite-facies overprint is controlled by the degree of the dehydration of zoisite during the exhumation of UHP eclogite.

KEYWORDS: catalyze; dehydration; granulite-facies overprint, UHP eclogite; zoisite

The UHP rocks of western Norway are allochthonous: Implications for late-orogenic exhumation and tectonics of the Scandinavian Orogen

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The ultrahigh pressure (UHP) province of western Norway has long been considered to represent the lowest structural level of the Western Gneiss Region, forming the footwall to the major late-Caledonian extensional detachment in western Norway – the Nordfjord-Sogn Detachment Zone (NSDZ). We carried out a detailed structural, metamorphic and thermochronological analysis of the Nordfjord area, examining the transition from lower pressure rocks westward to the UHP province. Our findings show, in contrast to the widely held view, that the NSDZ actually *underlies* the UHP province, and implies that the UHP rocks are allochthonous with respect to the Baltica basement.

In the Nordfjord area, the NSDZ is a 3-km thick, shallowly NW-dipping shear zone with pervasive asymmetric shear indicators indicating top–W extension at amphibolite-facies conditions. It juxtaposes a lower plate of Baltica basement (Western Gneiss Complex), containing eclogites equilibrated at peak pressures ≤ 2.0 GPa, against a higher level, mixed gneiss complex (Nordfjord Complex) that hosts the well-known UHP (P> 2.8 GPa) eclogites of Stadlandet. Between these two units, the decollement of the NSDZ coincides with a strongly deformed package of mixed paragniesses and orthogneisses, correlated with the deformed sedimentary cover of the Western Gneiss Complex basement. At higher structural levels, the Hornelen Detachment, which brings Devonian molasse down against the Nordfjord Complex, is a later greenschist-facies feature that cuts the hanging wall of the NSDZ.

This new understanding of the geometry of the NSDZ has important implications for the exhumation mechanics of the UHP province. If the top–W extensional displacement along the NSDZ is removed, the UHP rocks are restored to a structurally higher position ~100 km farther inland, overlying the lower pressure WGC basement. Thus the NSDZ—or a similar structure—must have originally operated as a contractional fault during the collision, emplacing a wedge of the telescoped Baltica margin, with UHP rocks at deeper levels, eastward over the Baltica autochthon. This top–foreland thrusting accompanied or postdated UHP metamorphism at mantle depths, but was terminated once the UHP rocks reached the base of the crust, where a regional amphibolite-facies metamorphic event reset U/Pb isotopic systems in titanite and monazite at ~398–395 Ma. Crustal thinning accompanying top–W shearing on the NSDZ then raised the UHP rocks from lower to mid-crustal levels. Finally, $^{40}Ar/^{39}Ar$ muscovite ages of ~393–390 Ma, in both the hanging wall and footwall of the NSDZ, indicate that this structure became inactive once it reached the mid-crust, and denudation was then transferred to the structurally higher Hornelen Detachment.

Our mapping has shown that the mylonitic fabric of the NSD continues northwest-dipping from Nordfjord to the Geiranger area, where it folds over a broad culmination and dips east. Therefore, large areas of the Western Gneiss Region as far north as Runde, containing most of the UHP localities, lie structurally above the NSD. The UHP province is likely developed then within the Middle Allochthon – part of the edge of Baltica that was subducted, then imbricated back over the craton during the Caledonian orogeny.

The structural characteristics of the minerals in the eclogite and peridotite from the Su-Lu UHP metamorphic terrane

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X-ray diffraction analysis and Raman spectroscopy measurements were carried out on olivine, pyroxene and garnet crystals recovered from the eclogite and peridotite samples of the CCSD (Chinese Continental Scientific Drilling) project. The olivine crystal in the garnet peridotite, referred to as UHP-olivine, with a composition of $(Mg_{1.83}Fe_{0.17})SiO_4$ was refined to a final R factor of 3.4% with a full-matrix least-squares method and 377 independent intensity data. The largest difference electron peak and hole are 0.694 and -0.582 e/A^3, respectively. A mantle-derived high-pressure olivine crystal, $(Mg_{1.8}Fe_{0.2})SiO_4$, occurred in the xenolith of a Miocene basalt from Taiwan, referred to as XENO-olivine, was also analyzed for structural comparison purpose. Both structures exhibit negative deviations in their unit cell parameters and interatomic bond distances, in comparison with the low-pressure crustal olivine structure. The mean Si-O distance in UHP-olivine (1.6379A) are comparable to that of XENO-olivine (1.6372A). However, the cell dimensions and M1-O and M2-O bond lengths of UHP-olivine are slightly shorter than those of the XENO-olivine crystals. All of the thermal ellipsoids of the constituent atoms in the UHP-olivine crystals are also consistently smaller than those in XENO-olivine. The observed variations in the structural features suggest that at the time of crystallization of olivine, the UHP rocks might have been subjected to a slightly higher-pressure condition than the xenolith in the Miocene basalt.

A pyrope-rich garnet, $(Mg_{2.09}Fe_{0.51}Mn_{0.03}Ca_{0.37})(Al_{1.87}Cr_{0.13})Si_3O_{12}$, in peridotite and a grossular-rich garnet, $(Ca_{2.03}Fe_{1.08})(Al_{1.90})Si_3O_{12}$, in eclogite were structurally refined to the final R factors of 5.4% and 2.1%, respectively. The pyrope itself is a high-pressure variety of garnet minerals. The grossular structure also displays a significant shortening effect in the cell parameter, 11.619A versus 11.743A. The latter value was theoretically calculated based on the garnet compositions and the associated end-member cell dimensions. The bond distances in the grossular structure are also showing negative deviations relative to the low-pressure counterpart, apparently due primarily to the crystallization pressure environment.

Raman scattering measurements indicate that the Raman peaks of UHP-olivine and XENO-olivine are essentially identical, except that the Raman modes of UHP-olivine are slightly better in resolution than those of the XENO-olivine crystals, especially in the 900 to 1000cm^{-1} region.

The crustal structure and the exhumation of UHP rocks of Qinling Orogen from seismic reflection profiling

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Following the discovery of coesite and diamond in Dabieshan Area, eclogite and coesite were discovered in Qinling orogen to the west of Dabieshan (Hu Nenggao et.al.,1994). Yang Jingsui et.al.discovered diamond in gneiss and eclogite in Qinling group in Qqinling orogen (Yang Jingsui et.al,2002), thus provided evidence farther for there exist a UHP belt from the Dabie shan to the Qinling.

Seismic reflection profiling has been completed acrossing Qinling orogen (Yuan Xuecheng,1996). In order to compare with the seismic profiling across the Dabie orogen, the profile across the Qinling orogen was reprocessed with the same flowing chart of which we used in Dabieshan area, especially the DMO tecnique, and obtained obviously promoted result.

The crustal structure of the Qinling orogen can be divided into two parts along the Shangdan collision belt. The crust of the South Qinling has a double crusts structure. The South Qinling nappe thrusted to the Yangzi block from the north to the south, and the North Qinling was a microcontinent undergone multiple structural movement. The extension of Dabieshan orogen to the west can be correlated to the Douling group in South Qinling.

First recorded lawsonite eclogite from the Dominican Republic: Analogue for cold subduction of oceanic crust

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Lawsonite eclogite is a rare rock type described only from a few natural occurrences (Corsica: Caron and Pequignot, 1986, Lithos 19, 205-218; Pinchi Lake: Ghent et al., 1993, J. Met. Geol. 11, 279-290; Ward Creek: Shibakusa and Maekawa, 1997, Min. Petrol. 61, 163-180; Garnet Ridge: Watson and Morton, 1968, Am. Min. 54, 267-285; Port Macquarie: Watanabe et al., 1997, 5th Int. Eclogite Conf.). In contrast, laboratory experiments and thermal models predict that lawsonite eclogite should be widespread in subducted oceanic crust deeper than 1.5 GPa (Schmidt and Poli, 1998, EPSL 163, 361-379). Here I report a new lawsonite eclogite find from the Samana Peninsula, Dominican Republic, that provides additional constraints on the petrogenesis of these important rocks.

In the Dominican Republic sample, lawsonite occurs as inclusions in garnet cores. In garnet rims, epidote is the dominant inclusion phase. Omphacite inclusions occur throughout garnet, demonstrating eclogite-facies conditions during garnet growth. Lawsonite also occurs as large porphyroblasts (up to 1 mm) outside garnet and are partly replaced at their margins by epidote and zoisite. Phases interpreted to coexist with lawsonite are omphacite, pale glaucophane, phengite and garnet cores. Peak pressure conditions estimated from phengite-omphacite-garnet compositions are ca. 360oC / 1.6 GPa. Calculated temperatures derived from omphacite inclusions and neighboring garnet increase from garnet core to rim. These observations are consistent with the experimentally-derived stability field of lawsonite eclogite if we envision that the Samana sample crossed from the lawsonite eclogite stability field into the zoisite eclogite field with increasing temperature at about 1.5 GPa.

An obvious, but important question regarding lawsonite eclogite is its scarcity. Lawsonite pseudomorphs are reported from several localities, so it could be argued that lawsonite decomposes readily during uplift. However, this would be in contradiction to the observation that lawsonite is not only preserved as inclusions in garnet in all lawsonite eclogites, but that it also occurs as almost pristine lawsonite porphyroblasts outside garnet in the samples from Pinchi Lake, Corsica, Ward Creek and Samana. According to Ghent et al. (1993), no epidote or zoisite can be observed as a breakdown product of lawsonite in Pinchi Lake eclogites. In the Samana sample, lawsonite is largely preserved even though the lawsonite to epidote transition occurred at increasing temperature. The rarity of lawsonite eclogite might therefore not be related to a preservation problem but rather to their extreme PT formation conditions, which are rarely reached by rocks escaping the subduction factory.

With the discovery of this lawsonite eclogite from the Dominican Republic, a critical mass of reported localities has been reached. This allows some generalizations about the tectonic setting of such rocks found at the surface today. Four out of six reported lawsonite eclogites occur in close spatial association with melanges that formed in accretionary wedges. The Pinchi Lake eclogites are detached blocks, but outcropping ultramafic rocks, blueschist and melanges occur a few km away (Ghent et al., 1993). Eclogite from Port Macquarie, together with blueschists and enclosing serpentinite melange, are part of an Early Paleozoic accretionary wedge (Watanabe et al., 1997). In the Samana Peninsula, eclogite is associated with chlorite-talc schist (Giaramita & Sorensen, 1994, CMP 117, 279-292) in a transpressive

accretionary wedge (Goncalves et al., 2000, Geodin. Acta 13, 119-132), and the Ward Creek eclogite occurs in the Franciscan Complex, the most intensively studied fossil accretionary wedge. It is speculated that accretionary wedges are favourable locations for the detachment of "normal" oceanic crust slices at great depths (ca. 60 km) from the subducting plate. Subsequently, the detached fragments are rapidly uplifted towards the surface by subduction channelling, serpentinite diapirism and/or extensional underplating. Such a setting can lead to spatially related blueschist and eclogite, with lawsonite eclogite originating from the deepest part of the accretionary wedge. In contrast, most orogenic eclogites are found in thinned, passive continental margin sequences, which are subductable to beyond 100 km, but follow warmer PT paths due to a slow-down in convergence rate during collision, therefore do usually not enter the stability field of lawsonite eclogite.

The discovery of Paleozoic eclogites on northern part of North China Craton

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Chicheng-Chengde region is a part of the northern North China Craton. A ~EW trending fault (Chicheng-Congli Fault) runs cross this area. Rocks that occur in the south to the Chicheng-Congli Fault are called as the Congli complex of 2.8-2.6 Ga, whilst rocks that occur in the north to the Chicheng-Congli Fault are called as the Hongqiyingzi complex of 2.5-2.35 Ga. All rocks underwent metamorphism of granulite to amphibolite facies and have similar metamorphic history since from Palaeoproterozoic. A series of garnet-amphibolite lenses occur in the Hongqiyingzi complex along the northern side of the Chicheng-Congli Fault. These garnet amphibolites have been recognized to be retrograded eclogites. Mineral assemblages and reaction textures reveal three metamorphic stages that are successively of eclogites, high-pressure granulite and amphibolite facies. The mineral assemblage of the first eclogites stage is composed of Ca-rich garnet + omphacite + rutile + quartz, which were preserved as inclusion minerals in garnets. The estimated P-T condition is 1.6-1.55 Gpa and 780-770 ℃. The second mineral assemblage represents a decompressive mineral reaction from eclogites facies to high-pressure granulite facies with strong ductile deformation. Albite (Ab=79.6-66.8) and Na-poor clinopyroxene was exsolved from omphacite and formed fine-grained symplictite. The third stage is represented by replacement of amphibole and plagioclase to symplectitic minerals, and metamorphic condition is 0.75-0.65 Gpa and 610-530℃. Geochemically, garnet amphibolites have flat or slightly LREE-depleted chondrite-normalized REE patterns, implying the N-type MORB affinity. They mostly plot in MORB field in other trace element discrimination diagrams. Fourteen analyses on 10 zircons from the sample 170411 and sixteen analyses on 8 zircons from the sample 819034 using the SHRIMP technique yielded ages 325 +/- 6 Ma and 325 +/- 4 Ma. An analysis on core of a zircon from the sample 170411 yields an age of 438 +/- 11 Ma with higher U/Th value of 0.14. The $^{40}Ar/^{39}Ar$ plateau ages of amphiboles are 311-332 Ma. The ages of 438, 325 and 311-332 Ma are suggested to represent formation of protolith, peak metamorphic stage of eclogites facies and amphibolite facies overprinting, respectively. In addition, voluminous lenses of peridotite and gabbro of ~400 Ma have been found along northern side of the Chicheng-Chengde Fault, associated with the garnet amphibolites in the space. The discovery of the Paleozoic eclogites in the northern part of the North China Craton causes a question why the Palaeozoic high-pressure metamorphic rocks occur within the craton? A possible answer is that these foreign lenses were from Palaeo-Mongolia Sea, tectonically overlapped southward on the Hongqiyingzi complex by a large –scale Hercynian overthrust. The more study results will be reported in the future.

Two contrasting eclogites in the North Qaidam Mountains,western China

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Eclogites were recently discovered in the Xitieshan area, the middle segment of the North Qaidam Mountains(NQD). These eclogites, together with the eclogites which have been previously recognized in the Yuka area of the western segment of the NQD and in the Dulan area of the eastern segment of the NQD, form a 350km long eclogite belt. The eclogites from the Yuka area and the Xitieshan area show different petrographical characteristics, mineral assemblages, specially, different PT path and cooling rate during decompression and exhumation. Eclogites from the Yuka area bear evidence of prograde metamorphism, such as the preservation of prograde mineral relics in garnet and growth zoning of garnet, showing a hairpin shape PT path with a coincidence of the pressure and the thermal peak of metamorphism, and with a rapid cooling rate which reflects the rapid burial and exhumation. Sm-Nd isotopic compositions show obvious Sm-Nd disequilibrium, and an isochron age representing early Paleozoic metamorphism have not been obtained. The U-Pb zircon ages in combination with the ^{40}Ar-^{39}Ar ages constrain a cooling rate of 13-15□ /Ma .In contrast, the Xitieshan eclogites have been subjected to higher eclogite facies and post-eclogite facies metamorphism, showing an obvious granulite facies overprint. The tentative PT path for the Xitieshan eclogites suggests that pressure peak precedes the thermal culmination, and thermochronologic data indicates a slower cooling rate than that of the eclogites in the Yuka area. Sm-Nd isotopic determination of Wr-Grt-Cpx gives an isochron age of early Paleozoic. The differences between the two eclogites imply their differing tectono-thermal histories during burial and exhumation. The similar eclogite-facies age and possible UHP metamorphism evidence for two different eclogites suggest that they are Integral parts of an early Paleozoic HP-UHP metamorphic belt cut by the Altyn Tagh fault.

Discussion on the relationships between eclogites and their enclosing country rocks in the Altun--North Qaidam UHPM belt of the northwestern China——"tectonic emplacement" or "in situ metamorphism" model?

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The Altun-North Qaidam area between the Qaidam block and Qilian blocks in northwest China has become the focus of recent attention because of the discovery of aboundant eclogites and the occurrence of UHP metamorphic evidences in both eclogites and their enclosing country rocks. The Altun metamorphic complex(Altun Group) and the North Qaidam metamorphic complex(Dakendaban group), previously regarded respectively as early Proterozoic metamorphic basement of the Tarim and Qaidam block, are mainly made up of felsic orthogneiss, paragneiss and amphibolite with minor eclogite, granulite,ultrabasic rock(garnet predotite) and marble, more recently, they have been considered as the results of Jingning period (0.9-1.0Ga) orogeny. Our geochemical and Sm-Nd isotopic data show the protoliths of the eclogites in the Altun-North Qaidam were derived from a long-term depleted mantle with an oceanic affinity, probably a "T" or"E" type MORB source, whereas their enclosed gneisses are similar to the gneisses of the Qilian block with Nd model age of 1.8-2.2Ga, indicating a continental affinity. Therefore, the geochemical and Sm-Nd isotopic data seem to favor tectonic emplacement relationship between eclogites and their country rocks. However, the field relationship indicating that there is not large scale tectonic displacement between eclogites and their country rocks, and petrographic data(e.g. coesite inclusions in country rocks) imply that eclogites and their country rocks experienced a common UHP metamorphism and exhumation ,which favor in situ relationship. The controversy cases can be explained as: the protoliths of the eclogites may derive from geotectonic setting with an oceanic basin rather than a large, mature, oceanic demain, probably a rifting setting. This implies that protolith of eclogite with tholeiitic composition (on the basic of zircon U-Pb dating. It is reasonable to assume that the fomation age of the protolith of eclogite is about 750-800Ma) emplaced into thinned Precambrian continental crust(with crust-formation age of 1.8-2.2Ga and recycling age of 0.9-1.0Ga during Jingning orogeny), and they experienced a common early Paleozoic HP-UHP metamorphism and following exhumation. Generally, although both model can not be reconciled completely with the observed phenomena, up to now, the "in situ" metamorphism model is seems more reasonable to explain the present field structure ,petrological, geochemical and radiometric data.

Keywords: Altun-North Qaidam, HP-UHP metamorphic belt, tectonic emplacement, *in situ* metamorphism

SHRIMP U-Pb zircon dating of HP-UHP metamorphic rocks from Western Tianshan, China

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Recent petrological studies show that the western Tianshan eclogite facies metamorphic rocks have undergone ultrahigh pressure metamorphism (Zhang, et al., 2002a, b). They formed by the subduction from the Tarim plate beneath Yili-central Tianshan plate when the south Tianshan paleo-ocean closed up. It extends westward to connect with the Atbashy UHP eclogites in Kazakhstan and maybe the largest UHP belt of oceanic rocks in the word. Sensitive high resolution ion micro-probe (SHRIMP) U-Pb analyses of zircons separated from eclogites and eclogitic micaschists are used to constrain the ages and geological evolution of Chinese Western Tianshan UHP-HP metamorphic belt. Two samples of homogeneous zircons with oscillatory zones under calthodoluminescence emission give $^{207}Pb/^{206}Pb$ ages of 310±5 Ma (10 analyses grains) and 310±7 Ma (6 analyses grains) respectively. One zoned zircons sample analyses yield three groups ages: 413±6 Ma (the ages of the core with high Th/U ratios), 255±3~276±3.1 Ma (the ages of the mixing mantle between core and rim) and 232±8 Ma (the ages of rims with rutile inclusions inside and low Th/U ratios). They plot in the same curve of concordia diagram. These three zircons analyses of eclogites suggest that the protoliths ages of eclogites vary from 310±5 Ma to 413±6 Ma formed in Late Paleaozoic, and the ages of eclogite facies metamorphism are about 232±8 Ma. One zoned zircons sample from eclogitic micaschist give two group ages: 1895±22 Ma upper intersect ages of the core and 215±23 Ma lower intersect ages of the rims in concordia diagram, which implies that the protoliths ages of eclogitic micaschist are Proterozoic and the age of eclogite-facies metamorphism is 215±23 Ma similar to that of eclogites. Because the peak metamorphic temperature and pressure of eclogite-facies rocks nearly coincide (Zhang, et al., 2002a, b), the Indisinian ages (215±23 to 232±8 Ma of zircon rim) could be considered as the ages of the deepest subduction of Chinese Western Tianshan eclogite-facies rocks.
Consequently, the HP-UHP metamorphism in Western Tianshan could happen in Indisinian epoch and the South Tianshan paleo-ocean appeared during Late Paleozoic.

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Titanium solubility in coexisting garnet and clinopyroxene at very high pressure: the significance of exsolved rutile in garnet

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Exsolution microstructures including ilmenite ± garnet in clinopyroxene and rutile in garnet are common in clinopyroxenite and eclogite from the Sulu UHP terrane. In order to understand the phase relations and Ti solubility in both garnet and clinopyroxene in a natural TiO_2-bearing system, several experiments at 5-15 GPa, 1000-1400°C were carried out using the multianvil high-pressure apparatus. The Hujianlin ilmenite-rich garnet clinopyroxenite showing exsolution microstructure was selected as starting material, because it closely approaches a composition lying in the TiO_2-CaO-MgO-FeO-Al_2O_3-SiO_2 system. Except for minor melt in one experiment at 1400°C and 5 GPa, other run products contain majoritic garnet + clinopyroxene ± ilmenite (or rutile) and exhibit neoblastic texture. With increasing pressure, Ti and Ca, Mg and Si contents of neoblastic garnet increase with decreasing Al. The principal coupled substitutions are $Ca^{2+}Ti^{4+}$ □ $2Al^{3+}$ and $Si^{4+}Mg^{2+}$ □ $2Al^{3+}$ responding to majorite component increase. Titanium solubility (0.8-4.5 wt% as TiO_2) in garnet and Grt_{Ti}/Cpx_{Ti} ratio have a pronounced positive correlation with pressure between 5 and 15 GPa. On the other hand, the coexisting clinopyroxene contains low Ti (0.13-0.53 wt% as TiO_2), and shows no significant pressure effect. Rutile exsolution in garnet is coupled to that of pyroxene exsolution; both are exsolved from majoritic garnet on decompression. Therefore, the amount of such exsolved lamellae is a potential indicator of high-pressure metamorphism in exhumed rocks, whereas the TiO_2 content of clinopyroxene coexisting with garnet is not sensitive to pressure change.

Origin of ultrahigh-pressure corundum-rich garnetite in Sulu garnet peridotite from eastern China

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Massive, coarse-grained corundum-rich garnetite occurs as an isolated block or thin dike in mantle-derived, ultrahigh-pressure garnet lherzolite in Donghai of the Sulu terrane. This rock consists of ~80 vol% garnet and ~20 vol% corundum. Minor secondary Mg- and/or Al-rich hydrous phases, such as zoisite, pargasite, Mg-staurolite, Mg-chloritoid, sapphirine and chlorite, occur along thin cracks. Pyropic garnet ($Prp_{54-63}Grs_{26-36}Alm_{10-12}$) exhibits an unusually sinusoidal REE pattern characterized by strong depletion in light REE relative to middle REEs (MREE). The LREE increase in abundance from Ce to Sm (peak at Sm and Eu); however, the MREE (+ some HREE) decrease in abundance from Eu to Er, and Tm-Lu show less variation. These characteristics may have resulted from metasomatism and incomplete re-equilibration of refractory garnets with LREE-enriched melt or fluid. Furthermore garnet shows positive Ba, Ta, Pb and negative Nb, Ti anomalies; this may be caused by continental crust contamination. Red corundum grains with variable size (0.6 - 6 mm) contain considerable amount of Cr_2O_3 (1.1-1.4 wt%), and show three oriented sets of exsolved rutile needles. Delta O^{18} values of garnet and corundum are 5.1 ± 0.3 and 5.6 ± 0.2 per mil, respectively. Both garnet and corundum contain fine-grained, euhedral inclusions of Ni-Fe sulfides, Mg-rich allanite (MgO > 4 wt%) and apatite. The sulfides are intergrowths of heazlewoodite [69.4-70.9 wt% Ni; $(Ni,Fe)_{3-x}S_2$ (x = 0.22-0.37, and Fe ≤ 0.02)] and pentlandite [36.3-37.5 wt% Ni; $(Ni,Fe)_{9-x}S_8$ (x = 0.36-0.48, Fe ≤ 3.61-3.78)]. According to the phase relations of the metal-rich portion in the Fe-Ni-S system at 850°C (Sugak, and Kitakaze, 1998), these sulfides fall in the field of high-form pentlandite (hpn) + monosulfide solid solution (mss) + liquid. The sulfide inclusions in garnet and corundum may have crystallized from a trapped melt enriched in Ni-Fe-S contents at about 800°C. The protolith of the corundum-rich garnetite with very high Al_2O_3 content (>30 wt%) could be a cumulate rock with Opx + Cpx + Spl assemblage crystallized from a melt in the upper mantle. Both garnet peridotite host and its enclosing corundum-rich garnetite have been subjected to subduction-zone UHP metamorphism at > 800°kC and 4.5 GPa. Garnet and corundum were formed according to a reaction:

$$\underset{\text{Opx}}{MgSiO_3}+\underset{\text{Cpx}}{2CaMgSi_2O_6}+\underset{\text{Spl}}{CaAl_2SiO_6}+3MgAl_2O_4 = \underset{\text{Grt}}{Ca_3Al_2Si_3O_{12}}+\underset{\text{Grt}}{2Mg_3Al_2Si_3O_{12}}+\underset{\text{Crn}}{Al_2O_3}$$

Fluid infiltration along fractures during exhumation resulted in crystallization of hydrous phases. Stability relations of Mg-staurolite, Mg-chloritoid, sapphirine and chlorite provide a well-constraint retrograde P-T path. In short, the occurrence of corundum-rich garnetite in mantle-derived peridotite suggests mantle heterogeneity and a significant effect of mantle metasomatism and continental crust contamination.

Metamorphism and fluid evolution of the UHP rocks from the pre-pilot hole of the Chinese Continental Scientific Drilling Project

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The eclogite, garnet peridotite, orthogneiss, paragneiss and quartzite from the First Pre-Pilot Hole of the Chinese Continental Scientific Drilling Project (CCSD-PPH1), located in the eastern part of the Dabie-Sulu UHP metamorphic belt, constitute a rock association of metamorphic supracrustal rocks, granitic gneiss, and mafic and ultramafic intrusives. All of the rocks have been subjected to an early eclogite-facies UHP metamorphic event and later amphibolite-facies retrogression. The P-T conditions for the coesite-bearing eclogite and eclogitic gneiss are 785-820°C and > 2.7GPa. Those for the garnet peridotite, however, are probably 1100-1200°C and 6.3-8.0 GPa, implying a very low geothermal gradient with a great depth of 200 km. The difference of P-T conditions between the eclogite and garnet peridotite and their tectonic contact relationship indicate strongly that the latter had emplaced into the country rocks by tectonic transformation. Significant diffusion compositional zoning in the rim of garnet and clinopyroxene porphyroblast from the garnet peridotite has been recognized, suggesting that the rims of the two minerals are in chemical disequilibrium. This is probably the main cause for the estimation of lower P-T values for the UHP metamorphism in the Sulu terrane as suggested by some of the previous workers. A complex chemical metasomatism is present in the garnet peridotites that have experienced low-pressure hydrous alteration. Many crustal materials with high Na, K and Ca contents, and a large volume of fluid have been added into the garnet peridotite, and changed its original composition.

Fluid inclusion study shows that four types of fluid inclusions are present in the UHP rocks from the CCSD-PPH1 hole. (1) aqueous inclusions containing high-salinity $CaCl_2$-NaCl-H_2O fluid (type I) which occur in garnet, omphacite of eclogite and in kyanite of quartzite and have probably trapped the fluid present in the peak of UHP metamorphism; (2) inclusions containing mixed H_2O-CO_2 (±N_2) -NaCl±other solids (type II) which occur in quartz of the eclogite and in kyanite that may reflect the fluid introduced into the UHP rocks during their exhumation and retrogression; (3) inclusions containing aqueous solution of medium-low salinity (type III) in the eclogite, kyanite quartzite and gneisses that have been trapped in the amphibolite-facies retrogression and even later; (4) carbonic inclusions of medium-low density (type IV) which are distributed along transgranular fractures of quartz in kyanite quartzite.

Generally, the pressure derived from the isochores of type I inclusions based on microthermometric data is much lower than the pressure obtained from the mineral thermobarometer. This implies that most type I inclusions have suffered changes in composition and density (decrease) to various extent after their trapping, including leakage, partial decrepitation and fluid-rock interactions. In rare case, high-density type I inclusions are found in the eclogite; the isochore or pressure thus calculated is compatable with that of the peak eclogite-facies metamorphism. Fluid inclusion data also suggests that the fluid system was more or less a closed one and there was no large-scale fluid flow during the peak of UHP metamorphism in the region.

Poly-phase deformation of the UHP rocks in the Sulu UHP Belt, eastern China: implications for continental subduction and exhumation

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The Sulu UHP metamorphic belt is the eastern extension of the Qinling-Dabie collisional orogenic belt, central China developed in the Middle to Late Triassic when the North China plate collided with the Yangtze plate. The Sulu UHP metamorphic belt extends over 500 km NE-SW from Donghai County in northern Jiangsu Province to Weihai City on the northeastern corner of Shandong Province, eastern China. The UHP rocks resulted from deep continental subduction and subsequent exhumation show poly-phase deformation and metamorphism during its long journey to the mantle and return to the surface. Detailed study of the structural geometry, kinematics, rheology and metamorphism of the UHP rocks will help understanding the tectonic processes of the deep continental subduction and exhumation. Folding and shear structures are developed at eclogite-, amphibolite- and greenschist-facies metamorphism. Folds developed at eclogite facies fold the layering in eclogitic rocks and garnet peridotite. They are tight folds with slightly thickened hinge area and thinned limbs, and of Ramsay type I_c. The hinge lines and axial planes of the folds vary from block to block including recumbent folds, upright folds and vertical folds. No penetrative schistosity is observed associated with the folding deformation at eclogite facies condition. Strain-localized ductile shear zones of eclogite facies are well developed. They range from centimeter-scale to km scale in the Sulu UHP belt. UHP minerals such as omphacite, garnet, kyanite and rutile (occasionally coesite) are variably deformed and refined showing strong strain-localization and partition also on a micro-structural scale. A regional scale HP-UHP ductile shear zone running 200 km NE-SW in the UHP belt, lies structurally under the UHP rocks and above the none-UHP rocks. The HP-UHP shear zone has well-developed foliation and lineation. The foliation dips variably due to later phases of folding but the lineation plunges mostly to the S-SE and N-NW. Kinematic indicators show consistently top-to-the-north sense of shear. The most pronounced structural feature in the Sulu UHP belt is a regional penetrative schistosity, which is developed at amphibolite facies condition and overprints structures of the eclogite facies. The schistosity is defined by amphibolite facies mineral assemblage and is structurally parallel to the axial planes of isoclinal folds developed at the same metamorphic condition. Mineral lineation on the schistosity surface is usually faint. The isoclinal folds have very thickened hinge area and thinned limbs. They are of Ramsay type I_c to II. The fold hinges and axial planes as well as the schistosity are variably oriented due to refolding at greenschist-facies condition. Ductile shear zones developed at the amphibolite facies show either strike-slip or normal sense of shear deformation. Overprinting on all the early structures is a regional folding deformation that refolds the schistosity, fold surfaces and the shear zones. The last phase folds are characterized by tight to isoclinal folding with little thickening in the hinge area or thinning on the limb. An axial plane cleavage is sometimes seen developed around the fold closure and cuts the schistosity developed at amphibolite facies. We interpret the eclogite facies folds as a localized feature developed either during subduction or early exhumation. The geometric relation between the HP-UHP shear zone and the UHP- and none-UHP- rocks, suggests that it is probably a regional detachment that evolved during the early stage of exhumation of the UHP rocks in the region. Kinematic indicators suggest that the UHP slab was thrust to the north during the early stage of exhumation. Nd and Pb isotope data from post orogenic granites, mafic and ultramafic intrusions show that the Sulu UHP belt is underlain by the North China Plate. Combining the structural observations with the Nd and Pb isotope data, we suggest that the subduction polarity in the Sulu region is the North China Plate down

to the south rather than the Yangtze Plate down to the North as commonly believed. The amphibolite folding and shearing are related to a regional extension deformation at a late stage of the exhumation of the UHP rocks in the region.

The nature of protoliths for UHP metamorphic rocks in the Dabie-Sulu Orogen: Evidence from zircon oxygen isotope and U-Pb age

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UHP metamorphic rocks in the Dabie-Sulu orogen consist of eclogite, paragneiss (including quartz schist and jadeite quartzite), marble, garnet peridotite, and granitic orthogneiss. A number of petrologic and geochemical studies have devoted to recovery of their protoliths, and the predominance of igneous protoliths with a bimodal composition is evident. Oxygen isotope analyses, U-Pb dating and cathodoluminescence observation were carried out for zircons from the UHP rocks in order to retrieve the age and evolution history of their protoliths.

The oxygen isotope analyses were completed by the laser fluorination technique, and the results show a large variation in zircon $\delta^{18}O$ values from −10.9‰ to +8.5‰, most of them are lower than the mantle zircon $\delta^{18}O$ values of 5.3±0.3‰. Because the oxygen isotope composition of zircon would not be affected by subsolidus hydrothermal alteration and granulite-facies metamorphism, protoliths of low-$\delta^{18}O$ eclogite and granitic orthogneiss correspond to mafic and felsic igneous rocks with low $\delta^{18}O$ values, respectively.

Two types of zircon U-Pb dating were carried for the UHP rocks of igneous origin. One is the conventional single grain method and thus the protolith ages are obtained from the upper intercept age of the conventional Wetherill-type discordia line with the concordia curve. The other is the SHRIMP ionprobe technique to read $^{206}Pb/^{238}U$ or $^{207}Pb/^{206}Pb$ ages for zircon cores. All the available results show an U-Pb age range of 620 to 880Ma with a mode range of 700 to 800Ma and a pronounced cluster at about 750Ma. These ages are interpreted to correspond to igneous rocks emplaced in the Neoproterozoic along the northern margin of the South China Block. Protolith ages of paragneisses, some eclogites and granulites were dated by the conventional U-Pb discordia method to range from about 1.2 to 3.4Ga. This is consistent with the common consensus that the Neoproterozoic protoliths of the orthogneiss and some eclogites intruded themselves into the Mesoproterozoic to Archean basements in the South China Block. Sedimentary succession on the South China Block during Middle to Late Neoproterozoic is called the Sinian system that mainly consists of tillites, platfomal carbonates, phosphorite deposits and black shales.

Widespread ^{18}O depletion is identified in the magmatic zircons of mid-Neoproterozoic age, with an outcrop area of over 20,000km^2 along the northern edge of the South China Block. The Neoproterozoic low-$\delta^{18}O$ magmatic activity is contemporaneous with Rodinia supercontinent breakup and global glaciation (the snowball earth event), and thus there are genetic relationships among them. Early mafic magma intruded the middle crust along the rift zones in the northern margin of the South China Block, and the magma served as the heat source to cause glacier melting and deep circulation of surface water in the interior of rift zones, resulting in high-T hydrothermal alteration. As a consequence, remarkable decrease in oxygen isotope ratio occurred for felsic country rocks and intruded mafic rocks. Remelting of hydrated rocks due to decrease in melting point produced large areal bimodal magmatism at middle Neoproterozoic in the northern margin of the South China Block, from which low-$\delta^{18}O$ zircons crystallized. Therefore, oxygen isotope negative anomaly for UHP metamorphic

rocks in the Dabie-Sulu orogen is inherited from their Neoproterozoic protoliths of low $\delta^{18}O$ values, its genesis is related to meteoric-hydrothermal alteration at supersolidus temperatures that was caused by coupled Rodinia breakup, snowball earth event and rift magmatic activity.

Tectonic Evolution of UHP Metamorphic Belt in Dabie –Sulu Massif, Central China

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The basic principles of rheology of the lithosphere and analytical tectonics are used to examine deformational features of the UHP and HP metamorphic rocks and the processes responsible for their formation and exhumation in the UHP and HP metamorphic belt within the Tongbai-Dabie-Sulu region, China. Detailed structural studies combined with detailed petrological analysis enabled us to distinguish structures related to the Triassic continental collision from those related to post-collisional deformation in the UHP metamorphic belt. The collisional or compressional structures include the massive eclogite with a weak foliation, foliated eclogite or UHP ductile shear zones, as well as upper amphibolite facies shear zones, whereas the post-collisional deformation is characterized by a regionally, flat-lying foliation containing stretching lineations and common reclined folds. The former represents orogenic thickening or syn-collisional events, while the latter shows sub-vertical shortening and ductile thinning of the metamorphic rock stack.

On the basis of structural analysis, and combined with the data of petrography, P-T paths of UHP metamorphic rocks and geochronology, a speculative rheological evolution model for the UHP and HP metamorphic belts is proposed. In this model, the age of 250-220Ma is considered as the most reliable estimate for the time of the UHP and HP metamorphism and also the continental collision between the Sino-Korean and Yangtze cartons. The main consequence of this collision was building of a crustal-stacking wedge. The UHP and HP metamorphic rocks were exhumed from the mantle depth to the surface during a multistage history including wedge intrusion (230-200Ma), crustal ductile thinning and extension flow (210-170Ma), and late-orogenic collapse and unroofing.

The deformation features in the massive eclogite lenses and the country rocks shows that metamorphism and deformation partitioning played an impotant role in the preservation of the fresh massive eclogites as record-keepers of the deep subduction within the Dabie-Sulu UHP metamorphic belt. UHP structures related to collision are present exclusively in the eclogite lenses and marked by the development of anastomosing ductile shear zones hosting massive eclogites.

Structures accompanied by initial exhumation of UHP rocks and their decompressional retrometamorphism were essentially displayed along the margins of eclogite lenses, or observed in the form of small-scale discrete shear of 0.1 to 1 m thick in the UHP shear zones, indicating that the deformation was progressively localized in the pre-existing high strain zones. The structures including foliation, lineation and symplectites postdated the formation of UHP shear zones. The foliation is also characterized by an anastomosing pattern, formed under compresional environment The deformation accompanied by the initial exhumation and retrometamorphism of UHP rocks at upper amphibolite facies conditions, suggesting that the deformation was associated with metamorphic decompression and amphibolitization of the eclogites. The anastomosing UHP shear zones and the upper amphibolite facies shear zones are both with steep-dipping foliations. Field relationships and microstructural observations indicate that partial melting was synchronous with, or probably, slightly later than the deformation. It is believed that the reheating played an important role in the tectonic evolution and thermal history of the UHP metamorphic belt.

In the subsequent late event, previously formed structures were modified. The main structures related to the early collision or compression was strongly overprinted by extension. The exhumation of UHP rocks up to middle-upper crustal levels was mainly accomplished by the formation of a Cordilleran-type extensional complex, predated a Cretaceous reheating of the crust (~140 Ma). The extensional tectonic framework has well documented on a regional scale, indicating that the development of multi-layered extensional detachment zones was an efficient agent for exhuming UHP rocks of the Dabie-Sulu massif. Part of the lower continental crust may drag out from beneath the superficial levels.

To sum up, the tectonic exhumation process can be divided into three stages. During the first or initial exhumation stage, about 230-200 Ma, the UHP metamorphic rocks or the subducted wedge were rapidly extruded from the mantle depth to middle-lower crustal levels, accompanied by the formation of garnet-bearing granites following partial melting under a compressional regime, probably driven by the collision process between the Yangtze and Sino-Korean cratons and delamination of the overthickened lithospheric mantle. The exhumation of UHP rocks up to middle-upper crustal depths was accomplished principally by the development of a Cordilleran-type metamorphic core complex within a regional extensional strain field, that is, most of the crustal ductile extension and thinning had been accommodated during the second exhumation stage, about 210 -170 Ma. Cretaceous and Cenozic unroofing and orogenic collapse occurred after the regional extension, belonging to the third exhumation stage.