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High Pressure (HP) and Ultrahigh Pressure (UHP) metamorphism in continental crust and oceanic lithosphere («subduction metamorphism»)

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Abstract of the talk given on June 21, 2014, in Aosta, Hotel Europa, at the 81st SASEG Convention.

Subduction and eclogite-facies metamorphism

According to Plate Tectonics, the unifying Earth's Science theory, the lithospheric plates may be subjected to three main relative movements:

1. At passive boundaries, the plates slide horizontally past each other (see Fig. 1 left), such as the San Andreas fault in California;
2. At divergent boundaries, plates move apart and create new lithosphere (see Fig. 1 center), such as in the mid-ocean ridges;
3. At convergent boundaries, plates collide and one is pulled down (subducted) into the mantle and recycled (see Fig. 1 right). Three different types of subductions may be distinguished:

a. oceanic plate sinking below oceanic plate,
b. oceanic plate sinking below continental plate (Fig. 1 right), or
c. continental plate colliding against another continental plate (Fig. 2).

This last type of collision produces the so-called «collisional orogens», such as the Himalayan-Alpine mountain belt. It is important to point out that, before collision, the two continental plates (in the case of the Western Alps the European plate to the north and the African (or Adria) plate to the south) were separated by an ocean (the Mesozoic Tethys) which favoured the subduction of oceanic lithosphere below continental lithosphere. With advance of subduction, the ocean basin progressively disappears until the two continental blocks (plates) collide (Fig. 2). However, remnants of the former oceanic basin – squeezed between the two blocks – are preserved and allow to recognize the «*oceanic suture*», i.e. the original location of the disappeared ocean. These oceanic remnants are known as «*ophiolites*». In the Alps, the *Piemonte zone of Calcschists with meta-ophiolites* (Fig. 5) is the remnant of the former Mesozoic Tethys oceanic basin.

During subduction, within the subducting plate the isotherms are deflected downwards, because the rock thermal re-equilibration is slower than the velocity of the sinking lithospheric plate (see Figs. 1, right, and 2). As a consequence, in the subducting plates the geothermal gradients (i.e. the rate of increasing temperature with respect to increasing depth in the Earth's interior), which are normally ~ 25 °C/km, may decrease down to ~ 5 °C/km, depending on the speed of the subducting plate.

Most minerals or mineral assemblages, stable at «normal» gradients (i.e. within the fields of greenschist, amphibolite and granulite facies, Fig. 3), become unstable and transform into new minerals as a consequence of the pressure increase.

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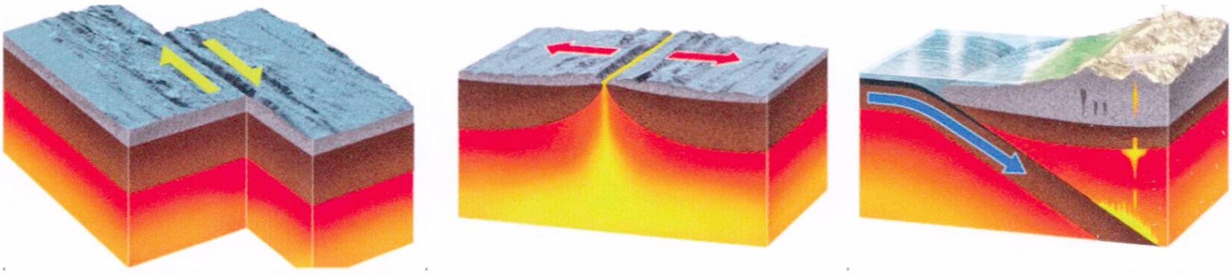

Fig. 1: The three main relative plate movements expected by the Plate Tectonics Theory. Left: passive plate boundaries; center: Divergent plate boundaries, where new ocean floor is generated by uprising basaltic magma; right: convergent plate boundaries, where lithospheric plates sink (subduct) into the mantle and andesitic magma (in yellow) is generated. Grey: oceanic (thinner) and continental (thicker) crust; brown: rigid lithospheric mantle, forming the prevailing part of the lithospheric «plates»; red to yellow: ductile upper (asthenospheric) mantle. *T* is progressively increasing with depth (from red to yellow) [from Press et al. 2003].

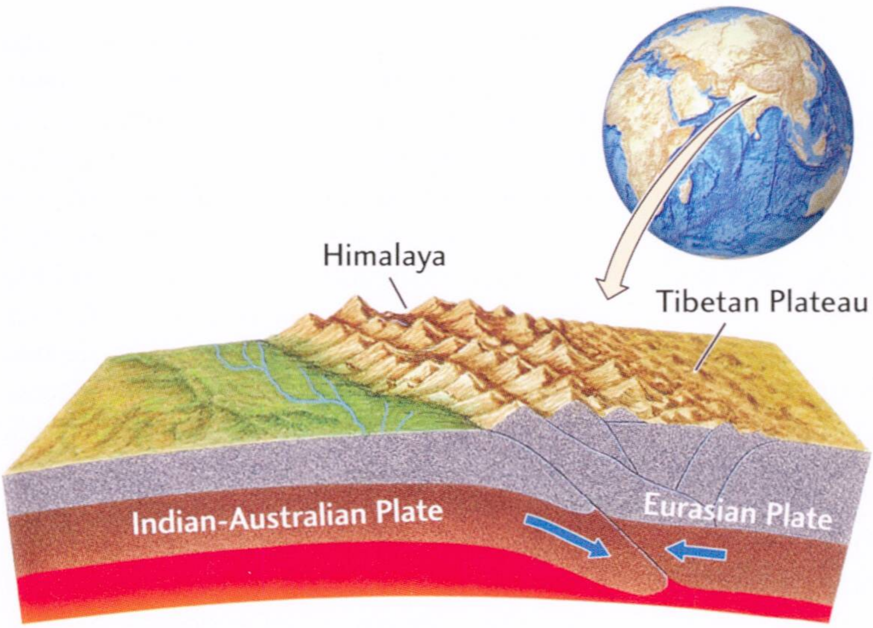

Fig. 2: The best example of a collisional orogen is the Himalaya chain, formed by the collision of the Indian-Australian Plate against the Eurasian Plate. In grey the continental crust of the two plates, in brown the lithospheric mantle, and in red the asthenospheric mantle [from Press et al. 2003].

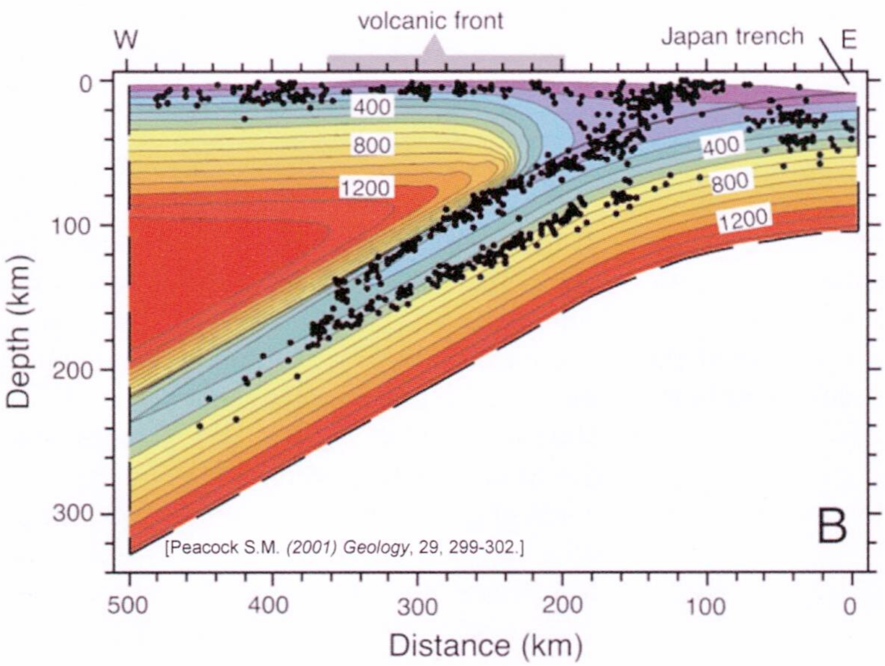

Fig. 3: The downward deflection of the isotherms in a subducting slab is well exemplified by the Japan Islands subduction zone. The *T* distribution is highlighted by different colours, at constant intervals of 400 °C. The black dots show locations of the earthquake foci.

The subduction metamorphism corresponds to P-T conditions of the blueschist facies and of the eclogite facies (green in Fig. 4), which is named after eclogite, the most typical rock type. The eclogite facies has been further subdivided into the quartz-eclogite subfacies, where quartz is the stable silica phase, and coesite-eclogite subfacies, where coesite – its higher-P polymorph – is the stable silica phase (Fig. 4). Rocks recrystallized under the quartz-eclogite subfacies are said to belong to the High Pressure (HP) metamorphism (darker green in Fig. 4), whereas those recrystallized under the coesite-eclogite subfacies to the Ultra High Pressure (UHP) metamorphism (lighter green in Fig. 4).

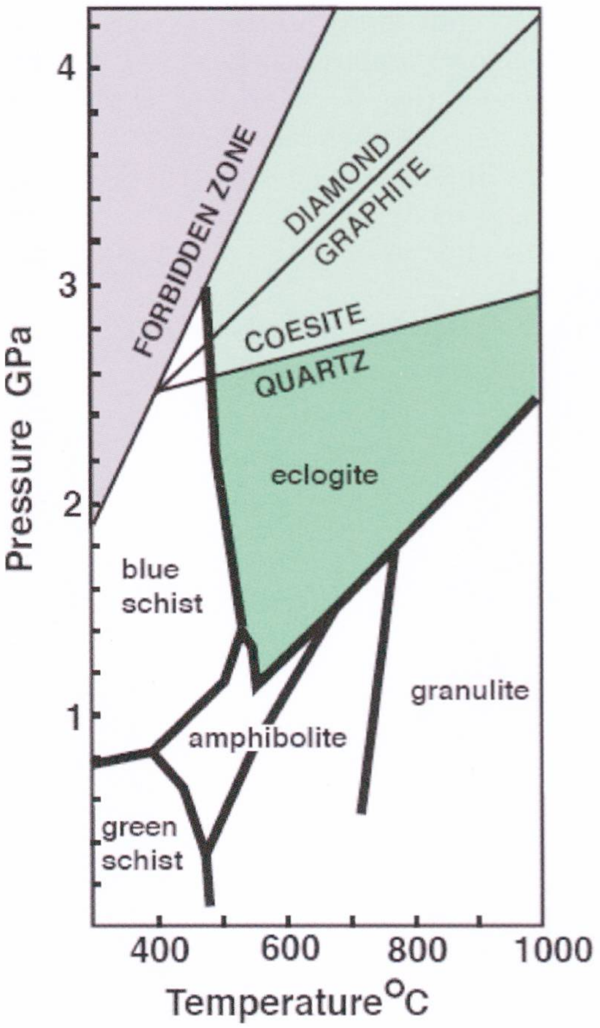

Fig. 4: P-T diagram which shows in green the eclogite-facies field, characterized by low- (10–20 °C/km) to very low (down to ~ 5 °C/km) geothermal gradients. In darker green the quartz-eclogite subfacies (i.e. the field of High-Pressure (HP) metamorphism), and in lighter green the coesite-eclogite subfacies (i.e. the field of Ultra-High-Pressure (UHP) metamorphism) where diamond may be present at the higher-pressure portion. In grey the «forbidden zone», bounded by the 5 °C/km geotherm line, which corresponds to extremely low geothermal gradients so far never observed in nature (drawn by Jane Gilotti).

The basalt to eclogite transformation

Because the eclogite is the most typical HP rock, mineral reactions leading to its formation are useful to understand the process of the subduction metamorphism.

The eclogite is a mafic rock with the bulk chemical composition of a basalt (or a gabbro, its equivalent plutonic rock). The most significant reactions, leading to the conversion of basalt (or gabbro) to eclogite, are triggered by the P increase and accompanied by a density increase from 3.0 (basalt) to 3.5 (eclogite).

Basalt (or gabbro) consists of two igneous minerals: *plagioclase* (anorthite-rich) and *clinopyroxene*, and *eclogite of* two main metamorphic minerals, *garnet* and *omphacite* (a Na-clinopyroxene). However, each phase is a complex solid solution of two or more pure end-members.

Plagioclase is a solid solution of albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$), the *clinopyroxene* of diopside ($CaMgSi_2O_6$) and hedenbergite ($CaFeSi_2O_6$). *Garnet* is a solid solution of three main end-members, almandine ($Fe_3Al_2Si_3O_{12}$), pyrope ($Mg_3Al_2Si_3O_{12}$), and grossular ($Ca_3Al_2Si_3O_{12}$), and *omphacite* is a solid solution of jadeite ($NaAlSi_2O_6$), diopside ($CaMgSi_2O_6$) and minor aegirine ($NaFe^{3+}Si_2O_6$).

The eclogite usually includes, in addition to the anhydrous minerals garnet and omphacite, accessory rutile (TiO_2), quartz or coesite. However, locally other hydrated mineral phases may be present, which are useful to infer the peak eclogite-facies conditions: they are amphiboles (mainly glaucophane, ~ 2 wt % water), zoisite (0.5–2 wt %), lawsonite (12–13 wt %), white micas (phengite and/or paragonite, ~ 4 wt %), etc. The hydrated minerals are also very important for the transfer to depth and later release of water during subduction, which favours the andesitic magma generation of the volcanic arc (cf. Fig. 1 right).

The basalt to eclogite transformation, therefore, may be summarized by the following simplified mineral reactions (in black the igneous and in red the metamorphic minerals):

albite (component in Pl) ($NaAlSi_3O_8$)			→	jadeite ($NaAlSi_2O_6$)	+	quartz (SiO_2)
anorthite (component in Pl) ($CaAl_2Si_2O_8$)			→	grossular (component in **Grt**) ($Ca_3Al_2Si_3O_{12}$)		
or			→	zoisite ($Ca_2Al_3Si_3O_{11}\,OH$)		
or			→	lawsonite ($CaAl_2\,(OH)_2\,[Si_2O_7]\,H_2O$)		
diopside ($CaMgSi_2O_6$)	+	jadeite ($NaAlSi_2O_6$)	→	omphacite ($CaMgSi_2O_6 \cdot NaAlSi_2O_6$)		

An interesting consequence of the albite breakdown is the release of free silica (lacking in the original basalt), which may crystallise as either quartz (at lower *P*) or coesite (at higher *P*) (see Fig. 4).

The geologic cross section of the lower Val d'Aosta

This short introduction to the subduction metamorphism is essential to the understanding of the outcrops visited in the first day of the 2014 SASEG field excursion along the lower Val d'Aosta cross section.

During mountain building, deformation processes – folding, thrusting and faulting – are accompanied by metamorphism and magmatism. In the western Alps, magmatism is limited to the small Oligocene intrusions of Brosso-Traversella (Fig. 5) and of Valle del Cervo with related andesitic dykes and flows. On the contrary, two main types of orogenic metamorphism are observed: an earlier high-P metamorphism, which generates during subduction and collision, and a low-P metamorphism, which develops during the subsequent rock exhumation. Usually, in most orogenies this second event pervasively obliterates, especially in continental crust, the minerals formed during the HP event. However, in the western Alps, the Eclogitic Micaschist Complex of the Sesia Zone shows extraordinary fresh HP mineral assemblages, well preserved most likely because a very fast exhumation prevented retrogression. Between Ivrea and Châtillon (Fig. 5) both the continental crust of the «Eclogitic Micaschist Complex» (EMC) of the Sesia zone (Fig. 5, Stops 1 to 4) and the ocean-derived Piemonte zone of «Calcschists with meta-ophiolites» (Fig. 5, Stop 5) are extensively exposed on fresh surfaces polished by the Val d'Aosta Quaternary glacier.

For the stops description we refer to the Field Excursion Guide-book.

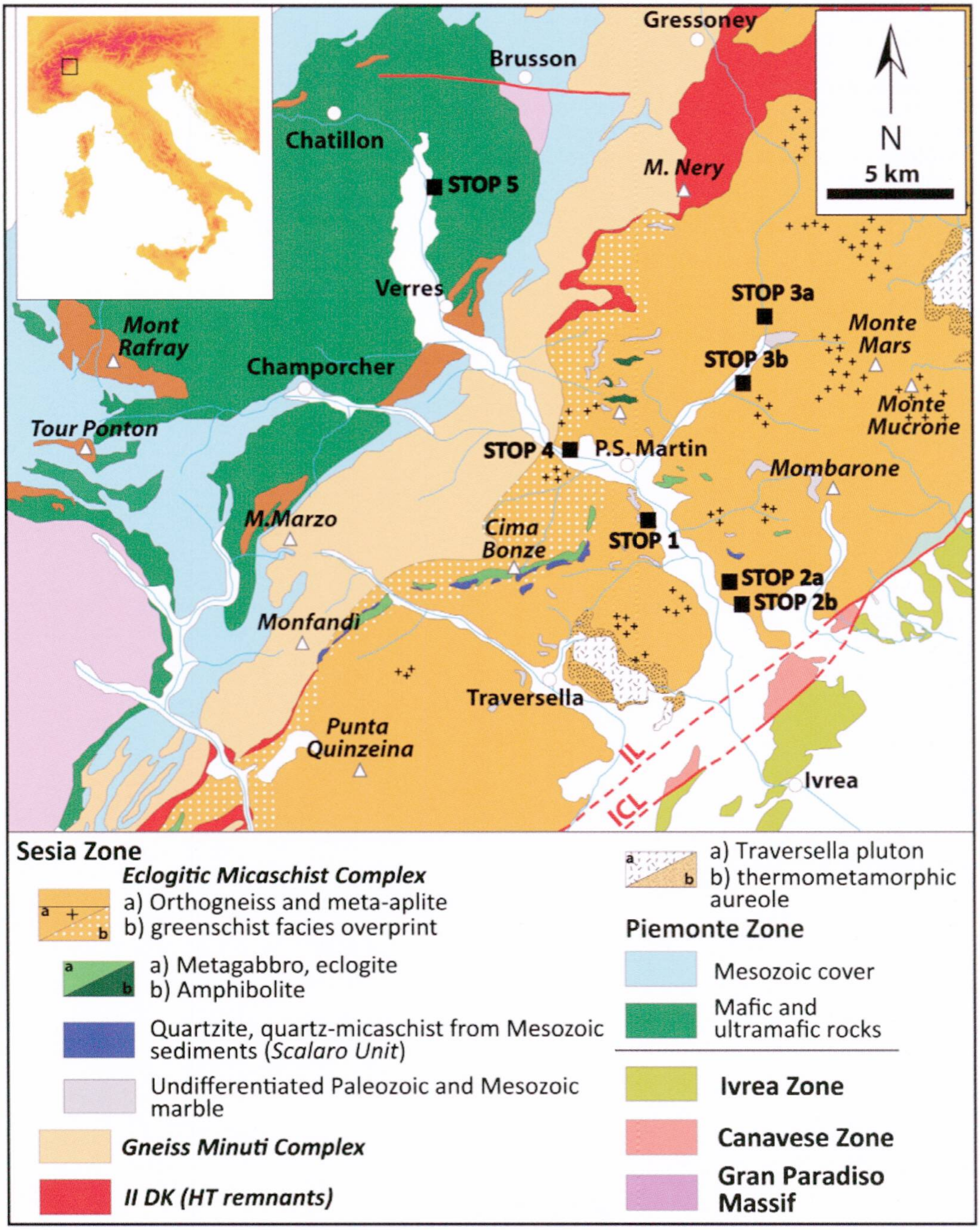

Fig. 5: Geotectonic map of the lower Val d'Aosta with location of the stops visited during the 2014 SASEG excursion. Stops 1 to 4 are within the eclogite-facies continental crust of the Eclogitic Micaschist Complex of the Sesia Zone, Stop 5 within the eclogite-facies Piemonte zone of Calcschists with meta-ophiolites [from Compagnoni et al. 2014].

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