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INTERNATIONAL LITHOSPHERE PROGRAM (ILP)

new Task Force: 2010-2014

PROPOSAL

Continental Collisional Orogens: from Atomic Scales to Mountain Buildings

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Scientific rationales and objectives

The plate tectonics theory postulates that almost all geological activities at the Earth's surface—e.g., volcanic eruptions, earthquakes, tsunamies, formation of sedimentary basins, mountain building, and even changes of composition of the atmosphere and hydrosphere—are related to processes that operate in Earth's interior. In the past decade, significant efforts have been made toward understanding how plate movements relate to mantle dynamics and how these processes result in deep subduction of continental and oceanic crust into the deep mantle, earthquakes, and volcanic activities. Continental collision occurring at convergent boundaries is one of the basic mechanisms of plate tectonics that have led to continental accretion and the growth of the supercontinents throughout the history of the Earth. Ancient collision zones are deeply eroded but may still be recognized due to the preservation of relics of ultrahigh-pressure metamorphism (UHPM), intense ductile deformation, and plutonic activity that separates tracts of continental crust having different geologic histories prior to the collision. Wide spectra of geological and geodynamic events recorded in the collisional orogens link together large-scale processes such as deep subduction of the lithospheric plates, mantle convection, and mountain range formation.

They include high-pressure (HP) and ultrahigh-pressure (UHP) metamorphism, mineral phase transformations, thermodynamics and kinetics of mineral reactions at extreme *PT*-conditions, stable isotope characteristics, the fate of deep-subducted slabs, and/or delaminated lower crust, mineral phase transformations, UHPM rock exhumations, the origin of orogenic igneous rocks, fluid-assisted element mobility, and their transportation from the surface and subsurface shallow levels into Earth's deep interior. The former Task Force IV established a strong intellectual network between geologists representing 26 countries for studies of the UHPM rocks within worldwide known collisional orogens in EuroAsia, North and South America, Australia, Antarctica, and Greenland, and *promoted innovative analytical technologies, synchrotron-assisted resources, advanced instrumentations, and numerical modeling.* Such cooperation has significantly enriched the international Earth sciences community and strengthened ILP missions through workshops, special sessions, international summer schools, and scientific contributions in high-quality proceedings. As a result, it has brought the UHPM discipline to a higher quantitative level of research; extended our fundamental knowledge of deep-mantle processes, leading to better understanding of the enormous forces that move lithospheric plates, shape continental margins, and trigger volcanic eruptions and earthquakes; and enabled visible interdisciplinary and educational impacts. Many young scientists and students took part in Task Force IV forums and became active members of the UHPM community.

During the Task Force IV term, due to our integral multidisciplinary approach, there were several new breakthroughs in studying UHPM formations and related tectonic processes operating within continental collisional orogens. Some of these have forced geologists and geophysicists to engage in a serious rethinking and reappraisal of existing knowledge and concepts. We use them as a foundation for the new Task Force intellectual background.

NEW TIME – NEW FOCUS

1. Discovery of coesite – a high pressure polymorph of SiO_2 in metamorphosed oceanic crust. One of the recent remarkable achievements is discovery of the coesite within Pliocene eclogites, the youngest documented UHPM rocks, exposed in the eastern part of Papua New Guinea at the convergent Australian-Pacific plate boundary zone (Baldwin et al., 2004). The great importance of this discovery is that eclogite exhumation from depths of ~75–80 km was extremely rapid and occurred at a plate tectonic rate of ~1 cm/yr. Although the Papua New Guinea youngest coesite-bearing eclogites associated with blueschists are considered to be a fragment of the sialic crust subjected to UHP metamorphism, a new observation came from British Columbia, Canada that involved a lawsonite eclogite exposed within blueschists that represents a fragment of the oceanic crust recrystallized at depth of ~90 km within a "cool" *P-T* gradient of ~5 °C km^{-1}(Chent et al., 2009). This is a first observation that suggests that rocks within oceanic subduction systems can achieve depths characterized by ultrahigh-pressure metamorphism.

2. Discovery of stishovite, a very high pressure polymorph of SiO_2, in Central Orogenic Belt of China.. The second achievement is grouped around a new finding of the minerals recording subduction of the continental material to a depth of >350 km. The preservation of UHP minerals in deeply subducted rocks during their uplift depends upon fast exhumation and encapsulation of the UHP mineral relics into fluid-impermeable host materials such as zircons, garnet, and pyroxene. Until recently, the deepest minerals recognized in UHP terranes were coesite, diamond, and former majoritic garnet (Chopin, 1984; Smith, 1984; Sobolev and Shatsky, 1990; Xu et al., 1992; Dobrzhinetskaya et al,.

1995; van Roermund and Drury, 1998). New UHP minerals such as TiO_2 II with αPbO_2 structure have been described within diamond-bearing gneisses of the Bohemian massif in Europe and the Central Orogenic Belt in China (Hwang et al., 2000; Wu et al., 2005). Supercilisic titanite with coesite lamellae exsolution, Si-K-rich CPx and aragonite + magnesite inclusions in diamonds from the Kazakhstan diamond-bearing collisional orogen record a depth of subduction of ~190–280 km (Katayama et al., 2000; Ogasawara et al., 2002; Dobrzhinetskaya et al., 2006). A recent startling discovery of a precursor stishovite replaced by polycrystalline aggregates of quartz in sialic gneisses of the Altun Tagh UHP terrane of China suggests that this rock may have been exhumed from a yet greater subduction depth of >350 km (Liu et al., 2007).

3. Connection between deep mantle convection and partial melting. The geochronological studies of the Norwegian garnetites at Otroy containing decompressed majoritic garnet have suggested that the garnet peridotite is a fragment of Archean mantle that was "tectonically intruded" into a Caledonian ultrahigh-pressure package of metasedimentary/metaigneous rocks containing coesite and diamond (van Roermund and Drury, 1998; Spengler et al., 2006). This casts light on deeper-mantle dynamics by raising the question of how large rock fragments from a nearly 600-km depth can arrive at the surface. The evidence of decompressional breakdown of the majorite discovered in the WGR garnet peridotites suggests that mantle convection may move large volumes of solid rocks upward by hundreds of kilometers at a time. This type of mantle convection accompanied by a partial melting of the peridotites as well as their decompression may be applicable for other collisional orogenic belts.

4. The global and deep Earth circulation of volatiles. The critical step ahead is a new focus on the global circulation of H_2O and other volatiles (e.g., CO_2, CH_4, N_2O, and C_2F_4), which, when they collect in the atmosphere, cause a greenhouse effect leading to climate change, and when they are sequestrated in the Earth's interior form mineral-rich deposits, such as diamonds, and possibly metal-nitrides and metal carbides. In a larger scale, the transportation of H_2O into Earth' mantle through being chemically bonded as OH^- group in mineral structures at high *PT*, and then being released due to decompression may drastically change lower solidus temperatures and viscosities. Moreover, dissolution of the molecular H_2O into grain-boundary melts may promote more rapid mantle convection, return flows, mantle plume formations, and mantle devolatization, resulting in volcanism releasing deep CO_2, H_2O-vapor, N_2O, and C_2F_4 into the atmosphere and thus increasing the greenhouse effect caused by human activity. Experimental synthesis of "hydrous" wadsleyite and ringwoodite, stable at depths of 510–670 km, demonstrated that they can accommodate up to 2–3 wt% of H_2O, and calculations concluded that the potential H_2O storage capacity in the Earth's mantle transition zone is ~5x that of the volume of the modern oceanic water (e.g. Otani, 2005).

5. Deep diamonds, volatiles and D"-layer. Studies of diamonds from UHPM terranes and superdeep diamonds of kimberlitic sources showed that they contain nanometric inclusions of a supercritical C-O-H fluid enriched with K, P, Cl, S, F, and N. Observations on the diamonds and experiments suggest that these elements are highly soluble in supercritical fluids at high *PT* conditions, indicating that such fluids have probably been circulated from shallow depths to lower mantle, and possibly deeper to the D"-layer. Measuring stable isotope of $\delta^{13}C$ and $\delta^{15}N$ in diamonds showed that all UHPM diamonds are formed from a biological carbon (e.g. Cartigny et al., 2001; Ogasawara, 2005). The studies of diamonds from UHPM terranes has received a new "breath" due to the recent discovery of the microdiamond inclusions in the oldest terrestrial zircons (~3.8–4.2 Ga) from early Archean Jack Hills conglomerate from Australia (Menneken et al., 2007). Mineralogical and carbon isotope features of the Jack Hills diamonds resemble those of diamonds from UHPM terranes and suggest a relatively thick continental lithosphere and crust-mantle interaction at least 4.2 billion years ago. Furthermore, the high content of light carbon, ^{12}C, in Jack Hills diamonds (similar to diamonds from UHPM terranes), suggests that organic matter was involved in their formation and opens a discussion about the possible presence of living organisms on the earlier Earth (Nemchin et al., 2008).

6. New carbon-bearing high pressure minerals – a deep carbon observatory. Other forms of high-pressure, carbon-bearing minerals such as moissonite (SiC) and boron carbide (BC), as well as metal nitrides such as osbornite (TiN) and cubic boron nitride (BN), were recently discovered within UHPM rock-fragment incorporated in the mantle section of the Loubasa ophiolite of Tibet (e.g. Yang et al, 2007, Dobrzhinetskaya et al., 2007). The ophiolite fragment of Loubasa lies within the Yarlung-Zangbo suture zone, the collisional boundary between Asia and India (Aitchison et al., 2002). The new finding demonstrates that some fragments of oceanic lithosphere also include UHP phases derived from deep within the upper mantle, but that their protolith probably had a near-surface origin according to $\delta^{13}C$ signatures of moissanite. Until recently, consideration of the global carbon and nitrogen cycles were focused mostly on the near-surface low-*T* reactions. The knowledge was bracketed by the assumption that the oceans, atmosphere, and shallow surface and oceanic sediments represent a "closed system" with respect to biological carbon and "continental" nitrogen. However, new findings of carbides and nitrides in different terrestrial sources have changed this paradigm and demand a new reappraisal of the role of carbon, nitrogen, and other volatiles as a flux that could trigger chemical reactions and control light elements that (1) partition between solid and melt, and (2) strengthen mineral plastic flows in the deep Earth.

We propose new Task Force that *will make new breakthroughs in studying integrated processes that control deep recycling of the lithospheric plates; in our understanding of their assimilation into the deep mantle through mineral reactions, melting, and the solid-state flow of minerals at extreme PT conditions, as well as the role of the mantle convection and mantle plumes in mass-transfer; and in our extended search for new geological settings accommodating UHPM rocks/minerals, exhumation of the UHP rocks, and their assembling into mountain ranges.*

The proposed program fits with the mission of ILP in promoting studies of the solid Earth with consideration of geological phenomena as a part of an integrated process connecting the "core" and "the surface;" strengthening and coordinating multidisciplinary cooperation with emphases on numerical modeling, laboratory experiments; and exploration of novel geotechnologies, and advanced analytical instrumentations. The new Task Force will have also a strong intellectual connection to well-established U.S. national interdisciplinary organizations such as COMPRES (the Consortium of Materials Research in the Earth Sciences), and DEEP CARBON OBSERVATORY. All together we will promote "Science – for the better Life".

Project description

The goal of the Project:

1. International integration and cooperation for research in *a frontier of science* and strengthening the relationship with other Task Forces of ILP.
2. Promotion of solid Earth's sciences for understanding fundamental questions of plate tectonics and implementation of this knowledge to the needs of society.
3. Educational outreach

The Project brings together scientists and students from 26 countries: Australia, Austria, Bulgaria, Canada, China (including Academia of Sinica in Taiwan), Chech Republic, France, Hungary, Germany, Greece, India, Italy, the Netherlands, Kazakhstan, Norway, Japan, Poland, Russia, South Korea, Sweden, Slovakia, Switzerland, Spain, Mexico, UK and USA.

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Administration of the Project

The office of new Task Force is established at the Institute of Geophysics and Planetary Physics, University of California at Riverside, USA.
The project description will be placed on a Website to make it available to the scientific community. The meetings of the active members will be held once a year during official conferences and workshops. Between the meetings, the chairperson and vice chairs of the

project will communicate with active members and ILP administration via e-mail, fax, and telephone.

Scientific goals of the project

One of the principal underpinnings of our project is to take a multidisciplinary approach in studies of continental orogenic belts and elements of their formation through the combination of field observations on natural collisional orogenes, experiments conducted in laboratories, and numerical modeling. While regional geological, petrological, and geophysical studies of collisional orogens and UHPM terranes remain as a foundation of our new Task Force, ***we prioritize the directions described below*****.**

1. Crust-mantle interaction: melt and volatiles under "microscopes" and from field observations

Ultra-deep subduction of lithospheric plate fragments to depths ranging from a hundred kilometers to the core-mantle boundary has been recently recognized based on geophysical, geochemical, and petrological observations. This process is inherently linked to the studies of UHPM complexes, mantle xenoliths, and ultra-deep kimberlitic diamonds containing records of geodynamic histories of both crustal and mantle rocks at sub-lithospheric depths. Substantial quantities of crustal materials on the downgoing plate are recycled to various levels in the subduction zone. Some of them return to the shallow crust during forearc accretion and dewatering, some return to the arc crust via volcanism, some are mixed back into the deep mantle, and some may even re-emerge in mantle plumes. Present knowledge on the melt and volatiles in the Earth's mantle are based on information derived from eclogitis and peridotitic xenoliths and diamonds from kimberlites, and also from MORB basalts. Larger fragments of mantle-derived garnet peridotites and eclogite are known within UHPM terranes of collisional orogens, as well as microdiamonds that contain evidence of their crystallization from fluids enriched in both crustal and mantle microelements.

Furthermore, new evidence comes from ancient collision zones that they contain UHP minerals: stishovite replaced by coesite; TiO_2 II and metal nitrides, carbides, and boron-nitrides; and diamonds where found within exposed fragments of fossilized oceanic lithosphere. The presence of carbides and nitrides suggests that some places in the deep mantle regions are characterized by very low oxygen fugacity, which therefore points to heterogeneous oxidation in the deep Earth. In connection with volatiles storage in the mantle, we will emphasize increasing interest for understanding deep carbon and nitrogen reservoirs and their role in the global recycling process. Documentation of the presence of volatiles in UHPM rocks, garnet peridotite, and eclogite of mantle origin, and the presence of H_2O and other volatiles—incompatible elements partitioning in the deep Earth—is a problem of great importance for quantification of the mantle flow. Such integrated knowledge will be a strong basis for our better understanding of the rheology, the thermal characteristics of different mantle sections of the Earth, the origin of the partial melting in the deep mantle, and will be applied to the large-scale processes such as formation of the continental and oceanic lithospheres and fluid + volatiles evolution in time and their circulation from surface to the core.

2. Microstructures, mineral reactions and rheology at mantle *PT*-conditions

Large-scale processes underlying continental collisions, such as UHPM rock formation during deep subduction and mantle convection, UHPM rock exhumation, and mountain building, involve plastic deformation of rocks simultaneously with metamorphism. The microstructures produced by recrystallization and deformation are the chronological "memory" of UHPM rocks. The mineral microstructures are critical for interpretation of the conditions and kinetics of metamorphic reactions and rheology. However, quantitative interpretation requires expertise from both field observations of natural rocks and laboratory measurements of synthetic samples at high pressure and temperature, which are traditionally studied by two different groups of geoscientists. Although studies of microstructures of natural rocks can provide insights into the dynamic processes operating in Earth's interior, the interpretations sometimes can be controversial. Experimental studies in such cases are desirable because they enable us to reproduce the observed microstructures and measure quantitatively the physical and chemical properties of minerals and rocks at high *PT* conditions. The interpretations of experimental results, however, require extrapolations up to ten orders of magnitude of conditions (stress, strain rate, time, etc.) in comparison with those that have occurred during geological time. Recently, it has been shown that comparison of microstructures can bridge the gap between natural observations and experimental results. The petrological, geochemical, and plastic flow (creep) processes that occur at the atomic level also control large-scale properties of minerals and rocks during continental and continent-ocean collisions, their rate of exhumation, and earthquake formation. Therefore, it is important to bring mineralogists and petrologists who work on UHPM rocks together with mineral physicists involved in quantitative measurements of mineral reactions and rheology at high pressures and temperatures.

The following directions of investigation are important: (1) the role of fluid (including water and melts) during the metamorphism and/or deformation in natural UHPM rocks, (2) the influence of deformation on the metamorphic reactions in natural UHPM rocks, and (3) the collection of experimental data reflecting influences of fluid and deformation on metamorphic reactions and rheology during deep subduction and exhumation. Quantitative experimental studies of plastic properties of minerals under deep-mantle conditions are challenging, and major progress in this area has often been associated with the development of new techniques. Until recently, reliable rheological studies have been performed only at relatively low pressures <0.5 GPa (at ~15 km depth in Earth). We plan to coordinate and promote a new generation of experimental studies of plastic deformation of minerals under deep-mantle conditions by combining synchrotron-based *in situ* stress-strain measurements with newly designed high-pressure apparatuses. This chapter of our project has tremendously important implications for our understanding of the geodynamic sense of the seismic anisotropy, mantle viscosity, and mantle flow. It also represents a great step forward in understanding processes of flow and recrystallizations during subduction and exumation of UHPM rocks.

3. Experimental synthesis of new phases containing volatiles participating in "green house effect" over a wide range of mantle pressures and temperatures

Syntheses of new phases at given high *PT* conditions is a direct method for prediction of the kind of mineralogical assemblages that represent both crustal and oceanic lithosphere fragments subducted to mantle depths. We will extend our knowledge on UHPM terranes through experimental synthesis of high-*PT* phases using chemical analogs of the "granitoid" and "carbonate" systems. We will conduct experimental research at a wide range of *PT* (7–130 GPa; 1,200–1,600 ^{o}C) using both multi-anvil and diamond-anvil cell techniques to explore stability fields of the silicate from the granitoid bulk chemistry and carbonate phases, which add subsequently different volatiles. The experimental results will provide valuable information that will allow us to trace the path of K and C into deep Earth during subduction. *This knowledge is of great importance because ^{40}K has a strong influence on the Earth's thermal evolution, and because carbon reservoirs in the deep mantle may represent an example of carbonate subduction into the mantle as well as a possible way for sequestration of CO_2 and CH_4 to cause a greenhouse effect when they "contaminate" the atmosphere.* Moreover deeply stored organic carbon is a potential supplier for diamond formations, which now, in addition to kimberlitic sources and UHPM terranes of collisional orogens, are found within non-traditional geological settings such as oceanic islands (Wirth and Rocholl, 2003), fore-arc environments (Mizukami et al., 2008), and ophiolite (Yang et al., 2007).

As a new step in experimental research, we propose also experimental studies of nitrides at extreme pressures (5–130 GPa) and temperatures (1,000–3,000 ^{o}C). Establishing the phase boundaries for TiN that we have recently discovered in UHPM rock at high PT will begin to outline whether nitrogen can be a significant constituent in the Earth's mantle and core. Other metal nitrides, including Li-nitride, will also be synthesized at high pressures and temperatures to explore the synthesis of high-density metal nitrides by reaction of the nitrogen pressure medium with elemental metal substrates.

This part of experimental studies has a high technological significance because high-density nitrides show promise for both ceramic and electronic applications. The lithium nitride (LiN_3) compound is a potential material to be used in the future for fuel cells and hydrogen storage, which fits with the alternative energy interests of our society.

4. Raising the use of state-of-the-art microanalytical techniques for micro- and nanoscale observations

During past decade, many Earth science disciplines were broken up by technological progress in development of new instrumentations and novel techniques. A series of high-resolution analytical instruments, which primarily were built for condensed-matter physics and materials science, have recently become available for the study of Earth's materials, allowing us to recognize nanometric solid and fluid inclusions incorporated in microdiamonds and to establish their chemical composition and structure. This new direction, nanoscale geoscience, has had a major impact on establishing a sound correlation between results obtained with different techniques such as (1) synchrotron light sources; (2) focused ion beam (FIB)-assisted, high-resolution transmission; scanning electron microscopy (TEM and SEM); and nano-secondary ion-mass spectrometry (nano-SIMS) applied to natural minerals and their synthetic analogues, as well as new UHP synthetic phases that have not yet been found within terrestrial minerals.

In addition to the new generation of analytical transmission electron microscopes, the Titan™ 80-300 series is one of the only instruments capable of viewing and analyzing individual atoms and the bonds that join them. This new TEM gives scientists an unprecedented chance to bring research to the highest level of atomic detail available today—down to the sub-Ångstrom level—and provides critical data for process development and materials research on a highly stable, easy-to-use platform. The electron energy-loss spectroscopy available in conjunction with the Titan™ is a superb instrument package for detection of light element content in minerals and synthetic materials. New deformation apparatuses, including DDIA capable of performing deformation experiments at confining P = 4 to 10 GPa, and the rotational Drickramer apparatus—performing stress/strain experiments at confining P = 10–18 GPa—are examples of synergies of 21st-century science and technologies. Both apparatuses have special devices that allow them to be connected to synchrotron radiation facilities, and such connections between deformation apparatuses and high-energy synchrotron X-ray sources provide new *in-situ* observations that are beyond the earlier work with piston-cylinder deformation apparatuses of the Grigg's type (e.g. Karato and Weidner, 2008). In this new system of deformation mechanisms, the synchrotron–generated, high-energy X-ray beam penetrates the sample material during the experimental run and provides simultaneous measurements of diffraction and direct imagining of the run products at given *PT* and *σ*. Therefore, this new technology provides a unique opportunity to reproduce the rheological properties of the rocks up to the mantle transition zone.

5. Diamonds for education, science and novel technologies

Diamond is a unique Earth material that links together education, science and technological needs. Due to diamond's chemical inertness and its stability over geologic time, it is a near-perfect container for fluid and solid inclusions that are trapped during diamond growth. The chemistry and structure of such inclusions are used to reconstruct the mineralogy in Earth's deep horizons and the conditions of diamond-forming media. All of this provides valuable information for understanding the movements and collisions of continental plates; mountain building; CO_2-storage in the deep Earth, and mantle enrichment with H_2O, wide range of light elements, including ^{40}K: all of them strongly influence the Earth's thermal evolution, volcano eruptions, and earthquakes.

Diamond is valued as a gemstone and as a unique industrial/technological material due to its extraordinary hardness, transparency, high thermal conductivity, and ability to be a semiconductor when doped with boron. It is one the most important materials used in high-technology and many industrial applications.

Yet, being so useful for human life and society, diamonds unfortunately are used to fuel and finance armed conflicts—such diamonds are known as "bloody diamonds" or "conflict diamonds." The United Nations General Assembly has recognized that conflict diamonds are a crucial factor in prolonging brutal wars in parts of Africa. In Angola and

Sierra Leone, conflict diamonds continue to fund the rebel groups that are acting in contravention of the international community's objectives of restoring peace in the two countries.

The project will promote knowledge on diamonds to groups of interested, upper division undergraduates and graduate international students participating in a new Task Force forums, such as Workshops and field trips related to Task Force/ILP conferences. The students will be screened and selected on the basis of their academic standing and performance, major, relevant skill sets, and their collaborative capabilities. Participating in our forums they will learn different aspects flowing from existing diamond-research projects, including ethical considerations related to “conflict diamonds”, experimental and industrial designs for diamond synthesis and their novel technological applications. Through such an involvement, students will have a thorough knowledge of the research process, they will establish new contacts and networks in an intended career or academic area.

Short- and Long-Term Activities

1. Organizing workshops and special sessions at international meetings for scientific exchanges and field excursions to typical collisional oroogenic belts, especially to newly discovered ones.

2. Preparing special scientific issues of international journals to publish new developments and achievements.

3. Circulating information by setting up an electronic mailing list and a Web site.

4. Strengthening relationships with other task forces’ ILP programs in order to achieve better understanding of continental dynamics and leading directions of the relevant science and technologies.

5. Promoting education in earth materials and related novel technologies through workshops and involvement of younger generations of geologists/geophysicists.

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