Convergent Plate Boundaries and Collision Zones

Jan H. Behrmann[1], Jingsui Yang[2], and the CoZone Working Group*

[1]IFM-GEOMAR, Wischhofstr. 1-3, 24148 Kiel, Germany
e-mail: jbehrmann@ifm-geomar.de (corresponding author)

[2]Institute of Geology, Chinese Academy of Geological Sciences, 26 Baiwanzhuang Road, Beijing 100037, China

Abstract

Within the framework of the International Continental Drilling Program (ICDP) we propose a comprehensive initiative to drill the continental crust bordering modern and ancient convergent and collisional plate boundaries. These zones host the vast majority of modern megacities and industrial installations on Planet Earth, and at the same time are loci of major earthquakes, tsunamis, volcanic eruptions and other associated great natural threats to human life and to economies. In-depth understanding of dynamic Earthprocesses at convergent and collisional plate boundaries is not possible without scientific drilling embedded into integrated research programmes.

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*CoZone Working Group is: Marco Bohnhoff (GFZ Potsdam, Potsdam, Germany), Andrea Förster (GFZ Potsdam, Potsdam, Germany), Ulrich A. Glasmacher (MPI Kernphysik, Heidelberg, Germany), Jan Golonka (AGH University of Science and Technology, Kraków, Poland), Roy Hyndman (Geological Survey of Canada, Sidney B.C., Canada), Christopher Juhlin (Uppsala University, Uppsala, Sweden), Yrjö Kähkönen (University of Helsinki, Helsinki, Finland), Achim J. Kopf (RCOM, Bremen, Germany), Ilmo Kukkonen (Geological Survey of Finland, Espoo, Finland), Marek Lewandowski (Polska Akademia Nauk, Warszawa, Poland), Jason McKenna (Southern Methodist University, Dallas, U.S.A.), Roland Oberhänsli (Universität Potsdam, Potsdam, Germany), Julian A. Pearce (Cardiff University, Cardiff, UK), Victoria Pease (Stockholm University, Stockholm, Sweden), Paul T. Robinson (Dalhousie University, Halifax, Canada), Hiroshi Sato (University of Tokyo, Tokyo, Japan), Robert J. Stern (University of Texas, Dallas, U.S.A.), Tetsuro Urabe (University of Tokyo, Tokyo, Japan), Kelin Wang (Geological Survey of Canada, Sidney B.C., Canada)

The set of scientific questions identified here is rooted in the plate tectonic paradigm of a dynamic Earth. Proposed studies derived from these questions target on (1) the dynamics of active subduction and collision zones, with focus on the seismogenic zone at the plate interface, and the distribution of deformation and seismicity in general, (2) the role of mantle plumes in orogeny, (3) supra-subduction magmatism in arc systems, (4) the geological manifestation of deep subduction and exhumation of the lithosphere, and (5) aspects relating to continental birth and growth through Earth history. ICDP drilling in convergent and collisional plate margins faces unprecedented challenges regarding drilling technology, drilling depth and requirements for long-term monitoring of Earth processes in downhole observatories.

1 Introduction: The Role of Future ICDP Drilling

Continental crust is formed, deformed, and destroyed at convergent plate margins and collision zones. Subduction of plates at convergent margins is one of the most fundamental geological processes happening on Earth that contributes, in a long run, to continental growth and magmatic accretion in island arcs and, in places, to continental erosion. Subduction zones are complex, dynamic systems in which the thermal, hydraulic, and mechanical properties of the converging plates rapidly evolve in time and space. It is believed that most of the downwelling in Earth's large scale mantle convection system takes place at subduction zones.

There, one of the most life-threatening geological phenomena occurs: huge earthquakes on subduction megathrusts, including the 2004 Sumatra-Andaman earthquake (M 9.0, with the associated devastating tsunami), the 1960 Southern Chile earthquake (M 9.5), the 1964 Alaska earthquake (M 9.2), and the 1923 Kanto earthquake (M 7.9) that destroyed Tokyo, the capital of Japan. Accompanying geohazards include tsunamis, landslides, powerful volcanic eruptions, and other threats to human life, infrastructure and economies, and to ecosystems. Given that 60% of Earth's population lives within the frontal 50 km of the coast, there is a strong need for scientific and economic efforts, to shed light on the processes responsible for such ocean margin geohazards as well as their mitigation. Scientific drilling has a high potential for such studies and must be an integral and indispensable part of this effort.

Subduction and collision zones are loci of large differential movements at rates of centimeters per year or tens of kilometers per million years, and on the scale of hundreds of kilometers, with very large vertical components. Although the role of subduction in the transport of oceanic lithosphere back to the Earth´s mantle is fully appreciated in plate tectonic theory, the fate and kinematic history of rocks that were carried down to great depths but were later brought back to the surface is not well understood. The phenomenon is known since tectonic melanges were recognized as parts of fossil subduction complexes. Large size blocks or rock belts containing high-pressure or ultra-high-pressure metamorphic assemblages are viewed as resulting from differential exhumation, either driven by buoyancy forces or by upward flow in a confined subduction channel. This concept was later extended to include ductile extrusion of large, hot rock masses in zones of continental collision, and the exhumation of continental rocks having undergone deep subduction and ultra-high-pressure metamorphism in orogenic belts in general. Drilling is essential to create the base of information necessary to advance understanding of material flow and mass budgets in these zones.

A major “deep time issue“ related to subduction and collision processes lies in the old (Meso-Paleozoic and Precambrian) orogenic belts on Earth. How were continental shields being born and is the process continuing, and how do they amalgamate to form terrane collages, continents and supercontinents? While modern convergent and collisional margins are capable of yielding a wealth of “real time“ information on plate dynamics and mountain building, only the study of fossil orogens provides us with a picture of the deeper structural levels of such orogens, as required to understand how orogens evolve with time. Scientific drilling can provide a four-dimensional record of these processes, and is indispensable in the ground-truthing of geophysical measurements and observations.

Productive future research of these active geological processes by means of drilling will require comprehensive programs of coring and other sampling, of downhole measurement and experiments, and long-term monitoring. Thus, scientific drilling does not only open opportunities for encountering rocks by core sampling, but also offers new and challenging possibilities for the *in situ* and *in vivo* study of processes in the subsurface. Some of the features of interest at convergent plate boundaries and in collision zones are temperature, coupled thermo-hydraulic processes, seismicity, stress/strain, and hydrogeological parameters including pore pressure, permeability and hydrochemistry. The latter two require the performance of well testing experiments (e.g., pumping tests) and downhole fluid sampling.

The study of subduction and collision zones has always played a fundamental role in understanding plate tectonics. Among all active zones of convergence on Earth, the active continental margins, where the oceanic lithosphere is subducted beneath continental and arc lithosphere, have the greatest scientific potential for ICDP.

2 Key Scientific Questions

Many fundamental problems in the understanding the dynamics of the Earth System, its natural history and evolution can only be addressed by study of convergent plate margins and collision zones. Key scientific questions deal mostly with aspects of deformation, stress/strain, rheology of Earth materials, solid and fluid mass budgets and transfer. In most cases these aspects cannot be treated independently. The list below, we think, provides a comprehensive, but not exclusive listing of most of the outstanding problems:

- The mechanics of plate motion,
- Rheology of Earth materials,
- Stress field, kinematics and time scale of deformation,
- Strain localization and strain rate gradients,
- Topography building in response to changes in driving forces and lithosphere rheology (especially thermal structure),
- Exhumation of high-pressure and ultra-high-pressure metamorphic rocks,
- The role of fluids and melts (volcanism, plutonism etc.) in generation and modification of continental crust,
- Mass transfer budgets and the recycling of crust in modern convergent plate boundaries and collision zones,
- The birth of continents: Dynamics of fossil accretionary and collisional orogens,
- Crustal architecture and calibration of geophysical observations.

Figure 1 provides a geographical overview of the drilling locations and target areas mentioned and discussed in the text below. Any of these present a “world-class-target“ in the sense that fundamental questions can be addressed in an optimal way. Note, however, that this is a list of examples, not an exclusive list. As future developments and modifications to scientific questions to be answered by drilling occur, there will be ongoing new definition of drilling targets.

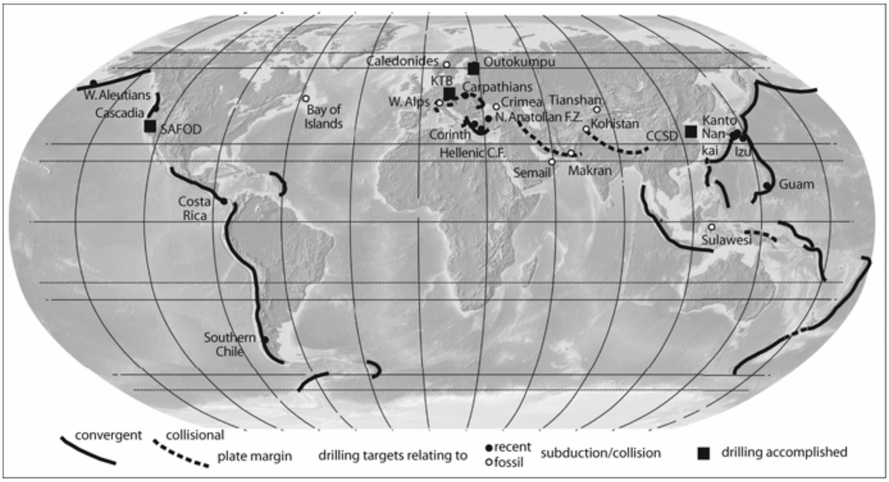

Fig. 1. Map showing distribution of convergent and collisional plate boundaries, accomplished ICDP drilling, and possible drilling targets and areas discussed in the text.

3 Specific Examples of Possible Drilling Targets

3.1 Active Subduction and Collision Zones

3.1.1 The Seismogenic Zone at the Plate Interface

Recently, our understanding on the behavior and nature of subduction megathrusts has been advanced through earthquake observations and seismic profiling (e.g., Shipley et al. 1994; Nedimovic et al. 2003; Bangs et al. 2004; Kodaira et al. 2004). The important new concept is the finding of the "asperity" on subduction megathrusts, based on the analysis of the source mechanism of interplate earthquakes (e.g., Matsuzawa et al. 2002; Yamanaka and Kikuchi 2004). The asperities on a fault surface are the zones that are interpreted to be locked during interseismic periods and generate large amounts of co-seismic slip. For example, Hayakawa et al. (2002) and Fujie et al. (2002) divided seismogenic zone on the subduction mega-thrusts into aseismic and locked parts based on observations at the Japan Trench off the Sanriku coast (Fig. 2). The aseismic part is marked by abundant small magnitude seismic activity with occurrence of repeated earthquakes and strong seismic reflection coefficients from the thrust. On the contrary, the locked part (zone of asperity) is characterized by less small magnitude seismic activity and poor seismic reflection. Close examination of the spatial relationship between the asperity and the reflectivity suggests that the asperity is generated by differences in physical properties along the megathrust plane.

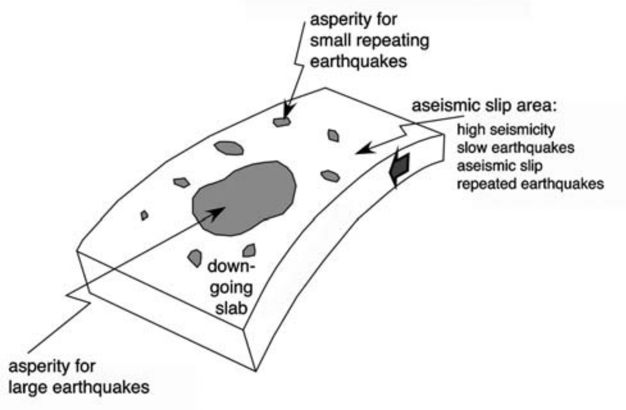

Fig. 2. Schematic diagram showing the distribution and types of asperities on a subduction megathrust, modified after Matsuzawa (2001).

It is suggested that very large inter-plate earthquakes will be initiated by rupture of these asperity patches. In other words, the physical properties of the asperity zones on subduction megathrusts control the behavior of the entire megathrust. However, it is extremely difficult to define or estimate the physical properties of the subduction megathrust from the surface. Besides, it is almost impossible to locate asperities in fossil subduction megathrust structures, and thus the only way for the direct observation of asperities is deep drilling.

Candidate sites for the asperity zone drilling of a subduction megathrust must satisfy the following conditions; a) the depth of the asperity on the subduction megathrust must be shallower than 10 km from a land-based drill site, as this depth seems to be the drillable limit from an engineering point of view, b) the site should be monitored permanently by a network of seismometers, GPS arrays, and other geophysical methods to provide a substantial enhancement of the scientific merits of the drilling, and c) the recurrent megathrust earthquake has to have a large societal impact to justify the cost of drilling. From these criteria, the greater Tokyo metropolitan area (Kanto area; Fig. 1), central Japan, could be the most suitable, although challenging drilling target of this kind in the world. Careful examination of the depths of subduction thrusts elsewhere may also locate other possible sites where the thrust is within drilling depth limits.

The Philippine Sea plate is currently subducting northwestward beneath the Tokyo metropolitan area at a rate of 30-40 mm/yr. Due to the arc-arc collision between the Izu-Bonin-Mariana and Honshu arcs, the Philippine

Sea plate shows an antiformally plunging surface from the Izu peninsula, southwest of Tokyo. Thus the part of the subduction megathrust reached to the surface as an onshore spray fault. The subduction causes megathrust earthquakes, such as the 1703 Genroku earthquake (M8.0) and the 1923 Kanto earthquake (M7.9), which caused more than 105,000 fatalities, mainly due to extensive fires after the main shock. If a recurrent M8 earthquake would occur today beneath the Tokyo metropolitan area, the economic loss may reach to the amount of Japanese annual gross national product (GNP), and trigger a worldwide economic recession. After the Kobe earthquake in 1995 (M7.2) with 6,433 fatalities and 100 billion US dollars economic loss, Japanese islands have been covered by a very dense network of seismic and GPS stations.

Inversion of continuous GPS measurements in the Tokyo metropolitan area has identified an area of slip deficit on the subduction megathrust (Sagiya 2004). This area, which is locked during the present inter-seismic period, represents an asperity patch where a future great earthquake may recur. The co-seismic asperity patches are also revealed by the inversion based on the data of triangulation before and after the 1923 Kanto earthquake and seismic records (Matsu'ura et al. 1980; Wald and Somerville 1995; Kobayashi and Koketsu 2005).

Since 2003, deep seismic profiling has been performed in the Tokyo metropolitan area for the purpose of precise estimation of strong ground motions. The geometry of the subduction megathrust is clearly imaged by four reflection seismic sections down to 25 km in depth (Sato et al. 2005; Fig. 3). By combining the above-mentioned data sets, the asperity patches beneath the Tokyo metropolitan area have been precisely determined. It should be noted that the asperity zone on the subduction megathrust is within the reach of continental scientific drilling. Nevertheless, a deep drilling project into the subduction megathrust named JUDGE (Japanese Ultra-Deep Drilling and Geo-scientific Experiments) project had been proposed since late 80's (Urabe et al. 1997), but the necessity and justification, and drilling requirements of the project are more clearly defined recently with the advance in the research on the subduction zones.

According to the historic records, two large megathrust-earthquakes occurred in 1703 and 1923 in the area and seismic cycles that consist of frequent M7-class-earthquakes before and after the large M8-class-events were observed. Judging from such temporal change in seismic activity, many seismologists agree that in the Kanto region the quiet period in seismic activity probably has gone and we are going to move into a pre-M8 earthquake cycle. We may have certain time to the next M8-class-earthquake, however, we have to start the preparation as soon as possible to be able to monitor the whole seismic cycle using an ICDP deep drill-hole.

Drilling of the subduction megathrust zone is also proposed along the Nankai Trough (Fig. 1) and Costa Rica (Fig. 1) subduction zones within the framework of the Integrated Ocean Drilling Program (IODP). Together with the scientific results from such foregoing projects, we can obtain the comprehensive information about the physical properties of subduction megathrusts at a wider depth range.

The other important contribution of deep drilling into a subduction megathrust is the long term geophysical monitoring of such a structure at depth. In general, fault zones are weak in comparison with their host rocks, thus their behaviour is very sensitive for the changes of stress and strain conditions, and they may act as amplifiers for such changes. Deep drilling projects into the subduction megathrust or seismogenic zone are already proposed as SEIZE experiments to IODP at Nankai Trough (Nantro-SEIZE), SW Japan and Central America (e.g., MARGINS Program Science Plans 2004), including geophysical monitoring. These projects are complementary to each other, and all sites have their own scientific necessity, and specific advantage. The added benefit of a land-based drill hole is to be available for long-term geophysical monitoring, desirably over several decades to cover the whole seismic cycle.

3.1.2 Processes in Active Subduction Zones

Active accretionary, erosional, and related near-trench processes at subduction zones have been targets of many DSDP, ODP, and IODP projects. IODP has now planned to sample and monitor the most seaward part the seismognic zone of the subduction thrust at the Nankai subduction zone through deep drilling. Given the numerous fundamental processes in continental forearc and back arc systems, ICDP also has an important role to play in the study of active margins. Because of the general inaccessibility of most of the research targets by continental boreholes in this environment, the ICDP involvement must be innovative and unconventional. Three aspects of the future ICDP efforts are of particular importance: determination of the thermal and mechanical states of the overriding plate, borehole observatories, and joint land-ocean borehole networks. The principal scientific issues to be addressed are as follows.

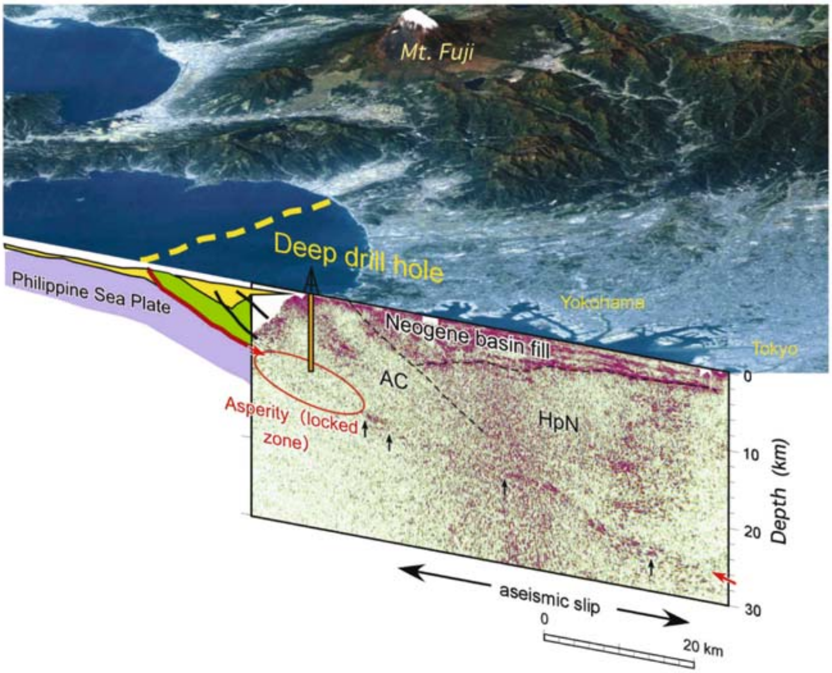

Fig. 3. Proposed deep drilling into the subduction megathrust beneath the Tokyo metropolitan area. Seismic reflection section is after Sato et al. (2005). A zone characterized by low reflectivity of the plate boundary thrust can potentially be reached and sampled by superdeep drilling.

Forearc Thermal Regime. Rock rheology and metamorphic reactions in subduction zones are strongly controlled by the thermal regime, which depends mainly on the age of the incoming plate, convergence rate, and thickness of incoming sediments. The landward limit of the megathrust seismogenic zone may be a thermally controlled downdip transition from velocity-weakening to velocity-strengthening behavior of the plate interface for young and warm slabs, or where the slab is in contact with the hydrated lithospheric mantle of the overriding plate (Hyndman and Wang 1993; Peacock and Hyndman 1999). Thermally controlled depth of brittle-plastic transition and its spatial variation affect the depths of upper plate seismicity and style of long-term forearc deformation. Temperature-controlled slab dehydration facilitates earthquakes in both converging plates, causes serpentinization of the forearc mantle wedge above the slab, and trigger melting, magma production, and hence arc volcanism (Kirby et al. 1996; Peacock and Wang 1999; Hyndman and Peacock 2003).

Despite the importance of the thermal regime in subduction zone dynamics, there have been very few good borehole heat flow measurements in this environment. The most complete land-marine heat flow profiles are probably across the northern Cascadia and the southwest Japan subduction zones. Most of the existing holes are either too shallow for high accuracy or were drilled for industrial purposes and ill suited for precision scientific objectives. There is also a lack of systematic observational quantification of the often large and rapid horizontal transitions between the thermal states of the forearc, arc, and backarc regions. Only through relatively deep (>500 m) drilling and logging at carefully selected sites, measurements of thermal conductivities and rates of radiogenic heat production on drill cores, and correlating with structural and hydrological studies, can we determine the effects of climatic and hydrological perturbations on surface heat flow values, the partition of heat budget between deep-seated processes and contribution from crustal heat production. Only by determining heat flows at multiple sites, can we constrain the spatial changes in heat flow patterns and processes that cause these changes such as mantle flow, melt migration, and frictional heating along the plate interface.

Forearc Stress Regime. Lithospheric stresses, especially those in forearcs, are direct indicators of plate driving forces and mechanical coupling between converging plates (Wang and He 1999). It is important to know how the orientation and magnitude of the stresses change in both the margin-normal and margin-parallel directions, from seaward of the trench to landward of the volcanic arc. Fundamental questions, such as the strength of the subduction fault, the effect of oblique subduction, and the role of mantle wedge flow as a potential basal driving force for the forearc – back arc system, are yet to be fully addressed. But the states of stress of the overriding plate in the forearc environment are not well constrained. One approach is to use fault mechanisms from larger earthquakes or composite mechanisms from smaller events. However, dense networks are required for accurate determination of focal mechanisms of small upper plate earthquakes. These networks exist only in a few forearcs. In addition to regional earthquake data, much of our knowledge of forearc stresses comes from studies of active faults. An important additional approach is through direct borehole observations using techniques such as borehole breakouts and other in-hole measurements that provide information on the orientation and values of stresses. The boreholes must be deep enough to avoid surface effects. Measurements are needed from multiple sites so that comparison with data of very different depth and temporal scales, such as focal mechanisms and fault, motion can be made, where these data are available.

The case for borehole observatories. An important contribution of ICDP boreholes for subduction zone studies is to conduct continuous monitoring of transient changes in geophysical and geochemical parameters related to active subduction processes. Recent geodetic, seismological, and ocean-borehole observations at convergent margins have detected a wide range of tectonic activities that were not known to us previously. These activities provide new challenges and opportunities for ICDP. ICDP borehole monitoring distinguishes itself from seismic and geodetic monitoring by covering a larger depth range and frequency band, and for allowing *in situ* sampling of large volumes of the crust.

Boreholes are needed in the forearc region to monitor seismic and aseismic motion of the megathrust and related crustal deformation. Most great earthquake ruptures have their landward termini beneath the coastal area, where the plate interface behaviour changes from updip seismogenic to downdip stable sliding and, at somewhat greater depth, from frictional to viscous. Coseismic slip of the megathrust may be extremely broadband, generating ground shaking of millisecond periods to excitement of very long-period normal modes of tens of minutes (Stein and Okal 2005). The slip on the thrust may be over seconds (seismic), to minutes (tsunami generation), to weeks or years (slow slip detected geodetically). Postseismic deformation includes afterslip of months to years duration downdip of the rupture zone and long-term viscoelastic relaxation of decades (Melbourne et al. 2002; Wang 2004). The coastal region is by no means dormant during the interseismic period. Elastic shortening of the forearc region is frequently interrupted by “silent slips” on the thrust at the downdip end and beyond the seismogenic zone (Dragert et al. 2001; Ozawa 2002). At the Cascadia subduction zone, such GPS-detected silent slips are closely accompanied by low-frequency seismic tremors (Rogers and Dragert 2003), but the tremors appear to extend into the overlying crust. Crustal strain associated with these motions can be identified with borehole monitoring.

Although shallow-borehole strain meters, such as those being installed by the Plate Boundary Observatory (PBO), are very useful in detecting seismic and aseismic strain changes on land, they are very sensitive to fine-scale structure and rock heterogeneities. At sea, experiments in instrumented ODP and IODP boreholes have shown the value of using fluid pressure observations to constrain tectonic strain pulses (Davis et al. 2001, 2004). These boreholes have hydraulically opening sections communicating with seafloor formations. Volumetric strain changes due to seismic and aseismic tectonic events induce significant changes in formation fluid pressure. A network of pressure-monitoring boreholes may define the pattern of the pressure changes and yields information about the source of the strain events. The poroelastic fluid pressure response “samples” a large rock volume and thus is less sensitive to fine-scale structure and heterogeneities. Recent fluid pressure observations in two near-trench ODP holes at the Nankai subduction zone (Fig. 4) detected a strain pulse correlated with very-low-frequency earthquakes within or beneath the accretionary prism (Davis et al. 2005). On land, fluid pressure monitoring in ICDP boreholes drilled into selected confined aquifers and aquitards in the coastal region will allow the detection of similar strain events across the continental margin and help constrain the spatial extent and frequency contents of their sources.

Broadband seismometers, tilt meters, accelerometers, strain meters, temperature sensors, and fluid samplers in deep boreholes all have been used to detect changes in various geophysical and geochemical parameters associated with subduction processes. Jointly analyzing the temporal and spatial patterns of the changes and correlating with data from seismic and geodetic networks will provide unprecedented constraints to the activities and earthquake and tsunami hazards of active margins. Borehole observatories, especially land-marine profiles across the coast can also be designed to monitor forearc fault systems and volcanic activities.

The case for land-ocean borehole networks. Observation targets at subduction zones, such as the plate thrust interface, are only under a few exceptional circumstances within reach of continental boreholes (i.e., less than 10 km; see above). Large-aperture observation networks that monitor subduction thrust targets and the overlying forearc, from different directions in 2-D and 3-D are thus important; they have the potential to become part of the standard observational infrastructure in subduction zones. Coastal land boreholes and offshore boreholes must be grouped together to form land-ocean profiles or networks. Such a new generation of borehole networks will provide excellent opportunities for correlating signals with other, such as current and planned standard seismic and geodetic networks. Coordinating ICDP drilling and monitoring activities with ocean drilling efforts such as those of the IODP requires innovative planning and execution.

Here we use the Nankai subduction zone, SW Japan, as a case example to illustrate the potential and feasibility of land-ocean borehole networks to monitor the rich variety of transient signals that is becoming evident. The Nankai margin has produced many great earthquakes, often accompanied by distinctive tsunamis. A transect of eight marine boreholes across the seaward part of the subduction thrust, including two deep holes using the Japanese riser drillship technology, has been planned under the IODP project NanTroSEIZE to sample and monitor the seismogenic zone of the subduction fault (http://ees.nmt.edu/NanTroSEIZE/) (Fig. 4). Although drilling will only reach the updip limit of the seismogenic zone, the addition of a number of continental boreholes along the coast will allow the seismogenic zone to be monitored from both ocean and land directions (Fig. 4).

As an example mentioned in the preceding section, fluid pressure transients have recently been detected in existing ODP holes at Nankai. The strain pulses causing these pressure transients indicate ongoing deformation that appears to come from slip near the downdip end of the otherwise locked subduction fault. Further seaward, a large number of very-low-frequency earthquakes also has been detected within or beneath the accretionary prism by a high-sensitivity seismic network on land, also pointing to the activitiy near the updip end of the locked fault (Obara and Ito 2004) (Fig. 4). GPS networks have captured a number of aseismic "silent" slip events that occur within or downdip of the seismogenic zone in this region and many other active margins. Numerous nonvocanic low-frequency seismic tremors occur in the deeper part of the forearc region (Obara 2002) (Fig. 4), possibly related to the dehydration of the downgoing slab. Although accelerometer data at seismic stations suggest strain changes coincident with the tremor activities (Obara et al. 2004), their relation with GPS-detected silent slips has not been established like at the Cascadia subduction zone. All these ongoing geodynamic activities call for a combined land and ocean borehole network to monitor changes in stress, strain, fluid pressure, temperature and fluid chemistry in relation to fault motion and earthquakes.

Other world-class case areas where land-ocean borehole networks would be very useful include Cascadia (Fig. 1), a very well studied typical accretional margin, Costa Rica (Fig. 1), a typical erosional margin, and Southern Chile (Fig. 1), where tectonic accretion and erosion seems to occur intermittently (Behrmann and Kopf 2001). Like Nankai, all these subduction zones have been well surveyed and studied using numerous techniques. Seismic structure onshore and offshore, and geodetic deformation patterns are quite clear. Offshore boreholes exist for tectonic or gas hydrate studies, and a number of these holes have been instrumented and used as observatories. Additional oceanic boreholes have been either planned or proposed. For Cascadia, the NEPTUNE seafloor cable system and the Plate Boundary Observatory (PBO) geodetic network will allow signals to be correlated on a plate scale. At Costa Rica, a borehole transect including land borehole to define the spatial variation of the thermal regime over a short trench-arc distance is both urgently needed and technically feasible.

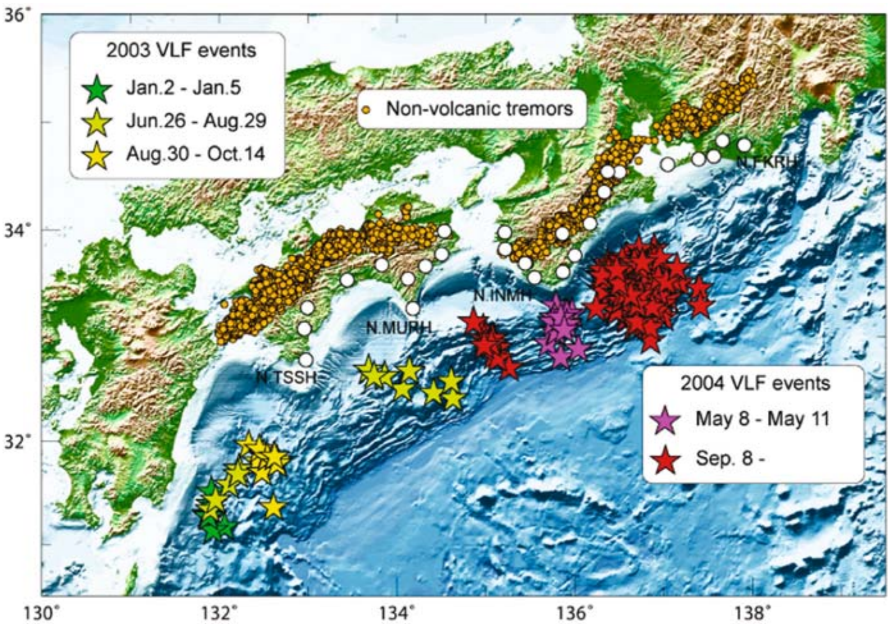

Fig. 4. Nankai Trough subduction zone showing the locations of the planned IODP borehole transect and a possible additional continental borehole transect to form a land-ocean borehole monitoring network. Boreholes are shown as yellow-filled orange circles fill, with the large one showing the approximate planned location of the deepest IODP hole using the riser technology. The three land borehole sites are arbitrarily placed to illustrate the concept. Small brown circles are locations of non-volcanic tremors reported by Obara (2002). Very-low-frequency offshore earthquakes reported by Obara and Ito (2004) are shown as stars color-coded for time of occurrence. Modified from Obara and Ito (2004).

3.1.3 The Hellenic Collision Factory

Given the highly dynamic setting and complexity, collision zones are still poorly understood. In the first ICDP white paper (Zoback and Emmermann 1994), the shortcomings in understanding collision zones as well as the emerging key questions along active plate boundaries have already been identified. Nonetheless, to date no ICDP project has attempted to penetrate and/or instrument a plate boundary fault, or drill a transect of holes across one key collisional margin.

Zoback and Emmermann (1994) have proposed numerous regions for collision zone drilling, including central Japan, the Alps, Himalayas, Marianas, southern Chile, and Greece. We have reviewed this preselection and have discussed it in a wider context, namely based on ongoing activities within other programmes such as marine scientific drilling and observatory science. In recent years, new light has been shed on individual processes with the subduction factory as well as onshore fault and collision zones. However, since many of the processes vary with time (e.g., transient fluid flow, earthquake cyclicity), scientific drilling has started to implement boreholes with observatories capable of monitoring crucial parameters *in situ*. Those initiatives include ICDP-SAFOD (see Fault zone chapter, this volume), IODP- NanTroSEIZE (Nankai Trough Seismogenic Zone Experiment; Tobin et al. 2002), and ocean floor networks such as MARS (Monterey Bay), NEPTUNE (Juan de Fuca plate) or ESONET (European Seafloor Observatory Network).

Among modern collisional settings on Earth, one that covers a very large variety of aspects, and could hence be favoured for a comprehensive large-scale scientific drilling approach: The Hellenic Trench-Backarc (HTB) in the Eastern Mediterranean Sea. It represents a mature subduction zone where African crust is thrust beneath Eurasia, and contains a wide backstop area of partly old accreted strata (marine), occurrence of HP/LT rocks (exhumed on the island of Crete and the Cyclades), an extensional submerged landward forearc (Cretan Sea), and a volcanic arc and backarc basin (Aegean Sea). Furthermore, the HTB hosts the fastest extensional system (Gulf of Corinth) and a major strike-slip zone (North Anatolian Fault Zone, NAFZ) presently representing a large-scale transtensional regime in northwestern Turkey (Marmara Sea). Both domains are earthquake-prone, hazardous geo-environments. The HTB was earlier identified as a promising research target: both, seismic onshore and offshore networks (Harjes et al. 1997; Bohnhoff et al. 2004) and deep-sea cables (e.g., NESTOR) already exist. Observatory science programmes (e.g., EuroCORES, ESONET), which would greatly benefit from ICDP drilling, have already listed the HTB as a prime target for future activities.

Scientific drilling and long-term monitoring in the HTB would be a powerful means to study densely populated areas (megacities like Istanbul and Athens) to minimize societal and environmental dangers, which millenia ago destroyed entire cultures, two of the seven wonders of the world (Colossus of Rhodes 224 BC, Lighthouse on Pharos 365 AD), and several historical sites in the in the circum-Mediterranean.

The HTB retreating convergent margins was capable to generate M>8 earthquakes (365 AD, western Crete, see above) and devastating volcanic eruptions (1650 BC, Santorini) in historic times. Collisional processes which are well recorded over the past ca. 35 million years, including an intermittent stage of micro-continent collision between about 30 and 20 Ma, followed by breakoff of a subducting slab, followed by incipient collision with the passive African margin today. The island of Crete represents a megascopic horst structure developed within the last 5 million years in the central forearc and provides excellent onshore access to the internal structure (Fig. 5).

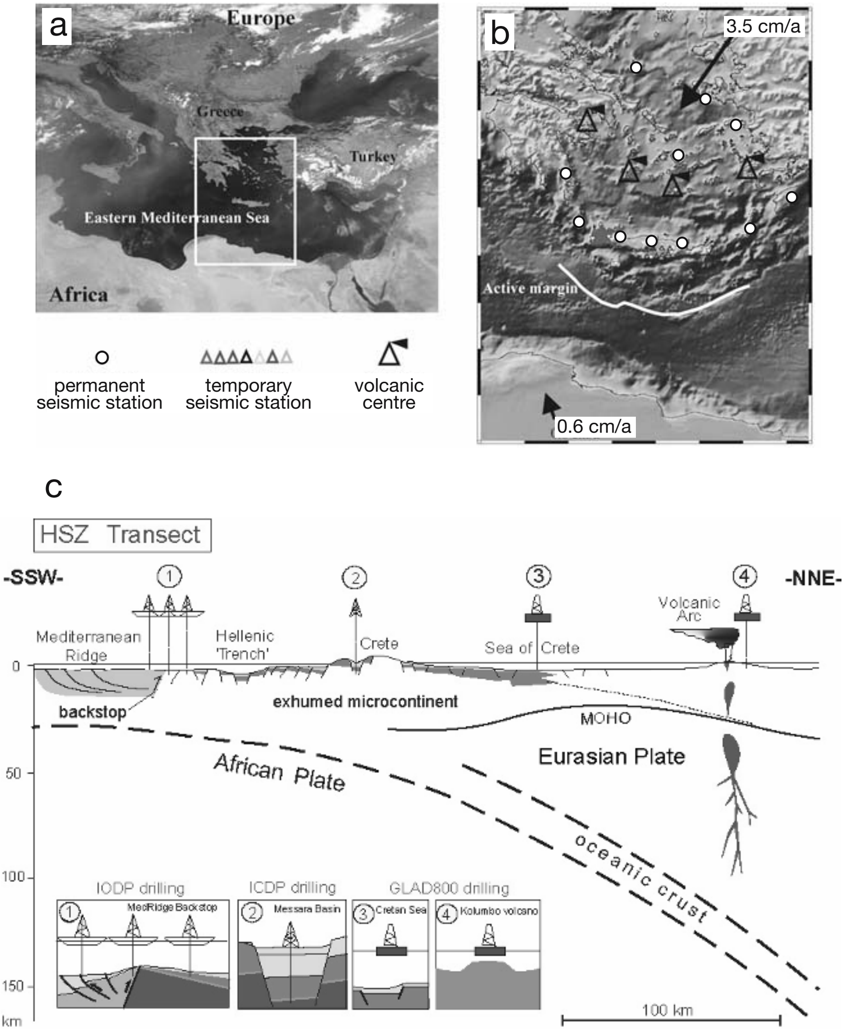

Fig. 5. a. Overview of the Eastern Mediterranean region. The rectangle marks the Hellenic Subduction Zone (HTB) that is enlarged in b. **b.** Overview map of the HTB. Arrows give the GPS-derived horizontal velocity field (simplified, after McClusky et al. 2000) in a Eurasian-fixed framework. Black triangles represent the volcanic centres of Aegina, Milos, Santorini-Kolumbo and Nisyros (from west to east). Triangles and circles mark stations of temporary and permanent seismic networks (Hanka and Kind 1994; Harjes et al. 1997; Bohnhoff et al. 2004), respectively. **c.** Transect of ICDP and marine targets for the investigation of the Hellenic Subduction-Collision Zone.

A combined onshore-offshore programme of scientific drilling and multi-parameter monitoring would address the following key questions:

- How are variations in pore pressure, temperature and stress linked to regional seismogenesis; which of these parameters may act as EQ precursors if monitored in real-time?
- How is the mechanical coupling between the plates achieved, and how are these processes tied into seismogenesis and earthquake magnitude and recurrence time?
- What determines the boundary between contractional and extensional deformation – the „backstop“ geometry, rheology, or both? How do forearc regions N and S of Crete differ mechanically and how is kinematics partitioned in space and time?
- Which are the geometrical pathways of the extensional exhumation of the subducted micro-continent? Can the proposed asymmetric buoyant escape model serve as a general concept for continental growth in retreating subduction zones?
- How is the incipient volcanism in the central magmatic arc related to the transtensional regime, to crustal zones of weakness, and to distinct magma pathways from the Benioff zone towards the surface?
- How is stress partitioned between tectonic faults (contractional as well as extensional) and magmatic processes, and what causes the different pulsation frequencies between micro-earthquakes (t=1 yr) and vertical movements in the volcanic arc (t=10 yr)?

Collision factory drilling is envisaged to contain the following components:

- A land-sea drilling transect through the HTB system to study the Aegean natural tectonic laboratory. This transect comprises a northern (ICDP-driven) and a southern (IODP-driven) domain. After an ICDP workshop on Crete in 1998, proposals for backstop drilling in the Cretan Sea (ICDP), on Crete (ICDP), and in the Mediterranean Sea (IODP) were developed and later combined to form an onshore-offshore deep drilling transect along the HTB (Fig. 5). With moderately deep marine drill sites (ca. 1 km depth) in the backstop region south of Crete, one continental 3-4 km deep drill hole onshore Crete, and further ICDP (GLAD 800) offshore holes within the Cretan Sea (i.e., the forearc-backarc transitional zone) and the volcanic arc (i.e., the submerged Kolumbo volcano as part of the Santorini volcanic complex), a substantial contribution to the understanding of earthquake hazard and mitigation, tectonic evolution and rheology of active collision zones is anticipated. From north to south, the key sites are:

- The Volcanic Arc (proposed ICDP GLAD 800 drilling). A well-developed Benioff zone was identified here by seismological observations to a depth of 150-180 km below the magmatic arc (HVA). The HVA follows the four main volcanic centres of the Hellenic subduction zone (Aegina, Milos, Santorini and Nisyros/Kos, from West to East). The central HVA forms the Cyclades archipelago, a classical example of a high-pressure belt in a back-arc environment (Trotet et al. 2001). Major extensional detachments define metamorphic core complexes (e.g., Lister et al. 1984; Gautier and Brun 1994). Extension was accompanied or alternated with horizontal shortening producing large NE-SW to NNE-SSW trending folds (Avigad et al. 2001) and the Santorini-Amorgos zone of crustal weakness. Here the explosive Santorini volcano (Volcanic Explosivity Index 6.9 or 7.0; Dominey-Howes 2004) is located. The most recent volcanic and seismic activity, however, occurs at the Kolumbo volcanic reef 10 km NE of Santorini, where a new volcanic centre broke the water surface in 1650 AD (e.g., Vougioukalakis et al. 1994). At present Kolumbo is in a state of uplift and its caldera reaches a minimum water depth of 18 m only. We propose to drill into Kolumbos' caldera using the cost-effective GLAD 800 drilling equipment.
- The Cretan Sea (proposed ICDP GLAD 800 drilling). The Cretan Sea represents the northernmost portion of the extensive forearc domain in the HTB, between Crete to the south and the volcanic arc to the north (Fig. 5). Given the small tidal range in the area, shallow GLAD 800 drilling would be feasible in this seismically active, hazard-prone area (Manakou and Tsapanos 2000) to install borehole instruments and a cable for later observatory science. The extensional regime is a critical link between the Cretan drillsite (see below) and the HVA. One of the key aspects here is the remarkable contrast in seismic activity and deep fluid venting north and south of the exhumed Cretan forearc high. Studies here are particularly crucial since the regional stress regime is expected to change: the landward part of the system is decoupled, while the frontal forearc accommodates high basal stresses along the plate boundary fault (the latter causing subduction erosion; Kopf et al. 2003).
- Central Crete ICDP drilling. Crete represents a tectonic window that provides insight into the internal structure and tectonic history of the forearc, and in fact into the deep crustal level. Crete Island formed after a short-lived cycle of subduction, slab breakoff, uplift and thrusting, accompanied by normal faulting within the forearc-high due to exhumation, that way allowing for accretion further south. A rigid stack of nappes formed the continental backstop since about 19 Ma (Thomson et al.

1998), and has since caused very rapid outward growth of the Mediterranean Ridge accretionary margin (Kopf et al. 2003). The major part of the pre-Neogene basement exposed on Crete (comprising the „lower nappes“) is derived from the sedimentary cover of the microcontinent (e.g., Bonneau 1984) that – as a part of the African plate - entered the precursor of the Hellenic subduction zone in the Oligocene/Miocene. High pressure – low temperature metamorphic rocks were exhumed within a very short time span, forming the footwall of a major extensional detachment (Fassoulas et al. 1994) by about 19 Ma (Thomson et al. 1998). Present high seismicity could be linked to a large system of fluid circulation induced by the plate convergence. Some of the fluids contained within the thick sediment cover of the forearc are expelled in mud volcanoes of the accretionary prism (Kopf 2002). Another portion of the fluids within the sediments or in the hydrated upper oceanic crust may be subducted, and trigger strong seismicity at the plate interface. We propose a deep (3-4 km) borehole to study in-situ both the HP-LT history (Kopf et al. 1999) and the source region of micro-earthquake cluster.

- Backstop drilling in the Hellenic forearc (IODP proposal 555-full3). Within ODP (Ocean Drilling Program) and its predecessor DSDP (Deep Sea Drilling Project), several convergent margins have been investigated. However, all these regions have in common that drilling focused entirely on the frontal portion of the forearc prism. In contrast Kopf et al. (1999) proposed to drill a transect of three sites south of the island of Crete from the distal part of the Mediterranean Ridge accretionary prism (MedRidge) across the backstop. Backstops (or mechanical buttresses) to accretionary complexes are among the most important pathways for deep fluid flow processes and define solid material flow within an accretionary prism. Fluid flux at the buttress must influence fluid budgets of the accretionary complex, and earlier work attested that flux rates in the backstop domain exceed those near the toe of the accretionary complex (Kopf et al. 2001). The IODP marine transect aims to illuminate (1) mass and fluid transfer at an accreting convergent margin, (2) the significance of spatial variability of fluids from mineral dehydration and diagenetic alteration at depth, and their interaction with the rock, and (3) their possible effect on seismicity. Each of the three 1km-deep drill holes in the backstop domain will penetrate deep-seated thrusts and backthrust faults and fluids there act as “geochemical windows“ down to several km depth. Fluids will be indicative of enhanced dewatering reactions, and fluid motion possibly cause EQ swarms in the area. Monitoring of fluid-flow and pressure variations would dramatically improve our understanding of fluid budgets and global mass balances, and seismogenesis in accretionary systems.

- A powerful integration of natural laboratory data and observations from the HTB transect is possible with the results from Corinth rift drilling (Fig. 1), and future drilling at the North Anatolian Fault Zone (Fig. 1). This way rifting, transform and thrust regimes, the three natural tectonic expressions of collision, could be interactively studied within the small, well-studied and easily accessible Aegean-Anatolian region. Long-term observatories, both in boreholes and as surface networks, will further address many of the highest priority targets of ICDP and IODP.

3.1.4 The Roots of Arc Systems

Understanding the roots of arc systems is important for a number of scientific and socio-economic reasons: placing constraints on rates and mechanisms for growth of the continental crust; understanding the processes leading to explosive volcanism; and understanding the processes leading to formation of economic ore deposits, such as porphyry copper deposits. We believe that an initial focus should be on juvenile, intra-oceanic arcs (IOA) because these reveal most clearly how arc crust forms and thickens. IOA are also thin enough to targets in deeper parts of the crust to be reached by drilling. These objectives can be reached by drilling in active IOA (e.g., Izu-Bonin-Mariana; W. Aleutians; Tonga-Kermadec) and in fossil IOA (e.g., Talkeetna, Kohistan, Tanzawa).

Modern active seismic sounding is a powerful tool for resolving the arc crustal structure, but this has only been applied to a few IOA. The seismic structure of volcanic arcs is known in only a few locations. Suyehiro et al. (1996) provided the first high-resolution seismic refraction profile through an IOA: the primitive, oceanic Izu arc at 33ºN (Figs. 1, 6). They found that the crust to be about 20 km thick, i.e., thicker than normal oceanic crust. The distinctive feature of this profile is a middle-crustal layer of intermediate (6.0-6.3 km/s) seismic p-wave velocities. It is overlain by an upper crust with velocities up to 5.8 km/s, and overlies a lower crust with velocities of 6.6-7.3 km/s.

The upper crustal layer in the Izu section comprises mainly volcano-sedimentary rocks and minor intrusions. The middle crustal layer may be interpreted as intermediate to felsic plutonic rocks, on the basis that these rocks that have been dredged from the remnant Palau-Kyushu arc and is exposed on land in the Tanzawa Mountains of Japan, where the Izu arc has collided with Honshu. The lower crust in the Izu section actually comprises two sub-layers: one with velocity of 6.6-7.2 km/s, and a deeper layer with a velocity of 7.3 km/s. One interpretation is of mafic cumulates overlying mafic-ultramafic cumulates but the layers could also include granulitic residues from intracrustal melting as well as fragments of pre-existing oceanic lithosphere. It must be appreciated in this context that active magmatic arcs are very dynamic systems, which must continue to evolve as they thicken. Added information in Fig. 6 shows an interpretation (from Stern et al. 2003) of active magmatic processes beneath an IOA that is consistent with the Izu seismic section.

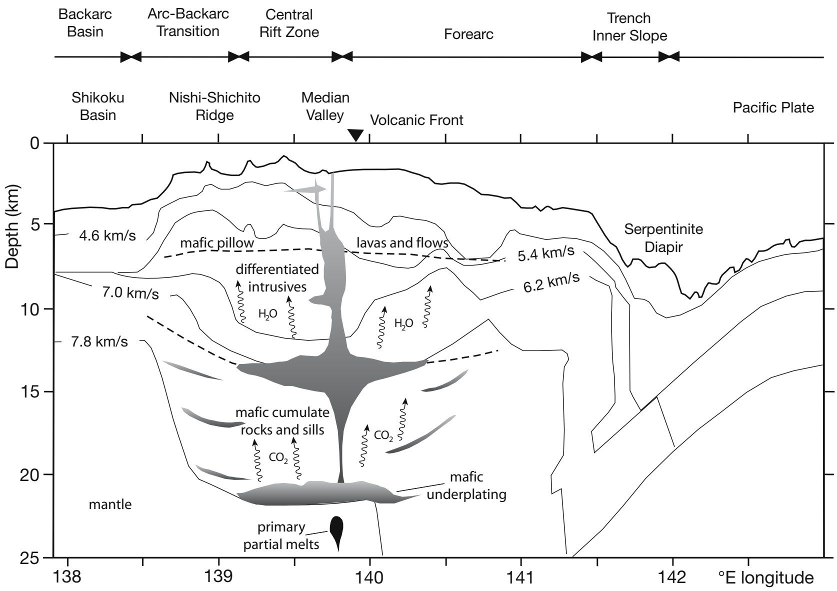

Fig. 6. The seismic section of Suyehiro et al. (1996) across the Izu arc, highlighting the presence of a 'tonalitic layer' in the middle crust resulting from melting and crystallization processes in differentiating magma chambers. Added geological information comes from an interpretative section drawn by Stern (2003) through an intraoceanic arc. Many deep crustal processes are poorly understood and drilling would help to understand arc roots and thus document mechanisms of crustal growth.

Seismic profiles for other IOA differ in detail from this model (Stern 2002). The only other oceanic arc with a comparable seismic profile is the Aleutian Arc with higher density middle crust if compared to the Izu arc, but a lower-density and thicker lower crust. The differences may be explained by tectonic variations between the arcs, or may reflect the fact that the Izu arc has evolved over a shorter time period. Arcs built on continental lithosphere are sometimes referred to as "Andean-type arcs" (ATA). Of these, crust beneath the Cascades (Fig. 1) is thicker (35 km) but otherwise not too dissimilar from the Aleutian section. Andean crust is the second-thickest on Earth (after Tibetan crust) and is up to 70 km thick. Yuan et al. (2000) used teleseismic P-to-S converted phases to image the deep structure of the Andes. They inferred a mid-crustal section characterised by 'dehydration and melting' and a lower crustal section characterised by 'dry refractory crust'. The extent to which ATA and IOA lower crust consists of residue or cumulates is an important unanswered question.

Overall, the objectives in studying arc roots resemble those in studying lower oceanic crust. Key questions include:

- How does arc crust evolve in time from nascent arcs to evolved arcs?
- What is the nature of the magma plumbing system whereby magma fed from the mantle traverses the crust and is delivered to sub-volcanic magma chambers, and what are the associated processes?
- What are the sizes, nature and depths of magma chambers within the arc crust?
- At what depths are volatiles released within the crust and how does this impact melting, fractionation, and mineralization?
- What is the thermal budget of crust and how does this constrain the assimilation and melting of pre-existing crust?
- How do deep crustal processes influence the likelihood of explosive eruptions or mineralization at sub-volcanic levels?
- What is the bulk composition of especially intra-oceanic arcs and what is the role of arcs in crustal growth? How important is delamination of high-density lower crust beneath arcs?
- How does arc crust differentiate as it ages and thickens?
- What is the nature of the Moho beneath arcs? Are there both petrological and seismic Mohos beneath arcs, as is observed for ophiolites and inferred for oceanic crust?

As with oceanic crust, drilling type sections for sampling, analysis and downhole experiments is a key approach for interpreting seismic profiles and understanding the origin and composition of the crust. It may be possible to drill through relatively thin crust of IOA forearc, but not through the crustal welt associated with magmatic arc. Even more so than is the case for much thinner oceanic crust, a single drilled section through typical arc crust to the Moho is currently unrealistic. Scientists studying mid-oceanic ridges overcame this problem by offset drilling – drilling a series of holes through different layers that have been tectonically uplifted until a composite section could be constructed. This is almost certainly the best approach for understanding arc crust. Offset drilling of the deeper parts of oceanic crust has revolutionised our concept of oceanic crustal growth and we believe that drilling arc roots would similarly revolutionise our understanding of the evolution of arc crust. In devising a strategy for studying arc roots by continental drilling, it is our view that the optimal approach is to start by studying simple arc systems of known setting (young, intraoceanic) and subsequently to investigate more complicated targets. Focussing on IOA also provides opportunities for synergistic drilling in co-ordination with IODP.Below we present three important targets for scientific drilling in IOA: Nascent arcs, Middle crust of a Mature Arc, and Lower Crust-Upper Mantle of a Mature Arc.

Drilling Target 1: Nascent arcs. One way to understand arc processes is to drill arcs in their incipient stages of formation, in supra-subduction zone ophiolites and subduction initiation regimes. The advantage of this type of target is that it highlights magma-genetic processes, i.e., it enables the arc to be studied before millions of years of crustal processes modify the crust beyond recognition. Some Supra-Subduction Zone ophiolites record the transition from spreading to subduction. These include parts of the Semail ophiolite in Oman, the Pindos and other ophiolites in Greece and Albania, and the Bay of Islands Ophiolite in Newfoundland (Fig. 1). Some forearc terranes also provide exposures of the earliest arcs, examples being Eua (Tonga), Guam and the Ogasawara Islands. Drilling ophiolites can be done by ICDP alone but drilling nascent arc crust requires close co-ordination with IODP.

Probably the best targets are in the Izu-Bonin-Mariana forearc, where a strong case has been made that Eocene crust is an in situ ophiolite that formed during the initial stages in the formation of a subduction zone (Stern and Bloomer 1992). One attractive locale for drilling is Chichijima and other parts of the Ogasawara islands, the type location for the boninite magma type. The island exposes a boninite volcano built on an edifice of pillow lavas and dyke swarms. Although we do not know the depth to the Moho, the fact that dyke swarms are exposed in the lower parts of the island may indicate that it is feasible to drill through the volcanic edifice and its basement. ODP Leg 125 nearby drilled through the flanks of a boninite volcano into the dyke-swarm of the underlying oceanic crust (Pearce et al. 1992) and could be drilled to greater depth; however, on-land drilling would reach any Moho more cheaply and easily. Another attractive possibility is drilling on Guam, which exposes boninite pillow lavas. A prerequisite for all forearc drilling, however, is a detailed seismic refraction survey and detailed other geophysical and geological data.

Drilling Target 2: Arc Middle Crust. Suitable drilling locations exist where lower sections have been tectonically exposed or exposed by erosion. There are many examples of these in older arcs, notably the Cretaceous Kohistan arc in Pakinstan where a complete arc section is believed to be exposed. However, given the need to place the drill hole in context by understanding the setting of the arc being drilled, the best known at present is the Tanzawa belt in Japan.

The Izu arc terminates in the north against Honshu in the Izu collision zone, a rare example of active arc collision and terrane accretion. Accretion has led to the uplift and exhumation of the roots of the arc in the Tanzawa Mountains. The Tanzawa Plutonic complex likely represents the middle crust of the Izu arc of Upper Miocene (4.7 to 10.7 Ma). The complex has been studied on land where the tonalite suite contains a series of features of interest: cumulate layering, xenoliths, evidence of magma mingling and leucocratic veins. Drilling will provide the core for evaluation of the complex relationships between the components of the middle arc crust, and for testing the hypothesis of Kawate and Arima (1998) that the tonalities formed by amphibolite melting. This crustal section also has the advantage of helping to constrain the Izu arc seismic line (Fig. 6).

Drilling Target 3: Arc Lower Crust and Upper Mantle. Fundamental questions about magmatic processes in the lowermost crust and uppermost mantle beneath mature IOA require the identification of suitable sites for drilling. The Moho of Supra-Subduction Zone ophiolites present one target as they highlight ways in which subduction-derived magma can infiltrate and react with pre-existing oceanic lithosphere. Another type of target is the deep roots of accreted arcs. The Talkeetna terrane of southern Alaska (De Bari and Coleman 1989), which exposes lower crust and upper mantle, may present one of the best such targets, given that the 'classic' Kohistan arc in Pakistan lies in a presently politically-unstable region.

3.1.5 Plume-modified Orogens: the Case of the Carpathians

In its western part the Carpathian Orogen (e.g., Kovác et al. 1998) consists of an older unit known as the West Carpathians (WC) and a younger one, known as the Outer Flysch Carpathians (Fig. 1), the latter being overthrusted onto the southern part of the European platform (Cadomian or Hercynian basement). The depth of the cratonic basement in the suture zone, according to the results of the deep seismic (CELEBRATION profile; Guterch et al. 2001), magnetotelluric and magnetic soundings (e.g., Zytko 1997), is below 6-8 km (the basement depth calculated from the platform bending is 10 km). An enigmatic basement uplift exists despite the general southward dip of the European platform under north-western Carpathians that may be caused caused by the geothermal uplift of the asthenosphere, replacing delaminated lithosphere or by mantle plumes, or by basement-involving thrust faults. The boundary between the overriding

WC (Alcapa plate, e.g., Plasienka et al. 1997) and the European plate is the Pieniny Klippen Belt (PKB) The outcropping segment of the PKB is an almost 700 km long, strongly compressed and tectonically complicated suture zone. Here, many questions regarding the evolution of the Central European Alpine system could be answered by drilling. The principal ones are:

- The stuctural position of PKB within Carpathians and its role in the reconstruction of the Cenozoic Alpine system of Europe. The PKB is bounded by first-order strike-slip faults, both, in the North and the South. The deep structure and geometry of the PKB is unknown. Drilling here could help define the nature of the contact zones as well as magnitude and sense of relative displacement between contacting units. It could verify models of the subduction type (A or B) and its direction within the Carpathians, and determine the total thickness of the Lower Miocene deposits in the context of the evolution of the foreland basin. Furthermore, tectonic units buried underneath the Magura Nappes overthrust can be identified, and the palaeogeographic disposition of the PKB basins may be clarified.
- The relationship between geotectonic and geodynamic setting and magmatogenesis. The Outer Flysch Carpathians, adjacent to PKB from the North contains andesitic Neogene volcanic rocks, whose origin is interpreted as a combined effect of the mantle uplift and subduction processes (e.g., Kovac et al. 1998). Here an extensional regime is exerted within the generally compressional European stress field, a situation unique within the Alpine system of Europe. A temporal and spatial and compositional definition of the igneous activity is of fundamental importance in order to solve the relative contributions of asthenosphere and lithosophere to the magmatic products emplaced during the Alpine orogenesis.
- Nature of geophysical anomalies. A first-order, unexplained magnetotelluric (M-T) anomaly is known north of the Tatra Mountains running parallel to the Carpathian orogenic axis (Jankowski 1967). Two competing hypotheses exist: the origin of M-T anomaly in the Carpathians has been related to the presence either of graphite or of low-resistivity brines at depth (Jankowski et al. 1985). The origin of an associated negative gravity anomaly, the axis of which is oblique with respect to the PKB, is also unclear. If the M-T anomaly is caused by low-resistivity brines, then drilling is instrumental for discovery of new renewable energy resources.
- Geodynamic reconstruction of the Mesozoic-Cenozoic basins. Particularly important are time and tectonic context of the Carpathian basins

development, followed by palinspastic restoration and paleogeographic reconstructions showing a provenance of these basins with respect to other crustal blocks, currently incorporated into the European Alpine fold belt. A better correlation of the main structural units of West and East Carpathians is one of the main goals. Verification requires the occurrence and age of the supposed oceanic floor in these basins.

- Oil generation and migration. Identification of petroleum systems of the West Carpathians and their basement and formulation of a general model for the other oil and gas reservoirs in thrustbelt setting is scheduled. To achieve project goals, scientific drilling is important.
- Regional heat-flow evolution. The Carpathians are affected by the European hotspot field, as marked by Neogene volcanism and high heat flow. The heat flow peak is now located in the Pannonian basin (Cermak 1989), To the north, Neogene volcanic rocks of the Transcarpathian Ukraine are on the Alcapa plate, while the PKB andesites and the Silesian basalts are located entirely within the European plate, and cut obliquely the Outer Carpathian nappes. This distribution may point to the ancient position of the centre of the heat-flow anomaly: the shift towards the Pannonian basin could be due to the northerly drift of the European plate, overriding a thermal anomaly.
- Identification and definition of the Cadomian-Hercynian basement structure of the Carpathians. Paleogeographic reconstructions of the basement terranes, reconstruction of the Hercynides during the circum-Carpathian geodynamic evolution and mutual relations of the fore-Alpine terranes could be addressed in detail by scientific drilling (Golonka et al. 2000).
- Paleostress evolution and its changes in horizontal and vertical section. Reconstruction of paleostress fields associated with the Carpathian development, geodynamic and palinspastic reconstruction of the Western Carpathians and Pieniny Klippen Belt during the Miocene.

Based on the current stage of knowledge, if the basement of the Alpine orogen reached and rocks responsible for M-T anomaly are to be reached, target depth for the drilling should be 8000 m. The drilling location would be optimally situated along the CELEBRATION 2000 deep seismic profile line, and profiting from already available from drillholes completed by the Polish Geological Institute and the Polish Oil Industry (e.g., Cieszkowski 1985).

3.2 Deep Subduction and Exhumation of the Lithosphere

During subduction and especially during later exhumation, tectonic accretion occurs in the subduction channel. The processes of tectonic accretion take place under varying physico-chemical and thermo-mechanical conditions (Borghi et al.1996). Metamorphic and deformational processes change the densities and mechanical behaviour of the rocks moving in the subduction channel (TAC; Engi et al.2001; 2004). The direction of particle movement in the subduction channel is controlled by the rheology and density of the rocks as well as by the 3-D distribution of heat flow through time (Platt 1993; Jamieson et al. 1998; Brouwer 2000; van de Zedde and Wortel 2001; Brouwer et al. 2004). Initial exhumation of deeply subducted material might be related to buoyant rise or forced return flow of subducted material (Chemenda et al. 2000; Burov et al. 2001; Gerya et al. 2002). Further exhumation is caused by coupled tectonic transport and erosion (Willett et al. 1993). Even late-stage exhumation into the upper crust and to the surface may strongly influence the tectonized accretionary rock assemblage. In the past few years processes in subduction channels have been successfully simulated by numerical computer models (Chemenda et al. 2000; Burov et al. 2001; Gerya et al. 2002; Roselle et al. 2002; Brouwer et al. 2004). Information related to the varying processes is stored in the mineral phases, their element composition and in nano- to micrometer scale deformational features. Because of the speed of subduction and exhumation, the mineral phases do in many cases not reach equilibrium with the surrounding physicochemical and thermo-mechanical conditions. Currently, special emphasis is given to mineral inclusions on the sub-micron scale that are formed during subduction and/or accretion and therefore give hints to the processes involved. A better understanding of elemental distribution between mineral phases and of element cycles in this special environment is needed to reveal the history of the rock transformation within the subduction and accretion channel, as well as during exhumation (Goffé et al. 2003; Zack et al. 2003; Paquin et al. 2004; Kelley et al. 2005). Various geospeedometry techniques and thermochronological dating techniques have been further developed to quantify the speed of exhumation of HP and UHP rocks. In addition, the influences of pressure on the thermochronological systems and the effects of radioactive decay (e.g., fissioning, movement of alpha-recoil nucleus) on the stability of metamorphic phases have been partly studied.

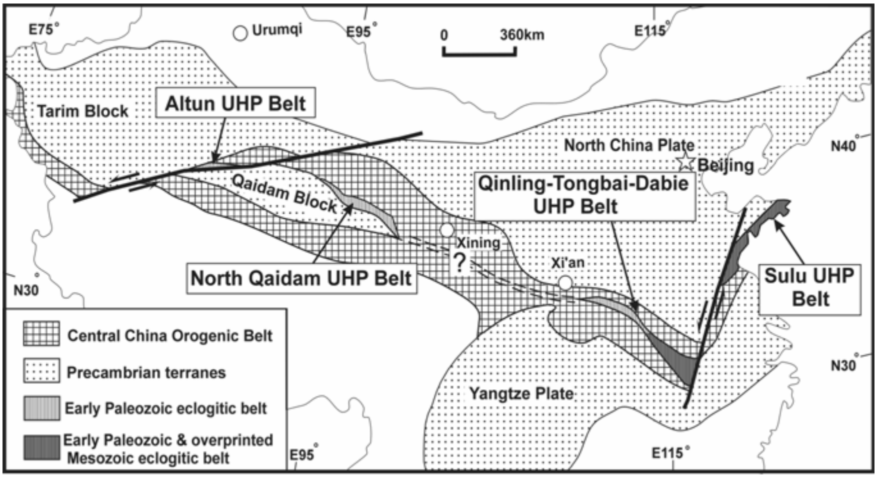

Fig. 7. Two ultra-high-pressure (UHP) events of Early Paleozoic and Triassic age are recognized in the 4000- km-long Central China UHP belt (after Yang et al. 2005). The North Dabie Shan is a good candidate for future drilling to investigate the relationship between the two events and to understand the dynamics of continental collision.

In the following, the most important tectonic scenarios for deep subduction and exhumation of lithosphere will be discussed.

Continental Lithosphere. Most ultra-high pressure metamorphic (UHPM) rocks are formed in continental plate collision zones, and have been recognized in the Caledonian, Variscan, Alpine and Himalayan orogenic belts. The oldest UHPM rocks are known from Late Precambrian and Neoproterozoic Pan-African nappes of Northern Mali and SE Brazil, where they formed in a continental plate collision zone at around 630–640 Ma. Older UHPM rocks have yet to be recognized. Because much older oceanic crust has been reported from several locations in the world, older UHPM rocks may have been formed, but not preserved. The Dabie-Sulu Triassic UHPM belt (Fig. 7) is the largest and best known occurrence in the world. It extends across central China for over 1000 km, and is offset by the Tanlu strike slip fault for about 500 km. Deep continental drilling in China (Chinese Continental Scientific Drilling Project – CCSD; Fig. 1) has sampled a 5-km-deep section of the Sulu UHPM terrane. Recent work has identified an older, parallel belt on the north side of the Dabie-Qinling Mountains, which has been dated as Ordovician (~500-440 Ma) (Yang et al. 2001 2003). This older belt extends northwestward for nearly 4000 km through the Qilian Mountains into northern Tibet where it is offset by the left-lateral Altyn Tagh Fault (Yang et al. 2005). The critical question here is the relationship between these two belts, their spatial distribution, and tectonic implications. This is a potential site for future drilling, to further investigate continental subduction and exhumation. Coesite-bearing UHP eclogite recently discovered in the Himalyan region provides a new perspective on UHPM in a collision zone and on the formation of the Tibet Plateau. This is another potential site for future drilling.

Oceanic Lithosphere. Two types of subduction, i.e., A-type and B-type, have been proposed. The A-type represents continental subduction along with UHP metamorphism, whereas the B-type represents oceanic subduction with HP metamorphism (Maruyama et al. 1996). Most known UHPM rocks occur within continental crustal sequences, and various lines of evidence indicate that large volumes of continental material have been subducted in "A-type" continent–continent plate collision zones. However, at least three UHPM occurrences, the Zermatt–Saas Zone of the Western Alps, Sulawesi in Indonesia, and the SW Tianshan in China (Fig. 1), are interpreted to have formed in deeply subducted oceanic crustal sequences, i.e., in "B-type" subduction zones. Exhumation of deeply subducted oceanic crust is even more difficult to understand than exhumation of continental crust. However, oceanic UHP rocks do occur at the Earth's surface. Exhumation of such UHPM rocks to the Earth's surface is likely to be a rare event requiring unusual, as yet unclear, geodynamic circumstances (Carswell and Compagnoni 2003).

Two vastly different architectures of accretionary wedges can be envisaged (see Fig. 8): closed wedge architecture and open wedge architecture. Which type of architecture is formed is mainly controlled by rates of convergence and/or subduction, the dip of the subducting plate, and the sedimentary and tectonic processes in the frontal part of the overriding plate:

Closed Wedge Architecture. At high convergence rates oceanic crust and sediments, as well as portions of the wedge sediments, enter the subduction channel and are emplaced in tectonic accretionary zones. During exhumation, their HP to UHP mineralogy is thermally and tectonically overprinted under metamorphic conditions ranging from amphibolite to lower greenschist facies. Metamorphic wedge sediments occur mainly in tectonic mélanges and imbricate "Schuppen Zones". Their mineralogy either reflects escape from subduction (low-temperature and low-pressure metamorphic parageneses) or overprinting of blueschist facies mineralogy by greenschist to lower amphibolite facies. Remnants of former UHP and HP mineral parageneses occur in restricted areas, but in general are scarce. The pressure-temperature-time (p-T-t) paths recorded in such rocks typically suggest a clockwise evolution with thermal decompression. The Dabie Shan - Sulu UHP-HP belt is regarded as a key location to study processes within “closed wedge architecture”. Therefore, the drill core of the CCSD-ICDP drill hole at Donghai is crucial for further detailed research on the processes of subduction, accretion and exhumation in this type of setting.

Open Wedge Architecture. This scenario, related to slow convergence rates, produces different metamorphic assemblages. The accreted sediments, mostly low-grade high-p/low-T rocks in more or less coherent stratigraphic sections, do not enter the subduction channel. This rock assemblage will be overprinted under variable metamorphic conditions ranging from amphibolite to granulite facies. Where fluids are present, partial melting of large rock volumes (migmatisation) will occur. In an open-wedge setting, the sediment pile is dominated by pelitic and carbonaceous material whereas mafic rocks are less common. High-p, low-T metamorphic histories in rocks belonging to open-wedge scenarios, are recorded by carpholite or other Al-rich minerals such as chloritoid, pyrophyllite or cookeite in metapelites (Goffé and Chopin 1986; Goffé et al. 1988; Oberhänsli et al. 1995). Until recently, these associations had only been identified in Peri-Tethyan belts, and reflect the coolest prograde and retrograde P-T-t paths inferred from metamorphic belts (Becker 1993; Gebauer 1996). Petrologic data suggest pseudo-geotherms of 6 to 10°C/km (Goffé and Bousquet 1997). The stratigraphic setting, and in some cases the excellent preservation of primary stratigraphic relations (e.g., Bousquet et al. 2002), suggest that such rock sequences never entered a subduction channel, and were tectonically accreted.

The physical conditions under which HP rocks are generated coincide with the top of the seismogenic zone (Hyndman et al. 1997). Underplating of sediments and preservation of large stratigraphically coherent blocks is possible. Where sediments enter the subduction channel, conditions corresponding to either the upper or the lower sections of the seismogenic zone are recorded in the exhumed rocks. The exhumed material forms disrupted melanges or tectonically accreted sequences. Only subducted continental material seems to retain a certain lithostratigraphic coherence, as reported from UHP terrains such as the Dabie Shan – Sulu belt (e.g., Schmid et al. 2000; Xu et al. 2000; Liu et al. 2004; Xu et al. 2004) and the Himalayas (e.g., O’Brien 2001).

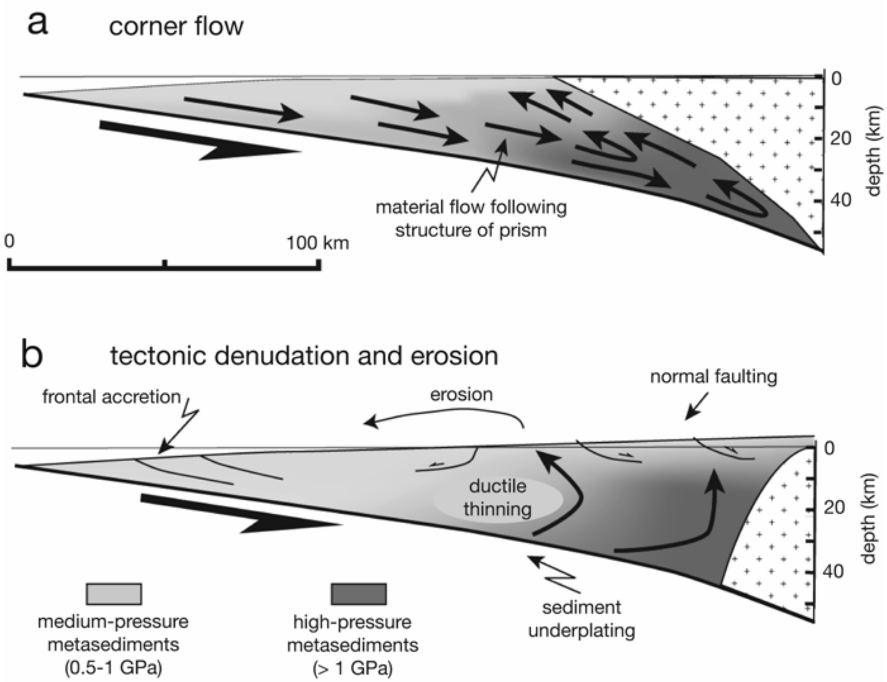

Fig. 8. Architecture of accretionary wedges and material flow as proposed by **a.** Cloos (1982, 1985), **b.** Platt (1986) or Feehan and Brandon (1999). Redrawn from Bousquet (1989)

"Open wedge architecture" has not been studied by scientific drilling, but would be important for further understanding of the processes producing the two different end-member architectures of orogens. Two key areas can be identified in which to study slowly converging accretionary systems. One is the frontal part of the Hellenic Collision Factory (see above) with strong extension and very rapid exhumation (e.g., Wortel and Spakman 1992; 2000). A second key candidate area is Makran in Pakistan and Afghanistan (Fig. 1), where there is a transect from an active accretionary complex on land to oceanic crust. Again, a joint ICDP-IODP land-sea venture should be envisaged here.

Besides geological considerations, all tectonics settings of deep subduction and exhumation of the lithosphere discussed above provide the ideal testing ground for the development new thermochronological dating techniques. To achieve progress here, it is only continuous coring by drilling that yields sufficient exposure and structural continuity.

3.3 Anatomy and Evolution of Fossil Orogens and Terrane Collages

By studying fossil orogens of different ages, with exposure of different crustal levels, orogenic process and their changes with time may be better understood. Processes that may have changed with time include how the crust has grown and stabilized, the response of the mantle to orogeny, and the production of granitoids associated with orogeny. Many ancient orogens are hidden by younger sedimentary rocks; consequently drilling is the only available means to answer fundamental questions about their age and evolution.

Aside from studying orogenic processes, scientific drilling of fossil orogens allows various geoscientific questions about the continental crust to be addressed. Boreholes (2-4 km) into stable old crust provide opportunities for heat flow measurements at depths that are unaffected by recent glaciations. Glaciation is known to significantly disturb present-day heat flow data (Kukkonen and Joeleht 2003). Long-term climate change can be studied by inversion of geothermal borehole data. Early deep biosphere and its role in fluid and gas chemistry of the continental crust is a key question calling for deep boreholes. Forms of early life can be investigated when drilling into Precambrian low-grade meta-sedimentary rocks. Economic aspects include the study of processes related to the formation of mineral deposits and low enthalpy geothermal energy. Finally, these boreholes can act as monitoring stations for longer term surface geophysical measurements (magnetotellurics, seismic, magnetics, gravity, heat flow).

Criteria for site selection include the need for drilling (limited exposure, etc.), the quantity and quality of existing seismic data, longer term monitoring aspects, and the scientific questions only a deep borehole can answer. Other surface (non-seismic) geophysics and geological models will also be important considerations in the selection of any potential drilling site. Reflection seismic data acquired over active orogens often result in poor images of the crust. For example, the modern Banda arc (Snyder et al. 1996) is generally transparent, if compared to the Paleozoic arcs of the Urals (Steer et al. 1998) or the Svecofennian orogen of the Baltic Shield (BABEL Working Group 1993). Is this inherent to modern crust, or is it due to poorer signal quality in modern orogens, caused by large volumes of low velocity material overlying the more competent deeper crust? Are the crustal structures observed in fossil orogens on reflection seismic sections really present in modern orogens, and just unobservable with seismics, or is this difference due to unfinished metamorphic processes or removal of fluids from the rocks? These are very fundamental questions that cannot be ultimately answered without comparative drilling in young (see sections 3.1 and 3.2) and old (this section) orogens.

Crustal stacking, heating and exhumation are important components of collisional orogeny (see above). During convergence the crust is shortened, thickened, and deformed. The re-distribution of radioactive heat sources by crustal thickening, partial melting and melt transport to the upper crust define metamorphic P-T-t paths and result in thermal stabilization of the lithosphere. Thickened crust may become gravitationally unstable, leading to syn- or post-orogenic extension (Dewey 1988). This process is closely related to the exhumation of high pressure and ultra-high pressure fragments, and even mantle slices. How these slices are brought to the surface is an important question that can be addressed by drilling in old orogens that possess a geometry caused by complete collapse (e.g., the Norwegian Caledonides). Also, recent seismic reflection data from FIRE (Finnish Reflection Experiment) over the Paleoproterozoic Svecofennian orogen (1.89-1.87 Ga) show clear listric reflectors extending from the surface to the lower crust. These structures may represent a cycle of crustal shortening, stacking and late extension during this orogeny. Understanding the nature of these hidden reflectors is crucial to documenting syn- or post-orogenic extension.

In the Paleozoic Scandinavian Caledonides (Fig. 1), nappes have been transported hundreds of kilometers from west to east. How has the crust below the basal thrust deformed? Reflection seismic data over the Caledonides show clear deformation patterns (Juhojuntti et al. 2001). Drilling 2-4 km into the crust will answer questions about the rheological state of the crust during deformation, later (Cenozoic) uplift processes, the nature of present-day and ancient fluids in the decollement zones, as well as provide important constraints on reflection seismic and other geophysical data.

Pre-existing structural discontinuities in the lithosphere often define sites of later deformation; consequently it is important to understand the structures of ancient orogens and the role they play in the evolution of the crust. For example, Mesozoic strata of the Crimean Mountains in the southern Crimean Peninsula (Fig. 1) have been deformed during the Jurassic-earliest Cretaceous (poorly defined) and post-middle Eocene (well-defined) via transpression (Stephenson et al. 2004). Geophysical methods (seismic reflection, magnetotellurics) aid in mapping these structural discontinuities at depth, for example the geomagnetic anomaly along the Pieniny Suture Zone (see section 3.1.5) stretches several hundreds of km (Jankowski et al. 1985).

Recent deep drilling Outokumpu, eastern Finland (Fig. 1), has shed new light on the deep structure of a classical Precambrian ore province containing massive sulphide deposits in an ophiolitic and metasedimentary setting. Strong seismic reflectors (Fig. 9) are being re-interpreted and new ideas on crustal evolution based on recovery of saline fluids and gases have emerged. Paleoproterozoic thrust sheets may be much thicker than anticipated. Fundamental questions regarding the deep biosphere, origin and motion of deep fluids, the stress field, seismic structure and the Phanerozoic thermal history of the eastern part of the Baltic Shield (Kukkonen 2004) may be addressed and answered here.

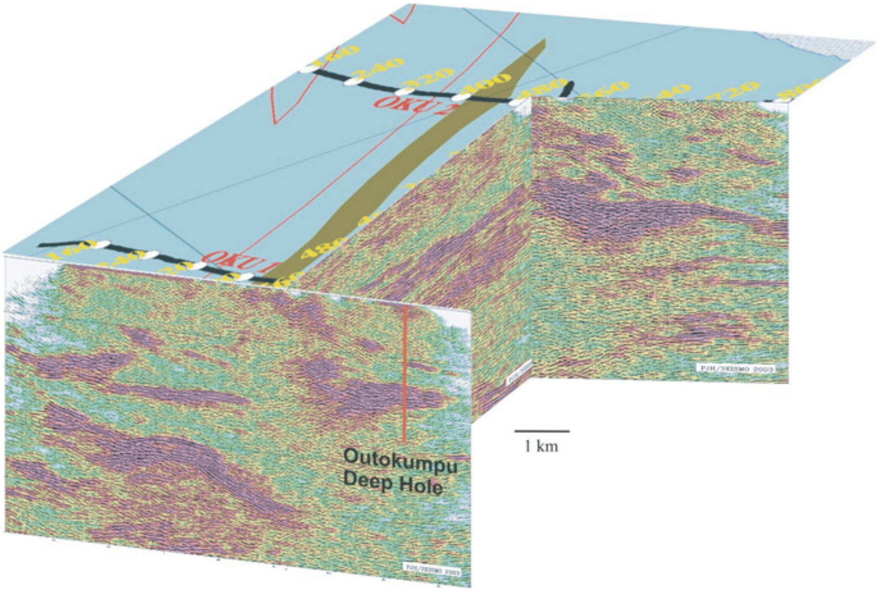

Fig. 9. Deep drilling (2.5 km) into a Paleoproterozoic ophiolitic and metasedimentary formation in Outokumpu, eastern Finland, has revealed the nature of strong reflectors in the upper crust. These consist of alternating layers of serpentinite, skarn rocks and black schists enveloped by mica schists. The 3-dimensional model was constructed from migrated high resolution reflection seismic data by the FIRE project (Kukkonen et al. 2004) and a lithological surface map (Geological Survey of Finland). The seismic sections extend to a depth of 5 km. The amplitude scale of the reflectors has been color coded for clarity indicating higher reflection amplitudes. Colors of the surface geological map: blue - mica schist; brown - serpentinite, skarn rock, and black schist.

Apart from answering overriding questions in tectonics and Earth history and integration with other research themes, future fossil orogen research boreholes at all other conceivable locations will need to be geared at:

- Saline fluids and gas sampling,
- Deep biosphere studies,

- Heat flow measurements,
- Oriented core recovery,
- Petrophysical property measurements,
- Fission track studies.

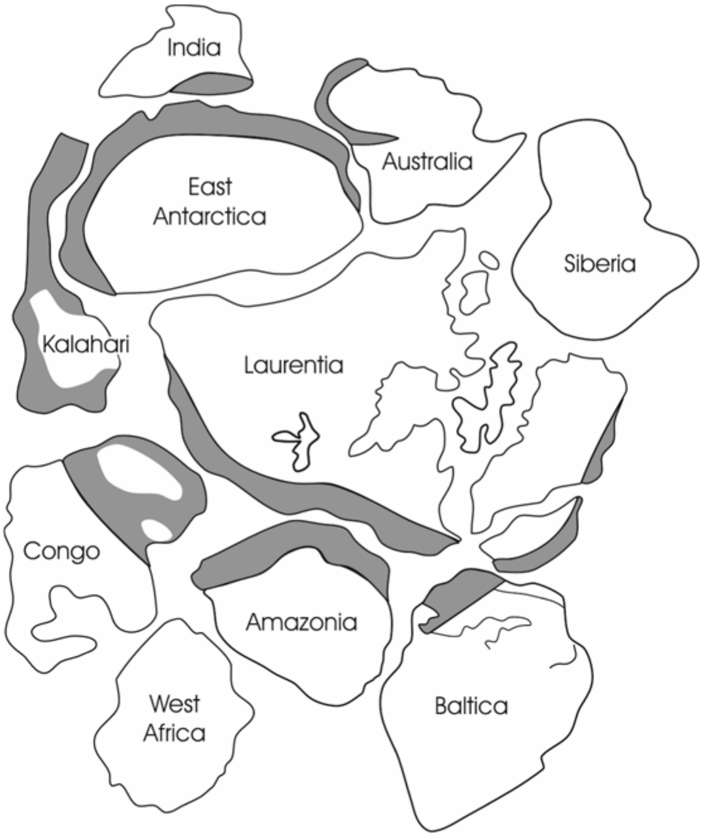

Fig. 10. Tectonic reconstruction of Rodinia (after Hoffman 1991), based on linking Grenville-age orogens (grey) found around the world. Ancient collisional orogens like the Grenville are repositories of economic mineral resources on a global scale.

Drilling objectives will focus on answering questions about orogenic processes in time and space. Other ICDP themes integrate directly into all potential drilling sites, especially climatic disturbances up to 100,000 years ago, because deep boreholes in crustal rocks provide unique laboratories to study major changes in surface temperatures. Economic mineral deposits are also important as many types of mineral deposits are associated with collisional processes and therefore ancient orogens. Extensive study of old orogens by drilling will ultimately improve our understanding how are continental shields being born, how they amalgamate to form terrane collages, continents and supercontinents (Fig. 10), and how they are being fragmented and destroyed.

4 Technological Needs

4.1 Drilling Technology

Most of the scientific drilling proposed here may be accomplished using drilling rigs and equipment available on the market for hydrocarbon and ore exploration drilling today. However, any program of scientific drilling addresses questions that cannot be answered without the use of novel and dedicated technology, to be developed within the framework of the individual projects. Therefore, extensive accompanying programs of borehole logging and on-site geophysical and geochemical monitoring will require a continuous effort of building and improvement of technologies, especially those developed and used in the course of earlier ICDP-sponsored continental deep drilling ventures. Examples pertaining to convergent and collisional plate margin drilling are the German KTB wells, the Dabie-Sulu Project in China, and the recently completed SAFOD drilling on the San Andreas Fault near Parkfield, California, USA (Fig. 1). Some of the targets identified above, especially those involving penetration of plate boundary zones and the associated seismogenic zones, may require drilling to unprecedented depths, and present major technological challenges.

4.2 Requirements for Instrumentation of Drill Holes

Instruments needed for convergent-boundary borehole observatories fall into two categories, the “standard” instruments that in principle should be used in most observatories and the special-purpose instruments that are designed to monitor processes of particular importance to a given borehole site. The standard set should includes a broadband seismograph, a tilt meter, a borehole strain meter, at least one fluid pressure sensor, and a number of temperature sensors at different depths.

The variety of special-purpose instrumentation can be limited only by one’s imagination. In the following, only a few examples are given.

Hydrogeological transients in association with seismic and aseismic tectonic strain changes have been both puzzling and exciting. Well water level is known to fluctuate before, with, and after earthquakes. For many (currently 29) instrumented ODP and IODP boreholes, fluid pressure changes have been demonstrated to be sensitive, robust, and to be very broadband strain indicators. In more advanced recent designs, fluid pressures are monitored in isolated depth sections communicating with rock formations of different hydraulic and mechanical properties (Davis and Becker 2004). These sensors record regular (such as tidal) pressure variations as well as tectonic pressure pulses.

Temperature variations are sensitive indicators of fluid flow. Temperatures can be monitored at carefully chosen discrete depths using resistor thermal sensors or for a continuous depth range using the fiber-optic *Distributed Temperature Sensing* (DTS) instrument (Förster et al. 1997; Macfarlane 2002). Successful applications of the latter have been made within ICDP in the Hawaii project (Büttner and Huenges 2002) and in the Mallik gas-hydrate project in Canada (Henninges et al. 2005), although the currently limited life-span of fiber-optic instruments is of some concern for long-term (decades) observatories.

For strain monitoring, the use of the fiber-optic *Bragg-grating technology* (FBG) was successfully demonstrated in the Corinth Rift Laboratory (Moretti et al. 2002). This technology was combined with a downhole electrode array to study the long-term deformation and hydraulic properties of a major fault zone. While the DTS technology can be employed both inside and outside borehole casing, the FBG technology to measure strain is restricted to use outside casing. Outside-casing installations have to be made during borehole casing.

Recently, there have been approaches to use *downhole triple axis accelerometers* (TAA) as part of the casing. These devices will allow for continuous monitoring of the seismic background with very low signal strengths. The installation of monitoring instruments outside the borehole casing constituting a “smart casing” has the advantage that the inner part of the cased borehole can be used for other instrumentations or regular logging runs.

For near-field monitoring of active faults, many of the technologies currently designed and employed at the SAFOD site can be used (see Reches and Ito this volume). Fluid samplers may be needed for geochemical monitoring and analyses. The installation of the standard and special-purpose tools/techniques requires sophisticated engineering design so that they do not interfere with one another’s operation and they can function at desired pressure and temperature conditions. The design needs to begin developing at an early stage as part of the drilling plan.

5 Synopsis

Here, we have developed a comprehensive initiative to drill the continental crust bordering modern and ancient convergent and collisional plate boundaries, encompassing the following:

1. Dynamics of active subduction and collision zones, with focus on the seismogenic zone at the plate interface, and the distribution of deformation and seismicity,
2. The role of mantle plumes in orogeny,
3. Supra-subduction magmatism in arc systems,
4. The geological manifestation of deep subduction and exhumation of the lithosphere, and
5. Aspects relating to continental birth and growth through Earth history.

ICDP drilling in convergent and collisional plate margins faces unprecedented challenges regarding drilling technology, drilling depth and requirements for long-term monitoring of Earth processes in downhole observatories.

The continental areas bordering convergent and collisional plate boundaries host the vast majority of modern megacities and industrial installations on Planet Earth, and at the same time are loci of major earthquakes, tsunamis, volcanic eruptions and other associated great natural threats to human life and to economies. As 60% of Earth's population lives within the frontal 50 km of the coast in or near convergent or collisional plate boundaries, there is a strong need for scientific and economic efforts, to elucidate and understand the processes responsible for such geohazards as well as for strategies aiding their mitigation. Scientific drilling will play a vital role in such studies and is an integral part of this effort.

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