EUG XI

Symposium LS09

The Subduction Factory

Convenors

Catherine Chauvel
Tim Elliot

Sunday PM Session

LS09 : SUpm25 : G0
Role of Subduction Factory in the Evolution of the Solid Earth

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Subduction zones are located at the junction of two converging tectonic plates, where one sinks (subducts) beneath the other into the Earth's mantle. The central role for subduction zones in the evolution of the solid Earth has been repeatedly emphasized. Raw materials, such as pelagic/terrigenous sediments, oceanic crust, and mantle lithosphere, are fed into the subduction factory. Output products, such as arc magmas emerge from the factory and may form continental crusts. The remainder of the material, which is processed in the subduction factory, sinks into the deep mantle and may have contributed to the geochemical evolution of the Earth's mantle. The continental crust possesses an andesitic composition, although basaltic magmas dominate the magmatism on the modern Earth. This fact is probably the greatest dilemma facing those interested in theories of the origin of the continental crust. Further, at least four geochemical reservoirs, in addition to the primitive mantle, would be required within the Earth's mantle to explain the isotopic variations observed for ocean island and mid-oceanic ridge basalts; EMI (Enriched Mantle I), EMII (Enriched Mantle II), HIMU (high-μ), and DMM (Depleted MORB Mantle). Among these, the origin of the enriched components is essential for understanding the dynamics and evolution of the deep mantle, because such components typify magmas rising from deep-seated hotspots. Geochemical formulation of dehydration, partial melting, and fluid-solid reactions suggests that a process, which includes slab-dehydration-induced mantle melting, basalt magma generation, and remelting of the initially created basaltic crust, can reasonably explain the major and trace element compositions of the andesitic bulk continental crust. It should be further stressed that the mechanism requires delamination of mafic melting residues from the initial crust and recycling of such 'anti-crustal' materials into the mantle. Isotopic modeling suggests that a pyroxenitic delaminated component formed at 3-4 Ga possesses Sr-Nd-Pb isotopic compositions typical of the EMI component, one of the enriched geochemical endmembers in the mantle. Mobilization of elements during dehydration processes in the subducting plate was examined by high-pressure experiments on a pelite and an amphibolite, both typifying subducting plate materials. The results confirm selective transport of particular elements such as Pb and Rb, and document effective element fractionation during dehydration processes within the subduction factory. Isotopic modeling based on such experimental results suggests that subducting sediments and oceanic crusts, which have been stored in the deeper part of the mantle, may form the EMII and HIMU endmember components, respectively.

LS09 : SUpm26 : G0
Subduction Cycling of U, Th and Pb: Perspectives from Altered Oceanic Crust

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Many studies call upon subducted altered oceanic crust (AOC) to ultimately reside in the ocean island basalt (OIB) source. The existing geochemical budget of AOC from DSDP 417/418, however, generates low ^{208}Pb compositions that do not approach the OIB array (Hart & Staudigel, 1989). With this in mind, we re-evaluate the existing AOC estimate at another drill site, and consider the effect of subduction processing on the composition of the slab.

Our AOC estimate comprises ICP-MS analyses of 46 discrete and 14 composite samples from ODP Site 801, which is an extrusive sequence (470 m) of fast-spreading Jurassic MORB east of the Marianas. Uranium determined in discrete samples correlates well with data from natural gamma logs, which both indicate a 4x enrichment of U over pristine glass (0.09 vs. 0.4 ppm). Lead is locally redistributed with no net gain or loss, and both average Pb and Th remain close to the pristine glass composition. U-enrichment creates high μ(^{238}U/^{204}Pb) (μ AOC = 61, μ DMM = 8), but leaves ω (^{232}Th/^{204}Pb) nearly unchanged from the mantle value (ω AOC = 25, ω DMM = 20).

These data yield higher μ and ω for AOC than 417/418, but would still evolve to low ^{208}Pb. AOC thus must be chemically processed by subduction before reaching the OIB source. To constrain slab losses, we use the global model of Elliott, et al. (1999), which provides permissible bounds on μ, ω and κ (^{238}U/ ^{232}Th) in mantle reservoirs. Assuming AOC retains Th, we subtract AOC ω and κ from Elliott, et al.'s OIB reservoir to calculate 58% of Pb and 88% of U lost from AOC during subduction. Lead loss of 58% is consistent with Ce/Pb models and hydrothermal mobility studies, but 88% U-loss is larger than predicted by current partitioning data. Mixing calculations also indicate μ of the slab-derived fluid contributing to arc volcanism is as low as 2.6-4, which suggests that much less U is lost to the arc than overall. Uranium loss is controlled by breakdown of its mineral host, and our data show that carbonates, which may be stable to great depths, bind significant U in AOC. Carbonate control may provide a mechanism for some U to be lost from the slab to the upper mantle, below the arc magma source, which may account for the decrease in κ with time in the depleted mantle.

LS09 : SUpm27 : G0
The Behaviour of HFSE in Subduction Zones: New Insights from Hf Isotopes and High Precision Measurements of Nb/Ta, Zr/Hf and Lu/Hf in Arc Rocks from Kamchatka

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The characteristic HFSE depletion in subduction rocks is commonly explained by (1) the immobile behaviour of these elements during slab dehydration or (2) by the presence of residual minerals (rutile, amphibole) in the magma sources. To assess these possible models, we performed isotope dilution analyses for Nb/Ta, Zr/Hf and Lu/Hf together with ^{176}Hf/^{177}Hf-isotope measurements on arc rocks from Kamchatka that represent a traverse across the arc. Using a mixed ^{180}Ta-^{94}Zr-^{180}Hf-^{176}Lu tracer and the MC-ICPMS in Münster, we are able to achieve external precisions and accuracies of ±0.5 to ±1% for Lu/Hf and Zr/Hf and of ±5% for Nb/Ta (2σ uncertainties). In contrast to existing techniques (e.g. quadropole ICPMS), this analytical protocol results in a nearly 10 fold improvement in analytical resolution.

The trace element budget of the Kamchatka rocks along the studied cross-arc transect at 56°N is largely controlled by variable fluid flux into the subarc mantle (Dohrendorf et al., 2000), thus representing a suitable arc system to evaluate the possible fluid mobility of HFSE under high pressure. Coupled Hf-Nd isotope variations (εHf = 12-18, εNd = 6-10) in samples from the central Kamchatka depression (CKD) and from the back-arc suggest mixing between an OIB source and a MORB source in the wedge. In the fore-arc, however, the samples are slightly displaced from the Hf-Nd array towards less radiogenic Nd, indicating selective addition of minor sediment derived Nd to the mantle wedge by fluids high in Nd/Hf. The Zr/Hf (30-42) in all arc rocks are anti-correlated with Lu/Hf (^{176}Lu/^{177}Hf= 0.01-0.03), suggesting that the budget of Zr and Hf is controlled by the degree of mantle depletion rather than by the slab component. Only the back-arc samples show superchondritic Zr/Hf (> 36), consistent with the presence of an OIB source component (typical Zr/Hf>36) in their source. In the fore-arc and CKD, ^{176}Hf/^{177}Hf are constant at varying ^{176}Lu/^{177}Hf, thus indicating a very young (post upper Tertiary) depletion age of the subarc mantle.

Nb/Ta in the Kamchatka rocks (11-18) are decoupled from Zr/Hf and Lu/Hf. In the fore-arc and CKD samples Nb/Ta increases with Ba/Th (200-600). Both observations indicate that the Nb-Ta budget in these samples is controlled by fluids that were derived from the subducted slab. The fluid must have had a Nb/Ta of at least 16, lying at the high compositional end of typical subducting MORB (10-16). Such high Nb/Ta in the fluid suggest a scenario, where Nb partitions preferentially into the fluid relative to Ta during slab dehydration. Rutile, the main carrier of Nb and Ta in the eclogitic portion of the subduting slab, is capable of generating such Nb-Ta patterns. Recent experimental evidence (Green, 2000) indicates that rutile has higher mineral/fluid partition coefficients for Ta than for Nb.

Dorendorf F, Wiechert U & Wörner G, *Earth Planet. Sci. Lett*, **175**, 69-86, (2000).
Green TH, *State of the Arc 2000 Abstracts*, (2000).

LS09 : SUpm28 : G0
Hf Isotopes in Arc Lavas Point to Sediment Melting in the Mantle Wedge

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It is well known that sediments from the continental crust subduct together with oceanic crust in subduction zones and contribute to the source of island arc magmas. What is less clear is the manner by which their geochemical signature is transferred to the arc lavas. A sedimentary contribution to arc volcanism can result from sediment dehydration or bulk sediment melting, followed by transfer of fluid or magma to the mantle wedge.

A combination of Hf, Nd, Sr and Pb isotopes helps to solve the question because Hf is far less mobile in fluid phases than Nd, Sr and Pb. In contrast, Hf behaves like Nd during melting. If the sediment signature of arc lavas is acquired through dehydration of the sedimentary pile, Nd and Hf isotopes should be decoupled and should define an array distinct from that of usual mixtures of crustal and mantle materials.

We report Hf isotopic compositions for several islands along the Luzon-Taiwan volcanic arc in the west Pacific. Their Hf isotopic compositions are very unusual: ε_{Hf} remains always high (+17 and + 6) while ε_{Nd} defines an enormous range, from + 8 to -6. In Nd-Hf isotopic space, the samples define an almost horizontal array starting in the MORB field and extending to far above the general OIB field at the most negative ε_{Nd} values. Batan island, which is located in the middle of the Luzon-Taiwan arc, is an exception because its low ε_{Nd} values (-5 to -2) are associated with low ε_{Hf} (+1 to -3). The Hf-Nd relationship in Batan is similar to that for arcs located near continents.

The unique Hf-Nd isotopic trend defined by the Luzon-Taiwan arc tightly constrains the process responsible for sediment input into the volcanic arc. The curvature of the mixing array suggests that the sedimentary end-member has a Nd/Hf ratio of about 9. This value is much lower than that expected in a fluid phase (Johnson and Plank, 1999, G3) but resembles ratios in muds of continental origin. The Hf isotopes of Batan lavas require a sedimentary end-member with a low Nd/Hf of about 5, a ratio typical of sandy sediments. This suggests that the sedimentary pile that melts under Batan has a composition and origin different from the rest of the arc.

Because other arcs located next to continental margins (Lesser Antilles and Banda) have compositions similar to our Batan data, we suggest that in most such cases the sedimentary input to arc volcanism is dominated by sandy material.

Our new Luzon Hf isotopic data indicate that the sedimentary geochemical characteristics of island arcs are primarily due to melting of the sedimentary pile and not to transport of fluid liberated by dehydration of subducted material.

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LS09 : SUpm29 : G0
Petrogenetic Significance of Hf Isotope Variations in Island Arcs

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Because Hf is one of the few incompatible high field strength elements with a readily-measurable isotope ratio, Hf isotopes provide a new dimension for studying volcanic arc petrogenesis. Specifically Hf isotopes provide a potential 'isotopic window' into the nature of the sub-arc mantle wedge, as well as constraining the flux of Hf from slab to wedge and the extent of crustal involvement in arc magma genesis. The combination of Hf and Nd isotope and element data provide a means of interpreting the HFSE anomalies in arc magmas.

In a recently published paper (Pearce et al., 1999), we demonstrated that subduction-related fractionation of Hf and Nd produces a correlation between the magnitude of a Hf anomaly on extended chondrite-normalized REE diagrams and the isotopic shift relative to the appropriate MORB-OIB array on a Hf-Nd isotope plot. Both the anomaly and the isotope shift can be expressed mathematically as functions of the Hf/Nd ratios in the subduction component and the mantle, and of the mass fraction of the subduction component in the mantle wedge. In our study of the Izu-Bonin-Mariana arc-basin system, we found that the Hf anomaly and the isotope shift did correlate significantly and thus that the anomaly could be explained by selective mobilization of Nd during the subduction process. The data were further used to demonstrate that pelagic sediment is less significant than volcanogenic sediment as a source of the excess Nd. Our additional data sets from Tonga-Kermadec and Vanuatu support this work. Both arc systems exhibit two components of variation, one (independent of HFSE anomaly) due to variations in mantle provenance and one (correlated with HFSE anomaly) due to the subduction flux. In both SW Pacific arc systems, the mantle provenance varies systematically from 'Pacific' to 'Indian', the latter locally having a 'Samoan Plume' component. In both arc systems, also, the greatest subduction fluxes (most negative HFSE anomalies) are in those regions that experience the greatest sediment input flux.

The data also permit evaluation of the extent of Hf (and, by inference, HFSE) mobilization from the subducted plate. None of the oceanic arcs studied exhibit the Hf-Nd isotope 'crustal trend' reported from continent-proximal arcs such as the Lesser Antilles or areas of continent-arc collision such as the Banda arc. Modelling the various trends on the Hf-Nd isotope plot shows that Nd/Hf ratios in the subduction component are high (>10x mantle) to infinite in all the arcs studied, consistent with the concept that Hf is a high-field strength element and partitions strongly into the subducting plate during devolatilization. In addition, modelling shows that these ratios can only be explained by sediment-derived aqueous fluids or (possibly) low-temperature, aqueous melts, thus putting an upper bound on temperatures at the slab-wedge interface.

Pearce JA, Kempton PD, Nowell GM & Noble SR, *J. Petrol*, **40**, 1579-1611, (1999).

LS09 : SUpm30 : G0
The Trace of Wedge Melts in Mantle Rocks

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The mafic-ultramafic massif of Finero, N-Italy contains highly depleted peridotites which have experienced a pervasive metasomatic overprint including formation of phlogopite, amphibole, ±apatite, ±carbonates (e.g. Zanetti et al., 1999). The $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$ ratios, and incompatible trace element pattern of the phlogopite peridotites clearly indicate that the melts causing formation of phlogopite and amphibole derived from subducted sediments (Voshage et al., 1987; Hartmann and Wedepohl, 1993). Sediments are characterized by high $\delta^{18}O$ numbers of 10 to 20 ‰ and silica rich pelagic sediments exhibit even higher $\delta^{18}O$ values typically from 30 to 35 ‰ relative to SMOW. In general, sediments are ^{18}O enriched compared to mantle olivine with $\delta^{18}O$ = 5.2 ±0.2 ‰. Therefore, even 1% crustal material should be detectable with oxygen isotopes using laser fluorination. However, virtually no difference between olivine of xenoliths from lithospheric mantle with MORB signature (5.25 ±0.08 ‰) and olivines from phlogopite peridotites of Finero (5.35 ±0.11 ‰) has been detected. Also, pyroxenite veins show a very small range of $\delta^{18}O$ values within typical mantle values. It is clear that these pyroxenite veins cannot be crystallized from sediment derived melts, unless these melts were equilibrated with mantle rocks. On the other hand $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ ratios and incompatible trace element patterns are unambiguously dominated by crustal material. It will be shown that this de-coupling of oxygen isotopes and radiogenic isotopes can be generated by melts reacting with harzburgitic rocks in the mantle wedge. At temperature < 1500°C hydrous slab melts would not induce any significant melting of harzburgite but will exchange O and incompatible elements. It will be shown that the oxygen isotope ratios are within error identical with the mantle from a harzburgite/melt ratio of about 20, but a difference for $^{87}Sr/^{86}Sr$ is detectable even at a ratio of 500. We conclude that the metasomatism of the Finero peridotites has been caused by crustal melts that percolated and reacted with harzburgitic rocks in a mantle wedge. Similar hydrous wedge melts might cause fluid-induced melting in cpx-rich, lherzolitic mantle at temperatures between 1200 and 1300°C. The Finero peridotites provide a unique opportunity to look at processes in a mantle wedge without having distortions by partial melting, crystal fractionation and crustal contamination as seen in volcanic rocks.

Zanetti A, Mazzucchelli M, Rivalenti G, Vannucci R, *Contrib. Mineral. Petrol.*, **134**, 107-122, (1999).
Voshage H, Hunziker JC, Hofmann AW, Zingg A, *Contrib. Mineral. Petrol*, **97**, 31-42, (1987).
Hartmann G, Wedepohl KH, *Geochim. Cosmochim. Acta*, **57**, 1761-1782, (1993).

LS09 : SUpm31 : G0
Slab Melt-Mantle Wedge Interaction and Adakitic (Na) Metasomatim beneath the Lesser Antilles Arc

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The composition and geochemical signatures of a mantle wedge beneath the southern Lesser Antilles arc are documented by the abundant ultramafic xenoliths sampled by Nb-enriched arc basalts (NEAB) on Grenada (the Queens Park and Grenville occurrences). The xenoliths consist of dominant harzburgites (50%), minor lherzolites and dunites (15% each) and subordinate wherlites and pyroxenites (up to 20%). In addition to the primary (i.e., pre-metasomatic) ol + opx + cpx + Cr-spinel assemblage, Grenada xenoliths contain metasomatic phases such as Al-rich clinopyroxene (Al_2O_3up to 10 wt%, Na_2O up to 0.9 wt%), plagioclase (An_{45-80}), Al-rich spinel (Al_2O_3 from 53 to 64 wt%), pargasitic amphibole and Si- and Al-rich glasses (SiO_2 up to 66 wt%). According to the experimental evidence and natural occurrences from Kamchatka and Philippines, this Na- and Al-rich mineral assemblage is that expected in a sub-arc peridotitic mantle infiltrated by adakitic melts, to which the metasomatic glasses are compositionally similar. To investigate the trace-element signatures of primary and metasomatic phases, with special emphasis on the REE, Sr, Y and Nb compositions which allow Na (adakitic) metasomatism to be clearly identified, LA-ICP-MS and SIMS in-situ analyses have been carried out on selected samples. Clinopyroxenes from both lherzolite and harzburgite xenoliths have U-shaped REE profiles; they are characterised by L- and HREE enrichment (about 5 x C1) and are marked by large positive Sr anomalies (4 x C1) and large negative Nb, Ta and Zr, and Hf anomalies (0.5-1 x C1). U-shaped REE profiles and unusually high Th, U (up to 15 x C1) and Sr (up to 0.4 x C1) concentrations are also observed in coexisting orthopyroxenes. The geochemical signatures of clinopyroxene are very similar to those reported for most clinopyroxenes from subduction-related mantle xenoliths worldwide and are clearly distinct from those of clinopyroxenes in equilibrium with host lavas. These latter clinopyroxenes have convex-upward REE patterns with a maximum in the MREE region (15 x C1), low Th, U contents and a negative Sr anomaly. Glasses show a narrow compositional range, with trace-element profiles intermediate between those of host lavas and adakites, thus suggesting that both these melts largely interacted with wedge-peridotites. As a whole, the in-situ data may be explained either by secondary enrichment of the mantle wedge by slab-derived melts/aqueous fluids after significant melting episodes or by reactive porous flow of adakitic melts. It is suggested that the mantle wedge beneath the Lesser Antilles underwent complex peridotite-melt reaction processes operated by slab-derived melts and, later on, by magmas similar in compositions to the host high-Nb arc basalts. The second event partially erased the former adakitic geochemical signatures, leading in places to the almost complete melting of the early metasomatic assemblage.

LS09 : SUpm34 : G0
Experimental Evidence for Mantle Metasomatism by Hydrous Silicic Melts Derived from Subducted Oceanic Crust

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In order to constrain the physico-chemical conditions of the genesis of adakitic magmas, we have performed high-pressure experiments on an adakite (the 1991 Pinatubo dacite), and on a potential source of adakite (an altered MORB). Interaction experiments between adakite melt and Fo-rich olivine have also been performed to simulate reaction between slab melts and the lithospheric mantle during their ascent.

Phase equilibrium experiments on the dacite in the pressure range 400-2000 MPa showed that this magma evolved continuously from near H_2O-saturated conditions at temperatures close to or below 900°C. Moreover, these experiments suggest that pressures in excess of 2000 MPa are required to stabilize garnet as a near-liquidus phase in the dacite.

Crystallization experiments on the altered MORB under both excess water and low temperature conditions produced hydrous tonalitic melts in the pressure range 1000-2000 MPa and hydrous trondhjemitic melts at 3000 MPa. This shows that alkali contents of the melts produced during the hydrous partial melting of basaltic ocean crust increase with pressure.

Interaction experiments between such hydrous alkali silicic liquids and mantle olivine yielded an Opx + liquid assemblage at 1000°C. At 900°C, pargasitic amphibole and phlogopite are also reaction products. Opx has not been observed either as a phenocryst phase in adakites or as a near-liquidus phase in any of the experiments at high H_2O -contents performed on the dacite. Therefore, adakitic magmas are not in equilibrium with a metasomatized peridotite at mantle pressures, suggesting that their interaction with the mantle is very limited. One explanation is that the infiltrating slab melt may be close to equilibrium with mantle peridotite.

Our experimental data imply that the preservation of the slab melt composition during its lithospheric ascent in the mantle may be a function of the pressure of magma generation in the slab : the trondhjemitic melts produced at 30 kbar are very different from the mantle melts produced at this pressure, and will therefore interact extensively with the peridotite that they infiltrate. Such metasomatized peridotites could be the source of the unusual HFSE-rich basalts associated with adakites in various localities.

LS09 : SUpm35 : G0
Upper Mantle and Crustal Seismic Anisotropy across the Taupo Back-Arc Region, New Zealand

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From January to June 1995, the Institute of Geological and Nuclear Sciences, the University of Memphis, and the University of Leeds jointly conducted a large-scale seismic experiment in the Central Volcanic Region (CVR), New Zealand. Sixty-four short-period seismometers and 27 broadband sensors were deployed in the Central North Island as a supplement to the permanent stations of the New Zealand National Seismographic Network. We also present results from 3 National network stations located around the CVR. Upper mantle and crustal deformation in the CVR are investigated by shear wave splitting measurements of local phases as well as of four SKS phases recorded at this network. SKS phases, which mainly sample the mantle, give consistent fast polarisation directions from station to station that result in an average direction of 43° ±4°. This is also the azimuth of the strike of the Hikurangi subduction zone. Similar fast directions were also obtained in the lower North Island with SKS phases (Marson et al., 1999). All together, the SKS results suggest a large scale trench paralel flow in the upper mantle. However, in the western part of the CVR, local events from 100-160 km depth give a fast direction at 60° from the SKS results (ϕ=-15° ±15°) and fast directions from shallow events are mainly trench perpendicular. At East Cape, the region that is furthest to the northeast and closest to the Hikurangi trench, fast directions from local events and from SKS phases do agree with a trench parallel fabric of anisotropy. Between those two regions, in the middle of the CVR and on its eastern boundary, fast directions show significant variation and suggest that in this area, the nature of anisotropy has spatial changes in both the horizontal and the vertical plane. Our results also suggest that the extension regime could extends down to 150 km depth. Thus, trench parallel anisotropy might be a deep process, unless different scale anisotropic features co-exist at the same depth.

Marson K, Savage M, Gledhill K, and Stuart G, *Journal of Geophysical Researsh*, **104**, 20277-20286, (1999).

LS09 : SUpm36 : G0
Mantle Dynamics and Element Recycling at the Tonga-Kermadec Subduction Zone: Geochemical Evidence from Lavas of the Kermadec Island Arc and Havre Trough

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The Tonga-Kermadec island arc is part of an about 2500 km long subduction system in the SW Pacific where Pacific oceanic crust of Cretaceous to Jurassic age is subducted. Behind the Tonga island arc the backarc spreading centre of the Lau Basin propagates southwards into old island arc crust. In contrast, the Havre Trough behind the Kermadec volcanic front is in a backarc rifting stage. During cruise 135 of RV Sonne four locations in the backarc rift of the Havre Trough and five submarine volcanoes of the Kermadec island arc were sampled. While the arc lavas range from basaltic to rhyolitic in composition, young glassy basalts were recovered in the backarc. The Havre Trough basalts show chondrite-normalized La/Sm of 0.8 to 1.2 and Sr isotope ratios of 0.7026 to 0.7032. The isotope and incompatible element ratios indicate a range from Pacific MORB-like to island arc-like compositions. The Havre Trough basalts have higher ^{206}Pb/^{204}Pb than neighbouring island arc volcanic rocks. Lavas from the northern Kermadec arc have Nb/Zr comparable to Tonga arc basalts while southern Kermadec rocks have significantly higher Nb/Zr. The isotopic compositions of lavas from each island arc volcano are relatively constant but there are significant variations between different volcanoes. Lavas from the northern Havre Trough have Pacific MORB-like isotope compositions implying that the boundary between the Pacific and Indian MORB-like mantle domains below the backarc lies north of 24°S. The Havre Trough basalts form by relatively low degrees of partial melting compared to magmas from the Lau Backarc Basin in agreement with their formation in a rifting stage. The Kermadec mantle wedge north of about 30°S is more depleted by previous melting processes than the mantle source further south but no correlation between the depletion and backarc magma production is observed. The isotopic compositions of Havre Trough basalts and Kermadec arc lavas allow no simple mixing relationships between the backarc source and a slab component. Thus, either the backarc mantle is heterogeneous before addition of the slab component or the mantle has been altered by several events of material addition from the slab. The slab component in the northern Kermadec and southern Tonga magmas consists of a fluid from altered basaltic crust and possibly sediments while a sediment melt appears unlikely. In contrast, the source of the southern Kermadec magmas contains a significant amount of sediment from the slab.

LS09 : SUpm37 : G0
Lead Sources in the Lesser Antilles Arc: Constraints from Double-Spike Pb Isotope Data

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Understanding of the lead flux from mantle to crust at subduction zones is critical to crustal growth models since continental crust is anomalously enriched in Pb relative to the mantle. Excess Pb in arc magmas may originate in hydrous fluid transport from subducted basaltic crust, and fluid or melt transport from subducted sediment. These should result in different relationships between Pb/Nd and Pb isotope composition. Unfortunately, the ability to distinguish multiple Pb sources in arc magmas is compromised by the poor resolution of conventional Pb isotope analyses of differences in ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb relative to ^{206}Pb/^{204}Pb, coupled with the abundance of published Pb isotope data for unleached powders, which may be up to 0.4 inaccurate in ^{206}Pb/^{204}Pb (Thirlwall, 2000).

Analyses of acid-leached rock chips using the double spike Pb isotope technique on both TIMS and MC-ICP-MS (Thirlwall, 2000) are reported for selected islands in the Lesser Antilles arc where, based on MORB-like Sr-Nd isotope compositions, it has been inferred that high-level crustal contamination is absent (e.g. Heath et al., 1998). These are islands with low-K, low La/Y magmas transitional between tholeiitic and calc-alkaline: the northern Antilles (e.g. Montserrat, Statia) and St. Vincent in the south of the arc. Northern Antilles islands show a limited Pb isotopic range (^{206}Pb/^{204}Pb = 18.90-19.05), with tight Pb isotopic correlations indicating mixing between Atlantic MORB with ^{206}Pb/^{204}Pb c. 18.6 and local subducted sediment. Despite very similar MORB-like Sr-Nd-O isotope compositions, lavas from St. Vincent display a much wider range of ^{206}Pb/^{204}Pb (19.02-19.47). Samples from the south and east of the island show tight correlations between ^{206}Pb/^{204}Pb and ^{87}Sr/^{86}Sr and δ^{208}Pb. The latter intersects the Northern Antilles correlation at δ^{208}Pb = +10, substantially higher than MORB, implying a sediment contribution of identical Pb composition to that required in the north. The radiogenic Pb and Sr end of this correlation has strongly negative δ^{208}Pb = -20, a feature seen elsewhere in the south of the arc, absent from seafloor sediments worldwide and hence interpreted as a high-level contaminant. This might also be indicated in St. Vincent since the unradiogenic end is required to be subducted sediment. However, many samples from north and west St. Vincent are offset from these correlations to higher ^{87}Sr/^{86}Sr and less negative δ^{208}Pb. This offset is clearly the result of crustal contamination since these lavas contain metacarbonate xenoliths with appropriate Pb-Sr-Nd compositions, and one flow is isotopically heterogeneous at the sub-cm scale.

Although the origin of the component with radiogenic Pb remains elusive, it is quite clear that shallow contamination effects must be taken into account in quantifying Pb fluxes at subduction zones, even in islands with MORB-like Sr-Nd-O compositions.

Heath E, Macdonald R, Belkin H, Hawkesworth C & Sigurdsson H, *J. Petrology*, **39**, 1721-1764, (1998).
Thirlwall M, *Chem. Geol*, **163**, 299-322, (2000).

LS09 : SUpm38 : G0
Spatial and Temporal Variation of Magmatism of the Izu-Bonin Arc Based on Trace Element Chemistry and Isotope Systematics

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New isotopic, trace element and Ar-Ar age data for back-arc volcanics from the northern and middle parts of the Izu-Bonin arc are presented. The Izu-Bonin arc exhibits wide variation of volcanotectonic features in both along-arc and across arc directions. Both the northern and middle sections of the arc have back-arc seamount chains. However, back-arc rifting occurs only in the middle part of the arc. Age data indicate that volcanism on the back-arc seamount chains was active between 17 and 3 Ma in the middle part of the arc, and continued at least until 1.7 Ma in the northern part. In the middle part of the arc, back-arc rifting initiated ca. 2.8 Ma in the older rift zone (back-arc knolls zone) and has been active until recent in the active rift zone.

Strontium isotopic compositions of volcanics systematically become more radiogenic to the north, which is identical to the Sr isotope trend found along the frontal arc (Taylor and Nesbitt, 1998). No systematic along-arc variation was observed in ^{143}Nd/^{144}Nd for both volcanic front and back-arc. The fluid-mobile and less mobile element ratios like Ba/Th and Cs/La show clear positive correlation with ^{87}Sr/^{86}Sr and also show northward increase along the arc, while fluid immobile element ratios do not show any significant variation (e.g., Th/Nb). This indicates a direct link between the along-arc chemical variation and the amount or the composition of fluid added to the mantle. Across the arc into the back-arc, ^{87}Sr/^{86}Sr decreases and fluid-mobile element enrichment becomes less significant. This is most pronounced in the middle part of the arc, where the back-arc seamount chain and rift zone volcanism have similar fluid-mobile / less mobile element ratios to MORB. Correlations between ^{143}Nd/^{144}Nd and trace element ratios suggest that an underlying isotopic heterogeneity exists in the back arc mantle. Superimposed on this heterogeneity are the effects of polybaric melting, fluid addition and homogenization of melt fractions in the crust. In this respect we have identified a more enriched source (low ^{143}Nd/^{144}Nd; high LREE/HREE) in the back-arc region of the middle of the arc, especially in the older part of the rift. The appearance of enriched or more depleted mantle signatures in the back-arc may relate to the processes of homogenization or spatial/temporal heterogeneity.

Taylor RN & Nesbitt RW, *Earth Planet. Sci. Lett.*, **164**, 79-98, (1998).

Sunday PO Session

LS09 : SUpo01 : PO
No Significant Element Transfer from the Oceanic Plate to the Mantle Wedge during the Subduction Process, Even at Great Depth: *Evidences from the Tethysian Oceanic Lithosphere Involved in the Alpine Orogeny*

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The geological setting of western alpine ophiolites results from subduction and collision processes during Alpine orogeny. The ophiolitic sequence is found within several nappes thrusted west- and northwest-wards upon the European continental margin of the Tethys. The lower/internal nappes (Vanoise; Queyras) record a two-stage metamorphic evolution: 1- a subduction-related prograde evolution from low-grade to blueschist and eclogite facies; 2- a collision-related retrograde evolution during which the subducted oceanic lithospheric plate was accreted. The upper/external nappes (Chenaillet-Montgenèvre) escaped to the subduction process and are only weakly metamorphosed. Representative samples of serpentinized mantle, gabbros and basalts coming from slightly to highly metamorphosed units have been analysed for major and trace elements, and Sr-Nd isotopic ratios, on whole-rocks and mineral separates (gabbros only). The data show that, compared to similar lithologies from recent oceans, the protoliths have rather well preserved major element compositions, and did not suffer any gain or lost of trace elements, nor Nd isotope exchange, whatever their metamorphic grade. However the Sr isotopic ratios record significant but irregular variations (sea water contamination). Analyses on plagioclase and clinopyroxene separates of gabbros in greenschist and amphibolite facies evidence that, while metamorphism induces major element exchanges between minerals in a closed system at rock scale, it does not lead to any significant trace element exchange between minerals inasmuch as their structures are themselves preserved.

Thus, in spite of strong prograde then retrograde metamorphic transformations inducing successively hydration-dehydration-rehydration, no chemical lost or gain due to water circulation (except for Sr isotopes) can be identified. No significant transfer to the mantle wedge occurred during the subduction process, even at great depth.

It results that trace element and Nd isotope geochemistry of mantle and magmatic products from the Tethys lithospheric plate, constrained by geometric relationships in the field, can be used to decipher ancient sea-floor spreading.

Serpentinized mantle retained the signature of a rather heterogeneous sub-continental mantle (slightly LREE-depleted or -enriched; U/Ta>1). Gabbros are mainly cumulates of plagioclase and clinopyroxene. Some gabbros represent total crystallization of the primary melt. Normalized trace element spidergrams of these minerals allow determination of their crystallization order and calculation of the composition of the initial and residual melts in the case of cumulates. In all cases, gabbros crystallize from melts with the same compositions as basalts, and the residual melts are impovershed in trace elements relative to the initial melts and have a negative Eu anomaly. Basalts are regularly depleted in the most incompatible elements and never show any negative Eu anomaly. Therefore basalts and gabbros cannot be related by fractional crystallization. They originate from the same residual mantle source (asthenosphere) below the sub-oceanic mantle. This mantle had a sub-continental history before its denudation during opening of the Tethys.

LS09 : SUpo02 : PO
Cretaceous Eclogite-Facies Metamorphism in the Eastern Alps: New Insights, Data and Correlations from an Interdisciplinary Study

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In the last 20 years, the metamorphic evolution of the Austroalpine basement complex of the Eastern Alps has been unraveled by numerous petrological and geochronological investigations. Age-data have shown that major parts of the crystalline basement were subjected to eo-Alpine (i.e. Cretaceous) orogenic processes with considerable deformation and metamorphism (cf. Thöni, 1999). Eo-Alpine high-pressure metamorphic rocks occur within the Saualpe and Koralpe crystalline, the Schober- and Kreuzeck basement and the SE Ötztal basement. These occurrences have similar tectonic positions within the southern part of the Austroalpine basement, N of the Periadriatic lineament. This 'eo-Alpine high-P metamorphic belt' (Thöni & Jagoutz, 1993) was formed after the closure of an ocean ('Meliata-Hallstatt') further to the E during late Jurassic and early Cretaceous, as a consequence of lateral propagation into continental subduction towards the W. In the present study, we compare results from several occurrences of eo-Alpine high-pressure metamorphic rocks in the Austroalpine basement unit. Structural, petrological and geochronological data are correlated with geodynamic modeling in order to address the following objectives: *Can we constrain the age of the pressure peak and subsequent thermal reequilibration and cooling?* New and improved Rb/Sr- and Sm/Nd- data from the Schneeberg Complex yielded a pressure maximum at 100-90 Ma and subsequent cooling below 300°C at around 80 Ma. *What do the PT-paths in the investigated high-pressure metamorphic areas look like? What are the metamorphic conditions of the major deformation phases?* Preliminary results yielded at least similar or higher maximum pressure conditions in the SE Ötztal basement relative to the occurrences from the Sau- and Koralpe (~2 GPa/680-700°C), but a different T-evolution during both P_{max} and decompression. *Which exhumation processes caused the transport of the eclogite facies rocks to the surface?* Detailed structural investigations were carried out in the SE Ötztal basement and the Schober basement. Kinematic modeling was performed to approach the polyphase deformation during the emplacement of the HP-rocks. Numerical thermal modeling shows that PT-paths of high-pressure rocks are in the first order sensitive to the initial depth and the exhumation rates. The observed difference in T-evolution during decompression suggests slightly different boundary conditions during the exhumation of the HP-rocks in the Ötztal and the Sau-/Koralpe basement, respectively.

Thöni M, *Schweiz. Mineral. Petrogr. Mitt*, **79**, 209-230, (1999).
Thöni M & Jagoutz E, *Schweiz. Mineral. Petrogr. Mitt*, **73**, 177-189, (1993).

LS09 : SUpo03 : PO
A Preliminary Study of Nitrogen in Phengites from HP-UHP Metapelites: Petrological Controls and IR-Calibration

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Constraining the nitrogen exchange between mantle and exosphere requires a good knowledge of the amount of nitrogen degassed from the mantle and recycled via subduction zones. To date, few studies were devoted to the amount and isotopic composition of nitrogen in metamorphic rocks and very little is known. Because of the earlier presence of organic matter in sediments, the major contribution of recycled nitrogen is brought by pelites rather than mafic and ultramafic rocks. Nitrogen occurs in metasediments as ammonium ion. Because of similarity of both charge and ionic radius, it substitutes for potassium and is thus concentrated in phengitic muscovites.

In order to follow nitrogen behaviour during subduction, several metapelites formerly subducted to different depths (30-100 km) before being exhumated are presently under investigation. The main difficulty consists in distinguishing and separating primary phengites formed during burial and secondary phengites formed during exhumation. Solving this problem requires punctual ammonium quantification method associated with strong petrological controls. We combine petrological observation and nitrogen content determination using IR microspectroscopy to select fresh primary homogeneous single crystal. As a first step, we determined carefully the IR extinction coefficient for ammonium ion in muscovite. Phengites from subducted metapelites (as several muscovites from granites) were analysed by FTIR spectrometry. This analyses, coupled with thickness mechanical measurement, allowed us to deduce a semi-empirical law for muscovites thickness calculation by infrared spectroscopy. Ammonium concentrations of these single muscovite grains (0.5 mg) were then determined by sensitive manometric measurements. Using a correlation between this concentration and ammonium IR light absorbance, we assessed ammonium molecular absorptivity for a wavenumber of 1430 cm^{-1} (NH_4^+ bending) to about 567 $l.mol^{-1}.cm^{-1}$.

Several grains from two metapelites (from western Italian Alps) subducted at 18 and 30 kbars show N-contents higher than 1500 ppm. Since phengites represent about 30% of the whole rock, we can deduce a total nitrogen content of about 450 ppm. These few results are compatible with the idea that no evolution (fluid loss) occurs after 18 kbars. These results show that high amounts of nitrogen can be recycled through the mantle via subduction zones. Nitrogen isotope data are presently investigated and will be presented at the conference.

LS09 : SUpo04 : PO
Subduction-Accretion History of the Central Asian Orogenic Belt; Constraints from Mongolia

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The Central Asian Orogenic Belt (CAOB), one of the world's largest accretionary orogens, formed largely by subduction and the accretion of juvenile material from the Neoproterozoic through the Palaeozoic; Mongolia occupies a key central position. It is fringed by the Siberian craton in the north and by the Tarim and Sino-Korean cratons in the south. Several very different summaries, syntheses and models have been proposed to explain the development of the CAOB. Most authors have suggested the closure of small ocean basins by multiple subduction, the obduction of ophiolites, the accretion and collision of island arcs and microcontinents, and the formation of multiple suture zones. In contrast, Sengör et al. (1993) envisaged continuous, oceanward migration of a single subduction zone to create the entire Altaid collage.

We have subdivided the geology of Mongolia into forty-four terranes: island arcs, continental margin arcs, ophiolites, accretionary wedges, passive continental margins, microcontinents, and overlap basins. Strike-slip faulting has dismembered many terranes such as island arcs and ophiolites. The subdivision allows us to make much-needed, detailed studies of individual terranes and their boundaries in order to confirm or modify their character and make-up.

There are perhaps as many as eleven microcontinents, the oldest of which is the Baydrag block in central Mongolia that has a zircon age on high-grade biotite tonalitic gneiss of 2646 ±45 Ma (Mitrofanov et al., 1985). Ophiolites have a similar isotopic age from south to north; Khantayshir (568 ±4 Ma, U-Pb zircon), Dariv (573 ±6 Ma, U-Pb zircon), Bayankhongor (569 ±21 Ma, Sm-Nd whole rock), and Agardagh in Siberia just north of Mongolia (569 ±1.1 Ma, U-Pb zircon, Pfänder et al. 1999). Some ophiolites with offshore arcs were thrust northwards over their continental margins, but others southwards, from which we infer different senses of subduction polarity. These relations point to a geometrically complex tectonic assembly with variably oriented subduction zones. South of the Bayankhongor ophiolite is a 20 km-wide accretionary wedge with common chlorite-muscovite-graphite schists intruded by andesite dykes. Island arcs range from Neoproterozoic in the north of Mongolia to late Palaeozoic in the south. A continental magmatic arc in southern Mongolia has $^{40}Ar/^{39}Ar$ ages of 364 ±3.5 Ma on porphyry copper ore and 313. 0 ±2.9 Ma on a cross-cutting porphyry dyke (Lamb and Cox, 1998). Some terranes previously synthesised from early-published records have been incorrectly defined.

Our results place limits on earlier tectonic models. The processes of subduction-accretion in Central Asia were more complex than previously realised. At present the paucity of reliable data prevent the creation of a single viable tectonic model to explain the subduction-accretion history and processes with time.

Lamb MA & Cox D, *Econ. Geol*, **93**, 524-529, (1998).
Mitrofanov FP et al, *Doklady Acad. Nauk. USSR*, **284**, 670-675, (1985).
Pfänder Jet al, *Ofioliti*, **24**, 151-152, (1999).
Sengör et al, *Nature*, **364**, 299-307, (1993).

LS09 : SUpo05 : PO
Precise U-Pb Ages from the Kohistan Complex (Northern Pakistan) Illustrate Rapid Formation of Arc-Type Crust

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The Kohistan Arc Complex in northern Pakistan was formed in the Tethys ocean in Mesozoic times and subsequently obducted onto the Indian plate along the Indus Suture in the Late Cretaceous - Paleocene times. The tectonic evolution of the arc can be subdivided into (1) a juvenile stage (estimated at ca.110-95 Ma) involving lithospheric growth through partial melting of a fertile mantle in an intraoceanic subduction environment; (2) intra-arc rifting (around 85 Ma) marked by the emplacement of large volumes of volcaniclastic rocks in the intra-arc extensional basin and underplating of the arc crust by gabbronorites; (3) a mature stage with Andean-type granitoid magmatism, which ceased with the India-Asia collision 60 to 40 Ma ago. The structurally lowest levels of the Kohistan Arc Complex comprise the Jijal complex, which consists of ultramafic rocks overlain by granulite-facies gabbros. The complex is covered by a pile of metamorphic gabbroic to tonalitic dykes and sills overlain by metabasalts and metasediments. This association was intruded by partial melts of mantle origin (gabbros, tonalites, granitoids) representing the first stages of crustal growth (stage 1) in an intraoceanic arc. Precise age determinations yielded for a sub-granulitic gabbro and a granitoid sheet-like intrusion significantly discrete ages of 99 and 97 Ma, respectively; a tonalite body was emplaced into the same environment at 92 Ma. The whole complex was again penetrated by mantle melts (gabbronorites to granitoid dykes) during rifting (stage 2). A gabbronorite from the so-called Chilas Complex and a granitoid kyanite-bearing dyke yielded ages of 85 Ma and 83 Ma, respectively. The time period for the initial arc buildup with intrusion of gabbroic to granitoid melts is constrained to a short time period between 99 and 92 Ma. Intra-arc rifting characterized by the intrusion of gabbronorites and granitoid dykes is dated between 82 and 85 Ma. The ages represent the first protolith ages from the sub-arc mantle-crust transition. Initial arc magmatism may therefore be constrained to at least three magmatic pulses of <5 m.y. duration with each magmatic cycle most likely comprising gabbroic to granitoid lithologies, pointing to rapid differentiation processes. The granitoid stocks, sheets and dykes were emplaced prior to obduction onto the Indian plate.

LS09 : SUpo06 : PO
The Tastil Batholith (NW Argentina): A Case of Polyorogenic, Suduction-Related Magmatism in the Andean Basement

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The Tastil batholith in Salta (NW Argentina) is one of the key areas for understanding the tectonic evolution of the Lower Paleozoic ? Neoproterozoic basement of the Central Andes. It is now widely accepted that the Tastil batholith consists of grey granodiorites and red granites, and that an angular unconformity separates Lower Paleozoic sandstones from the underlying red granites. New field data are presented for this batholith which show that: (1) in addition to grey and red granites, large areas of the batholith consist of dacites; there are also two NE-SW-trending domes of monzodiorites with related trachytes piercing through grey granites and dacites, (2) as the red granite has xenoliths from (and cuts the bedding of) the overlying sandstones, the contact between them cannot be longer interpreted as an unconformity but as an intrusive contact, (3) field criteria indicate that the sequence of intrusive events is, from older to younger: grey granites/dacites, red granites, monzodiorites/trachytes, (4) the occurrence of red granite pebbles in Tremadocian conglomerates constraints the minimum age of the red granites and suggests an older, Cambrian age for underlying sandstones (Mes-n Group), grey granites and dacitic rocks; in contrast, the monzodiorite has to be related to the Tertiary magmatism of the Andes, on the basis of comparison with similar rocks from the Nevado de Acay peak.

Geochemical and structural data are also consistent with two igneous suites. Most granite and dacite samples are peraluminous and high-K calc-alkaline to shoshonitic, whereas the monzodiorite suite falls within the metaluminous domain and is of shoshonitic affinity. This study converges toward the conclusion that these magmatic suites represent high-K plutons emplaced at shallow levels during crustal extension related to subduction processes. New U-Pb zircon ages are consistent with field data. A dacite sample yielded an age of 526 ±2 Ma (Middle Cambrian). Preliminary results suggest an age of c. 520 Ma for the red granite and a Tertiary age for the monzodiorite. From these data, it appears that the granite suite of the Tastil batholith is not related to the Neoproterozoic evolution of the Andean basement as previously considered, but to initial stages of extensional tectonics leading to the development of Eopaleozoic basins.

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LS09 : SUpo07 : PO
Mud Volcanism as a Powerful Tool in Dewatering Accretionary Prisms

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Deep drilling results from two mud volcanoes on the Mediterranean Ridge accretionary complex as well as bottom sampling and the wealth of geophysical data acquired recently have provided fundamental knowledge of the 3D-geometry of mud extrusions. Mud volcanism is related to buoyancy (density inversion) and collision of the African and Eurasian blocks, forcing undercompacted clayey sediments to extrude along faults in the central and hinterlandward parts of the prism.

Volumetric estimates of extruded mud in several well-studied areas were based on pre-stack depth-migrated seismic profiles across the entire, up to >150 km-wide prism. The resulting volumes of mud were combined with ages from mud dome drilling, so that rates of mud extrusion were obtained. Subtracting the solid rock mass from the bulk mud volume using physical property data, fluid flux as a function of mud volcanism alone has been quantified for the first time. The volume of fluid extruding with the mud is found to be variable, but reaches up to 15 km^3 fluid per km trench length and Ma along cross sections with abundant mud volcanoes. Such large fluid quantities in a region some 50-150 km behind the deformation front exceed estimates from toes elsewhere (where undoubtedly the majority of the interstitial fluid is lost due to compaction). Such fluids near the backstop are likely to result predominantly from mineral dehydration and diagenetic reactions at depth, and consequently provide a window to understand deeper processes along the deep décollement. More importantly, the enormous rates with which such fluids and liquefied mud escape along the out-of-sequence faults alter fluid budget calculations in subduction zones drastically.

LS09 : SUpo08 : PO
Physical Properties of Dehydrating Serpentinite

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Serpentinite dehydration is thought to be an important factor for several subduction related processes: Dehydration embrittlement has been suggested as a major cause of intermediate-depth earthquakes (e.g., Davies, 1999); lenses of serpentinite may control the rheological behaviour of the subduction zone; water released from the subducting slab may cause hydration of the mantle wedge (Peacock, 1993) and trigger melting of lower crustal rocks in the overriding plate.

Thus better knowledge of the physical properties of serpentinite is needed to improve our understanding of the processes related to subduction. We have therefore performed laboratory experiments to determine the change of physical properties of serpentinite with changing temperature and pressure beyond the dehydration reaction of serpentine to talc, forsterite and water. The physical properties investigated are seismic velocities, electrical conductivities and thermal conductivity and diffusivity on various well-characterised serpentinites (by optical microscopy, TEM, X-ray diffraction and XRF) from SE-Germany, Val Malenco and from Crete.

Preliminary results of the electrical conductivity measurements of wet serpentinites showed a significant increase of the surface conductivity with increasing temperature. Thermal conductivity shows an unusual behaviour in so far as it increases slowly with temperature, while thermal diffusivity decreases. The dehydration reaction is marked by a pronounced maximum in thermal conductivity, followed by a strong decrease in both thermal conductivity and diffusivity with further increasing temperature, which we attribute to the loss of water. The transition to forsterite causes a clear increase in both thermal conductivity and diffusivity.

Ongoing experiments address these properties at in-situ conditions, i.e. at elevated temperatures and pressures in a gas-apparatus on large volume samples in drained and undrained conditions.

Davies, JH, *Nature*, **398**, 142-145, (1999).
Peacock, SM, *Chemical Geology*, **108**, 49-59, (1993).

LS09 : SUpo09 : PO
S, Cl and F in Olivine Melt Inclusions from Mafic Arc Rocks in Kamchtka

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Sulfur, chlorine, fluorine and major element contents as well as sulfur speciations were analyzed by electron microprobe in olivine and pyroxene melt inclusions and pyroxenites from Kamchatka. These samples represent a traverse covering the Eastern Volcanic Front (EVF), the Central Kamchatka Depression (CKD), and the back arc region of the Sredinniy Ridge (SR). All samples are medium- to high-K calkalkaline rocks and display a increase in HFSE and relative decrease in fluid mobile elements (Leeman et al. this meeting) from front to back-arc. Because volatile-bearing minerals do not occur as phenocrysts, the behavior of volatile elements is influenced only by fractional crystallization and degassing. Potassium is strongly incompatable and unaffected by degassing, thus K/volatile ratios are a degassing index. Whole rock sulfur contents are always less than 200 ppm. However, sulfur contents in inclusions from EVF and CKD rocks range from 100 to 1250 ppm. Highest sulfur concentrations were measured in inclusions from CKD lavas. K/S ratios in SR magmas show a strong increase (i.e. degassing trend) with decreasing Mg#. Sulfur speciation measurements show that the majority of inclusions contain only S6+. Few inclusions have S2-, but mixtures of both species in one inclusions are not observed. The highest concentrations of chlorine occur for EVF and high-Mg CKD rocks (1710 ppm and 1720 ppm, respectively), decreasing in high-Al basalts of Kluchevskoy volcano and rocks in the northern CKD (1280 ppm and 1140 ppm). A further decrease in Cl is observed to back arc SR rocks (788 ppm). K/Cl ratios in general show a degassing trend, only a few melt inclusions in olivines have constant K/Cl at variable Mg#. Fluorine concentrations are similar for EVF and CKD (420 ppm - 520 ppm) but twice as high in SR inclusions (950 ppm). F-enrichment is also observed in inclusions in SR-pyroxenites. Because fluorine is not affected by degassing, K/F ratios are constant during differentiation. F/Cl ratios are lower than 1 in EVF and CKD inclusions, but strongly increase (to 2) in SR rocks. This regional variation is mostly due to variations in fluorine. We propose that S and Cl contents in across - arc Kamchatka lavas are mostly controlled by degassing. EVF rocks appear to be least degassed and most enriched in Cl (and fluid mobile elements, Leemann et al, this meeting). Enrichment in CKD rocks in S, high oxidation state (S6+) in most inclusions and correlation of S with fluid-mobile elements suggests a high fluid flux. High F and F/Cl ratio in melt inclusions from back arc lavas and xenoliths (SR) show that in contrast to EVF and CKD, mantle sources were enriched in fluorine resulting from melting F-bearing phases (phlogopite) or from deep fluids below SR (400 km above the subducted slab).

LS09 : SUpo10 : PO
Trace Element and Isotopic Trends as Indicators for Fluid-Versus Melt-Dominated Sediment-Wedge Transport in the East Sunda Arc (Indonesia)

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Four arc volcanoes in the Pantar Strait (Indonesia) lie in a straight line perpendicular to the trench, with depths to the Benioff zone increasing from 145 to 170 km. The volcanoes are extinct, reflecting ongoing collision between the arc and the Australian continent. Preliminary age dating puts their activity at 0.8 Ma. Clear across-arc geochemical trends are observed, with most incompatible elements increasing (at similar SiO_2 concentrations) towards the back of the arc: K_2O contents at 57.5% SiO_2 increase from 1.5 to 4 wt%. On average, ratios of fluid mobile/fluid less mobile elements (Pb/Ce, Sr/Nd) decrease towards the back of the arc, while La/Nb and Th/Ce ratios increase, although trends are not always smooth. Sr and Pb isotope ratios decrease while Nd isotope ratios increase towards the back of the arc. The across-arc change in isotopic ratios indicates that the observed geochemical changes cannot only be explained by the breakdown of specific mineral phases in the slab or mantle wedge. Sr and Nd isotopes point towards increased importance of sediment in the budget of these elements behind the front. The across-arc decrease in Pb isotopic ratios may imply that the sediments have lost much of their Pb during mobilisation under the front arc volcanoes. This isotopic behaviour contrasts with that seen on the neighbouring island of Alor, where volcanism ceased 1.3 Ma ago. Here Pb isotopic ratios increase with decreasing Nd and increasing Sr isotopic ratios. Changes in isotopic ratios are not accompanied by pronounced changes in ratios of fluid mobile/fluid less mobile elements, suggesting that signatures reflect variable amounts of sediment involved in magma genesis, rather than different transport mechanisms from slab to mantle wedge. Element ratios such as Ce/Yb, Zr/Nb and La/Th in the frontal Pantar Strait volcano do not coincide with those of N-MORB, and overlap with the field for local sediments, which suggests involvement of a sediment-derived melt. Similarly, the very high Ce/Yb ratios in the back arc volcano are most easily interpreted as representing the addition of a partial melt of sediment, rather than wholesale sediment addition. Alternatively, the mantle wedge contains a non-MORB component, the evidence for which could also be inferred from Pb isotope systematics. The Pb isotopes cannot be explained by mixing Indian MORB mantle with local sediments, as models require a mantle component that is more enriched in ^{208}Pb, which would be more consistent with the presence of an OIB-type mantle in the wedge. It is also conceivable, however, that the isotopic signatures were generated by involvement of subducted Australian continental lithologies with high $^{208}Pb/^{204}Pb$, in addition to the local sediments.

LS09 : SUpo11 : PO
The Origin of Rhyolite in Oceanic Island Arc Crust: Evidence from the Izu-Bonin Volcanic Arc

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The northern Izu-Bonin volcanic arc with crustal thickness ~ 22 km (Suyehiro et al., 1996) extends 550 km from Izu Peninsula, Japan (~35°N), to north of Nishinoshima Trough or Sofugan Tectonic line (~29°N). The arc is one of segments of Izu-Bonin-Mariana (IBM) arc system, which is an excellent example of an intra-oceanic convergent margin.

Seventeen Quaternary volcanoes of the Izu-Bonin volcanic arc including 6 volcano islands and 9 submarine silicic calderas lying on the front of the arc, and 1011 chemical analyses of these volcanoes were reviewed to estimate relative proportions of magmas erupted. The number-of-analyses vs. SiO_2 histogram is converted into volume-weighted histogram by the method of Aramaki & Ui (1978). Apparently, basalt and basic andesite (SiO_2 less than 57 wt.%) are dominant rock types of the Izu-Bonin arc, but rhyolite (SiO_2 more than 70 wt.%) has another peak in volume. The latter peak would be more emphasised if rhyolite pumices from submarine calderas, which had deposited far from the source calderas, were taken into consideration.

The melts produced in dehydration-melting experiments of calc-alkaline andesite at low pressures (less than 7 kb) (Beard & Lofgren, 1991) have major element compositions that are indistinguishable from those of the Izu-Bonin rhyolites. Moreover, groundmasses of calc-alkaline andesites of the Shirahama Group, Izu Peninsula (Tamura, 1995), have compositions similar to those of most rhyolites. These lines of evidence suggest that the enormous amount of rhyolite, which erupt in the Quaternary Izu-Bonin arc volcanoes, are produced by dehydration-melting of calc-alkaline andesite in the upper to middle crust. This leads us to another interesting conclusion that a huge amount of calc-alkaline andesites (3~5 times as large as rhyolite) exist within the oceanic arc crust despite that voluminous calc-alkaline andesite eruptions only occur in evolved island arc or continental marginal regions. Given that calc-alkaline andesite magmas are water-saturated, they would freeze in the crust. Remobilizations of calc-alkaline andesite magmas by intrusion of mafic magmas are indicated at the Soufriere Hills volcano, Montserrat (Murphy et al., 2000) and at the Lascar volcano, Chile (Matthews et al., 1999). Rhyolite eruptions could also be triggered by influx of hot basalt magmas, which reheats and softens the frozen calc-alkaline andesite magma bodies. Dehydration melting of these frozen magma bodies is a viable mechanism for the formation of rhyolite in the Izu-Bonin arc.

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LS09 : SUpo12 : PO
Thrust Sheet and Decollement Zone in the Ancient Accretionary Complex; An Example from the Miocene Hota Group in the Boso Peninsula, Central Japan

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The Miocene Hota Group in Boso Peninsula, Central Japan, preserves early stage deformation structures formed at in shallow levels due to repid accretion onto the shallow part of accretionary wedge (Hirono & Ogawa 1998).In this area, the volcaniclastic sandy/muddy sediments have undergone complicated deformation. We report here a conspicuous shale-matrix melange zone adjacent to relatively coherent but severely deformed strata which bear abundant water-escaping structure. The fault system in the coherent part indicates compressive stress field and which in the melange zone indicates the shearing. This suggests that the relatively coherent part have behaved as a thrust sheet and the melange zone as a decollement. In the matrix of melange, scaly fabric is developped penetratively. Scaning electron microscope and thin section analysis show that the surface of the fabric was made of preferented orientation of clay mineral. The material in the melange zone shows low bulk density and high porosity. It suggests that they were formed under high-pore fluid pressure condition. These lines of observations are consistent with the results of downhole logging data of the ODP.

Hirono T & Ogawa Y, *Geology*, **26**, 779-782, (1998).

LS09 : SUpo13 : PO
Petrogenesis of East Scotia Ridge Lavas- South Sandwich Back-Arc, Southern Ocean

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The East Scotia Ridge is an active back-arc spreading center west of the South Sandwich Island arc in the South Atlantic Ocean consisting of nine main segments, E1 (north) to E9 (south). Recent sampling campaigns now provide complete coverage of the East Scotia Ridge. Major and trace element composition are presented together with the water content and radiogenic isotope (Sr, Nd, Pb) data for lavas taken along the active ridge axis. Crystal fractionation processes occur mainly along segments E2 and E8 with differentiated magmas erupted at the topographic highs on the centres of the segments, implying that a magma chamber where low pressure fractionation processes take place is situated beneath these segments. Magmatism along the East Scotia Ridge is chemically heterogeneous, but a common source for all the East Scotia Ridge magmas is the MORB component. An almost unmodified MORB-source mantle underlies the central

part of the back-arc. A sediment component is found at the northern and the southern ends of the ridge, and there is a marked sediment melt input of up to 2% in segment E4 and overlapping part of E3. The enrichments in water-mobile elements, coupled with high magmatic water contents of up to 2.2 wt% speak of a role for fluid in the element transport. This fluid could come from either the altered oceanic crust or the subducted sediments. The subduction of predominantly silica-rich (diatomaceous) sediments, coupled with the large enrichments in Rb and Ba, seems to imply the involvement of a sediment-derived rather than an altered-crust-derived fluid component. Primitive (plume) mantle is present beneath segment E2 and E9 at the northern and southern ends of the ridge, suggesting that plume mantle is flowing westward around the edges of the subducting slab. The southern part of segment E8 is unique in that its magma source is sub-arc depleted mantle.

LS09 : SUpo14 : PO

Petrogenetic Evolution of Cayambe Volcanic Complex: Evidences for Slab Melts-Mantle Wedge Interaction

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Recent developments in subduction zones clearly demonstrate that at least two main sources could be implied in calc-alcaline magmatisme: the mantle wedge and the subducted slab. In cold subduction environments, metasomatised mantle wedge melts generate the calc-alkaline magmas, whereas slab melting is restricted to the relatively rare hot subduction cases. Nevertheless, the process of the transition from one source to the other, as well as their possible interactions are not well understood and still under debate.

Cayambe volcanic complex (CVC) is located in the northern part of the Ecuadorian Andes. The main part of this arc has been developed facing the subducting Carnegie Ridge which represents the trace of the Galápagos hotspot across the Nazca Plate. The ridge entered in subduction 5 Ma ago inducing a flat slab subduction (Gutscher et al., 1999). Gradually, the CVC has displayed a transition from: (1) an older mostly lavic volcano (VCAY), whose lava composition evolves from mafic andesites to rare dacites with a clasical calc-alcaline character (Yb_N ~8-12 ; $(La/Yb)_N$ ~7-18). (2) a younger, more explosive, dome complex (NCAY), mainly dacitic and with quite typical adakitic characteristics (Yb_N ~3-7; $(La/Yb)_N$ ~8-41).

In addition, mineralogy, major and trace element geochemistry as well as Sr-Nd isotopes, demonstrate that the whole CVC has an hybrid character. Geochemical modelling applied to VCAY rocks leads to interpret their features in terms of modification of the composition of the mantle wedge source by both dehydration fluids and slab melts. On the contrary, similar modelling applied to the NCAY, indicates that the magmas have their origin in both the partial melting of the slab and subsequent interactions with the mantle wedge.

Consequently, our interpretation considers that the CVC's magmas could result from an increasing interaction of slab-derived melts with mantle wedge or with mantle melts. When the Carnegie ridge entered into subduction, the geothermal gradient increased along the Benioff plane such that slab melting was allowed. At the beginning the whole volume of slab melts was consumed by interaction with mantle minerals, producing the VCAY mantle derived hybrid magmas. As subduction of the ridge and the degree of interaction progress, the adakitic melts have been able to reach the surface and produce the mantle contaminated adakitic NCAY magmas. These results ruled out the hypothesis of Ecuadorian adakites genesis by underplated basalt melting.

Gutscher MA, Malavielle J, Lallemand S & Collot JY, *Earth and Planetary Science Letters*, **168**, 255-270, (1999).

LS09 : SUpo15 : PO

The Role of Fluid Release in Subduction Dynamics: A Chemo-Thermo-Mechanical Model

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Several studies over the last 30 years have emphasized that the key to understanding the fate of fluids, especially water, in subduction zones is to understand the thermal structure of the subducted plates and overlying mantle. Earlier works have shown that this thermal structure is a function of several variables like the age of the incoming oceanic lithosphere, the rate of subduction, and the dip angle. However, the impact of chemical reactions and heat transport by fluid flow on the thermal structure have yet to be thoroughly explored. The latent heats of reaction are likely to be large. For example, if a serpentinite is completely 'dewatered' back into olivine and enstatite, it can absorb heat equivalent to a temperature drop of 300°C. This suggests that deserpentinization can have a major impact on the thermal structure of the downgoing crust and lithosphere. Here we present results of numerical model calculations that account for metamorphic reactions in the heat budget of the subducted plate. The goal is to better understand the role of fluids in subduction zones and the impact of dehydration processes on subduction dynamics in general. The model we use is based on one developed for modeling mid-ocean ridges. It solves for the flow and the temperature distribution in the region of interest as well as accounting for melting and melt migration. In this study we have enhanced this model to apply to a subduction zone geometry and to implement dehydration reactions inside the downgoing slab. This is done through a continuous update of the latent heat and fluid release within the slab.

In our initial study we wish to analyze the interaction between fluid release into the ambient mantle and its impact on the thermal structure and location of the downgoing slab. These general results may help to place better quantitative constraints on the initial budget of water stored in hydrous minerals, and on the timing and volume of slab-derived fluids released during slab decent.

LS09 : SUpo16 : PO

Chlorine Isotopic Constraints on Expelled Fluids in Subduction Zones: Implications to Recycling?

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The few chlorine isotope data reported in litterature cover a large range of $\delta^{37}Cl$ values (from -14‰ to +10‰ versus SMOC). Experimental studies on chlorine isotope fractionation lack presently to understand the origin of such fractionations and to constrain the global chlorine geochemical cycle.

This spreading is particularly true for subduction zones (-8‰ to +10‰). However, the published results are scattered over several subduction zones and are not all very well constrained chemically and isotopically. These studies do not allow to distinguish between chlorine isotopic fractionations due to physical and/or chemical processes and an isotopic evolution of the chlorine reservoirs.

That is why we focused this chlorine isotopic study on a single zone, the Barbados accretionary prism, using a collection of fluids from the outer (Manon site) and inner (Trinidad) deformation front (Godon et al., 2000). These expelled fluids probably result from sediment consolidation processes, from diagenetic or metamorphic dehydration and/or from the breakdown of hydrous minerals and gas hydrates, and from seawater circulations. This collection is completed by samples from the Lesser Antilles island arc. Chlorine from these samples may partly come from residual subducted fluids which have migrated through the mantle wedge to the arc volcanism.

At the outer edge of the Barbados sedimentary complex, hot fluids expelled by sub-marine mud volcanoes (5000 mbsl; Dia et al., 1995) show very negative $\delta^{37}Cl$ values, down to -5.24‰. At the inner edge of this prism, hot fluids expelled by terrestrial mud volcanoes (Dia et al., 1999) show less negative $\delta^{37}Cl$ values, down to -3.16‰. Such negative $\delta^{37}Cl$ fluids have also been found off shore of the Peru and Japan subduction trenches (this work and Ransom et al., 1995). Our first result from an andesite (Martinique) shows a $\delta^{37}Cl$ value of -0.05‰ (±0.20‰), and we measured strictly positive values for Guadeloupe Soufrière's condensates (from +0.81‰ to +1.95‰).

Deduced from positive $\delta^{37}Cl$ values for most MORB (10 values), 13 amphibole-rich rocks and 2 smectites (Magenheim et al., 1995), we can consider a positive or nil $\delta^{37}Cl$ values for the whole altered and serpentinised oceanic crust (with its sediments and interstitial fluids). Expulsion of very negative $\delta^{37}Cl$ fluids through the prism implies the effect of processes (expulsion by compaction and dehydration, migration and fluid-rock interactions) producing important combined chlorine isotopic fractionation. These observations may reflect a lower isotopic fractionation effect, related to physical and chemical constraints of evolution between the beginning of the subduction and the arc. But they possibly also reflect a ^{37}Cl enrichment of the subducted residual reservoir while the slab is subducting. In all cases, this data set implies the recycling of a positive or nil $\delta^{37}Cl$ material into the mantle.

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Monday AM Session

LS09 : MOam01 : G0
Boron and Fluid-Mobile Element (FME) Fluxes Across Kamchatka

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Kamchatka arc volcanism comprises three major zones: (1) Eastern volcanic front (EVF), (2) Central Kamchatka depression and the Kluchevskaya group (CKD), and (3) western Sredinny range (SR). A 300 km traverse sampled Holocene and Quaternary stratovolcanoes, and monognetic cones from the volcanic front at Komarova through the Kluchevskaya Group into the backarc Achtang monogenetic field and Ichinsky stratovolcano. Medium- to high-K calkalkaline rocks dominate, with high-Mg basaltic-andesites and high-Al-basalts (CKD), and rare low-K tholeiitic rocks (EVF). Low HREE but high Nb and Ta and Ta/Yb ratios characterize backarc rocks, whereas volcanic front rocks have less-depleted HREE and significantly lower Nb, Ta, and Ta/Yb ratios. The Kamchatka mantle wedge appears variably depleted prior to slab component addition (Churikova et al., in press). Sr-Nd-, Pb-isotopic data preclude significant subducted sediment contributions; heavy O-isotope values suggest a large fluid-flux derived from the subducted Emperor seamount chain below our transect (Dorendorf et al., 2000). Fluid-mobile elements (FMEs: e.g., B, As, Sb) and B-isotopes were determined in mafic to intermediate rocks (4-10% MgO) to evaluate the fluid flux. Elements indicative of sediment-derivation show no systematic variations with slab depth: e.g., Ba/Zr ratios (2-7) are near-constant across the arc. By contrast, FMEs more characteristic of dewatering of subducted basaltic crust show systematic variations: B/La, B/Nb B/Be, and B/Zr ratios decrease rapidly from the arc front to backarc from values around 5, 12, 55, and 0.25 (EVF) to less than 0.5, 1.0, <10, and 0.05 (SR), respectively. Relatively high magma production at Kluchevskoy is characterized by slightly higher fluid-mobile element contents compared to surrounding centers. Maximum B-enrichment occurs in the most mafic rocks and is attributed to strong B enrichment of magma sources by slab-derived fluids (which may also enhance melt production). More evolved lavas often have lower B-enrichment, which may reflect AFC processes involving low-B crustal rocks. Excellent positive correlations are observed between fractionation-corrected (i.e., Ce-normalized) abundances of chalcophile elements such as Sb, As, Sn, and Mo and the B/La ratio. We argue that : - large enrichments and systematic decrease in abundance of fluid-mobile elements across the arc reflect dewatering of the downgowing hydrated basalts rather than sediment melting or dehydration - High magma production rate and strong fluid-mobile element enrichment in the Kluchevskoy Group, 80 km behind the active arc, suggests that active mantle upwelling involved previously enriched mantle during ongoing intra arc rifting and formation of the CKD. - Subduction of the Emperor Seamount chain is responsible for the anomalously large fluid flux (and magma production rate) below Kamchatka

Dorendorf F, Wiechert U & Wörner G, *Earth Planet Sci Lett*, **175**, 69-86, (2000).
Churikova T, Dorendorf F & Wörner G, *J Pet*, in press.

LS09 : MOam02 : G0
Boron Isotope Compositions of Tourmaline in High- and Ultrahigh-Pressure Metasedimentary Suites: Records of Subduction-Zone Boron Cycling

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Boron partitioning among fluids, tourmaline, and micas (and other B-rich phases) dictates the extent and location, and isotopic composition, of B loss in subducting slabs (and any additions to arc sources or deeper mantle), but the scarcity of information regarding mineral-fluid fractionation limits efforts to quantitatively model B isotopic evolution. To clarify tourmaline's role in B redistribution during devolatilization of subducting sediments, we have analyzed tourmaline $\delta^{11}B$ in several HP and UHP suites, employing high-precision ($2\sigma_{mean}$ = 0.5-0.8‰) ion microprobe methods.

Catalina Schist and Sambagawa Belt metasediments (sub-blueschist to amphibolite facies, <1.2 GPa) show contrasting systematics in whole-rock B content and tourmaline abundance. The Sambagawa shows uniform whole-rock B across grade, but an increasing proportion of B in tourmaline and decreasing proportion in micas at higher grades (Nakano and Nakamura, 2001). Catalina Schist rocks contain less tourmaline, and at higher grades show up to 75% whole-rock B loss (Bebout et al., 1999) with correlated decreased mica B. In both suites, some higher-grade (~epidote-amphibolite) rocks contain abundant zoned dravitic tourmaline. In these rocks, tourmaline cores have lower $Mg/(Mg+Fe^{+2})$ and Ca/(Ca+Na) and higher $\delta^{11}B_{SRM951}$ (up to +1.6‰, mostly -6 to -2‰), and tourmalines show increased $Mg/(Mg+Fe^{+2}$ (up to 0.825) and Ca/(Ca+Na) and decreased $\delta^{11}B$ (approaching -15‰) toward rims. These variations are consistent with significant prograde growth. Some higher-grade tourmalines have thin outermost zones compositionally similar to cores and attributed to retrogradation. The $\delta^{11}B$ of less-abundant tourmaline in lower-grade rocks (-7 to +4.5‰) overlaps with, or is higher than, that of tourmaline cores in higher-grade rocks, and some cores in low- and high-grade rocks are regarded as detrital. Lago di Cignana UHP metasediments (peak 2.7-2.9 GPa; Reinecke, 1998, who reported coesite inclusions in tourmaline) contain dravitic tourmaline zoned in $Mg/(Mg+Fe^{+2})$, Ca/(Ca+Na), and $\delta^{11}B$. We tentatively associate cores with garnet and rutile inclusions, $Mg/(Mg+Fe^{+2})$ up to 0.95, and $\delta^{11}B$ as low as -12‰ with prograde, high-P/T metamorphism, and rims with clinozoisite and quartz inclusions, lower $Mg/(Mg+Fe^{+2})$, and higher $\delta^{11}B$ up to +4.3‰ with overprinting during exhumation.

The HP suites illustrate contrasting B behavior reflecting the significance of sedimentary processes, bulk-rock/fluid chemistry, or kinetic factors (e.g., need for sedimentary or lower-grade metamorphic "seed crystals") in controlling the presence and growth of tourmaline at higher-grades. In the absence of tourmaline, devolatilization can reduce whole-rock B (Catalina), whereas tourmaline growth may serve to retain whole-rock B lost from micas and minimize change in whole-rock $\delta^{11}B$ (Sambagawa). At Lago di Cignana, tourmaline (with $\delta^{11}B$ = -16 to -9‰) was apparently stable to depths of ~90 km, and correlated major element and B isotope zoning (>16‰) demonstrates tourmaline's ability to preserve metamorphic history spanning large P-T ranges.

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LS09 : MOam03 : G0
Lithium Systematics of Arc Lavas

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The process of subduction recycles continental material back into the mantle via sediments and alteration products in the basaltic oceanic crust. Contributions from two recycled components have been identified in the chemistry of arc lavas: subducted sediments and a 'fluid' from the altered oceanic crust. Both these 'slab' components, together with contributions from the mantle wedge, shape the composition of arc lavas. Although the influence of the slab components is well established the magnitude of their contribution is still debated. The two major components of the subducting slab, marine sediments and altered oceanic crust, are highly enriched in Li, in addition to being isotopically distinct from the mantle as a result of surface fractionation. Therefore Li isotopes have a great potential as unequivocal tracers of recycled material in arc lavas. Understanding of the behaviour of Li in the subduction zone is in its infancy, however, and here we initially address the elemental behaviour of Li. Three oceanic arcs with variable sediment contributions to their sources have been targeted for this study: namely the Mariana, South Sandwich, Banda and East Sunda Arcs. Li concentrations have been measured in all the arc lavas by isotope dilution using ICP quadrupole MS. This gives a reproducibility of better than 2%. Li concentrations range between 3.1 and 20.4 ppm. All island arc lavas generally show strong enrichment in Li relative to Y (an element of similar incompatibility) compared to MORB. However, the range of Li/Y of the arc lavas is highly variable and ranges vary between 0.18 and 0.89, compared to a typical MORB value of 0.16. The variation in Li/Y is not clearly related to other geochemical indices. Within the sediment rich samples from Indonesia, there appears to be some correlation of increasing Li/Y with indices related to sediment addition. In the Marianas, in contrast, it is the island of Guguan, with the least sediment rich source, which shows the highest Li/Y. This may be attributable to the 'fluid' component, although the correlation of Li/Y with indices of fluid addition, such as Ba/La is far from perfect. It thus appears that recycled contributions to the Li budget of arcs can be derived from both sediment and fluid, and may in part account for some of the complexity of its behaviour. The samples are being further investigated using Li isotope ratios and data will be presented to constrain better the causes of elemental Li variation.

LS09 : MOam04 : G0
Ubiquitous Salt-Rich Brines in HP and UHP Rocks

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Fluid inclusion and mineral analysis have shown that fluids with low water activities due to the presence of salt in solution and/or of Cl radicals in minerals can be present in eclogite facies rocks and in lower crustal granulites. The origin of salt has been attributed either to a relic testimony of seafloor hydrothermal alteration or to a progressive enrichment of Cl in the fluid attending hydration or melting reactions during eclogite or granulite facies metamorphism.

In order to verify if salt and Cl-rich minerals formed through a desiccation mechanism are common features of HP and UHP rocks, we investigated a variety of eclogitic rocks for their fluid inclusion composition and halogen content of hydrous minerals. The HP and UHP facies rocks studied are from the Seve nappe (Swedish Caledonides; 1.5 GPa and 550 ±70°C, courtesy of H. van Roermund), the Dabieshan (China; 2.9 GPa and 750-830°C, courtesy of P. O'Brien), the Himalayas (Upper Kaghan Valley, Pakistan; 1.8 GPa and 650±50°C, courtesy of P. O'Brien) and the Sesia Zone (western Alps, Italy; 1.5 GPa and 500-550°C). To constrain the origin of Cl enrichment, we chose to analyze slightly retrogressed samples containing secondary amphiboles and micas that developed at the expense of primary eclogitic assemblages, but which based on textures and thermobarometry formed still under HP conditions.

In most samples investigated, three main types of fluid inclusions were recognized in quartz. These are: Primary, salt-bearing aqueous inclusions several µm in size occurring as randomly distributed clusters throughout quartz grains (type 1 inclusions containing 32 to 44 weight% NaCl equivalent), secondary, Ca-rich (type 2) and low-to moderate-salinity (type 3; 1 to 16 weight% equivalent NaCl) aqueous brines lining along healed fractures. (Type 3 inclusions are absent in the Caledonides samples.) Textural relationships indicate that the Ca-bearing type 2 inclusions formed prior to the type 3 inclusions. In all cases, Cl content of hydrous minerals attending retrograde metamorphism is systematically low (from 0 to 0.37 weight% in amphibole and up to 0.07 weight% in the micas), which suggests that the hydrosilicates formed from a water-rich fluid.

These results imply that the highly saline brines were present in eclogitic rocks prior to retrogression, thus providing further support for the ubiquity of highly-saline brines under HP conditions.

LS09 : MOam05 : G0
Phase Relationships in Hydrous Peridotites at High Pressure: Consequences for Water Transport at Subduction Zones

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Subduction zone dynamics is strictly related to the occurrence of hydrates both in the slab and in the mantle wedge. This experimental study focuses on the stability of hydrous phases at subsolidus conditions in the model system Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O. Multianvil and piston cylinder experiments were performed at the Dipartimento di Scienze della Terra, Milan, running seeded gels at 2.0-6.0 GPa and 650-800°C. Starting materials consist of two different synthetic peridotites corresponding to the Tinaquillo lherzolite and to a pyroxenite. Runs lasted up to 2 months. All experiments were performed at fluid saturation conditions and buffered with graphite. Run products were characterized by X-ray powder diffraction, backscattered and secondary electron images and microprobe analyses. Preliminary experiments devoted to in-situ determination of phase relationships and fluid properties at high pressure were performed in a hydrothermal DAC.

Amphibole is stable at 700°C together with chlorite and olivine (±pyroxenes) at 2.2 and 2.4 GPa and at 800°C and 2.0 GPa with garnet, olivine and othopyroxene. With increasing pressure chlorite was found with clinopiroxene + olivine + garnet at 4.2 GPa, 680°C. A Dense Hydrous Magnesium Silicate, the 10A phase, appears with clinopyroxene + olivine + garnet at the expenses of chlorite at 4.8, 5.3 and 6.0 GPa (680°C). The anhydrous assemblage olivine + garnet + orthopyroxene + clinopyroxene was found at 4.6 GPa, 750°C and 3.0 GPa, 800°C. Mineral chemistry and chemographic analysis suggest that the phase assemblage chlorite + orthopyroxene + clinopyroxene is not stable when amphibole is present. The stability of amphibole is controlled at water saturation conditions by the degenerate H_2O-conserving reaction: amphibole + olivine = orthopyroxene + clinopyroxene + chlorite. The ultimate breakdown of amphibole is controlled by the reaction amphibole = chlorite + garnet + orthopyroxene + clinopyroxene, which should be observed only at H_2O-undersaturated conditions. Chlorite thermal stability, related to the reaction: chlorite + enstatite = garnet + olivine + water, is depressed towards lower temperatures in the peridotite model system as compared to MASH system, due to the preferential partitioning of iron into garnet. Chlorite disappears to form a 10A phase, having, at the electron microprobe scale, a homogeneous aluminous composition. The surprising coincidence in composition between such 10A phase and the mixed-layered mineral kulkeite (clinochlore:talc=1:1; Schreyer et al. 1982), may suggest a structural rearrangement of chlorite intercalating aluminum-free 10A phase through a continuous reaction. The thermal stability of the 10A phase is governed by the reaction: 10A phase + clinopyroxene = garnet + orthopyroxene + H_2O at T > 700°C. Mass balance calculations suggest a preliminary experimentally determined H_2O budget along subduction zone involving hydrated ultramafics. Major variations of H_2O contents related to amphibole are within its stability field and not at its breakdown. At pressures above the stability field of chlorite, 10A phase may represent a relevant H_2O reservoir.

In mature subduction environments the 10A phase plays a fundamental role in transferring this component from antigorite/chlorite to DHMS, e.g. phase A, at depths greater than 200 km.

Schreyer W, Medenbach O, Abraham K, Gebert W & Miller WF, *Contrib. Mineral. Petrol*, **80**, 103-109, (1982).

LS09 : MOam06 : G0
Experimental Constraints on the Water Content of Primitive Arc Basalts from St Vincent, Lesser Antilles

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Liquidus phase relationships have been determined for a picritic (MgO=12.5 wt%, Ni=250 ppm, Cr=728 ppm) basalt from St Vincent (Lesser Antilles arc) to place constraints on the water content of primitive arc magmas. Piston-cylinder experiments were conducted between 7.5 and 20 kbar under both hydrous and oxidized (>NNO+1) conditions. AuPd capsules were used as containers. Compositions of supraliquidus glasses and mass balance calculations show that Fe loss is less than 10% in most experiments. Two series of melt water concentrations were investigated (i) 1.5 wt% and (ii) 4.5 wt% H_2O, as determined by SIMS analyses on quenched glasses. Redox conditions were not buffered but calculations based on Fe^{3+}/Fe^{2+} partitioning between Cr-Al spinel and melt and olivine-spinel equilibria show that oxidizing fO_2 were imposed (NNO+1.5 for the 1.5 wt% H_2O series, NNO+2.3 for the 4.5 wt% H_2O series). For both series of melt water concentrations, the picritic liquid is multiply saturated with a spinel lherzolite phase assemblage (Ol-Cpx-Opx-Sp) on its liquidus, respectively at 1235°C, 12 kbar (1.5 wt% H_2O) and 1195°C, 17 kbar (4.5 wt% H_2O). Liquidus mineral phases have compositions (Ol: Fo91-92; Cpx: Mg# 80-85; Opx: Mg# 87-89; Sp: Cr# 25-37) compatible with mantle compositions. These results suggest that the investigated picritic basalt represents a primary mantle-derived magma. Modal proportions of Opx and Cpx crystallizing on the liquidus vary with the melt water content. The Opx/Cpx modal ratio is higher in the 4.5 wt% H_2O than in the 1.5 wt% H_2O series, suggesting that Opx enters the melt in a progressively higher proportion when the H_2O content of the mantle source increases. The experimental results can be integrated with data on partial melting of peridotite, allowing P-T conditions of mantle equilibration to be determined for basaltic liquids as a function of their H_2O and MgO contents. Application to the Lesser Antilles arc shows that basaltic magma generation occurs over a range of P-T-H_2O melt conditions. Temperatures of primitive basalts from the Lesser Antilles arc are < 1200°C which indicates magmatic H_2O contents > 4 wt%. From the experimental correlation between MgO concentration and degree of melting, this indicates F < 15-20% and consequently a H_2O content of the mantle source of < 0.6-0.8 wt%.

LS09 : MOam07 : G0
Seismic Images of the Japan Subduction Factory

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In this report I will review the recent seismological findings on the structure, magmatism, and dynamics of the Japan subduction factory. High-resolution seismic tomography has revealed clearly the subducting Pacific and Philippine Sea slabs which have a thickness of 90 and 35 km, respectively. Prominent low-velocity (low-V) and high-attenuation (low-Q) zones are visible in the crust and uppermost mantle just beneath active arc volcanoes and extend to 200 km depth in the mantle wedge. The low-V/low-Q zones are located in the central portion of the mantle wedge and lie 30 to 50 km above the subducted Pacific slab. The mantle wedge low-V/low-Q zones also exhibit strong seismic anisotropy. These results suggest that arc magmatic systems are not limited to the near-surface areas, but are related to the deep processes, such as the convective circulation in the mantle wedge and dehydration reactions in the subducted slab. These low-V/low-Q bodies form the deep roots and sources of the arc magmatism and volcanism. Large crustal earthquakes in Japan are found to occur around low-V zones that may represent weak sections of the seismogenic crust. The crustal weakening is thought to be closely related to the subduction of the oceanic Pacific and Philippine Sea plates in this region. Along the volcanic front and in back-arc areas, the crustal weakening may be caused by the active volcanism and the presence of magma chambers. In the forearc areas under southwest Japan, fluids were detected in the 1995 Kobe earthquake (M 7.2) source area, which may have contributed to the rupture nucleation and may be related to the dehydration of the subducted Philippine Sea slab. These results suggest that large crustal earthquakes may not strike anywhere, but only in anomalous areas which may be detected with geophysical methods.

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Zhao D, Ochi F & Hasegawa A, *J. Geophys. Res*, **105**, 13579-13594, (2000).

LS09 : MOam10 : G0
Sources and Ascent Paths of Fluids and Melts in the Central Andean Subduction Zone from High Resolution Attenuation Tomography

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We present high resolution tomographic Models of P-wave attenuation from the Central Andean subduction zone. The models have been derived from over 1600 local earthquakes recorded at three temporal seismic networks covering the forearc, arc, and backarc region of the Andes around 23°S. Whereas the forearc region is characterized by homogeneously low attenuation, prominent high attenuation anomalies are found beneath the volcanic front and the backarc. High attenuation regions in mantle and crust are interpreted as indicating presence of aqueous fluids and partial melts. Continuous anomalies connect the different earthquake clusters in 100 and 200 km depth and the active volcanoes in the Western Cordillera and in the backarc. It is suggested that water is conveyed into the mantle wedge due to earthquake ruptures that may trigger hydro-fracturing. Water then fluxes melting in the hot mantle wedge. Melt ascent ways, as imaged by seismic Qp, are not straight up to the base of volcanoes, as is often implicitly assumed. Instead, melt sources are located on significantly different depth levels, and ascent ways follow different patterns and cover significant horizontal distance.

LS09 : MOam11 : G0
Crustal Structure and Rate of Growth of the South Sandwich Arc from Wide-Angle Seismic Data

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The South Sandwich island arc is the surface expression of a classic intra-oceanic subduction zone located in the South Atlantic Ocean, where the small Sandwich plate is overriding the South American plate at a rate of 70-85 mm/yr. Its simple tectonic setting makes it ideal for studying subduction processes, and estimating the rates at which they modify the crust.

As part of the Sandwich Lithospheric and Crustal Experiment (SLICE), four 600 to 900-km-long seismic profiles were acquired across the trench, arc and back-arc basin. Multichannel seismic reflection data were acquired using a 6000 cu.in. (98 l) airgun source and a 2.4-km-long, 96-channel hydrophone streamer. Wide-angle seismic data were acquired using ocean bottom seismometers deployed along two of the profiles, and from land stations on two of the islands.

We present results from the southern profile which crosses the trench at ~ 60° S. The wide-angle seismic data were modelled using 2-D travel-time inversion and synthetic seismogram methods to obtain a velocity model of the crust. The seismic reflection data were used to constrain the shallow structure in the model. Coincident gravity data were also used to place additional constraints on the model. The main features of the South Sandwich arc structure are as follows: 1) a crustal thickness beneath the arc of 15 km; 2) a relatively low velocity (4.0-5.5 km/s) upper crust, interpreted as a combination of extrusive and intrusive igneous rocks and volcaniclastic sediments; 3) a mid-crustal layer with a velocity of 6.0-6.5 km/s, interpreted as a composite granitic or dioritic intrusion; 4) a lower crust with velocities 6.8-7.2 km/s, interpreted as pre-existing oceanic crust intruded and underplated by mafic rocks; 5) large-scale extensional block faulting in the outer forearc extending through the whole crust; 6) no significant accretionary prism at the base of the forearc slope.

Magnetic anomalies identified in the back-arc show that the present arc is built on oceanic crust that was formed at the back-arc spreading centre, and that spreading in the back-arc basin commenced at approximately 15 Ma. Taking this age to be the maximum age of the crust beneath the present arc and inner forearc, and assuming that the crustal structure is uniform along strike, allows us to place a constraint on the minimum rate of magmatic addition to the crust at the South Sandwich arc.

LS09 : MOam12 : G0
The Thermal Structure of Subduction Zones, Honshu – A Case Study

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Subduction zones have long been recognized as places to recycle oceanic crust and sediments back into the earth's mantle. Subsequent interaction of the subducted material with the overlying mantle wedge provides a mechanism to generate arc magmatism due to dehydration of the top part of the slab. However, it is much less clear if dehydration is complete or incomplete, the latter raising the possibility to transport water to much great depth within the earth. A prerequsisite to study these issues is the pressure and temperature distribution in the slab and the mantle wedge at depth.

To determine the thermal structure of subduction zones we used high resolution finite element models, using a geometry and physical properties similiar to the models of Peacock and Wang (1999). We focused in particular on the well known singularity in the strain rate field at the tip of the wedge. Using explicit comparisons with analytical cornerflow solutions for an isoviscous wedge we found that the cornerflow solution can be modelled accurately only if high grid resolution (less than 500 m in the tip) and a smooth transition of the boundary conditions over a small interval (about the length of three elements) are employed. This allows us to accurately predict the thermal structure with temperature- and stress-dependent wedge rheology. For these model simulations we used average grid spacing of 500 m and local refinements in the wedge and crust down to 150 m.

Our preliminary results show that the temperature distribution depends strongly on the rheological properties of the mantle wedge. For Honshu, a fast subducting plate, the slab-wedge interface temperatures for isoviscous and diffusion creep models differ by more than 200ºC at 125 km depth. Towards the interior of the slab temperatures decrease rapidly, for example, at a depth of 5 km within the slab, temperatures are more than 200ºC lower than at the interface. These large temperature changes indicate that detailed modelling of subduction zones in necessary to obtain reliable thermal models.

Peacock S & Wang K, *Science*, **286**, 937-939, (1999).

LS09 : MOam13 : G0
Balancing Transpressional Magmatic Arc Crustal Thickening-Tectonic Shortening Versus Magmatic Underplating

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Underplating of mantle-derived basalts is an important process in forming and transforming continental crust, yet its effect on crustal thickening is not well established. Previous authors argued that mafic underplating may provide up to 25 km of new crust.

Andean orogeny (200 Ma to Present) was accompanied by largely consistent subduction-related magmatism and intermitting episodes of crustal shortening. If mafic underplating operated throughout this period, it should have affected both thickness and seismic structure of the continental arc crust. Changing geochemical patterns through time support such an hypothesis.

We have balanced crustal thickening of the late Cretaceous-Paleogene Andean paleo-arc in north Chile (21-26°S) in order to estimate the relative proportions of tectonic and magmatic crustal thickening. During the Eocene (~48-36 m.y.), this predecessor of the modern Andean magmatic arc seated in the Western Cordillera has experienced substantial transpressive deformation resulting in shortening and thickening of the crust, and coeval emplacement of shallow-level plutonic bodies. Timing and magnitude of crustal thickening due to magmatism and transpression are constrained by ages and geochemistry of late Cretaceous-Paleogene magmatic rocks and balanced structural cross-sections and kinematic modeling of transpressional structures.

Balancing was carried out using a simple monoclinic crustal-scale transpression-model. Geochemical data of pre- and post-transpressional magmatic rocks suggest that crustal thicknesses were in the order of ~37 km prior to transpression, reaching a value of ~45 km after deformation. Volume-constant transpression only accounts for 67% of the needed increase in crustal thickness (8 km), the remainder must have been accomodated by underplating of mantle-derived basalts at or near the base of the arc crust prior to and during transpression. The ratio of tectonic crustal thickening/magmatic underplating therefore lies in the order of ~2:1. Whole magmatic addition-rates (basal and crustal) during the ~12 m.y. duration of transpressional arc-setting are in the order of 35 $km^3/km_{model-length}$/m.y. and therefore are in agreement with estimates from previous authors.

In our model, mafic underplating must have operated during the Andean orogeny, but does not seem to be an efficient mechanism for thickening of the crust. Most crustal thickening was due to discrete episodes of tectonic shortening. Our results support earlier studies on the modern central Andean arc and backarc which argue that most of the crustal thickening can be explained by crustal shortening.

The late Cretaceous-Paleogene Andean arc is representative for estimating crustal thickening and continental crustal growth within a transpressional setting, because it is a typical continental arc with thickened crust. Therefore, our results might apply to other continental arcs and should be tested by the examination of similar systems.

LS09 : MOam14 : G0
Seismic and Gravity Analyses Show Accretionary Process and Underplating beneath Juan de Fuca Strait (Cascadia Subduction Zone)

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Combined seismic and gravity analyses along the Juan de Fuca Strait in the Cascadia Subduction Zone lead to determination of the limits and structures of accreted terranes and deep parts of the overriding plate. Two 2-D velocity models were developed along northern and southern Juan de Fuca Strait using wide-angle seismic data. The northern model shows two landward dipping reflectors within the margin. We interpret the upper one as the base of accreted Crescent Terrane, which appears to have an anomalously large thickness beneath eastern Juan de Fuca Strait. The lower one has been located on the coincident MCS section and corresponds to the top of a reflector band in the lower crust. This reflector band may represent sheared, underplated sediments, and its base is interpreted to coincide with the inter-plate décollement. Rock velocities between the two reflectors are very high (7.6 km/s) and may be related to serpentinised peridodites or tectonically underplated magmatic material. The gravity analysis helps to understand the complex 3D structure of the margin and gives additionnal constraints on the thickness of accreted terranes. Our study shows the importance and complexity of frontal accretionary and underplating processes in the construction of active margins.