The Institute for Geosciences, Johannes Gutenberg University of Mainz

Earth's Magmatic Systems Symposium

Wednesday November 26, 2014

Senatssaal (7th floor)

Program & Abstracts

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

VAMOS RESEARCH CENTRE

The Institute for Geosciences, Johannes Gutenberg University of Mainz

Earth's Magmatic Systems Symposium

Wednesday November 26, 2014

Senatssaal (7th floor)

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08.45: Jörg Elis Hoffmann, Freie Universität Berlin

The birth of Earth's continental crust – insights from petrology and geochemistry

09.45: Sonja Aulbach, Goethe Universität Frankfurt

Petrologic-geochemical perspectives on the role of magmatism in the (trans)formation of continental lithosphere

10.45: Coffee

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Formation of Continental Crust by Arc Magmatism

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Tertiary Geodynamic Development of the Alpine-Himalayan belt: Magmatic Perspective

14.45: Coffee

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Formation and differentiation of igneous layered intrusions

16.15: Christoph Beier, GeoZentrum Nordbayern, Universität Erlangen-Nürnberg

Oceanic volcanoes - cloudy windows into melting

Symposium sponsored by the "Volcanoes-Atmosphere Magmatic Open Systems" Research Centre.

The birth of Earth's continental crust – insights from Petrology and Geochemistry

Jörg Elis Hoffmann, Freie Universität Berlin

The knowledge about the early stages of crustal evolution is very limited due to the restricted ancient rock record. Preserved early crustal remnants are only found in high-grade gneiss terrains that experienced diverse secondary processes including migmatization, deformation and metamorphic overprint. The terrains consist up to 90% of grey gneisses with broadly tonalitic-trondhjemitic-granodioritic (TTG) composition as well as to minor degrees of supracrustal rocks and granites. TTGs differ in major element composition from average modern continental crust by being on average more SiO2-rich. In the past decades, the knowledge about the formation conditions of TTGs increased significantly and experimental studies, petrological phase equilibrium modeling as well as geochemical studies suggest that juvenile TTGs formed by melting of hydrated basalt. However, there is still no consensus about the tectonic settings in which they were generated. Formation models involve slab melting in subduction zones, melting of over-thickened mafic crust either in a plume-related oceanic plateau setting or of accreted arc crust.

One of the best preserved areas to study the earliest formation of continental crust is the 3600-3900 Ma Itsaq Gneiss Complex of southern West Greenland. It contains the Isua Supracrustal belt, which is one of the oldest known fragments of Eoarchean oceanic crust, well preserved ultramafic rocks that were interpreted to resemble Eoarchean mantle as well as non-gneissic tonalites that preserve their magmatic texture. Therefore, the Itsaq Gneiss Complex is the ideal area to investigate tectonic processes operating on the early Earth.

In a pioneering case study on the earliest TTGs and Greenstones (3700-3800 Ma) from the Itsaq Gneiss Complex, petrogenetic phase equilibrium calculations were conducted to estimate the mineral assemblages of the precursor basalts at different pressure/temperature conditions in combination with trace element modeling and isotope geochemistry to trace a genetic relationship between both rock types. The results reveal that the earliest continental crust of Greenland formed from polybaric melting of hydrated tholeiitic basalts that are similar to those exposed in the Isua Greenstone Belt in the P/T range of 10-14 kbar. Melting degrees varied between 5 and 30 % at temperatures of ca. 800 to 920 °C and TTG plutons formed by pooling the melts of different source depths following ponding in the middle crust as plutons. Further differentiation led to the formation of further granitoids that ultimately led to the stabilization of the crust.

Another early Archean block with rocks as old as 3660 Ma is the Ancient Gneiss Complex of Swaziland. The area is dominated by 3.20-3.66 Ga grey gneisses, the Ngwane gneisses and a 3.48-3.43 Ga diorite to tonalite suite, the Tsawela gneisses, that intrudes into the >3.50 Ga components of the Ngwane gneisses. Mafic and ultramafic fragments are present as inclusions differing in scale from cm to km size. The origin of these mafic remnants is ambiguous. Some of them may represent fragmented intrusive dykes, others cumulates or greenstone remnants. The Hf-in-zircon isotope compositional varieties of the Ngwane gneisses are highly variable suggesting the incorporation of older crustal components in the sources of these crustal rocks. This is in agreement with observations from other early crustal terrains indicating that reworking processes within the early crust was an important process during the early crustal evolution. During what process older crustal components were incorporated can be studied on the 3.48-3.43 Ga Tsawela gneisses. Major, trace element and Hf-Nd isotope modeling on the Tsawela gneisses hint at a process differing from the initial partial melting model that is proposed to form early continental crust. The model shows that the gneisses formed by mixing of basaltic melts with melts that derived from the older Ngwane gneisses. Therefore, magma mixing might have been an alternative process involved in the formation of ancient continental crust that has been underestimated so far in isotopic crustal evolution models.

Overall, the compositional and genetic differences of the two studied early Archean blocks suggest that the stabilized continental crust of both cratons represent two different crustal evolution stages and may represent different crustal levels.

Petrologic-geochemical perspectives on the role of magmatism in the (trans)formation of continental lithosphere

Sonja Aulbach, Goethe Universität Frankfurt

Earth is a planet with distinct spheres, finite resources and a precariously narrow set of environmental conditions allowing habitability. Many questions remain regarding the processes that gave rise to our present-day highly differentiated planet. For example, when and in which tectonic setting did the continents and their underlying lithospheric keels form? How did Earth's dynamics change through time and how did this affect element cycles, including the formation of ores that we need for our modern lifestyles? The application of geochemistry and petrology to these problems contributes pieces to the puzzle that must integrate observations from the field, geophysics, laboratory and numerical experiments and modelling if we are to obtain and refine our answers. Magmatism has played a pivotal role in shaping the Earth's reservoirs and in the re-distribution of elements, from the formation and crystallisation of global magma oceans during Earth's accretion, to early plume-dominated processes and finally modern-style plate tectonics. One key driver for a secular change in terrestrial dynamics is the decrease in mantle temperatures through time.

Continental lithosphere becomes viscous and buoyant, thus stable and non-convecting, through extraction of partial melts from the mantle, requiring a decrease in pressure, increase in temperature or change in composition. Though controversial, active upwelling in hot plumes, rather than passive upwelling beneath mid-ocean ridges, may have been important in the generation of Earth's earliest continents (cratons). The resultant deep onset of partial melting would allow extraction of larger and more iron-rich melt fractions than possible during shallower partial melting in ridge settings, or during later melting in a cooler Earth. Cratonic mantle samples, carefully screened for the effects of transformation (metasomatism) by passing melts and fluids during their long existence in deep lithospheric keels, bear evidence for an origin as FeO-poor harzburgite residues. Thus, they experienced deep melting paths, attesting to the importance of mantle plumes in early terrestrial dynamics. This generated continental lithospheres that are hard, though not impossible, to destroy.

The transformation of continental lithosphere by interaction with fluids and melts through time, though it obscures constraints on its origin(s), is itself worthy of study as it has important implications for the stability and evolution of continents. All cratonic mantle samples have been chemically enriched by asthenosphere-derived, incipient decompression melts (carbonatites, kimberlites, lamproites), which can be harbingers of continental rifting (e.g. North American craton). The ensuing thermo-mechanical erosion and eventual addition of dense basaltic material can lead to spectacular thinning and loss of even cratonic lithospheric keels (e.g. Tanzanian craton). Addition of water, for example from subducted oceanic slabs, can also fatally destabilise the lithosphere (e.g. North China craton), a clear indication that cratons are not all as long-lived as once thought.

Considering that partial melts extracted from the mantle during lithosphere formation are (ultra-)mafic, the evolved (broadly andesitic) nature of the continental crust appears paradoxical. One solution is to partially melt basaltic or picritic oceanic crust after it has been metamorphosed to either garnet-bearing amphibolite or rutile-bearing eclogite, which generates a continental crust-like melt with the necessary geochemical attributes (e.g. high LREE/MREE and Sr/Y, low Nb-Ta-Ti). This requires that basaltic crust be brought to appropriate depths and relates to the question of the onset of terrestrial plate tectonics. Cratonic eclogite xenoliths have signatures (fractionated stable isotopes, Eu- and Sr-anomalies requiring plagioclase accumulation) indicative of an origin as oceanic crust. Many show depletions in LREE, apparently consistent with loss of a silicic partial melt that eventually formed continental crust. However, such depletions can also be generated by cumulate processes on the ocean floor (gabbro formation) and by interaction with deserpentinisation fluids in subduction zones. The latter process was important in the formation of 1.85 Ga eclogites from the Slave craton (Canada), which attest to modern-style element cycling in Palaeo-Proterozoic convergent margins. On the other hand, cratonic granulite xenoliths have textures and compositions suggestive of crystallisation in deep crustal magma chambers, whereby the residual melts may have evolved to more silicic compositions forming the upper continental crust. Complementary dense, gravitationally instable cumulates may have been lost by delamination, similar to observations for modern exposed arcs. Cratonic pyroxenites may represent as yet understudied examples of such delaminated material that became trapped in the viscous underlying lithosphere.

Formation of Continental Crust by Arc Magmatism

Oliver Jagoutz, Massachusetts Institute of Technology

From all rocky planets in our solar system the Earth is unique because it has a two compositionally distinct crusts: the basaltic oceanic crust (SiO2 ~ 50 wt%) and the andesitic continental crust (SiO2~60 wt%). The andesitic composition of the continental crust (CC) results in a low density, which allows the CC to be preserved on geologic timescales. Based on trace element similarities between magmas formed above subduction zones and that of estimated bulk continental crust it is generally thought that CC is formed through arc magmatism. Modern oceanic arcs, however, have distinctly different seismic properties compared to the bulk continental crust, and mantle-derived melts are generally basaltic, not andesitic.

In this presentation I will show results from our field studies in the Kohistan arc, an exposed section of a paleo-oceanic arc. Exposure of the Kohistan arc crust is complete, with unmetamorphosed sediments on the top to high pressure (>50 km) ultramafic rock at the bottom. Our results show that a complex interplay between magmatic and metamorphic processes ultimately produces the andesitic continental crust. Important are both magmatic fractionation and metamorphic processes in the lower crust to form (I) a felsic upper crust and (II) a density-unstable mafic component. Metamorphic reactions form rock denser that the upper mantle at depths ≥ 40 km that will founder back into the mantle. Dynamic calculations indicate that foundering is an episodic process that occurs in most arcs with a periodicity of five hundred thousand to five million years. Moreover, because foundering will continue after arc magmatism ceases, this process ultimately results in the formation of the shape continental Moho observed seismically. Our improved knowledge of this process allows us to better understand the magma flux throughout the global subduction system as well as its importance for the Earth's heat flux.

Tertiary Geodynamic Development of the Alpine-Himalayan belt: Magmatic Perspective

Dejan Prelević , Johannes Gutenberg University Mainz

The Alpine-Himalayan orogeny is one of the three major orogenic phases defining the geology of Europe and Asia, along with the Caledonian and the Hercynian orogenies. It generated accretionary orogen that occurs at a diffuse and long lived convergent zone between Eurasia and Gondwana, which has been active since Permian-Mesozoic times resulting in the consumption of major Tethyan ocean(s). The convergence varies in style involving accretion of small continental slivers and numerous oceanic island arcs in the west, to the world's most comprehensive continental collision in the east. It eventually gave rise to a complex collage enclosing continental crustal blocks intercalated with ophiolitic terrains of various sizes and ages forming superimposed mountainous belts. The orogeny resulted in generation of Tibetan plateau that represents the world's highest and largest plateau, with an area of 2200000 square kilometres. Its uplift has been linked to a decrease in atmospheric CO2 concentrations over the past ~40 Myr and to global cooling in Cenozoic times.

Magmatism that occurs within these belts postdates final accretionary events forming the Alpine–Himalayan chain. It is diachronous with the most voluminous and widely distributed episode(s) beginning from the late Cretaceous. Associated with postcollisional magmatism occurs a global metallogenic unit including a number of world-class Cu-Pb-Zn-Au-Ag-Te deposits. The magmatism is derived from both the mantle and the crust, and is geochemically extremely heterogeneous, but dominantly potassium enriched. Its origin and relationship to the large-scale elevations in several massifs (Tibet, Menderes etc.) of the orogen is controversial, particularly the significance of the widespread geochemical signal typical for recycled continental crust. Two competing scenarios invoke direct melting of continental crust during deep intercontinental subduction versus removal of heavily metasomatised mantle lithosphere by delamination into the convecting mantle. However, no direct evidence has been found to distinguish between these two models so far.

In my lecture I will draw conclusions about the geodynamic interpretation of orogenic lithospheric mantle within the Alpine–Himalayan combining the field and geochemical studies of K-rich post-collisional mantle-derived lavas from Spain, Italy, Balkans, Turkey, Iran and Tibet with high-pressure experiments. The composition of K-rich postcollisional lavas suggests that the orogenic mantle underwent much more intense and complex material recycling than anticipated only by fluid- or melt- dominated transport. This is based on several fundamental constraints: i) The lavas are strongly incompatible-element enriched with elevated $^{87}Sr/^{86}Sr$, $^{207}Pb/^{204}Pb$, $^{187}Os/^{188}Os$ and low $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ ratios. All these tracers represent a hallmark for continental crust; ii) The presence of an ultra-depleted component in the source of the K-rich lavas is identified by usual presence of refractory Cr-spinel, high Fo olivine and relatively low whole-rock FeO abundances; iii) Finally, extremely high Th/La is coupled with high Sm/La of potassic mantle-derived lavas points to a genetic relationship with the melange.

The above observations suggest that neither fluids nor melts alone are able to precondition orogenic mantle using known mechanisms that are active during material recycling within subduction zones, thus a new model is required. I will present a hypothesis that the orogenic mantle along the Alpine-Himalayan system is preconditioned during previous episode(s) of "dirty" subduction. This process involves formation of a new mantle lithosphere formed by accretion of suprasubduction fore-arc oceanic lithosphere plus trench sediments beneath older lithosphere during convergence within the Alpine-Himalayan system. The model demands conversion of principally oceanic lithosphere (including melange) into the phlogopite-bearing continental lithospheric mantle and production of K-rich post-collisional lavas, which is a multi-component and multi-episodic process.

The incorporation of mechanically imbricated slabs that react with the depleted peridotite, may be important for lithosphere formation in general. The accretion of island arcs and small continental blocks is a realistic scenario for the Archaean, when the volume of continental crust was smaller and so oceanic accretion may have been correspondingly more important. Cratonic peridotites share the characteristics of Alpine post-orogenic mantle of extremely high Mg# olivine and the cratonic lithosphere includes blocks of eclogite with isotope and trace element characteristics consistent with their derivation from subducted ocean crust. The timing of formation of cratonic mantle lithosphere is broadly coeval with the formation and stabilization of the crust, so that the orogenic accretion model may apply to the late Archaean.

Formation and differentiation of igneous layered intrusions

Olivier Namur, Gottfried Wilhelm Leibniz Universität Hannover

My talk will address the main mechanisms contributing to the mineralogical and geochemical evolution of cumulate rocks observed in continental mafic layered intrusions. It will be organized in two parts. Part I will be a lecture that introduces the general concept of layered intrusions; Part II will focus on some recent research projects dealing with the mechanisms of differentiation in layered intrusions.

Part I. Partial melting of the mantle predominantly results from adiabatic decompression of the mantle or from flux melting due to water addition in the mantle. These two processes account for the majority of the volcanic activity on Earth but a third model of mantle plume may contribute to abundant production of magma. Mantle plumes are large thermal anomalies, generally originating from the core-mantle boundary, which bring hot mantle material all the way to the upper mantle, where abundant melting occurs. Melting in the upper mantle produces abundant basaltic volcanism, forming Large Igneous Provinces (LIPs) at the Earth's surface either as oceanic plateaus or continental flood basalts. Although LIPs are dominated by effusive material (predominantly basalt), part of the magma does not erupt and accumulates in deep to shallow crustal magma chambers. Crystallization of the basalt at depth forms masses of cumulate rocks, generally called mafic layered intrusions. Mafic layered intrusions cover a very large range of sizes from the relatively small Skaergaard intrusion (Greenland; ~ 280 km^3) to the giant Bushveld Complex (South Africa; 900.000 km^3). They range in composition from ultramafic (i.e. dominated by olivine and pyroxenes) to gabbroic (with plagioclase as the dominant phase). From base to top, the cumulate sequence usually shows numerous changes in the assemblages of minerals and a continuous evolution of mineral compositions, which indicates that the composition of the melt is continuously changing during solidification. This will be illustrated using several intrusions as examples and will be used to discuss the process of fractional crystallization. Layered intrusions are also characterized by strong cumulate layering features (e.g. repeated succession of sheet-like rock layers with contrasted mineralogies), which will be fully described and explained in terms of sedimentary and fluid-dynamical processes.

Part II. Having introduced the concept of layered intrusions in the first part of the talk, Part II will focus on some recent research results gathered on the Sept Iles intrusion (Canada) and the Skaergaard intrusion (Greenland). Differentiation occurs by liquid-crystal separation in crystal mushes forming at the thermal boundary layers of mafic magma chambers. The mechanisms commonly proposed for crystal-liquid separation are compositional convection, due to compositional contrast between the interstitial melt and the main magma body, and compaction of the crystal mush, due to density contrast between the crystal matrix and the interstitial melt. While compaction leaves little evidence of its action other than textural modifications of the crystals, compositional convection was suggested to produce characteristic compositional zoning in plagioclase. The Skaergaard intrusion will be used as an example to show that zoning in plagioclase grains should not be restricted to a single mechanism but may arise from different processes such as thermal buffering of the mush liquid, silicate liquid differentiation and convection within the mush. The distribution of contrasted types of plagioclase profiles within the intrusion will then be used to discuss the degree of homogeneity of liquid distribution in crystal mushes. Another process of crystal-liquid separation is plagioclase flotation on basaltic melts. Although this mechanism is considered as the dominant process of anorthosite formation in Proterozoic provinces and in plagioclase phyric basalts, it has never received significant attention in mafic layered intrusions. The Sept Iles intrusion will be used to show that plagioclase flotation is a major differentiation process during the first stages of crystallization of basaltic layered intrusions. This process, however, stops soon after the saturation of Fe-Ti oxide minerals because fractionation of these phases results in a progressive decrease of the density of residual melt. Cumulate rocks from Sept Iles will then be used to discuss how to interpret cumulate rocks with mineral proportions not matching mineral proportions expected from cotectic crystallization at shallow-crustal pressure. The talk will be concluded by raising some unsolved questions about formation of layered intrusions and research perspectives.

Oceanic volcanoes - cloudy windows into melting

Christoph Beier, GeoZentrum Nordbayern, Universität Erlangen-Nürnberg

The study of melts erupted in the oceanic environment is a matter of interest because it is here where the relatively thin lithosphere compared to the continental environment allows to better constrain the processes of melt formation and melt ascent from the Earth's mantle through the crust. The geochemical compositions of melts erupted at intraplate volcanoes, along mid-ocean ridges and in the subduction zone environment differ significantly but all provide information on the processes and sources of melting and melt transport. These observations are crucial to further our understanding of the interaction between the geochemical composition and the impact of volcanism on climatic changes.

The petrology of whole rocks and the major and trace elements of whole rocks, glasses and minerals provide important information on the shallower level processes such as fractional crystallisation and assimilation of wallrock material but can also be used to constrain the composition of the primary melt and also melting temperatures. The calculation of temperatures and extents of melting are important because it is these parameters that potentially reflect a long-term evolution of the mantle but that also allow to determine the temperatures of melting in the intraplate environment and will have an impact on the mechanisms and styles of eruption.

One crucial conclusion of my work is that an increasing lithosphere thickness, corresponding to an increasing lithosphere age along the Louisville Seamount Chain, in the Azores archipelago and along the East Pacific Rise may lead to a decreasing melt column length and thus to smaller degrees of partial melting and a stronger enrichment of the melts. I will also present data from the Pacific-Antarctic Rise that imply that melts are significantly modified even in the thin lithosphere overlying the mid-ocean ridges. Underneath the thicker lithosphere of intraplate volcanoes, the earlier and deeper melting of the enriched mantle compared to the depleted upper mantle combined with the smaller degrees of partial melting lead to a preservation of the enriched, and volatile-rich sources. However, these enriched signatures may ubiquitously be present in the upper mantle potentially even underneath the mid-ocean ridge system. Higher extents of partial melting underneath the ocean ridges and underneath thinner lithosphere in the intraplate environment will obscure these enriched signatures. The changes in lithosphere thickness in the Azores are on the order of 20-30 km with increasing distance from the Mid-Atlantic Ridge and correspond to a change in degree of partial melting from 1-3% underneath thicker lithosphere to 5-8% underneath thinner lithosphere. These changes will significantly affect the trace element compositions of the erupted melts and we consistently quantify these effects in the ocean basins.

Thus, the results I will present have large implications for the interpretations of the presence and origin of enriched signatures in the oceanic environment. One important conclusion is that the impact of lithosphere thickness on the melting conditions must be taken into consideration when using the trace element and isotopic compositions to determine the origin of mantle sources in both intraplate settings but also along the mid-ocean ridges. When inferring on the compositions and processes of mantle melting the processes that may modify the final melt erupted need to be carefully investigated and may also have an impact on the eruptive processes. The variability of mantle sources and melting parameters may not be as large as previously suggested and the preferential melting of enriched sources leads to an overrepresentation of these lithologies at smaller degrees of partial melting that are usually found at intraplate settings compared to the mid-ocean ridges. This also indicates that the Earth's upper mantle may be more depleted than previously suggested.

Notes: