PRESERVATION OF ATYPICAL ARC ROCKS IN SUTURES

[1]SCARROW J.H., [1]BEA F., [1]MONTERO P., [2]FERSHTATER G., and [2]PUSHKAREV E.V. [1]Dept. Mineralogy and Petrology, Campus Fuentenueva, University of Granada, 18002 Granada, Spain; [2]Institute of Geology and Geochemistry, Russian Academy of Sciences, Pochtovy per. 7, Ekaterinburg, Russia.

Summary

Four broadly contemporaneous, compositionally diverse, mafic massifs preserved in the Uralian Palaeozoic arc-continent collisional orogen provide a rare opportunity to: identify paleo-subduction fluxes; consider how arc-products are preserved in orogens; and, determine what this reveals about regional palaeo-geodynamic evolution. The massifs were derived from mantle wedges with significantly different pre-subduction-component-addition compositions resulting from varying importance of residual source garnet and melt extraction prior to subduction-related melt generation. Subduction components in Syrostan, Verkhisetsk, Kytlym, and Petropavlovsk include variable proportions of one or more of: pore or dehydration fluids and melts from terrigenous sediment, pelagic sediment, volcanogenic sediment, and oceanic crust. Notably, slab melt was a significant subduction component in massifs near to major Uralian orogenic sutures, away from them sediment- and crust-derived fluids were more important. We suggest that subduction of young, buoyant crust resulted in preferential obduction/incorporation of resultant arc products during arc-continent collision.

Introduction

Notwithstanding intensive study numerous questions remain regarding subduction zone processes (Subduction Factory Science Plan, 1998): why, and how, does subduction initiate; how is material, in particular volatiles, cycled through subduction zones; how, and at what rate, is new continental material added to convergent margins; and what is the long term effect of subduction on the mantle.

Ancient arc studies have some advantages over modern convergent margins in addressing such questions because erosion has often exposed deeper, usually inaccessible, parts of the subduction zone. Although some information, such as subducting plate properties and movements, may be missing, compositions of a wide range of output products including extrusive and intrusive magmatic rocks, their associated mantle rocks, and metalliferous deposits can be determined. In addition, orogenic preservation may permit spatial and temporal consideration of across and along arc variations and, differences between arcs from the same ocean basin.

Study of gabbros from the compositionally diverse mafic massifs preserved in the Palaeozoic Uralian orogen, and comparison of these with products of well-characterized modern arcs, permits us to make inferences about fluxes through (Palaeozoic) subduction zones, draw conclusions regarding plate movement and physical property controls on these, and assess their significance in terms of orogenic processes and palaeo-geodynamic evolution of the region.

Regional geological framework

The Urals are a 2500 km long, north to south trending chain of mountains that extend from 68° to 48° N. To their west is the East European Craton (EEC) and to their east the Asian collage of terranes. The Uralian cycle began in Late Cambrian to Early Ordovician times with rifting and develδpment of a passive margin on the eastern edge of the EEC. Throughout the Palaeozoic the Pre-Uralian ocean was host to arc and back-arc formation. The main collisional event in the Southern Urals orogeny occurred during the Late Devonian to Early Carboniferous when continental lithosphere of the EEC was subducted beneath the Magnitogorsk oceanic arc. In Late Carboniferous to Permian times there was a final collision between the East European Craton, outboard terranes, and the Siberian craton.

Field relations

We consider four compositionally diverse Uralian mafic massifs. Syrostan is a 5 km long by 4 km wide body that crops out in the Main Uralian Fault orogenic suture. It is composed of gabbros, diorites, dominant granodiorites, trondhjemites and granites. Verkhisetsk is a 100 km long by 25 km wide composite batholith that crops out in the boundary between the orogenic suture zone and accreted oceanic terranes. It comprises an older outer envelope of tonalite-trondhjemite-granodiorite intruded by a younger core of granodiorite- adamelite-granite. Kytlym, the largest mafic massif of the Uralian platinum belt, is 50 km by 30 km massif located just to the east of the Serov-Mauk suture. It has a dunite core in envelope of clinopyroxenite which is surrounded by Cr-diopside gabbro. Petropavlovsk is another small, 4 km by 4 km, body of gabbro and, predominantly, diorite that intrudes the Akhunovo-Karagay granite and accreted oceanic terranes.

Petrography

The gabbros are medium to coarse grained with primary mineralogy of amphibole, plagioclase, and epidote, and biotite in Syrostan massif. Accessory minerals include variable proportions of Fe-Ti oxides, apatite, and titanite.

Whole rock geochemistry

Major and trace elements: The Kytlym gabbros are the most compositionally restricted and mafic, MgO 14-17 wt%, in the present study. Apart from elevated Fe_2O_3 and Sr they lie on an extension of the compositional trends of the other massifs. Gabbros from Syrostan and Verkhisetsk have a broad range of compositions from ~15-4 wt% MgO and although the data, in particular SiO_2 Fe_2O_3, K_2O, P_2O_5, Zr, Y, are somewhat scattered some general trends may be defined with decreasing MgO: in both massifs Al_2O_3 and Na_2O increase as do Sr and Ba in Verkhisetsk; CaO decreases in Verkhisetsk; and CaO and V are constant in Syrostan as is TiO_2 in Verkhisetsk. In the Petropavlovsk rocks, 13-4 wt% MgO, all elements show clear trends of: SiO_2 and K_2O (both doglegging at ~7 wt% MgO), Al_2O_3, Na_2O, Sr, Ba, Zr, and Y increasing; CaO, Cr, and Ni decreasing; and Fe_2O_3, TiO_2, P_2O_5, and V constant with decreasing MgO. Even though plagioclase is a major phase the general increase in Al_2O_3 and Sr with decreasing MgO indicates that it was not fractionating during evolution of these rocks. Whole rock data are more consistent with fractionation of olivine with or without clinopyroxene and amphibole.

Rare earth elements: All the gabbros show marked LREE/HREE typical of subduction related rocks. La_N/Yb_N varies in the different massifs being highest in Syrostan 11.3-21.1, intermediate in Verkhisetsk 4.5-11, and lower in Kytlym 6.5-7.6 and Petropavlovsk 5-7.6. Negative anomalies, relative to adjacent elements, are observed for Sm in the Syrostan and Verkhisetsk data, and in Eu in the Kytlym and some of the Verkhisetsk rocks.

Trace element normalization diagrams: Trace-element characteristics of the gabbros are also typical of subduction related rocks showing marked LIL enrichment and, in all except two Verkhisetsk rocks Ta-Nb depletion relative to adjacent elements in MORB-normalized diagrams. Irrespective of the gabbros degree of evolution Syrostan and some of the Verkhisetsk samples have the most elevated LIL values relative to MORB, other Verkhisetsk and Petropavlovsk rocks have intermediate values and the Kytlym gabbros have the lowest.

Lithium: Li is driven off the subducting slab along with many other large ion lithophile (LIL) elements. B in contrast is driven off at shallower levels (e.g., Bebout et al., 1999). This type of quantification of how elements behave in the subduction system, enables their concentrations to be used, particularly when combined with other compositional data, as subduction flux tracers to provide information about subduction processes and tectonic influences on these. In the gabbros from the Uralian massifs we see a clear positive correlation between Li concentrations and other indicators of subduction, e.g., K_2O and La_N/Yb_N. Such observations are key to unravelling which components of sediment- and slab-derived fluids and melts have contributed to the subduction system. This is discussed in detail below. B analysis is currently underway to complement the Li and other geochemicial, e.g., Sr and Nd isotopic, work.

Rb-Sr and Sm-Nd isotopes: The isotopic data were all recalculated to 330 Ma (see below). The rocks from the four massifs plot in distinct regions in Sr-Nd isotopic space (Fig. 1) and have distinct $^{87}Sr/^{86}Sr_i$ Syrostan 0.7031, Kytlym 0.7040, Verkhisetsk 0.7042, and Petropavlovsk 0.7044.

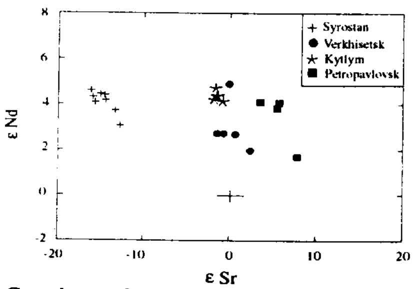

Figure 1

Geochronology

The gabbros from the different massifs are broadly contemporaneous. Gabbros from Syrostan have been dated at 333±3 Ma by single zircon Pb/Pb analysis and as somewhat younger, 330 Ma, by Rb/Sr whole rock analysis (Montero et al., 2000). Although the Kytlym gabbros have not been directly dated zircons extracted from large quantities of dunites from the massif yield a Pb/Pb rim age of 300 Ma consistent with their 330 Ma Rb/Sr whole rock age (Bea and Montero, unpublished data). Further single zircon analysis is currently underway to investigate observed zonation. Verkhisetsk gabbros have not been dated, as yet, but granitoids from the older unit of the massif have been dated at 318±4 Ma by single zircon Pb/Pb analysis which is comparable with Rb/Sr ages for this massif of 320±12 Ma and 316±6 Ma (Montero et al., 2000). Dating of the Petropavlovsk gabbros is currently underway.

Discussion

Subduction components added to arc magma source regions may have characteristic trace element and isotopic signatures. The contributions from the different components varies between arcs but can also vary temporally and spatially in the same subduction system. In the present work we attempt to characterize subduction components in preserved products of ancient Pre-Uralian oceanic arcs in order to consider subduction zone processes and tectonic controls on orogenic preservation. As a first approximation, we discount possible complex metasomatic reactions and model the sources of the Uralian mafic massifs by addition of subduction components to a depleted mantle wedge.

Mantle wedge: To understand how magmas are generated in the mantle wedge requires experimental analogues for hydrous flux, and decompression, melting of peridotites and amphibole peridotites at 2-4 GPa. The effects of crystallization and devolatilisation on such melts during ascent also needs to be experimentally determined or modelled. Specifically, the composition of unfractionated, primitive subduction related melts may be modelled experimentally to provide information about temperatures, pressures, and volatile contents at the point of melt generation within a subduction system. In general, primitive arc melts are rarely sampled because the most typical, generated by melting of subduction modified mantle peridotite, seldom survive as aphyric unfractionated lavas in degassed, fractionated extrusive arc products. Lower or middle crustal gabbros may, therefore, be more useful than the typically considered volcanic rocks in assessing primary magma compositions. It is therefore, significant that we consider the Uralian gabbros to represent solidified liquid compositions rather than cumulates. The latter are usually lower in LREE and incompatible elements, and have higher Mg#, of 70-90, than the rocks in the present study.

Compositional effects of post-magma generation crustal processes such as polybaric crystallization and crustal assimilation are minimized by comparing rocks with high, > 5 wt%, MgO. Normalizing to a constant level of evolution, e.g., MgO or MREE, to compare compositional variations is potentially useful but was not considered necessary here because only high MgO samples are being considered and all these have a restricted, 0-3.5 times MORB, range of Sm_N.

Primitive melt inversion modelling may permit estimation of the pre-subduction-component-addition depleted mantle wedge composition compared to fertile MORB mantle. Having assessed this it may be possible to calculate the composition of subduction components. Following the rationale of Bédard (1999), that MORB-normalized values of elements immobile during subduction, e.g., Nb, Ti and middle-heavy REE, approximate to unmetasomatized mantle compositions, it is clear that the four massifs were derived from mantle wedges with significantly different pre-subduction compositions. Those of Syrostan and Verkhisetsk III were variably enriched relative to MORB indicating that the mantle may not have undergone a melt extraction event prior to subduction-related melt generation. Verkhisetsk group I and Petropavlovsk compositionally approximate to MORB whereas the other Verkhisetsk groups and Kytlym are variably depleted.

In addition, differing Sm_N/Yb_N between the different massifs indicates variable importance of residual garnet in the mantle sources it being dominant in Kytlym, 4.71-5.29, Syrostan, 3.22-4.88, and Verkhisetsk group I, 3.27-4.27, indicating melting in the garnet stability field, and of variable and lessening importance in the other Verkhisetsk groups II 3.25-3.74, and III 2.97-3.05, and Petropavlovsk, 2.35-2.63, suggesting melting in the garnet-spinel stability field.

Subduction components: The characterization of partitioning of geochemical tracers in the subduction system, most likely possible in modern systems, is of key importance. Tracers include elements which give information about: sources of the subduction materials, e.g., Be^{10}, B, Li, Cl, and Ar; transport timescales in modern systems, e.g., the U-series nuclides U, Th, Ra, and Pa; mantle wedge composition, e.g., He^3, Nb, and Yb and melting mineralogy, e.g., REE, Sc, and Y. In addition, radiogenic isotopes such as Sr, Nd, and Pb, reveal source histories. Information from subduction tracers may permit determination of the composition of aqueous fluids or melts and of when they leave the slab and enter the mantle wedge. To do this, better experimental definition of

element partitioning between released-aqueous and sediment/slab-solid phases is required to understand and assess fluxes of pore or dehydration fluids from, or melts of, terrigenous and pelagic sediments, slab, and mantle.
Progress in mass balance modelling of fluxes may be made from study of lower and middle arc crust combined with experimental and theoretical studies of geochemical tracers.

Fluids: Volatiles are subducted as pore fluids and in hydrous minerals in oceanic sediments and altered basalt. They are first released from the subducting material by compaction freeing water trapped in pores and fractures. With increasing pressure and temperature, associated with subduction, more fluid is released by breakdown of hydrous slab minerals. When released at depth, the fluids are transported through the mantle and re-emitted in the products of arcs; or, in some cases, incorporated deep into the mantle altering its composition and physical properties. Most models of subduction zone magma production emphasize the importance of amphibole dehydration in the subducting ocean crust and amphibole and phlogopite stability in the overlying mantle. Other H_2O- and CO_2-bearing minerals such as phengite, lawsonite, aragonite, zoisite, and chloritoid can also be stable in sediments, altered basalts, and the mantle at suitable P and T. Ancient systems such as preserved in the Urals can give access to samples suitable for studies of mineral stability and element partitioning during prograde subduction metamorphism.
Although not well defined, the amount of volatiles added to the melt generation zone of the subduction system is expected to be greater from the altered ocean crust than from its sedimentary cover (e.g., Moriguti and Nakamura, 1998) because the latter may generally be expected to be released at too shallow a level to make a major contribution.
It is clear that volatiles were an important component in the Uralian mafic massifs (e.g., Fig. 2) However, since the elemental composition of volatile-rich components from subducting sediments and slab will be broadly comparable, i.e., LIL-rich, these components may be best distinguished using isotopic systems. Sediment-derived fluids should have elevated $^{87}Sr/^{86}Sr$ *and* depleted $^{143}Nd/^{144}Nd$ relative to those from ocean crust. So, we consider that Verkhisetsk and Petropavlovsk are the only massifs with a significant sediment-derived subduction fluid components (Fig. 1).
Moriguti and Nakamura (1998) distinguished altered-ocean-crust-fluid subduction component from oceanic sediment with the ratio Li/Y which they demonstrated to be elevated in the former and depleted in the latter. Figs 1 and 2 show therefore that ocean crust-derived LIL-, and in particular Li-rich, fluids were important in the genesis of Syrostan and Verkhisetsk groups I and III.

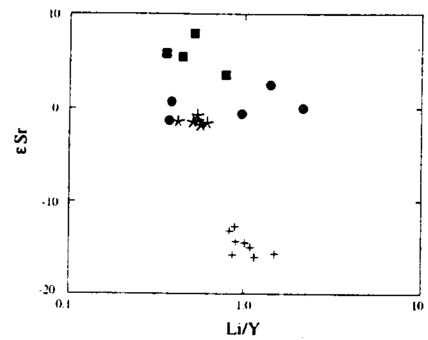

Figure 2

Sediments: In ancient systems it may be possible to use material sampled from the fore-arc region, generally not possible in modern systems except by shallow drilling, to determine the age and provenance of the likely subducted sediments. Such study could be possible in the Middle and Southern Urals given the exceptionally well preserved accretionary wedge and fore-arc region. Furthermore, in ancient systems erosion may have exposed the fore-arc sufficiently to permit determination of the physical behaviour, i.e., accretion/underplating, or subduction and subsequent dehydration diagenesis, of sediments in the system. In the absence of sampleable sediments, however, modelling may still be performed with average compositions of subducting material, e.g., from JOIDES resolution drilling or GERM (Staudigel et al., 1998).
Subducting sediments are most likely to be predominantly terrigenous (c.f., von Huene and Scholl, 1991) although may also include pelagic and volcanogenic material. Silicate melts of such material, in addition to contributing LILs to the system, also adds LREE and Th, generate negative Ti and Nb anomalies relative to adjacent elements in MORB-normalized plots, and elevate $^{87}Sr/^{86}Sr$. From these characteristics we suggest that sediment melts were an important component in the generation of the Verkhisetsk group I and IV, Kytlym, and Petropavlovsk gabbros.

Slab: Silicate melt from the subducting ocean crust does not usually contribute to the subduction melt generation zone unless it is young and the system is anomalously warm (Peacock et al., 1994). When it does, however, compositionally distinct melts with depleted Nb, and elevated Zr, Th, LREE and, notably, Sr/Y are produced (Defant and Drummond, 1990). Compositional indications of involvement of slab melts are absent in Petropavlovsk, most pronounced in the Syrostan gabbros, and also present in Kytlym and Verkhisetsk group I (Fig. 3). Such a component was also considered important in more evolved rocks from the Verkhisetsk massif (Bea et al. 1997). This being the case, the apparently paradoxical K-rich but $^{87}Sr/^{86}Sr$ depleted nature of the Syrostan gabbros can be explained by involvement of young crust. In addition, the negative Eu anomaly observed in the Kytlym and Verkhisetsk rocks can thus be attributed to source composition rather than invoking plagioclase fractionation which is inconsistent with major and trace element data (see above).

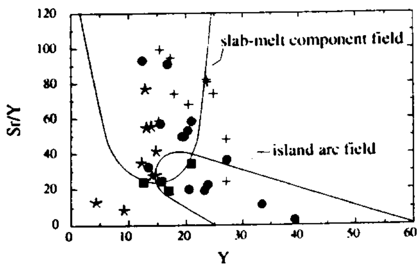

Figure 3

In summary, consideration of whole rock major and trace element and isotopic compositions of the four massifs of the current study indicates that: for Syrostan the main subduction components added to the mantle wedge were derived from dehydration fluids and melts from the subducting slab with minimal sediment involvement; for Verkhisetsk the different compositional groups reflect differing subduction components, in I all three main components were important, group II was affected by addition of the same components as group I but in smaller amounts, group III had little addition of crustal or sediment melts but instead a significant contribution from ocean crust dehydration fluid, and group IV sediment melt was most important; in Kytlym ocean crust and sediment melts contributed to the mantle wedge but fluid involvement was minimal; finally, for Petropavlovsk, we attribute the differences from the other groups to the subduction component being derived from sediment fluid and melt with little or no contribution from the subducting crust.

Thus, a general observation can be made about the MORB-normalized Ta-Nb trough in the different massifs: it is deepest in those with a significant sediment component, intermediate when the main subduction components come from the subducted slab, and shallowest when fluid is the dominant subduction component.

Conditions in the subduction zone: The composition of subduction products are affected by independent and dependent variables including: thickness of the overlying plate; rate and angle of subduction; and slab age, composition, thermal structure, alteration profile, sediment load, and volatile content.

The greatest uncertainties in the interpretation of subduction zones exist in defining how energy and mass move through them and in the estimates of material outputs including fluid fluxes to fore-arc and magma fluxes to arc crust especially the middle and lower crust. In particular information is required about how material transfers from the subducting to the over-riding plate, how different elements equilibrate with and migrate through the mantle wedge, how melts are generated in the mantle wedge and oceanic slab, how melts rise to the surface, and how they fractionate before they erupt.

Estimates of plutonic components from ancient subduction zones such as in the Urals may help to constrain the above unknown variables. Petrological and chemical studies of palaeo-subduction zones give information not obtainable in modern systems about intermediate depth processes: exhumed metamorphic assemblages from 40-100 km give information about volatile behaviour during metamorphism, localized melting, and slab composition changes with dehydration and metamorphism as P and T increase.

A principal control on subduction conditions, in particular the rate and angle of subduction, is the age of the subducting slab: old oceanic lithosphere is thick, cold, and dense and so subducts faster and at a steeper angle than younger, thinner, more buoyant crust. These differences result in different thermal structures in the system. When the slab is anomalously hot many of the fluid-mobile elements e.g., B, Cs, Sb, may be driven off above the melt generation zone, so enabling assessment of the contribution of other components to the system. In addition, under such anomalously warm conditions slabs can melt to produce adakites.

The above is consistent with our conclusions regarding subduction components in the Uralian massifs. In those with a major slab-melt contribution e.g., Kytlym, fluid involvement was minimal suggesting that it represents an end-member scenario of shallow subduction of young, hot crust. Petropavlovsk gabbros, by contrast, with no slab-melt component then represent the other end-member scenario of 'normal' angle and temperature subduction of older crust. Syrostan and many Verkhisetsk gabbros having variable contributions from slab-melt, crustal dehydration fluids, and sediment melts are intermediate between the two extremes.

Some consideration must also be given to intra- and inter-arc temporal progression. In compositionally diverse Verkhisetsk for example, the group III gabbros with little slab-melt component could be the products a melting event associated with subduction of 'normal' ocean crust. By contrast, group I could have been produced by later melting of young subducting crust in the same arc. Further dating work is required to investigate this possibility.

Orogenic preservation: The Urals are a particularly good area to study the question of orogenic incorporation of pre-collisional oceanic and arc crust because of the exceptional preservation of mafic massifs associated with the main sutures and away from them. In detail, we see a direct correlation between the main subduction components in the mafic massifs and their location in relation to the main sutures of the orogen. Kytlym, Syrostan, and Verkhisetsk, all of which have some component of slab-melt, are associated with Uralian orogenic sutures Petropavlovsk which, by contrast, has a sediment-dominated subduction character, is located at some distance from the sutures.

Palaeo-geodynamic setting: Geodynamic models of subduction zone behaviour must be consistent with what is deduced from geochemical studies. The final story of geodynamic evolution of the subduction zone should consider: lithosphere subduction and mantle convection beneath the fore-arc, arc, and back-arc; metamorphism, dehydration, and partial melting of subducted sediments and crust; aqueous fluid and melt flow to the site of melt generation; melt generation by decompression and hydrous fluxing: ascent of melts through the mantle to the base of the crust - diapiric ascent, porous flow, channelled flow, and melt-rock reactions; and melt storage in the crust and their subsequent fractionation, degassing, and eruption.

Evidently study of ancient subduction systems can only consider some of the above issues. Regarding three, Syrostan, Verkhisetsk, and Kytlym, of the four main massifs we suggest their preservation is associated, at least in part, to their production by atypical subduction. In particular, the anomalous tectonic plate configuration involving melting of young buoyant subducting slab, influenced the subsequent obduction/incorporation, rather than subduction, of the arc products during later arc-continent collision.

Our observation of preservation of products of atypical subduction associated with orogenic sutures could withstand further investigation by consideration of other Uralian massifs and, more broadly, mafic massifs in other arc-continent collisional orogens.

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