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Potassic “adakite” magmas and where they come from: a mystery solved?

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- **Adakites are volcanic and intrusive igneous rocks with 55 to 65 wt% SiO_2, Al_2O_3 > 15 wt%, K_2O/Na_2O typically < 0.6, high La/Yb and Sr/Y ratios and strong depletion in Yb, Y, and HFSE. The name is from Adak island in the Alaskan Aleutians (Aleut “adak” = father).**
- **They are typically found in island and continental arc settings.**
- **Some believe then to be equivalents of Archæan TTG rocks – hence their importance.**
- **Their geochemical and isotopic characteristics suggest an origin by partial melting of mafic crust at pressures high enough to stabilise garnet and eliminate plagioclase.**

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- **Adakites that occur in arcs have been interpreted as melts of the down-going slab.**
- **Thermal models suggest that slab melting should be restricted to young, hot subduction zones.**
- **Atherton and Petford (1993) suggested melting of young lower crustal rocks, in the upper plate, as an alternative to slab melting. There is some direct geological evidence for this alternative in some areas.**

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- **Late Mesozoic granitoids in eastern China occur over wide areas, and lack either temporal or spatial association with subduction.**
- **Apart from their SiO_2 contents, some have all the other geochemical attributes of typical subduction-related adakites, including a lack of Eu anomalies in their REE spectra, except that their K_2O/Na_2O > 0.95.**
- **This is possibly an erroneous attribution as “adakitic”. However this occurrence casts doubt on the assumption of a subduction-related origin for all adakitic magmas. So where do these “K-adakite” magmas come from?**

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- **Previous melting experiments on hydrous mafic rocks show that there are two ways of producing potassic, highly silicic melts – very low degrees of partial**

melting (< 10%) or high degrees of fractionation of hydrous medium- to high-K basaltic magma.

- **However, the K-adakites have high K_2O and high K_2O/Na_2O over a broad range of SiO_2 contents (~ 58 to 74 wt%).**

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- **Isotopes indicate crustal involvement (initial $^{87}Sr/^{86}Sr > 0.708$ and $\varepsilon Nd < -13$).**

- **However, Andean "adakites", that show isotopic evidence for significant crustal heritage, still have "normal", adakitic K_2O/Na_2O, and significantly lower Rb, Ba, Sr and Pb (LILE) abundances than K-adakites.**

- **In theory, the peculiarities of K-adakites could arise from potassic source compositions, from assimilation of lower crustal materials by the parent magmas, or through very high-*P* melting of ordinary mafic protoliths.**

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- **Assimilation of metasedimentary rocks might explain K-adakite chemistry, provided that the mafic magmas and the melts from the metasedimentary rocks remained in communication through diffusion.**

- **However, the probable high rates of magma generation, segregation and upward transport through fractures, in felsic magma systems, suggest that magma escape from source regions commonly occurs without any great degree of assimilation.**

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Approach to the Problem

- **existing geological and geochemical data on the K-rich adakites**

- **new high-*P-T* experiments**

- **additional field observations**

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Starting Material 1

(near-liquidus runs to constrain magma formation conditions)

- **Cretaceous Tiantangzhai porphyritic monzogranite (K-adakite)**

- **intrudes the Neo-Archæan Dabie Shan UHP metamorphic belt (metamorphosed TTG series)**

- **Pl (35 - 40 %), Kfs (25 - 30 %), Qtz (20 - 30 %), Bt (5 - 10 wt %), minor Hbl, Zrn, Tit, Ilm**

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- **high-K calcalkaline, very high Sr/Y (106), no Eu anomaly, strong depletion in HREE – indicating Grt, but no Pl, in the residue**

- high $^{87}Sr/^{86}Sr_i$ (0.708048) and very low εNd_t (-18.7) – suggesting a very ancient igneous source rock (protolith)

- lacks evidence for fractionation, so probably close to the parent magma composition

14 Experimental Strategy

- At the *P* and *T* of magma genesis, the melt will be in equilibrium with the mineral phases in the restite. If the magma then remained near its site of generation and crystallised, the near-liquidus phases would mimic the restitic phases.

- Experiments were carried out to locate the liquidus, at reasonable melt H_2O contents (2, 4 and 6 wt% H_2O), with the constraint that the near-liquidus assemblage should contain Grt but not Pl.

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Near-liquidus experiments provide:

- estimates of the conditions of formation of the K-adakite magmas
- mineral composition of the restite

Conditions, determined from these experiments, were then used for the fluid-absent partial melting experiments.

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Partial melting experiments:

- Like most granitic magmas, the K-rich adakites were most probably formed by fluid-absent partial melting reactions (Clemens and Watkins, 2001).

- Results are used to constrain the types of crustal source materials that could have been involved in the genesis of the K-adakites.

17 Experimental Methods

- -5 μm rock powders, dried at 110 °C
- Au capsules, arc welded
- + high-purity H_2O (near-liquidus runs only)
- non-end-loaded 12.7 mm piston-cylinder apparatus, hot piston-out
- $P \geq 1.8$ GPa (18 kbar) ± 0.02 GPa
- $T \geq 900$ °C ± 1 °C, type-K thermocouples
- NaCl-borosilicate glass cells, MgO filler, BN packing around capsule
- logfO_2 between QFM and QFM-2
- t = 25 to 72 hrs

18 Results of Near-liquidus Runs

- first run ~ 2 wt% H_2O, 2 GPa and 950 °C
- products = abundant crystals, two Fsp, Qtz, Bt, Grt
- such a low H_2O content is inappropriate

- **next series with ~ 3.7 wt% H_2O, with *P* = 1.5 to 2.5 GPa**
- **very high *T* needed, so experiments done at *T* up to 1075 °C**
- **at no conditions was Fsp absent at near-liquidus conditions**

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- **even 1075 °C was not close to the liquidus**
- **experiments with ~ 6 wt% H_2O succeeded in locating conditions very close to the liquidus, with only trace Grt and Cpx present, in addition to melt**
- **K-adakite magmas, though very H_2O-undersaturated, were quite hydrous**
- **if 6 wt% is reasonable for the initial H_2O content, the initial *T* was around 1080 °C.**
- **The pressure of generation was > 2 GPa and possibly near 2.5 GPa – The magmas were very hot, rather wet and formed deeper in the lithosphere than previously thought. (consistent with lack of Eu anomaly - true eclogite source!)**

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Partial Melting Runs

- **In view of the above results, the final partial melting experiments were carried out at 2.5 GPa and 1075 °C.**
- **Two starting materials:**
  olivine-normative shoshonite – SH
  quartz tholeiitic amphibolite – AM

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- **Experiment AM3 was carried out near the conditions inferred for the liquidus of the K-adakite. Results show peraluminous tonalitic (dacitic) glass coexisting with almandine-rich Grt (Pyp_{20}), omphacitic Cpx (Jd_{30}) and accessory Ru, Ap and Zrn.**
- **general chemistry of the melt in AM3 similar to K-adakite. K_2O/Na_2O of the melt (up to 0.65) is higher than in the starting material (0.27), but not typical of K-adakites (~ 1). Also, the melts were highly peraluminous, a feature not encountered among adakites.**
- **seems unlikely that K-adakites had basaltic protoliths**

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- **important experiment is SH3, carried out at the *P-T* conditions for K-adakite genesis**
- **Weakly peraluminous syenitic (trachytic) glass (with 64 wt% SiO_2, K_2O/Na_2O = 1.46 and Mg# = 40) coexists with Alm-rich Grt, sodic aluminous augite and accessory Ru and Ap.**
- **Shoshonite melting is most unsuitable as a mode of K-adakite genesis, but it might be OK for syenites!**

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Why the melts have higher K_2O/Na_2O at higher *P*

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Field Observations

- **visit to the Tiantangzhai pluton (131 Ma) to see whether there are any features that would corroborate the experimental inference of very high *T* for K-adakite magmas**

- **So, we travelled North to the Dabie Shan UHP metamorphic belt to look mainly at the Neo-Archæan (2.66 Ga) TTG country rocks of the Dabie Complex. UHP metamorphism at 218 Ma.**

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- **Within 300 m of the intrusion, the rocks are comprehensively retrogressed to amphibolite facies. The normally regular planar fabric begins to show signs of contortion, accompanied by the presence of small, cross-cutting strings and pods of leucocratic rock with an igneous texture.**

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- **Migmatisation becomes more intense as the pluton is approached and, at a distance of about 80 m from the pluton, the TTG rocks take on the aspect of diatexites, with enclaves of the more mafic layers from the protolith.**

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- **Since the country rocks were originally cold, at the time of K-adakite intrusion, these features suggest intrusion of a very hot magma and expulsion of abundant aqueous fluids.**

- **Both these conclusions match the predictions from the experiments.**

- **Previous experimental melting work suggests that TTG tonalite melting is the most likely mode of formation of K-adakite melts.**

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General Conclusions

- **K-adakites were high-*T* (> 1075 °C), hydrous magmas (~ 6 wt% H_2O) formed by fluid-absent partial melting of metatonalites, meta-andesites, and possibly potassic metabasalts**

at *P* > 2 GPa.

- **The chemistry is a consequence of both high K_2O/Na_2O in the protolith and very high *P*.**
- **The most likely tectonic setting is extreme crustal thickening, delamination of an eclogitic keel followed by later partial melting of this crustal material at mantle depths, with high mantle heat flow, during orogenic collapse.**

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Grand Unified Adakite Equation?

melt K_2O/Na_2O =

0.6773*source K_2O/Na_2O

+ 0.6105*melting *P*

- 0.0025*melting *T*

+ 1.8615

K_2O/Na_2O mass ratio, *P* in GPa, *T* in °C,
54 experimental points, $R^2 = 0.6268$

"true" adakites 1.7 - 2.0 GPa (basaltic source)

"K-adakites" ≥ 2.2 GPa (TTG or other felsic source)

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