

# The Origin, Evolution and Present State of Subcontinental Lithosphere

IUGS-SECE

(Commission on Solid Earth Composition & Evolution) Conference

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北京大學

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**Peking University, Beijing, China**

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## Preface

# The origin, evolution and present state of subcontinental lithosphere

Y. Niu, S.-G. Song, L.-F. Zhang

### Theme Description:

While the continental crust is volumetrically small, perhaps comprising no more than ~ 0.5% of the Earth's mass, it is an important geochemical reservoir. This reservoir is most accessible to us, yet a genuine understanding of its origin, accretion, precise bulk composition and evolution remains out of reach. The fact that the average continental crust is > 2.5 Ga whereas the oceanic crust is < 200 Ma tells us that the bulk continental crust (vs. the oceanic crust) is relatively *permanent*. The prevailing view holds that the subcontinental lithospheric mantle (SCLM) represents partial melting residues, and is thus compositionally depleted and physically buoyant (i.e., more refractory with high Mg/Fe ratio) with respect to the underlying asthenosphere. As a result, the buoyant SCLM, ever since its inception, has been physically isolated from the convective asthenospheric mantle. It is the buoyant nature of the SCLM that allows it to protect the overlying crust from being destroyed. The similar age of the SCLM and the overlying crust in some cratonic regions not only points to their physical association, but probably the genetic link as well. Thus, ***the origin, evolution and present state of subcontinental lithosphere*** is key to the understanding of many aspects of the continental crust. Is SCLM forever? If so, the continental crust would be forever except, perhaps, terrigenous sediments that can be transported to deep sea trenches and recycled into the deep mantle. If SCLM is not forever, then the continental crust may not be preserved. This has important consequences not only for the origin and evolution of continental crust over Earth's history, but also for the chemical geodynamics in the context of models of mantle circulation and chemical evolution (crustal recycling models).

Recent studies have shown that not all the subcontinental lithospheres are forever. Lithosphere thinning at zones of continental rifts is well known and in tectonically active regions (e.g, Sierra Nevada, Basin-and-Range provinces in the western US, the southern Andes, and Tibetan plateau) are inferred petrologically and seismically. Lithosphere thinning has also been recognized in tectonically relatively stable regions like eastern Australia, eastern China, and in particular beneath ancient cratons, which

are considered to be stable (e.g., the Wyoming craton, North China craton, portions of South America etc.). What may have caused the SCLM thinning and how?

### **Why Beijing, China?**

We choose to hold such a conference in Beijing, China, because eastern China, especially the North China Craton (also known as Sino-Korean Craton), presents us with an excellent modern example of SCLM thinning since the Mesozoic. The existence of Paleozoic diamondiferous kimberlites in the North China Craton (NCC) and elsewhere in eastern China all suggests a thick, ~ 200 km, lithosphere (SCLM plus crust) back in the Paleozoic. However, recent studies of mantle xenoliths associated with the wide-spread Mesozoic-Cenozoic “intra-plate” volcanism together with seismic studies in eastern China indicate a much thinner, < 80 km, present-day lithosphere. Because (1) the lithosphere thinning is the largest in scale in a global context, (2) the genetically-related Mesozoic-Cenozoic volcanism is wide-spread with abundant mantle materials (xenoliths), and (3) there are also abundant geophysical data (seismic, heat flow, gravity etc.) available, eastern China thus provides an ideal case for studying the intra-plate volcanism of the kind in particular and the cause/causes of lithosphere thinning in general, not only in eastern China, but in the world and in Earth’s history.

### **Scientific questions to be considered and discussed:**

(1) What may have caused the lithosphere thinning? (2) Is it plausible that the buoyant SCLM sinks into the dense asthenosphere by a process called “delamination”? (3) If so, why doesn’t such “delamination” seem to occur beneath ancient cratons such as beneath much of the Africa and western Australia? (4) What is unique then beneath eastern China since the Mesozoic? (5) Lithospheric extension can indeed cause lithosphere thinning, but is there any unambiguous evidence for extension in eastern China since the Mesozoic? Lithospheric thinning has affected other cratons, such as the Kaapvaal and Slave cratons, but has not produced such dramatic effects. How about the western USA, the southern Andes, and Tibet? (6) Lithospheric extension can lead to basin formation, but did the Mesozoic-Cenozoic basins in eastern China result from such inferred extension? (7) Mantle plumes may also cause lithosphere thinning by means of thermal erosion, but is there any evidence for the genetic links between mantle plumes and lithosphere thinning such as beneath eastern China in the Mesozoic? (8) If so, what observations may be exclusively or uniquely considered as evidence for mantle plumes? (9) In the absence of evidence for mantle plumes, what else may have plausibly caused the lithospheric thinning? (10) Is there any identifiable record of lithosphere thinning globally in Earth’s history? (11) If so, how can all these recorded events affect models of continental accretion over earth’s history? (12) If

lithospheric thinning is a process that “transforms” the basal lithospheric materials into the convective asthenosphere (not necessarily by means of “delamination”), this would cause mantle compositional heterogeneity in the context of chemical geodynamics, but then can we properly evaluate the nature and significance of mantle compositional heterogeneity as a result of SCLM thinning? (13) The inferred lithosphere “delamination” beneath Tibet has been interpreted as a result of continental subduction. The latter mechanism has been also invoked to interpret the SCLM thinning beneath NCC as resulting from northward subduction of the Yangtze craton in the early Mesozoic as recorded by the exhumed Dabie-Sulu ultra-high pressure metamorphic eclogites. Is there any geophysical, petrological and geochemical evidence in support of this interpretation? (14) Is it possible that the lithosphere thinning beneath eastern China may be genetically associated with western Pacific subduction in the Mesozoic?

The purpose of this 6-day conference is to bring together scientists of different disciplines from all parts of the world to discuss and share their views and research results on these and other relevant questions. We welcome field geologists, petrologists, geochemists, tectonophysicists, and geophysicists of all areas with a common goal of enhancing our understanding the working of the Earth by means of future collaborative efforts.

### **Field excursion:**

#### ***1) Mesozoic xenolith-bearing basalts in Fangcheng area, Linyi, Shandong Province***

Voluminous volcanic rocks erupted in Fangcheng area, Linyi County, Southeast NCC in the late Mesozoic (125 Ma) provide insights into the lithospheric processes in the Mesozoic. The geochemistry of these basalts points to their derivation from lithospheric mantle, and abundant xenoliths of pyroxenites and xenocrysts of pyroxene and olivine are also of lithospheric origin. The latter xenocrysts show compositional zoning as a result of interactions of ascending basaltic magmas with the thinning lithosphere.

#### ***2) Ultrahigh-pressure (UHP) metamorphic rocks in Sulu, Shandong Province***

The Dabie-Sulu UHP metamorphic belt is the largest UHP belt in the world. It is formed by the northward subduction of the Yangtze Craton beneath the NCC in the late Triassic. The northward subduction is considered to affect the integrity of the southern portion of the NCC lithosphere, leading to its thinning. Paragneiss and orthogneiss are the most common lithologies in the Sulu UHP belt. UHP eclogites, garnet-peridotites and marble occur as lenses, blocks and/or layers in the gneisses. Coesite have been found in both eclogites (rare) and gneisses (abundant), indicating deep subduction of whole continental lithosphere to depth in excess of 80 km.

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# Session 1

## Continental Lithosphere: Concepts, Problems and Hypotheses

# **Integration of geology, geophysics & geochemistry : a key to understanding the North China Craton**

**Martin Menzies**

*Department of Geology, Royal Holloway University of London, Egham, Surrey TW20 OEX*

*Email: [m.menzies@gl.rhul.ac.uk](mailto:m.menzies@gl.rhul.ac.uk)*

**Yigang Xu**

*Key Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of  
Geochemistry, Chinese Academy of Sciences, 510640 Guangzhou, PRC*

**Hongfu Zhang and Weiming Fan**

*State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics,  
Chinese Academy of Science, P.O.Box 9825, Beijing 100029, PRC*

Archaean-Proterozoic crust, atop a thick (180km), cold (40Mw/m<sup>2</sup>), melt-depleted mantle keel of garnet to diamond facies harzburgite (Griffin *et al.*, 1992, 1998, Zhang *et al.* 1999) characterised the North China Craton (NCC) at the beginning of the Phanerozoic. Differing age relationships for crust and underlying mantle reveal a Precambrian history of decoupling brought about by repeated orogenic events (Jahn *et al.* 1987, Gao *et al.*, 2002, Zheng *et al.* 2004, Wu *et al.*, 2003). The most recent record of crust-mantle decoupling occurred in the Mesozoic-Cenozoic when the melt-depleted keel was removed/transformed such that fertile spinel-garnet lherzolite constitutes much of the lower lithosphere (e.g., Fan *et al.*, 2000, Xu *et al.*, 2000, Rudnick *et al.*, 2004). Reports of high Mg # peridotites within Cenozoic basalt-borne suites of more fertile lherzolites points to the survival of remnants of pre-existent cratonic lithosphere and may help constrain the process (Zheng *et al.*, 2001). Against this background considerable debate surrounds the timing, the mechanism and the evidence for decoupling of crust and mantle in the NCC (e.g., Menzies *et al.*, 1993, Griffin *et al.*, 1992, 1998; Menzies and Xu 1998; Zheng *et al.*, 2001; Fan *et al.*, 2000; O'Reilly *et al.*, 2001; Xu *et al.*, 2000, Xu 2001, Gao *et al.*, 2002, 2004, Zhang *et al.*, 2003; Rudnick *et al.*, 2004, Xu *et al.*, 2004, Wu *et al.*, 2005).

**Timescales** - Whether the keel loss was caused by rapid delamination [Yang *et al.*, 2003, Gao *et al.*, 2004, Wu *et al.*, 2005] or a lengthy transformation [Griffin *et al.*, 1998, Menzies & Xu 1998, O'Reilly *et al.*, 2001, Xu 2001] depends on our interpretation of (a) Jurassic to Cretaceous volcanic rocks and whether the switch from enriched to depleted sources over a 80-100Ma time period, does in fact reflect a temporal change in the composition of the lower lithosphere (i.e., cratonic to oceanic), (b) the short-lived early Cretaceous mafic-felsic magmatic event(s) and whether we accept this as the surface manifestation of rapid delamination, and (c) the spatial extent and temporal significance

of high Mg # mantle rocks entrained by Cretaceous-Recent volcanic rocks (Zheng *et al.*, 2001) and whether an Archaean provenance can be proven.

**Mechanisms** - Triassic collision [between the north and south China Blocks] and delamination models (Li 1994, Menzies & Xu 1998, Gao *et al.*, 2002) are consistent with the short-lived magmatic peak in the Cretaceous. But such models do need to explain the NE-SW thermo-tectonic trends across the NCC, and the fact that maximum thinning is 1000km from the Triassic orogenic front. Plumes or superplumes (Jahn *et al.*, 1999, Wu *et al.*, 2005) are an alternative mechanism but are at odds with the lack of large igneous provinces and the systematic decline in magmatism from east to west. A very effective barrier to the upwelling plumes is provided by recycled slab graveyards [at the 660 km discontinuity] apparent from seismic tomographic models. Also if plumes affect cratons why has the Kaapvaal craton survived despite being atop a global superplume/upwelling. The destructive plate margins of the West Pacific may provide a back-arc environment that adequately explains the NE-SW trends within the NCC, the W-E spatial changes in magmatism and the radical W-E changes in lithosphere architecture across the NCC.

**Spatial changes** - The eastern part of the NCC appears to have been more prone to reactivation than elsewhere, particularly the raea between the North-South Gravity Lineament and the NE-SW trending Tan-Lu trans-lithospheric fault. The Tan-Lu is straddled by Ordovician diamondiferous and barren kimberlites and the NSGL and Tan-Lu are associated with early Cretaceous large mafic intrusions (Wu *et al.*, 2005). Today, the thinnest lithosphere (<50km) and thinnest crust (<32 km) (Ma 1987, Zhang 1998, Liang *et al.* 2004) lies adjacent to the Tan-Lu fault and thermal highs [ $>64\text{Mw/m}^2$ ] dominate a region previously occupied by the Pre-Cambrian diamondiferous keel. Has the Tan-Lu acted as a conduit for thermo-chemical change since the early Phanerozoic? Why are there such lateral changes across the NSGL? Does the presence of thermal highs, lithospheric thinning, and magmatic activity in the eastern NCC support a spatial link to the Pacific Rim and thus exclude other models?

### References :

- Fan, W., Zhang, H.F., Baker, J., Jarvis, K.E., Mason, P.R.D., and Menzies, M.A., (2000). On and off the North China Craton : where is the Archean keel ? *J Petrology* **41**, 933-950.
- Gao, S., Rudnick, R.L., Carlson, R.W., McDonough, W.F., and Liu, Y. (2002). Re-Os evidence for replacement of ancient mantle lithosphere beneath the North China Craton. *Earth and Planetary Science Letters* **198**, 307-322
- Gao, S., Rudnick, R.L., Yuan, H.-L., Liu, X.-M., Liu, Y. -S., Xu, W. -L., Ling, W.-L., Ayers, J., Wang, X.-C., and Wang, Q.-H. (2004) Recycling lower continental crust in the North China Craton. *Nature* **432**, 892-897.
- Griffin, W.L., O'Reilly, S.Y. & Ryan, C.G. (1992). Composition and thermal structure of the lithosphere beneath South Africa, Siberia and China : proton microprobe studies. *International*

- Symposium on Cenozoic Volcanic rocks and deep-seated xenoliths of China and its Environs*, Beijing, 20.
- Griffin, W.L., Andi, Z., O'Reilly, S.Y., and Ryan, C.G. (1998) Phanerozoic evolution of the lithosphere beneath the Sino-Korean craton. In "*Mantle Dynamics and Plate Interactions in East Asia*" [eds. Flower et al.] AGU Geodynamics Series, **27**, 107-126.
- Jahn, B. M., B. Auvray, J. Cornichet, Y. L. Bai, Q. H. Shen, and D. Y. Liu, (1987) 3.5 Ga old amphibolites from eastern Hebei province, China : field occurrence, petrography, Sm-Nd isochron age and REE geochemistry. *PreCambrian Research*, **34**, 311-346.
- Jahn, B.M., Wu, F.Y., Lo, C.H., and Tsai, C.H. (1999) Crust-mantle interaction induced by deep subduction of the continental crust : geochemical and Sr-Nd isotopic evidence from post-collisional mafic-ultramafic intrusions of the northern Dabie complex, Central china. *Chemical geology*, **157**, 119-146.
- Liang, C., Song, X., and Huang, J. (2004) Tomographic inversion of Pn travel times in China. *Journal of Geophysical Research*, **109**
- Li, Z.X. (1994) Collision between the North and South China blocks : a crustal detachment model for suturing in the region east of the Tan-Lu fault, *Geology* **22**, 739-742.
- Ma, X.Y. (1987) Lithospheric dynamics map of China and adjacent seas (1:4,000,000) and explanatory notes. *Geological Publishing House, Beijing, China*.
- Menzies, M.A. and Xu, Y. (1998) Geodynamics of the North China Craton. In "*Mantle Dynamics and plate interactions in East Asia*" (Eds. M. Flower, S-L. Chung, C-H Lo and T-Y Lee) American Geophysical Union Monograph , **27** , 155-165
- Menzies, M. A., F. Weiming, and M. Zhang (1993) Palaeozoic and Cenozoic lithoprobes and the loss of >120km of Archean lithosphere, Sino-Korean craton, China, *Geological Society of London Special Publication*, **76**, 71.
- O'Reilly, S. Y., Griffin, W.L., Poudjom Djomani, Y.H., and Morgan, P. (2001). Are lithospheres forever ? Tracking changes in subcontinental lithospheric mantle through time. *GSA Today* 4-9.
- Rudnick, R.L., Gao, S., Ling, W-L, Liu, Y-S., and McDonough, W. (2004) Petrology and geochemistry of spinel peridotite xenoliths from Hannuoba and Qixia, North china Craton. *Lithos* **77**, 609-637.
- Wu, F.Y., Walker, R.J., Ren, X.W., Sun, D.Y., and Zhou, X.H. (2003) Osmium isotopic constraints on the age of lithospheric mantle beneath northeastern China. *Chem Geology*, **196**, 107-129.
- Wu, F.Y., Lin, J.Q., Wilde, S., Zhang, Z., and Yang J.H. (2005) Nature and significance of the early Cretaceous giant igneous event in eastern China. *Earth and Planetary Science Letters* **233**, 103-119.
- Xu, X.S., S.Y. O'Reilly, W.L. Griffin, and X. Zhou (2000) Genesis of young lithospheric mantle in southeastern China : an LAM-ICPMS trace element study. *J. Petrology* **41**, 111-148.
- Xu, Y. (2001) Thermo-tectonic destruction of the Archaean Lithospheric Keel beneath the Sino-Korean Craton in China : evidence, timing and mechanism. *Phys. Chem. Earth*. **26**, 747-757.
- Xu, Y.-G., Chung, S.-L., Ma, J., and Shi, L., (2004) Contrasting Cenozoic lithospheric evolution and architecture in western and eastern Sino-Korean craton. *Journal of Geology*, **112**, 593-605.
- Yang, J.H, Wu, FY, and Wilde SA (2003) A review of the geodynamic setting of large-scale Late Mesozoic gold mineralization in the North China Craton: An association with lithospheric thinning. *Ore Geol Rev* **23**: 125-152

- Ye, H., Zhang, B., and Mao, F. (1987) The Cenozoic tectonic evolution of the Great North China : two types of rifting and crustal necking in the Great North China and their tectonic implications. *Tectonophysics*, **133**, 217-227.
- Zhang, A., Griffin, W.L., Ryan, C.G. and Andrew, A.S. (1999) Conditions of Diamond Formation beneath Liaoning and Shandong Provinces, China: Parageneses, Temperatures and the Isotopic Composition of Carbon. In: *The Nixon Volume (2)*. Proceedings 7th International Kimberlite Conference, (Eds : Gurney, J.J., J.L. Gurney, M.D. Pascoe, and S.H. Richardson). pp 940 -947. Red Roof Designs, Cape Town, South Africa.
- Zhang, H.F., Sun, M., Zhou, X.H., Zhou, M.F., Fan, W.M., Zheng, J.P. (2003) Secular evolution of the lithosphere beneath the eastern North China Craton: evidence from Mesozoic basalts and high-Mg andesites. *Geochim Cosmochim Acta* **67**, 4373-4387.
- Zhang, Y.S. 1998 Three-dimensional upper mantle structure beneath East Asia and its Tectonic Implications. In "*Mantle Dynamics and Plate Interactions in East Asia*" [eds. Flower, M., Ching, S.L., Lo, C.H., and Lee, T.Y.) AGU Geodynamics Series, **27**, 11-23.
- Zheng, J., Griffin, W.L., O'Reilly, S.Y., Lu, F., Wang, C., Zhang, F., and Li, H. (2004) 3.6 Ga lower crust in central China : New evidence on the assembly of the North China Craton. *Geology*, **32**, 229-233.
- Zheng, J., O'Reilly, S.Y., Griffin, W.L., Lu, F., Zhang, M., and Pearson, N.J. (2001) Relict refractory mantle beneath the eastern North China Block : significance for lithospheric evolution. *Lithos* **57**, 43-66.

# **Compositional evolution of the continental lithospheric mantle**

William F. McDonough

*Department of Geology, University of Maryland, College Park, MD 20742, USA*

*Email: [mcdonough@geol.umd.edu](mailto:mcdonough@geol.umd.edu)*

## **Dating the formation and evolution of continental lithospheric mantle**

D.G. Pearson<sup>1</sup> & A. Luguet

*Department of Geological Sciences, Durham University, South Rd,  
Durham, DH1 3LE, UK*

*Email: [d.g.pearson@durham.ac.uk](mailto:d.g.pearson@durham.ac.uk)*

Dating events experienced by the Earth's lithospheric mantle, such as the melting event responsible for its separation from the convecting mantle and subsequent phases of compositional modification (metasomatism) will always present a great challenge because of the complex, multi-stage history that most mantle fragments experience and because the temperatures experienced by these mantle portions during their residence in the mantle are above the theoretical blocking temperatures. Despite this, some notable success has been achieved in the past 15 years using a variety of isotopic systems.

The Re-Os isotope system has so far provided most of our available knowledge of the age of melting events responsible for dating lithosphere formation ages via melt depletion, especially for cratonic and circum-cratonic mantle lithosphere. The process being dated is the large degree melt extraction which removes sufficient melt to drastically change the density of the peridotite, causing it to become buoyant and accrete to the lithosphere. Significant success has been achieved with this method, notably in southern Africa where there is an excellent correspondence between the oldest Re depletion ages and the craton – circum-cratonic regions and even W. and E. portions of the craton. However, some recent models of the evolution of cratonic lithospheric mantle suggest formation during shallow melting to form oceanic lithosphere first and then subduction/tectonic stacking to form craton roots. In this situation, there may be more than a single melting event integrated into the Os isotope signature. If the initial melting to produce oceanic lithosphere removed most of the Re, any Os model age will largely reflect this event and not its transformation into continental lithosphere. The age difference could be minimal.

Other limitations from the Re-Os model age approach, on either whole rocks or sulfides, occur when relatively recent lithosphere formation events are being dated. There is significant uncertainty with the estimate of the recent Os isotope evolution of the mantle and there is abundant direct evidence that it has become more heterogeneous with time. This includes ancient depletion ages being obtained from abyssal peridotites and peridotite xenoliths that sample arc mantle regions. This makes the



dating of melting events in Neo-Proterozoic times or younger subject to significant overall error, whatever the precision of the analyses.

There are now numerous Re-Os isotope studies of both whole rock peridotites and/or sulfides. The two approaches contain complimentary information. In some studies, sulfides give proportionally more older depletion ages than whole rocks, although the maximum ages are very similar. In other situations, there are no magmatic sulfides, or, the whole rocks give significantly older ages than the dominantly metasomatic sulfides available, e.g., Norwegian "Caledonian" peridotites.

For late Proterozoic and more recent melting events, the Lu-Hf system seems promising for obtaining depletion ages because it is significantly more resistant to metasomatic disturbance than the Sm-Nd system.

# **Transformation of sub-continental lithospheric mantle through melt-peridotite interaction: implication from mantle xenocrysts and xenoliths**

Hong-Fu Zhang

State Key Laboratory of Lithosphere Tectonic Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, P.R. China.

*E-mail:* [hfzhang@mail.igcas.ac.cn](mailto:hfzhang@mail.igcas.ac.cn)

Removal of sub-continental lithospheric mantle beneath global cratons is an important event in craton evolution<sup>[1-2]</sup>. This is particularly true for the North China Craton, where more than 100 km lithosphere has been lost since the Phanerozoic. This dramatic lithospheric removal was accompanied with the compositional change from the Paleozoic thick cratonic mantle to Cenozoic thin oceanic one. The mechanism for such a change is hotly debated. Geochemical features of Mesozoic mantle-derived rocks demonstrate that the Mesozoic lithospheric mantle beneath the region was considerably different from both the Paleozoic refractory and the Cenozoic depleted ones, implying two times lithospheric compositional changes<sup>[1]</sup>. Mantle xenoliths, xenocrysts and cumulates entrained in Cretaceous basalts on the craton provides some evidences for such a compositional change. Occurrence of zoned olivine and clinopyroxene xenocrysts and reactant xenoliths demonstrate that the peridotite-melt reaction could have happened in the deep mantle. The zoned xenolith has a lherzolite core, a sheared zone and a reactant rim. The lherzolite is coarse granular and composed of olivine, opx, cpx and spinel. The sheared zone and the reactant rim comprise oriented olivine, secondary cpx and spinel, and fine-grained olivine, cpx and spinel, respectively. No orthopyroxene exists in the sheared zone and reactant rim. Mineral compositions in this zoned xenolith vary dramatically between different zones. Olivine in the lherzolite is relatively high in Mg# and NiO and in the sheared zone and the reactant rim are low. Clinopyroxene and spinel also shows clear compositional trend from the lherzolite to the reactant rim, with a decrease in Mg#, Cr<sub>2</sub>O<sub>3</sub> and Na<sub>2</sub>O and an increase in TiO<sub>2</sub>. Such a compositional feature in minerals of this zoned xenolith is different from that of peridotitic xenoliths entrained in both Paleozoic kimberlites and Cenozoic basalts on the craton, which have much higher Mg# (>90) in olivines. This highly fertile peridotite (i.e extremely low Mg# in constituent minerals) has never been found in lithospheric mantle

beneath the worldwide cratons. We believed this highly fertile xenolith provides petrological evidence for the replacement of sub-continental lithospheric mantle through peridotite-melt reaction. Estimation of melt composition on the basis of the olivine Mg# and clinopyroxene SIMS REE abundance of a mantle composite cumulate indicate that the melt were high in Si, K, and Ca and low in Mg# with extremely high LREE concentration. This melt circulated in the lithosphere could be derived from the subducted crustal materials of the Yangtze Craton. This melt-peridotite interaction resulted in the transformation of the lithospheric mantle from high-Mg# peridotite to low-Mg# peridotite beneath the North China Craton.

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## References

- [1] Lee CT, Yin QZ, Rudnick RL, Chesley JT, Jacobsen SB (2000). *Science* 289: 1912-1916
- [2] Riley TR, Leat PT, Kelley SP, Millar IL, Thirlwall MF (2003). *Lithos* 67: 163-179
- [3] Zhang HF, Sun M, Zhou XH, Fan WM, Zhai MG, Ying JF (2002) *Contrib. Mineral. Petrol.* 144: 241-254

# **Diachronous lithospheric thinning in the North China Craton and formation of the Daxin'anling-Taihang gravity lineament**

Yi-Gang Xu

*Key Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, 510640 Guangzhou, China*

*Email: [yigangxu@gig.ac.cn](mailto:yigangxu@gig.ac.cn)*

In North China, Cenozoic basalts were erupted in association with formations of graben basins and their regional boundary faults. Radiometric dating shows that eruption age is between early Tertiary to Quaternary (Liu et al., 1992). While Sr-Nd isotopic ratios and relative abundances of incompatible elements are consistent with a dominant asthenospheric origin, Cenozoic basalts from both sides of the Daxin'anling-Taihang gravity lineament (DTGL) that separates the North China Craton (NCC) into two parts, namely the western and eastern NCC, show contrasting evolution trends (Xu et al., 2004). In the western NCC, magmas evolved from xenolith-bearing alkali basalts of late Eocene-Oligocene age to coexisting alkali and tholeiitic basalts of late Miocene-Quaternary age. This change in basalt type is accompanied by a decrease in La/Yb and increase in Yb content. This temporal variation in basalt geochemistry is interpreted as reflecting progressive lithospheric thinning in the western NCC during the Cenozoic. An opposite trend is observed for Cenozoic basalts from the eastern NCC, suggesting lithospheric thickening during this time period. This thickening was probably related to regional thermal decay following peak magmatism in the late Cretaceous-Early Tertiary. Such contrasting lithospheric processes may reflect diachronous extension in the NCC, with extension taking place earlier in the eastern NCC than in western NCC. Recent seismic tomography reveals a flat subducting slab at the transition zone. The west end of this stagnant slab virtually coincides with the location of the DTGL. It is thus possible that Cenozoic volcanism resulted from interaction between two different tectonic regimes. The generation of Cenozoic basalts from the eastern NCC could be related to the back-arc extension owing to late Mesozoic-Paleogene Pacific subduction underneath the Asian continent, whereas subsequent extension in the western NCC may have been induced by the early Tertiary Indian-Eurasian collision. This model yields following implications:

(1) The lithospheric mantle in the western NCC is relatively old compared to that beneath the eastern NCC which may be a mixture of old lithospheric relicts and newly accreted mantle. This predicted lithospheric architecture is consistent with Sr-Nd

isotopic data and recent Re-Os age determination obtained from mantle xenoliths included in the Cenozoic basalts (Gao et al., 2002; Wu et al., 2003).

(2) The formation of the DTGL was likely coeval with the late Mesozoic destruction of the Archean lithospheric root beneath the eastern NCC.

### **References:**

- Gao, S.; Rudnick, R.L.; Carlson, R.W.; McDonough, W.F.; and Liu, Y.S. 2002. Re-Os evidence for replacement of ancient mantle lithosphere beneath the North China Craton. *Earth Planet. Sci. Lett.* 198: 307-322.
- Liu, R.X.; Chen, W.J.; Sun, J.Z.; and Li, D.M. 1992. The K-Ar age and tectonic environment of Cenozoic volcanic rock in China. In Liu, R.X., ed. *The age and geochemistry of Cenozoic volcanic rock in China*. Beijing, Seismologic Press, p. 1-43. (in Chinese)
- Wu, F.-y., Walker, R.J., Ren, X.-w., Sun, D.-y., Zhou X.-h, 2003. Osmium isotopic constraints on the age of lithospheric mantle beneath northeastern China. *Chemical Geology*, 196: 107-129
- Xu, Y-G, S.-L. Chung, J. Ma and L. Shi. 2004. Contrasting Cenozoic lithospheric evolution and architecture in western and eastern Sino-Korean Craton: Constraints from geochemistry of basalts and mantle xenoliths. *Journal of Geology* 112 (5): 593-605

## **Persistence of ancient lithospheric mantle: consequences for geodynamics and basalt geochemistry**

Suzanne Y. O'Reilly<sup>1</sup>, William L. Griffin<sup>1,2</sup>, Ming Zhang<sup>1</sup>  
and Yvette Poudjom Djomani<sup>1</sup>

1. *GEMOC National Key Centre, Department of Earth and Planetary Sciences,  
Macquarie University, NSW 2109, Australia*

*Email: [soreilly@els.mq.edu.au](mailto:soreilly@els.mq.edu.au)*

2. *CSIRO Exploration and Mining, North Ryde, NSW 2113, Australia*

Samples of the deep lithosphere are delivered to the surface as small xenoliths with restricted petrological context, and as tectonic slivers on the scale of km<sup>2</sup> but commonly with metamorphic petrological overprints. Geophysical information (especially tomography) allows us to extrapolate mantle rock-type domains between the magmatic virtual drill holes (kimberlites and basalts) that carry xenoliths, and to build up 3-D images of lithosphere composition, sometimes in time-slices (4-D) reflecting episodes of magmatic activity.

Xenolith data reveal significant differences in composition and physical properties between Archean and Phanerozoic mantle (Griffin et al., 1999); much intermediate "Proterozoic" mantle may represent reworked Archean material. Although depleted ancient SCLM cannot be recycled through convection due to its low density (eg O'Reilly et al., 2001), truly pristine Archean mantle may be very rare as these buoyant blobs undergo repetitive geochemical transformation to varying degrees.

Refined seismic tomography inversions image low density regions both in oceanic upper mantle and below the conventional lithosphere-asthenosphere boundary beneath continental and especially cratonic regions. In the latter, such low density domains persist, in some cases, down to the transition zone. Old Re-Os ages for some depleted mantle rock types beneath rift zones and oceanic areas suggest that these low-density blobs represent relict Archean SCLM, which has been mechanically disrupted and thinned. This implies that old lithospheric mantle is much more extensive, both laterally and vertically, than previously considered and proposed processes for the formation of Archean lithosphere have to consider this.

If coherent old SCLM persists at depth, this has important implications for the nature of global convection. Models involving large-scale horizontal components would be difficult to reconcile with these observations. Instead, convection may be dominantly in the form of upwelling vertical conduits with shallow horizontal flow (the

"mushroom-cloud model" of Yuan, or the lava lamp model of Kellogg et al. (1999). The locus of these conduits may be controlled by the geometry of the margins and the coherence of the buoyant lithospheric blobs. The convective plate motions in the upper asthenosphere are "eddies" between these buoyant blobs and can be preserved in the observed plate stress directions and anisotropy (eg Simons and van der Hilst, ). Mobile belts represent lithosphere accretion between the blobs.

The persistence of ancient SCLM beneath younger mobile belts and oceans also provides a logical explanation for the alphabet soup of mantle sources created by geochemists (EM1, EM2, HIMU etc; Zhang et al., 2001). All of these geochemical fingerprints are found in lithospheric material (eg xenoliths). If lithospheric volumes persist to very deep mantle levels (eg 400km) then interaction with upwelling mantle can "contaminate" these plumes and fluids. The requirement for mysterious hidden source regions to provide the geochemical alphabet is removed.

### **References**

- Griffin, W.L., O'Reilly, S.Y. and Ryan, C.G., 1999. The composition and origin of sub-continental lithospheric mantle. In: Y. Fei C. M. Bertka and B. O Mysen (eds) *Mantle Petrology: Field observations and high-pressure experimentation: A tribute to Francis R. (Joe) Boyd*, The Geochemical Society, Special Publication No. 6, p 13-43
- Kellogg, L.H., Hager, B.H., and van der Hilst, R.D., 1999, Compositional stratification in the deep mantle: *Science*, 283, 1881-1884.
- O'Reilly, S.Y., Griffin, W.L., Poudjom Djomani, Y.H., and Morgan, P., 2001, Are lithospheres forever? Tracking changes in subcontinental lithospheric mantle through time: *GSA Today*, 4-10.
- Poudjom Djomani, Y.H., O'Reilly, S.Y., Griffin, W.L., and Morgan, P., 2001, The density structure of subcontinental lithosphere through time: *Earth and Planetary Science Letters*, 184, 605-621.
- Simons, F.J., and van der Hilst, R.D., 2003, Seismic and mechanical anisotropy and the past and present deformation of the Australian lithosphere: *Earth and Planetary Science Letters*, 211, 271-286.
- Zhang, M., Stephenson, P.J., O'Reilly, S.Y., McCulloch, M.T., and Norman, M., 2001, Petrogenesis and geodynamic implications of Late Cenozoic basalts in North Queensland, Australia: trace-element and Sr-Nd-Pb isotope evidence: *Journal of Petrology*, 42, 685-719.

## **Understanding the evolution of the thermal boundary layer at the base of the continental lithosphere**

Marjorie Wilson

*Institute of Geophysics and Tectonics, School of Earth & Environment (Earth Sciences),  
Leeds University, Leeds LS2 9JT, UK  
Email: [M.Wilson@earth.leeds.ac.uk](mailto:M.Wilson@earth.leeds.ac.uk)*

In regions of extension-related, intra-plate volcanism the primary magma source region is likely to be within the thermal boundary layer (TBL) at the base of lithosphere. This is the region in which the geothermal gradient changes from conductive (in the overlying mechanical boundary layer or MBL) to adiabatic in the underlying asthenosphere, and in which the maximum overstepping of the mantle solidus (wet or dry) will take place. Thus, while the initiation of partial melting may occur much deeper in the mantle, the main magma generation zone will be close to the base of the TBL.

Within continental terranes which have experienced Phanerozoic tectono-magmatic events (e.g. western and central Europe), the lithosphere is typically ~ 100- 120 km thick. In such provinces extension-related, intra-continental plate, alkaline mafic magmas (alkali basalts, basanites, nephelinites) frequently exhume samples of the MBL in the form of spinel peridotite mantle xenoliths (usually from depths of no more than 10-20 km below the Moho). Samples of the TBL, however, are extremely rare, and may only be present in the form of xenocrysts from disaggregated mantle xenoliths (e.g. Wilson et al., 1995). Much of our information about the nature of the TBL must be based, therefore, on indirect evidence.

The TBL should not be regarded as a permanent part of the mantle lithosphere. It can grow by downward thermal capture of the underlying asthenosphere or by underplating of buoyant mantle derived from ascending mantle plumes or diapirs. Thus, the mantle part of the lithosphere should become progressively younger downwards, and ancient (? enriched) domains should be confined to the MBL. Where plates are moving rapidly, there may be significant shearing within the TBL which may destabilise it. It is unlikely that the TBL is ever much older than 200-300 Myr. The TBL may, locally, become enriched by infiltration of small-degree partial melts (e.g. carbonatites, melilitites, nephelinites) from the underlying asthenosphere.

Studies of primitive intra-continental plate alkaline mafic magmas from the Cenozoic magmatic province of western and central Europe (e.g. Wilson & Downes, 1991; 2005) indicate that the main zone of magma generation within the TBL spans the transition between spinel and garnet peridotite mantle facies. The REE and trace element



characteristics of the magmas provide good control on the depth and degree of partial melting and the evolution of the TBL over the past 60 Myr.

**Reference:**

- WILSON, M. & DOWNES, H. Tertiary-Quaternary extension related alkaline magmatism in Western and Central Europe. *Journal of Petrology* 32, 811-849 (1991)
- WILSON, M., ROSENBAUM, J.R. & DUNWORTH, E.A. Melilitites: partial melts of the thermal boundary layer. *Contributions to Mineralogy and Petrology* 119, 181-196 (1995)
- WILSON, M. & DOWNES, H. Tertiary-Quaternary intra-plate magmatism in Europe and its relationship to mantle dynamics. In: Stephenson, R. & Gee, D. (eds) *European Lithosphere Dynamics*. Geological Society of London Memoir (in press, 2005)

## **Late Mesozoic-Eocene mantle replacement beneath the eastern North China Craton: evidences from the Paleozoic and Cenozoic peridotite xenoliths**

Jianping Zheng <sup>a,b</sup>, W. L. Griffin <sup>b,c</sup>, Suzanne Y. O'Reilly <sup>b</sup> and Fengxiang Lu <sup>a</sup>

<sup>a</sup> *State Key Laboratory of Geological Processes and Mineral Resources, Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074, China.*

*Email: [jpzhang@cug.edu.cn](mailto:jpzhang@cug.edu.cn)*

<sup>b</sup> *GEMOC ARC National Key Centre, Department of Earth and Planetary Sciences, Macquarie University, Sydney, NSW 2109, Australia*

<sup>c</sup> *CSIRO Exploration and Mining, North Ryde, NSW 2113, Australia*

Xenolith-bearing Paleozoic kimberlites and Cenozoic basalts from the eastern North China Craton provide unusual insights into intra-plate processes and Phanerozoic lithospheric evolution. Paleozoic peridotite xenoliths represent samples of ancient cratonic mantle; P-T estimates show that a thick (ca. 230 km) and cold (ca 40 mW/m<sup>2</sup>) lithosphere existed beneath the craton in mid-Ordovician time. However, xenoliths from Tertiary basalts show a thin (< 90 km), hot (mean geotherm ca 80 mW/m<sup>2</sup>) and compositionally heterogeneous lithosphere beneath the same area in Cenozoic time. Fertile spinel-facies mantle makes up much of the Cenozoic lithosphere beneath the eastern North China Craton, especially in the regions along the translithospheric Tanlu fault. However, refractory spinel-facies xenoliths are found locally along the North-South Gravity Lineament, in areas far away from the Tanlu fault. These refractory xenoliths are interpreted as derived from shallow relics of the cratonic mantle, embedded in more fertile Cenozoic lithosphere. The increasing incidence of fine-grained and sheared microstructures in xenoliths from the North-South Gravity Lineament to the Tanlu fault suggests that the translithospheric fault system has played an important role in the Mesozoic-Cenozoic replacement of pre-existing lithospheric mantle by more fertile material. The modification of cratonic mantle beneath the eastern North China Craton was heterogeneously dominated by replacement of old lithosphere with the cooling products of weakly depleted asthenosphere, welling up along major shear systems. This lithosphere replacement was accompanied by a raised geotherm and a higher asthenosphere-lithosphere boundary.

## **Slab dehydration, subcontinental lithosphere thinning and Mesozoic/Cenozoic volcanism in eastern China: A special consequence of plate tectonics**

Yaoling Niu<sup>1</sup>, Shuguang Song<sup>2</sup>, Lifei Zhang<sup>2</sup>, Jinfu Deng<sup>3</sup>, Xuanxue Mo<sup>3</sup>, Shangguo Su<sup>3</sup>,  
Zhengfu Guo<sup>4</sup> and Jiaqi Liu<sup>4</sup>

<sup>1</sup>*Durham University, Durham DH1 3LE, UK (Email: [yaoling.niu@durham.ac.uk](mailto:yaoling.niu@durham.ac.uk))*

<sup>2</sup>*Peking University, Beijing 100871, China;*

<sup>3</sup>*China University of Geosciences, Beijing 100083, China;*

<sup>4</sup>*Chinese Academy of Science, Beijing 100029, China*

We present a hypothesis for the Mesozoic lithosphere thinning and Mesozoic/Cenozoic basaltic volcanism in eastern China. While the eastern China volcanism may be considered as “intra-plate” volcanism, it is in fact a special consequence of plate tectonics<sup>[1]</sup>. The Mesozoic lithosphere thinning in eastern China is best explained by a process that “transformed” the basal portion of the lithosphere into convective asthenosphere by hydration. The water that did so may come from dehydration of subducted Pacific (or predecessor) oceanic lithosphere that is presently lying horizontally in the transition zone beneath eastern Chinese continent as detected by seismic tomographic models<sup>[2]</sup>. The Mesozoic volcanism may be genetically associated with the lithospheric thinning because the basaltic source is ancient isotopically enriched ( $\epsilon_{Nd} < 0$ )<sup>[3]</sup> lithosphere - being converted to the asthenosphere. The *NNE-SSW* Great Gradient Line (*GGL*) marked by the sharp altitude, gravity anomaly, crustal thickness, and mantle seismic velocity changes from the plateau west to the hilly plains of eastern China is an expression of variation in lithospheric thickness from probably  $> 150\text{-}200$  km thick beneath the plateaus in the west to the thin, probably  $< 80$  km thick, beneath eastern China. The “remote” western Pacific subduction systems (“wedge suction”<sup>[1]</sup>) induce asthenospheric flow from beneath eastern China towards the subduction zones, which, in turn, requires asthenospheric material replenishment from beneath the western plateaus to eastern China. As a result, such eastward asthenospheric flow experiences upwelling and decompression (from beneath thickened to thinned lithosphere), which causes the flowing asthenosphere (e.g.,  $\epsilon_{Nd} > 0$ )<sup>[3]</sup> to partially melt and produce Cenozoic eastern China basaltic volcanism. Such volcanism may have actually begun at the end of the Mesozoic lithosphere thinning in the late Cretaceous<sup>[4]</sup>.

The above hypothesis, which requires further testing, is consistent with available observations and complies with straightforward physics. Our proposed mechanism of lithosphere thinning

- (1) does not require hot mantle plumes that may have not existed beneath eastern China; the horizontally-lain transition-zone slabs act as a cold thermal boundary layer that sucks

heat from above and below, thus preventing hot mantle plumes to rise from the lower mantle and to form in the upper mantle;

- (2) does not require lithospheric “delamination”, which describes that deep portions of the buoyant cratonic lithosphere sink into the dense asthenosphere – a scenario that is physically difficult;
- (3) does not require lithospheric extension/stretching whose existence and scale in the Mesozoic remain elusive;
- (4) explains the lithosphere thinning in the entire eastern China, not just the North China Craton (NCC); and thus
- (5) questions the significance of South China continental subduction as a cause of lithosphere thinning beneath the NCC.

Our suggested mechanisms for Mesozoic/Cenozoic volcanism in eastern China are consistent with the geochemistry of the basalts<sup>[3]</sup>, physical scenarios of mantle melting<sup>[1]</sup> and geophysical observations<sup>[1,2]</sup>. The latter principles and observations

- (1) disfavor the suggestion of hot mantle plume origin of eastern China volcanism (see above);
- (2) disfavor the suggestion of ocean ridge-like passive mantle upwelling and decompression melting because there is no unambiguous evidence for large scale rifting or lithosphere separation in eastern China since the Mesozoic;
- (3) argue that the eastern China Mesozoic/Cenozoic basins cannot be used as evidence for continental extension and rifting; the basins may very well be an isostatic response<sup>[1]</sup> to the horizontally-lain dense slab materials in the transition zone.

Important points to note:

- (1) The NNE-SSW *GGL*<sup>[1]</sup> is likely a young feature as a result of Indian-Eurasian collision since the early Tertiary;
- (2) subduction-zone dehydration is necessarily incomplete<sup>[1,5]</sup> because of formation of stable hydrous phases in the subducting slabs. For example, in the subducting crust, lawsonite forms. It can contain ~ 11 wt % H<sub>2</sub>O, and is stable up to 11 GPa<sup>[6]</sup>, way deeper than expected subduction-zone dehydration. Importantly, serpentines within the subducting lithospheric mantle beneath the crust<sup>[5]</sup> contains up to 13 wt % H<sub>2</sub>O, and is stable up to 7 GPa<sup>[7]</sup> before transformed to dense hydrous magnesium silicate phases (DHMS: A, B, D-F-G) that are stable at even greater pressures (~ 5 to 50 GPa<sup>[6,8]</sup>). This allows water transport to great depths in the mantle<sup>[9]</sup>. All these hydrous phases tend to decompose and form new and less hydrous phases (e.g., Wadsleyite, < 3.0 wt% H<sub>2</sub>O, Ringwoodite, < ~ 2.2 wt% H<sub>2</sub>O, and Mg<sub>2</sub>SiO<sub>4</sub>-spinel is essentially anhydrous) as the temperature increase<sup>[1,6]</sup>. The horizontal slabs in the transition zone beneath eastern China<sup>[1,5]</sup> experience isobaric (horizontal movement) heating with time, and will thus lose water accordingly. The water so released will form hydrous melts that transport upwards to

weaken the deep portions of the lithosphere and transform them into asthenosphere – thus the process of lithosphere thinning<sup>[1]</sup>;

- (3) mantle wedge suction, while less strong than ridge suction<sup>[6]</sup>, is an important driving force for asthenospheric flow;

the suggestion of more recent lithosphere accretion is in fact a straightforward consequence of conductive cooling of the asthenospheric mantle; however, the statement that “new lithosphere replaces old lithosphere” should be avoided if it is meant to emphasize the processes or physical mechanism because it is misleading.

### References:

- [1] Niu, Y., Generation and evolution of basaltic magmas: Some basic concepts and a hypothesis for the origin of the Mesozoic-Cenozoic volcanism in eastern China, *Geol. J. China Univ.*, 11, 9-46, 2005;
- [2] Káráson, H. & R. van der Hilst, Constraints on mantle convection from seismic tomography, *Geophys. Monogr.*, 121, 277-288, 2000.
- [3] Xu, Y.-G., Thermo-tectonic destruction of the Archean lithospheric keel beneath the Sino-Korean Craton in China: Evidence, timing and mechanism, *Phys. Chem. Earth (A)*, 26, 747-757, 2001;
- [4] Yan, J., J.-F. Chen, Z. Xie & T.-X. Zhou, Mantle xenoliths in Late Cretaceous basalts in eastern Shandong: New constraints on the timing of Eastern China lithospheric thinning, *Chinese Sci. Bull.*, 8, 1570-1574, 2003.
- [5] Niu, Y., Bulk-rock major and trace element compositions of abyssal peridotites: Implications for mantle melting, melt extraction and post-melting processes beneath ocean ridges, *J. Petrol.*, 45, 2423-2458, 2004.
- [6] Williams, Q. & R.J. Hemley, Hydrogen in the deep earth, *An. Rev. Earth Planet. Sci.*, 29, 365-418, 2001.
- [7] Ulmer, P. & V. Trommsdorff, Serpentine stability to mantle depths and subduction-related magmatism, *Science*, 268, 858-861, 1995.
- [8] Frost, D.J., The stability of dense hydrous magnesium silicates in earth's transition zone and lower mantle, *Geochem. Soc. Spec. Publ.*, 6, 283-297, 1999.
- [9] Kuroda, K. & T. Irifune, Observation of phase transformations in serpentine at high pressure and high temperature by in situ X-ray diffraction measurements, *Geophys. Monogr.*, 101, 545-554, 1998.
- [10] Niu, Y. & R. Hékinian, Ridge suction drives plume-ridge interactions (Chapter 9), In *Oceanic Hotspots*, edited by R. Hékinian & P. Stoffers, Springer-Verlag, New York, p. 257-279, 2004.

## Session 2

# Geochemistry of Lithospheric Mantle: Observations and Interpretations

# **Multiple Subduction of Hydrated Oceanic Lithosphere as the Cause of the Removal of Hydroweakened Subcontinental Lithosphere under Eastern China**

Brian Windley<sup>1</sup>, Shigenori Maruyama<sup>2</sup> and Wenjiao Xiao<sup>3</sup>

*1. Dept. of Geology, University of Leicester, Leicester LE1 7RH, UK*

*Email: [brian.windley@btinternet.com](mailto:brian.windley@btinternet.com)*

*2. Dept. of Earth & Planetary Sciences, Tokyo Institute of Technology, Tokyo 152-8551, Japan;*

*3. Institute of Geology & Geophysics, Chinese Academy of Sciences, Beijing 100029, China.*

Although the case for lithospheric thinning/collapse in the Mesozoic under eastern China is established, its cause is controversial or unknown. We present a new comprehensive model that explains the thinning based on physico-chemical principles of water subduction and mantle melting, and the relevant geo-tectonics of eastern Asia. Our model has four parts:

1. The amount of water transported by subduction zones to the mantle transition zone at 660-410 km depth depends largely on the age of the subducting slab (1, 2). If the age is older than ca. 50 Ma, the hydrated water can be transported to the mantle transition zone. In the western Pacific the Pacific plate has been subducting water westwards from 150-200 Ma to the present (Ryuku trench). 90% of the world's small ocean (marginal) basins have opened in the western Pacific since the Cretaceous. Three points are important; 1. The small ocean basalts are 0.2% richer in water than normal MORB; this would lower the solidus T. by 500<sup>0</sup>C at 200 km depth (3) and only 100-200 pm addition of water decreases mantle viscosity about two orders of magnitude (1). 2. The ocean floor in the marginal basins is 600-700 m deeper than in normal Pacific ocean at a given age, suggesting a lower-T mantle than that of normal oceanic mantle. 3. The common occurrence of augite phenocrysts in basalts in the marginal basins, reflects the higher water content and lower melting T of their mantle. However, subduction by the single Pacific plate (which is a common phenomenon) cannot explain the occurrence of the marginal basins (which is unique).

The answer lies in the fact that the SW Pacific is rimmed by double subduction zones; the Pacific plate from the east, and the Indo-Australian plate from the south (2). Thus, the largest amount of oceanic slabs on Earth has been subducting in the W. Pacific in the last 150 Ma; estimated lengths of 18,000 km from the east and 12,000 km from the south (4). The oceanic lithosphere, particularly in slabs older than ca. 50 Ma, may contain substantial amounts of water not only in the top MORB crust, but also in

the underlying peridotite layer. Based on the established phase relations of the MORB + H<sub>2</sub>O and peridotite + H<sub>2</sub>O systems, subduction of old and cold oceanic lithosphere would liberate water to the mantle wedge above the subduction zone to form dense magnesian hydrosilicates. These minerals can store water and move downwards in the subducting lithosphere and are transformed to  $\beta$  and  $\gamma$ -olivines at greater depths. These high-pressure olivine phases can store up to 2 to 3 wt% of water, and normally anhydrous clinopyroxene can contain up to 3000 ppm hydroxyl. These normally anhydrous mantle phases together with possible hydrous dense magnesian silicates can store abundant water in the upper mantle. An image of a subducting oceanic lithospheric slab shows that it flattens out along the 600 km discontinuity under the W. Pacific (5). Stored water in hydrous wadslyite and ringwoodite at 660-410 km depth become unstable with time due to conductive heating from the underlying lower mantle, and eventually decompose into anhydrous phases to release free water that would create hydrous plumes and initiate mantle convection to create the marginal basins. Double subduction was the principle cause of the dynamic processes in the W. Pacific.

2. There was a tectonic and volcanic connection between the opening of the Japan Sea and the volcanicity and extension in NE and E China from ca. 86 Ma to the present (6). We can reasonably assume that the double subduction would also have transported water to the sub-continental lithosphere below eastern China. But would that have been sufficient to hydroweaken the mantle for it to collapse/thin? Given the strong possibility of a major lithospheric keel/root originally below the Archaean-Proterozoic North China craton, probably not. Evidence from orogenic belts in eastern Asia suggests that the underlying sub-continental mantle was already heavily hydrated from four subduction zones before the double subduction started. Northward subduction of oceanic lithosphere since the early Palaeozoic led to formation of the Dabie Shan suture in the Permo-Triassic, and the suture between the North and South China cratons in the early Mesozoic. Southward subduction since the early Palaeozoic led to the Solonker suture in the Permo-Triassic in Inner Mongolia (7), and the Mongol-Okhotsk suture in the Jurassic-Cretaceous in E. Mongolia-Transbaikalia of Russia (8). Making the reasonable assumption that the Palaeozoic oceanic plates were as hydrated as modern ones, an aggregate total of at least 1200 million years of subduction would have transported considerable quantities of water to the sub-continental lithosphere beneath eastern China largely in the Palaeozoic. This hydrated mantle was then re-hydrated by the double subduction from the Indo-Australian and Pacific plates. The sub-continental lithosphere below eastern China must have incorporated more oceanic slabs and been more hydrated than any other Precambrian equivalent on Earth. Probably this is why the thinning of lithosphere there is so unique.



3. Did the hydrated mantle under eastern China self-collapse or was it 'pushed'? Was eastern Asia stable/passive in the Jurassic? The four orogenic belts and their forelands underwent extensive post-collisional thrusting largely in the Jurassic. In fact, the post-collisional thrusting associated with the Solonker orogen/suture was so enormous, it led in northern China to widespread, extensive thrusting in the Jurassic, voluminous Cretaceous crustal melt granites, and Cretaceous metamorphic core complexes; the post-collisional effects were probably even more than those associated with the Cenozoic Himalaya orogen (7), which has a crustal thickness of at least 60 km caused largely by post-collisional thrusting and magmatism. And the underlying Himalayan mantle also underwent considerable thickening (9). Accordingly, we propose that the post-collisional deformation of the crust and mantle throughout eastern China acted as the trigger for the collapse of the thickened and hydro-weakened sub-continental lithosphere.

4. The sub-continental Archaean lithosphere (keel), removed by thinning, delamination, collapse or convection in the Cretaceous, was substituted largely in the Cenozoic by new asthenosphere that gave rise to Cenozoic volcanoes and lava fields of alkali basalt in eastern China.

#### **References:**

1. Komiya and Maruyama, in press. A very hydrous mantle under the W. Pacific region: implications for formation of marginal basins, and style of Archean plate tectonics, *Tectonophys.*
2. Maruyama and Okamoto, in press. Water transportation mechanism from the subducting slab into the mantle transition zone. *Tectonophys.*
3. Iwamori, 1998. Transportation of H<sub>2</sub>O and melting in subduction zones. *Earth. Planet. Sci. Lett.*, 160, 65-80.
4. Engebretson et al., 1992. 180 million years of subduction. *GSA Today*, 2, 93-95.
5. Li and Yuan, 2001. Receiver functions in NE China-implications for slab penetration into the lower mantle in NW Pacific subduction zone. *Earth Planet. Sci. Lett.* 216, 679-691.
6. Liu et al., 2001. Cenozoic episodic volcanism and continental rifting in NE China and possible link to Japan Sea development as revealed from K-Ar geochronology. *Tectonophys.*, 339, 385-401.
7. Xiao et al. (2003) Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: termination of the Central Asian orogenic belt. *Tectonics*, 22, 6, 8/1-20.
8. Tomurtogoo et al., 2005. Zircon age and occurrence of the Adaatsag ophiolite and Muron shear zone, central Mongolia: constraints on the evolution of the Mongol-Okhotsk ocean, suture and orogen. *J. Geol. Soc. Lond.*, 162, 125-134.
9. Dewey et al., 1988. The tectonic evolution of the Tibetan plateau. *Phil. Trans. R. Soc. Lond.*, 327, 379-413.

# Mapping the Lithospheric Mantle: Tomography meets Geochemistry and Geothermics

W.L. Griffin<sup>1,2</sup>, Suzanne Y. O'Reilly<sup>1</sup>, Tara Deen<sup>1</sup>, Graham Begg<sup>3</sup>  
and Yvette Poudjom Djomani<sup>1</sup>

1. GEMOC ARC Key Centre, Dept. of Earth and Planetary Sciences, Macquarie University, NSW 2109 Australia. Email: [wgriffin@els.mq.edu.au](mailto:wgriffin@els.mq.edu.au)
2. CSIRO Exploration and Mining, North Ryde, NSW 2113, Australia
3. WMC Resources Ltd., PO Box 91, Belmont, WA 6984, Australia

Xenoliths from volcanic rocks show considerable variability in the subcontinental lithospheric mantle (SCLM). It is difficult to map small- to medium-scale compositional variations in the SCLM using xenolith data: the acquisition of statistically meaningful data sets is expensive and time-consuming, even where material is available. However, considerable information can be extracted from suites of xenocrysts, which are derived from the fragmentation of mantle wall rocks. Modern analytical technology allows the rapid analysis of many compositional variables in hundreds of grains from single localities, and the determination of their stratigraphic variation.

Single-grain temperatures currently can be determined for peridotitic garnet, clinopyroxene and chromite, and each grain can be placed in a depth context by reference to a local geotherm, which can be derived either from xenolith data, or from the mineral suites themselves. These geotherms tend to follow conductive models within the lithosphere; stepped geotherms are observed in SCLM with strong lithological layering, reflecting sharp changes in thermal conductivity. The base of the lithosphere should in principle involve a decrease in geothermal gradient (approaching the asthenospheric adiabat) but commonly is marked by a rapid increase in T with depth over short distances, reflecting advective heat transport associated with volcanic eruption.

The information contained in xenocryst analyses is plotted against depth; it can be simple variables, or the relative proportions of populations derived from multivariate analysis. The latter can be ground-truthed against xenolith suites to allow the mapping of specific rock types and metasomatic processes. An inversion of the garnet-olivine thermometer allows calculation of the mg# (%Fo) of olivine that coexisted with each garnet grain, and hence the mapping of olivine composition with depth. This parameter is especially significant for the realistic interpretation of seismic and gravity data. Using these techniques, we can map significant compositional boundaries within

the upper mantle, including the lithosphere-asthenosphere boundary, as well as gradual changes in composition with depth, which may be less obvious in geophysical data sets. Comparison of SCLM sections beneath regions with crust of different tectonothermal age has demonstrated a secular evolution in SCLM composition, from highly depleted (olivine \*Fo93) in the Archean to weakly depleted (Fo90) lherzolites, essentially cooled asthenosphere, beneath Phanerozoic areas. Archean and Proterozoic SCLM is intrinsically buoyant relative to the asthenosphere, and thus cannot be "delaminated"; it persists under many areas of younger reworked crust, though it may gradually become denser (and less stable) through metasomatic refertilisation. Phanerozoic SCLM is intrinsically much denser than Archean SCLM, but much of this density difference is offset (under young mobile belts) by higher T. Increased SCLM fertility is typically associated with higher geotherms, and both effects lead to lower seismic velocity; ca 25% of the observed range in Vs and Vp is due to composition. The positive correlations between fertility, density and geotherm, and the negative correlation between density and seismic velocity in peridotites, are the keys to using combined geophysical data sets to map SCLM composition. With broad constraints imposed by our knowledge of mantle composition, Vs data can be inverted to provide maps of the regional variation in the geotherm within the lithospheric mantle. These maps can then be combined with an understanding of regional crustal history and xenolith-derived compositional data, to map compositional variation within the SCLM.

Detailed maps of SCLM variability in space and time over several continental areas show how these may be correlated with geophysical data and tectonic history. In the Siberian Craton, we map vertical translithospheric terrane boundaries, and see the erosion of the SCLM by the plume associated with the Siberian Traps. In the Slave Craton, the SCLM is strongly layered, with a marked boundary at 140-150 km. The upper layer shows strong provinciality, while the lower layer, interpreted as a subcreted plume head, is laterally homogeneous across the province. In the Kaapvaal Craton, sampling of the SCLM by several generations of kimberlite shows changes in the composition and thermal state of the SCLM through time, and lateral variations that correlate with seismic tomography.

The current vertical resolution of these methods, constrained by thermometry uncertainties, is 5-10 km. The lateral resolution has, until now, been limited by volcano spacing. However, the ability to correlate SCLM composition with geophysical data (especially seismic properties) means that the mapping of compositional variability in the SCLM will improve to whatever resolution can be provided by better seismic data.

# The persistent myth of lithosphere melting

Nicholas Arndt

*LGCA, University Joseph Fourier, 38041 Grenoble, France*

*Email: [arndt@ujf-grenoble.fr](mailto:arndt@ujf-grenoble.fr)*

It is common to find references in the literature to the hypothesis that the sub-continental lithospheric mantle partially melts to form continental flood basalts and other large-volume magmas. The arguments used to defend the hypothesis are mainly negative: commonly, chemical criteria or geochemical modelling are used to test whether the magma being studied could have formed through crustal contamination or derivation from a plume, and when the magma is deemed to have failed the tests, the source is assumed, by default, to be the lithosphere. In this approach, the geochemists' definition of the lithosphere is used: "that part of the mantle with a composition appropriate for the source of the magmas being studied".

Although some relatively rare and unusual magmas such as lamprophyres may indeed come from the lithosphere, the following arguments indicate that voluminous and common mafic magmas come from a sub-lithosphere source, either a plume or upwelling asthenosphere.

1. The lithosphere is the coldest part of the mantle and it will only melt, in preference to hotter, deeper sources, if its melting temperature is lower than that of the deeper sources. Gallagher and Hawkesworth (1992) argue that metasomatised lithosphere containing significant water melts in preference to an anhydrous deep source. However, in many places where magmas from various mantle depths have erupted together, those from deeper sources contain higher volatile contents; the deep sources evidently were "wetter" than those at shallower, near-lithosphere depths.

2. The "crustal" geochemical signature found commonly in continental flood basalts (negative Nb-Ta anomalies, high  $^{87}\text{Sr}/^{86}\text{Sr}$  and low  $^{143}\text{Nd}/^{144}\text{Nd}$ ) is readily explained by assimilation of continental crust. This signature is largely absent in xenoliths from the sub-continental lithospheric mantle. Most do not have Nb-Ta anomalies and in those that do have coupled negative Nb-Ta and Zr-Hf anomalies, a feature absent from flood basalts. The coupled anomalies is attributable to carbonatite metasomatism, a process that affected the lithospheric mantle but not the source of the basalts.

3. It is commonly stated that crustal contamination produces heterogeneous magmas and that only the lithosphere yields homogeneous melt. In fact, most continental flood basalts have evolved, remarkably uniform compositions that coincide with crustal-level equilibration with ol, cpx and plag. These magmas assimilated crustal wall rocks and were homogenized in large crustal magma chambers. In contrast, the

sub-continental lithosphere probably is highly heterogeneous and yields magmas with a wide range of compositions.

High contents of platinum-group elements in continental flood basalts indicate that they formed by high-degree melting that eliminated sulfide from the residue of melting. High-degree melting is unlikely in a cold lithospheric source.

## **Age of the Lithospheric mantle beneath eastern North China Craton**

Fu-Yuan Wu, Jin-Hui Yang

*Institute of Geology and Geophysics, Chinese Academy of Sciences, 100029 Beijing,*

*China. Email: [wufuyuan@mail.igcas.ac.cn](mailto:wufuyuan@mail.igcas.ac.cn)*

Recent studies of eastern North China Craton (NCC) have suggested that a significant portion of the original subcontinental lithospheric mantle (SCLM) underlying Archean cratons was removed subsequent to the early Paleozoic. Several important questions, however, are still remained unsolved: (1) when did this removal take place? (2) how was it developed? and (3) what was it controlled? It is obvious that the age of the lithospheric mantle is vital for us to solve above questions.

From the comparisons of Sr-Nd isotopes and mineral compositions of the mantle xenoliths hosted in the Cenozoic basalts, it is concluded that the present lithospheric mantle beneath eastern NCC is juvenile. Archean Os model ages of the mantle xenoliths from Fuxian kimberlite strongly suggested that at least some portions of the SCLM underlying the NCC were Archean in the early Paleozoic (Gao et al., 2002), the refractory mantle xenoliths from Cenozoic basalts, however, did not provide any sign of Archean Os model melt extraction ages (Gao et al., 2002; Wu et al., 2003, 2005). Therefore, the original Archean SCLM was totally lost during the above lithospheric thinning.

## **Contrasting effects of melt percolation on Re-Os and sulfur systematics of the lithosphere beneath the Subei basin, China**

<sup>1</sup>Reisberg L., <sup>2</sup>Zhi X., <sup>3</sup>Lorand J-P., <sup>4</sup>Wagner C., <sup>2</sup>Peng Z. and <sup>1</sup>Zimmermann, C.

1) CRPG/CNRS, BP 20, 54501 Vandoeuvre-les-Nancy Cedex, France.

Email: [reisberg@crpg.cnrs-nancy.fr](mailto:reisberg@crpg.cnrs-nancy.fr)

2) School of Earth and Space Sciences, USTC, Hefei 230026, P.R. China;

3) CNRS UMR 7160 and MNHN, USM 201, CP 52, 61 Rue Buffon, 75005 Paris, France;

4) CNRS UMR 7160 and PMMP, Université Paris 6, Boite 110, 4, Place Jussieu, 75252 Paris Cedex 05, France

Ultramafic xenoliths carried by alkali basalts and kimberlites have provided most of our knowledge about the chemical composition of the subcontinental mantle lithosphere. Nevertheless, there is increasing evidence that many such xenoliths have been profoundly modified by melt and/or fluid percolation. Isotopic evidence suggests that this percolation was often fairly recent, and thus probably related to the tectonic processes, such as lithospheric thinning, that allow xenoliths to be brought to the surface. Siderophile and chalcophile element abundances are particularly sensitive tracers of melt percolation in mantle peridotites. Ultramafic xenoliths carried by Cenozoic alkali basalts of the Subei Basin, eastern central China, provide a striking example of the contrasting effects that melt percolation may produce. We investigated two volcanic centers from this region, Lianshan and Panshishan, both located in Jiangsu Province. These areas, separated by only six kilometers, have similar textures and major and moderately incompatible lithophile trace element compositions. In addition, the Os isotopic ratios of these two areas plot on the same trend relating  $^{187}\text{Os}/^{188}\text{Os}$  to indices of melt extraction such as whole rock Yb content. These Os isotopic systematics suggest that both areas were affected by a lower Proterozoic (~ 1.8 Ga) melt extraction event. Thus the two areas apparently shared the same long term lithospheric history. Nevertheless, sulfide abundances and whole rock S, Os and Re concentrations are much lower in Lianshan than in Panshishan, and the two localities have different incompatible lithophile trace element signatures. In Lianshan, lherzolite REE patterns are flat to moderately LREE depleted, but lack a systematic relationship with bulk rock chemistry, indicating that these patterns do not simply reflect varying degrees of partial melt extraction. Instead a strong correlation between La/Sm and CaO/Al<sub>2</sub>O<sub>3</sub> is observed. In Panshishan the patterns are flat to moderately LREE enriched, and no relationship exists between La/Sm and CaO/Al<sub>2</sub>O<sub>3</sub>. These differences may be explained by contrasting melt percolation styles between the two areas. Lianshan was affected by

extensive percolation of LREE enriched, sulfur undersaturated melts that removed Re, Os and S, while leaving clinopyroxene. Panshishan experienced interaction with highly evolved melts or fluids that added LREE as well as Re, Cu and S, but had no effect on Os abundances. The lack of correlation between  $^{187}\text{Os}/^{188}\text{Os}$  and  $^{187}\text{Re}/^{188}\text{Os}$ , compared with the good correlation between  $^{187}\text{Os}/^{188}\text{Os}$  and Yb, indicates that the perturbation of the Re and Os concentrations must have been fairly recent, and perhaps related to Mesozoic or Cenozoic lithospheric thinning in eastern China.

The Lianshan Os concentrations are typical of those of off-cratonic mantle xenoliths, while the Panshishan Os concentrations are closer to those of most abyssal and orogenic peridotites. This suggests that the low Os concentrations, and by extension, the low concentrations of all of the highly siderophile elements (HSE) typically observed in alkali basalt borne mantle xenoliths, may result from recent melt percolation processes, probably directly or indirectly related to the magmatism that brought the xenoliths to the surface. Thus ultramafic xenoliths may not provide reliable estimates of the HSE contents of the upper mantle, and variations in HSE abundances between xenolith localities should not be used to define global scale processes. On the other hand, Os and other HSE abundances may prove to be sensitive indicators of melt percolation, and may provide information about the degree of sulfur saturation of the melts. Finally, the resistance of the Os isotopic ratios of most samples to modification during recent melt percolation confirms the utility of this system for dating ancient melt extraction events.



## Re-Os isotopes in mantle xenoliths from SE China: age constraints and evolution of lithospheric mantle

Xisheng Xu<sup>1,2</sup>, W. L. Griffin<sup>2</sup>, S.Y. O'Reilly<sup>2</sup> and N. J. Pearson<sup>2</sup>

<sup>1</sup> State Key Laboratory for Mineral Deposits Research, Department of Earth Sciences, Nanjing University, Nanjing 210093, China. Email: [xsxu@nju.edu.cn](mailto:xsxu@nju.edu.cn)

<sup>2</sup> ARC National Key Centre for the Geochemical Evolution and Metallogeny of Continents, Macquarie University, NSW 2109, Australia

*In situ* (LAM-MC-ICPMS) Re-Os isotopic data have been obtained from sulfides in mantle xenoliths from 7 localities in SE China. These data place constraints on the age of the lithosphere and reveal profound changes in the nature of the deep lithosphere.

The present-day Os isotopic compositions of sulfide in the studied peridotites vary over a wide range. Os contents of the sulfides vary from 0.6 to 235 ppm; these values are much higher than Os contents of whole-rock peridotites from eastern China, and reflect the concentration of PGE in mantle sulfides. Re/Os ranges from 0.001 to 0.422 (median 0.081). <sup>187</sup>Re/<sup>188</sup>Os ranges from 0.029 to 1.987, but most are subchondritic (< 0.401). <sup>187</sup>Os/<sup>188</sup>Os ranges from 0.1098 to 0.1691; most samples are subchondritic, having ratios < 0.127.

Samples from the 7 localities give a wide range of T<sub>RD</sub> and T<sub>MA</sub> model ages. Samples with higher <sup>187</sup>Re/<sup>188</sup>Os and higher <sup>187</sup>Os/<sup>188</sup>Os than modern chondritic averages give future T<sub>RD</sub> ages, and reflect the mobility of Re and Os in the lithospheric mantle ("Re addition").

Some sulfides enclosed in olivine show late Proterozoic to mid-Proterozoic T<sub>RD</sub> ages but T<sub>MA</sub> ages ranging from late Archean to mid-Archean. Three such sulfides show Paleoproterozoic T<sub>RD</sub> and T<sub>MA</sub> ages. Two enclosed sulfides give minimum ages (T<sub>RD</sub>) that are mid-Proterozoic, and give T<sub>MA</sub> ages that are also mid-Proterozoic. However, in the same samples interstitial sulfides may show Paleozoic or even Mesozoic T<sub>RD</sub> and T<sub>MA</sub> ages.

Nd model ages of granites, and Hf isotope data for zircons of granites in SE China, indicate three major periods of Precambrian crustal growth, in late Archean (~2.5-2.7 Ga), Paleoproterozoic (~1.8 Ga) and early Mesoproterozoic (1.3-1.5 Ga) time. Other major events include Paleozoic to Mesozoic and Cenozoic mafic and felsic magmatism. The *in situ* Os isotope data indicate that these same events are recorded by different generations of sulfides in the peridotite xenoliths. This observation implies that sulfide-bearing melts or fluids moved through the lithospheric mantle, and were trapped in the peridotites, during each of these major crustal events.

# **Nd-Sr isotopic compositions of the Hannuoba peridotite xenoliths beneath the North China Craton: implications for mantle enrichment process**

Masako Yoshikawa<sup>1</sup>, Xiachen Zhi<sup>2</sup> and Katsuhiko Suzuki<sup>3</sup>

1. *Beppu Geothermal Research Laboratory, Institute for Geothermal Sciences Graduate School of Science, Kyoto University, Noguchibaru, Beppu, 874-0903 Japan.*

*Email: [masako@bep.vgs.kyoto-u.ac.jp](mailto:masako@bep.vgs.kyoto-u.ac.jp)*

2. *Division of Geochemistry, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui Province, 230026, P.R. CHINA*

3. *Institute for Research on Earth Evolution (IFREEE), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Natsushima, Yokosuka, 237-0061 Japan*

In order to understand evolution of subcontinental lithospheric mantle (SCLM) beneath the north China, we determined Sr and Nd isotopic compositions of the mantle-derived xenoliths in Cenozoic alkali basalts from Hannuoba. Our 4 acid-leached clinopyroxene separates yield narrow ranges of both  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios (0.51304 - 0.51329 and 0.7026 - 0.7032, respectively). These data are within the previously reported variation (e.g. Song and Frey 1989; Tatsumoto et al., 1992; Rudnick et al, 2004).

Song and Frey (1989) divided the six Hannuoba peridotite xenoliths into three types, that is, depleted, PREMA and LoNd-like mantle types based on Sr and Nd isotopic compositions of distinct mantle components (Zindler and Hart, 1986). The data of three samples (P15, P16 and P17) obtained in the present study overlap with those of the depleted mantle type and that of sample P12 is plotted on the PREMA mantle type.

The samples P12 and P17 are plotted on reference isochron of 1.9 Ga in the  $^{147}\text{Sm}/^{144}\text{Nd}$  -  $^{143}\text{Nd}/^{144}\text{Nd}$  diagram. This age is the Re-Os isochron age of peridotite xenoliths, which was interpreted as the formation age of the present lithospheric mantle beneath Hannuoba through replacement of Archean SCLM (Gao et al., 2002). On the other hand, the samples P15 and P16 are consistent with reference isochron of around 1.1 Ga. Song and Frey (1989) suggested that LREE enrichment of LoNd-like type xenoliths had occurred at 1.1 Ga ago based on the Sm-Nd reference isochron of their samples. The Sm-Nd systematics of the clinopyroxene separates possibly support the scenario that Archean SCLM under the Central Orogenic Belt/Trans-North China orogen (e.g. Zhao et al., 2000) of the North China Craton were replaced by younger Proterozoic lithospheric mantle as suggested by Gao et al. (2002).

According to the contents of heavy rare earth elements (HREE)(Zhi, unpublished data), the xenoliths were divided into three groups. The samples P12 and P17, which have relatively enriched Sr isotopic signature, belong to  $(\text{HREE})_{\text{N}} < 10$  group (the subscript N indicates a chondrite-normalized value). On the other hand, the samples P15 and P16 are in  $(\text{HREE})_{\text{N}} > 10$  group. The samples with relatively high REE contents and relatively low Sr isotopic compositions possibly preserve the primary Nd isotopic compositions. In this case, the reference isochron of 1.9Ga could represent a mixing line between ancient (around 1.9Ga) depleted mantle and enriched component.

# **Evidence for subduction-related components in the subcontinental mantle from noble gas isotopic compositions in mantle xenoliths from Far Eastern Russia**

Junji Yamamoto<sup>a</sup>, Ichiro Kaneoka<sup>b</sup>, Shun'ichi Nakai<sup>b</sup>, Hiroyuki Kagi<sup>c</sup>,  
Vladimir S. Prikhod'ko<sup>d</sup> & Shoji Arai<sup>e</sup>

*a* Institute for Geothermal Sciences, Kyoto University, Noguchibaru, Beppu, Oita-pref.  
874-0903, Japan. Email: [jyama@bep.vgs.kyoto-u.ac.jp](mailto:jyama@bep.vgs.kyoto-u.ac.jp)

*b* Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032,  
Japan

*c* Laboratory for Earthquake Chemistry, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo  
113-0033, Japan

*d* Institute of Tectonics and Geophysics (Far-Eastern Branch, Russian Academy of Sciences), 65  
Kim Yu Chen Str., Khabarovsk 680063, Russia

*e* Department of Earth Sciences, Faculty of Science, Kanazawa University, Kakuma, Kanazawa  
920-1192, Japan

To obtain geochemical influences of subducted components on the subcontinental lithospheric mantle, we have analysed noble gas isotopic compositions of subcontinental mantle-derived xenoliths from Far Eastern Russia. In the Far Eastern Russia area, oceanic crusts have been subducted underneath the Eurasian plate since about 100 Ma. Hence, the mantle beneath Far Eastern Russia had been influenced by the components derived from the subducted crustal materials.

By applying both vacuum crushing and stepwise heating methods for the extraction of noble gases, we have discovered  $^3\text{He}/^4\text{He}$  ratios much lower than the atmospheric ratio ( $\sim 0.3R_A$ ;  $R_A$  is the atmospheric  $^3\text{He}/^4\text{He}$  ratio of  $1.4 \times 10^{-6}$ ) and relatively low  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios ( $< 1000$ ) in olivine separates from some subcontinental mantle-derived xenoliths from Far Eastern Russia. Olivine is relatively retentive for helium, and in-situ addition of radiogenic  $^4\text{He}$  generated from U and Th is considered to be quite small due to their very low contents in olivine. Further, the crushing method is thought to be effective in extracting noble gases trapped in liquid inclusions or shrinkage bubbles in melt inclusions, which contain little in-situ generated nuclides. Therefore, the low  $^3\text{He}/^4\text{He}$  ratios cannot be explained by the addition of radiogenic  $^4\text{He}$  generated in-situ after the eruption of magma entraining the xenoliths.

Spectroscopic and petrographic observations confirm that there are at least two compositionally distinct fluids in these xenoliths; liquid  $\text{CO}_2$  inclusions and melt inclusions with shrinkage bubbles. Based on the crushing experiments, it is inferred that

the inclusions of liquid CO<sub>2</sub> have a high <sup>3</sup>He/<sup>4</sup>He ratio similar to that of MORB, and the component with the low <sup>3</sup>He/<sup>4</sup>He ratio is derived from the shrinkage bubbles in the melt inclusions.

For the present samples, the <sup>40</sup>Ar/<sup>36</sup>Ar ratios obtained by crushing were less than 1000, suggesting incorporation of atmospheric components in the source materials. Since low <sup>40</sup>Ar/<sup>36</sup>Ar ratios were observed irrespective of the occurrence of the CO<sub>2</sub> inclusions, the atmospheric component exists in the melt inclusions.

Since the Far Eastern Russia area was located at a subduction zone in the Jurassic-early Cretaceous Period, it is most likely that the melt inclusions displaying atmospheric noble gas characteristics together with low <sup>3</sup>He/<sup>4</sup>He ratios have been derived from the old subducted slab. On the other hand, <sup>3</sup>He/<sup>4</sup>He ratios observed in the CO<sub>2</sub> inclusions, which are similar to the MORB-like value, might reflect the general character of the upper mantle. The Far Eastern Russian mantle may therefore be a MORB-like source that has been partly infiltrated by subduction-related fluids.

## **Noble gas signatures in the ultramafic xenoliths from NE China: MORB-like and metasomated reservoirs in the subcontinental mantle**

Yong Lai, Yulin Liu, Baolin Huang and Yanjing Chen

*School of Earth and Space Sciences, Peking University, Beijing 100871, China*

*Email: [yonglai@pku.edu.cn](mailto:yonglai@pku.edu.cn)*

Noble gas abundances and isotopic compositions in mantle-derived xenoliths were analyzed by crushing method, which from Wudalianchi, Heilongjiang Province, Kuandian of Liaoning Province, Northeastern China. Compared with the MORB and other subcontinental areas,  $^3\text{He}/^4\text{He}$  ratios in the samples from Wudalianchi vary between 4.5-5.3RA, obviously lower than that of the MORB, and  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios change from 557 to 4005. On the other hand, the samples from Kuandian show a MORB-like  $^3\text{He}/^4\text{He}$  ratio (7.30-7.52RA), with  $^{40}\text{Ar}/^{36}\text{Ar}$  ratio of 1496-7677. Both areas show Ne-Kr-Xe isotopic ratios equivalent to those of atmosphere. Comparing the characteristics of noble gases with evidences from published Sr-Nd isotope data and alkali basalt petrology, it was estimated that there was a palaeo-subduction event took place in Wudalianchi area, and the upper mantle was metasomated by subducted atmospheric component, and caused forming phlogopite-bearing lherzolite. Meanwhile, there is a MORB reservoir-like mantle beneath Kuandian area. These results indicate the heterogeneity of subcontinental lithospheric mantle beneath northeastern China.

## **Mineral chemistry of garnet peridotites from Paleozoic and Cenozoic lithosphere and Mesozoic UHP terrain: constraints on lithospheric evolution, east China**

J. P. Zheng<sup>1</sup>, W. L. Griffin<sup>2,3</sup>, R. Y. Zhang<sup>4</sup>, S. Y. O'Reilly<sup>2</sup> and J. G. Liou<sup>4</sup>

*1. State Key Laboratory of Geological Processes and Mineral Resources, Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074, China*

*2. GEMOC ARC National Key Centre, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia*

*3. CSIRO Exploration and Mining, P. O. Box 136, NSW 1067, Australia*

*4. Department of Geological and Environmental Sciences, Stanford University, CA 94305, USA*

Major- and trace element data on the minerals of garnet peridotite xenoliths from early Paleozoic (457-500 Ma) and Neogene (16-18 Ma) volcanics within the North China Craton are compared with those from the tectonically exhumed Triassic Sulu ultra-high pressure (UHP) terrain along its southern margin. *P-T* estimates for the Paleozoic and Neogene garnet peridotite xenoliths reflect different geotherms corresponding to model surface heat flow of ~ 40 mW/m<sup>2</sup> (Paleozoic) and ~ 80 mW/m<sup>2</sup> (Neogene). Paleozoic peridotite xenoliths are compositionally major element depleted similar to peridotites from other areas of cratonic mantle; they have low Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> contents, magnesian olivine (mean Fo<sub>92.7</sub>), Cr-rich garnet (mean Cr<sup>#</sup> = 27.6), and high Ni and La/Yb in diopside. Neogene garnet peridotite xenoliths are derived from fertile mantle, and have high Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> contents, low-Mg olivine (mean Fo<sub>89.5</sub>), low-Cr garnet (mean Cr<sup>#</sup> = 3.5), and diopside with flat REE patterns. The differences between the Paleozoic and Neogene xenoliths suggest that the buoyant refractory lithospheric keel presented beneath the eastern North China Craton in Paleozoic time was largely replaced by younger, hotter and more fertile lithospheric mantle during late Paleozoic-Paleogene time. The Sulu UHP peridotites have slightly lower Mg<sup>#</sup> in olivine (91.5±1.0) and garnet (73.2-82.0), Cr<sup>#</sup> in garnet (1.9-18.3), and Al<sub>2</sub>O<sub>3</sub> in enstatite (0.15-0.34) than the Paleozoic xenoliths. The diopsides have very low HREE contents and display sinusoidal to LREE-enriched patterns and negative Nb, Zr and Ti anomalies. The garnets have low REE contents and strongly negative Ce anomalies ( $\delta\text{Ce} = 0.24\text{-}0.56$ ). The UHP peridotites are interpreted as having evolved from protoliths similar to the Paleozoic xenoliths, through interaction with crustally-derived melt/fluids, as both the crustal and the mantle components were being pushed down further into the mantle during UHP metamorphism. Exhumation of the Sulu UHP rocks was accompanied by an extensional regime responsible for the upwelling of asthenosphere. Peridotites sampled by Neogene basalts represent the newly accreted lithosphere derived from cooling of the upwelling asthenospheric mantle in Jurassic-Cretaceous and Paleogene time.

## **Nature and evolution of Late Mesozoic lithospheric mantle beneath the North China Craton: evidence from mantle xenoliths in Junan Cretaceous volcanic breccia**

Jifeng Ying, Hongfu Zhang, Yanjie Tang, Jin Zhang

*State key Laboratory of Lithosphere Tectonic Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, Email: [jfying@mail.igcas.ac.cn](mailto:jfying@mail.igcas.ac.cn)*

North China Craton (NCC) is an Archean craton with crustal remnants as old as 3.8 Ga. Taking into account the well-accepted model that the Archean craton is underlain by thick, cold and refractory lithospheric mantle, the lithospheric mantle beneath the NCC should also be thick, cold and refractory. This was a case for the NCC prior to the Paleozoic as indicated by the occurrence of Ordovician diamondiferous kimberlites and their borne xenoliths and xenocrysts. However, widespread basalts and their entrained xenoliths suggest the presence of thin (<80km), hot and fertile mantle in the Cenozoic. This required a dramatic change in the lithospheric architecture during the Phanerozoic. Although this lithospheric removal is well-accepted, the timing and mechanism responsible for such a change still remain unsolved.

Recently, newly-discovered mantle xenoliths entrained in Junan basaltic breccia, Shandong province provide some petrological and geochemical constraints on the lithospheric evolution. The basaltic rocks intruded porphyritic syenite at 67 Ma and contain mantle and lower crustal xenoliths, including peridotites, pyroxenites, granulites. Peridotitic xenoliths have two types, of which type 1 is mainly spinel lherzolites with coarse-grained texture. Major and trace element geochemistry and estimated T-P conditions are similar to those of lherzolite xenoliths entrained in the Cenozoic basalts, eastern China. Type 2 xenoliths are still spinel lherzolites, but have geochemical features similar to those of xenoliths from Archean lithospheric mantle, including much higher  $Mg^{\#}$  and lower MnO in olivine, convex-upward REE pattern in cpx and higher pressure. We proposed that the high  $Mg^{\#}$  xenoliths represent the relics of old lithospheric mantle and the low  $Mg^{\#}$ , i.e. type 1 xenoliths the newly-accreted lithospheric mantle in late Cretaceous. Contrasting elemental and geochemical features of two type xenoliths suggest that they recorded different geotherms. The high  $Mg^{\#}$  xenoliths might originate from garnet stability field and re-equilibrate to spinel facies mantle where they were entrained due to the Mesozoic extension in eastern China.

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## **Origin of the Mesozoic magmatism in the north China craton: constraints from SHRIMP U-Pb zircon ages and geochemical data**

Bin CHEN<sup>1,3</sup>, Mingguo ZHAI<sup>2</sup>, Yoji ARAKAWA<sup>3</sup>

*1 School of Earth and Space, Peking University, Beijing 100871, China*

*E-mail: [binchen@pku.edu.cn](mailto:binchen@pku.edu.cn)*

*2 Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China*

*3 Institute of Geosciences, Tsukuba University, Ibaraki-ken 305-8572, Japan*

The Mesozoic rocks from eastern North China craton (NCC) range in composition from gabbroic to monzogranitic, showing high-K calc-alkaline to shoshonitic affinity, high Sr-Ba and high Sr/Y, La/Yb, and highly enriched Sr-Nd isotopic compositions. SHRIMP zircon dating for rocks from Taihang-Yanshan, westernmost NCC, yields ages of 138-129 Ma, which, along with published ages for rocks from other parts of eastern East Asia, reveal a northwestward younging trend of calc-alkaline magmatism from Japan and Korea, through Jiaodong, to Taihang-Yanshan. This suggests genesis of the Mesozoic rocks in the NCC was linked to the subduction of the paleo-Pacific plate, rather than to the Triassic collision between the Yangtze block and NCC. Moreover, they probably originated from mixing between mafic magmas from enriched mantle sources and crust-derived granitic melts, followed by fractionation, rather than from melting of mafic lower crust as previously suggested by many others.



## Session 3

# Crustal Geochemistry & Tectonics: Observations and Interpretations

# The Differentiation and Rates of Generation of the Continental Crust

Chris Hawkesworth and Tony Kemp

*University of Bristol, UK. Email: [c.j.hawkesworth@bristol.ac.uk](mailto:c.j.hawkesworth@bristol.ac.uk)*

A complete picture of crustal evolution involves integration of the different records preserved in sedimentary and igneous rocks, and Hf and O isotopes in detrital and inherited zircons offer a unique way to do this. (i) The igneous record preserves the ages of the specific events in which new continental crust was generated. (ii) The sedimentary record comprises mixtures of material from different sources, and so it is a record of the average composition of the upper crust at different times, rather than of specific periods of crustal growth. (iii) Zircons offer the most representative record of the geological history of the crust because they are common in the rocks of the upper crust, they are very robust, and they crystallised from magmas that were themselves derived from sedimentary or igneous source rocks.

New data on zircons from the Lachlan Fold Belt in SE Australia have established major magmatic episodes at ~ 500 and 1000 Ma, but these did not involve the generation of new crust. The Hf model ages reflect the time when new continental crust was generated, and the zircons from magmas from igneous and sedimentary rocks (low and high  $^{18}\text{O}$  respectively) yield different Hf model ages. The zircons from magmas from igneous sources have Hf model ages indicating periods of new crustal growth at 1.6 and 2.7 Ga. In contrast, the zircons from magmas from sedimentary source rocks have Hf model ages peaking at 1.7-1.8 Ga, and so they represent mixtures of rocks generated at 1.6 and 2.7 Ga. The separate records from igneous and sedimentary rocks provide the basis for models of crust generation (e.g. the extent that it is episodic and so reflects deep seated mantle disturbances) and evolution - both in terms of the rates at which pre-existing crust is processed by later igneous events, and by erosion and sedimentation, and how those changed with time.

Finally we explore a different approach to evaluate the rates of crust generation, and hence the quantities of incompatible elements processed through the continental crust over the last 4 Ga. Average new crust is modelled as a 9:1 mixture of subduction-related and intraplate magmas, and the median composition of granitic magmas with  $\text{Eu}/\text{Eu}^* = 0.7$  is strikingly similar to that of the average upper crust. In the simplest model the upper crust represents ~14% melting, or 86% fractional crystallisation, and for a 12.5 km upper crust there would be 77 km of residual material. Thus, the residence times of elements in the lower crust is much less than in the upper crust. The average rates of crust generation are inferred to have been in excess of six times those in the recent geologic past, and over 4 Ga more than half the K, and one quarter of the Li in the silicate Earth may therefore have been processed through the continental crust.

## **Contrasting zircon Hf and O isotope signatures in the two episodes of bimodal magmatism during the Neoproterozoic superplume event**

Yong-Fei ZHENG, Yuan-Bao WU and Shao-Bing ZHANG

*School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China, Email: [yfzheng@ustc.edu.cn](mailto:yfzheng@ustc.edu.cn)*

Temporal relationship between juvenile crust growth and water-rock interaction is an important issue with respect to the mass and heat transfer between mantle and crust during a superplume event. A combined study of Hf and O isotopes in zircons from mid-Neoproterozoic bimodal intrusives in South China provides evidence for the occurrence of plume-triggered magmatism and its related surface fluid activity along rift tectonic zones. Two generations of bimodal magmatism show contrasting features in both zircon Hf and O isotope compositions. The ca.825 Ma granitoids principally exhibit neutral to weakly negative  $\epsilon_{\text{Hf}}(t)$  values of  $0.1 \pm 0.7$  to  $-4.4 \pm 1.9$  with the old Hf model ages of  $1795 \pm 76$  to  $1987 \pm 89$  Ma, and high  $\delta^{18}\text{O}$  values of 8.67 to 10.42‰ with disequilibrium fractionations between some of minerals. These indicate that the source material of granitoid magmas was derived from remelting of Paleoproterozoic basement that possesses the geochemical nature of enriched mantle and experienced chemical weathering cycling before the remelting, with overprinting of subsolidus hydrothermal alteration during magma emplacement. In contrast, the ca. 750-760 Ma bimodal intrusives are characterized by positive  $\epsilon_{\text{Hf}}(t)$  values of  $3.3 \pm 0.4$  to  $9.3 \pm 0.7$  with young Hf model ages of  $954 \pm 31$  to  $1190 \pm 31$  Ma, and both low and high  $\delta^{18}\text{O}$  values of 4.20 to 6.23‰ relative to the normal mantle zircon. Contributions of depleted mantle to their magma sources are different in amount from the two episodes of crust-mantle mixing at ca. 825 Ma and ca.750 Ma, respectively, with high-T water-rock interaction and local low- $^{18}\text{O}$  magmatism along the tectonic zones of progressively developed rift. The present study demonstrates the considerable growth of juvenile crust during the mid-Neoproterozoic superplume event and thus the significant transport of both heat and material from the depleted mantle to the continental crust along the rifted margins in association with the supercontinent breakup. The Neoproterozoic superplume may begin at a thermal boundary layer at the base of the upper mantle rather than at the core-mantle boundary.

# **Magmatic Evidence for Processes controlling Neogene Crustal and Mantle Lithospheric Evolution of the Central and Southern Andes**

Suzanne Mahlburg Kay

*Dept. of Earth and Atmospheric Sciences and INSTOC, Cornell University, Ithaca, NY 14853;*

*Email: [smk16@cornell.edu](mailto:smk16@cornell.edu).*

The Andean margin is a major site for creation, modification and destruction of post-Archean continental crust and mantle lithosphere. Creation processes include additions associated with arc and intraplate magmatism. Removal can occur by continental lithospheric thinning in association with shallow subduction, lithospheric “delamination” in which thickened eclogite-facies continental crust along with the underlying lithosphere is removed, forearc subduction erosion, and thermal thinning in response to mantle thermal anomalies residual to continental breakup. Evidence for modification and loss comes from four major settings: shallow subduction zones, steepening subduction zones, parts of the margin where the frontal arc has been displaced eastward, and the Patagonian backarc mafic volcanic province. The magnitudes of gain and loss have implications for crustal and mantle recycling rates and calculations of continental crustal growth rates.

Perhaps the site of greatest continental lithosphere loss occurs above shallowly dipping or nearly horizontal segments of a subducting oceanic plate. These zones have occurred repeatedly at various places along the Andean margin for at least the last 30 Ma. Importantly, the current subduction angle of the Nazca plate, which has a maximum near 30°, is among the shallowest of circum-Pacific slabs. The best studied modern segment with an extreme shallow dip is the Chilean flat-slab region between 28°S and 33°S. Estimates near 30°S latitude suggest that up to 70% of the basal continental lithosphere in a 400 km long east-west cross-section has been lost in the last ~ 18 Ma, most of this in the last 9 Ma. This loss cannot be attributed to thermal thinning as it is associated with cooling of the mantle wedge above a shallowing slab and a thickening crust. Magmas erupted up to 700 km east of the trench could contain lithospheric components incorporated into the asthenospheric wedge further west. Greater amounts of lithospheric loss must have occurred over the wider modern shallowly subducting segment of the Nazca plate under Peru from 3°S to 15°S where the shallow part of the slab extends more than 300 km east-west and 1000 km north-south. Elsewhere along the margin, magmatic and tectonic histories provide evidence for transient shallowly dipping segments under the Altiplano north of 21°S

during the Oligocene, under the northern Puna between 24°S and 21°S in the early to mid Miocene, and in the south-central Andes between 35°S and 37.5°S during the mid to late Miocene,

An important stage in continental lithospheric modification occurs when these shallow subduction zones steepen. The effects depend on the preexisting state of stress and lithology of the overlying crust and lithosphere. Steepening of the early to mid Miocene shallow subduction zone under the northern Puna led to widespread crustal melting resulting from heating by intrusion of mafic magmas formed in the mantle wedge above the steepening subduction zone. Current models suggest that dense eclogitic crust along with the underlying lithosphere delaminated as the slab was steepening; large ignimbrites erupted as the crust collapsed horizontally under contractional stress. Ongoing contraction has led to the rethickening of this lithosphere. A similar scenario for delamination of a dense crustal root along with the underlying mantle was proposed in the southern Puna. This delamination event is thought to have followed a transient subducted episode of mid to late Miocene shallow subduction and to have led to eruption of intraplate and arc-like mafic magmas along transpressional and normal faults, and voluminous silicic ignimbrites. The removal of over-thickened basal crust and lithosphere is also reflected by high topography, changes in the crustal deformational regime, and geophysical evidence for a thin lithosphere. Evidence for melting of eclogitic lower crust comes from glassy dacitic flows with La/Yb ratios up to 100 and  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7098$ . Further south, Pliocene to Holocene steepening of the shallow subduction zone under the south central Andes has been associated with eruption of large volumes of mafic plateau lavas with intraplate chemical signatures. The lack of associated large siliceous ignimbrites can be attributed to a lower crust that was depleted in its low temperature melting fraction by a Mesozoic granite-rhyolite event and to a mildly extensional stress regime.

Another major process of continental lithospheric modification and loss is thought to be maximized during transient peaks of forearc subduction erosion at times of frontal arc migration. Up to 50 km of eastward arc migration near 26°S-28°S latitude at 8 to 3 Ma, and 85 km of eastward motion near 33°S- 34°S reflecting two stages at 20 to 16 Ma and 8 to 3 Ma latitude are consistent with loss of forearc crust/ lithosphere by forearc subduction erosion. Evidence for crust entering the mantle wedge comes from transient steep REE patterns, high Sr and Na contents, and 'enriched isotopic signatures' in arc magmas. Support comes from both mafic and silicic magmas. High La/Ta ratios reflect oxidizing, hydrous conditions above the shallowing slab. Transient steep REE patterns can be associated with tectonically removed forearc crust that was subjected to high pressure metamorphism and partially melted as it entered and mixed

into the mantle wedge. Estimates of crustal and lithospheric loss suggest that ~ 95% or more of the crust and mantle removed could be recycled into the mantle.

Another region of continental lithospheric modification associated with widespread intraplate magmatism is in the Patagonia backarc of the southern Andes. This is an area where large volumes of mafic retroarc magmas not associated with major extension have erupted ever since the beginning of the Mesozoic breakup of Pangea. Tectonic causes for Eocene to Recent events and associated lithospheric processes are sometimes elusive but include formation of an asthenospheric slab window in association with ocean ridge-trench collision, the steepening of a transient shallow subduction zone mentioned above, and mantle instabilities during a period of major changes in the plate configuration in the Pacific to the west. A little discussed additional factor affecting the backarc could be times of westward advance and eastward retreat of the South American lithosphere over the deeper hotspot reference frame. Comparison with contemporaneous Tertiary to Recent events on the African plate suggests a role for factors beyond simple plate convergence changes involving the South American plate.

**Selected References:**

- Gorring, M.L., Kay, S. M., and 4 others, 1997, Neogene Patagonian plateau lavas: Continental magmas associated with ridge collision at the Chile Triple Junction: *Tectonics* 16, 1-17.
- James, D. E., and Sacks, S.I, 1999, Cenozoic formation of the Central Andes: a geophysical perspective: in Skinner, B., ed., *Geology and Ore Deposits of the Central Andes*: Soc. Economic Geology Special Publication 7, 1-25.
- Kay, S. M., and Abbruzzi, J. M., 1996, Magmatic evidence for Neogene lithospheric evolution of the central Andean "flat-slab" between 30° and 32°S: *Tectonophysics* 259, 15-28.
- Kay, S. M., Coira, B. and Viramonte, J., 1994, Young mafic back-arc volcanic rocks as guides to lithospheric delamination beneath the Argentine Puna Plateau: *Central Andes*, *J. Geophys. Res.* 99, 24323-24339.
- Kay, S. M., Godoy, E., and Kurtz, A., 2005, Episodic arc migration, crustal thickening, subduction erosion, and magmatism in the south-central Andes: *Geol. Soc. America Bulletin*, 67-88.
- Kay, S. M., Mpodozis, C., and Coira, B., 1999, Magmatism, tectonism, and mineral deposits of the Central Andes (22°-33°S latitude: in Skinner, B., ed., *Geology and Ore Deposits of the Central Andes*: Soc. Economic Geology Special Publication 7, 27-59.
- Kay, S.M. and Mpodozis, C., 2002, Magmatism as a probe to the Neogene shallowing of the Nazca plate beneath the modern Chilean flatslab: *Journal of South American Earth Science*, 15, 39-59.
- von Huene, R., and Scholl, D. W., 1991, Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust: *Reviews of Geophysics*, v. 29, p. 279-316.

## **Mesozoic tectonic regime inversion in eastern North China Block: related to an upwelling mantle?**

Ming-Guo Zhai

*Key Laboratory of Mineral Resource, Institute of Geology and Geophysics,  
Chinese Academy of Sciences, Beijing, 100029  
Email: [mgzhai@mail.igcas.ac.cn](mailto:mgzhai@mail.igcas.ac.cn)*

One of the focuses of tectonic evolution and geodynamics in China is Mesozoic tectonic regime inversion, including lithosphere thinning and large-scale metallogenic explosion, in the eastern North China Block (NCB). The Mesozoic tectonic inversion was reflected, at least, in the following aspects:

(1) Tectonically, the EW-trending structure frame was transformed to NE-NNE-trending structure frame, and a compressive tectonic system in Palaeozoic to an extensional tectonic system in Late Jurassic-Early Cretaceous.

(2) Geodynamically, the collision and amalgamation between different continental blocks were transformed into intracontinental tectonic movement.

(3) In view of lithosphere evolution and change in thickness, there happened large-scale mantle upwelling and strong lithosphere removal. According to previous studies, the thickness of lithosphere was more than 200 km in Palaeozoic, but thinned to less than 80 km in Mesozoic.

(4) Little magmatic activity took place in Proterozoic and Paleozoic, whilst voluminous magmatic activity and granitic invasion began to occur from Mid-Jurassic and reached the summit at 120-110 Ma, indicating a strong mantle-crust interaction. Mafic and lamprophyre dyke swarms of 110-100 Ma are extensively exposed in the eastern North China.

(5) Geophysical data and geochemistry show the Proterozoic-Palaeozoic lithosphere mantle and lower crust of the NCB were mostly substituted by a new lithosphere mantle and lower crust in Mesozoic. Most xenoliths of mantle and lower crust in basalts within the NCB have 140-120 Ma isotopic ages.

(6) As a result, geological fluids and large-scale metallogenesis were well developed in the eastern North China craton.

Our studies of structure, basin analysis, geothermal history, magmatism, gold metallogenesis and paleomagnetism indicate that the time-range of the Mesozoic tectonic regime inversion is from 140 Ma to 100Ma with a peak of ~120-110 Ma. However, Mesozoic tectonic inversion process was complicated, showing multi-stage changes and time-space differences along the margins and within the craton. In the

south (east) of the craton, a compressive structural event occurred mainly at 230-210 Ma, and a peak time of extensional tectonic inversion is 130-110 Ma. In the north, two compressive events occurred at 230-210 Ma and 180(170)-160(150) Ma, respectively, and a peak time of extensional tectonic inversion is also 130-110 Ma. Evolution of Mesozoic basins shows diversity. In Yanshan area, the pre-Late Jurassic basins belong to compressive-flexure, and coexisted with NEE-trending thrust zones. The Late Jurassic NEN-trending rift basins coexisted with uplift zones. The post-Late Jurassic basins trend NE-NEN and coexisted with active uplift zones, controlled by NEE-trending thrust zones. The south and north Dabieshan units have different uplifting histories. Study of deep-seated structure shows that lithosphere of the eastern North China began to thin and a strong interaction and replacement of mantle-crust occurred at Mesozoic, reached their limit at 130—110 Ma.

Our studies also show that the Mesozoic tectonic regime inversion in the eastern North China does not have characteristics of orogenic belt and could be related to an intracontinental geodynamic process.

Some hypotheses were suggested, such as long-distance effect of Pacific Plate, comprehensive constraints of the adjacent blocks (including subducted and extinct Kula plate), adjustment of the stress after the deep subduction of the Qinling-Dabieshan Orogenic Belt, large-scale sinistral strike-slip, delamination of lithosphere and /or continental root-plume tectonics, do great benefit for the study of Mesozoic tectonic regime inversion, but these ideas are still not given rise to complete theoretical framework. Therefore, one aspect should be pointed out that the Mesozoic tectonic regime inversion took place about 120-100 Ma later than collision between the North China-Yangtze Blocks and Mogolia (Siberia)-North China Blocks. In another aspect, the time range of the Mesozoic tectonic regime inversion (140 –100 Ma with a peak of 120-110 Ma) is coupled with boundary between Jurassic and Cretaceous and Cretaceous catastrophic event, which is very important and controversial geological event. It is possibly related to a large-scale upwelling mantle that caused by under jointly attacked from the surrounding blocks.



# Secular (136 to 0 Ma) Chemical Variation of Mantle-Derived Mafic Magmas in the Sino-Korean Craton: Constraints on Mantle Evolution

Ming Zhang<sup>1</sup>, Weiming Fan<sup>1,2</sup>, Suzanne Y. O'Reilly<sup>1</sup>, Jianping Zheng<sup>1,3</sup>  
& William L. Griffin<sup>1,4</sup>

1. GEMOC ARC National Key Centre, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia. Email: [mzhang@els.mq.edu.au](mailto:mzhang@els.mq.edu.au)
2. Lab of Lithospheric tectonic Evolution, Institute of Geology & Geophysics, Chinese Academy of Sciences, Beijing 100029, China
3. Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074, China
4. CSIRO Exploration and Mining, North Ryde, NSW 2113, Australia

Geochemical studies of mantle xenoliths from early Paleozoic kimberlites in North China demonstrate that the subcontinental lithospheric mantle (SCLM) beneath the Sino-Korean Craton was then cold, refractory and about 200 km thick. In contrast, mantle xenoliths from late Tertiary basalts of the region suggest that the present SCLM is hot, relatively fertile and <80 km thick, consistent with geophysical data. This contrast indicates a removal of at least 120 km of old mantle root during the period. Systematic geochemical variations of mantle-derived magmas (136 – 0 Ma) in the region can constrain the nature and evolutionary history of the SCLM beneath the North China craton.

The mantle-derived rocks include high-Mg andesites (136-107 Ma), minettes (103-91 Ma), tholeiites (61-25 Ma), and strongly alkaline basalts (16-0.7 Ma). The Cretaceous high-Mg andesites form a Sr-Nd isotope trend pointing to EM1 ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.7040-0.7049$  and  $\epsilon_{\text{Nd}} = -5$  to  $-14$ ), while the minettes have very low  $\epsilon_{\text{Nd}}$  ( $-13$  to  $-18$ ) and variable high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (0.7056-0.7100), showing a trend between EM1 and EM2 mantle source types. Both of them have fractionated incompatible-element patterns. The Late Tertiary alkaline basalts have Sr-Nd isotopic ratios (0.7032-0.7037 and  $+3.8$  to  $+5.8$ ) and incompatible element patterns indistinguishable from Ocean Island Basalts (OIBs). The Early Tertiary tholeiites are intermediate between the old and young rocks in terms of Sr-Nd isotope ratios and incompatible element patterns. The Late Tertiary alkaline basalts have  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios between 17.89 – 18.49 with  $\Delta 8/4$  values of  $+50$  to  $+70$ , typical of the Dupal-OIB signature. In contrast, most of the Cretaceous lavas have lower  $^{206}\text{Pb}/^{204}\text{Pb}$  (mostly between 16.59-17.84), but higher  $\Delta 8/4$  values ( $+55$  to  $+120$ ). Some of the early tertiary tholeiites have Pb isotopic

signatures similar to the Cretaceous rocks, but others show both high  $^{206}\text{Pb}/^{204}\text{Pb}$  (19.37-19.44) and  $\Delta 7/4$  values (+20).

The integration of these new data with published data for the Paleozoic kimberlites, Mesozoic and Tertiary basalts and mantle and lower crustal xenoliths entrained in these rocks indicates that the temporal geochemical variations can be explained as the consequence of the diminishing role of the Archean SCLM beneath the Sino-Korean Craton in magma generation as it was gradually destroyed since Late Cretaceous. The enriched geochemical signatures of the Cretaceous mafic lavas may have derived directly by contamination from the old metasomatised refractory SCLM beneath the North China craton without the necessity for the involvement of crustal material from the subducted Yangtze plate during Early Triassic times.

## Using geochemistry to unravel continental dynamics I: Re-Os of mantle xenoliths

Roberta L. Rudnick<sup>1</sup> and Shan Gao<sup>2</sup>

*1 Department of Geology, University of Maryland, USA*

*Email: [rudnick@geol.umd.edu](mailto:rudnick@geol.umd.edu)*

*2 Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an 710069, China*

Recycling of continental lithosphere via density foundering from its base has become an increasingly popular hypothesis to explain the non-basaltic composition of the bulk continental crust [e.g., 1, 2, 3]. However, robust empirical evidence for the operation of this process remains thin. One test of the hypothesis is provided by Re-Os investigations of peridotitic xenoliths. Assuming that lower crustal foundering occurs in association with loss of the mantle lithosphere, regions that have experienced foundering significantly post-dating crustal growth are expected to have lithospheric mantle that is younger than the overlying crust.

The North China craton is one region where a multitude of evidence exists for loss of the lithospheric mantle [plus or minus lower crust – see 4] during the Phanerozoic [5, 6], and the processes responsible for this replacement is a topic of hot debate. Re-Os studies of mantle xenoliths provide a means of mapping the extent of lithospheric loss and, under favorable circumstances, the timing of lithospheric replacement. Re-Os investigations of peridotitic xenoliths from the eastern block of the North China craton [7, 8] confirm earlier suggestions that the original Archean lithosphere was removed beneath the eastern block during the Phanerozoic [7]. These data also demonstrate that lithosphere replacement occurred during the Proterozoic within the Central orogenic block [Hannuoba xenoliths, 7, 8] and at the northeastern margin of the craton [Longgang xenoliths, 8]. In these regions, the ancient, Proterozoic lithosphere persists to the present day, suggesting no, or incomplete, lithospheric thinning occurred during the Phanerozoic.

The existing Re-Os data demonstrate that lithospheric replacement was diachronous within the North China Craton – it occurred during the Proterozoic in the Central orogenic belt and northeastern margin of the craton, and during the Phanerozoic in the Eastern block. Whereas the timing of replacement is reasonably well constrained by the Re-Os data to have occurred at  $1.9 \pm 0.2$  Ga within the Central orogenic belt [a time of collisional orogeny, 9], the Re-Os data for the northeastern craton margin and Shandong Peninsula do not provide precise enough ages to determine the timing of replacement in these regions, nor do they illuminate the processes that are responsible.

Such insights are more likely to arise from study of Mesozoic xenoliths [10, 11] and lavas [e.g., 4].

## References

- 1 N.T. Arndt and S.L. Goldstein, An open boundary between lower continental crust and mantle: its role in crust formation and crustal recycling, *Tectonophysics* 161, 201-212, 1989.
- 2 R.W. Kay and S.M. Kay, Creation and destruction of lower continental crust, *Geol. Rundschau* 80, 259-278, 1991.
- 3 M. Jull and P.B. Kelemen, On the conditions for lower crustal convective instability, *J. Geophys. Res.* 106(4), 6423-6446, 2001.
- 4 S. Gao, R.L. Rudnick, H.-L. Yuan, X.-M. Liu, Y.-S. Liu, W.-L. Xu, W.-L. Ling, J.C. Ayers, X.-C. Wang and Q.-H. Wang, Recycling lower continental crust in the North China Craton, *Nature* 432, 892-897, 2004.
- 5 A. Menzies, W.-M. Fan and M. Zhang, Paleozoic and Cenozoic lithoprobes and the loss of >120 km of Archean lithosphere, Sino-Korean craton, China, in: *Magmatic Processes and Plate Tectonics*, H.M. Prichard, H.M. Alabaster, T. Harris and C.R. Neary, eds., pp. 71-81, Geological Soc., London, 1993.
- 6 W.L. Griffin, A.D. Zhang, S.Y. O'Reilly and C.G. Ryan, Phanerozoic evolution of the lithosphere beneath the Sino-Korean Craton, in: *Mantle Dynamics and Plate Interactions in East Asia*, M. Flower, S.-L. Chung, C.-H. Lo and T.-Y. Lee, eds., pp. 107-126, American Geophysical Union, Washington, D.C., 1998.
- 7 S. Gao, R.L. Rudnick, R.W. Carlson, W.F. McDonough and Y. Liu, Re-Os evidence for replacement of ancient mantle lithosphere beneath the North China Craton, *Earth and Planetary Science Letters* 198(3-4), 307-322, 2002.
- 8 F.Y. Wu, R.J. Walker, X.W. Ren, D.Y. Sun and X.H. Zhou, Osmium isotopic constraints on the age of lithospheric mantle beneath northeastern China, *Chemical Geology* 196(1-4), 107-129, 2003.
- 9 G.C. Zhao, S.A. Wilde, P.A. Cawood and M. Sun, Archean blocks and their boundaries in the North China Craton: lithological, geochemical, structural and P-T path constraints and tectonic evolution, *Precambrian Res.* 107, 45-73, 2001.
- 10 W.L. Xu, D.Y. Wang, X.C. Liu, Q.H. Wang and J.Q. Lin, Discovery of eclogite inclusions and its geological significance in early Jurassic intrusive complex in Xuzho-northern Anhui, eastern China, *Chinese Science Bulletin* 47(14), 1212-1216, 2002.
- 11 J.P. Zheng, M. Sun, F.X. Lu and N. Pearson, Mesozoic lower crustal xenoliths and their significance in lithospheric evolution beneath the Sino-Korean Craton, *Tectonophysics* 361(1-2), 37-60, 2003.

## **Constraints on recent mantle processes beneath northeast China by Th isotopes**

Haibo Zou<sup>1</sup>, Qicheng Fan<sup>2</sup>, Axel K. Schmitt<sup>1</sup>, Mary Reid<sup>1,3</sup>, Xisheng Xu<sup>4</sup>, Yupeng Yao<sup>5</sup>

<sup>1</sup>*Department of Earth and Space Sciences, University of California, Los Angeles, CA  
90095, USA. Email: [hzou@ess.ucla.edu](mailto:hzou@ess.ucla.edu)*

<sup>2</sup>*Institute of Geology, China Seismological Bureau, Beijing 10029, China*

<sup>3</sup>*Department of Geology, Northern Arizona University, Flagstaff, AZ 86011, USA*

<sup>4</sup>*Department of Earth Sciences, Nanjing University, Nanjing 210093, China*

<sup>5</sup>*Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100037,  
China*

In northeastern China, Holocene (<10,000 years) volcanic activity occurs at Wudalianchi, Jingbohu, Long-gang and Tianchi along northeast-southwest trending basins, possibly as a result of decompression-induced melting or fluid-induced melting. Short-lived U-Th disequilibrium along with long-lived Nd isotopes may provide insights into the origin of these young lavas and recent mantle geodynamical processes.

We measured Th isotopes by both thermal ionization mass spectrometry and secondary ion mass spectrometry. The Wudalianchi lavas were measured by thermal ionization mass spectrometry while chemically separated thorium samples from Jingbohu, Long-gang and Tianchi were measured by a recently implemented technique using the UCLA Cameca IMS 1270 ion microprobe. Secondary ion mass spectrometry is advantageous due to its much higher ionization efficiency for thorium than thermal ionization mass spectrometry.

The Wudalianchi lavas display strong (24-33%) <sup>230</sup>Th excesses with enriched Nd isotopic compositions ( $\epsilon_{Nd} = -3.7$  to  $-5.0$ ). Jingbohu lavas display variable extents of <sup>230</sup>Th excesses (7 to 28%) and moderately depleted Nd isotopic compositions ( $\epsilon_{Nd} = +1.5$  to  $+3.3$ ). Long-gang lavas have pronounced (20 to 35%) <sup>230</sup>Th excesses and slightly depleted Nd isotopic compositions ( $\epsilon_{Nd} = +0.5$  to  $+0.7$ ). The Tianchi lavas display moderate (12%) <sup>230</sup>Th excesses and slightly enriched Nd isotopic compositions ( $\epsilon_{Nd} = -1.0$  to  $-1.1$ ).

Since <sup>230</sup>Th enrichments in all these Holocene lavas are uncharacteristic of melts generated by subduction, these Holocene lavas were not generated as a result of fluid-induced melting. Thus, recent subduction of the Pacific plate under the Eurasian plate did not directly contribute subduction-related fluids to the source rocks for these basalts. Instead these basalts represent mixtures of melts derived from partial melting of enriched lithospheric EM1 mantle and depleted asthenospheric mantle in the deep garnet-stability field, due to decompression-induced melting as a result of lithosphere rifting and asthenosphere upwelling.

## **Growth rate curve of continental crust through time— An estimate from the river mouth zircons**

Maruyama, S., Rino, S. and Iizuka, T.

*Tokyo Institute of Technology, O-Okayama 2-12-1, Tokyo, Japan*

*E-mail; [smaruyam@geo.titech.ac.jp](mailto:smaruyam@geo.titech.ac.jp)*

The continental growth curve has long been argued, and numbers of different models have been proposed as categorized into three groups, (1) thermal, (2) geochemical and geological considerations.

We have initiated to draw the realistic curve, using the river mouth zircons from major 25 rivers over the world to carry out in situ U-b and Lu-Hf isotope analyses. Here we summarize the results from N. America, S. America, Africa and East Asia, as follows. (1) The growth curve does not show the continuous trend, instead the episodic growth at 2.7 Ga, 2.1 Ga, 1.8-1.1 Ga, and 0.7 Ga, (2) the least formation at 2.3–2.5 Ga and 0.9-0.8 Ga was one order of magnitude lower than that of the maximum period at 2.1 Ga, suggesting the variably changed activity of plate tectonics through time, (3) major growth period was Proterozoic, ca. 75%, with lesser amounts of 20% in the Archean, and 5% in the Phanerozoic, (4)  $\epsilon$  Hf values show that the most Phanerozoic and minor late Archean TTG crusts were reworked in origin.

The newly obtained growth curve satisfies the constraint that the growth rate of orogenic belt estimated by Hurley & Rand (1969) and Maruyama & Liou (1997), and is best matched to that estimated by Sr isotope of carbonate by Veizer & Jansen (1979).

The Archean geology in W. Australia, N. America, S. Africa and Greenland where we have mapped during the last 15 years, clearly show that the collision and amalgamation of oceanic island arcs was the major process to grow continents. The modern analogue is the western Pacific where numbers of intra-oceanic island arcs are subducting without accretion within the oceanic domain, rather than the collision-amalgamation, suggesting the common occurrence of subduction of Archean arcs into mantle, rather than extensive accretion.

Our estimate of the Archean growth of continental crust was small < 20%, very small about 5% before 3.0 Ga in spite of expected high geothermal gradient. If the arc was subducted into the mantle, the TTG would have melted to form tectospheric mantle by a reaction of olivine plus quartz-rich melt = orthopyroxene. However, the subducted TTG may not be melted in the present western Pacific, due to lower T than in the Archean, hence no formation of tectosphere at present.

# **A possible model for the lithospheric thinning of North China Craton: Evidences from the Yanshanian (Jura-Cretaceous) Magmatism and tectonic deformation**

Deng Jinfu, Su Shangguo, Zhao Guochun, Liu Cui, Mo Xuanxue,  
Zhao Xingguo, Wu zhongxu

*China University of Geosciences, Beijing 100083, China*

*Email: [dengjinfu@21cn.com](mailto:dengjinfu@21cn.com)*

As is well known, the North China Craton was formed mainly in late Archean, and was reactivated during the Jura-Cretaceous (Yanshanian) time and transformed into an orogenic belt, which is believed to be related to the lithospheric thinning to the thickness of about 60-70Km from the cratonic continental root with the thickness of about 200-250Km. The main question is that what mechanism and processes may have caused the lithospheric thinning of the buoyant continental root which is generally believed to be tectonically stable forever? This paper is tried to discuss how to destroy the continental root and to transform it into a dense one, and then to be delamination, based on the Yanshanian magmatism and tectonic deformation.

We present a new scheme of magmatic-tectonic event sequence in the Yanshan orogenic belt, North China, including the volcanic rock assemblage, sedimentary formation, intrusive rock assemblage, tectonic deformational phase, metamorphism, crustal uplift and erosion, and unconformity-formation etc events. Five orogenic episodes have been recognized on the basis of the unconformities, i.e. (1) pre-and initial orogenic episode ( $J_1$ ), (2) early orogenic episode ( $J_2$ ), (3) peak orogenic episode ( $J_3$ ), (4) late orogenic episode ( $K_1^1$ ), and (5) post-orogenic episode ( $K_1^2$ ); and each episode corresponds to a short cycle of the geological event. It begins with volcanic eruption, through sedimentation, plutonism, deformation and metamorphism, and ended with uplifting and erosion, except for the latest post-orogenic episode.

In contrast to both the pre-and the post-orogenic episodes characterized by the extensional deformation and the coal-bearing sedimentation, three episodes of the contractional deformation (folding and thrusting) associated with molasses formation in the fore-land basin during late  $J_1$ , late  $J_2$ , and late  $J_3$  have been developed, which indicates that the thickened crust with mountain root may be occurred in  $J_3$  and  $K_1^1$ .

The HKCA igneous rock series are dominated to be developed, the linear volcanic in  $J_1$  和  $J_2$  implies a lithospheric rupture, along which the basaltic magma ascended and underplated in the crustal base, however, the areal volcanic eruptives in  $J_3$  and  $K_1^1$  show regional lithospheric delamination and basaltic underplating. The high-pressure trachyte-latite and syenite-monzonite with no negative En-anomaly and high ratio of Sr/Y are occurred in  $J_3$  and  $K_1^1$ , which indicates the eclogitic source, as well as higher  $K_{60}$  is developed in  $J_3$  and  $K_1^1$ , all of which may be suggested that the thickened crust

are about 50-60Km in thickness. The “picritic” gabbro ( $\text{SiO}_2$  47.68%, MgO 19.09 (wt%) ( $132.90 \pm 0.66\text{Ma}$ , Zircon SHRIMP dating) might be suggested to be generated from the asthenosphere at the depth of about 60~70Km, which may be implied the upwelling asthenosphere in contact with Moho. The discover of Jura-Cretaceous (120~140 Ma) granulite and eclogite facies pyroxenites xenoliths in the Cenozoic Hannuoba basalt gives good support to the Yanshanian thickened crust and basaltic underplating.

Our thermal modeling shows that the ratio of the total granitic melt and the total extractable granitic magma generated in the tonalitic lower crust to the total amount of the underplated basalt-magma crystallized is about 0.25 and 0.08, respectively. It is suggested that a large amount of the underplating basaltic magma is required to heat the cold tonalitic lower crust of the Craton to be partial melting and melt extraction. For an example, if the total granitic batholiths with the thickness of about 5Km are formed during Jura-Cretaceous time, then the total thickness of about 62.5 Km of the underplated basalt-magma crystallized is necessary. In turn, if such large amount of the basalts at the Moho can be transformed to the eclogites, then the density of the lower part of the lithosphere might be enough dense to be taking delamination.

The regional tectonic framework may give the condition of the North China Craton to be reactivated during the Yanshanian stage. After the combined Mongolia-North China – South China blocks amalgamated during the Permian-Triassic periods, it is surrounded by the oceanic subduction zones, and then is accreted to the Siberia Craton during the Jura-Cretaceous time. Thus, during the Yanshanian stage the North China Craton is generally situated in the combined subduction-collision-related tectonic setting, which is consistent with the orogenic nature of the magmatism and deformation, therefore, the regional tectonic framework may give a basic environment for the lithospheric thinning of North China Craton.

From above-mentioned discussion, we may gain some conclusion: (1) the underplating basaltic magma heated and in turn weakened the previous strong crust, and then a rheological condition was reached to facilitate contractional deformation and crustal thickening, (2) the contractional deformation is necessary in order to thicken the crust, and in turn, transform the underplated basalt rocks to the eclogites, (3) the input of the large amount of the convective asthenospheric materials into the Craton is required to cause the crust to be partial melting, (4) the combination of above (2)&(3) is necessary for the formation of large amount of eclogites, and subsequent lithospheric delamination, (5) the combined subduction-collision-related tectonic setting may be one of the good environment for the development of the cratonic lithospheric thinning.

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## Possible contribution of the lithosphere to the Tibetan collisional and post-collisional volcanism

Xuanxue Mo, Zhidan Zhao, Jinfu Deng, Xuehui Yu, Zhaohua Luo,  
Guochen Dong and Su Zhou

*1 State Key Laboratory of Geo-Processes and Mineral Resources, China University of Geosciences, Beijing 100083; E-mail: [moxx@cugb.edu.cn](mailto:moxx@cugb.edu.cn)*

*2 School of Earth Science and Resources, China University of Geosciences, Beijing 100083*

Many evidence supports that the collision of India with Eurasia proceeded from “soft” to “hard” phases between c. 65-70 Ma and c. 45 Ma (Yin and Harrison, 2000, Flower et al., 2001, and refs therein), tremendously disturbed the lithosphere/asthenosphere system in terms of both mass and energy. Wide-distributed collision and post-collision related igneous rocks in Tibetan Plateau provide an ideal lithoprobe for understanding geodynamics of these processes (Mo et al., 2005).

A large scale of the Tertiary Linzizong volcanics and Gangdese granitoids aging c.65—45 Ma in the Gangdese magmatic belt, parallel to the Yarlung Tsangpo suture, was considered as a magmatic response to the India-Eurasia collision. Petrological records suggested that Neo-Tethyan oceanic lithosphere subducted underneath the Lhasa block, followed by subduction of Indian subcontinental lithosphere along Yarlung Tsangpo suture. Driven by orogenic compression, huge amount of subduction-collision-induced basaltic magma underplated at the base of the continental crust, which caused extensive melting of the crust and produced 2 km thick by 100 km wide by 1300 km long Linzizong felsic ignimbrite on one hand, and caused hybridization between mantle-derived and crust-derived magmas, giving rise to the formation of a 2000 km by 100 km mafic microgranular enclaves (MMEs) – containing granitoid belt and Linzizong andesite as well, on the other hand. Gangdese post-collisional potassic-ultrapotassic volcanic rocks give constraints on the subduction of Indian subcontinental lithosphere beneath Tibetan plateau. The Gangdese post-collisional volcanic rocks aging c. 28—10 Ma aligned in a long distance with the strike of the Gangdese belt, extremely vary in  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.705778—0.736451) and  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.511075—0.511814) ratios. While the post-collisional volcanic rocks to the east of 87°E are restricted to a limited range with higher Nd but lower Sr isotopic ratios and closer to the end member of Neo-Tethyan oceanic mantle in the diagram  $\epsilon\text{Nd}$  versus  $^{87}\text{Sr}/^{86}\text{Sr}$ , those to the west of 87°E have highest  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (0.705778—0.736451) and lowest  $\epsilon\text{Nd}$  values ( $\epsilon\text{Nd}$  -9.59— -14.86) among all kinds of post-collisional volcanic rocks and closer to the end member of High Himalaya crust. It implies that Indian subcontinental lithosphere including the crust was deeply involved in post-collisional subduction beneath the Lhasa Block in western Gangdese, whereas it was not the case in the east. It seems that post-collisional volcanic rocks in eastern Gangdese were probably caused by post-collision slab breakoff, originated either from deep-seated potassium-rich ‘phlogopite pyroxenite’ layers underneath subduction zone

(Wyllie, 1983), or from a refractory, K-rich mantle source (RKM) as proposed by Flower et al. (1998)'s RLM (Refractory Lithospheric Mantle) tectonic erosion model.

The geodynamic regime in northern Tibetan Plateau was seemingly different from the Gangdese (Lhasa Block) speculated from the constraint of post-collisional potassic volcanic rocks. Post-collisional volcanic rocks in northern Plateau show a diffused distribution pattern rather than a linear alignment as in the Gangdese. Isotopic composition, especially Nd and Sr isotopes, for all post-collisional volcanic rocks from various parts of northern Plateau concentrated in a limited compositional range, showing little variation. It implies that the mantle source underneath northern Plateau have likely reached an isotopic equilibrium state. Being different from the Gangdese, northern Tibetan Plateau underwent the evolution of Paleo-Tethys from the opening, subduction to the closure during the period from Early Carboniferous to the end of Triassic (c. 360—200 Ma). As a result, the mantle source beneath northern Tibetan Plateau was presumably metasomatized by subduction-induced K-rich and HFSE-depleted aqueous fluids or interstitial melts during the Paleo-Tethyan period. Subsequent fluid circulation since c. 200 Ma might continue impacting on the mantle source and reached isotopic equilibrium. It seems that a wave-like outward propagation of the asthenosphere upwelling produced the decompression partial melting of the magma source according to the outward migration pattern of post-collisional volcanism. Post-collisional volcanic rocks occurring near the northern margin of the Tibetan Plateau show similar magma source but different mechanism for magma generation in comparison with the interior of northern Plateau. That is, it is likely that large strike-slip faults triggered decompression partial melting on the margins.

Furthermore, it is supposed that peridotite-nodule-bearing kamafugite primary magma in western Qinling, clearly showing OIB geochemical signatures, presumably originated at the base of lithosphere between 90 km and 120 km in depth triggered by plume-like upwelling of the asthenosphere underneath (Yu et al., 2003).

Thus, at least three geochemical reservoirs can be distinguished for Tibetan lithospheric mantle: (1) Indian-Ocean-type Neo-Tethyan mantle with DUPAL anomaly (Zhang et al., 2005), (2) Indian subcontinental lithospheric mantle with strong EM II signatures, and (3) Tibetan original lithospheric mantle with inherent isotopic imprints formed prior to India-Asia collision. The interaction among the three reservoirs in various proportions gave rise to the heterogeneity in geochemistry of the mantle sources. The deep processes taken place during the India - Eurasia collision and post-collision were likely the subduction of Neo-Tethyan oceanic lithosphere, followed by subduction of Indian subcontinental lithosphere and underplating-magma mixing along the India-Tibet suture (Yarlung Tsangpo), collision-induced upwelling of the asthenosphere in the interior of northern Tibetan Plateau and strike-slip- triggered decompression melting on the margins of the Plateau, respectively. To keep the dynamic system work, it seems to require an eastward asthenospheric flow from beneath Tibetan Plateau to beneath eastern China induced by both India-Eurasia collision (Flower et al., 1998, 2001; Russo et al., 1998; Liu et al, 2005) and remote Western Pacific wedge suction (Niu, 2005).

## References

- Flower, M., Tamaki K. and Nguyen Hoang, 1998, Mantle extrusion: A model for dispersed volcanism and DUPAL-like asthenosphere in East Asia and the Western Pacific. In Flower et al. eds, Mantle Dynamics and Plate Interaction in East Asia, Geodynamics 27, American Geophysical union, 67-88
- Flower, M., Russo, R.M., Tamaki K. and Nguyen Hoang, 2001, Mantle contamination and the Izu-Bonin-Mariana (IBM) 'high-tide mark': evidence for mantle extrusion caused by Tethyan closure, *Tectonophysics* 333: 9-34
- Liu, M., Cui, X., Liu, F., 2005, Cenozoic rifting and volcanism in eastern China: A mantle dynamic link to the Indo-Asian collision? In: M.F.J. Flower, C.T. Chi, N.T. Yem, V. Mocanu eds, *Tectonophysics, special issue: "Mantle and Lithosphere Responses to Tethyan Closure"* (in press)
- Mo, Xuanxue, Zhidan Zhao, Jinfu Deng, Martin Flower, Xuehui Yu, Zhaohua Luo, Youguo Li, Su Zhou, Guochen Dong, Dicheng Zhu and Liang Wang, 2005, Post-collisional volcanic rocks and implications for heterogeneity of the lithosphere and collision-deduced mantle flow in Tibetan Plateau. GSA Special Paper *Post-collisional tectonics and Magmatism in the East Mediterranean Region* (in press)
- Niu, Yaoling, 2005, Generation and Evolution of Basaltic Magmas: Some Basic Concepts and a New View on the Origin of Mesozoic-Cenozoic Basaltic Volcanism in Eastern China. *Geological Journal of China Universities* (in press)
- Russo, R.M., M.F.J. Flower, V.I. Mocanu, 1998, Infiltration history of asthenosphere beneath Indochina: proposal for an integrated study, 1998 Fall Meeting, San Francisco, CA., *EOS, Transactions of the American Geophysical Union*, 79 (45) 848
- Wyllie, P.J., 1983, Experimental and thermal constraints on the deep-seated parentage of some granitoid magmas in subduction zones. Atherton, M.P. and Gribble, eds. *Migmatites, Melting and metamorphism*. Springer-Verlag, Berlin
- Yin, A., Harrison, T.M., 2000, Geologic evolution of the Himalayan-Tibetan orogen, *Annual Review of Earth and Planetary Sciences*, 28: 211-280.
- Yu, X., Mo, X., Flower, M., Su, S. and Zhao, X., 2001, Cenozoic kamafugitic volcanism in western Qinling, Gansu Province and its tectonic significance. *Acta Petrol. Sinica* 17 (3): 366-377
- Zhang S.-Q, J. J. Mahoney, X.-X. Mo, A. M. Ghazi, L. Milani, A. J. Crawford, T.-Y. Guo, Z.-D. Zhao, 2005, Evidence for a Widespread Tethyan Upper Mantle with Indian-Ocean-Type Isotopic Characteristics, *Journal of Petrology Advance Access published January 21, 2005*

***Flat-slab Subduction Followed by Slab Foundering and  
plate-capture:***  
**Mesozoic Indosinian Orogeny and Jurassic-Cretaceous  
Anorogenic Magmatism in South China Revisited**

Z.X. Li<sup>a</sup> and X.H. Li<sup>b</sup>

<sup>a</sup> *Tectonics Special Research Centre, School of Earth and Geographical Sciences,  
The University of Western Australia, Crawley, WA 6009, Australia*

*Email: [zli@tsrc.uwa.edu.au](mailto:zli@tsrc.uwa.edu.au)*

<sup>b</sup> *Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, PO Box  
1131, Guangzhou, China*

The current South China topography was largely inherited from Mesozoic tectonics. Whereas the Qinling-Dabie Orogen to the north and the Longmenshan ranges to the west are due to either continental collision or terrane accretion, the ca. 1300km-wide orogen that affected at least the southeastern half of the continent can not readily be explained. Equally hard to explain is the widespread post-orogenic (often rifting-related) magmatism in this part of the continent. An early archipelago models by Hsü and co-workers (e.g., Hsu, 1994) contradicts many geological observations such as facies continuity between coastal South China (or Cathaysia) and its interior (Yangtze Craton) since at least Devonian (e.g., Liu and Xu, 1994). The far-field stress model related to the North China-South China collision by Li (1998) failed to explain the extraordinary width and intraplate nature of the orogen.

Here we present a flat-slab model for the broad Indosinian intracontinental orogen, and a model involving slab delamination/fundering and plate-capture for the Jurassic-Cretaceous anorogenic magmatism and basin-and-range development.

*Flat-slab subduction and Indosinian intro-continental orogeny:* Apart from its enormous width, other key features of the Indosinian Orogeny in South China include (1) the orogeny started from the southeastern coastal region in as early as mid-Permian, and migrated inland toward the northwest until the Late Triassic/Early Juraasic (Li, 1998); (2) accompanying the northwest-ward migration of the orogeny was a similar migration of (but rare) arc-type magmatism at the front of the orogen; and (3) the development of shallow-marine basins tailing the NW-migrating orogen. We thus propose that like the Cretaceous to early Paleogene Lamaride Orogeny in the Cordillera and section of the Andes during the Cenozoic, the Indosinian Orogeny in southeastern South China was also due to a phase of flat-slab subduction. This model explains the migration of orogenesis and arc-magmatism, and the over 1300km width of the orogen.

The development of topographic down-warping at the tail of the orogen was possibly due to the gravitational pull of the flat-subducted oceanic lithosphere as it cooled and possibly going through phase changes.

*Post-orogenic slab delamination/foundering, arrival of an oceanic ridge, and widespread anorogenic magmatism:* Previous models typically involve a continental arc (e.g., John et al., 1990; Zhou and Li, 2000) for explaining the widespread Jurassic-Cretaceous anorogenic magmatism in the region. The difficulties with those models that (1) those magmatism are not typically of arc-type; rather, they are bimodal and many are intraplate alkalic rocks (Li et al., 2003; Li et al., 2004; Wang et al., 2005); (2) there was also a basin-and-range province developed in southeastern South China at that time (Gilder et al., 1991); (3) the magmatic province stretched to ca. 1000 km from the continental margin, not just along the coastal region; and (4) the temporal-spatial distribution of the magmatism was not a simple coast-ward migration as the model by Zhou and Li (2000) requires. We propose here that this wide anorogenic magmatic province was partly due to the delamination and foundering of the subducted flat-slab, partly due to the coupling of the coastal region with the oceanic plate during the Late Jurassic-Cretaceous. We envisage that cooling and phase-changes of the flat-slab after subduction first led to the slab foundering at the central part of the flat-slab, causing the intrusion of the ca. 190 Ma granites and ca. 175 -170 Ma alkaline mafic and felsic volcanic and plutonic rocks in southern Hunan to southern Jiangxi Province. This was followed by the further delamination and foundering of slab in regions to the west-southwest, as shown by the intrusion of the 165-155 Ma granites (including A- and I-type granites) and minor syenites.

During the Late Jurassic (ca. 150 Ma) and the Cretaceous, a basin-and-range province was developed in the coastal region (Gilder et al., 1991), with extensive intrusions/extrusions of bimodal magmatism (including A-type granite, syenite, dabbro, diorite/granodiorite, and gabbro) which display a general coast-ward migration trend (Zhou and Li, 2000). We believe that two mechanisms were at play during that time. First, the sea-ward retrograde steepening of the remaining subducted flat-slab explains the sea-ward migration of the magmatism and some extension. Second, the arrival of the Pacific-Izanagi ridge during the Late Jurassic led to the coupling of the Isanagi Plate (oceanic) with the coastal region of East Asia, causing the development of a basin-and-range province and widespread left-lateral faults.

### **References**

- Gilder, S.A., Keller, G.R., Luo, M., and Goodell, P.C., 1991, Timing and spatial distribution of rifting in China: *Tectonophysics*, v. 197, p. 225-243.
- Hsu, K.J., 1994, Tectonic facies in an archipelago model of intra-plate orogenesis: *GSA Today*, v. 4, p. 289-293.

- John, B.M., Zhou, X.H., and Li, J.L., 1990, Formation and tectonic evolution of Southeastern China and Taiwan: Isotopic and geochemical constraints: *Tectonophysics*, v. 183, p. 145-160.
- Li, X.H., Chen, Z., Liu, D.Y., and Li, W.X., 2003, Jurassic gabbro-granite-syenite suites from Southern Jiangxi province, SE China: Age, origin, and tectonic significance: *International Geology Review*, v. 45, p. 898-921.
- Li, X.H., Chung, S.L., Zhou, H.W., Lo, C.H., Liu, Y., and Chen, C.H., 2004, Jurassic intraplate magmatism in southern Hunan-eastern Guangxi:  $^{40}\text{Ar}/^{39}\text{Ar}$  dating, geochemistry, Sr-Nd isotopes and implications for tectonic evolution of SE China, *in* Malpas, J., Fletcher, C.J., Aitchison, J.C., and Ali, J., eds., *Aspects of the Tectonic Evolution of China*. Geological Society, London, Special Publications, Volume 226, Geological Society, London, Special Publications, p. 193-216.
- Li, Z.X., 1998, Tectonic history of the major East Asian lithospheric blocks since the mid-Proterozoic -- a synthesis, *in* Flower, M.J., Chung, S.-L., Lo, C.-H., and Lee, T.-Y., eds., *Mantle dynamics and plate interactions in East Asia*, Volume 27: *Geodynamics Series*: Washington, DC, United States, American Geophysical Union, p. 221-243.
- Liu, B., and Xu, X., 1994, *Atlas of Lithofacies and Paleogeography of South China*: Beijing, Science Press, 188 p.
- Wang, Q., Li, J.W., Jian, P., Zhao, Z.H., Xiong, X.L., Bao, Z.W., Xu, J.F., Li, C.F., and Ma, J.L., 2005, Alkaline syenites in eastern Cathaysia (South China): link to Permian-Triassic transtension: *Earth and Planetary Science Letters*, v. 230, p. 339-354.
- Zhou, X.M., and Li, W.X., 2000, Origin of Late Mesozoic igneous rocks in Southeastern China: implications for lithosphere subduction and underplating of mafic magmas: *Tectonophysics*, v. 326, p. 269-287.

## **Mesozoic-Cenozoic modification of the North China lithosphere: a review**

Z. X. Li

*Tectonics Special Research Centre, The University of Western Australia, Crawley WA 6009, Australia; Email: [zli@tsrc.uwa.edu.au](mailto:zli@tsrc.uwa.edu.au)*

The North China Block (NCB) consists of two major Archaean crustal nuclei that collided together by ca. 1800 Ma (e.g., Zhao, 2001), although some argue that they came together as early as ca. 2500 Ma (e.g., Zhai and Liu, 2003; Kusky and Li, 2003). No orogenic event is known within the NCB from ca. 1800 Ma until Permian.

The shape and lithospheric architecture of this seemingly stable continental block were significantly reworked by Mesozoic-Cenozoic events. Continental collision between the NCB and South China Block (SCB) started from their eastern ends as early as Permian, leading to the initial continental subduction and subsequent exhumation of 240-235 Ma UHP metamorphic rocks (e.g., Hacker et al., 2000; Ayers et al., 2002) to the crustal level by ca. 220 Ma (Hacker et al., 2000). This was followed by the development of flake tectonics in the region east of the Tanlu Fault between Late Triassic and mid-Jurassic (Li, 1994, 1998), where the lower crust and lithospheric mantle of the SCB continued to subduct beneath the NCB, whereas the upper crust of the SCB, along with the UHP rocks at the upper crustal level along the former plate margin, were obducted over the lower crust of the NCB for up to 500 km. We thus have a composite crust in the Sulu-Yellow Sea-central Korea region. Extensive thin- to thick-skinned thrusting also developed in both the Jiao-Liao region east of the Tanlu Fault and the Xu-Huai and Luxi regions west of the Tanlu Fault during this process, all within the upper crust of the NCB. This complex crustal architecture may still influence distribution of epicentres in the region.

Late Jurassic-Cretaceous thin-skinned thrusts were well developed along northern NCB (e.g., Davis et al., 1998) possibly due to the closure of the Mongolo-Okhotsk sea to the north. During the Cretaceous and early Tertiary, eastern NCB underwent dramatic lithospheric thinning (locally total erosion of lithospheric mantle?) (e.g., Liu, 1987; Menzies et al., 1993; O'Reilly et al., 2001; Xu, 2001). The temporal-spatial distribution of this major episode of lithospheric thinning suggests a likely linkage to the rollback of the subducting oceanic slab in the Western Pacific (Northrup et al., 1995; Ren and Xiao, 2002), which is supported by recent seismic tomographic data (Rubie and van der Hilst, 2001). Although new (still very thin) mantle lithosphere was subsequently regenerated in this region, lithospheric thinning continues today in central NCB (Xu et al., 2004),

possibly related to the India-Eurasia collision (Menzies et al., 1993; Liu et al., 2004). The significantly thinned (80–60 km) lithosphere in eastern NCB may be partly responsible for the abnormally high intra-plate seismicity in the region.

## References

- Ayers, J.C., Dunkle, S., Gao, S., and Miller, C.F., 2002, Constraints on timing of peak and retrograde metamorphism in the Dabie Shan Ultrahigh-Pressure Metamorphic Belt, east-central China, using U-Th-Pb dating of zircon and monazite: *Chemical Geology*, v. 186, p. 315-331.
- Davis, G.A., Cong, W., Zheng, Y.D., Zhang, J.J., Zhang, C.H., and Gehrels, G.E., 1998, The enigmatic Yinshan fold-and-thrust belt of northern China: New views on its intraplate contractional styles: *Geology*, v. 26, p. 43-46.
- Hacker, B.R., Ratschbacher, L., Webb, L., McWilliams, M.O., Ireland, T., Calvert, A., Dong, S., Wenk, H.R., and Chateigner, D., 2000, Exhumation of ultrahigh-pressure continental crust in east central China: Late Triassic-Early Jurassic tectonic unroofing: *Journal of Geophysical Research (B)*, v. 105, p. 13,339-13,364.
- Kusky, T.M., and Li, J.H., 2003, Paleoproterozoic tectonic evolution of the North China Craton: *Journal of Asian Earth Sciences*, v. 22, p. 383-397.
- Li, Z.X., 1994, Collision between the North-South China blocks: A crustal-detachment model for suturing in the region east of the Tanlu fault: *Geology*, v. 22, p. 739-742.
- Li, Z.X., 1998, Tectonic history of the major East Asian lithospheric blocks since the mid-Proterozoic -- a synthesis, in Flower, M.J., Chung, S.-L., Lo, C.-H., and Lee, T.-Y., eds., *Mantle dynamics and plate interactions in East Asia*, Volume 27: *Geodynamics Series*: Washington, DC, United States, American Geophysical Union, p. 221-243.
- Liu, G.D., 1987, The Cenozoic Rift System of the North China Plain and the Deep Internal Process: *Tectonophysics*, v. 133, p. 277-285.
- Liu, M., Cui, X.J., and Liu, F.T., 2004, Cenozoic rifting and volcanism in eastern China: a mantle dynamic link to the Indo-Asian collision?: *Tectonophysics*, v. 393, p. 29-42.
- Menzies, M.A., Fan, W.M., and Zhang, M., 1993, Palaeozoic and Cenozoic lithoprobes and the loss of >120 km of Archaean lithosphere, Sino-Korean craton, China, in Prichard, H.M., Alabaster, T., Harris, N.B.W., and Neary, C.R., eds., *Magmatic Processes and Plate Tectonics*, Volume 76, Geological Society of London Special Publication, p. 71-81.
- Northrup, C.J., Royden, L.H., and Burchfiel, B.C., 1995, Motion of the Pacific Plate Relative to Eurasia and Its Potential Relation to Cenozoic Extension Along the Eastern Margin of Eurasia: *Geology*, v. 23, p. 719-722.
- O'Reilly, S.Y., Griffin, W.L., Poudjom, D.Y.H., and Morgan, P., 2001, Are Lithospheres Forever? Tracking Changes in Subcontinental Lithospheric Mantle Through Time: *GSA Today*, v. 11, p. 4-10.



- Ren, J.Y., Tamaki, K., Li, S.T., and Junxia, Z., 2002, Late Mesozoic and Cenozoic rifting and its dynamic setting in Eastern China and adjacent areas: *Tectonophysics*, v. 344, p. 175-205.
- Rubie, D.C., and van der Hilst, R.D., 2001, Processes and consequences of deep subduction: introduction: *Physics of the Earth and Planetary Interiors*, v. 127, p. 1-7.
- Xu, Y.G., 2001, Thermo-tectonic destruction of the archaean lithospheric keel beneath the Sino-Korean Craton in China: Evidence, timing and mechanism: *Physics and Chemistry of the Earth Part a-Solid Earth and Geodesy*, v. 26, p. 747-757.
- Xu, Y.G., Chung, S.L., Ma, J.L., and Shi, L.B., 2004, Contrasting Cenozoic lithospheric evolution and architecture in the western and eastern Sino-Korean craton: Constraints from geochemistry of basalts and mantle xenoliths: *Journal of Geology*, v. 112, p. 593-605.
- Zhai, M.G., and Liu, W.J., 2003, Palaeoproterozoic tectonic history of the North China craton: a review: *Precambrian Research*, v. 122, p. 183-199.
- Zhao, G.C., 2001, Palaeoproterozoic assembly of the North China Craton: *Geological Magazine*, v. 138, p. 87-91.

## Syn- to post-collisional magmatism in the Sulu UHP belt, eastern China

Jing-Hui Guo<sup>1</sup>, Fu-Kun Chen<sup>1</sup>, Wolfgang Siebel<sup>2</sup>, Ming-Guo Zhai<sup>1</sup>

*1 Institute of Geology & Geophysics, Chinese Academy of Sciences, Beijing, 100029, China*

*Email: [jhguo@mail.igcas.ac.cn](mailto:jhguo@mail.igcas.ac.cn)*

*2 Institut für Geowissenschaften, Universität Tübingen, 72074 Tübingen, Germany*

Numerous Mesozoic plutons are exposed within the ultrahigh-pressure (UHP) metamorphic terranes in the Weihai-Rongcheng-Rushan area of the northern SuLu UHP belt. They form multi-pulse intrusive complexes or small size stocks of diversity rock types including shoshonitic gabbros and syenites, S-type granites, and I-type granites of high K alkaline series. A temporal evolution has been established on the basis of precise zircon U-Pb ages and geochemical investigations.

(1) Shoshonitic magmatism commenced shortly after UHP metamorphism in the late Triassic. Typical plutons of shoshonitic series represented by Xingjia alkali gabbros ( $212.8 \pm 4.4$  Ma;  $211.1 \pm 4.5$  Ma), Jiazishan pyroxene syenite ( $211.9 \pm 1.5$  Ma;  $209.0 \pm 6.5$  Ma) and Chashan granite ( $205.7 \pm 1.4$  Ma). They have  $\epsilon_{Nd}(t)$  of  $-12 \sim -16$ ,  $Isr$  of  $0.706-0.708$  indicating that they derived from mantle contaminated by subducted continental crust. They were likely the response to mantle upwelling induced by slab breakoff after continental subduction.

(2) Jurassic calc-alkaline intrusions postdated the UHP metamorphism by 60-80 Ma. The Duogushan granodiorite ( $160.7 \pm 1.3$  Ma), the Wendeng monzogranite ( $159.8 \pm 3.2$  Ma) and the Kunyushan monzogranite and garnet-bearing leucogranite ( $142.0 \pm 2.8$  Ma) are representative plutons. These granites contain most inherited zircons of 700-800 Ma suggesting that they were melting products of the South China Block. They have  $\epsilon_{Nd}(t)$  of  $-10 \sim -20$  with  $Isr$  of  $0.708-0.716$ . They were likely to be originated from crustal melting induced probably by lower crustal delamination after the Triassic UHP collision.

(3) The final magma pulse appeared in early Cretaceous at  $\sim 120-108$  Ma, represented by the Gejia syenogranite ( $121.1 \pm 1.9$  Ma), Liudusi pyroxene diorite ( $114.5 \pm 0.8$  Ma), Taiboding Kf-porphyritic granite ( $113.6 \pm 1.4$  Ma), Sanfoshan Kf-porphyritic granite ( $113.4 \pm 1.3$  Ma) and Weideshan granite ( $108.0 \pm 1.8$  Ma) and numerous small intrusions. They vary from monzogabbro, diorite, monzonite, K-feldspar porphyritic granite to monzogranite with characteristics of the high-K calc-alkaline and shoshonitic series. These granites are ascribed to strongly crust-mantle interaction during Cretaceous mantle upwelling and lithospheric thinning commonly observed in eastern China.

## **Geochemical diversity of magmatism during plate convergence, crustal extension and seafloor spreading in the Gulf of California**

Paterno Castillo and Peter Lonsdale

*Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093-0212, USA. Email: [pcastillo@ucsd.edu](mailto:pcastillo@ucsd.edu)*

The Gulf of California originated by intra-continental rifting of the young orogenic terrain near the western margin of the North American continent. Prior to the development of the Gulf, much of the western interior of North America was covered by Basin-and-Range-type rifting and rift-related magmatism and the western margin of the continent had been a convergent plate boundary. The lithospheric rupture in the Gulf began in the middle Miocene (12Ma) and this was accompanied by the cessation of subduction along the western margin of Baja California. Before the end of the Miocene (5.5Ma), a proto-gulf was formed and a rifting zone that rapidly matured to a system of spreading centers ruptured the Peninsular Batholith in the mouth of the Gulf. During the Pliocene, the Gulf evolved into a system of spreading axes, linked by transform fault zones and by broader non-transform belts of oblique shearing. At present, the Gulf exhibits transition along strike from what are clearly oceanic spreading axes of the Alarcon Rise, a normal mid-ocean ridge system in the Alarcon Basin that has been active since at least the past 2 m.y., in the south to the less obvious and sediment-covered spreading axes of the Salton Trough in the north. The complex tectonic history of the Gulf was accompanied by a general evolution of magmatism from those associated with suprasubduction zone and Basin-and-Range faulting to alkalic magmatism associated with intense rifting and then to increasing tholeiitic magmatism associated with nascent spreading axes. Basalt xenoliths in the Salton buttes and subsurface basalts at Cerro Prieto at the northern end, igneous rocks intruded into sediments in the youthful Guaymas Basin in the central part and extrusive lavas near the margin of Baja California at the southern end of the Gulf are indeed tholeiitic in character and are similar in many respects to mid-ocean ridge basalts (MORB). These tholeiites, however, have slight but significant geochemical differences with typical MORB collected from or near the axis of the EPR segment immediately outside the Gulf. Only the lava samples from the Alarcon Rise, its southeastern flank and near-ridge seamounts on its northwest flank are typical Pacific MORB. Calc-alkaline magmatism also has continued into Pleistocene and even Recent times on Gulf islands such as Islas Coronados and San Esteban and most especially along the Baja California coast although the main Miocene (Comondu) arc became extinct when subduction ceased at the Baja California trench. The diverse geochemical signature of magmas in the Gulf suggests that the entire region is underlain by a Pacific mantle, but it is variably contaminated by continental materials and there are isolated remnants of subducted slab, or subduction-metasomatized materials at least, in the mantle beneath the Gulf.

## **Recognition of Toudao, Baishan and Laofangzixiaoshan Formations and their significance**

Haiquan Wei<sup>1</sup>, Bolu Jin<sup>2</sup> and Chunmao Li<sup>3</sup>

1、 *Institute of Geology, China Earthquake Administration, 100029*

*Email: [weihq2002@sohu.com](mailto:weihq2002@sohu.com)*

2、 *The Sixth Geological Survey of Jilin Province, Yanji, 133001*

3、 *Institute of Prospecting Technology of Jilin Province, Changchun, 130061*

Based on a systematic survey and K-Ar dating of the Shield-forming basalts mainly NE of Tianchi volcano, the authors divide the basalts around Tianchi cone into 4 Formations: Toudao F, Baishan F, Laofangzixiaoshan F and Laohudong F. Before this research Junjianshan Formation, an old name for the shield-forming basalts of Tianchi volcano, was used to describe the strata units feature of the basalts compositing the lava shield in age between 1.48 Ma and 4.5 Ma.

The single or multiple pahoehoe of Toudao F during the shield-forming period effused from Tianchi volcano and flowed northward to a distance of a few to tens of kilometers with a wideness of hundreds to thousands meters and a thickness of a few to tens of meters. The basalts of Toudao F have a K-Ar age of between 1.908 Ma and 2.769 Ma. Baishan F, first introduced from Baishan Forestry Centre, is represented by 1.642 Ma olivine basalt covered by a 0.583 Ma feldspar-enriched basaltic lava flow at an outcrop near Bailong Power Station. The lava flows east of Erdao River, at a distance of 15 to 30 km north of Tianchi cone, has generally a younger K-Ar dating of 1.276-1.392 Ma compared with the lavas west of the river. The even younger basalts in Laofangzixiaoshan F, distributed to the NE part of Tianchi volcano in age of 0.931-0.963 Ma, preserve generally a surface flow feature of the lava flows. Basalt in Laohudong F is the youngest lava flow unit and is mainly distributed to the NE side of the volcano along a regional NE fault. Lava flows in age of 0.308 Ma—0.466 Ma from the parasitic scoria cones covered the former lavas. There exist also basalts along Heishi River (0.34 Ma) and Jinjiang River (0.402—0.417 Ma) showing a multiple centers feature of the eruption during that period.

The basaltic magma of the early and late stage of the different Formations of Tianchi basalts experienced obviously a magma mixing or wiggling process in the magma chamber as well differentiation. The field evidence of mixing and wiggling of magma batches in different color, grain size and mineral composition is in good consistence with the enormous remelt, reaction, resorb and growing rim texture features of feldspar, olivine, and pyroxene phenocrysts. Sample chemistry showing two ends member reaction implies a critical influence of the magma mixing mechanism not fully understood.

## Characteristics and Origin of Early Cretaceous Igneous Rocks in Yanshanian Orogenic Belt

SU Shangguo, DENG Jinfu, ZHAO Guochun, LIU Cui, ZHAO Xinguo

*China University of Geosciences, Beijing, 100083, China*

*Email: [susg@cugb.edu.cn](mailto:susg@cugb.edu.cn)*

There are a series of ellipse complex with long axis of northwest direction in early cretaceous in Yanshanian orogenic belt. The Xuejiashiliang complex is one of them. It is located in the Changping district, north Beijing. It consists mainly of gabbro, monzogabbro, monzonite, syenite, and granite (Fig. 1). Zircon SHRIMP dating shows that gabbro is 128.8 Ma, monzogabbro is 130 Ma, monzonite is 125.1Ma, syenite is 124.2 Ma, granite is 123.7 Ma. So the complex formed almost at the same time, at the early stage of early Cretaceous period ( $K_1^1$ ).

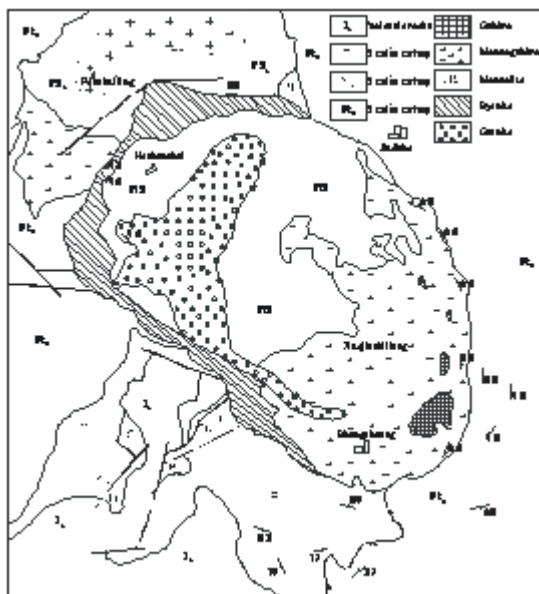


Fig. 1 Geological sketch map of Xuejiashiliang complex, northwest Beijing

There is a great controversy to the genesis of mesozoic igneous rocks in Yanshanian orogenic belt. Zhang et al. (2001), Zhou et al. (2001), Qian et al. (2002), Hong et al. (2003) think they are derived from an enriched mantle source (EMI type), because the gabbro, monzogabbro, monzonite and syenite have similar Sr-Nd isotope signatures and high negative  $\epsilon$  (Nd) values; Alternatively, Chen et al. (2002) think that magma mixing between mantle-derived and crust-derived melts was involved in their genesis, and fractional crystallization could have coupled with the process of magma mixing.

Geochemical characteristics of Xuejialiang complex show that the gabbro is enriched in Nb, Pb, Ti, It is different with the enrichment mantle with Nb positive anomalies and Pb negative anomalies (Hofmann, 1997); and the monzogabbro is enriched in Nb, and depleted in Pb, Ti, they are also is opposite to the enrichment mantle in Ti abundance; The monzonite, syenite, and granite are enriched in Pb, and depleted Nb, Ti, the trace-element patters resemble that of continental crust. The diagram of Th-Hf/3-Ta (fig. 2) and Th/Yb-Ta-Yb (fig. 3), show that the petrogenesis of the Xuejiashiliang complex is the mixing of mantle and crust.

Qipangyan complex is another typical complex of early cretaceous ( $132.90 \pm 0.66$ Ma, Zircon SHRIMP dating). There is “picritic” gabbro ( $\text{SiO}_2$  47.68%, MgO 19.09%) in the complex. It might be suggested to be generated from the asthenosphere.

We tentatively suggested as follows. Underplating of mantle-derived magma represented by gabbro magma induced partial melting of the thickened continental crust (lower crust) and thus led to produce syenite magma. The monzonite is due to mixing between gabbro magma and syenite magma. The monzonite is consistent with the existence of many dark microgranular enclaves within the monzonite.  $\text{SiO}_2$  and major elements for the gabbro, monzogabbro, monzonite and syenite shows the linear correlation, it is also the result of magma mixing. With magma mixing, Sr, Nd, Pb is so easy homogeneous that it isn't a useful signature in determining the orogenic igneous sources.

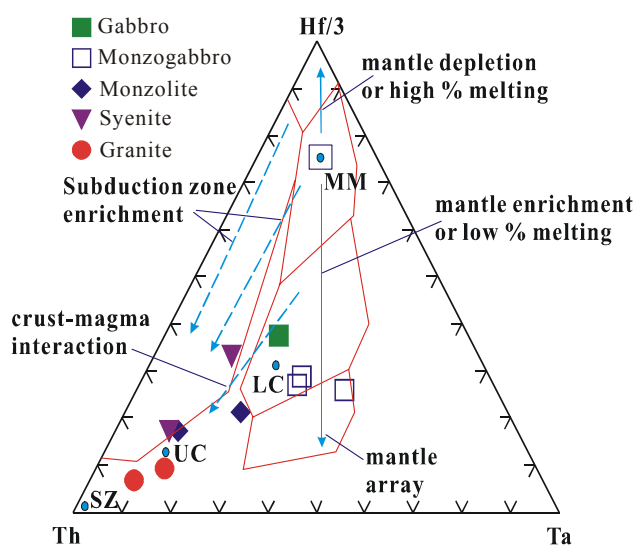


Fig. 2 Th-Hf/3-Ta diagram for the Xuejiashiliang complex (Pearce, 1995)

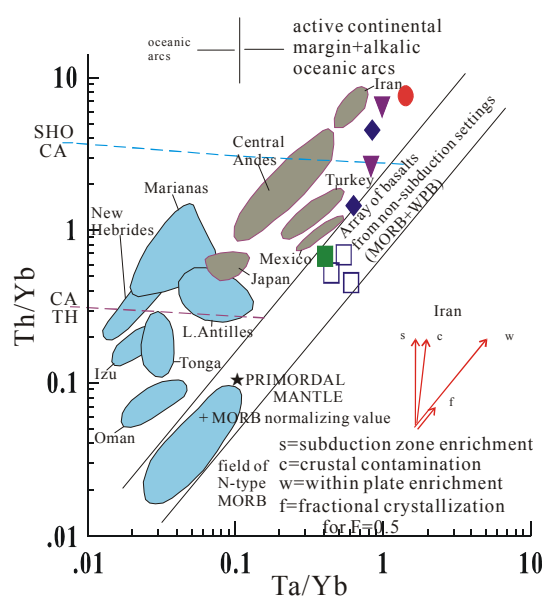


Fig. 3 Th/Yb versus Ta/Yb diagram for the Xuejiashiliang complex (Pearce, 1982)

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## References

1. Chen bin, Jahn Borming, Wei Chunjing. Petrogenesis of Mesozoic granitoids in the Dabie UHP complex, Central China: Trace element and Nd-Sr isotope evidence. *Lithos*, 2002, 60: 67~88
2. Deng, J.-F., Su, S.-G., Zhao, H.-L., Mo, X.-X., Xiao, Q.-H., Z.S., Liu, G., Zhao, G.-C. Deep processes of Mesozoic Yanshanian lithosphere thinning in North China. *Earth Science Frontiers*, 2003, 10, 41-50 (in Chinese with English abstract)
3. Hong, D.-W., Wang, T., Tong, Y., Wang, X.-X. Mesozoic granitoids from North China block and Qingling-Dabie-Sulu orogenic belt and their deep dynamic process. *Earth Science Frontiers*, 2003, 10, 231-256 (in Chinese with English abstract)
4. Hofmann A. W. Mantle geochemistry: the message from oceanic volcanism. *Nature*, 1997, 385, 219-228

5. Pearce, J.A., Harris, N.B.W., Tindle, A. G. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology*, 1984, 25, 956-983
6. Pearce, J.A. and Peate, D.W. Tectonic implications of the composition of Volcanic Arc magmas. *Ann. Rev. Earth Planet. Sci.*, 1995, **23**, 251~285
7. Qian, Q., Chung S.-L., Lee, T.-Y., Wen, D.-J. Geochemical characteristics and petrogenesis of the Badaling high Ba-Sr granitoids: A comparison of igneous rocks from North China and the Dabie-Sulu orogen. *Acta Petrologica Sinica*, 2002, 18, 275-292 (in Chinese with English abstract)
8. Zhang, Q., Wang, Y., Qian, Q., Yang, J.-H., Wang, Y.-L., Zhao, T.-P., Guo, H. The characteristics and tectono-metallogenic significances of the adakites in Yanshan period from East China. *Acta Petrologica Sinica* , 2001, 17, 236-244 (in Chinese with English abstract)
9. Zhou, X.-H., Zhang, G.-H., Yang, J.-H. Sr-Nd isotope mapping of Late Mesozoic volcanic rocks across northern margin of North China Craton and implications to geodynamic processes. *Geochimica*, 2001, 30, 10-23 (in Chinese with English abstract)
10. Wang, Y., Zhang, Q. A granitoid complex from Badaling area, North China: Composition, geochemical characteristics and its implications. *Acta Petrologica Sinica*, 2001, 17, 533-540 (in Chinese with English abstract)
11. Zhang, Q., Qian, Q., Wang, E., Zhao, T., Hao, J., Guo, G, An East China plateau in mid-late Yanshanian period: implication from adakites. *Scientia Geologica Sinica*, 2001, 36, 248-255 (in Chinese with English abstract)

## **K-rich glasses in harzburgite from Damaping mantle xenoliths, Northern east China**

Y-F. ZHU

*The Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing 100871, China*  
*Email: [yfzhu@pku.edu.cn](mailto:yfzhu@pku.edu.cn)*

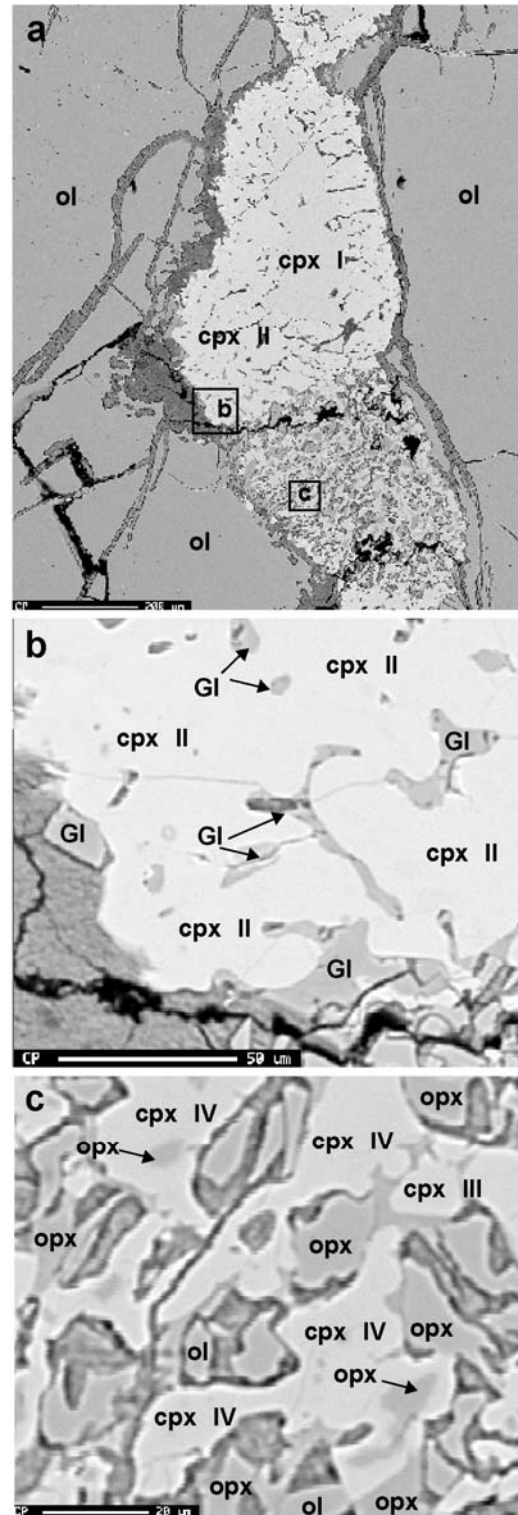
Glass-bearing mantle xenoliths provide essential information for unraveling the evolutionary history of different portions of the upper mantle. However, since most xenoliths have experienced partial melting, including the alteration of phase relations and bulk compositions, it is unclear as to whether these xenoliths truly represent their source region. Based on petrographic and experimental observations, it is clear that these melts migrated from source and were trapped in equilibrium with a peridotitic assemblage (e.g. Edgar et al., 1989; Ionov et al., 1994; Schiano et al., 1995; Draper & Green, 1999; Dawson, 2002). Although glass inclusions in minerals and interstitial glasses are principally similar in composition, the interstitial melt veins and pockets are considered to form in an open system with respect to melt inclusions trapped within single crystals (Schiano & Bourdon, 1999). Since the composition of some mantle glasses are strongly controlled by infiltrating melt(s) and primary mantle mineral reactions, glass compositions can be used to elucidate the reaction processes and to determine the nature of the original metasomatizing agents (e.g. Coltorti et al., 2000). The alkalic composition of the glasses indicates that the metasomatic agent was most likely H<sub>2</sub>O-, Si- and alkali-rich. The nature and origin of such metasomatic agents are thus highly enigmatic. Determining the origin and genesis of such glasses still has an important role for discussion. This manuscript describes the partial melting of clinopyroxene (cpx) and spinel within spinel harzburgites from Hannuoba region, northeastern China. The phase relations and chemical characteristics of the mineral paragenesis indicate that the pre-existing cpx and spinel were stable at mantle depths of >210km, and the potassium-rich glasses formed via incipient (near-solidus) melting of K-bearing cpx.

Potassium- and silica-rich glasses (SiO<sub>2</sub> = 65.3 % ~ 67.4 %; K<sub>2</sub>O = 7.1 % ~ 9.8%; Na<sub>2</sub>O = 4.4 % ~ 6.5%) in spongy clinopyroxene rim and spinel with core-rim texture from anhydrous spinel harzburgite xenoliths collected from Damaping of Hannuoba region, northeastern China, were studied in this manuscript. These K-rich glasses were most likely formed by incipient partial melting of clinopyroxene due to pressure decrease during mantle upwelling. The degree of clinopyroxene melting is estimated to



be higher than 15% based on Na and Ca mobility, which is mostly consistent with the composition of Cr-rich spinel in same rocks. In order to generate glasses with  $K_2O$  contents of 7.0~9.8% by cpx partial melting at a degree of 15% in a closed system,  $K_2O$  contents in the primary clinopyroxene should be >1.0 wt.%. Clinopyroxene with such high  $K_2O$  contents are stable at the depth of ~210km. The Cr-poor spinel core ( $Cr\# < 30$ ) is surrounded by a spongy rim, consisting of Cr-rich ( $Cr\# > 37$ ) spinel and an unknown  $H_2O$ -bearing phase (the X-phase). The spongy rim was stable in much higher-pressure environment relative to its core. A mantle recycling mechanism is involved to explain the observed core-rim texture of spinel. The Cenozoic asthenosphere under north China craton probably experienced insulation heat release. The K-rich melt that was formed by clinopyroxene melting in asthenosphere, however, are least possibly the magma source of the host alkali basalts based on their greatly difference in composition.

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## **Global tectonic and climatic control of mean elevation of continents**

Zhang Youxue

*Department of Geological Sciences, The University of Michigan, Ann Arbor, MI  
48109-1005, USA*

*E-mail: [youxue@umich.edu](mailto:youxue@umich.edu)*

Mean elevation of all continents, as well as mean elevation of individual continents, should be at the fundamental level controlled by the global tectonic and climatic systems. I propose a first-order model considering the interplay of the two factors in controlling mean elevation of continents. The model is able to account for the positive correlation between the present-day mean elevation and area of individual continents (except for Antarctica). Furthermore, it can also explain the low sea level during the times of supercontinents. Finally the model is used to evaluate the variation of continental crust thickness with time.

## **The thickness and modification of the lithosphere of stable continental areas: the role of basal drag**

Z. Garfunkel

*Institute of Earth Sciences, Hebrew university, Jerusalem, Israel, 91904*

*E-mail: [zvi.garfunkel@huji.ac.il](mailto:zvi.garfunkel@huji.ac.il)*

The lithosphere, the earth's outer strong part, forms the plates that move as coherent units over the asthenosphere. Because silicate rock rheology is temperature dependent, the lower parts of the plates become progressively more ductile downward, so the bottom of any plate is a zone of downward increasing diffuse deformation rather than a sharp boundary. Here the base of the lithosphere is placed where the sliding velocity of material relative to the rigid top of any plate exceeds some threshold (e.g. 2 mm/y=2000 km/Ga), so over geologic time spans the deeper material becomes effectively decoupled from the moving plates. The deformation at the bottom of the plates is controlled by the viscous drag and shear stresses that arise because of the sliding of the plates over the asthenosphere. This determines the effective plate thickness and their decoupling from the deeper levels.

The effects of the basal shear are modeled by using the experimentally determined flow properties of olivine - the mineral which controls the rheology of lithospheric mantle rocks. The situations corresponding to various geotherms are examined. Based on models of plate driving mechanics, the basal drag is taken to be in the range of 0.5-1.5 MPa. It is found that the threshold velocity is reached at the bottom of ca. 20 km thick transition zones in which shearing rapidly increases downward. The depths of these zones depend on the geotherm, the magnitude of the basal drag, and the presence of fluids. In dry lithospheric mantle beneath Archean cratons the threshold velocity is reached at a depth of 200-240 km, depending on the magnitude of the basal drag, but it is reached at shallower depth where higher temperatures prevail. Because the rheology also depends on pressure, the transition zone is deeper where the geothermal gradient is lower, all other factors being equal. Consequently the threshold velocity is reached at different temperatures in different areas, so the base of the lithosphere does not correspond to a particular isotherm.

These results show that the thickness of the lithosphere underlying stable continental areas is determined by a combination of several factors. Therefore, if these change then lithospheric thickness will also change. In particular, changes of plate motions and/or of the vigor of convection can change the magnitude of the basal drag. The resulting changes in lithospheric thickness lead to a positive feedback because of thermal interaction with the asthenosphere, so the total effect can amount to tens of kilometers if

the change in basal shear persists long enough. It also follows that for the lithosphere to persist it is not enough that it should be buoyant, but it also must escape being sheared off laterally. Continental lithosphere may be thinned because of enhanced flow next to subduction zones or in an intra-plate setting by hot spots; when thinned it can also be reworked in orogenic belts.

Old lithosphere beneath Archean cratons most likely cooled since its formation because of decay of radioactive elements in the crust and of cooling of the mantle. Thus it could have been stabilized in the first place and maintained its thickness only if the drag at its base was smaller than at present.

# Lithosphere Structure and Deformation of Chinese Continent from Pn Tomographic Inversion

Xiaodong Song<sup>1,2</sup>, Chuntao Liang<sup>1</sup>, and Jinli Huang<sup>2</sup>

1. *Geology Department, University of Illinois at Urbana-Champaign, USA*

*Email: [xsong@uiuc.edu](mailto:xsong@uiuc.edu)*

2. *Institute of Earthquake Prediction, China Seismological Bureau, Beijing, China*

Pn travel times are affected by crustal velocity and thickness as well as uppermost mantle Pn velocity and anisotropy. Pn velocity, in turn, varies with changes in temperature and material composition and Pn anisotropy may indicate the history of mantle deformation. Thus, Pn tomography provides an important tool to probe lithospheric structure and dynamics. We have recently used a large data set of Pn arrival-time picks from Chinese national, Chinese local, and international earthquake bulletins to invert for Pn velocity and anisotropy and crustal thickness in China (Liang et al., *J. Geophys. Res.*, 2004). In addition, to improve the resolution in the Tibetan Plateau, we have also added new data from temporary station deployment and newly installed Chinese digital stations. Our inversion reveals significant features that correlate well with surface geology. The major basins in the west are characterized by high Pn velocities and relatively weak anisotropy, suggesting they are strong and cold with little deformation. Strong anisotropy is also found beneath other high deformation regions (the Tibetan plateau, western Tien Shan, and part of North China), suggesting the anisotropy is mostly related to recent large-scale tectonic activities. Slow Pn velocities are found in areas of active volcanoes (Myanmar and western Yunnan) and Quaternary volcanisms in northern Tibet, in seismically active areas in North China and western Tien Shan, and in the south China (the Hainan plume). A prominent belt of slow velocity is found connecting northern Tibet and the eastern margin of the Tibetan Plateau, which separates the high velocities of the southern Tibet to the south, the Tarim and Qaidam Basins to the north, and the Sichuan Basin and Yangtze Block to the east. We speculate that the fast-slow boundary along the Banggong Nujiang Suture and the border of the eastern India and Myanmar marks the strong Indian lithosphere and the highly deformed and weakened Eurasia lithosphere. The anisotropy pattern in the eastern margin of the Tibetan Plateau suggests a mantle lithospheric deformation similar to the clockwise rotation of material observed at the surface. A large area of North China shows prominent slow Pn velocity beneath Archean basement with thin crust. The observations are consistent with rifting, lithospheric thinning, and mantle upwelling in the region. The Pn anisotropy in North China is consistent with a dextral simple shear in the NNE direction in the lithosphere mantle during the last (and ongoing) major deformation period. The locations of gold ore and oil deposits in North China correlate remarkably well with the slow Pn velocities, suggesting the metallogenesis and oil formation of the region may closely related to magma and thermal activity in lithospheric mantle and crust-mantle interaction since Mesozoic and Cenozoic.

## **A Seismic Perspective of the Rio Grande Rift and Adjacent Regions**

James Ni

*George W. Gardiner Professor of Physics, Department of Physics, MSC 3D, New Mexico State University, Las Cruces, NM 88003-8001*

*E-mail: [jni@nmsu.edu](mailto:jni@nmsu.edu)*

The seismic structure of the crust and upper mantle of the southwestern United States has been examined using teleseismic arrivals recorded by the RISTRA Array. Crustal thickness averages  $44.1 \pm 0.3$  km beneath the Great Plains and  $45.6 \pm 0.1$  km beneath the Colorado Plateau. Crustal thinning beneath the RGR is broadly symmetric about the rift axis, with the thinnest crust (35 km) located directly beneath the rift axis, suggesting a pure shear stretched lithosphere beneath the RGR. The tomographic image from a joint inversion of seismic body and surface waves show a strong low velocity (4.2 km/sec) feature in the shallow mantle beneath the Rio Grande Rift and indicating solidus temperatures and the existence of partial melt. The high velocity mantle beneath the Great Plains extends to 300 km depth and appears to continue below 410 km into the transition zone. The lateral velocity gradients are the result of thermal variations which could drive small-scale convection.

## **Finite element modeling of transient saline hydrothermal fluids in multi-faulted crust: implications for ore-forming processes**

Jianwen Yang

*Department of Earth Sciences, University of Windsor, Ontario, N9B 3P4, Canada*

*Email: [jianweny@uwindsor.ca](mailto:jianweny@uwindsor.ca)*

A finite element algorithm is developed to simulate the fully coupled transient fluid flow, heat and solute transport in multi-faulted crust and yield the regional-scale free thermohaline convection patterns for the McArthur basin in northern Australia.

Numerical results indicate that salinity variation through the basin has an important influence on fluid migration and thermal regime. The spatial and temporal distribution of saline fluids can either promote or impede free convection. Relatively saline conditions at the basin floor favour free convection; whereas high salinities at depth suppress the development of convective hydrothermal systems. When salinity increases with depth, a higher geothermal gradient is required to induce significant fluid circulation.

# The importance of subsolidus processes in interpreting geochemical trends and textures in mantle peridotites and pyroxenites

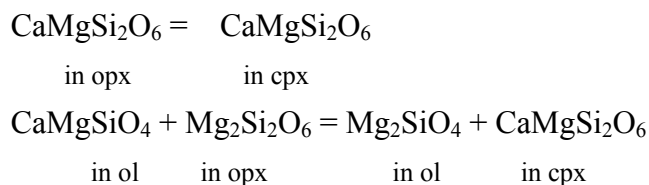
Hugh O'Neill

*Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia. E-mail: [hugh.oneill@anu.edu.au](mailto:hugh.oneill@anu.edu.au)*

Upper mantle peridotites are generally thought to be residues of the partial melting that produces basalt, and have accordingly been much studied by geochemists to constrain better the processes involved in basalt generation. However, all mantle peridotites exhibit a complex subsolidus history that must be taken into account before inferences regarding melting and melt extraction can be made. From the geochemical perspective, these processes can be divided into two kinds:

1. Cooling and decompression under isochemical conditions (whole-rock chemistry unaffected):
  - a) The phase relations (controlled by major element chemistry) that affect the modal abundance of all phases
  - b) The exchange of trace elements between phases as a function of temperature
2. "Metamorphic" processes, such as strain-induced mineral segregation, local vein or dyke formation, and mechanical mixing, which produce changes in whole-rock chemistry

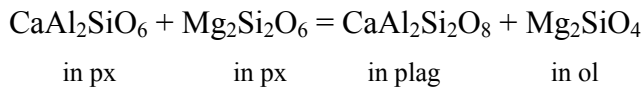
The isochemical changes are generally well understood, but their essential importance to geochemical interpretation continues to be overlooked. As regards modal mineralogy, there are two processes in the spinel peridotite facies that are particularly significant. Firstly, the exchange of CaO among olivine (ol), orthopyroxene (opx) and clinopyroxene (cpx) with cooling results in the subsolidus production of cpx in depleted harburgites and dunites, e.g., according to the reactions:



The CaO in olivine should not be forgotten. Much experimental and thermodynamic evidence shows that there is > 0.25 wt% CaO in olivine in equilibrium with any reasonable basaltic melt in the spinel peridotite facies, yet preservation of such high amounts of CaO is rare (usually CaO is less than 0.1 wt %).



Secondly, the decrease in the solubility of  $\text{Al}_2\text{O}_3$  in pyroxenes with decreasing temperature results in the formation of either spinel or, at lower pressures, plagioclase, e.g., according to the reaction:



The phase equilibria controlling the solubility of  $\text{Al}_2\text{O}_3$  in pyroxenes are complicated by the effects that  $\text{Cr}_2\text{O}_3$  has, and are difficult to predict with our present knowledge; however, subsolidus plagioclase should carry a distinct geochemical signature in having low MgO relative to any plagioclase that may have been in equilibrium with melt. Plagioclase attributed to “melt impregnation” from textural interpretations has this signature, arguing that it is in fact subsolidus.

A common assumption has been that cpx carries most of the whole-rock’s incompatible trace elements, such that analysis of cpx by SIMS or LA-ICP-MS can yield melt compositions that were in equilibrium with the peridotite. This assumption is generally unlikely to be valid; the temperature-dependence of cpx/opx and even cpx/ol partition coefficients means that significant fractions of incompatible trace elements may be held in opx ( $\pm$ ol) at magmatic temperatures, which will repartition during subsolidus cooling into cpx. The interpretation of cpx trace-element patterns (indeed, any kind of mineral trace-element pattern) in terms of equilibrium with a melt (or fluid) therefore requires not only the reconstruction of mineral compositions as a function of temperature, but also an estimate of the temperature at which the rock would have been in equilibrium with the melt or fluid. Hypotheses from the trace-element geochemistry of cpx regarding the existence of highly depleted melts may simply be an artefact of subsolidus reequilibration in a harzburgite that is residual to a normal MORB-like melt.

Processes that affect the whole-rock chemistry of peridotites are more controversial, but also potentially more insidious. One kind of process will be discussed. The field evidence of well-preserved mantle sections argues that many mantle peridotites have been affected by a process that starts with the formation of chrome-diopside segregations. A variety of petrological and geochemical evidence argues that these Cr-diopside pyroxenites or websterites are produced locally in the host peridotite (on the scale of cm or a few metres at most), rather than being a product of large-scale melt or fluid transport. Chemically, the Cr-diopside websterites are characterized by high Cr and Cr# (molar  $\text{Cr}/(\text{Al}+\text{Cr})$ ), similar to the adjacent peridotites. Mg#s are primitive (molar  $\text{Mg}/(\text{Mg}+\sum\text{Fe}) > 0.89$ ). Cpx are relatively refractory in terms of their incompatible-element contents (Na, Ti, REE, etc); both cpx and opx are compositionally similar, if not identical, to these phases in the adjacent peridotites. The youngest segregations form dikes with sharp margins cutting the peridotite foliation, and contain no olivine. The lack of olivine is highly significant in demonstrating the

local origin of the Cr-diopside pyroxenites, because the primary phase volume of olivine expands with decreasing pressure, making olivine ( $\pm$ chromite) the first phase to crystallise from any primary mantle melt. Field relations show that with increasing deformation the dikes are rotated into the plane of the foliation, becoming stretched and smeared out; the sharp margins are lost, and olivine from adjacent peridotite is tectonically introduced into the pyroxenite. Ultimately the pyroxenite is more-or-less completely reworked back into the peridotite, with only diffuse layers enriched in pyroxene ( $\pm$  spinel) remaining. I hypothesise that this process is widespread in mantle peridotites, and has commonly affected whole-rock geochemistry. For example, apparent variations in the amount of melt extracted in some peridotite suites (as represented on plots of CaO, Al<sub>2</sub>O<sub>3</sub>, etc vs. MgO) may be due to different degrees of pyroxene depletion and re-enrichment caused by this process, rather than indicating trapped melt or metasomatism.

# **The role of lower continental crust during continental subduction/collision and later lithospheric thinning, examples from the Dabieshan, eastern China**

Kai YE<sup>1</sup> Jingbo Liu<sup>1</sup> and Min SUN<sup>2</sup>

<sup>1</sup> *State Key Laboratory of Lithosphere Tectonic Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, P.O.Box 9825.*

*Email: [yekai@mail.igcas.ac.cn](mailto:yekai@mail.igcas.ac.cn)*

<sup>2</sup> *Department of Earth Sciences, University of Hong Kong, Hong Kong, PR China*

It is known that ultrahigh-pressure metamorphic rocks in collisional orogen record evidence of subduction of continental crust to depths exceeding 80-120 km (coesite and diamond stability fields). However, most of the orogenic ultrahigh-pressure (UHP) metamorphic belts are composed of subducted upper crustal rocks, and are lack of rocks typical of middle to lower continental crust. Theoretical approaches indicate that the variation of the contents of hydrous minerals in the upper and lower continental crust could result in contrasting metamorphism during the continental subduction and collision. The hydrous greenschist- to amphibolite-facies upper crust tends to be completely transformed to equilibrium high-pressure (HP) or ultrahigh-pressure (UHP) equivalents driven by fluid deducing from dehydration of the hydrous minerals during subduction. However, the dry granulite-facies lower crust likely maintains metastable during subduction, due to the lack of a fluid phase. The different metamorphic behavior must result in disparities in rheology, density, deformation and volume change, and thus induce the decoupling of the HP and UHP upper crust from the metastable granulitic lower crust. The HP and UHP slices exhume back to the crustal level, driven by buoyancy force during collision. Meanwhile, the metastable lower crust still attaches to the underlying lithospheric mantle, and they may roll back by buoyancy force and underplating to the bottom of the active continental margin and form the mountain root after break-off of the subducted slab. The granulitic thickened crustal root maintains stable under conditions in the absence of fluid. When fluid penetrates into the mountain root, for example during later rifting, the metastable mafic granulite transforms to eclogite, and results in the delamination of the underlying lithosphere, and subsequently upwelling of the asthenosphere. The upwelling of the anthenosphere further results in partial melting and uplift of the felsic granulite of the mountain root. Such theoretical considerations are supported by recent observations in the Dabieshan collisional orogen.

## **Petrology, geochronology and tectonic evolution of UHP metamorphic eclogites from southwestern Tianshan, China**

Lifei Zhang, Yongliang Ai, Qiang Li, Xuping Li,  
Shuguang Song, Chunjing Wei

*School of Earth and Space Sciences, Peking University, Beijing, China*

*Email: [lfzhang@pku.edu.cn](mailto:lfzhang@pku.edu.cn)*

A newly recognized ultrahigh-pressure (UHP) terrane in the Chinese Western Tianshan orogenic belt contains blueschists, eclogites and metapelites. This belt extends westward to the "South Tianshan" in Tajikistan, Kyrgyzstan, Kazakhstan and Uzbekistan for more than 2500 km long in central Asia. The petrological studies show that the metamorphic evolution of Southwestern Tianshan UHP eclogitic rocks can be divided into three stages, peak UHP stage (560-600°C, 4.95 ~ 5.07 GPa), retrograde UHP eclogite facies stage (598-496°C, 25.72~26.66±1 kbar) and retrograde epidote-blueschist facies stage. The geochemical characteristics of UHP eclogites from southwestern Tianshan indicate that the protolith rock assemblages of UHP eclogitic rocks can be grouped into three types, type I eclogite assemblage (EC1), type II eclogite assemblage (EC2) and blueschist assemblage (BS1). The type I eclogite assemblage (EC1) is geochemically akin to alkaline within-plate oceanic island basalt (OIB). EC2 shows affinity to enriched mid-oceanic ridge basalt (EMORB). REE and other immobile trace element characteristics of blueschist assemblage BS1 resemble those of normal mid-oceanic ridge basalt (NMORB). These three assemblages are likely formed on a seamount setting. Southwestern Tianshan UHP metamorphic belt is thus interpreted as a subduction-accretionary complex formed by tectonic juxtaposition and imbrication of seamount, seafloor, trench and volcanic arc sequences during oceanic crust subduction. New ion microprobe (SHRIMP) U-Pb dating of zircon from UHP eclogites and metapelites indicates Triassic ages for the collision in western Tianshan. Zircon from four eclogites yield magmatic ages of 310 ~ 413 Ma in the cores and one metapelite contained detrital zircon cores as old as 1886±20 Ma. Zircon rims reveal peak metamorphic ages of 233±4 ~ 225±6 Ma. The geochronological data suggest that a South Tianshan paleo-ocean was developed between the Tarim continent and the Yili-central Tianshan Craton before the Carboniferous (>310 Ma). A new tectonic evolution for HP-UHP metamorphic rocks of the Chinese Western Tianshan orogenic belt represented by HP-UHP metamorphic eclogitic rocks is proposed in the light of recent palaeomagnetic, paleontologic, sedimentary and stratigraphic studies, that is that the Paleo-southwestern Tianshan Ocean appeared before the Carboniferous (>310 Ma), oceanic basalts underwent HP/UHP metamorphism and uplifted to the surface during the Permian-Triassic subduction and continent collision.

# Evolution from Oceanic Subduction to Continental Collision: A Case Study of the Northern Tibetan Plateau Inferred from Geochemical and Geochronological Data

Shuguang Song<sup>1,2</sup>, Lifei Zhang<sup>1,2</sup>, Yaoling Niu<sup>3</sup>, Li Su<sup>4</sup>, Biao Song<sup>2</sup> and Dunyi Liu<sup>2</sup>

<sup>1</sup> *Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing 100871, China*

*Email: [sgsong@pku.edu.cn](mailto:sgsong@pku.edu.cn)*

<sup>2</sup> *Shrimp Laboratory, Institute of Geology, CAGS, Beijing 100037, China*

<sup>3</sup> *Department of Earth Science, Durham University, Durham DH1 3LE, UK*

<sup>4</sup> *Geologic Lab Centre, Chinese University of Geosciences, Beijing 100083, China*

Two apparently distinct paleo-subduction zones are recognized in parallel along in the northern margin of the Tibetan Plateau: the North Qilian *Oceanic-type* Suture Zone with ophiolitic mélanges and high-pressure eclogite and blueschist in the north, and the North Qaidam *Continental-type* UHP Belt in the south with ultrahigh-pressure (UHP) metamorphic terranes comprising pelitic and granitic gneisses, eclogite and garnet-peridotite. Eclogites from both belts have protoliths broadly similar to MORB or OIB with overlapping metamorphic ages (480–440 Ma, with weighted mean ages of 464±6 Ma for the North Qilian and 457±7 Ma for the North Qaidam) by zircon U-Pb SHRIMP dating. On the other hand, coesite-bearing zircon grains in pelitic gneisses from the North Qaidam UHP Belt yield a peak metamorphic age of 423±6 Ma, which is about 40 Myrs younger than eclogite formation, and a retrograde age of 403±9 Ma. These data, together with the regional geology and data on the Precambrian basement, allow us to infer that these two parallel belts may represent an evolution sequence from oceanic subduction, to continental collision, to continental underthrusting and to the ultimate exhumation. That is, the Qilian-Qaidam Craton, probably a fragment of the broken Rodinian super-continent with a passive margin and extended oceanic lithosphere in the north, subducted beneath the North China Craton reaching depths greater than 100 km at about 423 Ma and exhumed at about 403 Ma (zircon rim ages in pelitic gneiss). Our new data and interpretations offer new insights into on global tectonic evolution in the early Paleozoic era.

# Calculated Phase Relations for UHP Eclogites and Whiteschists in the System $\text{Na}_2\text{O} - \text{CaO} - \text{K}_2\text{O} - \text{FeO} - \text{MgO} - \text{Al}_2\text{O}_3 - \text{SiO}_2 - \text{H}_2\text{O}$

Jian-Jun Yang<sup>1,2</sup> and Roger Powell<sup>2</sup>

<sup>1</sup> *State Key Laboratory of Lithosphere Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China*

*Email: [jjyang@mail.igcas.ac.cn](mailto:jjyang@mail.igcas.ac.cn)*

<sup>2</sup> *School of Earth Sciences, The University of Melbourne, Parkville, Victoria 3010, Melbourne, Australia*

Pressure-temperature grids in the system NCKFMASH ( $\text{Na}_2\text{O} - \text{CaO} - \text{K}_2\text{O} - \text{FeO} - \text{MgO} - \text{Al}_2\text{O}_3 - \text{SiO}_2 - \text{H}_2\text{O}$ ) and the subsystems have been calculated in the ranges of 15 – 45 kbar and 550 – 900 °C, using an internally consistent thermodynamic dataset and newly developed models of complex solid solutions, with the software THERMOCALC. Minerals considered for the grids include garnet, omphacite, diopside, jadeite, hornblende, actinolite, glaucophane, zoisite, lawsonite, kyanite, coesite, quartz, talc, muscovite, paragonite, biotite, chlorite, and plagioclase, with kyanite, muscovite, coesite/quartz, and  $\text{H}_2\text{O}$  (and also garnet in the case of full system) assumed to be in excess. Compatibility diagrams are used to analyse the consistency and validity of the grids. P-T pseudosections prove to be a powerful approach to model natural eclogites of different compositions and a whiteschist from UHP terranes in China. Water content contouring of P-T pseudosections along with appropriate geotherms provides more reliable information about dehydration in subducting slabs.

## Stepwise Recrystallization during Subduction Metamorphism

Clarke, G.L.<sup>1</sup>, Powell, R.<sup>2</sup> & Fitzherbert, J.A.<sup>1</sup>

<sup>1</sup>*School of Geosciences F05, University of Sydney, Sydney, NSW 2006, Australia*

*Email: [geoffc@mail.usyd.edu.au](mailto:geoffc@mail.usyd.edu.au)*

<sup>2</sup>*School of Earth Sciences, University of Melbourne, VIC 3010, Australia*

Eocene MORB-type eclogites in northern New Caledonia record peak assemblages involving barroisite, winchite, garnet, omphacite, clinozoisite, phengite and quartz that reflect conditions of  $P \approx 2.0$  GPa and  $T \approx 600^\circ\text{C}$ . These occur as pods in glaucophanite that form a nappe tectonically overlying a disrupted sequence of Cretaceous to Eocene metasedimentary and metavolcanic rocks recrystallised at blueschist to eclogite facies conditions. Systematic changes in mineral assemblage in the latter rocks reflect a field gradient that extended from lawsonite-omphacite equilibrium conditions ( $P = 0.7\text{--}1.0$  GPa,  $T = 350\text{--}400^\circ\text{C}$ ) to eclogite facies conditions ( $P \approx 1.7$  GPa,  $T \approx 550^\circ\text{C}$ ) that has been tectonically-disrupted. The metamorphic evolution of the MORB-type eclogites is inferred from calculated  $P$ - $T$ - $\text{MH}_2\text{O}$  pseudosections for bulk rock compositions appropriate to these rocks in the model system  $\text{CaO}\text{--}\text{Na}_2\text{O}\text{--}\text{K}_2\text{O}\text{--}\text{FeO}\text{--}\text{MgO}\text{--}\text{Al}_2\text{O}_3\text{--}\text{SiO}_2\text{--}\text{H}_2\text{O}$ , and additional context provided by the blueschist assemblages. Mineral inclusions in garnet from the MORB eclogites include actinolite, glaucophane, chlorite, omphacite and clinozoisite, reflect prograde blueschist facies conditions of  $T \approx 450^\circ\text{C}$  and  $P \approx 15$  kbar. On the basis of calculated mineral modes and water budgetary considerations, subsequent recrystallization is inferred to have halted until  $T \approx 550^\circ\text{C}$ , when comparatively rapid garnet growth preserved relics of the metastable prograde assemblage. Progressive recrystallization then continued to peak conditions, the eclogite becoming progressively less water-rich. Metastable persistence of the prograde assemblage between 450 and  $550^\circ\text{C}$  in the New Caledonian eclogites reflects a process that may occur commonly in subduction metamorphism involving staged or stepwise recrystallization linked to fluid availability.

## **The metamorphic evolution of eclogitic rocks from the main hole of Chinese Continental Scientific Drilling in north Jiangsu, China: an elucidation on the uplift processes of the ultrahigh-pressure metamorphic terrane**

You Zhendong<sup>1)</sup>, Su Shangguo<sup>2)</sup>, Liang Fenghua<sup>3)</sup>, and Zhang Zeming<sup>3)</sup>

<sup>1</sup>*China University of Geosciences, Wuhan 430074, China*

*E-mail: [zdyou@263.net](mailto:zdyou@263.net)*

<sup>2</sup>*China University of Geosciences, Beijing 100083, China*

<sup>3</sup>*key Laboratory of Continental Dynamics, MLR*

*Institute of Geology, Academy of Geological Sciences, Beijing 100037, China*

A close study on the petrography of the metamorphic rocks from the main hole of the Chinese Continental Scientific Drilling (CCSD) reveals that the major metamorphic rock association comprises: (1) Eclogites and garnet clinopyroxenites ; (2) Eclogitic gneisses; (3) Garnet peridotites; (4) Biotite (hornblende) two-feldspar gneiss (granitic gneiss) and (5) Fault breccia and mylonites. The rock association elucidates the architecture of the deep subducted slab. Most of the eclogites are mafic protoliths having a long residence history in the crust before the deep subduction of the continental slab. However the garnet clinopyroxenites are closely related with garnet peridotites which occur within the 607—783m level of the drill hole. Based on their mineralogical and petrochemical characteristics they were ultramafic complexes incorporated into the subducted slab from the surrounding mantle during the deep subduction of the continental slab and had undergone ultrahigh –pressure metamorphism (UHPM). The eclogitic gneisses, equivalent partly to paragneiss as called by some geologists, are UHPM rocks of intermediate acidic protolith associated with the mafic ones. The granitic gneisses are of diverse origin, however, judging from the amphibole and biotite schist relics most of them are products of decompressive partial melting of the retrogressive amphibolite and biotite gneiss.

The metamorphic evolution of the eclogitic rocks can be divided into 3 major stages. The first (M1) is the ultrahigh pressure metamorphism (UHPM) as evidenced by coesite inclusions within garnet, omphacite and rutile grains in eclogites. The titanite in garnet peridotites is an evidence for their ultrahigh-pressure history. The second (M2) is the retrogressive stage during which most of the UHPM rocks were turned to rocks of high-pressure eclogite facies, amphibolite facies and then epidote amphibolite facies. At this stage the eclogites are characterized by the growth of symplectites and coronas. These peculiar structures reflect the disequilibrium and re-equilibrium history of the rock. The eclogitic gneiss is retrograded to be biotite



(hornblende) plagioclase gneiss and epidote biotite (amphibole) gneiss which are partly remelted or owing to K-metasomatism of the HP supercritical fluid turned to biotite hornblende two feldspar gneiss (so-call orthogneiss). Some of them are allanite (Ce)-bearing. The allanites are zonal with  $La/Ce=0.42-0.72$  and are rimmed by epidote, representing the later overprint of epidote amphibolite facies retrometamorphism. The third stage (M3) is characterized by the formation of tectonic breccia and mylonites in response to the brittle and ductile-brittle deformation related to the uplift. The matrix of the tectonites containing chlorite, actinolite and calcite indicates the greenschist facies of metamorphism (M3). All of the above-mentioned 3 stages of metamorphism are records of the tectonic processes surpassed by these eclogitic rocks. Careful microtextural analysis can reveal the time relations of crystallization to evidences of deformation.. Based on the petrographic study combined with geochronological work published hitherto it is possible to delineate a clock-wise metamorphic  $PTtD$  path of the Donghai UHP terrane which is comparable in pattern with those of the Dabieshan.

The metamorphic evolution and the successive deformational events found in the CCSD main hole have cast some light on the Mesozoic continental dynamics in eastern China. It confirms that during the Triassic collision of the two (Yangtze and North China) plates (around 240Ma) voluminous crustal materials including granitic rocks can deeply be subducted to mantle depth and then rapidly returned back to the Earth's surface. The exhumation of the UHP terrane was a complicated process. The earlier uplift subsequent to the peak metamorphic stage of the UHP rocks was very rapid (c. 5 km/Ma) and were nearly adiabatic and then was followed by retrograde metamorphism of amphibolite facies during which decompressive partial melting had taken place (as late as 180 Ma). Regional partial melting of the continental crust would eventually caused the further uplift of the slab and the presence of extension regime. The extensional tectonics of the subducted -extruded continental crust was accompanied by the albite epidote amphibolite facies to greenschist facies of retrometamorphism.

## **Genesis of adakitic magmas in south Tibet: interaction between Asian mantle lithosphere and subducted Indian continental basaltic crust**

Zhengfu Guo <sup>1,2</sup>, Marjorie Wilson <sup>2</sup> & Jiaqi Liu<sup>1</sup>

<sup>1</sup>*Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, P. R. China. Email: [zfguo@mail.iggcas.ac.cn](mailto:zfguo@mail.iggcas.ac.cn)*

<sup>2</sup>*School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK*

Adakites, which are considered to be products of partial melting of subducted oceanic lithosphere, are mainly located in the circum-Pacific margins. Age of adakites, which have been found in the Lhasa terrane (south Tibet), ranges from 10 Ma to 18 Ma. Collision between the Indian and Eurasian continents occurred in 55-50 Ma. These adakites in south Tibet were generated in the post-collision tectonic setting. Moreover, there is no contemporaneous oceanic lithospheric subduction beneath the Lhasa terrane. Thus, the adakites in south Tibet did not derive from partial melting of subducted oceanic lithosphere. We describe adakites in Lhasa terrane, which have characteristics of high Mg values, Cr and Ni contents. We present evidence that the adakites formed by interaction between Asian mantle lithosphere and subducted Indian continental basaltic crust. This mechanism of adakite generation probably is a common model for genesis of adakites occurred in continent - continent collision belts, which is an additional way of forming adakitic magmas.

## **Petrogenesis of a big dunite body in the Qinling orogenic belt, central China**

L. Su<sup>1</sup>, S.G. Song<sup>2</sup>, D. W. Zhou<sup>3</sup>

*1 Geologic Lab Centre, Chinese University of Geosciences, Beijing 100083, China*

*Email: [suli@cugb.edu.cn](mailto:suli@cugb.edu.cn)*

*2 Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing 100871, China*

*3 Department of Geology, Northwest University, Xi'an 710069, China*

The Songshugou dunite body is the largest ultramafic block in the Eastern Qinling Orogenic Belt, Central China. It occupies an area of about 20 km<sup>2</sup> and consists predominantly of dunite (95 vol.% of the total body), and its country rocks consist of high-pressure granulite, garnet clinopyroxenite and amphibolites with or without garnet. Some researchers regarded it as a mantle peridotite of the basal part of an ophiolite suite, and others suggested that this dunite body is of properties of magmatic crystallization. On the basis of characteristics of petrography, melt inclusions, mineral and whole-rock geochemistry, we indicate that the Songshugou dunite body is the product of reaction between plume-originated high-Mg melt and mantle rocks through melt porous percolation flow.

Four types of rocks have been distinguished in the body. (1) Fine-grained mylonitic dunite with > 90 % olivine (Fo 90.37–91.57) and minor secondary phases of serpentine, talc, antholite and tremolite, it shows strong ductile shear deformation characterized by well-developed foliations and mylonization structures. (2) Coarse-grained Dunite with up to 98 modal percent of olivine (Fo 90.51-90.98) and minor chromite. Chromite occurs as cumulate bands within some coarse-grained dunite blocks. (3) Orthopyroxene peridotite: It consists of olivine (Fo 90.32–91.31) and enstatite (En 91.52–92.06) with minor diopside (< 2%) and chromite. The modal contents of olivine and enstatite vary largely in different samples, and orthopyroxene can reach up to 80 % in some samples. Most rocks have interlayering structure of the cumulate determined by variations in content of olivine and pyroxene. (4) Olivine diopsidite: It occurs as dykes in the fine-grained dunitic mylonite. Olivine in this rock contains significant lower Fo content (< 81) than that in other rocks.

The normalized REE and trace element patterns show that fine- and coarse-grained dunites is flattened or broad U-shaped patterns, suggesting that a high-Mg melt has strongly modified the mantle harzburgites through melt-rock interactions. Primitive melt inclusions were mainly observed in olivine, enstatite and diopside, and sometimes in Cr-spinal from all types of rocks. Composition of daughter minerals and homogenization temperature of these melt inclusions in olivines suggest olivines mostly have precipitated through rock-melt reaction during a large quantity of high-Mg melt porous percolation at high temperatures (~ 1300 °C), which was mostly a mantle plume environment.

## Calculated Phase Relations in the System NCKFMASH (Na<sub>2</sub>O–CaO–K<sub>2</sub>O–FeO–MgO–Al<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub>–H<sub>2</sub>O) for High-Pressure Metapelites

Chunjing Wei<sup>1</sup> AND Roger Powell<sup>2</sup>

<sup>1</sup>*School of Earth and Space Sciences, Peking University, Beijing 100871, China*

*Email: [cjwei@pku.edu.cn](mailto:cjwei@pku.edu.cn)*

<sup>2</sup>*School of Earth Sciences, University of Melbourne, Victoria 3010, Australia*

Petrogenetic grids in the system NCKFMASH (Na<sub>2</sub>O–CaO–K<sub>2</sub>O–FeO–MgO–Al<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub>–H<sub>2</sub>O) and the subsystems NCKMASH and NCKFASH calculated with the software THERMOCALC 3.1 are presented for the  $P$ – $T$  range 7–30 kbar and 450–680°C, for assemblages involving garnet, chloritoid, biotite, carpholite, talc, chlorite, kyanite, staurolite, paragonite, glaucophane, jadeite, omphacite, diopsidic pyroxene, plagioclase, zoisite and lawsonite with phengite, quartz/coesite and H<sub>2</sub>O in excess. These grids, together with calculated compatibility diagrams and  $P$ – $T$  and  $T$ – $X_{\text{Ca}}$  and  $P$ – $X_{\text{Ca}}$  pseudosections for different bulk rock compositions show that incorporation of Ca into the NCKFMASH system leads to many of the NCKFMASH invariant equilibria moving to lower pressure and/or lower temperature, which results, in most cases, in the stability for jadeite and garnet being enlarged, but in the reduction of stability of glaucophane, plagioclase and AFM phases. The effect of Ca on the stability of paragonite is dependent on mineral assemblage under different  $P$ – $T$  conditions. The calculated NCKFMASH diagrams are powerful in delineating the phase equilibria,  $P$ – $T$  conditions of natural pelitic assemblages. Moreover, contours of the calculated phengite Si isopleths in  $P$ – $T$  and  $P$ – $X_{\text{Ca}}$  pseudosections confirm that phengite barometry in NCKFMASH is strongly dependent on mineral assemblage.

# The Mechanism of Lithosphere Thinning in Southeast Asia<sup>1</sup>

WEI Xi<sup>1, 2</sup> DENG Jinfu<sup>1</sup> ZHU Yongjun<sup>2</sup> ZHAO Guochun<sup>1</sup>

*1. Earth Science and Resources College, China University of Geosciences, Beijing  
100083, China; Email: [weixi6367@163.com](mailto:weixi6367@163.com)*

*2. The South China Sea Oil & Gas Company, Liaohe Oil Field, PetroChina, Panjin 124010,  
China*

Lithosphere thinning can be caused by lithospheric extension, thermal erosion by mantle plumes, and lithosphere delamination. The lithosphere thinning in Southeast Asia (SE Asia) is mainly the result of its extension.

The power which caused lithospheric extension in SE Asia comes from asthenosphere flowed southeast from Qinghai-Tibet Plateau (Deng Jinfu et al, 1996; Wei Xi, 2004) and gathered and upheaved here and there in SE Asia. Much different from mantle plumes, this kind of asthenosphere has no root and its quantity and energy are controlled by continent-continent collision between Eurasian and Indian plates, which consequently decide the lithospheric extension degree and its duration. The facts that the oceanic crusts of South China Sea become gradually lower and lower from their edges to expanding centre and have no obvious central upheavings show that the mass and energy of asthenosphere below is limited. These indicate that there exists a coupling between the Qinghai-Tibet Plateau uplifting and the lithospheric extension in SE Asia. Both the Qinghai-Tibet Plateau uplifting and lithospheric extension in SE Asia were multistage and occurred approximately at the same period: mainly in Cenozoic (Coleman et al, 1995; Mercier, 1987; Li Tingdong et al, 1990; Fielding, 1997; Shi Yafeng et al, 1998; Zhao Wenjin, 2003; Taylor and Hayes, 1983; Zhang Yueqiao et al, 2003; Yao Bochu et al, 1994). Every uplifting of the Qinghai-Tibet Plateau aroused asthenosphere flowing southeastwards and going up in the SE Asia, leading to lithospheric extension. Subductions of western Pacific, Indian, and Australian plates (Fig.1) are necessary conditions. These subducting plates (lithospheres) block off the asthenosphere coming from northwest and consequently make it gathered and upheaved.

Lithospheric extension caused by asthenosphere upheaving, which can lead to basin formation, is the main style of its thinning in SE Asia. Up to now, scientists have put forward 3 kinds of models about lithospheric extensions: pure-shear model (McKenzie, 1978, 1980), simple-shear model (Wernicke, 1981, 1985), and layered-shear model

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(Yao Bochu, 1998). Layered-shear model brought forward according to the evolution of the South China Sea indicates that different layers in lithosphere have different deformation characteristics. Upper- and mid-continental crusts are brittle, therefore their thinnings are caused by plow-shaped faults which led to rotation of blocks and formation of graben and half graben. Lower continental crust is malleable and its thinning is caused by plastic creep. Upper mantle is brittle and its thinning is caused by fault deformation. In fact, many oil bearing basins in South China Sea, Selebes Sea, Java Sea and so on are the results of lithospheric extension.

Located in the convergence region of Eurasia, Indian, Pacific and Australian plates, the lithosphere extension in SE Asian region is a local deformation under a large scale compressed background (Fig.1). Many lithospheric extension zones, compressed or subducted zones, continental accretion and magmatism coexist in this local area surrounded by Eurasia (N) and a few big arcuate subducted zones (W, S and E). These are the response and expression of mantle flow to the continent-continent collision, which also occurred in the Mediterranean region, the collision zone between Eurasian and African plates (Deng Jinfu, 2004). Lithospheric extensions in different parts of this area are various in expanding degrees, scales, and directions, which were adjusted by crustal blocks rotation, escaping (Tapponnier P et al, 1982), strike-slip or transform faults, strip-shaped tectonics (Ma Zongjin and Wang Guoquan, 1999; Wei Xi et al, 2004) and subducted zones.

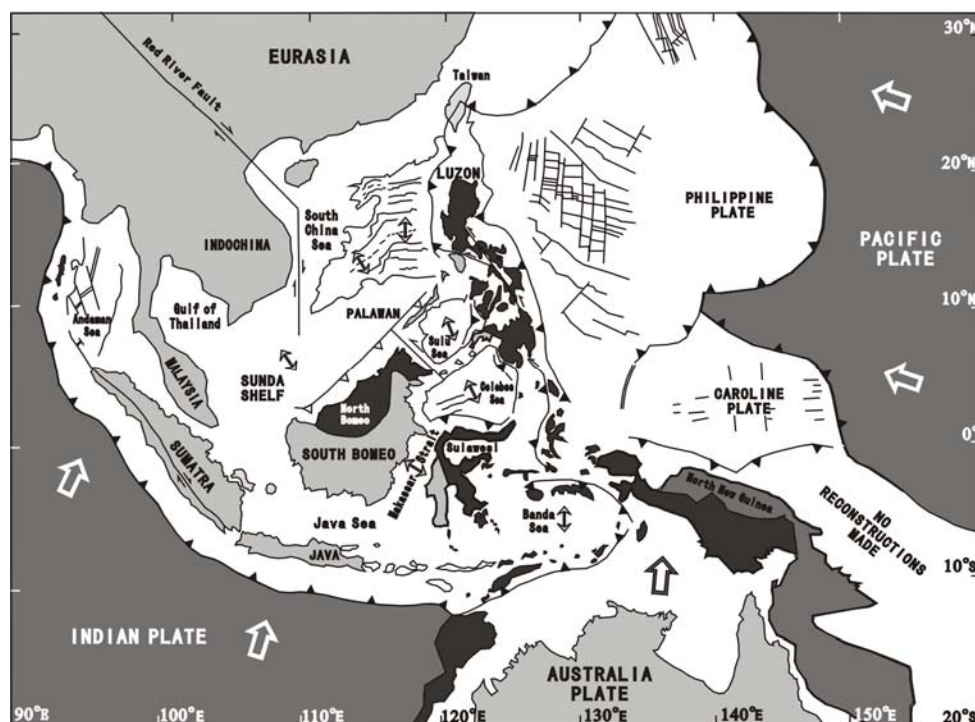


Fig.1 Simplified tectonic configuration of SE Asia (modified from ROBERT HALL, 1996)

Arrows represent plate moving directions. Arrows with two directions represent extension directions.

Other legends are the same with original figure.

# **Geochemistry and Sr-Nd-Pb-O isotopic composition of Cretaceous high-Mg diorites and adakitic granites in west Shandong: implications for slab melting and slab melt-modified lithospheric mantle beneath North China Craton**

Li-Hui Chen<sup>a</sup>, Xin-Hua Zhou<sup>b</sup>

*a Department of Earth Sciences, Nanjing University, Nanjing 210093, China*

*Email: [chenlh@nju.edu.cn](mailto:chenlh@nju.edu.cn)*

*b Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China*

The North China Craton (NCC) lost its Archean keels in the Phanerozoic. Prevalent and intensive magmatism, mineralization, and development of extensional basins in the late-Mesozoic NCC imply that the late Mesozoic could be the key stage for this transformation. Study of the genesis of mantle-derived rocks of this time can improve our understanding of the thinning process. Here we show geochemistry and Sr-Nd-Pb-O isotopic composition of a Cretaceous intrusive body in North China craton, Tietonggou pluton, which is composed of diorites, gabbros and granites. A lot of ultramafic xenoliths have found in the diorites and the gabbros. Tietonggou diorites, as well as other high-Mg diorites in west Shandong province (Xu et al., 2004), have low SiO<sub>2</sub> (57-60 wt%), high MgO (>6 wt%) and Mg# values (>0.7), high concentrations of Cr (>500 ppm) and Ni (>150 ppm), enrichments in Sr (>600 ppm) and Ba (>1000ppm), and high Na<sub>2</sub>O (3.1-3.4 wt%), K<sub>2</sub>O (1.8-2.4wt%), LREE, and La/Yb<sub>N</sub> ratios (>10) (Chen, 2001). The geochemical characteristics of Tietonggou diorites are similar to those of sanukitoids and low-SiO<sub>2</sub> adakites, which are thought to be partial melts from a mantle wedge whose composition has been modified by reaction with slab melts (see review by Martin et al., 2005). Tietonggou granites have high SiO<sub>2</sub> (70.5-72.0 wt%), high Na<sub>2</sub>O (4.5-5.2 wt%), Na<sub>2</sub>O/K<sub>2</sub>O>1, high Sr (590-670 ppm), high La/Yb<sub>N</sub> (50-100), and extremely depleted HREE (Yb<0.3 ppm) and Y (<4 ppm). The geochemical characteristics of Tietonggou granites are similar to those of high-SiO<sub>2</sub> adakites, which are broadly thought to be slab melts (see review by Martin et al., 2005). Sr-Nd-Pb-O multiple isotopic composition of the high-Mg diorites and adakitic granites suggest there might be a mixing process between a high <sup>143</sup>Nd/<sup>144</sup>Nd, <sup>206</sup>Pb/<sup>204</sup>Pb, <sup>207</sup>Pb/<sup>204</sup>Pb, <sup>208</sup>Pb/<sup>204</sup>Pb, and δ<sup>18</sup>O end member (slab melts?) and a low <sup>143</sup>Nd/<sup>144</sup>Nd, <sup>206</sup>Pb/<sup>204</sup>Pb, <sup>207</sup>Pb/<sup>204</sup>Pb, <sup>208</sup>Pb/<sup>204</sup>Pb, and δ<sup>18</sup>O end member (enriched lithospheric mantle?) in the mantle source. Thus, geochemical and isotopic evidence from the Tietonggou pluton

indicates that the lithospheric mantle beneath NCC might have been metasomatized by slab melts. Such observation is consistent with the observed Si (Na) metasomatism in the ultramafic xenoliths of Tietonggou (Chen & Zhou, 2005).

**References:**

1. Chen L.-H. and Zhou X.-H., 2005, *Geochem. Geophys. Geosyst.*, 6, doi: 10.1029/2005GC000938 (in press).
2. Martin, H., Smithies, R.H. Rapp, R. et al., 2005, *Lithos*, 79, 1-24.
3. Xu, Y. G., Huang, X.-L., Ma, J.-L. et al., 2004, *Contrib. Mineral. Petrol.*, 147, 750-767.



## **Age and origin of the Jurassic I- and A-type granites from Central Guangdong (SE China) and their tectonic significance**

Xian-Hua Li<sup>1</sup>, Zheng-Xiang Li<sup>2</sup>, Wu-Xian Li<sup>1</sup>, Ying Liu<sup>1</sup>, Chao Yuan<sup>1</sup>, Gangjian Wei<sup>1</sup>

<sup>1</sup> *Key Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China*

*Email: [lixh@gig.ac.cn](mailto:lixh@gig.ac.cn)*

<sup>2</sup> *Tectonics Special Research Centre, School of Earth and Geographical Sciences, The University of Western Australia, Crawley, WA 6009, Australia*

The Mesozoic geology of SE China is characterized by widespread Jurassic to Cretaceous igneous rocks consisting predominantly of granites and rhyolites. While it has been generally considered that the Cretaceous magmatism along the coast areas was genetically related to the northwestward subduction of the Izanagi plate, the tectonic regime that accounted for the inland Jurassic granitoids is still a matter of hot debate.

We report here systematic U-Pb zircon, geochemical and Nd-Sr isotopic data for the Nankunshan alkaline granite and the Fogang granitic batholith outcropping over an area of ca. 7000 km<sup>2</sup> in the southern slope of the EW-orientated Nanling Range, central Guangdong. Mineralogical and geochemical features suggest that the Fogang and Nankunshan rocks are I- and aluminous A-type granites, respectively. SHRIMP U-Pb zircon analyses yield consistent ages of 159±3 Ma to 165±2 Ma for four Fogang rocks, and an age of 157±5 Ma for a Nankunshan sample, indicating that these I- and A-type granites formed contemporaneously in the middle Jurassic. The Fogang granites, having  $I_{Sr} = 0.710-0.716$  and  $\epsilon_{Nd}(T) = -6.5$  to  $-9.5$ , were generated by partial melting of Proterozoic amphibolite protolith. The Nankunshan rocks, on the other hand, have lower  $I_{Sr} \approx 0.707-0.710$ , higher  $\epsilon_{Nd}(T) = 0.3$  to  $-2.4$  and some OIB-like trace element ratios. They were most likely generated through extensive fractional crystallization of alkaline basaltic magma in an extension- or rifting-related setting.

The studied I- and A-type granites are slightly younger than the 175-170 Ma alkaline mafic and felsic volcanic and plutonic rocks, but coeval with the 165-160 Ma syenites in the adjacent regions (southern Hunan to southern Jiangxi Province). We propose that the inland Jurassic granites, along with other bimodal alkaline igneous rocks, are anorogenic magmatism. They were formed by the delamination and foundering of a subducted flat-slab beneath South China continent.

## **Characteristics of mantle source for Jining Cenozoic basalts from southern Inter Mongolia: evidence from element and Sr–Nd–Pb isotopic geochemistry**

ZHAND WenHui, HAN BaoFu, DU Wei, LIU ZhiQiang

*The Key Laboratory of Orogenic Belts and Crustal Evolution, MOE, School of Earth and Space Sciences, Peking University, Beijing 100871, China*

*Email: [wenhui@pku.edu.cn](mailto:wenhui@pku.edu.cn)*

Jining Cenozoic basaltic field, located on the northern edge of the North China craton and to the west of Hannuoba basaltic field, is mainly made up of subalkaline tholeiitic basalt and alkaline olivine basalt, basanite, and tephrite. Their SiO<sub>2</sub> and TiO<sub>2</sub> contents vary from 44.10–53.07 wt.% and 1.57–2.95 wt.%, respectively, with variable Mg-number (43–63) and Ni contents (14–210ppm). The Primitive-mantle normalized incompatible element diagrams and Chondrite-normalized REE patterns are similar to those of OIB. Sr, Nd isotopic ratios are more enriched than Hannuoba basalts. The basalts were mantle-derived magmas with the fractional crystallization of olivine and clinopyroxene, but their trace-element and Sr, Nd, Pb isotopic geochemistry preclude the possibility that the magmas were contaminated significantly by crustal materials. The correlations of <sup>143</sup>Nd/<sup>144</sup>Nd, <sup>87</sup>Sr/<sup>86</sup>Sr vs. <sup>206</sup>Pb/<sup>204</sup>Pb indicates that Jining basalts were generated by the mixing of at least two mantle components: EMI and PREMA, similar to Hannuoba basalts. The mixing of low degree melts of spinel lherzolite (2–5%) and garnet lherzolite (<2%) can explain the REE features in Jining basalts. It can be speculated that EMI mantle component came from the lithospheric mantle of a depth <70km, and PREMA mantle component from asthenospheric mantle. It is possible that the differences between the subalkaline and alkaline basalts may be produced by the mixing of the melts from lithospheric EMI mantle and asthenospheric PREMA mantle in different proportion, implying that strong interactions occurred between lithosphere and asthenosphere beneath Jining area. The similar isotopic ratios and correlations suggest a similar mantle source for Jining and Hannuoba basalts. Therefore, the formation of Hannuoba basalts can be also interpreted by the mixing of the melts from EMI mantle and PREMA mantle in different proportion.

# Re-Os isotopic systematics of peridotite xenoliths in Mesozoic Tietonggou pyroxene-diorite complex from Western Shandong, North China: Implications for their petrogenesis

Xia-Chen Zhi<sup>1</sup> Qing Meng<sup>1</sup> Wen-Liang Xu<sup>2</sup> and Dong-Yan Wang<sup>2</sup>

<sup>1</sup> School of Earth and Space Sciences, University of Science and Technology of China, Hefei, 230026, China. Email: [xczhi@ustc.edu.cn](mailto:xczhi@ustc.edu.cn)

<sup>2</sup> School of Earth Sciences, Jilin University, Changchun, 130061, China

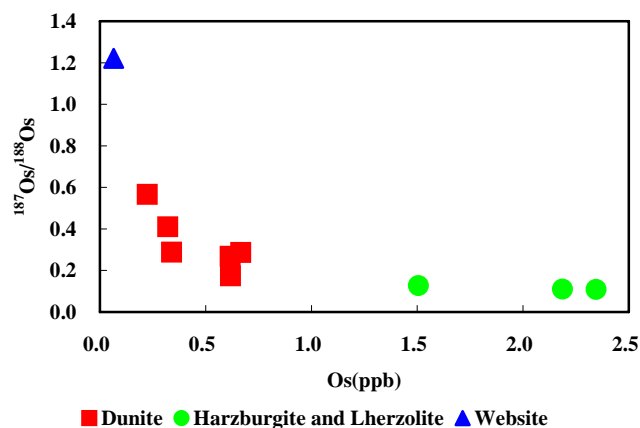
The samples in this study include 7 dunite, 1 harzburgite, 2 lherzolite and 1 websterite. The xenoliths were collected from Tietongguo intrusion complex, west Shandong and are usually considered as direct samples of subcontinental lithospheric mantle (SCLM) beneath the area, which may offer very interesting information on the nature and evolution of Mesozoic SCLM, in term of their major and trace element abundances as well as Sr-Nd isotopic ratios in the literatures.

Re and Os concentrations of the sample set vary 0.32-3.4ppt and 65-2346ppt. Their  $^{187}\text{Os}/^{188}\text{Os}$  and  $^{187}\text{Re}/^{188}\text{Os}$  ratios vary 0.1088-1.2213 and 0.097-3.700. The Os concentration and  $^{187}\text{Os}/^{188}\text{Os}$  ratio are closely relative to the rock type and they can be divided into three groups. Harzburgites and lherzolites have the highest Os concentration and lowest Os isotopic ratio, websterite has the lowest Os concentration and the highest Os isotopic ratio and dunite have middle Os concentration and Os isotopic ratio among the three groups (Fig. 1).

From the constraints of Re-Os isotopic systematics, we can deduce the petrogenesis of the peridotites and websterite xenoliths from the intrusion complex, West Shandong. The harzburgite and lherzolite probably are the fragments of relic ancient lithospheric mantle, the dunite are the fragment of ancient cumulates from melt derived from the convective mantle, and

websterite are the fragment of ancient mafic igneous rocks. The protoliths of all xenoliths probably were ancient ophiolite sequence subducted into the boundary between crust and mantle which were brought to surface by host intrusion complex in Mesozoic. So that Re-Os isotopic systematics is very useful tool for discrimination of the nature and petrogenesis of mafic and ultramafic xenoliths contained in host rocks.

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## **Comparison of Mesozoic extensional tectonics and magmatism on the southernmost Sino-Mongolia border with those within North China Craton: implications for geodynamics of delamination of continental lithosphere of NCC**

WANG Tao <sup>a</sup> ZHENG Yadong <sup>b</sup> HONG Dawei <sup>a</sup>

*a, Institute of Geology, Chinese Academy of Geological Science; Beijing, 100037, China, Email: [taowang@pku.edu.cn](mailto:taowang@pku.edu.cn)*

*b, Department of Geology, Peking University, China*

Late Mesozoic extensional tectonics and magmatism occur widely in north China craton (NCC). They are generally explained with delamination of continental lithosphere. However, geodynamics for the delamination is still in debate, and many models have been proposed. For example, it was related to subduction along the Pacific margin, collision between NCC with Yangtze craton, or subduction/collision along the Okhotsk suture in northeastern Mongolia. Recently, we recognized Mesozoic extensional tectonics and granitic and mafic magmatism in the Sino–Mongolian border area, i.e., hinterland of Middle-East Asia continent, far away from the above tectonic zones. These provide new information on the understanding of the geodynamic of extensional tectonics and magmatism within NCC. The Yagan area of the Sino–Mongolian border is located in the north to the Solonker suture separating Central Asian Orogenic Belt (CAOB) to the north and NCC to the south, belonging to the southern margin of the CAOB. This area is characterized by a large Mesozoic metamorphic core complex (MCC), a typical extensional feature, and voluminous granitoids. The MCC consists of a lower plate, an upper plate and a master detachment zone. The zone gently dips southward. All the lineation at different levels, including in the core of the MCC, where the rocks grade structurally upwards from low-amphibolite-facies/greenschist facies mylonites into chloritic microbreccias, has same south– southeast or south–southwest plunges and the shear sense is top-to the south. This suggests that the MCC underwent long-term progressive extensional shearing. Strikingly, a great thrust sheet southward, and lot of klippen consisting of Proterozoic rocks also occur in the area. They are transected by the detachment fault of the Yagan MCC, indicating that the MCC later than the thrust (Zheng et al., 1994). Webble et al. (1999) reported Ar–Ar age of 129–126 Ma for biotites from the MCC, and considered them as the MCC’s age. We obtained (SHRIMP) zircon ages of 228Ma from

gneissic granitoids, and 145 Ma from weakly mylonited granitoids and 135 Ma from undeformed large granitic pluton, and Rb-Sr age of 155 Ma for the weakly deformed garnet granites. These ages suggest that the MCC was formed by two stages: earlier deep-level ductile extension at least around or before 135Ma (160-145Ma), and later final formation (doming) at 135-126Ma. On the base of these studies, we proposed that two dynamics occurred in the north of the NCC: southward movement of the upper crust relative to the low crust (i.e., tangential shearing); underplating and delamination. Mesozoic MCCs also occur widespread in the NCC, such as Yunmenshan MCC, Louzidian MCC, and Hohhot MCC. They mostly have formed by southward detachment, and are finally formed at about 130-110 Ma. For example, the Hohhot MCC is located in the northwestern margin of the NCC. It is an E-W trending antiformal dome with a minimum length of 100Km (Davis et al., 2002; Wang X S et al., 2002). The main detachment zone dips southward and the shear sense is top-to-the south. The MCC was finally formed ca. 120-100 Ma. All these suggest that Yagan MCC is approximately the same or similar to MCCs within NCC in kinematics and age, indicating same geodynamics. Magmatism in the Yagan of the Sino-Mongolian border and the NCC are different in sources, but similarities in age and tectonic setting. New isotopic age data indicate that the granitoids in Yagan were emplaced in early and late Mesozoic times. The early Mesozoic granitoids with  $228 \pm 7$  Ma U-Pb zircon age are similar to those of potassic granites and shoshonitic series, and show an intraplate and post-collisional environment in tectonic discrimination diagrams. The late Mesozoic granitoids consist of lot of large plutons. They have a U-Pb zircon age of  $135 \pm 2$  Ma and are high-K calc-alkaline. These features are similar to those of NCC. Both the early and late Mesozoic granitoids have  $\epsilon_{Nd}(t)$  values of -2.3 to +5. This suggests that juvenile mantle-derived components were involved in the formation of the granitoids, which is omnipresent in Central Asia. In contrast, late Mesozoic granitoids and mafic rocks of NCC have features of old continental and enriched mantle source. We collected about 500 data from publications of granitoids and mafic plutons from the NCC. Most plutons occurred at ca. 140-120 Ma. Strikingly,  $\epsilon_{Nd}(t)$  values of these rocks evolved from -8 to +2 before Mesozoic and sharply to -8 to -25 during Mesozoic, particularly 140-120 Ma. We interpreted it as a result of delamination of old continental crust, which contaminated the mantle source. Almost the late Mesozoic granitoids of NCC are related to extensional tectonics (MCCs). Accordingly, the Mesozoic magmatism within the NCC and northwest to it is different in sources, but its age (140-120 Ma) and extensional setting are the same, implying same geodynamics.

All above indicate that the Mesozoic extension and magmatism not only occur in the NCC, but also in the southern margin of CAOB (hinterland of the Middle East Asia continent), that is outside of NCC, and suggest that they have same or similar

geodynamics. The former were generally explained by subcontinental delamination that could be related to the Pacific plate subduction, collision between NCC with Yangtze craton, or subduction/collision along the Okhotsk suture in northeastern Mongolia. The later, however, appears too far away from all these zones to have such relation, and what geodynamics for them. If the later is related to the post-orogenic processes of the CAOB, we should consider the effect of this process on the NCC. The information from outsides of NCC may be helpful for a study of inside delamination of NCC. Anyway, we should consider all the Mesozoic extension and magmatism in the southern margin of CAOB and NCC have same geodynamics together, and look for the same geodynamics. We suggest that the same geodynamics could be derived from breakup of the Pangea supercontinent, which formed at about 230Ma, and started breakup since 160 Ma (Veevers J.J. et al. 1994). This is an interesting question needs further study.

# **Mesozoic magmatism from North China Craton and Qinling-Daibie-Sulu orogenic belt and their deep dynamics process**

HONG Dawei<sup>1</sup>, WANG Tao<sup>1</sup>, TONG Ying<sup>1</sup>, WANG Xiaoxia<sup>2</sup>

*1. Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China;*

*2. Department of Geology, Changan University, Xi'an 710054, Chin*

Recent studies suggest that the Mesozoic granitoids and contemporary mafic and ultra-mafic rocks from the North China Craton (NCC) and Daibie-Sulu orogenic belt have the similar Sr, Nd characteristics, and many of the granitoids and mafic rocks exhibit some feature of Adakites. Interesting questions require studying. For example, is there any relation between two features; what is the relation, and what is their geodynamics?

We collected about 500 data on NCC, Daibie-Sulu orogenic belt and Qinling orogenic belt from publications. From the viewpoint of whole north China lithosphere, we have discussed the nature of the enriched mantle, the time and mechanisms of the formation of the enriched mantle, and further discuss the dynamic mechanism of the magmatism.

These collected about 500 data indicate that most granitoids and mafic rock from the North China Craton (NCC) formed in Mesozoic time, particularly at 140-120 Ma, and they have almost the same  $\epsilon$  Nd(t) values (most -8- -25). Furthermore,  $\epsilon$  Nd(t) values of these rocks evolved from -8- to +2 before Mesozoic and sharply to -8- -25 during Mesozoic, particularly 140-120 Ma. This suggests that the enriched mantle of NCC was mainly formed during Mesozoic time, particular at 140-120 Ma. This is coeval with subcontinental delamination of NCC. Therefore, we suggest that it is delamination that changes the mantle nature into much enriched by contamination of the delaminated old continental crust, and this happened in setting of a breakup of the Pangea supercontinent. Additionally, integrating with the data of the global seismic tomography, we have also discussed the significant of lower crust transferred from subduction oceanic relics, and the old craton substance for the source of the granitoids

## **Trace elemental and PGE geochemistry of the Bixiling and Raobazhai peridotites in the Dabie UHP belt, eastern China: petrogenetic and geodynamic implications**

Jianping Zheng<sup>1</sup>, Min Sun<sup>2</sup>, Mei-Fu Zhou<sup>2</sup>, Paul Robinson<sup>2,3</sup>, Guochun Zhao<sup>2</sup>

1 State Key Laboratory of Geological Processes and Mineral Resources, Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074, China

2 Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong, China

3 Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, Canada B3H2J5

The Dabie-Sulu ultra-high pressure (UHP) metamorphic belt was formed by the collision of the North China and Yangtze Cratons in the Triassic. The Bixiling and Raobazhai mafic-ultramafic complexes occur as tectonic slices in the southern and northern Dabie terranes, respectively. The Bixiling complex consists primarily of banded eclogites and minor peridotites, whereas the Raobazhai complex is a peridotite body enclosing minor eclogite and garnet pyroxenite. These bodies have been variously interpreted as magmatic cumulates, ophiolitic mélange, mafic-ultramafic intrusions or subducted subcontinental mantle. New mineral chemistry, and major, trace element and platinum-group element (PGE) data for the peridotites indicate that the Bixiling peridotites formed under high P/T conditions (mean 4.4 GPa and 700 °C), have high modal percentages of garnet, possess high HREE, S and other incompatible trace elements, and have low-Mg olivine and pyroxene, low Ni and PGE, and display flat REE patterns. They were first intruded into the crust-mantle transition zone and later subducted during formation of the Dabie-Sulu terrane. In contrast, the Raobazhai peridotites formed under low P/T conditions (about 15 Kb and 1000 °C), have high-Mg olivine and pyroxene, contain high Ni and PGE but low Pd/Ir (mean 3.0), and exhibit LREE enrichment ( $(La/Yb)_n \approx 3.5$ ), similar to refractory peridotites after up to 18% partial melting. They are believed to represent a mantle wedge of subcontinental lithosphere. However, a large range of  $Mg^\#$ , low Ni and Au, low  $(La/Yb)_n$ , and obviously negative Ce and HFSE anomalies and high SiO<sub>2</sub> contents (44.0-44.9 wt%) in the Raobazhai peridotites indicate that they were modified during the UHP metamorphism of the subducted continental crust.



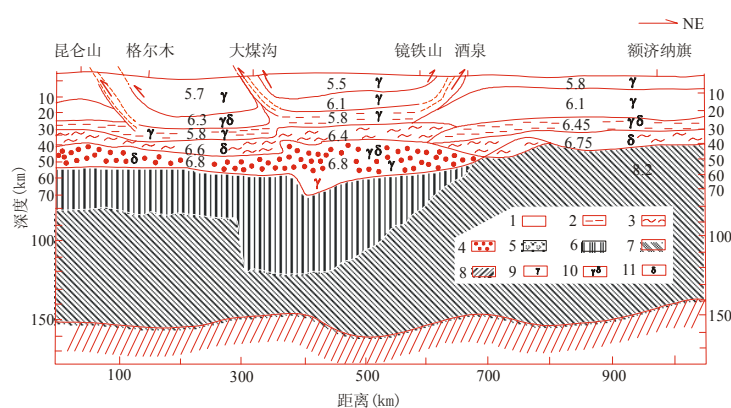
# Thickening and thinning processes of an orogenic lithosphere: Evidences from the Eastern Kunlun orogen

Luo Zhaohua, Mo Xuanxue, Zhan Huaming, Chen Hongwei

China University of Geosciences, Beijing, State Key Laboratory of Geo-Processes and Mineral Resources, Beijing, 100083, Email: [luozh@cugb.edu.cn](mailto:luozh@cugb.edu.cn)

The lithosphere collisions form mountains, which are characterized essentially by greater thickness of crust than the bordering area. The thickening process of an orogenic crust is generally considered as the result of lower crust flow. However, the mechanisms and causes of crustal flow remain in debate. Based on the energy view, the flow may be respond to the thermal injection or volatile concentration from deep depths (McKenzie et al., 2002). The efficiency of thermal conduction is much less than that required for crustal flow of an orogen, especially for magma generation. The thermal injection requires a convection regime, which could be related to the earth's degassing and/or mantle-derived magma underplating. An other important task, concerning orogenic crustal thickness, is that the olden orogen has a less ratio of surface relief to the thickness of the underlying crustal root than the younger. The widespread explanation is the surface erosion. The new evidences suggest that the orogenic cooling can be an important factor (Fischer, 2002), because the process could increase the crust density and decrease its buoyancy, and hence relaxes regional isostatic uplifting. The evidences from the Late Paleozoic – Early Mesozoic igneous activities indicate that the underplating of mantle-derived magma could be a necessary regime for regional magmatic activities and crustal thickening. Along with the orogenic cooling, there are will be rock differentiation, high-pressure metamorphism and subsequent lithosphere delamination. The orogenic crust will get back to a normal thickness level.

In the Eastern Kunlun mountains cropped out various intrusive rocks, including peridotitoids,



**FIG.1. THE PETROLOGIC STRUCTURE OF THE GOLMUD-EJINA GEOTRANSET (REDRAW FROM DENG ET AL., 1995)**

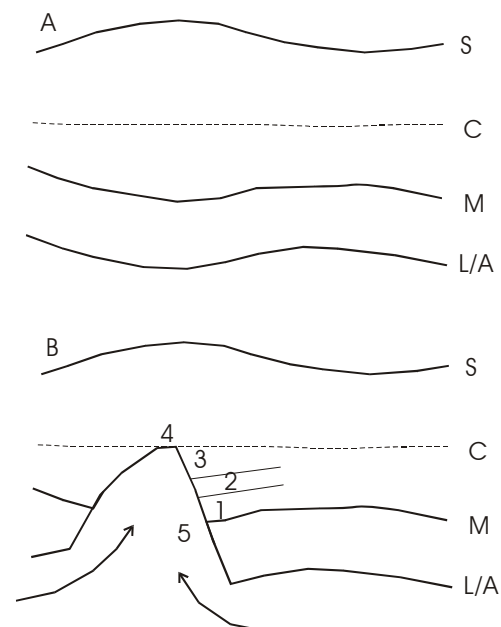
1. green schist phase upper crust; 2. amphibolite phase intermediate crust; 3. mid-pressure phase lower crust; 4. high-pressure thickened lower crust; 5. root granitic eclogite; 6. basic

gabbroids, dioritoids and granitoids. Among them the granitoid, especially the Late Paleozoic – Early Mesozoic granitoids get extremely widespread distribution (Luo et al., 1998). The Jialu river batholith can be recognized as a broad spectrum of rocks from hornblende gabbro to syenogranite. There are not clear connections between neighboring units. These imply they had formed simultaneously as shown by the zircon U-Pb dating (*ca.* 240Ma) by SHRIMP II (Liu et al., 2004). That there are many mafic microgranular enclaves (MME), disequilibrium mineral assemblages and element relationships showing mixing of mantle- and crust-derived magmas documented a magma mixing/mingling mechanism (Liu et al., 2002). The discovery of mantle-derived differentiation intrusion and gigantic mafic sills can be considered as a significant evidence of mantle-derived magma underplating (Luo et al., 2002). According to these, we can recognize the causal relationships of the extensive Late Paleozoic intermediate – acid crust-derived magmatism and mantle-derived magma underplating.

The amount of underplating magma can be estimated from the petrologic structure section inverted by Deng et al. (1995) on the bases of seismic exploration data (Fig.1). It is important to note that there is a mafic eclogite layer beneath the Moho of the Eastern Kunlun – Qaidam area. Its thickness beneath the Eastern Kunlun – Qaidam area is less ~40km than that beneath the Qilian mountains. This pattern suggests that a part of the eclogite layer has been removed together with the underling lithosphere peridotitic mantle into the asthenosphere. The seismic data support our interpretation (Leveque et al., 1999).

A direct result induced by lithosphere delamination is uplifting of the hotter and lighter asthenosphere to the shallow level. Two processes can be predicted: mantle decompress partial melting and partial melting of the heated roof of the diapir. Therefore, the delamination is often used to explain regional extension and widespread intermediate – acid magmatic activities. We don't consider their certain relationships. In order to resolve these problems, we have to better understand the fundamental factors controlled the magma generation process, lithosphere differentiation and the relationships between local and regional strain field. If the larger regional strain field remains compressional, the delamination in a smaller area could not induce to an extension with well-discriminated geological records. Therefore, there was not a widespread Early Mesozoic extension record in the Eastern Kunlun, because the effects of Tethyan convergent domain.

For the differentiations of the lithosphere components, we can consider the



**FIG.2. THE MELTING SYSTEMS DURING THE LITHOSPHERIC DELAMINATION OF THE EASTERN KUNLUN MOUNTAINS**  
1-mafic eclogite ( for adakite),  
2-transicinal phase (for adakitic

two aspects: the metamorphism of underplating layer and the lower crust flow. Accompanying to the orogenic compression, the mantle-derived magma underplating and the related plutonic magmatism will produce a thicker continental crust (Fig. 2). In the subsequent geological processes, the previous lower crustal components will be differentiated: the heavy mafic component flows down and the lighter felsic – up. So, the differentiated mafic component will be combined together with the underplated mafic rocks into a very thick mafic layer arranged between the overlying felsic crust and the underling lithospheric mantle peridotite. During cooling of the orogen, this mafic layer will be undergo metamorphism: the lower part can obtain the condition of eclogite phase, upwards transitional and granulite phase in turn of decrease of temperature and pressure. When the delamination process is occurring, the removed part will be that the average density of this part and the peridotitic lithosphere mantle exceeds that of the asthenosphere. So, the delamination uncertainly removes the entire mafic layer. In such condition, the hotter uplifting asthenosphere will be contacted with the eclogite with higher solidus temperature, and hence cannot induce extensive magma generation. The widespread dike assemblage (*ca.* 200 Ma), including lamprophyre, diabase, adakitic diorite, syenogranite – alkaline feldspar granite, requires sudden heating of resources with different features of melting dynamics. The simplest explanation is that as shown in the Fig. 2B.

The new evidences indicated successive events in the late orogenic stage of Eastern Kunlun Mountains. The event sequence is: mantle-derived magma underplating, widespread intermediate – acid magmatic activities, cooling of the orogenic lithosphere, lithospheric delamination, and magmatism from different sources. This model is widely applicable to most orogenic belts worldwide.

## **A coupled Lu-Hf and O isotope in zircon approach to granite genesis**

Tony Kemp, Chris Hawkesworth and Bruce Paterson

*Department of Earth Sciences, University of Bristol, Bristol, BS8 1RJ UK*  
*Email: [ais.kemp@bristol.ac.uk](mailto:ais.kemp@bristol.ac.uk)*

Metaluminous granitic rocks are typically the most voluminous constituents of plutonic belts, irrespective of age or tectonic setting. It is virtually axiomatic that these derive from unweathered 'infracrustal' sources, such as an accreted mafic underplate, in contrast to peraluminous granites that are assigned metasedimentary or 'supracrustal' protoliths. This notion has given rise to the I- and S-type paradigm that pervades the literature and forms the cornerstone for petrogenetic models involving granites. Yet, several lines of evidence point to the involvement of both sedimentary materials *and* juvenile mantle-derived liquids in hornblende granite genesis, degrading the I-type status. Quantification of these components is essential for understanding the processes of magmatic differentiation, and formulating realistic models for the thermal and compositional evolution of the continental crust. This aim is greatly hampered by the ambiguities with interpreting whole-rock isotope data, which registers the final state of the magmatic system but gives no information on the pathways by which this state was attained.

One way to resolve this problem is by unravelling the isotopic information encoded within the fine-scale growth zoning of minerals such as zircon, which potentially tracks the processes operative during crystallisation. A radiogenic-stable isotope pair is most advantageous, since this approach is uniquely capable of diagnosing a sedimentary source component. To this end we report a laser-ablation ICP-MS and SIMS study into the Hf and O isotope stratigraphy of magmatic and inherited zircons hosted by the classic I-type granites of the Lachlan Fold Belt (SE Australia). All grains were previously dated by U-Pb SIMS analysis. The Hf-O isotope systematics suggest that current ideas on the formation of these granites require revision. Many plutons derive from protoliths that had experienced a prior low temperature history and/or incorporated a sedimentary ingredient. Furthermore, covariation between Hf and  $^{18}\text{O}$  and certain trace elements can only be reconciled by open system behaviour during crystallisation, although in detail this differed between suites. Models for the generation of the Lachlan I-types based on these data shall be presented, together with implications for crustal differentiation processes along the palaeo-Gondwana margin.

# **Geochemistry of the Neoproterozoic (2800-2700 Ma) Taishan Greenstone Belt, North China Craton: Implications for Geodynamic History**

A. Polat<sup>1</sup>, J. Li<sup>2</sup>, T. Kusky<sup>3</sup>

<sup>1</sup>*Department of Earth Sciences, University of Windsor, Windsor, ON, Canada N9B 3P4*

*Email: [polat@uwindsor.ca](mailto:polat@uwindsor.ca)*

<sup>2</sup>*Department of Geology, Peking University, Beijing 100871 China*

<sup>3</sup>*Department of Earth and Atmospheric Sciences, Saint Louis University,  
St. Louis, MO 63103, USA*

The 2800-2700 Ma Taishan greenstone belt, North China Craton, consists of an association of komatiites, pillow basalts, banded iron formations, conglomerates, and greywacke sandstones. The belt was intruded by high-Al tonalite-trondhjemite-granodiorite (TTG) plutons and deformed under amphibolite-grade metamorphism at about 2700 Ma.

At the bottom of the association komatiites are characterized by well-preserved spinifex, cumulate, and breccia textures. Spinifex komatiites have uniformly high-MgO (31-33 wt.%), but low-Al<sub>2</sub>O<sub>3</sub> (2.8-5.7 wt.%), TiO<sub>2</sub> (0.14-0.24 wt.%), and Zr (4.6-9.6 ppm) contents. Towards the top of the sequence komatiites become less magnesian (MgO=22-23 wt.%), more aluminous (Al<sub>2</sub>O<sub>3</sub>=6.2-8.9 wt.%), and display higher concentrations of incompatible elements. Based on [Al<sub>2</sub>O<sub>3</sub>] versus [TiO<sub>2</sub>] molecular relations, these rocks plot mainly in the field of Al-depleted komatiites. Komatiites occurring at stratigraphically lower levels have concave-upward LREE patterns and negative Nb anomalies (Nb/Nb\*=0.19-0.96). Stratigraphically upper komatiites and pillow basalts also share the negative Nb anomalies.

There are strong correlations between the initial  $\epsilon_{Nd}$  values and indices of crustal contamination (e.g. Th/Nb, La/Nb, Th/Ce) and olivine fractionation, suggesting that the geochemical characteristics of the Taishan komatiites can be best explained by olivine fractionation and assimilation of 2-6 % LREE-enriched older continental crust or sediments. On an  $\epsilon_{Nd}(T)$  versus Nb/Nb\* variation diagram, most contaminated komatiites are displaced from the olivine controlled fractionation trend towards larger negative Nb anomalies, indicating that the negative Nb anomalies have resulted from crustal contamination.

Conglomerates are composed dominantly of gneissic, granitic, and amphibolitic clasts. Grain types and trace element characteristics of sandstones are consistent with a continental source area. There are zircon and apatite xenocrysts in the stratigraphically lower komatiites. Collectively, these geological features are consistent with the deposition of the greenstone belt on continental basement. Accordingly, we propose a geodynamic model of plume-craton interaction to explain the geological and geochemical characteristics of the Taishan greenstone belt. Interaction between the early Cretaceous Kerguelen mantle plume and eastern Gondwanaland would be a good Phanerozoic analog for the interaction between the Taishan plume and the North China Craton at ~2700 Ma.

## **Melt-peridotite interactions: Links between garnet pyroxenite and high-Mg# signature of continental crust**

Yongsheng Liu <sup>1,2\*</sup>, Shan Gao <sup>1,2</sup>, Cin-Ty Aeolus Lee <sup>3</sup>, Shenghong Hu <sup>1</sup>, Xiaoming Liu <sup>2</sup>, Honglin Yuan <sup>2</sup>

<sup>1</sup> *National Key Laboratory of Geological Processes and Mineral Resources, Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074, China.*

*Email: [yshliu@vip.sina.com](mailto:yshliu@vip.sina.com)*

<sup>2</sup> *Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an 710069, China.*

<sup>3</sup> *Department of Earth Science, MS-126, Rice University, Houston, TX 77005, USA*

Abundant lherzolite, garnet pyroxenite and granulite xenoliths are found in the Neogene Hannuoba basalt of the North China craton. Garnet pyroxenites generally occur as veins/layers in spinel lherzolites. There is a gradual decrease in olivine and an increase in orthopyroxene mode going from the lherzolite to the pyroxenite, suggesting that orthopyroxene may be forming at the expense of olivine. Garnet pyroxenites are enriched in the highly incompatible elements (e.g., Rb, K, Na, Sr, Ba, Nb and Ta) but have high and uniform Ni contents and Mg#s (83-90). This set of geochemical observations is paradoxical because the enrichments in highly incompatible elements signify derivation from a melt having either an evolved character or a significant fluid component, but the high Ni contents and high Mg#s suggest a much more primitive origin. A somewhat similar paradox is observed in the granulite xenoliths. Many of the granulite xenoliths have intermediate compositions, characterized by SiO<sub>2</sub>>50 wt%, high Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, and Sr contents, low Y and heavy rare-earth contents, and high Sr/Y, La/Yb and Na<sub>2</sub>O/K<sub>2</sub>O ratios. However, these intermediate granulites have unusually high Mg#s (54-71) and high Ni (21-147 ppm) contents for their SiO<sub>2</sub> contents and would otherwise suggest that these granulites are more primitive than their SiO<sub>2</sub> contents indicate.

It has been hypothesized that continuous melt-rock reaction between a silicic melt and ultramafic country rock (lherzolite) can convert olivine to orthopyroxene, ultimately resulting in the formation of a high Mg# garnet pyroxenite, similar to what is seen in the Hannuoba garnet pyroxenite composite xenoliths. In addition, silicic melts that have reacted with mantle peridotite would be predicted to have anomalously high Mg#s and Ni contents (due to the strong buffering capacity of peridotite for Mg and Ni), producing melts having compositions similar to the intermediate mafic granulite xenoliths in this study. It is thus possible that the Hannuoba garnet pyroxenites and

intermediate-mafic granulites share a common petrogenetic origin. Such a link is further supported by the fact that (1) the rare-earth element abundance patterns of melts calculated to be in equilibrium with the garnet pyroxenites roughly coincide with that of the intermediate granulites, and (2) the Sr-Nd isotopic compositions of garnet pyroxenites can be modeled by a simple mixing between intermediate granulite and mantle peridotite. It is concluded that the Hannuoba garnet pyroxenite-bearing composite xenoliths may present the first physical evidence for the hypothesized melt-rock reaction necessary for generating evolved magmas with high Mg# and hence, high-Mg# andesitic signature of the continental crust.

# **Geochemistry of Cenozoic basalts in eastern China: implication for asthenosphere- lithospheric mantle interaction**

Yanjie Tang, Hongfu Zhang, Jifeng Ying and Jin Zhang

*State Key Laboratory of Lithosphere Tectonic Evolution, Institute of Geology and Geophysics,  
Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, P.R. China*

*E-mail: [tangyanjie@mail.igcas.ac.cn](mailto:tangyanjie@mail.igcas.ac.cn)*

Cenozoic basaltic rocks are widespread in eastern China. They erupted in an Early Tertiary back-arc rift environment and from Late Tertiary and Quaternary volcanic eruption centers along active faults of the continent. These volcanic rocks are dominantly potassic tholeiites and alkali basalts with a variable composition.

Compositional distinction of these rocks provides critical information on their mantle sources, regional-scale mixing histories, and conditions of partial melt segregation. Alkaline basalts are systematically less radiogenic than geographically coextensive and contemporaneous tholeiitic basalts. The preferred hypothesis is that the alkalic magmas come from a deeper source, with long-term LIL-element depletion and low Rb/Sr ratio but relatively recent LIL-element enrichment. Conversely, the tholeiitic magmas are melts of subcontinental mantle lithosphere that is more LIL-element depleted than the source for alkaline rocks, at the time of magma genesis, but has an elevated Rb/Sr ratio for much of its post-consolidation history. Some high Sr and Pb and low Nd isotopic ratios indicate the variable addition of lithosphere to anomalous DUPAL-like asthenosphere in the formation of these basaltic rocks. Therefore, we suggest that the geochemistry of the Cenozoic basalts in eastern China reflect the involvement of both lithospheric and asthenospheric sources at variable melting degrees and the different degree of asthenosphere-lithosphere interaction.

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## **Coupling of mafic-ultramafic and adakitic magmatism in the Dabie orogen, central China: evidence for post-collisional delamination**

Fang HUANG<sup>1,2</sup>, Shuguang LI<sup>1</sup>, Feng DONG<sup>1</sup>

*1, Department of Earth and Space Sciences, University of Science and Technology of  
China, Hefei, Anhui 230026, China*

*2, Department of Geology, University of Illinois at Urbana-Champaign,  
1301 W. Green St., IL 61801, USA*

Post-collisional mafic-ultramafic (PCM) and intermediate intrusive rocks with similar ages of about 125 Ma from the Dabie orogen have been investigated to understand the deep process of the lithosphere of the collision zone in the Mesozoic. The Zhujiapu intrusion is mafic-ultramafic in composition, which shows obvious continental features, such as enrichments of large ion lithophile elements (LILE, i.e. Ba, Th) and depletions of high field strength elements (HFSE, i.e. Zr, Ti). The PCM intrusive rocks from the Dabie orogen roughly resemble the Mesozoic mantle-derived rocks from North China Block (NCB) in Sr-Nd-Pb isotopic composition, strongly suggesting involvement of lower crustal materials. These geochemical characteristics did not result from crustal contamination or magma mixing, but reflect the properties of the mantle source. Source mixing among the depleted mantle, lower crust, and EMII-typed lithospheric mantle is required to interpret the mantle source of the PCM intrusive rocks from the Dabie orogen. Intermediate intrusive rocks from the Chituling and Bixiling are andesitic. These rocks are enriched in the light rare earth elements (LREE), but have relative lower the heavy rare earth elements (HREE) contents. The Sr-Nd-Pb isotopic compositions are similar to those of the lower crust of the Dabie orogen. Interestingly, the Chituling and Bixiling intrusion have high Sr/Y, high Mg (Mg# 43-64), Cr (36-246 ppm), and Ni (15.5-87.3 ppm) content, consistent with high Mg adakites observed in Northeast China (Gao et al., 2004) and Ningzheng (Xu et al., 2002). These geochemical characteristics might suggest that the Chituling and Bixiling intrusions stepped from partial melting of deeply subducted lower crust, which was delaminated into the upper mantle. Combining the genetic relationship of the mafic-ultramafic and high-Mg adakitic rocks in the Dabie orogen, we propose that they both reflect the coupled consequences of lithospheric delamination in the collision zone.

Gravitational instability due to greater density of eclogitic lower mafic crust than the upper mantle results in lithospheric delamination creating upwelling of asthenospheric mantle. Interaction between the asthenospheric mantle, lithospheric mantle, and lower crust could produce the mantle source of the PCM intrusive rocks, while partial melts from the delaminated mafic lower crust might be revised by surrounding mantle rocks to form the high Mg, Cr, and Ni contents in the adakitic rocks from the Chituling and Bixiling intrusions.

## **Geochronology and geochemistry of volcanic rocks in Western Liaoning Province: constraints on mechanism for the lithospheric thinning**

Wei Yang and Shuguang Li

*Sch. of Earth and Space Sciences, University of Science and Technology of China, Hefei, China. E-mail: [blade\\_yw@163.net](mailto:blade_yw@163.net)*

Mesozoic volcanic rocks from Western Liaoning Province have been investigated to understand the timing and mechanism of the lithospheric thinning of North China craton from Paleozoic to Cenozoic. Geochronologic studies suggest that there are three periods of Mesozoic volcanisms in Western Liaoning Province, which are corresponding to the Lanqi Formation (166 – 144Ma), the Yixian Formation (126 – 120Ma) and the Zhanglaogongtun Formation (~105 Ma), respectively. The basalts from the Lanqi Fm. and the Yixian Fm. have similar isotopic compositions in low  $\epsilon_{Nd}(t)$  (-17 ~ -10), high  $^{87}Sr/^{86}Sr$  (0.705 ~ 0.707) and low radiogenic Pb isotopes, strongly suggesting the involvement of lower crustal materials in their mantle source. In the contrary, the Sr-Nd-Pb isotopic compositions of the basalts from the Zhanglaogongtun Fm. are similar to the depleted mantle. Geochemical property of the mafic rocks from Western Liaoning Province varies abruptly from 120 to 105 Ma, indicating that the lithosphere may be also thinned during this period due to the regional extension since 120Ma (Davis, et al., 2001). Depleted mantle component showed up about 30 Ma earlier in basalts from western Liaoning than from Shandong (Xu et al. 2004), suggesting that regional extension happened earlier in western Liaoning than in Shandong. This observation is consistent with the clockwise rotation of Korea Peninsula relative to Eurasia (Zhu et al. 2002).

Four andesites from the Yixian Formation have high Sr/Y and Mg, consistent with high-Mg adakites observed in Northeast China (Gao et al., 2004) and Ningzheng (Xu et al., 2002). These rocks might result from partial melting of the delaminated lower mafic crust. The Lanqi and Yixian rocks have similar Sr-Nd-Pb isotopic composition, consistent with the Mesozoic basalts from North China craton and high-Mg adakites. This indicates the lithosphere was still thick during this period. Therefore, although the lithosphere could be thinned during 159 – 125 Ma by delamination, the thinning might not be significant.

## Zircons in Rodingites and their U-Pb Ages from a Serpentinite Complex, Western Tianshan

Li XuPing<sup>1</sup>, Zhang Li Fei<sup>2</sup>, Ai YongLiang<sup>2</sup>, Qu Junfeng<sup>2</sup>, Song Biao<sup>3</sup> & Liu Xiaoming<sup>4</sup>

<sup>1</sup>*School of the Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China, E-mail: [lixuping@cugb.edu.cn](mailto:lixuping@cugb.edu.cn)*

<sup>2</sup>*School of Earth and Space Sciences, Peking University, Beijing 100871, China*

<sup>3</sup>*Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China*

<sup>4</sup>*The Key Laboratory of Continental Dynamics, Northwest University, Xi'an 710069, China*

The Chinese Western Tianshan orogenic belt lies between the Tarim plate to the south and the Yili-central Tianshan craton to the north. The rodingite derives from eclogite as tectonic inclusion enclosed in the ultramafic rocks of Changawuzi ophiolites in the Southwestern Tianshan ophiolitic mélange. Serpentinized ultramafic rocks occur together with interlayered south-dipping blueschists and greenschists in Changawuzi ophiolites suggesting a relict Silurian oceanic crust. Rodingites contain a mineral assemblage of prehnite, clinozoisite, hydrogrossular, diopside, vesuvianite and chlorite, while partial rodingitized rocks still preserve the relict omphacite and Fe-Mg-Al garnet. The calculated PT conditions show that the paragenesis of eclogite facies is stable at least 540°C / 17 kbar. The rodingitization started at 370 ~ 410 °C / 6.5 ~ 8.5 kbar, while pervasive rodingitization took place under conditions of 200 ~ 350 °C / 2 ~ 6 kbar.

Cathodoluminescence reveals that the most zircon grains from the intensely rodingitized rock consist of distinct rim and core. The jagged cracks cross zircon rim, showing clear fluid channels to the core. A well defined group  $^{206}\text{Pb} / ^{238}\text{U}$  age of  $422 \pm 10$  Ma (2 sigma) from rims of zircon shows an age of middle Silurian, suggesting a metamorphic age of Silurian oceanic crust. The ages from cores of zircons in rodingites vary from 422 Ma to 291 Ma, implying a continuous fluid alteration to the core of zircon during exhumation and giving mixed ages. REE patterns obtained by LA-ICP-MS analyses from zircons of the rodingite are also variable from recrystallized core to the zircon rim, which are clearly correlated to the extent of hydro-metamorphic overprint. The higher the total amount of REE present in the core of the zircon, the younger is its apparent age. The lower boundary of the core age was constrained by single grain zircons in the rodingite, which have no zoning texture observed and contain very low U (45~83 ppm) and common Pb (3~5 ppm), showing the typical hydrothermal zircons formed from fluid, and even their growing textures are clearly distinguishable. These single grain zircons around 291 Ma are considered formed during pervasive rodingitization, and the age correspondingly represents a Late Paleozoic hydrothermal event.