Available online at www.sciencedirect.com
ScienceDirect
EPSL
Earth and Planetary Science Letters 261 (2007) 179–200
www.elsevier.com/locate/epsl

# Multistage evolution of the Jijal ultramafic–mafic complex (Kohistan, N Pakistan): Implications for building the roots of island arcs

B. Dhuime [a,*], D. Bosch [a], J.-L. Bodinier [a], C.J. Garrido [b], O. Bruguier [c], S.S. Hussain [d], H. Dawood [d]

[a] *Laboratoire Géosciences Montpellier, Equipe Manteau-Noyau, UMR 5243, CNRS & Université de Montpellier 2, Cc 060, 34095 Montpellier cedex 05, France*
[b] *Departamento de Mineralogía y Petrología & Instituto Andaluz de Ciencias de la Tierra, Facultad de Ciencias, Universidad de Granada & CSIC, 18002 Granada, Spain*
[c] *Service Commun "ICP-MS", ISTEEM, CNRS & Université de Montpellier 2, Cc 57, 34095 Montpellier cedex 05, France*
[d] *Pakistan Museum of Natural History, Garden Avenue, Shakarparian, 44000 Islamabad, Pakistan*

Received 12 February 2007; received in revised form 15 June 2007; accepted 22 June 2007
Available online 7 July 2007
Editor: R.W. Carlson

**Abstract**

The ultramafic–mafic complexes located at the base of obducted paleo-island arcs are commonly interpreted as evidence for intra-crustal fractionation of primitive (high-Mg#) mantle melts. The present study, realized on the Jijal mafic–ultramafic basal section of the Cretaceous Kohistan oceanic arc (N Pakistan), discards a crystal fractionation model from a single parental magma to take into account the geochemical and isotope variations observed between the plutonic crust and the underlying ultramafic section. The basal ultramafic rocks, i.e. dunites, wehrlites and clinopyroxenites, show high Mg#, extremely depleted REE patterns, no marked HFSE anomalies and high LILE enrichment. Cpx and leached whole rocks from this unit yield restricted $\varepsilon_{Nd}$ values (+5.5 to +6.8), a large $\varepsilon_{Sr}$ range (−5.9 to +8.8) and mainly radiogenic $^{207}Pb/^{204}Pb$ ratios. The overlying mafic section, i.e. gabbroic rocks, displays low Mg# (46 < Mg# < 54), enriched REE patterns and marked HFSE anomalies. These plutonic rocks have also very homogeneous Sr and Pb isotopic compositions defining a restricted domain, which does not overlap that of the ultramafic samples. Moreover, Cpx from the basal ultramafics yield an Sm–Nd isochron at 117 ± 7 Ma interpreted as dating crystallization of the ultramafic section. Together, these results indicate that the mafic rocks on one hand and the ultramafic rocks on the other hand, originate from separate sources with specific emplacement underneath the subduction zone. A lherzolite lens, collected from the top of the mafic section, plots on the early Cretaceous Sm–Nd isochron and therefore yields the same $^{143}Nd/^{144}Nd$ initial ratio. This suggests that the ultramafic part of the lower Kohistan arc complex sampled the initiation stages of the subduction with production of magmas with boninite-like features. At this stage, the mantle wedge has been already modified by percolation of the first slab-derived fluids. On such a scenario the lherzolite lens would correspond to the lithospheric mantle underneath the arc before its

* Corresponding author. Tel.: +33 4 67 14 36 02; fax: +33 4 67 14 36 03.
*E-mail address:* dhuime@gm.univ-montp2.fr (B. Dhuime).


doi:10.1016/j.epsl.2007.06.026

initiation. A multi-stage history is proposed for the evolution for the Kohistan arc through ~30 Ma. Stage #1 reflects the spontaneous initiation of subduction associated with extensive boninitic affinity magmatism, stages #2 and #3 are related to arc building by tholeiitic melts and, a fourth step (stage #4) corresponds to the intra-crustal differentiation.


*Keywords:* Kohistan; island arc; subduction initiation; mantle wedge; pyroxenite; geochemistry

## 1. Introduction

Continental crustal growth by island arc accretion is the main continental crust-forming process during the Phanerozoic, which is well supported by abundant juvenile crust present at the rims of cratonic landmasses (e.g. McLennan and Taylor, 1985; Rudnick, 1995; Condie and Chomiak, 1996). The igneous processes that occur at active margins remain barely understood, namely the composition and the source(s) of primitive (i.e. Mg#>60) arc magmas and the nature of intra-crustal differentiation processes required to give the continental crust its evolved (i.e. Mg# ~50) bulk composition (e.g. Kelemen et al., 2003 and ref. therein). Arc formation processes can be studied through lower crustal and upper mantle xenoliths (e.g. Conrad et al., 1983; Maury et al., 1992; McInnes et al., 2001) or 'in situ', in obducted section of intra-oceanic arc lithosphere. Worldwide, only two examples of well-preserved exhumed arc sections, complete from their mantle roots to upper volcano-sedimentary levels, have been described: the Jurassic Talkeetna arc in south-central Alaska (e.g. Barker and Grantz, 1982; DeBari and Coleman, 1989 and the Cretaceous Kohistan arc in N Pakistan (e.g. Bard, 1983; Treloar et al., 1996).

The basal units of both Talkeetna and Kohistan arcs are made up of a lower ultramafic section of dunite–pyroxenite, overlaid by a gabbroic mafic section. The genetic link between the ultramafic and mafic sections is debated and two competing models exist in the most recent studies. The first model (model 1) suggests that a typical ultramafic–mafic sequence (e.g. dunites–wehrlites–pyroxenites–hornblendites–gabbronorites) may crystallize in the lower crust and upper mantle from a single primitive (high-Mg#) arc magma (DeBari and Coleman, 1989; DeBari and Sleep, 1991; Khan et al., 1993; Schiano et al., 2000; Kelemen et al., 2003; Greene et al., 2006). This model is supported by an experimental study of Müntener et al. (2001) which successfully reproduced – for hydrous conditions (>3% $H_2O$) and $P$–$T$ setting typical of the lower arc crust (i.e. $P$=1.2 GPa and $T$=1030–1250 °C) – high-Mg# pyroxenites (Mg#≤88) and low-Mg# liquids (Mg#≥53) from the crystallization of high-Mg# magmas. However in Kohistan, petrological observations and REE numerical modeling (Burg et al., 1998; Garrido et al., 2007) refute a cumulate origin for the dunite–wehrlite–pyroxenite ultramafic sequence and rather suggest an origin by melt–rock reaction at the expense of the sub-arc oceanic mantle (model 2).

Although isotopic data are a powerful tool to determine various sources involved in arc-related magmagenesis (e.g. Turner and Foden, 2001), the only detailed isotopic studies developed on the Kohistan island arc sections were focused on the middle- to upper-crustal levels (Petterson and Windley, 1985; Petterson and Windley, 1991; Khan et al., 1997; Schaltegger et al., 2002; Bignold and Treloar, 2003; Bignold et al., 2006) or, on the younger ultramafic–mafic Chilas complex (Khan et al., 1997; Schaltegger et al., 2002; Bignold and Treloar, 2003; Jagoutz et al., 2006) and no extensive study is yet available for the basal Jijal ultramafic–mafic complex (Yamamoto and Nakamura, 1996; Anczkiewicz and Vance, 2000; Yamamoto and Nakamura, 2000). In the present work, we combine Sr–Nd–Pb isotopic data (leached and/or unleached whole rocks and mineral separates) with major and trace element analyses for representative samples collected through the Jijal ultramafic–mafic complex. The main aims were to determine the origin of the various units of the Kohistan arc roots and to unravel the spatial/temporal evolution of the Jijal ultramafic–mafic complex. This has implications for magma generation in intra-oceanic island arc environments and allows us to propose a new multistage model for the earliest episodes of the Kohistan arc building.

## 2. Geological setting

The Kohistan arc complex (KAC, Fig 1a), in northern Pakistan, represents the exhumed section of a Cretaceous intraoceanic arc formed during the northward subduction of the Neo-Tethys Ocean beneath the Karakoram plate (e.g. Bard, 1983; Burg et al., 1998; Schaltegger et al., 2002). It is now sandwiched between the Karakoram (Asian) plate to the north and the Indian plate to the south, and is respectively separated from these blocks