Chemical Geology 298–299 (2012) 79–96

Contents lists available at SciVerse ScienceDirect

Chemical Geology

journal homepage: www.elsevier.com/locate/chemgeo

The formation and bulk composition of modern juvenile continental crust: The Kohistan arc

O. Jagoutz [a,*], M.W. Schmidt [b]

[a] Dept. of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, USA
[b] Institut of Geochemistry and Petrology, ETH Zurich, 8092 Switzerland

ARTICLE INFO

Article history:
Received 21 June 2011
Received in revised form 27 October 2011
Accepted 28 October 2011
Available online 9 November 2011

Editor: K. Mezger

Keywords:
Continental crust
Arc magmatism
Kohistan arc

ABSTRACT

The intraoceanic Kohistan arc, northern Pakistan, exposes a complete crustal section composed of infracrustal basal cumulates formed at ≤55 km depth, a broadly basaltic/gabbroic lower crust, a 26 km thick calc-alkaline batholith, and 4 km of a volcanoclastic/sedimentary sequence. The bulk composition of the Kohistan arc crust is approximated by estimating the relative volumes of exposed rocks through detailed field observations, in particular along a representative km-wide transect across the arc, through geobarometric constrains to determine the unit thicknesses, and through satellite images to estimate their lateral extent. We separated the arc into three major units: lower, mid-, and mid- to upper crust, which contain a total of 17 subunits whose average compositions were derived from employing a total of 594 whole rock analyses. The volume-integrated compositions of each unit yield the bulk composition of the arc crust. While the details of the resulting bulk composition depend slightly on the method of integration, all models yield an andesitic bulk supra Moho composition, with an average SiO_2 of 56.6–59.3 wt.% and X_{Mg} of 0.51–0.55. The Kohistan arc composition is similar to global continental crust estimates, suggesting that modern style arc activity is the dominant process that formed the (preserved) continental crust. A slight deficit in high field strength and incompatible elements in the Kohistan arc with respect to the global continental crust can be mitigated by adding 6–8 wt.% of (basaltic) intraplate type magmas. Our results document that infra arc processes, even in a purely oceanic environment, result in an overall andesitic crust composition in mature arcs, contrary to the widely accepted view that oceanic arcs are basaltic. Bulk crust differentiation from a basaltic parent occurs through foundering of ultramafic cumulates. Our results imply that secondary reworking processes such as continental collision are of secondary importance to explain the major element chemistry of the bulk continental crust composition.

Published by Elsevier B.V.

1. Introduction

Based on trace element similarities, it is widely accepted that modern continental crust is dominantly created at convergent margins (Rudnick, 1995; Barth et al., 2000). In subduction zones, fluid assisted melting of upwelling wedge mantle leads to primitive, dominantly basaltic melts, which ascend and fractionate (Kushiro, 1990; Grove et al., 2003). The so-called "andesite model" of continental crust growth (Taylor, 1967) holds that arcs produce andesitic bulk crust compositions, in accord with the broadly andesitic bulk composition of the continental crust (Rudnick and Gao, 2003). Estimates of the bulk composition of oceanic arcs however, indicate that the bulk composition of island arcs may be closer to basalt than to andesite (Smithson et al., 1981; Kay and Kay, 1986; Holbrook et al., 1999), implying that additional reworking processes that transform the basaltic island arc crust into andesitic continental crust are essential (Lee et al., 2007). Alternatively, Kelemen (1995) has proposed that island–arc crust may contain a substantial proportion of high-Mg andesites characterized by an X_{Mg} ($X_{Mg}=Mg/(Fe+Mg)$) that is higher than for modern average andesites and is therefore appropriate to explain the high X_{Mg} of the bulk continental crust.

To differentiate primitive basaltic melts and a possibly initially more basaltic bulk arc crust toward an evolved continental crust, an ultramafic fraction must be separated from the evolving melt. Most probably, this happens through accumulation and foundering of gravitationally unstable, mafic to ultramafic, dense cumulates precipitated at the base of the crust (Kay and Kay, 1993; Jull and Kelemen, 2001; Jagoutz et al., 2011). Alternatively, partial melting of the lower crust could lead to an eclogitic s.l. residue that may gravitationally slump into the mantle (Tatsumi and Kogiso, 2003). Understanding the details of these processes and thus the origin of continental crust is hampered by our limited knowledge of the composition and structure of volcanic arcs, in particular, their deeper sub-batholithic parts, which are rarely exposed and accessible.

* Corresponding author.
E-mail address: jagoutz@mit.edu (O. Jagoutz).

0009-2541/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.chemgeo.2011.10.022

In order to test such hypotheses of continental crust formation, it is crucial to constrain the composition and deep structure of arcs, ideally those where crust forms anew without interaction with preexisting continental crust. The ideal site for such an undertaking is the Cretaceous to Tertiary intraoceanic Kohistan island arc, where all levels of the arc are exposed, from ultramafic cumulates at the basis of the crust to granulite facies lower crust to a mid- and upper-crustal batholith, and finally to surficial volcanoclastics and sediments (Tahirkheli, 1979).

In this paper we provide a quantitative estimate of the bulk composition of the Kohistan arc crust. This is accomplished through reconstruction of the Kohistan arc section by approximating the proportions of each lithology based on geobarometric results combined with volumes derived from the present day exposure, integration of over 500 bulk rock analyses and, finally, calculation of the bulk crust composition. Finally, we discuss this composition and its direct implications for the formation of the continental crust.

2. Geological setting

The Kohistan arc (Fig. 1), exposed in NE Pakistan, is a fossil Cretaceous to Tertiary arc complex (Tahirkheli, 1979; Bard, 1983) formed over a presumably north dipping subduction zone in the equatorial part of the Tethyan ocean. The arc was obducted and sandwiched between the colliding Indian and Eurasian plates during the Himalayan orogeny. It is separated from the Eurasian margin by the Shyok or Karakoram–Kohistan sutures and from the Indian continent by the Indus suture zone (Fig. 1). Juvenile oceanic arc magmatic activity, constrained by U–Pb zircon ages, and Hf, Pb, Nd and Sr isotopic data occurred dominantly between 110 and 50 Ma (Jagoutz et al., 2009).

The large-scale geodynamic evolution of the arc is only in part well constrained. While it is well established that the Kohistan–India collision occurred around ~50 Ma (Garzanti et al., 1987; Gaetani and Garzanti, 1991), debate circles around the exact timing of the collision between the Kohistan arc and Eurasian margin, along the Shyok Suture. The closure of the Shyok Suture has been considered to predate the India–Eurasia collision (~104–85 Ma, Petterson and Windley, 1985; Treloar et al., 1996). However, the constraints on the timing of collision have been questioned (Jagoutz et al., 2009) and paleomagnetic data indicate that India collided first with Kohistan (<50–60 Ma, Bard, 1983; Khan et al., 2008) before colliding with Eurasia. The importance of this finding for this study is that, until collision with the Karakorum block, which then constituted the southern margin of Asia, the Kohistan arc must have developed in an intraoceanic setting. Irrespective of which collision scenario is correct, the absence of an old continental basement, the paleomagnetic data and the lack of evidence for any contamination of the Kohistan intrusives by (ancient) continental crust until <50 Ma (see discussion below) indicates formation of the Kohistan arc far removed from continental crust. Thus, the pre-50 Ma Kohistan arc represents juvenile continental crust.

Intra-arc extension followed by sandwiching between the Karakorum and Indian plate and the underplating of the Indian subcontinent led to complete exposure of a continuous section of arc crust from upper mantle rocks in the south to unmetamorphosed sediments in the north (Burg et al., 2006). Recent advances in understanding the complex geology of the Kohistan arc and increasingly available P–T determinations (Yoshino et al., 1998; Ringuette et al., 1999; Yoshino and Okudaira, 2004; Enggist, 2007) indicate that, overall, the exposed thickness of the Kohistan agrees reasonably well with geobarometrically derived pressures, suggesting that the crustal section is intact (Figs. 2–4). Major faults are absent in the east (Fig. 1), but some larger scale faults are present in the west (e.g., Dir-Kalam fault, Jagoutz et al., 2009; Sullivan et al., 1993; Treloar et al., 1996). Estimated equilibration pressures range from ~1.5 GPa at the base of the garnet gabbro, which constitutes the Moho, to ~0.8 GPa at the top of the Southern Plutonic Sequence (Fig. 2, see figure legend for references). This pressure difference of 0.7 GPa correlates well with the inferred lower crustal thickness (~26 km, Table 1). The batholith itself is continuously exposed from its deepest intrusion levels of ~0.8 GPa in the southeast to epithermal plutons in the northwest (Enggist, 2007) and continues into volcanoclastic, carbonate and terrigenous sedimentary rocks (Fig. 4). This picture is complicated by sedimentary sequences contained in and intruded by the batholith at much deeper levels (Fig. 1). Between the lower and middle to upper crust of the Kohistan arc, the extension-related Chilas gabbronorite complex (Fig. 3, Jagoutz et al., 2006, 2007) is exposed.

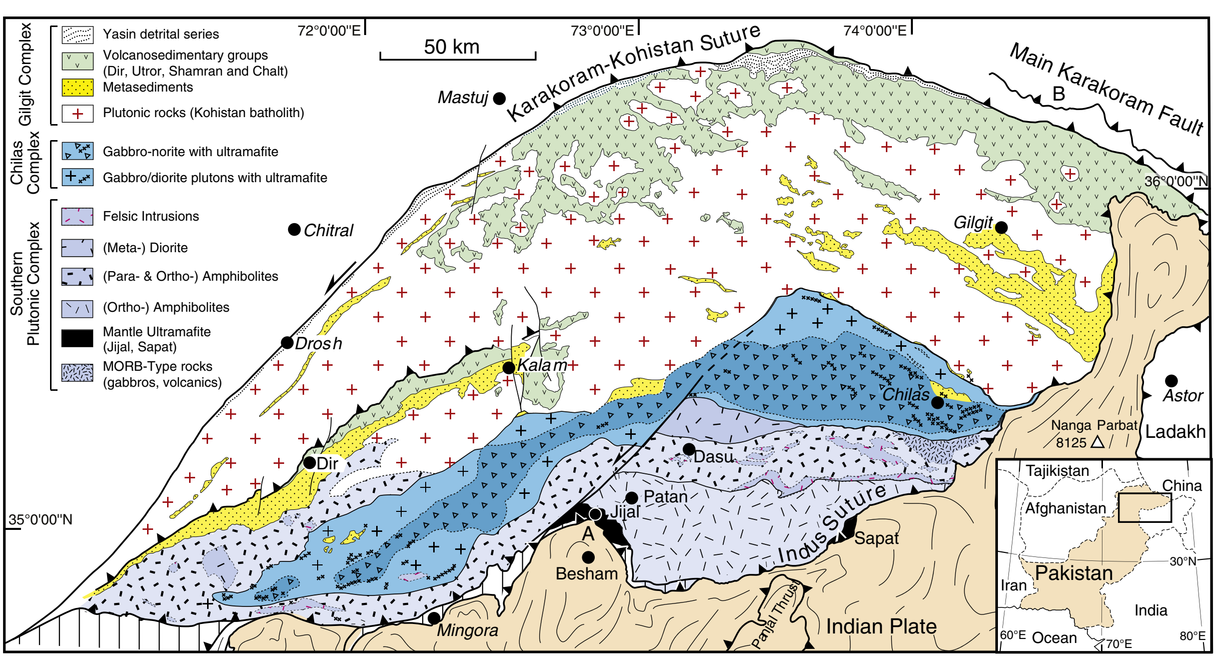

Fig. 1. Geological map of the Kohistan arc. The map illustrates well the dominance in outcrop area of the mid- to upper crust batholith with respect to the lower crust represented by the Southern Plutonic Complex. Geobarometry attributes similar thicknesses to the Gilgit Complex and the Southern Plutonic Complex.