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Formation of Juvenile Island arc Crust Through Melting of Sub-arc Mantle: Precise U-Pb Ages and Hf Isotopes from a Fossil Crust-Mantle Transition in the Kohistan Complex (Northern Pakistan)

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The Kohistan Arc Complex in northern Pakistan was formed in the Tethys Ocean in Mesozoic times and subsequently obducted onto the Indian plate along the Indus Suture in Late Cretaceous-Palaeocene times. It is a unique setting in that a fossil sub-arc crust-mantle transition zone and the initial formation of arc-type crust through partial melting of underlying mantle is fully exposed and can be studied in detail. The tectonic evolution of the arc can be subdivided into (1) a juvenile stage (estimated at ca.110-95 Ma): lithospheric growth through partial melting of a fertile mantle in an intra-oceanic subduction environment; (2) intra-arc rifting (around 80 Ma) with the emplacement of large volumes of volcaniclastic rocks in the intra-arc extensional basin and underplating of the arc crust by gabbronorites; (3) a mature stage with Andean-type granitoid magmatism of the Kohistan Batholith, which ceased with the collision of India and Asia 60 to 40 Ma ago. The structurally lowest levels of the Kohistan Arc Complex comprise the following lithological units: The Jijal complex, which consists of ultramafic rocks overlain by granulite-facies gabbros, is interpreted as fossil mantle-to-crust transition. It was probably buried to depths of more than 50 km (17 kbars) and subsequently re-equilibrated in granulite-facies conditions. Textural evidence suggests that the gabbros crystallized under granulite-facies conditions. The Jijal complex is covered by a pile of metamorphic gabbroic dykes and sills overlain by oceanic meta-basalts and metasediments. The metamorphic conditions of these crustal units never exceeded amphibolite-facies conditions. This association was intruded by partial melts of mantle origin (gabbros, tonalites, granitoids) during initial arc build-up (stage 1). The whole complex was again penetrated by mantle melts (gabbronorites to granitoid dykes) during rifting (stage 2).

Precise age determinations were carried out on lithologies representing the first stages of crustal growth in an intra-oceanic arc environment: Low-blank conventional U-Pb dating techniques using 5 to 200 microgram-fractions of low-U zircons (3 ppm to 500 ppm of U, and radiogenic Pb of as low as 0.05 ppm) yielded precise $^{206}Pb/^{238}U$ ages: A sub-granulitic gabbro and a granitoid sheet-like intrusion yielded significantly discrete ages of 98.9±0.4 and 97.1±0.2 Ma, respectively; a tonalite body was emplaced into the same environment 91.8±1.4 Ma ago, and a granitoid kyanite-bearing dyke yielded an age of 82.8 ±1.1 Ma. The ages represent the first protolith ages from the sub-arc mantle-crust transition and are in agreement with published ^{39}Ar-^{40}Ar, Rb-Sr and Sm-Nd mineral cooling ages. Initial Hf isotopic compositions of all dated zircon micro-fractions were determined using multicollector ICP-MS. The averaged data of 3 to 5 individual analyses of each lithology are indistinguishable within their error limits and amount to an epsilon Hf value of +14, indicating an unchanged source for all melts.

The following conclusions are drawn: The time for the initial arc build up with gabbroic to granitoid magmatism is constrained to a short period between 99 and 92 Ma, intra-arc rifting characterized by the intrusion of a granitoid dyke is precisely dated at 82 Ma; the latter age is similar to the 84 Ma age for the main underplated gabbro-norite (Zeitler et al. 1980). Initial arc magmatism may therefore be constrained to at least three magmatic pulses of 1-2 m.y. duration. Each magmatic cycle most likely comprises gabbroic to granitoid lithologies, pointing to rapid differentiation processes. The sub-arc mantle was slightly more radiogenic (epsilon Hf +14) than a depleted MORB-type mantle source (+16 to + 18); it did not undergo any important geochemical change within the earliest 17 m.y. of its tectonic history since all zircons recorded identical initial Hf isotopic compositions. The slightly enriched geochemical nature of the sub-arc mantle may be caused by fluid infiltration from the oceanic crust of the underlying downgoing slab. The hypothesis that all granitoid stocks, sheets and dykes were emplaced after obduction onto the Indian plate and thus represent crustal melts can be discarded.

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