Origin of the island arc Moho transition zone via melt-rock reaction and its implications for intracrustal differentiation of island arcs: Evidence from the Jijal complex (Kohistan complex, northern Pakistan)

Carlos J. Garrido*   Departamento de Mineralogía y Petrología & Instituto Andaluz de Ciencias de la Tierra, Facultad de Ciencias, Universidad de Granada & CSIC, 18002 Granada, Spain

Jean-Louis Bodinier
Bruno Dhuime
Delphine Bosch   Laboratoire Géosciences Montpellier, Equipe Manteau-Noyau, UMR 5243,
Ingrid Chanefo   CNRS & Université de Montpellier 2, cc 49, 34095 Montpellier cedex 05, France
Olivier Bruguier

Shahid S. Hussain   Pakistan Museum of Natural History, Garden Avenue, Shakarparian, 44000 Islamabad, Pakistan
Hamid Dawood

Jean-Pierre Burg   Structural Geology and Tectonics, ETH Zürich & Universität Zürich, Geologisches Institut, Leonhardstrasse, 19/LEB, CH-8092 Zürich, Switzerland

ABSTRACT

If the net flux to the island arc crust is primitive arc basalt, the evolved composition of most arc magmas entails the formation of complementary thick ultramafic keels at the root of the island arc crust. Dunite, wehrlite, and Cr-rich pyroxenite from the Jijal complex, constituting the Moho transition zone of the Kohistan paleo–island arc (northern Pakistan), are often mentioned as an example of high-pressure cumulates formed by intracrustal fractionation of mantle-derived melts, which were later extracted to form the overlying mafic crust. Here we show that calculated liquids for Jijal pyroxenites-wehrlites are strongly rare earth element (REE) depleted and display flat or convex-upward REE patterns. These patterns are typical of boninites and are therefore unlike those of the overlying mafic crust that have higher REE concentrations and are derived from light rare earth element (LREE)–enriched melts similar to island arc basalt. This observation, along with the lower $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios of Jijal pyroxenites-wehrlites relative to gabbros, rejects the hypothesis that gabbros and ultramafic rocks derive from a common melt via crystal fractionation. In the $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram, ultramafic rocks and gabbros lie on the same positive correlation, suggesting that their sources share a common enriched mantle 2 (EM2) signature but with a major depleted component contribution for the ultramafic rocks. These data are consistent with a scenario whereby the Jijal ultramafic section represents a Moho transition zone formed via melt-rock reaction between subarc mantle and incoming melt isotopically akin to Jijal gabbroic rocks. The lack in the Kohistan arc of cogenetic ultramafic cumulates complementary to the evolved mafic plutonic rocks implies either (1) that a substantial volume of such ultramafic cumulates was delaminated or torn out by subcrustal mantle flow from the base of the arc crust in extraordinarily short time scales (0.10–0.35 cm/yr), or (2) that the net flux to the Kohistan arc crust was more evolved than primitive arc basalt.

Keywords: island arcs, Kohistan, Jijal, Cr-rich pyroxenite, wehrlite, lower crust, Moho transition zone, boninite.

INTRODUCTION

Oceanic island arcs exhibit intense igneous activity characterized by volcanic and plutonic rocks that are more evolved than their mid-oceanic-ridge counterparts. The current paradigm is that parental arc magma is primitive basalt with Mg# > 60 [Mg# = 100 × MgO/(MgO + FeO) molar ratio] and major element chemistry similar to that of mid-oceanic-ridge olivine tholeiitic basalt (e.g., Stern, 2002; Kelemen et al., 2003). Experimental work and mass balance calculations indicate that primitive arc basalts undergo extensive intracrustal fraction-

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*E-mail: carlosg@ugr.es

ation of ultramafic cumulates to generate arc products with evolved composition, leaving a complementary ultramafic keel at the island arc root (Kay and Kay, 1985; DeBari et al., 1987; Muntener et al., 2001). Direct testing of the crystal-fractionation linkage of deep mafic and ultramafic rocks in nature has proven elusive, as terrains exposing the ultramafic roots of island arcs are scarce. The Jijal mafic-ultramafic complex (northern Pakistan) constitutes the deepest levels of the Kohistan paleo–island arc complex (Fig. 1A) (Jan and Howie, 1981; Bard, 1983). The abrupt appearance of gabbroic rocks overlying a thick ultramafic section in the Jijal complex constitutes the Moho transition zone of the

Kohistan paleo–island arc (Fig. 1B). This zone is interpreted either as the mantle-crust transition between the island arc plutonic crust and modified, subarc residual mantle (Bard, 1983; Burg et al., 1998), or as the transition between "crustal" ultramafic and mafic cumulates formed by high-pressure crystal fractionation from a common primitive arc basalt (Muntener et al., 2001; Kelemen et al., 2003). Here we present geochemical evidence that indicates that the Jijal Moho transition zone is a mantle-crust transition where residual subarc lithospheric peridotites reacted extensively with incoming arc melts.

THE ULTRAMAFIC ROOTS OF THE KOHISTAN ISLAND ARC

The Kohistan complex (Fig. 1) is an exhumed section of a Cretaceous island arc formed during subduction of the Neo-Tethys Ocean beneath the Karakoram plate (Bard, 1983; Khan et al., 1993; Treloar et al., 1996). The Jijal mafic-ultramafic complex is the structurally lower unit and together with the overlying Metaplutonic complex (Fig. 1) represents the plutonic section of the Kohistan island arc formed before 95 Ma (Schaltegger et al., 2002). The Jijal complex consists of an upper gabbroic section overlying a thick ultramafic section (Fig. 1B) (Jan and Howie, 1981). The gabbroic section contains minor hornblendite lenses and is dominated by gabbroic rocks (Fig. 1B) whose igneous textures and mineral compositions were pervasively overprinted by granulite-facies metamorphism (Yamamoto, 1993). Hornblende gabbronorite of the Jijal mafic section and the overlying Sarangar gabbros display melt-like, chondrite-normalized rare earth element (REE) patterns (Fig. 2) consistent with in situ, plutonic crystallization of island arc basalt (Garrido et al., 2006; their Figs. 9 and 17). The ultramafic section is composed of a basal peridotite zone, a pyroxenite zone, and a thin garnet-hornblendite zone (Fig. 1B). The field structure, petrology, and mineral

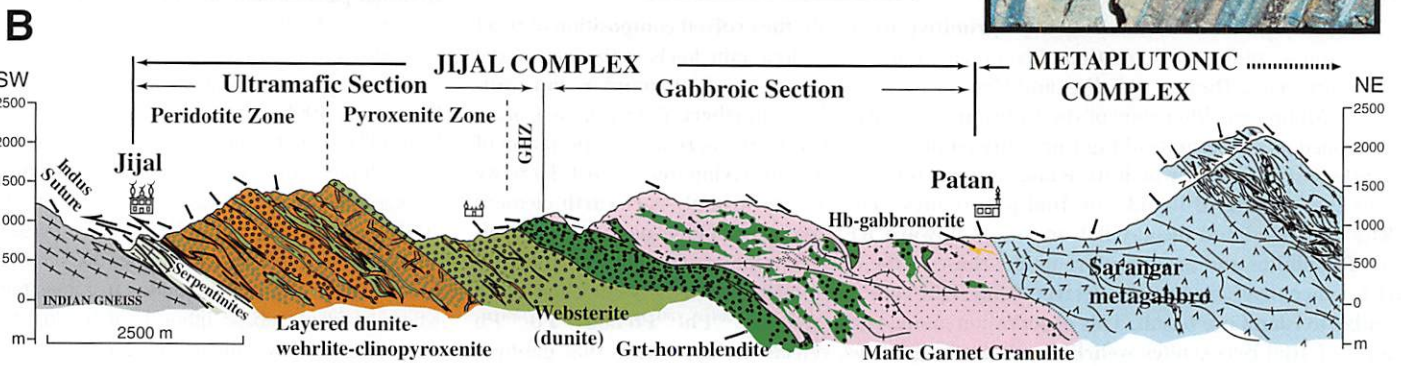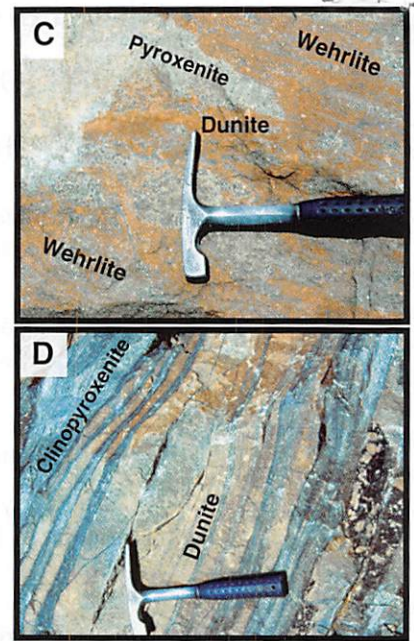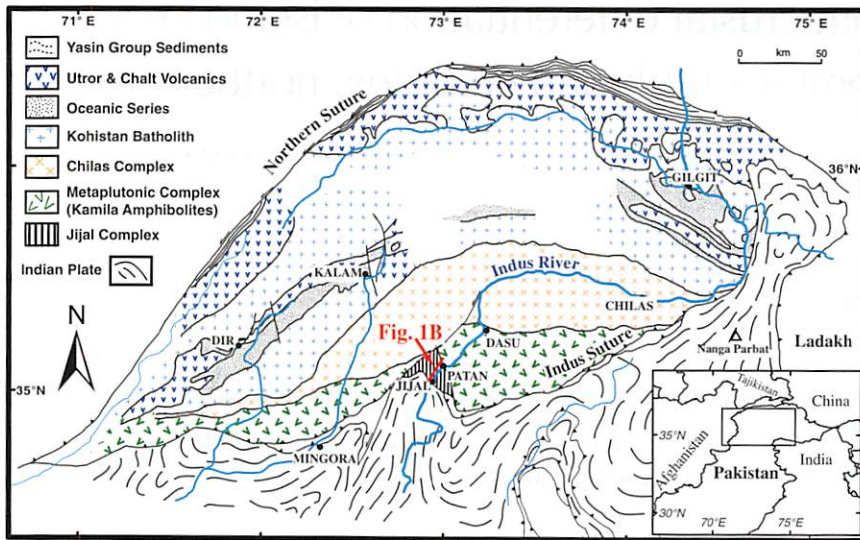# KOHISTAN PALEO-ISLAND ARC COMPLEX

Figure 1. A: Geological map of the Kohistan island arc complex (northern Pakistan) showing the location of the Jijal and the Metaplutonic complex transect (solid red line) (after Burg et al., 1998). B: Geological section along the Indus River valley of the Jijal mafic-ultramafic complex through the Sarangar gabbros of the Metaplutonic complex (modified after Burg et al., 2005). GHZ—garnet-hornblendite zone. C and D: Photographs of dunite, wehrlite, and pyroxenite in the Jijal peridotite zone.
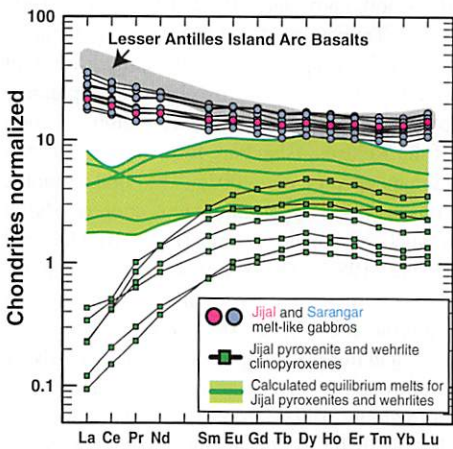

Figure 2. Chondrite-normalized REE patterns of Jijal and Sarangar melt-like gabbros (Garrido et al., 2006), compared to those of Jijal pyroxenite-wehrlite clinopyroxenes and calculated liquids in equilibrium with them. Also shown are the REE patterns of Lesser Antilles island arc basalts.

chemistry of Jijal ultramafics have been documented elsewhere (Jan and Howie, 1981; Burg et al., 1998). The peridotite zone is composed of dunite ($83 <$ Mg# < 91) with minor chromite. Dunites contain clinopyroxene-rich veins, which confer a wehrlitic appearance on outcrops and hand specimens (Fig. 1C), or thicker Cr-rich pyroxenite layers (Fig. 1D). In the pyroxenite zone, dunite grades into wehrlite ($84 <$ Mg# < 90) and Cr-rich, high-Mg# clinopyroxenite and websterite ($79 <$ Mg# < 90; $2500 <$ Cr ppm < 6100) (Jan and Howie, 1981; Jan and Windley, 1990). In both zones, forsterite content of olivine is rather variable (83%–93%), orthopyroxene is enstatite-rich (78%–91%), clinopyroxene is Cr-rich, and chromite has Cr# > 0.6. Representative whole-rock and clinopyroxene analyses of Jijal wehrlite-pyroxenite are provided in Tables DR1 and DR2 in the GSA Data Repository.[1]

LACK OF CRYSTAL-FRACTIONATION LINKAGE BETWEEN MAFIC AND ULTRAMAFIC PLUTONICS

Figure 2 shows the REE content of calculated liquids in equilibrium with Jijal pyroxenites-wehrlites obtained from separate clinopyroxene analyses (Table DR1) and cpx/melt distribution coefficients (Hart and Dunn, 1993); similar liquids are obtained using clinopyroxene (laser-ablation–inductively coupled plasma–mass spectrometry) LA-ICP-MS analyses (Table DR2). Calculated liquids are strongly REE depleted and have flat or convex-upward REE patterns (La$_N$/Yb$_N$ = 0.52–2.11) (Fig. 2). Such REE patterns and depleted compositions are unlike those proposed for primitive arc basalts (Kelemen et al., 2003), but resemble those of boninites (e.g., Crawford, 1989). Calculated liquids have lower REE abundances and display differ-

ent REE patterns with respect to the melt-like ones shown by Jijal and Sarangar gabbroic rocks (Fig. 2). Furthermore, Jijal pyroxenites-wehrlites have significantly lower $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios than Jijal gabbroic rocks, which show rather uniform Pb isotope ratios (Fig. 3). These trace element and isotopic differences rule out that Jijal pyroxenites-wehrlites and gabbroic rocks were derived simply by crystal fractionation from the same parental melt. In the $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram, Jijal pyroxenites-wehrlites and gabbroic rocks lie on the same positive correlation and within the Indian (mid-oceanic-ridge basalt) MORB compositional field, and define a mixing line between depleted MORB mantle (DMM) and enriched mantle 2 (EM2) end members (Fig. 3). In the $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram, gabbroic rocks plot on the DMM-EM2 mixing line, whereas pyroxenites-wehrlites plot off due to their higher $^{207}Pb/^{204}Pb$ values. This indicates that in the Pb isotopic space, Jijal ultramafic and
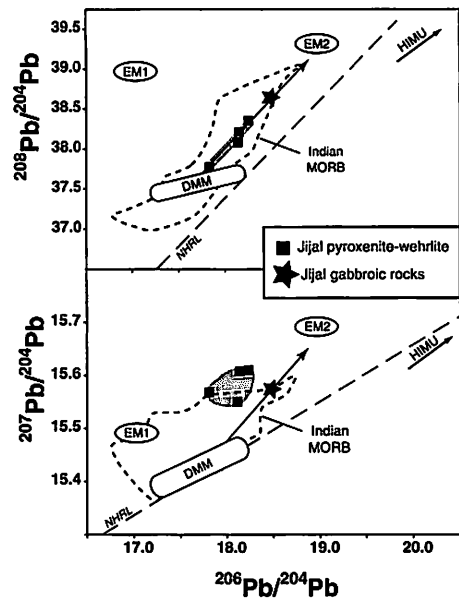
Figure 3. Pb radiogenic isotopes of Jijal pyroxenite-wehrlite and gabbroic rocks. Isotopic data of Jijal are for the same samples analyzed for REE (Table DR1). Jijal gabbroic rocks, including melt-like hornblende gabbronorite, are average of five analyses: $^{206}Pb/^{204}Pb$ = 18.479 ± 0.021; $^{207}Pb/^{204}Pb$ = 15.577 ± 0.007; $^{208}Pb/^{204}Pb$ = 38.646 ± 0.029. Total Pb blanks were <65 pg for a 100 mg sample. Pb isotopic compositions were determined by multicollector inductively coupled plasma–mass spectrometry (MC-ICP-MS) at École Normal Supérieur de Lyon, France, following the procedure of White et al. (2000). Isotopic end-member components and acronyms are after Hofmann (2003). EM1—enriched mantle 1; EM2—enriched mantle 2; HIMU—high U/Pb mantle; NHRL—Northern Hemisphere Reference Line; MORB—mid-oceanic-ridge basalt; DMM—depleted MORB mantle.

gabbroic sources shared a common, enriched component with an EM2 end member. However, the Jijal ultramafic source requires a major contribution of a depleted component with significantly higher $^{207}Pb/^{204}Pb$ than DMM (Fig. 3).

ORIGIN OF JIJAL PERIDOTITE-WEHRLITE VIA MELT-ROCK REACTION

Jijal ultramafic rocks may be interpreted as boninite cumulates; however, early crystal fractionation of boninite would have generated a cumulate sequence of dunite and orthopyroxenite similar to that observed in forearc ophiolites (Bédard et al., 1998). Such a sequence is unlike the Jijal ultramafic section that is dominated by dunite, wehrlite, and websterite (Fig. 1B). These Jijal lithologies may be cumulates of high-Ca boninites, but the expected cogenetic boninitic plutonic counterparts of Jijal pyroxenite-wehrlite crystallization are not observed in the overlying Metaplutonic complex (Jan, 1988; Treloar et al., 1996; Zeilinger, 2002; Dhuime, 2007). The few Chalt volcanic samples (Petterson and Treloar, 2004) that could arguably be classified as boninites were erupted in a backarc basin during late rifting of the Kohistan arc (Bignold et al., 2006) and are substantially younger (<85 Ma) than the Jijal and the Metaplutonic complexes (>95 Ma) (Schaltegger et al., 2002).

The Jijal pyroxenites-wehrlites may have been formed alternatively by reaction of incoming arc melts with pre-existing subarc mantle peridotite. This is supported by field evidence showing (1) that they were formed at the expense of dunite (Burg et al., 1998), (2) the great diversity of calculated melts that is symptomatic of rocks formed by melt-peridotite reaction, and (3) their Pb isotopic ratios suggesting the involvement of a depleted mantle component similar to rare, residual mantle peridotite in the Jijal section (Dhuime, 2007). Jijal dunite and pyroxenites-wehrlites would result from two melt-rock reaction stages resulting in the replacement sequence: subarc mantle peridotite → dunite → pyroxenite-wehrlite. The pyroxenites-wehrlites would have been formed via the peritectic reaction (Muntener et al., 2001): olivine + melt$_1$ → pyroxene + melt$_2$ at decreasing melt mass.

Melt-rock reaction modeling (Vernières et al., 1997) shows that the REE depletion, pattern shape, and variability of calculated liquids for Jijal pyroxenite-wehrlite (Fig. 4A) are explained adequately by reaction of arc melts with depleted mantle peridotite (Fig. 4B) similar to Jijal cpx-poor lherzolite with a normal mid-oceanic-ridge basalt (N-MORB)–like pattern (Dhuime, 2007). The long-dashed patterns in Figure 4B are the results of the melt-rock reaction for the choice of Jijal as reactant melt and for a mass ratio of precipitated olivine to partial melt of 0.1. Alternatively, if the reactant melt was more

REE depleted than Jijal melt-like gabbronorite, then (1) less depleted melt compositions of Jijal pyroxenites-wehrlites record a reaction involving a higher mass ratio of precipitated olivine to partial melt (short-dashed patterns in Fig. 4B with an olivine/melt ratio of 1.2), or (2) the liquid compositions were re-enriched during the later pyroxene-forming reaction stage.
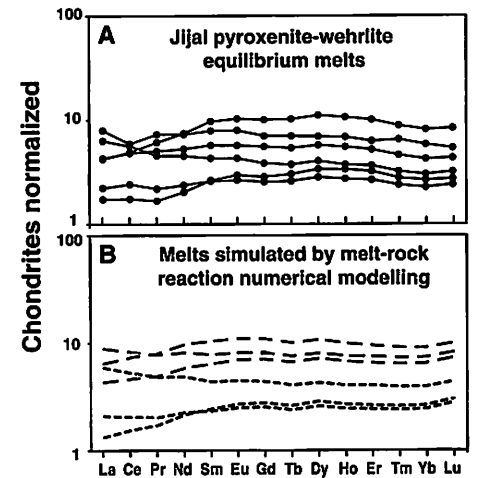
Figure 4. Chondrite-normalized REE patterns of melts in equilibrium with the Jijal pyroxenites-wehrlites (A) compared with those of melts produced by melt-rock reaction modeling (B). The melt-rock reaction is similar to model 2A of Vernières et al. (1997; their Fig. 7) simulating the evolution of REE concentrations in a reactive porous flow. The REE composition of melt involved in the reaction is Jijal melt-like gabbronorite, and REE and modal composition of the peridotite protolith is that of Jijal cpx-poor mantle lherzolite lens (Dhuime, 2007). An unknown of the model is the mass ratio of olivine to partial melt produced during the reaction. Two end members of the reaction process are shown assuming either predominant melt production (long-dashed patterns: reaction 1) or olivine precipitation (short-dashed patterns: reaction 2), with the ratio of olivine to partial melt produced during reaction varying from 0.1 (reaction 1) to 1.2 (reaction 2). The melt/rock ratio is adjusted to fit the REE composition of melts in equilibrium with the Jijal pyroxenites-wehrlites. This leads to the following reaction equations: $0.83melt_{i-1}$ + $0.12opx$ + $0.04cpx$ = $0.985melt_i$ + $0.015ol$, for reaction 1, and $0.67 melt_{i-1}$ + $0.26opx$ + $0.07cpx$ = $0.82melt_i$ + $0.18ol$, for reaction 2 (where $melt_{i-1}$ is the melt fraction infiltrated in a given reaction cell at increment i). The melt/rock ratio required to produce a dunite from the starting cpx-poor lherzolite is 0.3 for reaction 2, and 1.0 for reaction 1. The number of reaction cells is 10, and the dissolution increment is 0.02 in both models. The number of increments is 20 for reaction 1 and 10 for reaction 2 (cf. Vernières et al., 1997, for meaning of parameters). For clarity, only three cells of the calculated melt compositions for each reaction are shown.

IMPLICATIONS FOR INTRACRUSTAL FRACTIONATION OF ISLAND ARCS

Our geochemical data indicate that Jijal pyroxenite-wehrlite is not cogenetic with the overlying mafic crust. The Jijal Moho transition zone likely represents a mantle-crust transition formed via melt-rock reaction of incoming arc melts with subarc mantle peridotite. As in the Talkeetna paleo–island arc (Kelemen et al., 2003), the absence in the Kohistan paleo–island arc of a thick crustal section of ultramafic rocks cogenetic with the overlying mafic crust has profound implications for the intracrustal fractionation models of island arcs. If the net flux to the Kohistan arc crust was primitive arc basalt with Mg# = 70, then a 15–35-km-thick ultramafic sequence should be expected in Kohistan crust to balance the quite evolved composition (Mg# = 55) (Kelemen et al., 2003) of its ~35 km thick mafic crust. This implies that the time-integrated thickness of the Kohistan crust must have been ~50–70 km. Because such thicknesses are unlikely to exist at a given time in an island arc—and pyroxenite-dunite-wehrlite cogenetic with the overlying crust is missing in the Kohistan lower crust—such an intracrustal fractionation scenario implies that its crustal ultramafic roots must have been recycled back to the mantle in 10–15 m.y., which is the time interval of the accretion of the Kohistan arc plutonic section (Schaltegger et al., 2002). This entails a time-integrated, ultramafic crustal recycling rate of 0.10–0.35 cm/yr, which is similar to the rate of crustal generation at mid-ocean ridges. This is an extraordinarily short time scale even for recycling via delamination (Behn and Kelemen, 2006) and may reflect additional "recycling" mechanisms such as subarc mantle flow or plate thinning (Arcay et al., 2006). Alternatively, if the net flux to the Kohistan crust was more evolved than primitive arc basalt, ultramafic cumulates must have been crystallized back in the lithospheric mantle wedge. A third possibility is that primitive arc basalts are more evolved than has been previously anticipated.

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