



Petrology of blueschist from the Western Himalaya (Ladakh, NW India): Exploring the complex behavior of a lawsonite-bearing system in a paleo-accretionary setting



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ABSTRACT

Although the Himalaya is the archetype of collisional orogens, formed as a consequence of the closure of the Neo-Tethyan ocean separating India from Asia, high-pressure metamorphic rocks are rare. Beside few eclogites, corresponding to the metamorphosed continental Indian crust dragged below Asia or underthrust beneath southern Tibet, blueschists occur seldom along the Yarlung–Tsangpo Suture zone, i.e. the suture marking the India–Asia collision. These blueschists, mostly interpreted as related to paleo-accretionary prisms formed in response to the subduction of the Neo-Tethyan ocean below the Asian plate, are crucial for constraining the evolution of the India–Asia convergence zone during the closure of the Neo-Tethyan Ocean.

In the Western Himalaya, the best occurrence of blueschist is that of the Sapi–Shergol Ophiolitic Mélange in Ladakh. This unit is dominated by volcanoclastic sequences rich in mafic material with subordinate interbedding of metasediments, characterized by very fresh lawsonite blueschist-facies assemblages.

In this paper, the lawsonite blueschist-facies metasediments have been petrologically investigated with the aims of (i) constraining the P–T evolution of the Sapi–Shergol Ophiolitic Mélange, (ii) evaluating the influence of Fe₂O₃ and of H₂O on the stability of the high-pressure mineral assemblages, (iii) understanding the processes controlling lawsonite formation and preservation, and (iv) interpreting the P–T evolution of the Sapi–Shergol blueschists in the framework of India–Asia collision.

Our results indicate that (i) the Sapi–Shergol blueschists experienced a cold subduction history along a low thermal gradient, up to peak conditions of ca. 470 °C, 19 kbar; furthermore, in order to preserve lawsonite in the studied lithologies, exhumation must have been coupled with significant cooling, i.e. the resulting P–T path is characterized by a clockwise hairpin loop along low thermal gradients (<8–9 °C/km); (ii) the presence of ferric iron in the investigated system has a non-negligible (lowering) effect on pressure estimates, whereas temperatures estimates are not influenced by the oxidation state of the system; (iii) the observed sequence of mineral growth (i.e. simultaneous growth of lawsonite and garnet) suggests that (a) the system was initially H₂O-undersaturated and lawsonite growth was triggered by a protracted H₂O influx at high pressure (equilibrium approach), or (b) the system was H₂O-saturated since the beginning, but lawsonite growth was delayed due to the predominance of kinetic factors over equilibrium dynamics (nonequilibrium approach); (iv) the inferred P–T evolution is consistent with a cold subduction zone system in an intra-oceanic subduction setting. Moreover, the estimated peak P–T conditions roughly coincide with the maximum P–T estimates predicted by thermo-mechanical models for the metasediments exhumed in accretionary wedges, and with the maximum P–T conditions recorded by natural occurrences of blueschist accretionary complexes worldwide.

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1. Introduction

Lawsonite-bearing blueschists and eclogites are witnesses of cold subduction processes occurred along ancient convergent margins. Metamorphic processes involved in the generation and preservation

of lawsonite are crucial in many research areas, ranging from petrology to geochemistry, geodynamics, and geophysics (e.g. Hacker et al., 2003; Bebout, 2007; Hacker, 2008; Davis, 2011; Martin et al., 2011; Vitale Brovarone et al., 2011; Chantel et al., 2012; Abers et al., 2013; Cao et al., 2013; Kim et al., 2013; Spandler and Pirard, 2013). Therefore, lawsonite-bearing eclogites and, to a lesser extent, lawsonite-bearing blueschists have been the focus of several studies, especially in recent years (Tsuji-mori and Ernst, 2014 and references therein). Compared to

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the rare occurrences of lawsonite eclogites worldwide (see the review paper by Tsujimori et al., 2006), lawsonite blueschist units are reported from several orogenic belts (e.g. Agard et al., 2009; Tsujimori and Ernst, 2014 and references therein); however, in many cases, the lawsonite blueschist-facies assemblages formed at peak metamorphic conditions are widely overprinted by epidote blueschist and/or greenschist-facies retrograde assemblages during exhumation (e.g. Ernst, 1988; Agard et al., 2001a, 2001b, Agard et al., 2006; Jolivet et al., 2003; Schumacher et al., 2008; Plunder et al., 2012). Lawsonite preservation requires exhumation along cold geothermal gradients, comparable to those required for its formation during subduction. Such geothermal regimes are typical of ancient Pacific-type plate convergent margins (see Tsujimori and Ernst, 2014 for a review); the occurrence of well-preserved high-pressure lawsonite blueschists and eclogites in an orogenic belt is therefore an appealing clue of a peculiar tectonic setting.

Although the Himalaya is the archetype of collisional orogens, formed as a consequence of the closure of the Tethyan ocean separating India from Asia followed by continental collision between the two plates, high-pressure metamorphic rocks are rare along the orogen (e.g. Lombardo and Rolfo, 2000; Guillot et al., 2008). Moreover, most of the eclogites reported so far from the Himalaya correspond to the metamorphosed continental Indian crust dragged below Asia (NW Himalaya: Kaghan, Tso Moriri, and Stak massifs; Pognante and Spencer, 1991; Guillot et al., 1997, 1999, 2007, 2008; De Sigoyer et al., 2000; O'Brien et al., 2001; Sachan et al., 2004; Lanari et al., 2013), or underthrust beneath southern Tibet (E Himalaya: Kharta and Bhutan; Lombardo and Rolfo, 2000; Groppo et al., 2007; Chakungal et al., 2010; Grujic et al., 2011; Warren et al., 2011). Evidence of the ancient Tethyan oceanic crust subducted below Asia are also rare and locally occur within the Indus-Tsangpo Suture (ITS) zone, which separates the northern margin of the Indian plate to the south (i.e. the Himalaya s.s.) from the southern margin of the Asian plate to the north (represented, from west to east, by the Kohistan Arc, the Ladakh block and the Lhasa block). These evidences are (i) few lawsonite blueschists from the western part of the ITS zone in Pakistan (Shangla: Shams, 1972; Frank et al., 1977) and Ladakh (NW India) (Sapi-Shergol: Honegger et al., 1989; Zildat: Viridi et al., 1977; De Sigoyer et al., 2004), interpreted as related to paleo-accretionary prisms formed in response to the subduction of the Neo-Tethyan ocean below the Asian plate (e.g. Robertson, 2000; Mahéo et al., 2006; Guillot et al., 2008); (ii) few eclogite, lawsonite- and epidote blueschist-facies rocks reported from the Indo-Burmese Ranges (Nagaland Ophiolite Complex: Ghose and Singh, 1980; Acharyya, 1986; Chatterjee and Ghose, 2010; Ao and Bhowmik, 2014; Bhowmik and Ao, 2015; Chin Hill Ophiolite: Socquet et al., 2002), interpreted as the eastern extension of the ITS zone. These rare high-pressure/low-temperature (HP-LT) rocks are therefore crucial for constraining the evolution of the India-Asia convergence zone during the closure of the Neo-Tethyan ocean (Guillot et al., 2008); in this framework, the detailed reconstruction of their P-T paths is a fundamental step toward a reliable geodynamic interpretation.

The P-T evolution of the eclogites and blueschists from the Indo-Burmese Ranges has been recently constrained by means of modern petrological methods (e.g. pseudosections); variable peak P-T conditions have been reported from different portions of the suture zone, ranging from ~340 °C, ~11.5 kbar (lawsonite blueschists: Ao and Bhowmik, 2014) to 540 ± 35 °C, 14.4 ± 2 kbar (epidote blueschists: Bhowmik and Ao, 2015) to 580–610 °C and 17–20 kbar (eclogites: Chatterjee and Ghose, 2010). On the opposite, modern petrologic studies aimed at constraining the P-T evolution of the blueschist-facies rocks from the western sector of the ITS zone are lacking. Some 25 years ago, Honegger et al. (1989) reported peak metamorphic conditions of 350–420 °C, 9–11 kbar for the Sapi-Shergol lawsonite blueschists using conventional thermobarometry. P-T estimates for the Shangla blueschists were published even earlier (Guiraud, 1982; Jan, 1985) and suggest peak P-T conditions of ca. 400 °C, 5 kbar. Although detailed, these petrological studies are based on conventional

methods and need to be updated using more recent and powerful petrological approaches (e.g. isochemical phase diagrams).

In this paper, the lawsonite blueschists from Sapi-Shergol have been petrologically re-investigated with the aims of (i) constraining their P-T evolution, (ii) evaluating the influence of Fe₂O₃ and of H₂O on the stability of the high-pressure mineral assemblages, (iii) understanding the processes controlling lawsonite formation and preservation, and (iv) interpreting the P-T evolution of the Sapi-Shergol blueschists in the framework of India-Asia collision.

2. Geological setting

In the India-Asia convergence system, the ITS zone records the closure of the Neo-Tethyan ocean from Late Cretaceous to Tertiary time (Frank et al., 1977; Honegger et al., 1989; Cannat and Mascle, 1990). Among the few occurrences of high-pressure rocks along the ITS, those of Ladakh (NW India) are the best in terms of rock freshness, areal extent, and metamorphic assemblages. Blueschists in the Ladakh area occur along the ITS in few localities: from SE to NW these are Puga, Urtsi, Hinju, and Sapi-Shergol (Honegger et al., 1989). The largest outcrop is that of Sapi-Shergol (35 km south of Kargil), where the blueschists form a 12 × 1 km E-W trending narrow zone.

Tectonically, the Sapi-Shergol blueschists belong to a narrow belt called “Ophiolitic Mélange Unit” (Honegger et al., 1989) (Fig. 1), which outcrops over a distance of 250 km along the ITS suture. This belt consists of several thrust slices sandwiched between the Nindam-Naktul-Dras nappes to the north, and the Lamayuru-Karamba nappes to the south. The Ophiolitic Mélange Unit is interpreted as a relic of a paleo-accretionary prism formed in response to the northward subduction of the Neo-Tethyan ocean, originally separating the Ladakh arc to the south from the southern Asian active margin to the north (Mahéo et al., 2006). This paleo-accretionary prism consists of sedimentary units including blocks of (mainly) basic lithologies that have been metamorphosed under variable P-T conditions, ranging from low-grade metamorphism to lawsonite blueschist-facies metamorphism (Frank et al., 1977; Honegger et al., 1989; Jan, 1987; Reuber et al., 1987; Suture, 1990; Ahmad et al., 1996; Robertson, 2000; Mahéo et al., 2006).

The Sapi-Shergol Ophiolitic Mélange (SSOM) is a complex unit which includes slices of the paleo-accretionary prism, intercalated with numerous slices of other units including the Nindam and Lamayuru turbidites and low-grade meta-ophiolitic slices consisting of serpentinized peridotites intruded by basic dikes (“sheared serpentinites” of Robertson, 2000). The narrow blueschist zone cropping out close to the village of Shergol (Figs. 1, 2a) is overlain discordantly by the Shergol conglomerate of post-Eocene (Oligo-Miocene?) age (Honegger et al., 1989). Blueschist lithologies are dominated by volcanoclastic sequences of basic material (Fig. 2b,c) with subordinate interbedding of cherts and minor carbonatic lithologies. Mahéo et al. (2006) suggested that the blueschists derive from calc-alkaline igneous rocks formed in an intra-oceanic arc environment. K-Ar ages of whole-rocks and glaucophane suggest an age of ca. 100 Ma for the high-pressure metamorphism (Honegger et al., 1989).

2.1. Main blueschist lithologies of the SSOM

Metabasic and metavolcanoclastic rocks are the dominant lithologies in the SSOM, and they are associated to subordinate interbedded metasediments. These lithologies have been described in detail by Honegger et al. (1989); the most relevant petrographic features are therefore only summarized here.

2.1.1. Metabasic and metavolcanoclastic rocks

Metabasic rocks are mainly represented by fine-grained glaucophane-bearing schists (Fig. 2c,e) with variable amounts of lawsonite and minor clinopyroxene and phengite. Lawsonite can be either fine-grained or porphyroblastic and it generally overgrows the main foliation defined by the alignment of glaucophane ± phengite (Fig. 2e); where present,

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