Metamorphic CO2 degassing in the active Himalayan orogen: exploring the influence of orogenic activity on the long-term global climate changes.

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Abstract	A number of studies suggest that mountain ranges have strong impact on the global carbon cycle; metamorphic degassing from active collisional orogens supplies a significant fraction of the global solid-Earth derived CO_2 to the atmosphere, thus playing a fundamental role even in today's Earth carbon cycle. The Himalayan belt, a major collisional orogen still active today, is a likely candidate for the production of a large amount of metamorphic CO_2 that may have caused changes in long-term climate of the past, present and near future. Large metamorphic CO_2 fluxes are facilitated by rapid prograde metamorphism of big volumes of impure carbonate rocks coupled with facile escape of CO_2 to the Earth's surface. So far, the incomplete knowledge of the nature, magnitude and distribution of the CO_2-producing processes hampered a reliable quantitative modeling of metamorphic CO_2 fluxes from the Himalayan belt. This study, integrated in the framework of the Ev-K2-CNR SHARE (Stations at High Altitude for Research on the Environment) Project, focuses on the metamorphic decarbonation processes occurring during the Himalayan collision. We hereby present preliminary results focusing on the distribution of different types of metacarbonate rocks in the Eastern Himalaya, their petrographic description and the first reported petrological data about the nature of the CO_2-producing reactions in garnet-bearing calc-silicate rocks. These results represent a contribution toward a better understanding of the influence exerted by orogenic processes on climatic changes at global scale.
Keywords (separated by '-')	Orogenic CO_2 - Climate changes - Decarbonation processes - Himalaya - Metacarbonate rocks

5 Metamorphic CO_2 Degassing in the Active Himalayan Orogen: Exploring the Influence of Orogenic Activity on the Long-Term Global Climate Changes

Rolfo Franco, Groppo Chiara, Mosca Pietro, Ferrando Simona, Costa Emanuele, and Krishna P. Kaphle

Abstract

A number of studies suggest that mountain ranges have strong impact on the global carbon cycle; metamorphic degassing from active collisional orogens supplies a significant fraction of the global solid-Earth derived CO_2 to the atmosphere, thus playing a fundamental role even in today's Earth carbon cycle. The Himalayan belt, a major collisional orogen still active today, is a likely candidate for the production of a large amount of metamorphic CO_2 that may have caused changes in long-term climate of the past, present and near future. Large metamorphic CO_2 fluxes are facilitated by rapid prograde metamorphism of big volumes of impure carbonate rocks coupled with facile escape of CO_2 to the Earth's surface. So far, the incomplete knowledge of the nature, magnitude and distribution of the CO_2-producing processes hampered a reliable quantitative modeling of metamorphic CO_2 fluxes from the Himalayan belt. This study, integrated in the framework of the Ev-K2-CNR SHARE (Stations at High Altitude for Research on the Environment) Project, focuses on the metamorphic decarbonation processes occurring during the Himalayan collision. We hereby present preliminary results focusing on the distribution of different types of metacarbonate rocks in the Eastern Himalaya, their petrographic description and the first reported petrological data about the nature of the CO_2-producing reactions in garnet-bearing calc-silicate rocks. These results represent a contribution toward a better understanding of the influence exerted by orogenic processes on climatic changes at global scale.

Keywords

Orogenic CO_2 • Climate changes • Decarbonation processes • Himalaya • Metacarbonate rocks

5.1 Introduction and Aim of the Study

Metamorphic degassing from active collisional orogens supplies a significant amount of CO_2 to the atmosphere, playing a fundamental role in the long-term (>1 Ma) global carbon cycle (e.g. Kerrick and Caldeira 1993; Selverstone and Gutzler 1993; Bickle 1996; Berner 1999; Gaillardet and Galy 2008; Evans 2011). The Himalaya is the most prominent collisional orogen on Earth, where tectonic and erosional processes are still active today. Therefore, it is a likely candidate for the production of a large amount of metamorphic CO_2 that may have caused changes in long-term climate of the past and that may still influence the

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atmospheric composition in the near future (Gaillardet and Galy 2008). Large metamorphic CO_2 fluxes should have been (and should be) facilitated by rapid metamorphism of large volumes of metacarbonate rocks, coupled with facile escape of CO_2 to the Earth's surface. The nature and magnitude of the metamorphic CO_2 cycle in Himalaya, however, is still poorly known. This study, integrated since 2012 in the framework of the Ev-K2-CNR SHARE (Stations at High Altitude for Research on the Environment) Project, focuses on the metamorphic decarbonation processes occurring during the Himalayan collision. Fieldwork activity is combined with petrographic, petrologic, structural, geochronological geochemical and fluid inclusion studies with the aims of clarifying: (i) abundance and types of CO_2-source rocks, (ii) nature and rate of CO_2-producing reactions, (iii) nature and composition of the released CO_2-rich fluids, (iv) nature and distribution of the CO_2 escape-paths toward the Earth's surface, and (v) chronology of metamorphic CO_2-producing reactions occurred in the Himalayas at different structural levels and at different times. We hereby present a preliminary sketch map reporting the distribution of the different types of metacarbonate rocks in the Eastern Himalaya. The first petrological results on the nature of the CO_2-producing reactions in garnet-bearing calc-silicate rocks are summarized and discussed in the global perspective of the orogenic CO_2-cycle. These results represent a contribution toward a better understanding of the influence exerted by the orogenic processes on climatic changes at global scale.

5.2 Metacarbonate Rocks in Eastern Himalaya

5.2.1 Field Occurrences

In the eastern Himalaya, calc-silicate rocks are widespread in the lower and upper structural levels of the Greater Himalayan Sequence (GHS) (e.g. Goscombe et al. 2006), but they have received so far little notice. Field data acquired in more than 10 years in central-eastern Nepal and Sikkim allowed us to distinguish two different modes of occurrence (Fig. 5.1): (i) in the lower portion of the GHS (GHS-L), calc-silicate rocks generally occur as decimetre to metre-thick levels or boudins (Fig. 5.2a, b) within medium-to high-grade, locally anatectic, staurolite- and/or kyanite-bearing metapelites (e.g. Groppo et al. 2009; Mosca et al. 2012); (ii) structurally upward (GHS-U), calc-silicate rocks are hosted in anatectic kyanite-sillimanite- bearing gneisses (i.e. Barun Gneiss, see Groppo et al. 2012) and often occur as tens to hundreds of meter thick, folded or boudinated, levels occasionally associated to layers of impure marbles (Fig. 5.2c, d). The transition between the hosting paragneiss and the calc-silicate granofels is generally gradual and is characterized by the progressive disappearance of biotite, the appearance of clinopyroxene and the modal increase of plagioclase. A banded structure is locally observed in the calc-silicate rocks, defined by the different modal proportion of the rock-forming minerals in adjacent layers. This suggest that calc-silicate rocks derive from former marly intercalations within a thick sedimentary sequence.

5.2.2 Petrography

The studied samples have granofelsic structure, and sometimes show evidence of a brittle- to ductile deformation resulting in a local grain size reduction. Mineral assemblages are systematically different in the GHS-L and GHS-U, respectively.

5.2.2.1 Garnet-Bearing Assemblages (GHS-L)

The equilibrium assemblage consists of plagioclase + clinopyroxene + quartz + garnet ± zoisite. Garnet is locally very abundant and it is often intergrown with quartz (Fig. 5.3a, b). Microstructural evidence suggest that garnet grew at the expense of zoisite, clinopyroxene and calcite, the latter being only locally observed as inclusion in garnet. Coarse-grained graphite is locally very abundant and it has been interpreted as precipitated from a H_2O-CO_2 fluid released through decarbonation reactions during prograde and/or early retrograde metamorphic evolution (Groppo et al. 2013). Titanite and apatite are ubiquitous. Thin layers of phlogopite + white mica impure marbles are only occasionally associated to these calc-silicate rocks.

5.2.2.2 K-Feldspar + Scapolite Assemblages (GHS-U)

Calc-silicate rocks from the GHS-U consist of K-feldspar + clinopyroxene + quartz ± scapolite ± calcite, and later plagioclase, epidote, green amphibole and interstitial carbonates (Fig. 5.3c, d). Relict biotite often occurs within clinopyroxene and/or is replaced by K-feldspar. Clinopyroxene is often partially replaced by later green Ca-amphibole ± epidote ± calcite, whereas scapolite is locally partially replaced by fine-grained dusty aggregates of plagioclase + calcite and/or it is overgrown by coarse-grained epidote. In addition to the ubiquitous titanite, a strongly pleochroic allanite and a bluish to colorless tourmaline locally occur, whereas graphite is always absent. The decimetric to metric levels of marbles often intercalated with these calc-silicate granofels are characterized by the same mineral assemblage, but in different modal proportions.

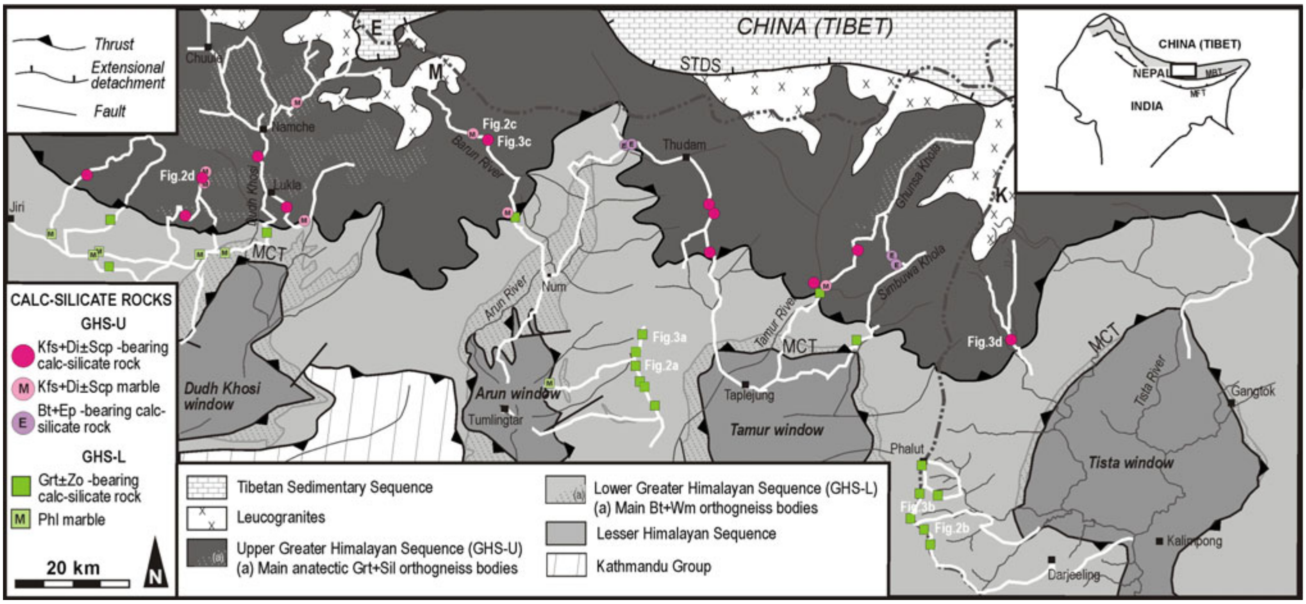

Fig. 5.1 Simplified geological map of the central-eastern sector of the Himalayan belt (modified from Goscombe et al. 2006; Dasgupta et al. 2004; Mosca et al. 2012, 2013) showing sample locations (*squares*: Grt + Zo calc-silicate assemblages and Phl marbles of the GHS-L; *circles*: Kfs + Di + Scp calc-silicate rocks and marbles of the GHS-U). *White lines* are the geotraverses investigated since 2004. The *double-dashed grey line* is the approximate political boundary between Nepal to the south, west, China (Tibet) to the north, India (Sikkim) to the east. MCT: Main Central Thrust; STDS: South Tibetan Detachment System; E: Everest, K: Kangchenjunga, M: Makalu. Inset shows the location of the study area (*black rectangle*) in the framework of the Himalayan chain. The *grey* shaded belt approximates the location of the Higher Himalayan Crystallines. MFT: Main Frontal Thrust; MBT: Main Boundary Thrust

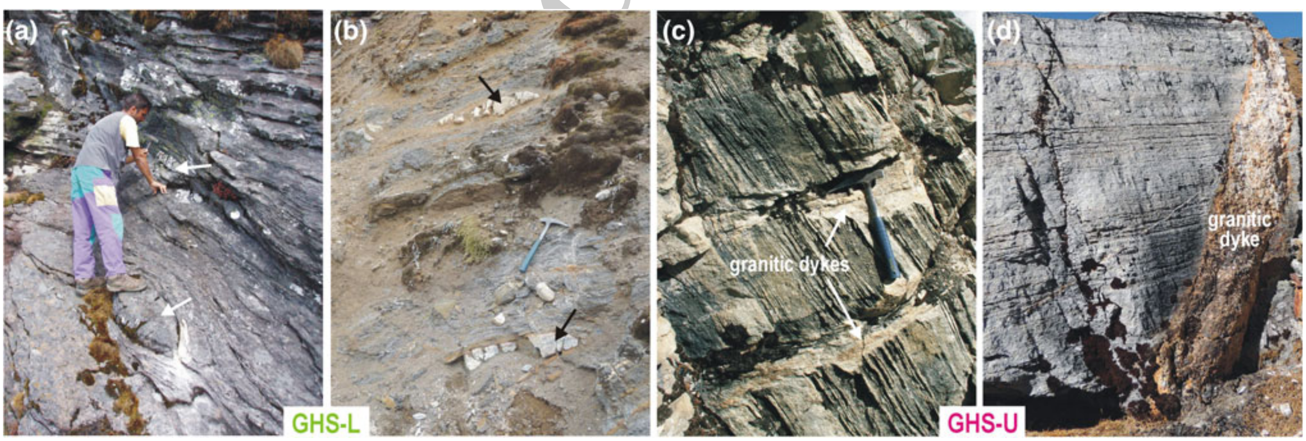

Fig. 5.2 Field occurrence of calc-silicate rocks from the GHS-L (**a, b**) and GHS-U (**c, d**). The *arrows* in **a** and **b** indicate the calc-silicate boudins

5.3 CO_2-Producing Processes in Garnet-Bearing Assemblages

The nature of the CO_2-producing reactions in the garnet-bearing calc-silicate rocks from the GHS-L has been petrologically investigated in the CFAS-CO_2-H_2O system using activity-corrected P-T phase diagrams at fixed fluid composition, isobaric T-X(CO_2) phase diagram sections, and phase diagram projections in which fluid composition is not explicitly constrained (Groppo et al. 2013).

The petrological results allowed to define the P-T-X_{fluid} regime during the metamorphic evolution of the studied calc-silicate rocks. A prograde heating up to peak-T of ca. 800° C (at about 10–11 kbar) involved the growth of grossular-rich garnet (Grs_{67-81}) in equilibrium with quartz at the expenses of zoisite, clinopyroxene and calcite; this

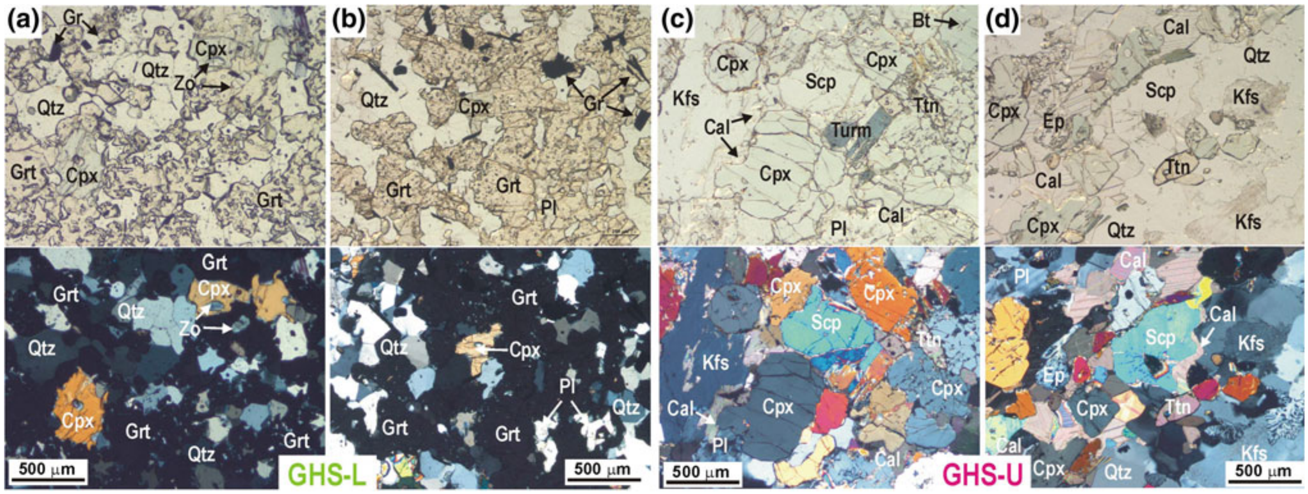

Fig. 5.3 Representative microstructures of calc-silicate granofels from the GHS-L (**a, b**) and GHS-U (**c, d**). *Top*: plane polarized light. *Bottom*: crossed polarized light

reaction released a CO_2-rich fluid ($XCO_2 = 0.20–0.44$). A grossular-rich garnet ($Grs_{67–76}$) additionally grew in equilibrium with plagioclase and quartz during either prograde heating or early decompression. Also this second reaction released a CO_2-rich fluid, with approximately the same composition ($XCO_2 = 0.30–0.44$) as that released through the first reaction. It follows that the amount of CO_2 released during garnet growth increases with the increase in grossular component of garnet (Groppo et al. 2013). The study of primary and secondary carbonic and aqueo-carbonic fluid inclusions occurring in quartz, plagioclase, clinopyroxene and, possibly, garnet and calcite will provide direct constrains on nature and composition of the involved CO_2-rich fluids.

Our results also demonstrate that the studied calc-silicate rocks behaved as a closed-system during their prograde and early retrograde evolution, although their volume abundance within the hosting paragneiss is low. In such a closed system, the CO_2-rich fluid released during prograde and early retrograde evolution induced the hydration of the adjacent silicates (mainly plagioclase and clinopyroxene); these hydration reactions, depleting the fluid in H_2O (i.e. enriching the fluid in carbon) triggered the precipitation of graphite.

5.4 Conclusions

In the eastern Himalaya, calc-silicate rocks are widespread in the lower and upper structural levels of the GHS. From field data and petrographic observations, two main calc-silicate assemblages have been recognized, reflecting differences in the protolith composition: garnet + zoisite assemblages in the GHS-L, and K-feldspar + scapolite assemblages in the GHS-U. Our preliminary petrologic study (Groppo et al. 2013) demonstrates that calc-silicate rocks of appropriate composition may act as CO_2-source during prograde heating and/or early decompression, releasing internal-derived CO_2-rich fluids through garnet-forming reactions. However, if the system remains closed, fluid-rock interactions may induce hydration of the calc-silicate assemblages and the in situ graphite precipitation, thereby removing carbon from the fluid. The interplay between these two contrasting processes—i.e. production of metamorphic CO_2-rich fluids versus carbon sequestration through graphite precipitation—must be taken in account when dealing with a global estimate of the role exerted by decarbonation processes on the orogenic CO_2-cycle. AQ1

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