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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 the metamorphic degassing from a Earth derived CO_2 to the atmosphere to the studies of the stu	hat mountain ranges have strong impact on the global carbon cycle; active collisional orogens supplies a significant fraction of the global solid- sphere, thus playing a fundamental role even in today's Earth carbon cycle.	
	The Himalayan belt, a major c	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		$c CO_2$ that may have caused changes in long-term climate of the past, metamorphic CO ₂ fluxes are facilitated by rapid prograde metamorphism of	
	big volumes of impure carbon	ate 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		
	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.		
	processes on climatic changes	at global scale.	
Keywords (separated by '-')	Orogenic CO_2 - Climate change	ges - Decarbonation processes - Himalaya - Metacarbonate rocks	

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 CO₂ 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 CO₂ 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 CO₂-producing processes hampered a reliable quantitative modeling of metamorphic CO₂ 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 CO₂-producing reactions in garnet-bearing calcsilicate 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 $CO_2 \cdot Climate$ changes \cdot Decarbonation processes \cdot Himalaya \cdot Metacarbonate rocks

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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 longterm 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 48 been (and should be) facilitated by rapid metamorphism of 49 large volumes of metacarbonate rocks, coupled with facile 50 escape of CO₂ to the Earth's surface. The nature and 51 magnitude of the metamorphic CO₂ cycle in Himalaya, 52 however, is still poorly known. This study, integrated since 53 2012 in the framework of the Ev-K2-CNR SHARE (Sta-54 tions at High Altitude for Research on the Environment) 55 Project, focuses on the metamorphic decarbonation pro-56 cesses occurring during the Himalayan collision. Fieldwork 57 activity is combined with petrographic, petrologic, struc-58 tural, geochronological geochemical and fluid inclusion 59 studies with the aims of clarifying: (i) abundance and types 60 of CO₂-source rocks, (ii) nature and rate of CO₂-producing 61 reactions, (iii) nature and composition of the released CO₂-62 rich fluids, (iv) nature and distribution of the CO₂ escape-63 paths toward the Earth's surface, and (v) chronology of 64 metamorphic CO₂-producing reactions occurred in the 65 Himalayas at different structural levels and at different 66 times. We hereby present a preliminary sketch map 67 reporting the distribution of the different types of metacar-68 bonate rocks in the Eastern Himalaya. The first petrological 69 results on the nature of the CO₂-producing reactions in 70 garnet-bearing calc-silicate rocks are summarized and dis-71 cussed in the global perspective of the orogenic CO_2 -cycle. 72 These results represent a contribution toward a better 73 understanding of the influence exerted by the orogenic 74 processes on climatic changes at global scale. 75

76 77 5.2 Metacarbonate Rocks in Eastern Himalaya 78

5.2.1 **Field Occurrences** 79

In the eastern Himalaya, calc-silicate rocks are widespread 80 in the lower and upper structural levels of the Greater 81 Himalayan Sequence (GHS) (e.g. Goscombe et al. 2006), 82 but they have received so far little notice. Field data 83 acquired in more than 10 years in central-eastern Nepal and 84 Sikkim allowed us to distinguish two different modes of 85 occurrence (Fig. 5.1): (i) in the lower portion of the GHS 86 (GHS-L), calc-silicate rocks generally occur as decimetre to 87 metre-thick levels or boudins (Fig. 5.2a, b) within medium-88 to high-grade, locally anatectic, staurolite- and/or kyanite-89 bearing metapelites (e.g. Groppo et al. 2009; Mosca et al. 90 2012); (ii) structurally upward (GHS-U), calc-silicate rocks 91 are hosted in anatectic kyanite-sillimanite- bearing gneisses 92 (i.e. Barun Gneiss, see Groppo et al. 2012) and often occur 93 as tens to hundreds of meter thick, folded or boudinated, 94 levels occasionally associated to layers of impure marbles 95

(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 \pm 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 H₂O-CO₂ 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-feld-127 spar + clinopyroxene + quartz \pm scapolite \pm calcite, and 128 later plagioclase, epidote, green amphibole and interstitial 129 carbonates (Fig. 5.3c, d). Relict biotite often occurs within 130 clinopyroxene and/or is replaced by K-feldspar. Clinopy-<u>1</u>31 roxene is often partially replaced by later green Ca-132 amphibole \pm epidote \pm calcite, whereas scapolite is 133 locally partially replaced by fine-grained dusty aggregates <u>1</u>34 of plagioclase + calcite and/or it is overgrown by coarse-135 grained epidote. In addition to the ubiquitous titanite, a 136 strongly pleochroic allanite and a bluish to colorless tour-137 maline locally occur, whereas graphite is always absent. <u>1</u>38 The decimetric to metric levels of marbles often interca-139 lated with these calc-silicate granofels are characterized by 140 the same mineral assemblage, but in different modal 141 proportions. 142

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Fig. 5.1 Simplified geological map of the central-eastern sector of the Himalavan 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

CO₂-Producing Processes 143 144 5.3 in Garnet-Bearing Assemblages 145

The nature of the CO₂-producing reactions in the garnet-146 bearing calc-silicate rocks from the GHS-L has been pet-147 rologically investigated in the CFAS-CO2-H2O system 148 using activity-corrected P-T phase diagrams at fixed fluid 149 composition, isobaric T-X(CO₂) phase diagram sections, 150

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 (Grs₆₇₋₈₁) in equilibrium with quartz at the expenses of zoisite, clinopyroxene and calcite; this 158

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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 CO₂-rich fluid (XCO₂ = 0.20-0.44). A 159 grossular-rich garnet (Grs₆₇₋₇₆) additionally grew in equi-160 librium with plagioclase and quartz during either prograde 161 heating or early decompression. Also this second reaction 162 released a CO₂-rich fluid, with approximately the same 163 composition (XCO₂ = 0.30-0.44) as that released through 164 the first reaction. It follows that the amount of CO₂ released 165 during garnet growth increases with the increase in gros-166 sular component of garnet (Groppo et al. 2013). The study 167 of primary and secondary carbonic and aqueo-carbonic fluid 168 inclusions occurring in quartz, plagioclase, clinopyroxene 169 and, possibly, garnet and calcite will provide direct con-170 strains on nature and composition of the involved CO₂-rich 171 fluids. 172

Our results also demonstrate that the studied calc-silicate 173 rocks behaved as a closed-system during their prograde and 174 early retrograde evolution, although their volume abun-175 dance within the hosting paragneiss is low. In such a closed 176 system, the CO₂-rich fluid released during prograde and 177 early retrograde evolution induced the hydration of the 178 adjacent silicates (mainly plagioclase and clinopyroxene); 179 these hydration reactions, depleting the fluid in H_2O (i.e. 180 enriching the fluid in carbon) triggered the precipitation of 181 graphite. 182

183 184 **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 calcsilicate 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 garnetforming reactions. However, if the system remains closed, fluid-rock interactions may induce hydration of the calcsilicate 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.

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