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Corresponding Author	Family Name	**Costa**
	Particle	
	Given Name	**Emanuele**
	Prefix	
	Suffix	
	Division	Department of Earth Sciences
	Organization	University of Torino
	Address	10125, Turin, Italy
	Email	emanuele.costa@unito.it
Author	Family Name	**Destefanis**
	Particle	
	Given Name	**Enrico**
	Prefix	
	Suffix	
	Division	Department of Earth Sciences
	Organization	University of Torino
	Address	10125, Turin, Italy
	Email	
Author	Family Name	**Groppo**
	Particle	
	Given Name	**Chiara**
	Prefix	
	Suffix	
	Division	Department of Earth Sciences
	Organization	University of Torino
	Address	10125, Turin, Italy
	Email	
Author	Family Name	**Mosca**
	Particle	
	Given Name	**Pietro**
	Prefix	
	Suffix	
	Division	
	Organization	IGG – CNR
	Address	10125, Turin, Italy

	Email	
Author	Family Name	**Kaphle**
	Particle	
	Given Name	**Krishna P.**
	Prefix	
	Suffix	
	Division	
	Organization	Nepal Geological Society
	Address	Kathmandu, Nepal
	Email	
Author	Family Name	**Rolfo**
	Particle	
	Given Name	**Franco**
	Prefix	
	Suffix	
	Division	Department of Earth Sciences
	Organization	University of Torino
	Address	10125, Turin, Italy
	Division	
	Organization	IGG – CNR
	Address	10125, Turin, Italy
	Email	franco.rolfo@unito.it

Abstract	Metamorphic degassing from active collisional orogens supplies a significant fraction of CO_2 to the atmosphere, thus playing a fundamental role even in today's Earth carbon cycle. Appealing clues for a contemporary metamorphic CO_2 production in active orogens are represented by the widespread occurrence, along the whole Himalayan belt, of CO_2 rich hot-springs mainly localized along major tectonic discontinuities. In contrast to these well-studied hot-springs, almost no chemical and isotopic data are actually available for cold-springs, especially for those located at high-altitude and in remote areas of the Himalayas. In the framework of the Ev-K2-CNR SHARE (Stations at High Altitude for Research on the Environment) Project, we have started a preliminary chemical and isotopic study on high-altitude cold-springs located at different structural levels in the eastern Nepal Himalayas. Chemical and isotopic data obtained from the high-altitude cold-springs are compared with those obtained by previous authors from hot-springs located along the MCT. The isotopic signature of stable isotopes of hydrogen and oxygen could help to identify the waters sources in the investigated Himalayan sectors, to individuate mixing phenomena between waters of different provenience and possible connection with different circulation nets. These first measurements on high-altitude springs from remote areas of eastern Nepal represent a first step towards a better definition of a reliable scenario of water resources availability and will contribute to the understanding of the water cycle in the studied area.

Keywords (separated by '-')	High-altitude springs - Chemical and isotopic study - Eastern himalayas - Hydrological cycle - Global carbon cycle

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Preliminary Chemical and Isotopic Characterization of High-Altitude Spring Waters from Eastern Nepal Himalaya

Emanuele Costa, Enrico Destefanis, Chiara Groppo, Pietro Mosca, Krishna P. Kaphle, and Franco Rolfo

Abstract

Metamorphic degassing from active collisional orogens supplies a significant fraction of CO_2 to the atmosphere, thus playing a fundamental role even in today's Earth carbon cycle. Appealing clues for a contemporary metamorphic CO_2 production in active orogens are represented by the widespread occurrence, along the whole Himalayan belt, of CO_2 rich hot-springs mainly localized along major tectonic discontinuities. In contrast to these well-studied hot-springs, almost no chemical and isotopic data are actually available for cold-springs, especially for those located at high-altitude and in remote areas of the Himalayas. In the framework of the Ev-K2-CNR SHARE (Stations at High Altitude for Research on the Environment) Project, we have started a preliminary chemical and isotopic study on high-altitude cold-springs located at different structural levels in the eastern Nepal Himalayas. Chemical and isotopic data obtained from the high-altitude cold-springs are compared with those obtained by previous authors from hot-springs located along the MCT. The isotopic signature of stable isotopes of hydrogen and oxygen could help to identify the waters sources in the investigated Himalayan sectors, to individuate mixing phenomena between waters of different provenience and possible connection with different circulation nets. These first measurements on high-altitude springs from remote areas of eastern Nepal represent a first step towards a better definition of a reliable scenario of water resources availability and will contribute to the understanding of the water cycle in the studied area.

Keywords

High-altitude springs • Chemical and isotopic study • Eastern himalayas • Hydrological cycle • Global carbon cycle

19.1 Introduction and Aim of the Study

Mountain ranges have strong impact on the global carbon cycle: metamorphic degassing from active collisional orogens, in fact, 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 (Evans 2011; Rolfo et al. 2014). Appealing clues for a contemporary metamorphic CO_2 production in active orogens are represented by the widespread occurrence, along the whole Himalayan belt, of CO_2 rich hot-springs mainly localized along the major tectonic discontinuities, such as the Main Central Thrust (Becker et al. 2008; Perrier et al. 2009). Peak

E. Costa (✉) · E. Destefanis · C. Groppo · F. Rolfo
Department of Earth Sciences, University of Torino, 10125 Turin, Italy
e-mail: emanuele.costa@unito.it

F. Rolfo
e-mail: franco.rolfo@unito.it

P. Mosca · F. Rolfo
IGG – CNR, 10125 Turin, Italy

K. P. Kaphle
Nepal Geological Society, Kathmandu, Nepal

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values of the measured CO_2 flux at these gas discharges are exceptionally high and similar to values reported on volcanoes (19,000 g m^{-2} day^{-1}; Perrier et al. 2009). In contrast to these well-studied hot-springs, almost no chemical and isotopic data are actually available for cold-springs, especially for those located at high-altitude and in remote areas of the Himalayas.

In the framework of the Ev-K2-CNR SHARE (Stations at High Altitude for Research on the Environment) Project, we have started a preliminary chemical and isotopic study on high-altitude cold-springs located at different structural levels in the eastern Nepal Himalayas (Khimti Khola, Likhu Khola and Dudhkund Khola catchments). Preliminary chemical and isotopic data obtained from these high-altitude cold-springs are hereby compared with those obtained by previous authors from hot-springs located along the Main Central Thrust.

These first measurements on high-altitude springs represent a first step towards a better definition of a reliable scenario of water resources availability and will contribute to the understanding of the water cycle in the studied area.

19.2 Sampling and Analytical Methods

19.2.1 Sampling

Eleven spring water samples were collected in the Numbur and Dudh Khunda region of eastern Nepal Himalayas in the post-monsoon season, November 2012. The investigated springs are located in the Khimti Khola, Likhu Khola and Dudhkhund Khola catchments (tributaries of the Sun Khosi river), at an altitude between 1,800 and 4,500 m a.s.l. (Fig. 19.1). Most of the springs are located in remote areas, far from villages and accessible through poorly known trails. Water sampling was further complicated by the high altitude environment and by the fact that, due to logistic reasons, the amount of collected water had to be minimized.

Temperature and pH were measured *in situ* at the source vents using an HANNA HI2211 pH meter, calibrated every morning with pH standards. Conductivity was measured with an HANNA HI8820 N. Water samples for chemical and isotopic analysis were collected in two polyethylene bottles of 250 ml, capped without head space to minimize degassing. The water samples to be used for DIC isotopic analysis were added with $SrNO_3$ and NaOH to precipitate all the dissolved inorganic carbon as $SrCO_3$, as suggested in De Groot (2004). A subsequent filtration of the samples that would have precipitated enough carbonate could have led to isotopic measurement of the Dissolved Inorganic Carbon.

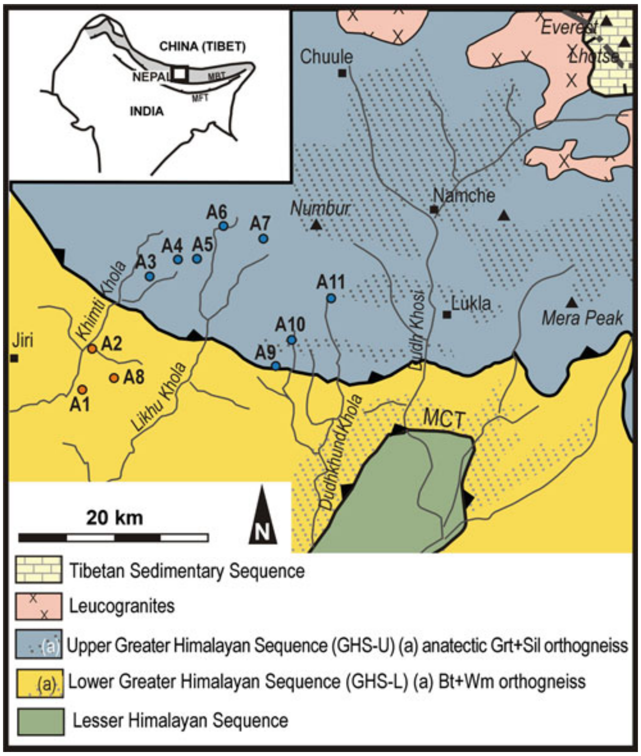

Fig. 19.1 Simplified geological map of the central-eastern sector of the Numbur and Dudh Khunda area, eastern Nepal Himalaya (modified from Mosca et al. 2013) showing sample locations. *MCT* Main central thrust. *Inset* shows the location of the study area (*black rectangle*) in the framework of the Himalayan chain. The *grey* shaded belt approximates the location of the Greater Himalayan Sequence. *MFT* Main frontal thrust; *MBT* Main boundary thrust

19.2.2 Geological Setting

The Khimti Khola, Likhu Khola and Dudhkhund Khola rivers cross the main tectonostratigraphic units of eastern Nepal Himalaya, flowing across the Greater Himalayan Sequence (GHS) and the Lesser Himalayan Sequence and crossing the Main Central Thrust Zone (MCTZ). Three of the investigated springs are located in the structurally lower GHS domain (GHS-L) (i.e. within the MCTZ), and seven are located in the upper GHS domain (GHS-U) (Fig. 19.1).

The GHS-L mainly consists of a metasedimentary sequence (mostly metapelites and minor calc-silicate rocks

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and impure marbles) recording an increase in metamorphic grade upward, passing from the staurolite zone to the sillimanite zone and, locally, to anatexis (Groppo et al. 2009; Mosca et al. 2013). The GHS-U is characterized by high-grade metamorphic rocks (metapelites, metacarbonate rocks and orthogneiss), often anatectic, recording a progressive decrease in peak-pressure structurally upward (Groppo et al. 2012, 2013). Most of the analyzed springs are hosted in silicate rocks, except springs A1 and A11 that are hosted in metasedimentary rocks including impure marbles and calc-silicate levels.

19.2.3 Analytical Methods

Samples for chemical analysis were collected in pre-cleaned HDPE 250 ml bottles, without any addition of acid substances, because the same sample has to be suitable for both cations and anions determinations. Analysis were done at the Dept. Earth Sciences (Univ. Torino), using a Metrohm IC 732 Ion Cromatography System for anions quantification, and a Spectro Iris Advantage II ICP-AES for cations evaluation. Isotopic analysis were performed on five representative samples from different structural levels at ISO4 Laboratories in Turin, using a Picarro L2120-i Isotope Analyzer, with a precision of $\pm 3\ \delta‰(3\sigma)$ for deuterium and $\pm 0.6\ \delta‰(3\sigma)$ for ^{18}O. So far, none of the samples was submitted to DIC isotope analysis for the evaluation of δ^{13}C; only sample A1 is rich enough in DIC to ensure the necessary amount of carbonate suitable for the determination.

19.3 Results

19.3.1 Geochemical Features

The analyzed springs are characterized by low discharge temperature varying between 3 and 16 °C, with a negative correlation between temperature and altitude (Table 19.1). They are characterized by a very low salinity (TDS $<$ 150 mg/L) and a correspondent very low conductivity ($<$200 µS/cm). The pH varies between 6.5 and 7.3 and the samples are Ca–Mg–HCO^{3-} in composition (Fig. 19.2a). No significant compositional variations are observed between the GHS-L and the GHS-U springs; the springs hosted in metacarbonate rocks show the highest TDS.

Overall the characteristics of the analyzed cold-springs are coherent with those described by previous authors in other areas of central Nepal Himalaya (e.g. cold-springs of the Marsyandi Valley: Evans et al. 2001; Becker et al. 2008). Cold-springs composition is significantly different from that of the well-known hot-springs located along the MCT, which are typically Na–Cl to Na–Ca–Cl type waters with high total dissolved solids (TDS up to 8,500 mg/L), vary in temperature between 20 and 60 °C and have a pH in the range 5.5–7 (e.g. Evans et al. 2004; Becker et al. 2008; Perrier et al. 2009).

19.3.2 Isotopical Features

The very low total dissolved solids of the measured samples hampered the possibility of analyzing their carbon isotopic composition. Five of the water samples were submitted to isotopic determination to measure hydrogen and oxygen values. These are typical of meteoric waters and show a very good correlation with the Global Meteoric Water Line (GMWL) of precipitation (IAEA 1970, 2005), lying directly upon or very near the GMWL (Fig. 19.2b). A difference is clearly visible between samples collected at minor altitude (A1 and A2) and those collected at higher altitude. The close correlation suggests the absence of any evaporation process prior of the infiltration of rain runoff, or exchange reactions between the infiltrated water and the host rocks. Topography and altimetry indicate that a short distance could be traveled through the hosting geological formation between recharge area and spring location; therefore, the short residence time, combined with the low water temperature, prevented reactions with silicates.

19.4 Conclusions and Further Studies

Our preliminary data obtained from Himalayan high-altitude cold-springs show waters with low salinity contents and an isotopic signature that clearly indicates a provenience from meteoric rain-fall. Low temperature of the waters, as well as the low content in chloride and other ions, suggest that these springs are unrelated to geothermal activity. Overall, chemical and isotopic data are in good agreement with the few data on Himalayan cold-springs already available in the literature.

Since the isotopic determinations are related to a single sampling campaign, they do not allow further hypothesis about water circulation and seasonal change, or variations in the hydrological cycle. However, these are amongst the first δD and δ^{18}O data for high-altitude cold-springs from remote areas of eastern Nepal Himalaya. New sampling

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Table 19.1 Location, field observations

Sample	Altitude (m a.s.l.)	GPS coordinates	Host rocks	Estimated discharge rale (l/sec) and field observations	T °C	pH	Conductivity (μS cm^{-1})	TDS	Na^{+} (mg/l)	K^{+} (mg/l)	Ca^{++} (mg/l)	Mg^{++} (mg/l)	NH^{++} (mg/l)	F^{-} (mg/l)
A1	1805	N27°36′27.0″ E86°17′47.4″	Wm+ CM Slladic schist and Phl + Wm imoure	10–20 l/sec; several discharge points in the alluvial sediments	16.1	73	172	134.4	0.83	1.57	12.70	4.50		0.02
A2	I960	N27°38′32.9″ E86°19′08.0″	Fine-grained two- micas Grl-beanng oneiss	<1 l/sec and discontinuous; few discharge points at ihe base of an alluvial tar	15.0	71	28	25.15	1.44	0.61	1.71	0.42	0.08	
A3	3930	N27°42′57.0″ E86°23′4.8″	Two-micas Grl- and Ky- beafing aneiss	<0.1 l/sec, single discharge point in the alluvial sediments	60	68	18	14.51	0.68	0.92	0.85	0.31		
A4	4510	N27°43′57.3″ E86°25′21.6″	Bt + Grt + Sil anatectc gneiss	01–0.2 l/sec. few discharge points from (he rock outcrop	30	69	21	17.11	0.5	0.32	2.22	0.29		0.01
A5	4370	N27°43′54.9″ E86°26′15.4″	Bt + Grt + Sii anatectc gneiss	2 l/sec, few discharge points at the base of an alluvial fan	51	72	7	8.27	0.14	0.3	0.81	0.28		0.00
A6	4140	N27°45′48.0″ E86°28′03.4″	Fine-grained Bt gneiss ivilh Sil + Qtz nodules	1 l/sec: single discharge point in the alluvial sediments	56	7	15	14.39	0.39	0.44	1.80	0.32		0.01
A7	4380	N27°45′11.0″ E86°30′37.5″	Bt + Grt + Sil anatectc gneiss	0.1–0.2 l/sec; single discharge point from Vie	36	7	25	23.66	0.24	0.39	2.74	0.46		0.01
A8	3090	N27°36′43.2″ E86°20′47.8″	Two-micas Grt-bearing quartzilic mica schist	0.1–0.2 l/sec; single discharge point from Vie colluvial sediments	92	68	8	10.29	0.04	0.47	0.60	0.42		
A9	3700	N27°38′00.1″ E86°32′04.6″	Bt + Grt + 311 anatectc augen-crneiss	0.1–0.2 l/sec; single discharge point from Vie colluvial sediments	69	69	16	15.97	0.64	0.57	1.28	0.46	0.13	0.00
A10	3870	N27°39′23.1″ E86°33′04.7″	Bt + Grt + Sil anatectc augen-	0.1–0.3 l/sec, single discharge point in the alluvial	79	63	15	14.28	0.55	0.68	1.40	0.42		
A11	4465	N27°41′44.6″ E86°35′4I.9″	Calc-silicate grancfels and imoure marble	50–100 l/sec; few discharge points from the rock outcrop	3.6	6.5	55	43.06	0.49	0.63	6.29	0.33		0.02

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Table 19.1 (continued)

Sample	Altitude (m a.s.l.)	GPS coordinates	Host rocks	Estimated discharge rale (l/sec) and field observations	Cl^- (mg/l)	HCO^{3-} (mg/l)	CO^{3-} (mg/l)	NO^{2-} (mg/l)	SO_4^{2-} (mg/l)	PO_4^{3-} (mg/l)	NO_3^- (mg/l)	$\delta^{18}O$ (‰ VSMOW)	δD (‰ VSMOW)
A1	1805	N27°36′27.0″ E86°17′47.4″	Wm + CM Slladic schist and Phl + Wm imoure	10–20 l/sec; several discharge points in the alluvial sediments	0.82	111.1	0.00	0.22	0.87	0.00	1.84	−8.74	−60.01
A2	I960	N27°38′32.9″ E86°19′08.0″	Fine-grained two- micas Grl-beanng oneiss	<1 l/sec and discontinuous; few discharge points at ihe base of an alluvial tar	0.21	19.53	0.00		0.42	0.00	0.73	−9.13	−61 78
A3	3930	N27°42′57.0″ E86°23′4.8″	Two-micas Grl- and Ky-beafing aneiss	<0.1 l/sec, single discharge point in the alluvial sediments	0.97	6.10	0.00		0.21	0.17	4.30		
A4	4510	N27°43′57.3″ E86°25′21.6″	Bt + Grt + Sil anatectc gneiss	01–0.2 l/sec. few discharge points from (he rock outcrop	0.10	9.75	0.00		3.40	0.00	0.51	−14.40	−102.46
A5	4370	N27°43′54.9″ E86°26′15.4″	Bt + Grt + Sii anatectc gneiss	2 l/sec, few discharge points at the base of an alluvial fan	0.09	4.88	0.00		1.19	0.00	0.58		
A6	4140	N27°45′48.0″ E86°28′03.4″	Fine-grained Bt gneiss ivilh Sil + Qtz nodules	1 l/sec: single discharge point in the alluvial sediments	0.23	9.76	0.00	0.01	0.90	0.00	0.52		
A7	4380	N27°45′11.0″ E86°30′37.5″	Bt + Grt + Sil anatectc gneiss	0.1–0.2 l/sec; single discharge point from Vie	0.09	17.09	0.00		2.30	0.00	0.35		
A8	3090	N27°36′43.2″ E86°20′47.8″	Two-micas Grt-bearing quartzilic mica schist	0.1–0.2 l/sec; single discharge point from Vie colluvial sediments	0.28	7.32	0.00		0.15	0.00	1.00		
A9	3700	N27°38′00.1″ E86°32′04.6″	Bt + Grt + 311 anatectc augen-crneiss	0.1–0.2 l/sec; single discharge point from Vie colluvial sediments	0.20	12.20	0.00		0.13	0.04	0.29		
A10	3870	N27°39′23.1″ E86°33′04.7″	Bt + Grt + Sil anatectc augen-	0.1–0.3 l/sec, single discharge point in the alluvial	0.36	9.76	0.00		0.89	0.00	0.22		−9327
A11	4465	N27°41′44.6″ E86°35′41.9″	Calc-silicate grancfels and imoure marble	50–100 l/sec; few discharge points from the rock outcrop	0.16	29.29	0.00		5.40	0.00	0.45	−15.52	−113.24

Stable Isotope, and chemical data for the cold-spring of the Numbur and Dudh Khund area

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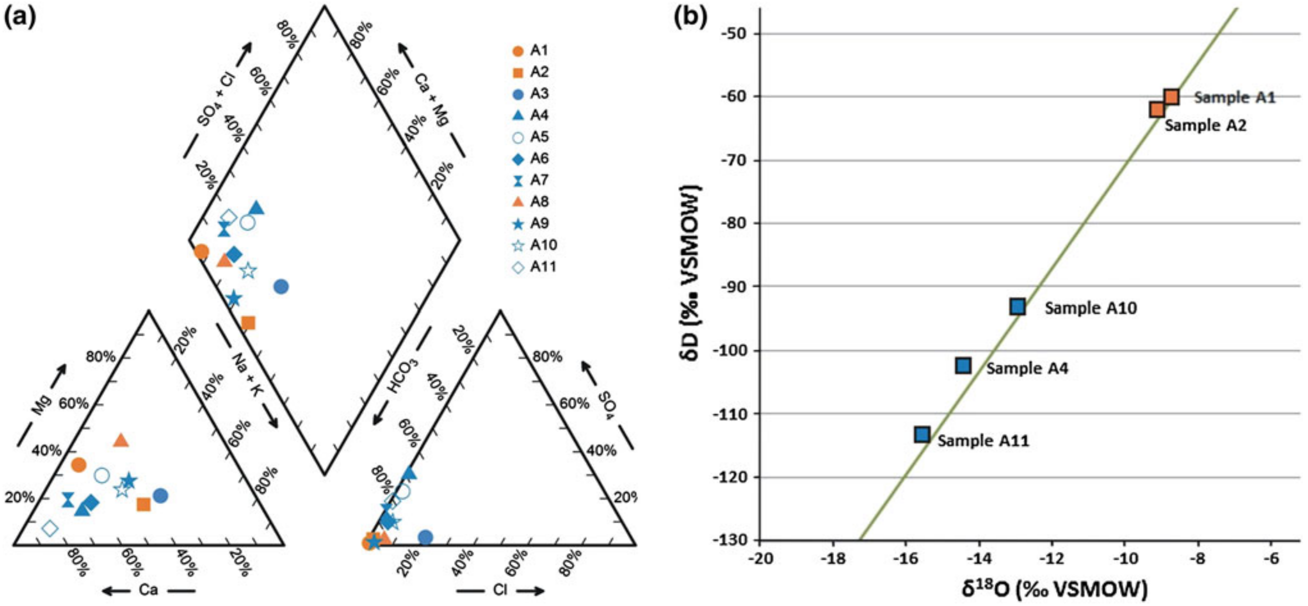

Fig. 19.2 **a** Piper diagram of the investigated water samples, showing their Ca–Mg–HCO_3 composition. **b** Projection of the isotopic data of the studied Himalayan cold-spring along with a projection of the Global Meteoric Water Line (in *green*). The studied samples are in good agreement (within the instrumental uncertainty) with rain waters with no (or very few) evaporation and/or exchange with the mineralogical assembly of the host rock. In both the diagrams, *orange symbols* GHS-L springs; *blue symbols* GHS-U springs

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campaigns, planned for the next future, will increase the sampling density of both cold- and hot- springs thus allowing to achieve a better understanding of the hydrological cycle in the area.

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