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Persistent CO₂ emissions and hydrothermal unrest following the 2015 earthquake in Nepal

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Fluid-earthquake interplay, as evidenced by aftershock distributions or earthquake-induced effects on near-surface aquifers, has suggested that earthquakes dynamically affect permeability of the Earth’s crust. The connection between the mid-crust and the surface was further supported by instances of carbon dioxide (CO₂) emissions associated with seismic activity, so far only observed in magmatic context. Here we report spectacular non-volcanic CO₂ emissions and hydrothermal disturbances at the front of the Nepal Himalayas following the deadly 25 April 2015 Gorkha earthquake (moment magnitude \( M_w = 7.8 \)). The data show unambiguously the appearance, after the earthquake, sometimes with a delay of several months, of CO₂ emissions at several sites separated by >10 kilometres, associated with persistent changes in hydrothermal discharges, including a complete cessation. These observations reveal that Himalayan hydrothermal systems are sensitive to co- and post-seismic deformation, leading to non-stationary release of metamorphic CO₂ from active orogens. Possible pre-seismic effects need further confirmation.

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Understanding fluid–earthquake interplay has long received a lot of attention\(^1\). For the last 20 years, there has been a growing number of evidence for fluid-driven earthquakes\(^2\). Deep fluids have been shown controlling aftershock distribution in the tectonic contexts of rifting\(^{3-5}\), subduction\(^{6-7}\), and reverse\(^8\) and strike-slip faulting\(^9\). Contemporaneously, numerous observations of earthquake-induced effects on near-surface aquifers have been reported\(^{10}\), including mainly changes in stream and spring discharge\(^{11-13}\), groundwater level\(^{14,15}\) and temperature\(^{16-19}\) in various tectonic contexts. These observations have suggested that earthquakes dynamically affect permeability of the Earth’s crust\(^{20,21}\). Carbon dioxide (CO\(_2\)) emissions were observed in association with seismicity in the case of the Matsushiro swarm\(^2\) in Japan or, recently, at the Lassen volcano\(^{22}\) (Cascades Range, USA) and in the Eger Rift\(^{23}\) (Czech Republic), which suggests connection between the mid-crust and the ground surface through gas transport. However, such examples so far were only observed in the presence of magmatic activity.

The Himalayan orogen results from the India–Eurasia collision\(^24\), the Main Himalayan Thrust (MHT) accommodating at 2 cm year\(^{-1}\) half of the shortening between the two continents\(^25\). The largest earthquake in Nepal before 2015, the 1934 Bihar-Nepal earthquake (moment magnitude \(M_w\approx 8.2\)) in Eastern Nepal, which claimed >15,000 lives, ruptured the MHT up to the surface over 150 kilometres along the Main Frontal Thrust\(^{26}\). Inter-seismic deformation is associated with intense background seismicity\(^{27}\), with 4–5 events of local magnitude \(M_l > 5\) per year, concentrated between 10 and 25 kilometres depth at the foot of the Himalayan topographic rise\(^{28}\). This region – the Main Central Thrust (MCT) zone\(^29\) – also exhibits numerous hydrothermal systems\(^{30}\) (Fig. 1). Following evidence of degassing from chemical and isotopic analysis of hot springs and rivers\(^{31,32}\), large CO\(_2\) emissions were discovered near hot springs\(^{33,34}\), with CO\(_2\) fluxes at places similar to diffusive fluxes from active volcanoes\(^{35,36}\). The seasonal and yearly stability of the soil–gas radon concentration time-series\(^{34,35}\), the invariant radon–CO\(_2\) fluxes relationship\(^{37}\), and the results of watering experiments\(^{38}\) at selected sites attest to the remarkable temporal stability of these hydrothermal systems, even during monsoon. These non-volcanic CO\(_2\) emissions are characterised by radiogenic helium, high radon content, and carbon isotopic compositions suggesting metamorphic CO\(_2\) production at >5 kilometres depth\(^{39-41}\). In the accepted conceptual model\(^31,32\), from the decarbonation source at >5 kilometres depth, CO\(_2\) percolates through fracture networks in the MCT zone, where it mixes with meteoric water. Near the water table, a fraction of CO\(_2\) may degas, and water discharges eventually at the surface as a hot spring. Degassed CO\(_2\) may also be transported faster to the surface through a network of interrelated faults without interaction with hydrothermal circulations\(^{37}\).

The \(M_w = 7.8\) 25 April 2015 Gorkha earthquake\(^38\) (Fig. 1) caused >9000 deaths, with fatality rates >1% in mountainous areas north of Kathmandu\(^39\), reaching 100% at some places\(^40\). It partly ruptured the MHT along a 120-kilometre-long segment east from the epicentre\(^41\), whose northern limit coincides with the

![Fig. 1](Image)
Table 1 Post-seismic effects on the carbon dioxide emissions at five hydrothermal sites in Central Nepal. Data of CO2 flux, total CO2 discharge, and carbon isotopic ratio of CO2 emissions are compiled before and after the Gorkha earthquake

| Site                      | Location       | Before/after Gorkha earthquake | CO2 flux (g m−2 d−1) | CO2 discharge (10−3 mol s−1) | δ13C of CO2 (V-PDB) (%) | Post-seismic effect |
|---------------------------|----------------|--------------------------------|----------------------|----------------------------|-------------------------|-------------------|
|                           |                | Before                        | After                | Geometric mean             | Before                  | After             | Increase         |
|                           |                | Min/max range                 |                       |                           | n.m.                    | n.m.              | Increase         |
| Budhi Gandaki Valley      | Near Hot Spring | 63(33)                        | 21.6/81,800          | 514 ± 16                  | >1240 ± 330            | 4(4)             | −3.2 ± 0.2       |
|                           | Upper Trisuli Valley | 36(33)                       | 13.2/94,700          | 640 ± 40                  | >580 ± 150             | 4(4)             | −1.4 ± 0.7       |
|                           | Machhakholo     |                               |                       |                           | n.e.                   | 3(1)             | −0.94 ± 0.01     |
|                           | Sanjen         |                               |                       |                           | n.e.                   | 4(1)             | −0.7 ± 0.1       |
|                           | Chilime         |                               |                       |                           | n.e.                   | 2(2)             | −1.5 ± 0.1       |
|                           | Syabru-Bensi    |                               |                       |                           | n.e.                   | 3(3)             | −1.50 ± 0.06     |
|                           |vanished        |                               |                       |                           |                         | n.m.             | Increase         |
|                           | Syabru-Bensi    |                               |                       |                           |                         | n.m.             | Increase         |
|                           | Timure          |                               |                       |                           |                         | n.m.             | Increase         |
|                           | Sanjen          |                               |                       |                           |                         | n.m.             | Increase         |
|                           | Chilime         |                               |                       |                           |                         | n.m.             | Increase         |
|                           | Syabru-Bensi    |                               |                       |                           |                         | n.m.             | Increase         |
|                           | Timure          |                               |                       |                           |                         | n.m.             | Increase         |

n.e.: not estimated, n.m.: not measured, $N_{\text{mean}}$ ($N_{\text{meas}}$): total number of measurements (total number of measurement points)

Data from: ref.39, 40, 41, 42, 43, 44, 45

Results

Outbursts of CO2 triggered by the Gorkha earthquake. New CO2 emissions were observed after the Gorkha earthquake, sometimes spatially associated with substantial changes from the pre-existing CO2 emissions (Table 1 and Supplementary Table 1). Because a large number of CO2 flux measurements (see Methods) were made before (n = 1718; December 2006 – January 2011) and after the earthquake (n = 1053; November 2015 – January 2018), a quantitative comparison of CO2 emissions before and after the earthquake can be undertaken in the Upper Trisuli valley. Spectacular effects were observed first in Syabru-Bensi, 56 kilometres east from the epicentre (Fig. 1), a site that had been extensively studied from 2006 to 2011. The main gas emission zone, located above the hot springs (Fig. 2; Supplementary Fig. 1), on the west bank of the Trisuli river, changed substantially. Significant CO2 fluxes and discharges appeared near the dwellings above the previously existing gas zone, in a cultivated area where flux level was close to local background levels before 2009. Hydrogen sulphide is now frequently smelled inside the houses. Total CO2 discharge in the area now reaches 1010 ± 110 mmol s−1 (3.8 ± 0.4 ton d−1), corresponding to an increase factor of 2.1 ± 0.3 (Fig. 2). Fluxes at two reference locations (K−6 and K+12; Fig. 2), regularly monitored since November 2015 (Fig. 3), peaked in November 2016 and, in January 2018, continued to remain 2-order of magnitude higher than their pre-seismic values. By contrast, the cavity characterised by the largest pre-earthquake CO2 fluxes (>106 g m−2 d−1) showed one-order-of-magnitude smaller CO2 emission after the earthquake (Supplementary Fig. 4). The cavity fluxes returned to pre-earthquake values in January 2018, more than 2.7 years after the mainshock.

Two kilometres to the west of Chilime, at the Sanjen hydropower construction site (Fig. 1), spectacular bubbling was suddenly noticed, beginning of November 2015, in two 40-metre-deep piezometers whose water level was being monitored. When construction resumed during 2016, CO2 emissions appeared at several locations in a tunnel being excavated nearby (Supplementary Fig. 7 and Movie 1). The CO2 emission in the tunnel was still present in January 2018. The CO2 concentration in the air of the tunnel then ranged from 4 to
5 vol%, thus creating a major health hazard, and the total CO$_2$
 discharge was estimated in the tunnel to 580 ± 150 mmol s$^{-1}$
 (2.2 ± 0.6 ton d$^{-1}$), hence of the same order as the main Syabru-
 Bensi discharge.

In the Budhi Gandaki valley, 16.5 kilometres to the epicentre
(Fig. 1), the highest CO$_2$ emissions ever reported in Central Nepal
were observed in January 2017 on the partly flooded riverbank,
where no phenomenon had been known to the locals before the
earthquake (Supplementary Movie 2). The CO$_2$ emission was
still present in January 2018, with a total discharge higher than
1240 ± 330 mmol s$^{-1}$ (4.7 ± 1.3 ton d$^{-1}$), similar to the whole
CO$_2$ discharge observed in Syabru-Bensi. In addition to the
flux from the bank, an innovative method was used to measure the
CO$_2$ flux from and through the hot water pond (see Methods and
Supplementary Fig. 8). This is the most spectacular new CO$_2$
emission observed so far in the Himalayas and elsewhere in the
absence of volcanic activity. Together with the Upper Trisuli
valley (Syabru-Bensi, Sanjen and Timure), such a persistent post-
seismic CO$_2$ outburst is unusual. For instance, small outbursts
following the 2008 Wenchuan earthquake in China lasted only a
few months$^{46}$. In the Marsyandi valley, further west (Fig. 1), by
contrast, no comparable phenomenon was observed and peak
CO$_2$ fluxes (5300 to 28,700 g m$^{-2}$ d$^{-1}$), while signifi-
cant, are smaller than in the Upper Trisuli valley.

All these CO$_2$ emissions were quantified in the field during the
dry season or in absence of rain, as shown by the 2015–2017
rainfall data in Dhunche (seven kilometres southwest to Syabru-
Bensi) and Timure (Fig. 3). At a given site, the CO$_2$
flux data were
obtained before and after the earthquake at about the same
periods under similar meteorological conditions. Besides, the
observed changes in the CO$_2$ emission were done contemporar-
ya at several sites separated by more than 10 kilometres. All these
care and observations preclude to these changes any environ-
mental, meteorological or shallow origin.

Figure performed using PV-WAVE® software (Rogue Wave)
Carbon isotopic ratio of the CO₂ emissions (δ¹³C; see Methods) was systematically measured at all occurrences (Table 1 and Supplementary Table 1), giving the most comprehensive data set (n = 77) so far in a seismically active area without magmatic activity. Along the rupture zone, average δ¹³C values range from −6.9 ‰ to −0.1 ‰, and appear similar at the various sites of a given valley. CO₂ emissions in Sanjen and Syabru-Bensi, although separated by eight kilometres, have comparable CO₂ concentrations (96–98%) and δ¹³C signature (from −0.9 ‰ to −0.7 ‰), precluding shallow sources, but instead suggesting similar CO₂ source and transport from a crustal-scale reservoir. In addition, the δ¹³C values remain relatively stable after the earthquake (Supplementary Fig. 4), indicating that the earthquake revealed a pre-existing CO₂ reservoir.

Hydrothermal unrest triggered by the Gorkha earthquake. The CO₂ emissions were associated with changes of hydrothermal activity (Table 2 and Supplementary Table 2). In Syabru-Bensi, new hot springs appeared after the earthquake, with a few persisting in January 2018, > 2.7 years after the mainshock. The temperature of the main Syabru-Bensi hot spring (SBP0), which had been stable at 60.7 ± 0.1 °C for more than 12 years before the earthquake (Fig. 3), increased to 64.1 ± 0.3 °C after the earthquake (November 2015 – January 2016), along with a significant flow rate increase of 16 ± 1%. Water temperature peaked about 1 year after the mainshock. Water warming of SBP0 persisted more than 2 years after the mainshock, before starting to decrease to pre-earthquake values in January 2018, more than 2.7 years after. Other springs in Syabru-Bensi (SBB5) also showed warming, persisting in January 2018 (Supplementary Fig. 9). A slight pre-seismic water-cooling was possibly detected in Syabru-Bensi (Fig. 3). More significantly, three other hot springs of the same valley (Timure, Langtang and Chilime) also showed cooling a few weeks before the earthquake (Supplementary Fig. 9). In Tatopani (Budhi Gandaki valley), locals reported hot spring temperature decrease a few weeks before the earthquake. While co-, post- and
**Table 2 Post-seismic effects on the hot springs at nine hydrothermal sites in Central Nepal. Data of temperature, flow rate, and dissolved inorganic carbon concentration and isotopic ratio of hot springs are compiled before and after the Gorkha earthquake**

| Site                      | Location             | Name            | Type     | Before/after Gorkha earthquake | Spring temperature (°C) | Spring flow rate (L s⁻¹) | Dissolved inorganic carbon (DIC) | Isotopic ratio of DIC | Post-seismic effect |
|---------------------------|----------------------|-----------------|----------|-------------------------------|-------------------------|--------------------------|--------------------------------|-------------------|-------------------|
| **Budhi Gondaki Valley**  |                      |                 |          |                               |                         |                          |                                 |                   |                   |
| Machhakhola               | Eastern Bank         | BUDO HS⁵, DDS   | After    | 59.8 ± 0.2                    | n.m.                    | 1                       | 26.4 ± 0.3                  | -0.5 ± 0.2         | Increase (New)   |
| Tatanpani Southern        | Secondary Springs    | BUD3B HS⁵       | After    | 43.2 ± 0.1                    | n.m.                    | 1                       | 25.6 ± 0.9                  | 0.9 ± 0.3          | Increase (New)   |
| Main Springs              |                      | BUD4B HS        | Before³  | 30 ± 1                        | 0.061 ± 0.002           | 1                       | 12.2 ± 1.2                  | 3.7 ± 0.3          | Decrease (Temp.) |
|                           |                      | BUD4C HS        | Before³  | 50 ± 1                        | 0.19 ± 0.04             | 1                       | 22.0 ± 0.2                  | 1.6 ± 0.3          | Decrease (Temp.) |
| **Sanjen**                |                      |                 |          |                               |                         |                          |                                 |                   |                   |
| Tunnel                    |                      | TSJ3 HS⁵, DDS   | After    | 20.3 ± 0.1                    | n.m.                    | 1                       | >55                           | -9.1 ± 0.7         | Increase (New)   |
| Piezometer                |                      | DH1 AQ, DDS     | After    | 18.9 ± 0.6                    | n.m.                    | 2                       | 43.8 ± 0.1                  | 1.6 ± 0.1          | Unknown          |
| Piezometer                |                      | DH2 AQ, DDS     | After    | 19.1 ± 0.8                    | n.m.                    | 1                       | 43.3 ± 0.1                  | 2.1 ± 0.1          | Unknown          |
| Chilime Hot Spring        |                      | CHI HS, DDS     | Before³  | 48.9 ± 0.4                    | 5.0 ± 0.2               | 3                       | 13.8 ± 13.3                 | 8.3 ± 0.4          | Decrease (Cessation) |
| Syabru-Bensi Western      | Bank                  | GZ3 HS, DDS     | After    | No spring                     | 0                       | 0                       | 0                             |                  |                   |
| Secondary Springs         |                      | FF2 HS⁵, DDS    | After    | 23.4 ± 0.1                    | n.m.                    | 1                       | 3.2 ± 0.1                   | 3.7 ± 0.1          | Increase (Tempr.) |
| DDDS                      |                      | SBP0 HS⁵        | Before³  | 60.7 ± 0.1                    | 0.087 ± 0.004           | 4                       | 25.8 ± 1.6                  | 4.7 ± 0.7          | Increase (Temp., flow, CDIC, δ¹³CDIC) |
|                          |                      | SBB5 HS         | Before³  | 64.1 ± 0.3                    | 0.104 ± 0.007           | 5                       | 34.3 ± 1.5                  | 1.0 ± 0.1          | Increase (Temp., flow, CDIC, δ¹³CDIC) |
|                          |                      | SBC2 HS         | Before³  | 31.8 ± 0.3                    | 0.282 ± 0.009           | 2                       | 25.8 ± 3.6                  | 0.9 ± 0.1          | Increase (Temp., flow, CDIC, δ¹³CDIC) |
|                          |                      | SBM HS⁵, DDS    | After    | 34.9 ± 0.2                    | 0.37 ± 0.02             | 4                       | 29.6 ± 0.9                  | 0.2 ± 0.3          | Decrease (Temp.) |
|                          |                      | SNB HS⁵, DDS    | After    | 50.1 ± 1.9                    | 2.1 ± 0.1               | 2                       | 17.8 ± 1.1                  | 2.6 ± 0.1          | Decrease (Temp.) |
|                          |                      | SBN2 HS⁵        | After    | 37.3 ± 0.8                    | 1.3 ± 0.1               | 3                       | 27.4 ± 0.1                  | 2.3 ± 0.1          | Increase (New)   |
|                          |                      | SBN HS⁵, DDS    | After    | 39.2 ± 0.6                    | 0.50 ± 0.02             | 3                       | 17.3 ± 1.1                  | 2.0 ± 0.2          | Increase (New)   |
| North Syabru Western      | Bank                  | TT1 HS, BB      | Before³  | 24.3 ± 0.7                    | 0.0               | 4                       | 35.8 ± 2.9                  | 12.3 ± 0.7         | Increase (Temp.) |
|                         |                      | SB5 HS          | Before³  | 25.3 ± 0.1                    | n.m.                    | 2                       | 38.3 ± 2.3                  | -0.6 ± 0.1         | Increase (Temp.) |
| Timure                    |                      | TIM HS          | Before³  | 63.1 ± 2.2                    | 0.20 ± 0.02             | 5                       | 17.3 ± 1.0                  | 3.3 ± 0.1          | Increase (Temp.) |
| Langtang                  |                      | LPAH HS         | Before³  | 70.7 ± 1.0                    | n.m.                    | 2                       | 14.2 ± 0.2                  | 2.1 ± 0.1          | Decrease (Temp.) |
| Bhoite Koshi Valley       |                      | KOD HS          | Before³  | 44.6 ± 1.2                    | 3.0 ± 0.2               | 1                       | 8.4 ± 0.3                   | -8.7 ± 0.1         | Increase (Temp.) |
|                          |                      | KOD2 HS⁵        | After    | 50.0 ± 0.1                    | 3.00 ± 0.04             | 0                       | n.m.                        | n.m.               |                   |
|                          |                      |                 | After    | 48.1 ± 0.1                    | n.m.                    | 0                       | n.m.                        | n.m.               | Increase (New)   |

n.m.: not measured; HS: hot spring; BB: bubbles; DDS: diffuse degassing structure; AQ: aqueous degassing

*New spring that appeared after the Gorkha earthquake

Compilation of new original data and of data compiled in ref.30., and in particular from: ref.32; ref.31 and 52; ref.63; ref.64; ref.51; ref.33

sometimes pre-seismic changes in hot spring temperature have been reported in the literature⑥,⑨, a two-year-long or longer warming is unusual.

The most spectacular change in hydrothermal activity, however, is the complete cessation of the Chilime hot spring at the end of October 2015, after periods of unusual intermittence between April and June 2015 (Supplementary Fig. 10). Before the earthquake, this spring had a stable flow rate of > 5 L s⁻¹; it was the pillar of local economy, being the most important in Central Nepal after the Kodari hot spring (Fig. 1). The village elders had previously reported spring intermittence at the time of the 1934 earthquake, but no cessation. Particularly impressive is the fact that it happened at about the time of the CO2 outburst in Sanjen.

Dissolved Inorganic Carbon (DIC) concentration and isotopic ratio (C DIC and δ¹³C DIC see Methods) were systematically measured for all hot spring waters (Table 2 and Supplementary Table 2). In Syabru-Bensi, where the number of measurements is significant (n = 8), C DIC of the SBP0 hot spring increased by 29 ± 2% after the mainshock and, in September 2017, returned to values measured before the mainshock (Fig. 3), while Ca and Na concentrations remained similar within 5%. The δ¹³C DIC decreased also significantly (Supplementary Fig. 11). These observations suggest a larger amount of dissolved carbon in the SBP0 hot spring after the earthquake, which is compatible with the aforementioned increase in gaseous CO2 emissions. Available pH values (Supplementary Fig. 9) also show a slow return to pre-earthquake values, with anomalously high values before the earthquake, a fact to be interpreted with caution given the lack of additional geochemical information. In Syabru-Bensi, dissolved radon and radium concentrations in SBP0 and SBBS hot springs changed after the earthquake (Supplementary Fig. 9). In January 2018, >2.7 years after the mainshock, the warmest spring in Syabru-Bensi returned to pre-earthquake conditions, while those more dependent on superficial effects (e.g., SBBS) did not yet.
Fig. 4 Conceptual models of the carbon dioxide and hydrothermal transport before and after the Gorkha earthquake. Pre- and post-seismic models are shown separately for a-b the Bhote Kosi valley (Syabru-Bensi and Timure) and c-d the Chilime valley (Chilime, Sanjen and Brapche). The CO₂ is produced at depth and a significant fraction is transported to the surface by hydrothermal circulations, which efficiently take advantage of fault network; some CO₂ can also move upwards independently, reaching the surface without hot spring (Sanjen, Syabru-Bensi GZ3) and accumulate in the subsurface reservoir revealed by CO₂ emissions following the earthquake. The main effect of the earthquake is an increase of vertical permeability with transient or permanent changes.

First non-volcanic earthquake-induced gaseous changes. Hydrologic responses to seismic stimulation have been observed in numerous instances, and correlated with Seismic Energy Density (SED) or Peak Ground Velocity (PGV) values. In Lassen (Cascades Range, USA) for example, a 2014 volcano-seismic swarm peaking at $M_s = 3.85$ at 5.7 kilometres distance, corresponding to $\text{SED} \sim 0.2 \text{ J m}^{-3}$ and $\text{PGV} \sim 0.2 \text{ cm s}^{-1}$, caused an outburst of geothermal fluids, explained by a two-fold permeability increase. In the case of the Matsushiro earthquake swarm in Japan, modeling indicates the necessity of a 2-order-of-magnitude permeability increase with a small overpressure of only a few megapascals. In Syabru-Bensi, the Gorkha earthquake produced $\text{SED} \sim 63 \text{ J m}^{-3}$ and $\text{PGV} \sim 26 \text{ cm s}^{-1}$ (see Methods; Supplementary Table 3), hence strong enough to affect the hydrothermal system, with several aftershocks maintaining high ground motion during the following 31 months (Supplementary Fig. 12). These estimates are confirmed by GPS time-series of the Chilime station and (Fig. 1), giving $\text{PGV} \sim 49 \text{ cm s}^{-1}$ (Supplementary Fig. 13). While the first clearly documented instances in the Himalayas, our observed near-field CO₂ outbursts and hydrothermal unrest remain compatible with previously compiled earthquake-induced changes (Supplementary Fig. 14). Our observed changes in the CO₂ emissions are however the first earthquake-induced gaseous changes in a non-volcanic region.

Discussion
The observations following the Gorkha earthquake give some indications that the standard model, where CO₂ is degassed from hydrothermal waters, needs some modifications at least at some part. Indeed, previous work in Syabru-Bensi identified large CO₂ emissions without the presence of an important hot spring in the vicinity. Now, the evidence for an extended reservoir of crustal CO₂ is overwhelming, which we accommodate with the following conceptual models (Fig. 4). In the case of the Trisuli valley (Syabru-Bensi and Timure) (Fig. 4a, b), hydrothermal circulations are important and increased after the earthquake. The main CO₂ source can therefore be the hydrothermal circulations, with near surface degassing and subsurface accumulation in the whole fault zone. Possible additional CO₂ can also be released in the footwall directly from the production source. The earthquake caused (Fig. 4b) an increasing water discharge, with increased CO₂ degassing, or better communication to the surface of previously accumulated CO₂. In the case of the Chilime valley (Chilime, Sanjen and Brapche) (Fig. 4c, d), however, the pervading presence of CO₂ revealed by the earthquake, kilometres away from hot springs, is better explained if CO₂ is directly accumulated from below, possibly through the water table, without advection by hydrothermal circulations.

Strikingly, CO₂ emissions with similar isotopic anomaly were observed over the whole region, whenever faults, boreholes or a tunnel gave the opportunity. These observations also attest the presence of a large, relatively shallow, reservoir of CO₂ in the Himalayan crust, suggesting that metamorphic CO₂ produced at depth is huge, as independently shown by petrological estimates, and unlikely sequestered. Nevertheless, as hot water could also be found when deep boreholes are available, the overwhelming presence of hot water could match the evidence of an extended CO₂ reservoir, and the debate cannot be considered as closed.

The effects of the earthquake on our hydrothermal systems are not unexpected. Indeed, our observed CO₂ emissions appear consistent with hydrothermal outburst effects, as observed in Lassen, suggesting that apparent two-fold permeability increases and/or changes in hydrothermal pathways for pre-existing CO₂ emissions could have been major effects of the Gorkha
In the Napa valley, a vertical permeability change, following (Supplementary Figs. 16 and 17). These vertical permeability modulate the Syabru-Bensi hot spring warming and increased fluid flow in October 2017 about 2.5 years after the mainshock, was initiated. A linear trend in the GPS time-series, continuing to independence con

The large post-seismic CO2 outburst and the Chilime cessation likely result from hydrogeological fluid diffusion.

Other explanations are, however, possible. In Central Nepal, post-seismic deformation (afterslip on the MHT) and associated aftershocks remained active several months after the mainshock. About 6 months after the mainshock, contemporaneous with the Syabru outburst and the Chilime cessation (Fig. 3a), the number of seismic events producing PGV>1 cm s⁻¹ in Syabru-Bensi increased, and a linear trend in the GPS time-series, continuing to October 2017 about 2.5 years after the mainshock, was initiated. Thus, some post-seismic CO2 emissions and hydrothermal unrest may be related to changes in the state of post-seismic relaxation. Incidentally, the time of the Syabru outburst and the Chilime cessation coincides with renewal of aftershock activity near Syabru-Bensi in the fall of 2015 (Fig. 3a), including an M₃ = 5.3 event a few weeks before. In addition, two M₃ > 4 events occurred at about the same time (end of October – beginning of November), less than 15 kilometres from Syabru-Bensi, producing PGV > 1 cm s⁻¹ (Supplementary Table 3).

The Himalayan hydrothermal systems appear highly sensitive to small deformation rates and are therefore in near-critical condition. This suggests that post-seismic relaxation of co-seismic stress may result from pore pressure changes, and that metamorphic CO2 may in turn play a role in the installation of the next inter-seismic regime. Alternatively, the still evolving CO2 emissions in Syabru-Bensi, Timure and Chilime may also indicate a currently unstabilized system, able to diverge unpredictably. Given the issue of a pending mega-earthquake in the region, long-term monitoring of CO2 emissions should be seriously considered as a chance to capture possible pre-earthquake signals.

In this paper, we have presented the first assessment of CO2 emissions triggered by a major earthquake, demonstrating the coupling between mechanical deformation and fluid transport properties at the crustal scale, highlighting that crustal deformation dynamically affects permeability during the seismic cycle. The large post-seismic CO2 emissions observed in the Narayani basin suggest non-stationary metamorphic CO2 production, and that its current estimate (1.3 x 10¹⁰ mol year⁻¹ with (1.0 ± 0.2) x 10⁹ mol year⁻¹ from direct gaseous CO2 emissions), independently confirmed by petrological studies, may be enhanced during a significant fraction of the seismic cycle. Metamorphic CO2 and its transport therefore emerge as an essential component of mountain build-up and the associated dynamics of large earthquakes.

Methods

Carbon dioxide flux measurement and mapping. The accumulation chamber method was used to measure surface CO2 flux and to quantify the total CO2 discharge of a given site and the associated uncertainties, whose assessment is based on numerous systematic tests and our 10-year experience. The method is robust, even in remote locations and during the monsoon, and allows the measurement of CO2 fluxes over more than five orders of magnitude (Supplementary Fig. 2). The gas concentration in the chamber is measured using one or several portable infrared CO2 sensors (Testo 535, Testo AG, Germany; AirWatch PM 1500, Geotechnical Instruments Ltd., UK; Vaisala CARBOCAP® Hand-Held GM70, Finland), that are regularly inter-calibrated in the laboratory. The CO2 flux is expressed in grams per square metre per day (g m⁻² d⁻¹). The total CO2 discharge, expressed in mol s⁻¹ (or ton d⁻¹), is estimated using the CO2 flux data-set by kriging and interpolation procedures. CO2 fluxes (n = 1720) and total CO2 discharges obtained before the Gorkha earthquake (from 2006 to 2011) are published elsewhere. Here we present for the first time CO2 fluxes (n = 1668) and total discharges obtained after the earthquake in the Marsyandi, Budha Gandaki and Upper Trisuli valleys relying on seven measurement campaigns carried out in November 2015, in January, May and November 2016, in January and September 2017, and in January 2018. Pre-earthquake and post-earthquake campaigns were performed outside the monsoon periods to reduce the meteorological effects on CO2 flux data. Every uncertainty is given around one-sigma standard deviation (68% confidence level) and averages are arithmetic means except otherwise stated. Data are summarised in Table 1 and Supplementary Table 1.

Carbon dioxide flux measurement through a water layer. The bubbling CO2 flux from or through water was measured at the new degassing site of Machhakhola (Budha Gandaki valley) in the following manner. A collecting container was installed upside down on the water with a pipe leading to an accumulation chamber installed on the ground nearby (Supplementary Fig. 8). Then, the flux was measured in this accumulation chamber as described above. This method yielded a minimum value to the large CO2 discharge observed in Machhakhola (Supplementary Movie 2).

Carbon isotopic composition of the gas phase. We sampled gas in the field using evacuated glass tubes. CO2 fraction of the gas sample was determined manometrically. The δ¹³C of CO2 of the gas, expressed in per mil relative to the Standard Vienna Pee Dee Belemnitne (VPDDB), was measured after off-line purification by mass spectrometry on a Finnigan MAT-253 mass spectrometer (Thermo Electron Corporation, Germany) in CRPG (Nancy, France). External repeatability of a given sample was ±0.1 %o. The twenty δ¹³C values measured before the Gorkha earthquake elsewhere in the field by emanometry in air and its current estimate are published elsewhere. Fifty-seven measurements were carried out after the earthquake from January 2016 to January 2018. Data are summarised in Table 1 and Supplementary Table 1.

Water temperature, pH and flow rate measurements. To measure water temperature of springs, we used thermometers (Generic TP101 Digital Thermometer, China) regularly inter-calibrated in the laboratory with a reference thermometer not calibrated in the field (Digital Thermometer model 4400 Ertco Eutechnics, USA), and compared with high-precision (10⁻³ °C) and high-sensitivity (10⁻⁴ °C) thermometers (Seabird 39plus, Sea-Bird Scientific, USA). Due to the time response of the instruments, several minutes are needed to measure temperature. Experimental uncertainty of a given measurement was ±0.1 °C. The pH of the twenty test springs was measured with various portable pH meters, Hach Germany; H981907 and H981930 pH meters, Hanna Instruments, USA), systematically recalibrated in the field using buffer solutions. Experimental uncertainty of a given measurement was ±0.1. The flow rate of thermal springs was determined using stopwatch and measured cylinders or buckets and was repeated at least three times. Data are summarised in Table 2 and Supplementary Table 2.

Carbon isotopic composition and DIC concentration in water. We sampled water in the field using two to three glass screw cap vials of 12 millilitres volume each. DIC concentration ([H₂CO₃] + [HCO₃⁻] + [CO₃²⁻]) and its isotopic composition (δ¹³C-DIC), expressed in mmol L⁻¹ and in per mil relative to V-PDB, respectively, were determined using a gas chromatograph coupled to an isotope ratio mass spectrometer (GCIRMS, GV 2003, GV Instruments, UK) in IGIP (Paris, France). The whole procedure is described elsewhere. The relative experimental uncertainty of DIC was 1–2% and the experimental uncertainty of a given δ¹³C-DIC measurement was ±0.1‰. For a given sample, final values correspond to weighted arithmetic averages of two to three measurements. The DIC and δ¹³C-DIC values measured before the Gorkha earthquake are published elsewhere. A total of 71 measurements were carried out after the earthquake from January 2016 to January 2018. Data are summarised in Table 2 and Supplementary Table 2.

Water radon-222 and radium-226 concentration measurements. Dissolved radon concentration in water was measured in the field by emanometry in air. Aqueous CO2 equilibrium is achieved by manual shaking. Radon concentration is inferred from scintillation flask sampling and photomultiplier counting, as described elsewhere. Radon concentration in water is measured in Bq L⁻¹.
Experimental uncertainty ranged from 5 to 30%. The radium concentration in water was similarly measured in the IPGP laboratory after keeping the bottle closed for at least 50–80 days. Expressed in mBq L−1, the experimental uncertainty was the same as for radon concentration in water. Here we present only the dissolved radon and radium concentrations in the main Syabru-Bensi hot springs (Supplementary Fig. 9).

Detection of thermal springs and CO2 degassing areas. The CO2 degassing areas were detected based on pervasive hydrogen sulphide odour, measurement of high radon-222 flux (radioactive gas of half-life 3.8 days), surface temperature anomalies, occurrence of water bubbles, presence of cavities, occurrence of inactive or active travertine deposits, and discussion with local people, or a combination of the above. In remote places, the detection of previously unknown thermal springs relied on the use of hand-held thermal infrared cameras (model 880–V3 before 2015 and model 875-11 after, Testo AG, Germany).

Determination of SED, PGV and PDS. At the sites which experienced the most significant post-seismic changes in CO2 emissions and hot springs, we calculated SED and vertical PGV produced by the Gorkha earthquake and its main aftershocks. Empirical equations were used to estimate SED and PGV. To study the effect of water flow changes on spring water temperature, we used a first-order model60 (Supplementary Fig. 17a). We calculated the SED, PGV and PDS produced at sites of the Upper Trisuli valley by three aftershocks located near Syabru-Bensi are also given.

Modelling of earthquake-induced changes. To study the effect of permeability changes on CO2 flux before and after the earthquake, we used a 2D model, described elsewhere, in which a vertical fault (f) surrounded by two media (a and b) transports the gaseous CO2 to the surface by advection. Each medium is characterized by permeability (k) and thermal conductivity (λ), that drives hot water from depth (z = h) to the surface (z = 0). We consider a vertical fault (f) driving the water flow to the surface, surrounded by two media (a and b). Each medium is characterised by permeability (k). Pressure source is fixed at depth. Solutions of the pressure distribution are expressed as a sum of exponential terms on horizontal axis, modulated by a sinusoidal signal along vertical axis. An example of calculation is shown in Supplementary Fig. 16.

To study the effect of water flow rate changes on hot spring exit temperature, we relied on an analytical first-order model60 (Supplementary Fig. 17a). We consider a vertical conduit, characterized by permeability (k) and thermal conductivity (λ), that drives hot water from depth (z = h) to the surface (z = 0), with flow rate Q, density ρ and specific heat Cp. Temperature at depth h is defined by T(h) = βh + T0), where β is the thermal gradient, which is poorly constrained in this hydrothermal region and taken to equal 55–75 °C km−1. We consider a quasi-static state having characteristic length λ and we define θ = –T(T0) and α = –pCPaQu/(kCpA). Using the initial conditions, the differential equation ( dθ/dz) + βz = −βz has the following solution: θ = exp(1–e−θ). Examples of calculation of the water temperature as a function of water flow rate, for two values of the thermal gradient, are shown in Supplementary Fig. 17b.

Data availability. The data that support the findings of this study are available in the article, in Supplementary Information, and from the corresponding author upon request (girault@ipgp.fr).

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Author contributions
L.B.A. provided aftershock catalogue and processed Fig. 1. C.F.-L. performed carbon isotopic measurements of the gas phase in the laboratory. F.A. performed carbon isotopic dissolved inorganic concentration measurements of the water phase in the laboratory. B.P.K. and M.B. participated to field CO2 flux measurements. S.S.M. participated in the discussions and managed the access to the Sanjen Hydroelectric Project sites. C.G. and F.R. performed water measurements a few weeks before the Gorkha earthquake at four hot springs. L.B. managed the assistance to NSC, seismic data processing, and provided detailed DEM and shared experience. F.G. performed water measurements, CO2 and radon flux measurements, and collected all samples. F.P. performed radon flux measurements and processed Supplementary Fig. 5. F.G. and F.P. wrote the paper.

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