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Scent of a myth: tectonics, geochemistry and geomythology at Delphi (Greece)

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Abstract: Extensive geochemical investigation (of water, travertine, soil and diffuse gas), coupled with geo-structural analysis, provides new insights into local fault–fluid interaction and allows us to pinpoint basic elements in the geological origin (or geomythology) of the Delphic Oracle, still debated by geologists. Delphi hosted the most famous oracle of antiquity, supposed to prophesy under the effects of intoxicating gas exhaling from a chasm in the ground. CO_2–H_2S-rich, ethylene-rich or CH_4-rich gases have been invoked to explain the mantic vapours. Although previous interpretations dismissed the results achieved by classical scholars, this study fits together history, archaeology, mythology and geology in a single coherent frame. We highlight that no hydrocarbon gas discharges are released at present to the surface in the area. The lack of any geochemical 'anomaly' indicates that the Delphi active fault does not at present constitute a preferential route for the circulation of thermogenic deep fluids. The mythological gas-exhaling chasm can plausibly be related to episodic seismic ruptures in the ancient past, which affected for a limited time gas pockets fed by a relatively deep confined hydrothermal system. The Delphi fault has produced shocks up to $Ms = 6.7$ (1 August 1870), and similar seismic faulting events in the past could have episodically triggered CO_2–H_2S-rich emissions.

The millennary Delphic Oracle (fourteenth century BC–fourth century AD), the most famous oracle of antiquity, brings together geology, archaeology and myth. Its origin has been alleged to be driven by geological phenomena, and it is one of the best documented and debated examples of the recently emerging discipline of geomythology (*sensu* Vitaliano 1973; Krajic 2005; Piccardi & Masse 2007). The Delphic Oracle is a perfect geomyth, because of the richness of literary, historical and archaeological sources available, and the clear correspondences emerging between phenomena described in myth and local geological reality. The prophetess (the Pythia) was said to utter her oracles sitting on a tripod, in a state of trance induced by inhalation of a gas emitted through a chasm in the earth. The actual existence of the sacred chasm and the mantic exhalations has been debated since antiquity. In modern times it has been the object of extensive literary, archaeological and geological investigations.

Modern opinion on the existence of the mythological chasm has mostly followed the work of Oppè (1904), who dismissed the sacred chasm and related exhalations as a Hellenistic invention. We note that the many scholars who denied the existence of the sacred chasm and vapours based their conclusions mostly on literary analysis, the lack of evidence of archaeological excavation being only an additional confirmation (e.g. Oppè 1904; Amandry 1950; Fontenrose 1981). Studying the marble basement of the sacred tripod and omphalos stone, Holland (1933) and Scott Littleton (1986) envisaged a mechanism of artificially channelling fumes through the pavement, so that the ecstasy of the prophetess might have been induced by addition of hallucinogenic substances to the fumes.

The idea that the sacred chasm referred to a natural geological fissure, as sustained by Farnell (1907), was recently revived when some geological hypotheses were proposed on the possible location and nature of the oracular chasm and of the gas emitted. Piccardi (2000) suggested that the original oracular chasm was related to a coseismic ground rupture, probably in the Shrine of Athena Pronaia, with the release of a CO_2–H_2S-rich gas (typically emitted during seismic faulting, e.g. Toutain & Baubron 1999). De Boer & Hale (2000) and de Boer *et al.* (2001) suggested that the mantic chasm could be related to the intersection of two active faults below Apollo's Temple, discharging ethylene-rich gases. According to those workers, ethylene, detected in the Kerna spring water only at trace level, would be derived from the interaction of fluids with the bituminous limestone formation present in the area. Such a C_2H_4-rich emission at Delphi was later dismissed by Etiope *et al.* (2006), who measured a slightly anomalous CH_4 flux at Apollo's Temple and at the foot scarp at the Kerna spring, suggesting that benzene, rather than ethylene, was the sweet component of a methane-rich gas exhalation.

The exact location of the original sacred chasm is difficult to determine beyond any doubt. Some scholars have proposed the Corcyrian Cave, on the Mt. Parnassus plateau, as a possible location, and other possibilities cannot be ruled out. Moreover, the location itself might have shifted with time, as a result of local tectonic activity and/or self-sealing effects. However, the locations possibly related to the gas-exhaling chasm within the archaeological site are the Shrine of Apollo, the Shrine of Athena and the Castalia Spring, the three most relevant places at Delphi.

The present paper, through an extensive geochemical investigation (spring water discharges, travertine, soil gases and CO_2 flux from soil), integrated with new structural–geological field work, proposes the first understanding of the Delphic myth in which geology and history (archaeological, literary and mythological evidence) fit without contrast. Here, new clues on the relationship between the seismotectonic setting and circulating fluid geochemistry of the region are discussed to trace present and/or past anomalous degassing activity at Delphi.

The Delphi active fault

Ancient Delphi lies above a seismogenetic structure, the Delphi active fault, which bounds to the south the calcareous massif of Mt. Parnassus (Figs 1–4). This structure represents the northernmost antithetic structure of the Gulf of Corinth half-graben (e.g. Armijo *et al*. 1996) (Fig. 1). From geological and geomorphological evidence, it is an active normal fault with a small component of right-lateral horizontal slip (Figs 2 and 3). The fault probably started its activity about 1 Ma ago (Péchoux 1977), in the present-day stress regime responsible for the fast active extension (>10 mm a^{-1}) of the Gulf of Corinth (e.g. McKenzie 1978; Billiris *et al*. 1991; Armijo *et al*. 1996; and references therein).

Figure 2c shows the main active faults of this area, and faults reported in the literature. De Boer & Hale (2000) and de Boer *et al*. (2001) invoked the presence of a Kerna fault, cutting across the Pleistos Valley from Mt. Parnassus to the north to Mt. Kedrias to the south (DB2 in Fig. 2a). This fault would intersect the Delphi fault (DB1) below the oracular cella of Apollo's Temple (Figs 2c and 7a). The authors documented the Kerna fault by means of three types of evidence: (1) remote sensing identification; (2) the stereographic projection of kinematic indicators on the fault plane; (3) the claimed alignment of five springs below Apollo's Temple (according to Higgins & Higgins 1996) (DB3 in Figs 2c and 7a). However, these types of evidence are not consistent. The alignment of five springs is not in itself evidence of the presence of a fault. Moreover, DB2 and DB3 do not coincide, and make an angle (Figs 2c and 7a). Etiope *et al*. (2006) envisaged two independent fault segments: one segment to the north, coinciding with part of DB2, does not cross the Palaeogene thrust surface but remains confined within the limestones, and a second segment, further south, coinciding with DB3, would join the Delphi fault at the Temple of Athena (E in Figs 2c and 7). Our field analysis confirms that the Delphi fault is the only active fault affecting the archaeological area (Figs 2–4). There is no evidence of a Kerna fault. A course of the Delphi fault as suggested by Etiope *et al*. (2006), although not clearly visible in the field, would be consistent with the local pattern of active faults.

To better constrain the activity rates on the Delphi fault, we

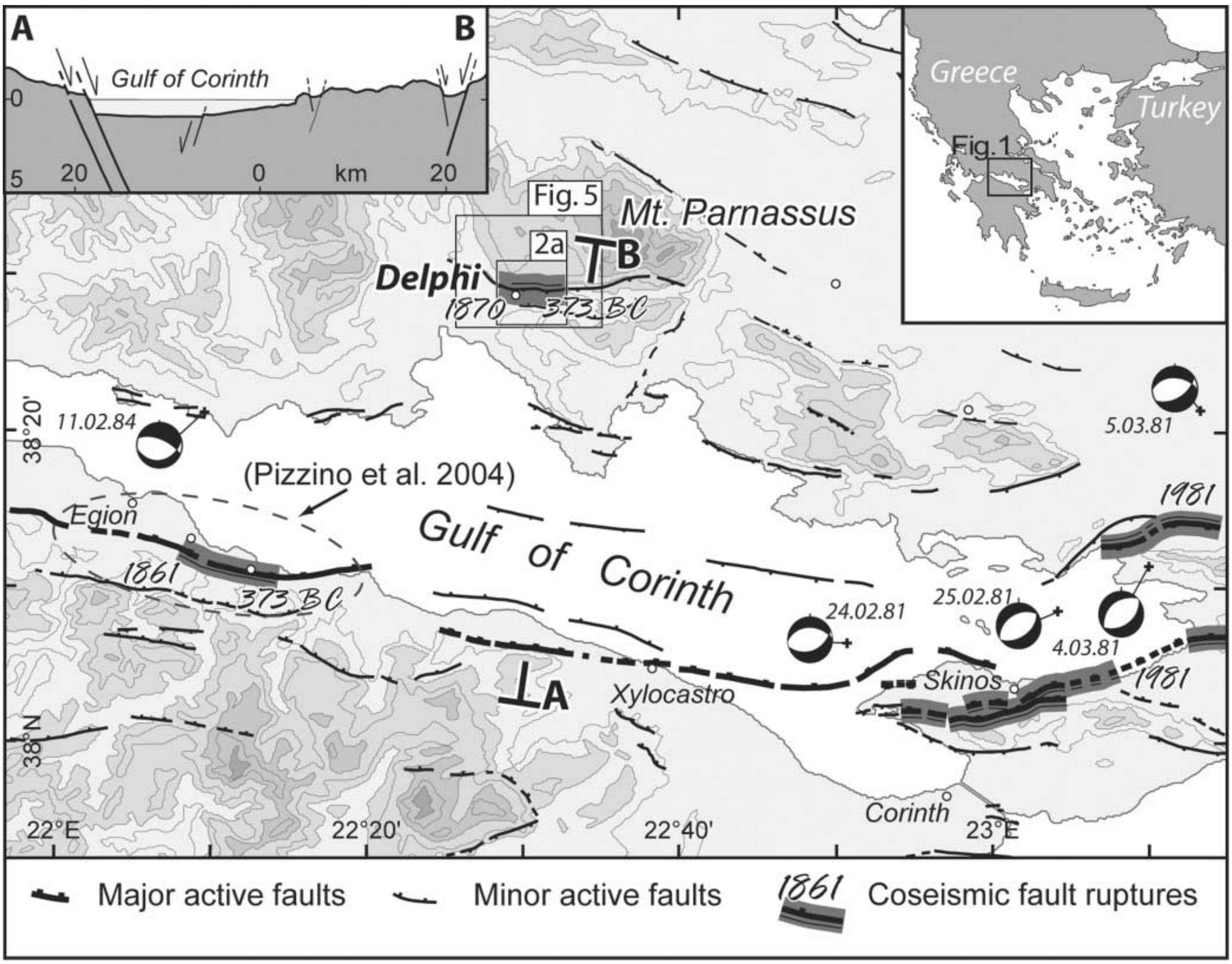


Fig. 1. Seismotectonic map of Gulf of Corinth (modified from Piccardi 2000). Dashed oval shows the area investigated by Pizzino *et al*. (2004). Inset shows cross-section, redrawn from Armijo *et al*. (1996).

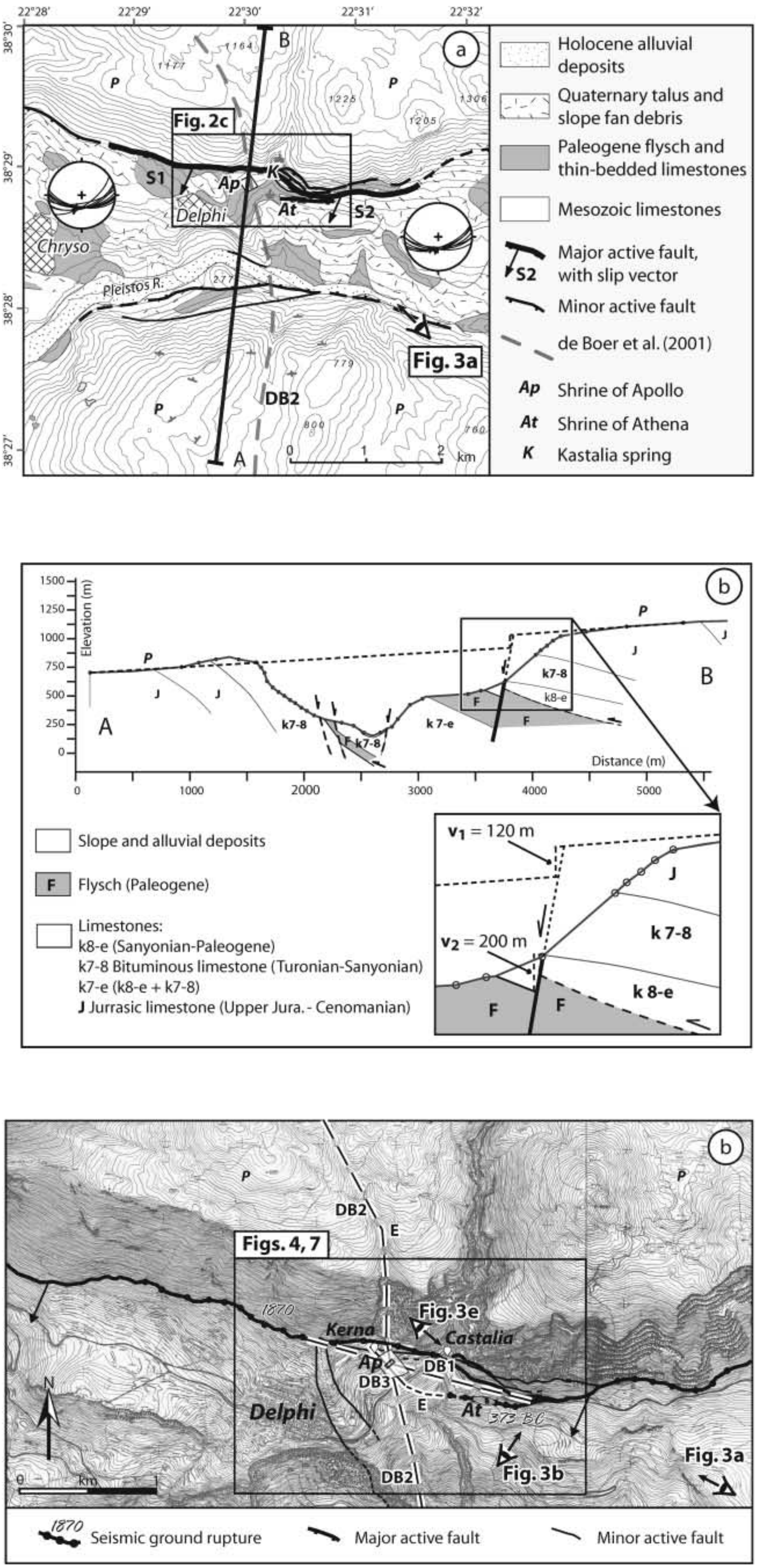


Fig. 2. (**a**) Geological map of the Delphi area, modified from Piccardi (2000). Geology from Zachos (1964) and Etiope *et al*. (2006). P indicates the summit palaeosurface. (**b**) Profile across the fault, with (detail) estimate of vertical throw from geomorphological and geological evidence. (**c**) Morphology of the area, showing the summit palaeosurface, with faults indicated by De Boer & Hale (2000) (DB1, DB2 and DB3), Piccardi (2000), Etiope *et al*. (2006) (E) and field work. Topography is from 1:5000 maps of Hellenic Army Geological Survey, sheets 63022 and 63031.

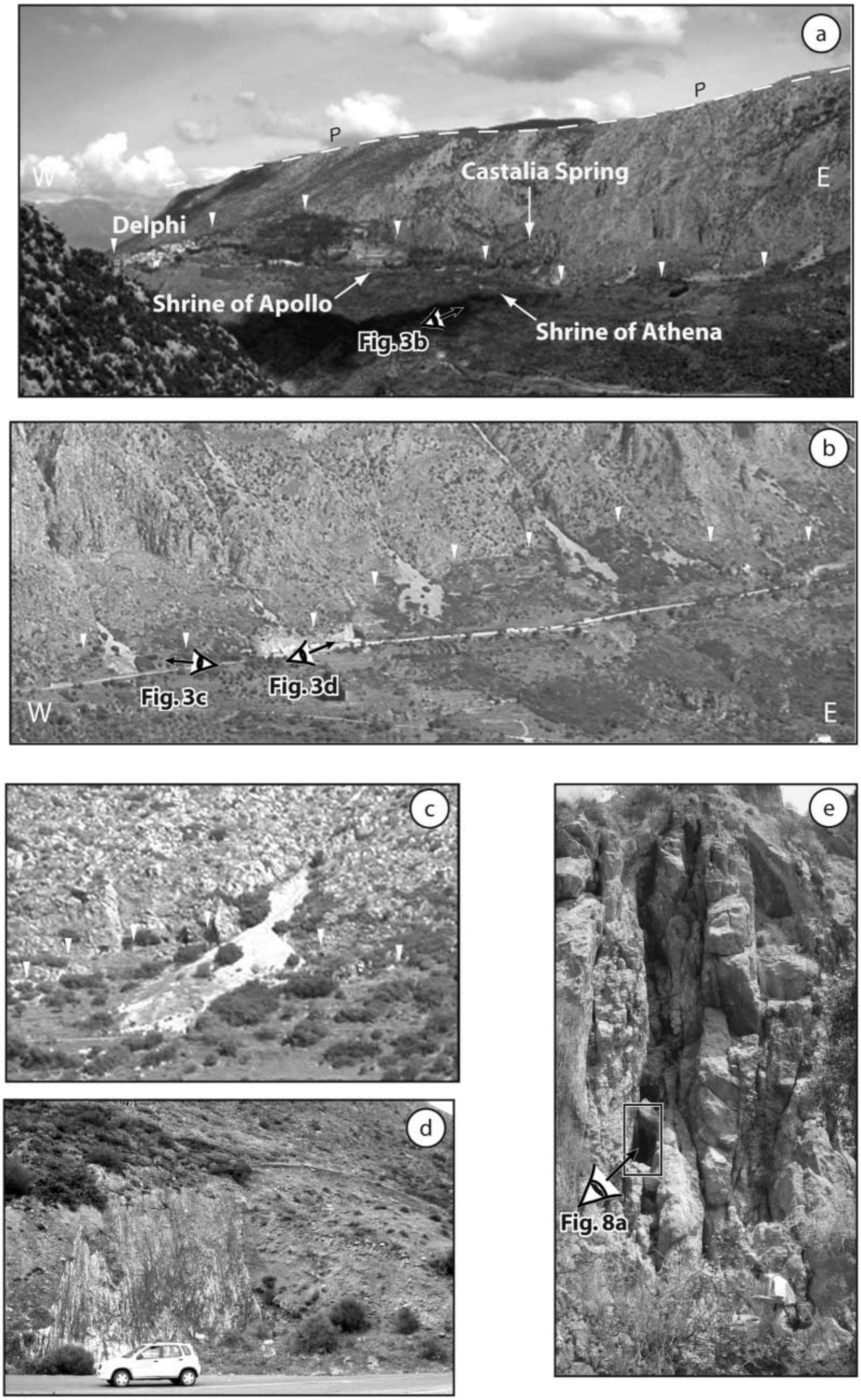


Fig. 3. Photographs of Delphi active fault. (**a**) Panorama towards the NW, with indication of main archaeological elements. (**b**) View of the fault trace east of the archaeological site. (**c**) Detail of faulted debris cone. (**d**) Exposed fault plane with slickensides, and faulted Quaternary debris. (**e**) View of the main Delphi fault zone, east of Castalia. Person at the bottom indicates scale.

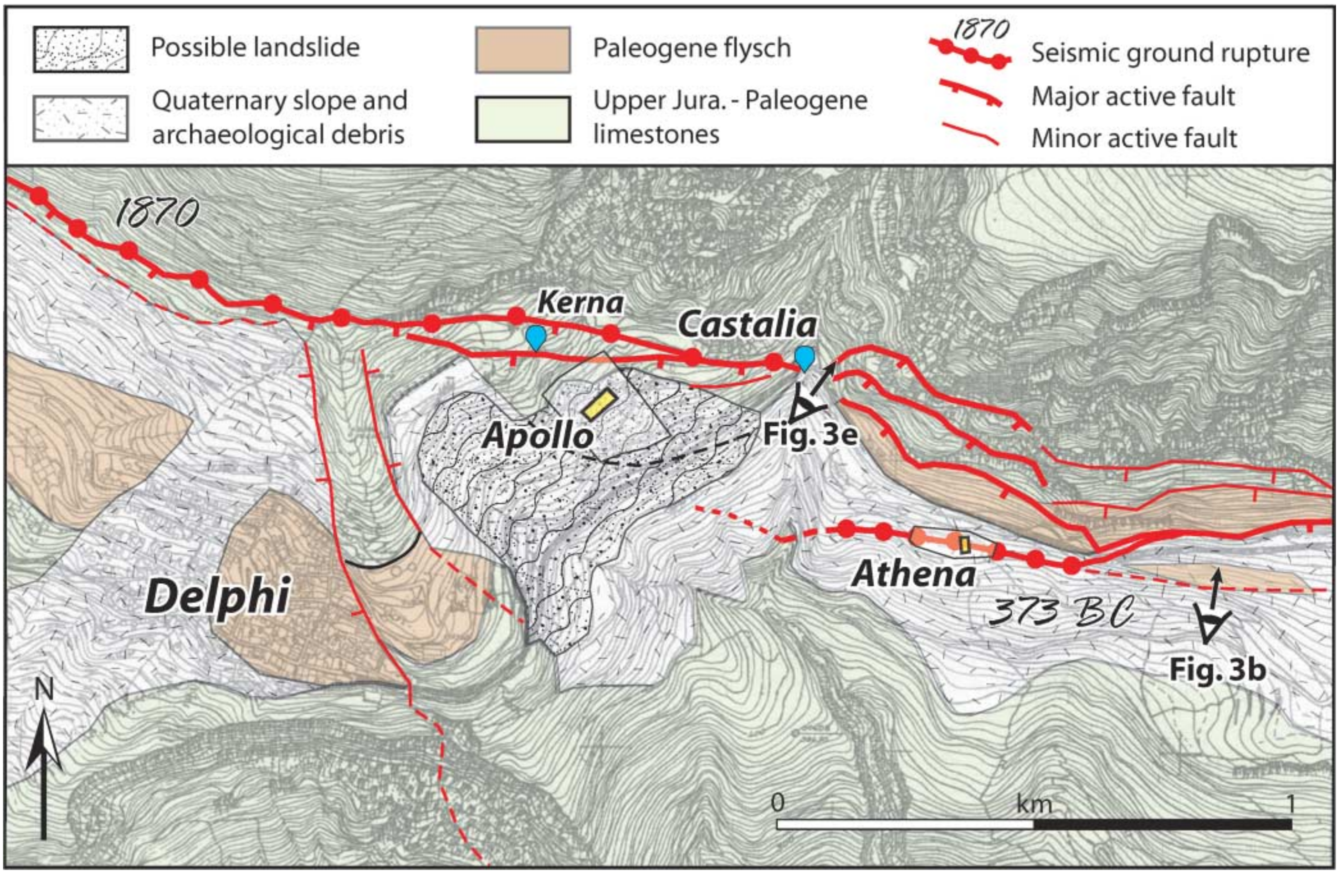


Fig. 4. Detailed structural geological map of the area surrounding Delphi (faults and geology were originally mapped at a scale of 1:10 000), with active faults as reported in literature.

re-evaluated the possible vertical displacement on the fault using geomorphological and geological markers. The palaeosurface on the summit of the Parnassus plateau (p in Figs 2 and 3a) may be considered to have an age of 1 Ma (Péchoux 1977). A rough morphological estimation of the displacement induced by the Delphi fault zone on this summit palaeosurface (Fig. 2a–c) is about 120 m (v1 in Fig. 2b). On the basis of geology, we have estimated the displacement of the thrust surface between Mesozoic limestones and Palaeogene flysch to be a maximum of about 200 m (v2 in Fig. 2b). The resulting vertical slip rate assuming the displacement to have occurred in the present-day stress regime (1 Ma) is about 0.1–0.2 mm a^{-1}, a lower rate than that previously reported by Piccardi (2000).

The Delphi fault is a seismic fault, capable of Ms >6.5 earthquakes. It is known to have ruptured a few times in the past: in 373 BC (Piccardi 2000), AD 551 (Ambraseys & Jackson 1998; Papazachos & Papazachou 2003) and, more recently, in the Ms = 6.7 earthquake of 1 August 1870 (Ambraseys 1996; Ambraseys & Jackson 1998; Papazachos & Papazachou 2003; Pavlides & Caputo 2004). The epicentre of this event was located at Kastri (the village that stood at that time on the main archaeological site of Delphi: Ap in Figs 2a,c and 4). The main shock occurred slightly to the east, and the two major aftershocks ($5.4 < M < 6.3$) occurred further west of it (Ambraseys & Pantelopoulos 1989). The discoloured and reddish appearance of water from some springs observed after the 1870 earthquake (Ambraseys & Pantelopoulos 1989) recalls the blood breathed forth by the Homeric dragoness after her death.

Earthquakes are mentioned not only in the history of Delphi (e.g. Plutarch, *De defectu oraculorum*, 52; Pausanias, *Description of Greece*, 10.23.1), but also in its myths. The first rulers of the oracle were Ge, Mother Earth, and Poseidon, the 'Shaker of Earth', god of earthquakes. The oracular chasm was guarded by a monster snake, Delphine or Python, which Apollo had to kill to conquer the oracle. The conception of the dragoness by goddess Hera was announced by an earthquake (*Homeric Hymn to Apollo*, Homer 1936, 331–342).

> 'Hear now, I pray, Earth and wide Heaven above, and you Titan gods who dwell beneath the earth about great Tartarus, and from whom are sprung both gods and men! Harken you now to me, one and all, and grant that I may bear a child apart from Zeus, no wit lesser than him in strength—nay, let him be as much stronger than Zeus as all-seeing Zeus than Cronos.' Thus she cried and lashed the earth with her strong hand. Then the life-giving earth was moved: and when Hera saw it she was glad in heart, for she thought her prayer would be fulfilled.

Also the description of the slaying of the serpent recalls an earthquake scenario, albeit clothed in mythological images

(*Hymn to Apollo*, 358–361). The monster: 'rent with bitter pangs, lay drawing great gasps for breath and rolling about that place. An awful noise swelled up unspeakable as she writhed continually this way and that amid the wood: and so she left her life, breathing it forth in blood'.

Ovid (*Metamorphoses*, 1.558–560) describes the serpent Python as enormous, outstretched at the foot of Mt. Parnassus' slope ('spread so far athwart the side of a vast mountain').

The description of the geomorphological effects of the M = 6.7 1870 earthquake (e.g. Schmidt 1879; Ambraseys & Pantelopoulos 1989; Pavlides & Caputo 2004) can provide a realistic idea of the coseismic phenomena and the possible scenario that started the myth of a supernatural chasm in the earth at Delphi. Extensive surface rupture occurred along the trace of the Delphi fault: 'large cracks developed at the foot of the cliffs above the village [Kastri] leading in a north-westerly direction'. The cracks extended east–west for a distance of about 18–20 km following the known active fault, with maximum vertical displacement of <1 m (Pavlides & Caputo 2004) (Fig. 4). Landslides and rock-falls were triggered in many places, being particularly intense in the area of the archaeological site. Near Chryso, 'ground cracks more than one metre wide and 5 metres deep were formed running along the mountain side for a short distance'.

Geochemistry of spring waters

Twenty water samples (18 springs and one tank-well) from Delphi and the surrounding areas (see Fig. 5 for location) were collected in spring 2004 (wet period). Ten of these waters, selected on the basis of their geochemical features, were re-sampled in summer 2005 (dry period) to determine the effects of seasonal changes on the chemical composition.

All waters are at $T < 20$ °C with slight alkaline pH ($6.80 < pH < 8.42$) and total dissolved solids (TDS) $< 0.7\ g\ l^{-1}$ (Table 1). No significant seasonal variations are observed. All the analysed waters can be classified as Ca–HCO_3 (Fig. 6a and b), typical of worldwide shallow and surficial waters (e.g. Appelo & Postma 1993; Drever 1997). In these springs chemical features typical of deep circulating fluids (e.g. high TDS values, high pCO_2) have not been recognized, and relatively high contents of NO_3 (up to $64\ mg\ l^{-1}$; Table 1) are found, likely related to anthropogenic pollution. Moreover, the lack of appreciable concentration of CO_2 ($< 0.5\ mmol\ l^{-1}$), as dissolved gas phase, and S^{II-} ($< 0.23\ mg\ l^{-1}$) further supports a negligible contribution from deep-seated fluids. On the whole, the chemical composition can basically be related to the interaction of meteoric water with the Mesozoic limestone bedrock.

To understand the hydrological fluid circulation at Delphi we

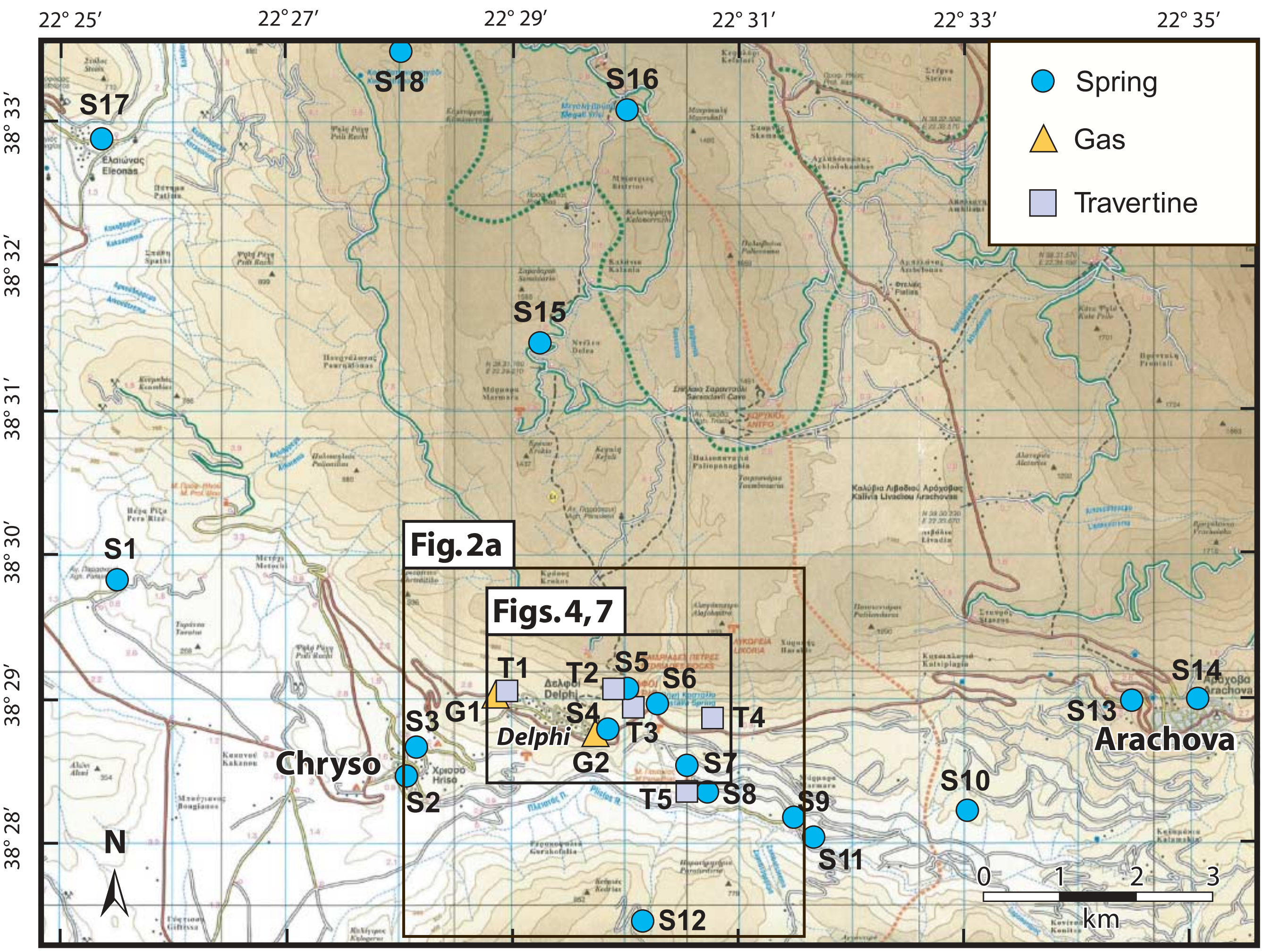
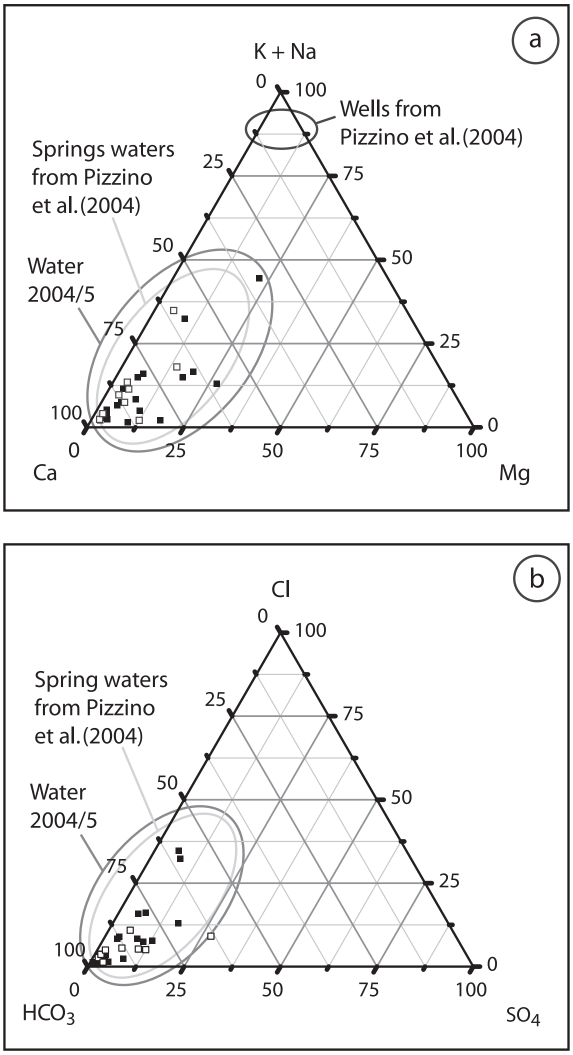


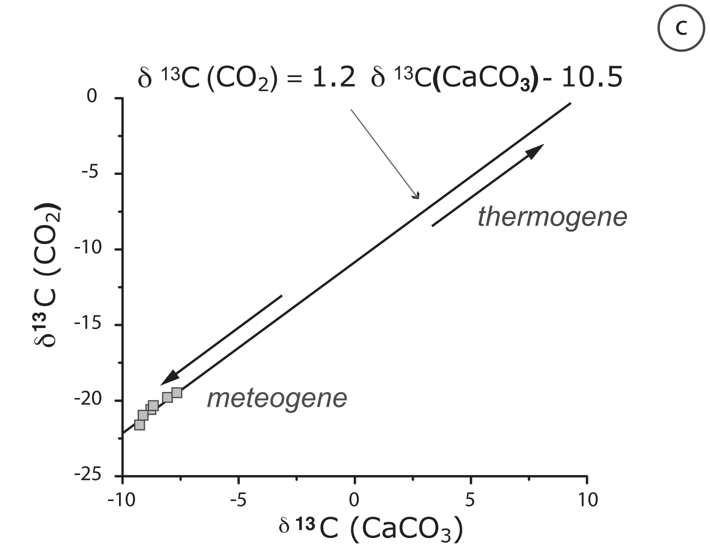
Fig. 5. Location map of the studied soil gases, springs, and travertine deposits. Topography is from 1:50 000 map 'Parnassus', Road Edition (Greece).

Table 1. *Geochemical data for main and trace species in water samples from the Delphi area*

Sample number	Spring	Latitude (N)	Longitude (E)	Elevation (m)	T (°C)	pH	TDS	log(pCO_2)	CO_2 (mmol l^{-1})	Na	K	Ca	Mg	NH_4	HCO_3	Cl	SO_4	NO_3	Br	F	S^{II-}	Error %
Sampling 2004																						
S1	Iliou	38°29′45″	22°25′38″	120	18	7.54	487	−2.248	0.51	30.7	8.2	119	21.7	0.04	464	24.5	48.0	2.1	bd	0.23	0.05	0.16
S2	Hriso 1	38°28′26″	22°28′04″	200	17	7.42	508	−2.337	bd	52.7	19.9	101	9.5	0.04	287	89.7	29.8	62.0	0.24	0.19	0.11	1.31
S3	Hriso 2	38°28′32″	22°28′13″	250	16	7.81	239	−2.946	bd	15.0	1.8	67	3.5	0.04	171	19.9	8.9	37.2	0.04	0.48	0.05	2.11
S4	Fountain 1897	38°28′41″	22°29′51″	550	16	7.51	312	−2.435	bd	12.9	13.7	97	4.1	0.07	279	16.3	23.0	5.0	0.32	0.04	0.05	4.19
S5	Kerna	38°29′01″	22°30′01″	630	16	7.52	293	−2.349	0.35	6.2	0.9	104	1.7	0.04	348	2.6	2.0	0.9	bd	0.04	0.09	1.56
S6a	Kastalia 1	38°29′07″	22°30′33″	550	13	7.17	272	−2.069	bd	3.5	0.8	102	2.0	0.04	305	6.3	3.5	1.0	0.48	0.03	0.07	1.66
S6b	Kastalia 2	38°29′07″	22°30′33″	550	13	6.80	279	−1.692	0.31	3.2	0.7	107	1.9	0.04	311	6.0	2.9	1.2	bd	0.04	0.05	2.87
S7	Panagia Zigoti	38°28′30″	22°30′36″	260	14.5	7.02	248	−1.955	bd	4.0	0.4	92	2.0	0.04	275	2.1	3.8	6.2	0.02	0.04	0.09	2.26
S8	Kephalovriso	38°28′38″	22°21′09″	450	14	6.95	240	−1.885	bd	2.2	0.3	84	2.2	0.04	275	6.4	2.5	5.0	0.24	0.02	0.05	3.55
S9	Santa Paraschevia	38°28′08″	22°31′32″	170	15	7.52	278	−2.483	bd	7.7	0.8	95	3.0	0.04	259	14.2	8.0	19.5	0.16	0.29	0.05	2.19
S10	Arahova 1	38°28′08″	22°32′43″	330	13	7.92	313	−2.894	bd	10.7	0.7	97	6.0	0.05	262	14.9	33.6	19.8	0.02	0.10	0.08	0.06
S11	Pleisto	38°27′52″	22°32′03″	170	7.5	8.42	406	−3.367	bd	24.7	2.1	103	16.0	0.05	311	33.3	59.5	11.2	0.08	0.25	0.22	3.18
S12	Kedrias	38°27′11″	22°30′12″	640	11.5	7.87	114	−3.141	bd	2.0	0.9	37	3.0	0.13	128	1.2	5.0	1.2	0.16	0.08	0.07	1.34
S13	Arahova 2	38°29′00″	22°34′37″	900	12	8.13	185	−3.354	bd	8.5	0.3	56	1.5	0.04	146	17.7	10.6	16.1	0.02	0.08	0.05	1.19
S14	Arahova 3	38°28′54″	22°35′01″	1000	9	8.01	120	−3.297	bd	1.0	0.2	47	0.7	0.05	128	2.8	3.2	1.2	bd	0.49	0.11	3.37
S15	Calanohari	38°32′11″	22°29′56″	1325	7	7.54	388	−2.341	bd	2.5	0.2	131	8.7	0.05	415	4.3	10.6	bd	1.60	0.19	0.06	1.21
S16	Megali Yrisi	38°33′05″	22°29′53″	1300	7	7.65	285	−2.559	bd	2.5	0.5	95	13.0	0.05	322	3.5	9.6	bd	0.24	0.08	0.11	3.20
S17	Eleonas	38°32′54″	22°25′02″	300	15	7.83	265	−2.779	bd	7.2	2.8	90	3.2	0.04	268	16.0	8.9	1.0	bd	0.06	0.12	1.17
S18	Droshokhori	38°35′22″	22°25′26″	1000	9	7.69	260	−2.655	bd	11.7	4.4	58	15.7	0.05	275	4.3	19.2	9.3	bd	0.25	0.08	3.80
Sampling 2005																						
S1	Iliou	38°29′45″	22°25′38″	120	20	7.15	435	−1.551	na	29.9	7.0	111	14.2	0.05	450	18.8	44.6	0.2	bd	0.19	na	3.75
S2	Hriso 1	38°28′26″	22°28′04″	200	17	7.30	503	−2.022	na	66.0	15.6	113	5.7	bd	276	69.8	30.0	64.9	bd	0.29	na	1.57
S3	Hriso 2	38°28′32″	22°28′13″	250	17.5	7.24	215	−2.056	na	9.7	1.0	65	2.4	bd	173	13.0	8.0	27.9	bd	0.53	na	0.90
S4	Fountain 1897	38°28′41″	22°29′51″	550	18	7.19	309	−1.800	na	11.5	8.6	89	2.4	0.22	281	12.0	13.0	29.8	bd	2.09	na	2.89
S6b	Kastalia 2	38°29′07″	22°30′33″	550	15	7.32	277	−1.906	na	4.6	0.5	98	1.3	bd	307	7.0	2.5	3.5	bd	0.49	na	1.03
S12	Kedrias	38°27′11″	22°30′12″	640	16	7.54	131	−2.488	na	3.5	0.8	40	1.7	0.16	127	2.0	5.0	0.2	bd	0.17	na	1.30
S14	Arahova 3	38°28′54″	22°35′01″	1000	13	7.95	120	−2.914	na	1.2	0.2	45	0.6	bd	129	1.4	2.5	0.1	bd	0.19	na	2.85
S16	Megali Yrisi	38°33′05″	22°29′53″	1300	9	7.70	248	−2.344	na	2.1	0.3	82	7.3	bd	289	3.5	8.0	0.1	bd	0.57	na	2.34
S17	Eleonas	38°32′54″	22°25′02″	300	15.5	7.80	261	−2.530	na	9.9	2.0	86	2.1	bd	221	20.0	10.0	20.0	bd	0.74	na	0.60

Concentrations are in mg l^{-1} with the exception of those of dissolved CO_2 (mmol l^{-1}). TDS, total dissolved solids; bd, below detection limit; na, not analysed. The analytical error for the main components is $<3\%$, whereas that for minor and trace species is $<5\%$.





	$\delta^{13}C(CaCO_3)$	$\delta^{18}O(CaCO_3)$	$\delta^{13}C(CO_2)$
T1/1	-9.26	-6.23	-21.07
T1/2a	-8.68	-6.18	-20.37
T1/2b	-8.62	-6.47	-20.24
T2	-7.54	-6.91	-19.09
T4	-9.12	-6.29	-20.90
T5	-8.26	-6.69	-19.38

Fig. 6. (**a**) Cation and (**b**) anion triangular diagrams for spring waters, sampled in the Delphi area: ■, 2004 sample; □: 2005 sample. Na^+, K^+, Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrophotometry, HCO_3- by acidimetric titration, and Cl− and $SO_4{}^{2}-$ by ion chromatography. The analytical error for the main components is <3%, whereas that for minor and trace species is <5%. (**c**) $\delta^{13}C(CaCO_3)$ PDB v. calculated $\delta^{13}C(CO_2)$ binary diagram and carbon isotopic values of the travertine deposits. Analytical error for carbon and oxygen isotopic values is 0.05 and 0.10‰, respectively.

can refer to the analysis of Pizzino *et al*. (2004) on the southern border of the Gulf of Corinth (Fig. 1), along the local master faults of the half-graben (Selianitika, Aigion, West and East Heliki faults). This area, about 30 km to the SW of Delphi, can be seen as analogous because it belongs to the same geodynamic environment, so that fluids are driven by similar tectonic structures, and it presents similar rock formations. Moreover, the geochemical investigation carried out by Pizzino *et al*. (2004) was based on a complete analysis of fluids, with similar criteria to those used in the present study. Pizzino *et al*. sampled both naturally discharging fluids and fluids deriving from deeper artesian wells. They found relatively high contents of CO_2, F and NH_4, referred to the upwelling of a Na–HCO_3 aquifer (Selianitika–Rododafni–Nerazes and Trapeza sectors; Pizzino *et al*. 2004), in the deeper fluids. However, no compounds that originated at depth were found in the springs. This suggests the presence of a completely confined deeper aquifer.

Travertine

Travertine deposits are a relevant element for understanding fluid circulation. De Boer *et al*. (2001) inferred these deposits to have derived from hydrothermal fluid circulation at some depth, within the bituminous limestone.

We sampled travertine deposits in the area of Delphi from several locations with respect to the springs and the main tectonic structures (Fig. 5). These deposits belong to three depositional contexts: active precipitation at the free air from circulating waters, active speleothems, and infilling of cracks and fractures in the bedrock. A total of six samples have been studied with optical microscope in thin section (30 μm), and a more detailed petrographic analysis has been carried out on the most representative ones (samples T1/1, T1/2b and T3). The results indicate a phytohermal origin.

The isotopic composition of carbon in travertine provides a helpful indication of the circulation path of the CO_2-rich fluids from which the travertine deposits were formed (Panichi & Tongiorgi 1975; Minissale 2004). To assess either shallow (meteogene) or deep (thermogene) origin of these travertine deposits, the six samples have been isotopically analysed (Fig. 6c). The $\delta^{13}C(CaCO_3)$ values are between −9.3 and −7.5‰ (PDB) (Fig. 6c), and by using the equation of Panichi & Tongiorgi (1975), $\delta^{13}C(CO_2) = 1.2\delta^{13}C(CaCO_3) - 10.5$, it is possible to recalculate the original $\delta^{13}C(CO_2)$ values of the fluids from which these travertine deposits were precipitated. The values obtained are between −21.1 and −19.1‰ (PDB), indicating a clear meteogene origin (Fig. 6c). A deep (hydrothermal) contribution, if present, is negligible. This corroborates the geochemical results for the spring waters analysed, suggesting that the shallow hydrological system is isolated from any system at greater depth.

The $\delta^{13}C(CaCO_3)$ value obtained for the travertine that is being deposited at present at the Kerna spring differs significantly from those obtained by Etiope *et al.* (2006) for a calcite scale (ranging between −15.9 and −18.4‰) from the cliff above the Kerna spring. Etiope *et al.* suggested that calcite from Kerna was derived from oxidation of hydrocarbons, in particular methane and/or thermal destruction of carbonates ($T > 90$ °C; i.e. depth of 1500 m). The great difference between the two analytical data could be due to the fact that the sample of Etiope *et al.* (2006), whose description has not allowed any correlation with our sample, did not belong to the deposit from which our travertine was collected.

CO_2 soil flux and gas geochemistry

In summer 2005, we carried out CO_2 flux measurements by the accumulation chamber method (e.g. Chiodini *et al.* 1998; Cardellini *et al.* 2003) at more than 140 locations, in and around the archaeological site and across the Delphi fault zone (Fig. 7).

The CO_2 flux values measured in the area of Delphi are between 2 and 10 g m^{-2} day^{-1} (Fig. 7), within the range of the normal background flux (1–47 g m^{-2} day^{-1}) ascribed to the common biological activity in any soil (e.g. Cardellini *et al.* 2003). The lack of anomalous values of CO_2 flux from soil has to be considered as strong evidence that, at least at present, this area shows no significant degassing related to a deep source.

To provide further insights into the presence of deep uprising fluids in the Delphi area, soil gases were collected, by using a Stitz probe, from two sites where limited gas emissions were reported in recent times (G1 and G2 in Fig. 5). Fontenrose (1981) claimed that in 1934, before the construction of a tourist hotel, gas emissions were present near the G1 site. Moreover, local people (E. Petrou, pers. comm.) described weak gas venting from an open fissure corresponding to the G2 site, at least until 1960, when the site was excavated to enlarge the local road. The composition of the sampled gases, determined by gas chromatography, corresponds to that of the air. Ethylene and benzene contents are $<0.0001\%$ by volume.

The presence of C_2H_4-rich gas is highly unlikely, as discussed by Etiope *et al.* (2006), as this light hydrocarbon is highly unstable and occurs in natural biogenic gases only in very low amounts. However, CH_4-rich manifestations are relatively common, although the CH_4 anomaly indicated by Etiope *et al.* (2006) refers to (1) a dissolved gas phase for a single sample collected at the Kerna spring, and (2) values of CH_4 soil flux, up to 145 mg m^{-2} day^{-1}, that are in the range of those commonly produced by bacterial activity in soils (0.5–550 mg m^{-2} day^{-1}; Batjes & Bridges 1994; Klusman & Jakel 1998).

Our data provide further indications that the emission of relatively high amounts of ethylene or benzene is very unlikely. This is supported by the relatively low S^{II-} contents in the springs, which clearly indicate the lack of any interaction between circulating fluids and bituminous limestone that would necessary to produce such organic gas compounds. Also, the lack of any geochemical 'anomaly' in springs, soil gases and travertine deposits indicates that, currently, the Delphi active fault system is not a preferential circulation route for thermogenic deep fluids, as is necessary in the 'ethylene' or 'benzene' hypotheses.

Nevertheless, the presence of fluids circulating at depth, characterized by a temperature of 20–21 °C, TDS >1 g l^{-1}, high CO_2 and slight enrichment in H_2S, NH_4 and B, in the southern border of the Corinth Gulf well waters (Pizzino *et al.* 2004), suggests the existence of two aquifers, which are probably also present at Delphi. Any connection (leakage) between these two water reservoirs is at present missing or not recordable. Nevertheless, connection between the two aquifers could be provided by the seismic rupture of the Delphi fault during earthquakes.

Scent of a myth: Plutarch v. Homer

The main positions maintained by modern scholars on the existence of gas exhalation at the oracle site can be summarized as follows: (1) vapours did not occur (e.g. Oppè 1904); (2) they were artificially created (e.g. Holland 1933); (3) they were a geological product (e.g. Farnell 1907).

Despite the relevance of the famous gas exhalation, only two ancient sources provide some indication about their nature: Plutarch (*On the obsolescence of oracles*, early 2nd century AD) and Homer (*Homeric Hymn to Apollo*, *c.* 6th century BC).

Plutarch describes a sweet smell: 'Not often nor regularly, but occasionally and fortuitously, the room in which sits the god's consultants is filled with a fragrance and breeze, as if the adyton were sending forth the essences of the sweetest and most expensive perfumes from a spring' (Plutarch, *De defectu oraculorum*, Plutarch 1936, par. 50). This was taken as conclusive evidence by de Boer *et al.* (2001) and Etiope *et al.* (2006), who proposed sweet-smelling ethylene or benzene, respectively, to be the exhaling gas. However, Plutarch, who lived all his life (*c.* AD 46–127) at Chaeronea, less than 40 km from Delphi, cannot be regarded as a neutral objective source. Plutarch's statements may have been biased by his lifelong devotion to the Sanctuary. Throughout his life he was anxious that the prestige of Delphi should be restored, after the Sanctuary had been looted by Sulla in 86 BC and by Nero in AD 51. He devoted himself to the purpose with an ardour that secured for him the special recognition of being appointed a Delphic priest (Barrow 1967; Scott Littleton 1986). Moreover, Plutarch wrote almost at the end of the oracle's millennary existence, when the sanctuary had already entered the final declining phase before being officially closed at the end of the fourth century. At his time the evidence of exhalation was apparently so weak that its existence was largely questioned by the contemporary philosophers (e.g. Cicero, *On divination*). Plutarch even wrote the *De defectu oraculorum* to provide an explanation for the decline of Greek oracles and in particular of Delphi (par. 38–52). It is in this book that one finds the above-mentioned description of the perfumed scent.

Other statements of Plutarch reveal how he was, in truth, doubtful about the existence of the mantic gas exhalation. One is Plutarch's comment on the traditional account of the discovery of the oracular chasm and its vapours (*De defectu oraculorum*, par. 46): 'unless this is nothing else than a nice fable, as I am inclined to believe'. Another is when he wonders (*De Pythiae*

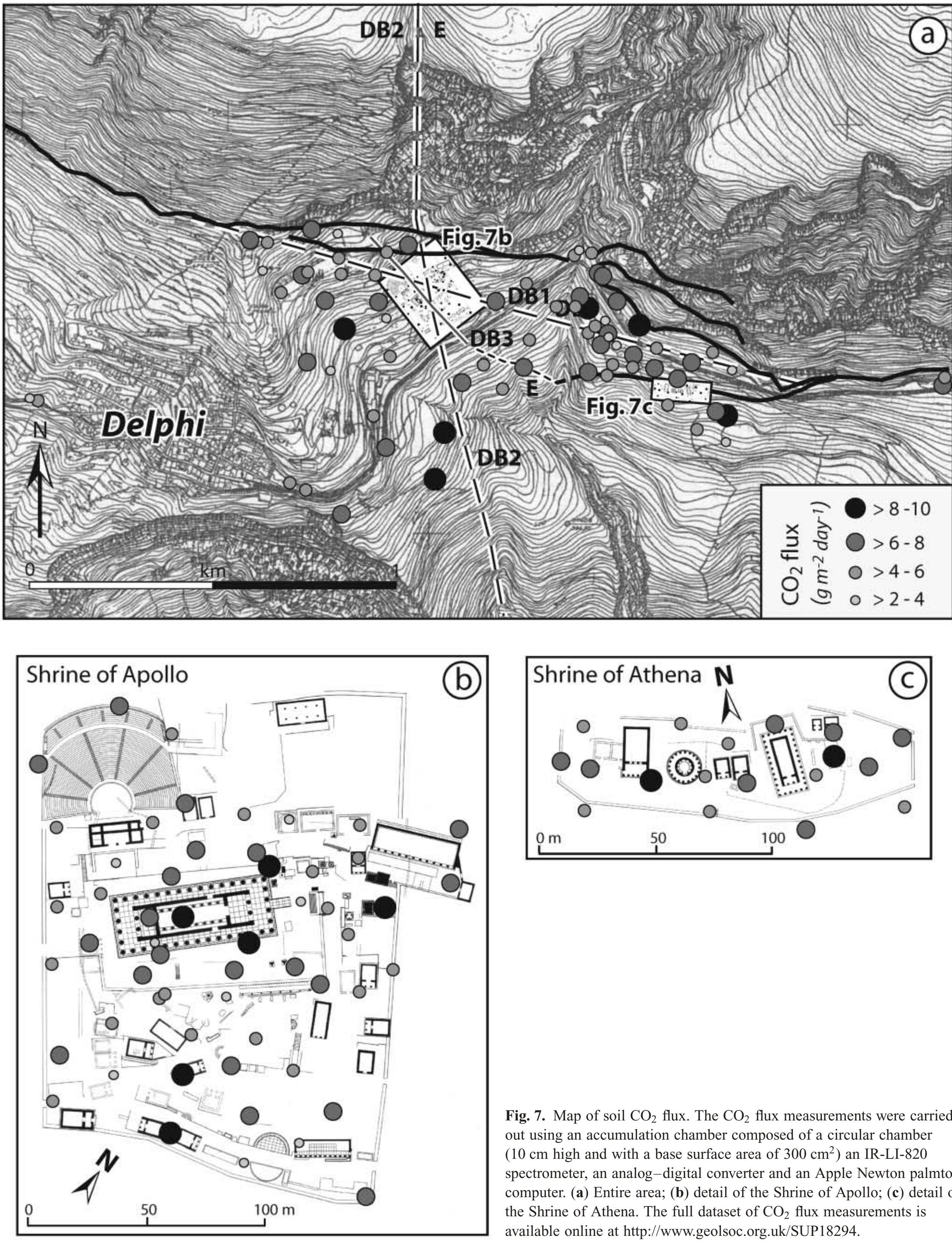


Fig. 7. Map of soil CO_2 flux. The CO_2 flux measurements were carried out using an accumulation chamber composed of a circular chamber (10 cm high and with a base surface area of 300 cm^2) an IR-LI-820 spectrometer, an analog–digital converter and an Apple Newton palmtop computer. (**a**) Entire area; (**b**) detail of the Shrine of Apollo; (**c**) detail of the Shrine of Athena. The full dataset of CO_2 flux measurements is available online at http://www.geolsoc.org.uk/SUP18294.

oraculis, par. 17): 'or the Pythia has no longer access to the place where the divinity is present, or the prophetic exhalation has completely exhausted', a statement that conflicts with the previous firm assertion of the sweet perfume from Apollo's Temple.

A few paragraphs before the statement that the prophetic gas at Delphi was sweet perfumed, we find in the same text Plutarch's description of a most holy hermit living on the shores of the Red Sea (*De defectu oraculorum*, par. 21). He was such a holy person that 'when he talks, the place is filled with a sweetest perfume breathing from his mouth". The use of the sweet smell seems to be a way of underlying the sanctity of the hermit, just as the 'fragrance and breeze' underlines the sanctity of the Oracle.

There are other examples of the poor reliability of some statements of Plutarch, such as the account of the proclamation of freedom of the Greek cities from the Macedonian King Philip (196 BC). He reports that the audience in Corinth shouted so loudly that a flock of crows flying overhead fell to the track killed by the sound (*Vita Flaminini*, 10.3–11): 'A shout of joy followed it, so loud that it was heard as far as the sea.... Crows that were accidentally flying over the course, fell down dead into it.'

A less biased indication can derive instead from Homer. He, together with Hesiod, was the first to have fixed at least part of Greek myths in written form. By that time, myths, going back to prehistory, had already undergone an extremely long process of cultural evolution and transformation. It is, in fact, only slightly later that rationalization started, which resulted in the definition of 'myth' as 'fiction' (e.g. Eliade 1998). The *Homeric Hymn to Apollo* (*c*. 6th century BC) is the earliest written account on the oracle. Here, Apollo is said to have acquired the oracle after having slain the guardian dragon–snake. The dragon was left to rot under the sun.

> 'Whosoever met the dragoness, the day of doom would sweep him away, until the lord Apollo, who deals death from afar, shot a strong arrow at her. Then she, rent with bitter pangs, lay drawing great gasps for breath and rolling about that place. An awful noise swelled up unspeakable as she writhed continually this way and that amid the wood: and so she left her life, breathing it forth in blood. Then Phoebus Apollo boasted over her:
>
> 'Now rot here upon the soil that feeds man! You at least shall live no more to be a fell bane to men who eat the fruit of the all-nourishing earth, and who will bring hither perfect hecatombs. Against cruel death neither Typhoeus shall avail you nor ill-famed Chimera, but here shall the Earth and shining Hyperion make you rot.'
>
> Thus said Phoebus, exulting over her: and darkness covered her eyes. And the holy strength of Helios made her rot away there; wherefore the place is now called Pytho, and men call the lord Apollo by another name, Pythian; because on that spot the power of piercing Helios made the monster rot away'.
>
> (*Hymn to Apollo*, v. 355–374).

Homer's description has the authority of an ancient source directly derived from the first oral tradition, whereas Plutarch's reference to 'the essences of the sweetest and most expensive perfumes' of the mantic exhalation is provided by a single devout individual, and may have been influenced by devotion to the sacredness of the oracle (or may have referred to something different from the original geological exhalation). A source such as Homer (6th–7th century BC), considered the first written source on Greek myths, is more contemporary with the origin of the Delphic myth, which is believed to be as old as the 14th century BC, and had no specific interest in Delphi. In contrast, Plutarch derived his knowledge from books eight centuries later, and dedicated his life to restoring the prestige of the oracle.

The rotting of the snake is the source of the site's original name, Pytho (= rotten). The serpent was said to have lived in the sacred chasm that became her grave, and the mantic vapours derived from her corpse (e.g. Holland 1933; Parke & Wormel 1956; Delcourt 1981). Chasm and vapours were therefore strictly associated, so that, following Homer's description, a repellent smell, characteristic of the presence of H_2S, can be identified with the mantic vapours.

Discussion and conclusions

This study provides an explanation of the origin of the Delphic oracle, which aligns history, archaeology, mythology and geology.

We believe, in accord with most of the Classical scholars studying Delphic history, that both 'gas exhalation' and 'chasm' had no physical geological reality during the time of the main functioning of the sanctuary (7th century BC–4th century AD). However, they were not merely a literary or mythological invention. We infer that they both were true physical elements connected with earthquake faulting by the time of the establishment of Delphic myths.

Our geochemical investigation shows that, at present, there are no sites of anomalous gas release in the area of Delphi. Nevertheless, the mythological gas-exhaling oracular chasm can be explained as an ancient seismic ground rupture, that existed episodically and for a limited time. When the fault ruptures, gases stored in the deep-seated aquifer and accumulated in underground pockets can rise to the surface. This is a common process that mainly involves CO_2–H_2S-rich gases (frequently associated with methane and radon). The place name Pytho, and its association with the smell of the rotting snake–dragon, supports the sulphurous nature of the mantic exhalation. The CO_2–H_2S-rich gas discharges from the sacred chasm can also explain the psychoactive effects. Medical investigations indicate that CO_2 has an impact on the human brain at concentrations of about 10 000–15 000 ppm by volume, causing dizziness, confusion, and hearing and visual dysfunctions (e.g. Gellhorn 1936; Sechzer *et al*. 1960).

High concentrations of ethylene, as hypothesized by de Boer *et al*. (2001), are thermodynamically impossible and are unrealistic in non-volcanic areas and in CO_2- and/or S-poor gas emissions (e.g. Capaccioni *et al*. 1993; Etiope *et al*. 2006). Also, the presence of methane-rich emissions (Etiope *et al*. 2006) is not likely to be at the origin of Delphic myths. Methane usually ignites in natural conditions. Such inextinguishable flames would have been noted and recorded in myth, as is the case for many geomyths related to places of methane emissions, which all make direct reference to fire (e.g. the myth of Chimaera, in Turkey), which is not the case at Delphi.

Our interpretation explains the mythological association of vapours, chasm and earthquakes, and fits with the opening of seismic ruptures at Delphi described in past legends (e.g. Pausanias, *Description of Greece*, 10.5.12) and historical time (e.g. Pavlides & Caputo 2004, and references therein). The chasm and exhalation may have existed only for a limited time in the ancient past, when the sacredness of the site was first established, and eventually closed. It started the myth that remained associated with the local sanctuary for almost two millennia. Later, its memory would have remained in the myth, its reality being forgotten up to the present day. The real geological origin of the Delphic Oracle had probably been forgotten at least since the 7th century BC, when the fame of Apollo's Oracle was at its climax. The case history of the Lernean Hydra (Piccardi 2004) similarly shows how, in prehistoric time, the original meaning of a real story or of a physical object can be completely forgotten in a few hundred years (2300–1800 BC), and the memory survives only as myth.

As a result of the low slip rate of the Delphi fault, the interval between successive ruptures may be long, favouring sealing processes that impeded fluid circulation. It is not unlikely that the chasm, accompanied by gas exhalations, would have become part of the Delphic myth also if its occurrence was only during the transient moments of comparatively infrequent earthquake ruptures. There are many examples in which such sudden and impressive events as volcanic eruptions, cosmic impact and earthquakes have started myths that lasted for many centuries (see Vitaliano 1973; Bentor 1989; Piccardi 2005; Piccardi & Masse 2007, for more detailed case histories).

The chasm, and not the vapours, was probably the main kernel of the Delphic myths, as in many similar ancient sacred places in the Eastern Mediterranean (Piccardi 2001). The word 'Delphi' itself (Gr. = uterus or womb) mirrors the word 'stomion' (Gr. = vagina or/and mouth), which was commonly used to indicate the sacred chasm of Delphi, reflecting the double meaning of womb of Mother Earth (recalling the famous omphalos–navel stone), and her prophetic mouth. The exhaling gas, a phenomenon still episodically present, remained associated with the myth and acquired importance in later traditions. The putrid odour of a rotting giant snake is associated with the place and its myths by the most ancient literary source, Homer, and by the oldest place name, Pytho, thus providing a double indication. This repellent smell is far from the sweet 'fragrance and breeze' described by Plutarch.

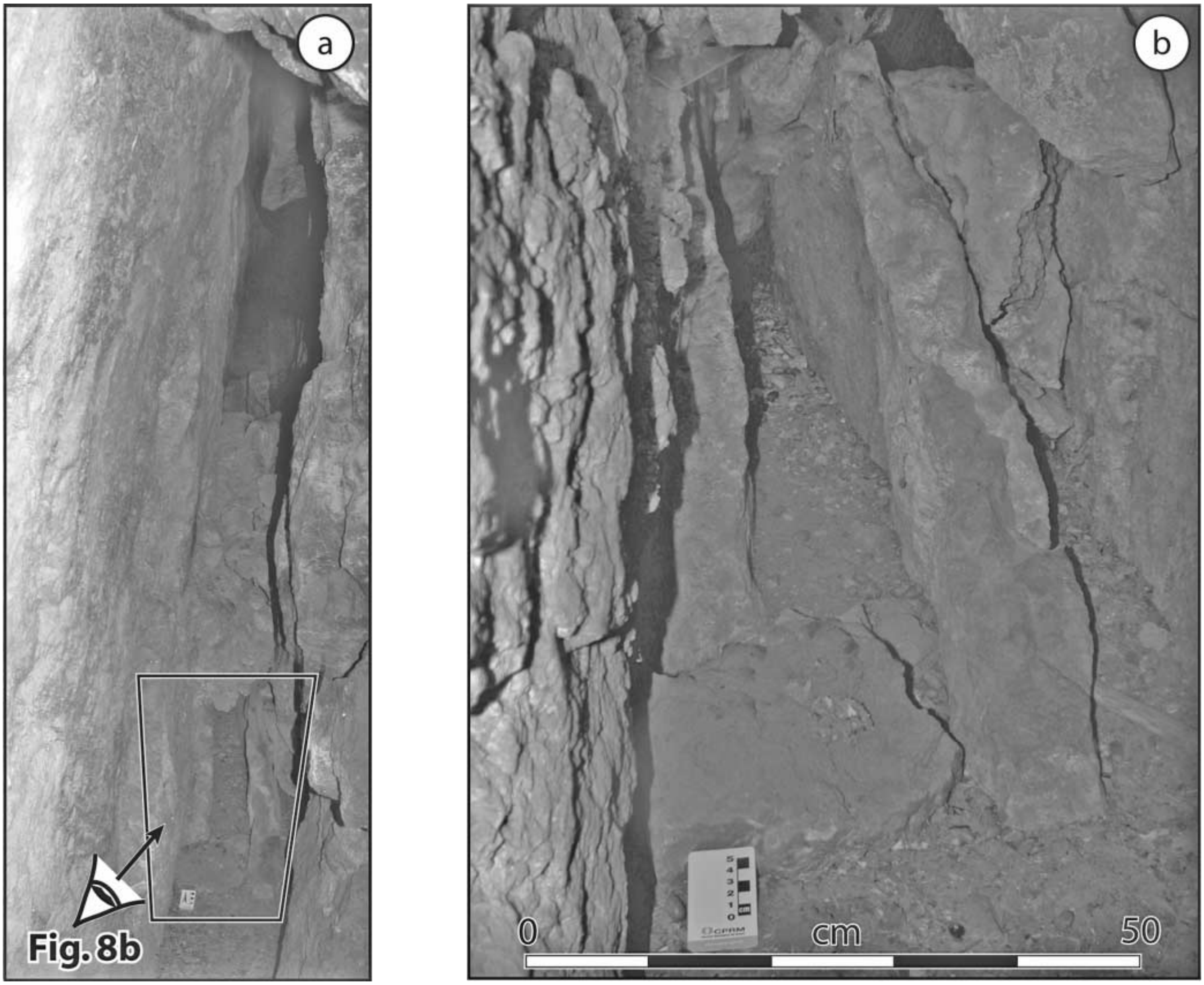


Fig. 8. (**a**) Detail of Figure 3e. Open cleft within the anastomosing main fault zone. (**b**) Detail of (**a**), showing a further open fissure within the larger one.

The exact location of the original sacred chasm is difficult to pin down, mostly because the origin of this sacred place is rooted in prehistory, and also because it is possible that, in time, the location of gas emissions may have migrated as a result of local tectonic activity and/or self-sealing effects. A shift in the position of the main cult site would find analogies in other famous sanctuaries that lasted thousands of years (e.g. Piccardi 2001, 2005). The Delphic Sanctuary had, in time, three main poles of attraction: Apollo's Temple, Athena's Temple and the Castalia Spring. All three positions may have possibly hosted the sacred chasm. For instance, just a few metres east of Castalia, the outcrop of the main Delphi fault zone provides a good example of a possible natural open chasm (Fig. 3e). Surely such a cave, formed directly within the core of the main seismic fault (Fig. 8a and b), must have been the seat of unusual natural phenomena, in particular during earthquakes. One cannot rule out the possibility that, in time, a secondary rupture or episodic emissions of gas might have occurred also at Apollo's Temple, as inferred by de Boer & Hale (2000) and de Boer *et al*. (2001). However, many indications point to the Shrine of Athena as the most likely original sacred site.

The positioning of the original sacred chasm in the Shrine of Athena (Piccardi 2000; Fig. 4) fits with the finding below Athena's Temple of many clay statuettes of a woman or goddess seated on a tripod. Archaeological data (e.g. Bommelaer 1991) indicate it as the most ancient sacred site of the area, originally dedicated to a female goddess related to the childbirth: the ancient cult site of Ge, Mother Earth.

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