The Geological Origins of the Oracle at Delphi, Greece[1]

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Ancient authors from Plato to Pausanias have left descriptions of Delphi's oracle and its mantic sessions. The latter were interpreted as events in which the Pythia (priestess) placed herself on a tripod over a cleft (fissure) in the ground below the Apollo temple. Here she inhaled a vapour rising from the cleft, and became inspired with the power of prophecy. French archaeologists who excavated the oracle site at the turn of the century reported no evidence of either fissures or gaseous emissions and concluded that the ancient accounts were myths. As a result, modern classical scholars and many archaeologists reject the ancient testimonies concerning the mantic sessions and their geological origin.

However, the geological conditions at the oracle site do not a priori *exclude the early accounts. A major WNW-ESE fault zone and a minor swarm of NNW-SSE fractures intersect below the site. These intersection(s) provided pathways for rising ground water, including a spring below the Apollo temple.*

The faults broke through a bituminous limestone formation at relatively shallow depth. Hydrocarbon gases that originated in this formation may have escaped during and after seismo-tectonic events. Such gases can induce mild narcotic effects. It is highly probable therefore that the Pythia's inspiration resulted from the inhalation of light hydrocarbon gases, which rose along a fissure (fracture) in the adyton below the Apollo temple.

The ancient Greeks believed that the power of the Delphic oracle derived from the geological setting of the sanctuary. According to a number of Greek and Roman authorities, the women who spoke the prophecies at Delphi sat on a tripod that spanned a cleft or fissure in the rock within the temple of Apollo. Vapours rose from this chasm into the inner sanctum or *adyton,* where they intoxicated the priestess and inspired her prophecies. The ancient testimonies have been challenged during the past half-century, as modern archaeologists failed to locate any cleft or source of vapours within the foundations of the ruined temple and therefore concluded that the ancient sources must have been in error. However, a recent geological study of the sanctuary and adjacent areas has shown that the preconditions for the emission of intoxicating fumes are indeed present at Delphi. These findings suggest that Greek and Roman texts may preserve an accurate record of ancient geological events and phenomena.

Bronze Age Greeks established a religious centre at Delphi in central Greece before 1200 BC, but the famous oracle can be traced back with certainty only as far as the eighth century BC. Tradition named Gaia (Earth) followed by Poseidon (Earthshaker) as gods originally worshipped at Delphi, but they were succeeded by Apollo, god of prophecy (Parke 1956). The oracle of Apollo at Delphi became the most prestigious in the Mediterranean. Gifts from those who consulted the oracle made the mountain village of Delphi one of the richest sites in

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Greece. Down to the end of the fifth century BC the oracle was consulted before new colonies were founded, wars were declared, or changes of government were made.

The woman who served as prophet, known as the Pythia, held her mantic or prophetic sessions only nine times during the year, on the seventh day after each new moon except during the cold, rainy months of winter. The historian Diodorus of Sicily (c. 90–20 BC) recorded a local legend that attributed the discovery of the Delphic chasm to goats grazing on the limestone slopes before the site was settled: "The herdsman in charge of the goats marvelled at the strange phenomenon and having approached the chasm and peeped down it to discover what it was, had the same experience as the goats, for the goats began to act like beings possessed and the goat-herd also began to foretell future events. After this as the report spread among the people of the vicinity concerning the experience of those who approached the chasm, an increasing number of persons visited the place and, as they all tested it because of its miraculous character, whosoever approached the spot became inspired. For these reasons the oracle came to be regarded as a marvel and to be considered the prophecy-giving shrine of Earth." (Diodorus Siculus 1952)

The geographer Strabo (c. 64 BC-AD 25) also wrote a description of the oracle that was instituted at Delphi, and the geological conditions associated with it: "They say that the seat of the oracle is a cave that is hollowed out deep down in the earth, with a rather narrow mouth, from which arises breath (pneuma) that inspires a divine frenzy; and that over the mouth is placed a high tripod, mounting which the pythian priestess receives the breath and then utters oracles in both verse and prose." (Strabo 1927)

Many other writers referred to the chasm and vapour, including Cicero and Pliny the Elder. One source added an additional element to the geological background of the Apollo temple and its surroundings: "They say that the water of Cassotis spring plunges underground and in the adyton (inner sanctum) makes the women prophetic." (Pausanias 1935) Pausanias was a travel writer and religious scholar of the second century AD, who described the site and the monuments of Delphi, including the Cassotis spring on the slope above the temple of Apollo. The tradition of a cavern or narrow cave-mouth linked to the oracle of Apollo goes back much earlier, however, to the poets Pindar and Aeschylus in the fifth century BC. Even the philosopher Plato (c. 429–347 BC) made a cryptic reference to "the rock" as the source of prophetic power at Delphi: "It was when they were mad that the prophetess at Delphi and the priestesses at Dodona achieved so much for which both states and individuals in Greece are thankful; when sane they did little or nothing . . . . The authorities of the temple of Zeus at Dodona say that the first prophetic utterances came from an oak tree. In fact the people of those days were content in their simplicity to listen to the oak tree and the rock, provided these spoke the truth." (Plato 1989)

The most valuable ancient source on the Delphic oracle is the Greek philosopher and essayist Plutarch (c. AD 50-120), who actually served at one time as priest of Apollo in the temple at Delphi. Plutarch was thus not only an eyewitness of the Pythia's performance, but also an insider familiar with the oracle's operations and traditions. The story of the goatherd discovering the chasm was known to him, and he actually cites the name of the man involved, a certain Koretas. Plutarch also knew that the Pythia drank water from the spring before each prophetic session.

Shortly before Plutarch arrived at Delphi an extraordinary incident had occurred, which was reported to him by the temple officials. Plutarch relates the story to make the point that the mind of the prophet must be in a receptive state for the vapour (*pneuma*) to have its proper effect.

A deputation from abroad had arrived at Delphi to consult the oracle, and the priests in their eagerness to please these visitors ignored the ill omens and compelled the Pythia to prophesy: "She went down into the oracle unwillingly, they say, and half-heartedly; and at her first responses it was at once plain from the harshness of her voice that she was not responding properly; she was like a labouring ship and was filled with a mighty and baleful spirit. Finally she became hysterical and with a frightful shriek rushed towards the exit and threw herself down, with the result that not only the members of the deputation fled, but also the oracle-interpreter Nicander and those holy men that were present. However, after a little, they went in and took her up, still conscious; and she lived on for a few days." (Plutarch 1936)

In old age, Plutarch wrote an essay known as *De defectu oraculorum* (On the obsolescence of the oracles) in which he speculates on the reasons for the weakening of the prophetic power at Delphi. His explanation is expressed in almost purely physical and geological terms. First, he considers how veins of silver, copper and asbestos may disappear when they have been exhausted through mining operations. Then he suggests that this disappearance may serve as an analogy for the disappearance of the vapour: "Plainly the same sober opinion is to be held regarding the spirits (*pneumata*) that inspire prophecy; the power that they possess is not everlasting and ageless, but is subject to changes. For excessive rains most likely extinguish them, and they probably are dispersed by thunderbolts, and especially, when the earth is shaken beneath by an earthquake and suffers subsidence and ruinous confusion in its depths, the exhalations shift their site or find completely blind outlets, as in this place [Delphi] they say that there are still traces of that great earthquake which overthrew the city." (Plutarch 1936)

In spite of these changes, Plutarch had himself experienced an unusual phenomenon in the adyton of the Apollo temple, which he offered as evidence that the exhalations still emerged at the site of the oracle although they fluctuated in intensity: "I think, then, that the exhalation is not in the same state all the time, but that it has recurrent periods of weakness and strength. Of the proof on which I depend I have as witnesses many foreigners and all the officials and servants at the shrine. It is a fact that the room in which they seat those who would consult the god is filled, not frequently or with any regularity, but as it may chance from time to time, with a delightful fragrance coming on a current of air which bears it towards the worshippers, as if its source were in the holy of holies (adyton)." (Plutarch, *Moralia* 1936).

Not one ancient source denied the existence of the chasm and vapour at Delphi, and thanks to Plutarch the statements of those writers who had not actually visited Delphi themselves are supported by the first-hand evidence of an important official within the temple hierarchy. Yet the ancient testimony concerning the geological origins of the Delphic oracle has been almost universally rejected by modern classical scholars and archaeologists. One influential monograph on Delphi states that "geologically it is quite impossible at Delphi where the limestone and schist could not have emitted a gas with any intoxicating properties." (Parke & Wormell 1956, 22). Another declares that "a close study of all reliable evidence for Delphic mantic procedures reveals no chasm or vapors, no frenzy of the Pythia, no incoherent cries interpreted by priests" (Fontenrose 1978, 10); an opinion echoed by Morgan (1990) and Maass (1993).

The primary source of the current scholarly opinions is a book on Delphic prophetic procedure by Amandry (1950), who cited the failure of archaeologists to discover a chasm under the Apollo temple. In addition, from a geological standpoint, he noted that the area around Delphi was not volcanic, and declared that it was therefore incapable of producing mephitic vapours (Amandry 1950, 196–230). This

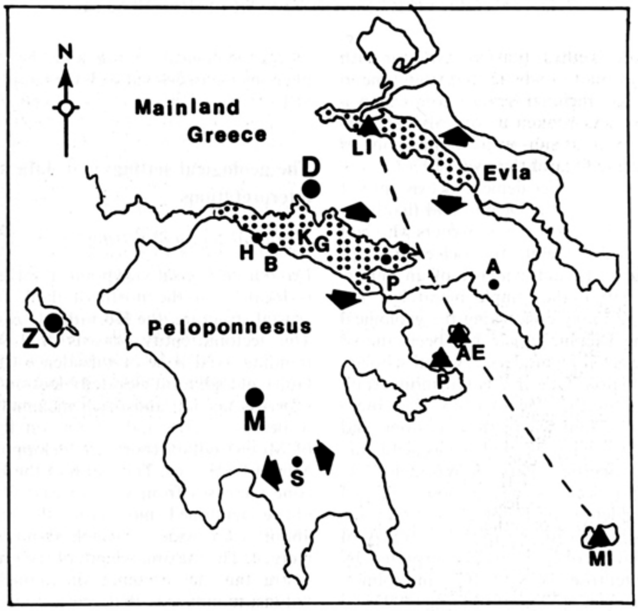

Fig. 1. Central Greece, with the Korinth (KG) and Evian Gulfs (riftsystems). (A) Athens; (AE) Aegina volcanic complex; (B) Boura; (D) Delphi; (H) Helice: (Li) Likades volcanic complex; (M) Megalopolis: (Mi) Milos volcanic complex; (P) Perachora peninsula: (Po) Poros volcanic complex; (S) Sparta; (Z) Zakinthos island. Arrows indicate principal directions of crustal extension.

negative view gained widespread acceptance. despite the fact that the French excavators had not actually reached bedrock under the foundations of the temple (Darcque 1991, 689–690). Amandry also failed to consider the possibility of non-volcanic sources of vapours. A recent geological study of a temple of Apollo in Turkey has reopened the question of the credibility of ancient writers such as Strabo and Pausanias. In examining the site of an ancient temple at Hierapolis (Pamukkale). a US team was able to demonstrate that Strabo's description of a chasm filled with misty, toxic vapour was in fact accurate in every detail (Cross & Aaronson 1988). The deadly vapour at the Hierapolis temple of Apollo was identified as carbon dioxide along with a fine aerosol of water from a hot spring. In view of the positive correlation established in this case between modern geological findings and the account of the ancient Greek geographer Strabo, who also reported the presence of a chasm and vapour at Delphi, it seemed worthwhile to undertake a fresh study of the geological setting and the geophysical phenomena associated with the temple of Apollo at Delphi.

The Geological Setting: New Data and Interpretations

Regional Tectonic Setting

From a geological viewpoint, the Delphi oracle is located on the northern flank of a major crustal structure, the Korinth rift zone (Fig. 1). This tectonic entity consists of a WNW-ESE trending axial zone of subsidence (the Korinth Gulf) and adjacent elevated blocks which rise in staircase fashion and reach maximal heights of respectively 2378 and 2458 m on the summits of Mount Killini (northern Pelopponesos) and Mount Parnassos. The width of the Korinth rift zone increases from west to east. Between the above-mentioned mountains the rift zone is about 70 km wide, of which about half is submerged. The maximal depth of the Gulf is about 400 m but the presence of a thick layer of sediments indicates that the crustal blocks underlying these relatively recently accumulated deposits sank to considerably deeper levels.

The rift zone's topography is mainly the result of crustal extension in a NNE–SSW direction (Fig. 1). Application of these forces led to crustal thinning, which was followed by regional arching, axial subsidence and pervasive fracturing. The majority of fractures trend WNW–ESE. Those in the northern

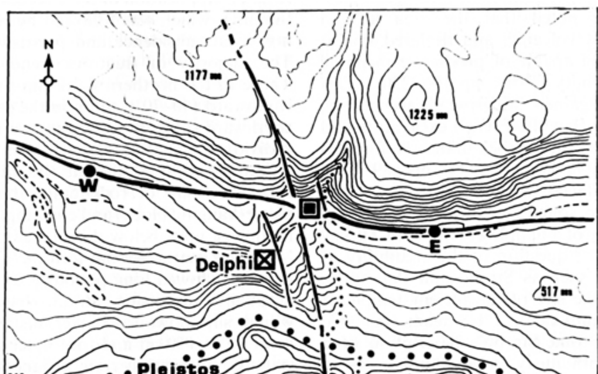

Fig. 2. Topography of the Delphi region and principal tectonic elements (W) western and (E) eastern exposures of Delphi faultzone. Dots indicate principal course of Pleistos river.

flank dip predominantly southward (40-70°); those in the southern flank northward (40-70°), forming conjugate sets. Individual fault lengths vary from about 10 to 40 km. Motion along the fractures involved downward slip of rock units above the fault plane (hanging block) and contemporary upward motion of units below this plane (foot block).

During major seismo-tectonic events. which usually followed long periods (50-150 years) of gradually increasing strain, hanging blocks would slip downward over distances varying from 50 to 150 cm and foot blocks rose by isostatic compensation over distances of 5-15 cm (Jackson et al. 1982). Energy released during such tectonic events caused both earthquakes and frictional heating of rock units adjacent to the fault.

The geological process that gave rise to the Korinth rift zone is believed to have been initiated in early Pliocene time (c. 5 Ma ago). In preceding geological times a crustal mass that used to be a huge submarine limestone plateau was thrust westward (and up) out of the subtropical waters of the Tethys (palaeo-Mediterranean sea) in which it had slowly accumulated. About 5 Ma years ago regional stress fields changed and this mass was broken up into long crustal slivers, which moved sub-vertically with respect to each other and formed the Evian and Korinth rift zones.

Stratigraphy

One of the most detailed geological studies of the oracle site and adjacent mountains was carried out by Birot (1959). Five years later Aronis & Panayotides (1964) published the geological map of the Delphi Quadrangle. More recently, an excellent geological analysis of the Delphi region was published by Pechoux (1992).

Aronis & Panayotides concluded that the basic geological stratigraphy of the Delphi region is relatively simple. The oldest (and lowermost) rock unit is composed of rather massive (locally bedded), white, microcrystalline limestones of Tithonian to

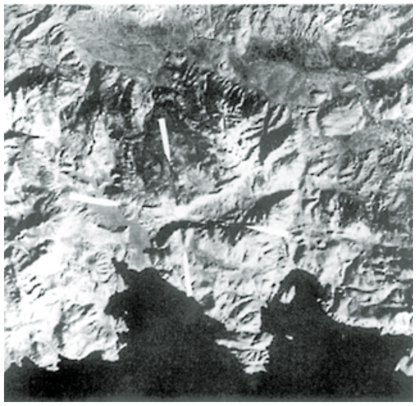

Fig. 3. Satellite photo of Delphi region. Arrows indicate trends of principal tectonic lineaments.

Cenomanian age (152–90 Ma). This up to 400 m thick unit is overlain by rather compact and microcrystalline limestones of Senonian to Turonian age (90–84 Ma). Limestones in the lower part of this 80–100 m thick unit are bituminous. Locally, the bituminous content of this unit can reach 20% (Aronis & Panayotides 1964). The limestone plateau, to which these Mesozoic formations once belonged, stretched from Iran to Italy. Bituminous units provided much of the oil found now in structural traps throughout the Near East and Arabia.

Overlying these limestone formations is a sedimentary unit of Paleocene age (66–58 Ma), which is composed of reddish brown and yellowish brown shales, sandstone and conglomerates (cumulatively referred to as flysch). These terrigenous deposits, which reflect regional uplift and erosion, are found mainly in valleys such as that of the Pleistos river.

Local Tectonic Setting

The topography of the Delphi region *sensu lato* is shown in Fig. 2. Two tectonic lineaments stand out: WNW–ESE and NNW–SSE trending fault zones, which intersect below the oracle site. These lineaments also clearly show on the satellite image (Fig. 3). The image further shows several WNW–ESE trending fault zones intersecting the Pangalos peninsula, reflecting a downward (to the Gulf) stepping series of parallel faults.

Fig. 4a. Exposure of curvilinear Delphi fault west of Delphi.

Fig. 4b. Exposure of curvilinear Delphi fault east of Delphi. Note abrupt discontinuation of Pleistocene and Holocene sediments against faultplane.

fault zone (Fig. 2). Because of an increase in the tilt angle of some flysch layers near the fault zone, Birot (1959) assumed this fault to dip northward in the area of the oracle. However, the phenomenon he observed is due to reverse drag along a listric (curved) fault zone that clearly dips southward. Pechoux (1992) showed this southward dipping fault on all his cross-sections and in addition found evidence that the fault intersects most if not all glacial and inter-glacial Pleistocene deposits. Our study supports Pechoux's observations

WNW–ESE fault: evidence and interpretation. The oracle site is located on or in limestone debris that has accumulated predominantly in the last million years (the Pleistocene period) at the foot of the Phaedriades cliffs, and on yellowish brown shales of the flysch formation.

The latter Paleogene deposits lie in contact with the much older Tithonian-Cenomanian limestone formation, which dominates the cliffs behind (to the north of) the oracle. Such juxtaposition of younger and older geological formations is possible only if the former moved down and/or the latter rose with respect to the other. This motion occurred along a major WNW–ESE trending fracture referred to as the Delphi

and indicates that the eastern segment of the Delphi fault zone experienced down-dip slip motion after deposition of the most recent (Würm) glacial deposits and overlying soils. This indicates that the fault zone should be classified as active, and it is at present in repose.

The Delphi fault zone is well exposed both to the east (1.5 km) and west (2.5 km) of the oracle site (Fig. 4a and b). Fault scarps can be traced virtually to the oracle's borders, where the fault zone disappears below debris from the Phaedriades and the oracle's ruins. The exposed fault segments are curvilinear, which is characteristic for most normal faults intersecting limestone formations in central Greece (de Boer 1992).

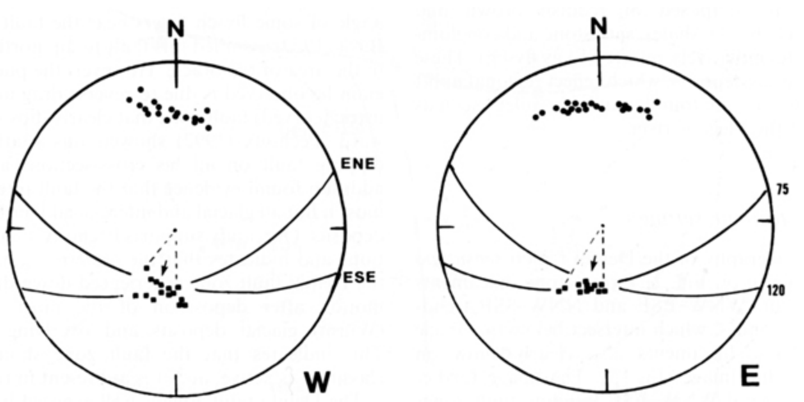

Fig. 5. Sterographic plots of western (W) and eastern (E) exposures of Delphi fault. Dots represent lower hemisphere plots of normals to faultplane segments. Squares indicate slip directions. Curved lines are plots of faultplane segments with maximal variation from common trend.

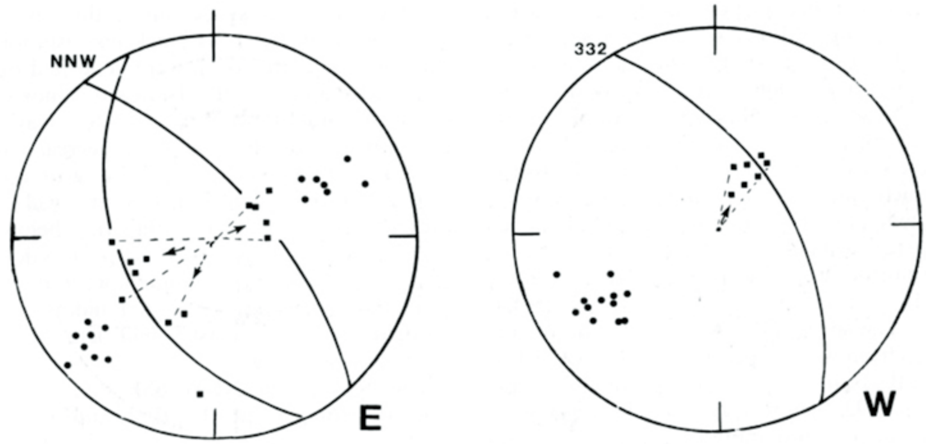

Fig. 6. Stereographic plot of NW trending fracture in limestone in eastern (E) and western (W) part of oracle site. Dots represent lower hemisphere plots of normals to the fractures. Squares indicate slip directions. Curved lines are plots of mean fault planes.

Figure 5 shows a plot of normals to different fault-plane segments and their variable trends.

Also shown are the slip directions of the latest (youngest) tectonic event along the fault segments. It is obvious that fault attitudes and slip directions are identical and that the fault segments exposed east and west of the oracle site form part of a single through-going fault zone. Cumulative dip-slip along the Delphi fault is estimated to amount to several hundred metres (Pleistos block down and Phaedriades block up), and to have occurred by relatively small (50-150 cm) offsets over millions of years.

NNW–SSE faults: evidence and interpretation. During fieldwork in 1981, de Boer noticed the presence of a major NNW–SSE fault zone in the limestone plateau south of the Pleistos valley (Figs 2 and 3). Upon crossing the latter valley the fault appears to splay into several NNW–SSE trending faults that intersect the oracle site. Birot (1959) mapped two of these faults along the eastern and western boundaries of the oracle site *sensu lato.* The most important in this fault swarm follows the Delphusa stream.

Figure 6 shows a plot of NNW–SSE faults (attitudes and slip directions) that intersect the limestone cliffs at the oracle site. The faults clearly form conjugate sets, dipping both ENE and WSW. Their slip directions indicate downward motion of the hanging blocks. Such fault sets result from ENE–WSW crustal extension (de Boer 1992). Evidence for their age is sparse. They do not clearly intersect glacial and post-glacial deposits as does the Delphi fault. However, an interesting offset occurs in the northwestern stand of the Stadium (F, in Fig. 7). The northeastern segment of its foot wall has moved about 14 cm downward and 40 cm southward with respect to its southwestern section. Shear fractures in the stone building blocks close to this offset trend NNW–SSE and dip predominantly ENE. Such deformation could have been caused by rather localized oblique slip along a buried NNW–SSE fault and suggests a young age.

The best information concerning the age of the NNW–SSE faults, however, is provided by seismo-tectonic events elsewhere. Sparta was destroyed in 464 BC by earthquakes related to dip-slip along a NNW–SSE trending fault separating this town from the Taygetos Range, and recently (1986) Kalamata was severely damaged by quakes originating along a NNW–SSE fault on the west side of the Taygetos mountains (Fig. 1). The tectonic forces responsible for such faulting are extensional and trend ENE–WSW. The NNW–SSE faults therefore should also be considered active although at present in dormant state.

Present-day crustal extension in a NNE–SSW direction dominates from the northern Pelopponesos northward, but ENE–WSW crustal extension predominates in the southern Pelopponesos (de Boer 1992). Delphi is located in a crustal zone where NNE–SSW crustal extension predominates. The ENE–WSW extensional stress, however, is present but plays a minor role and is responsible for dip-slip along NNW–SSE fractures.

Presence of Springs

The tectonic data show that the Delphi oracle site is located at the intersection of a major WNW–ESE, southward dipping fault zone and a swarm of minor NNW–SSE trending, predominantly east dipping fractures.

Intersections of "young" faults provide sub-vertical pathways through which ground water and/or gases can rise to the surface. Although little water surfaces at present at the oracle site, natural and anthropogenic evidence exists for at least six springs (Muller 1992). Their sites occur in two groups (Fig. 7). The three springs in the eastern group are aligned in a NW–SE direction. A fourth spring located below the Apollo temple (Hansen 1992) plots on the same alignment.

These springs are, from NW to SE, the Kerna (1), which emerges from below a large mass of cemented limestone fragments; an unnamed spring (2), which must have fed the spring house northeast of the theatre; and the well of the Muses (3), directly south of the Apollo temple. The spring (4) below the Apollo temple emerges from what appears to be bedrock below the southeastern terrace of the Apollo temple (Hansen 1992, section 4) (Fig. 8). This spring, or a spring in close proximity to it, probably represents

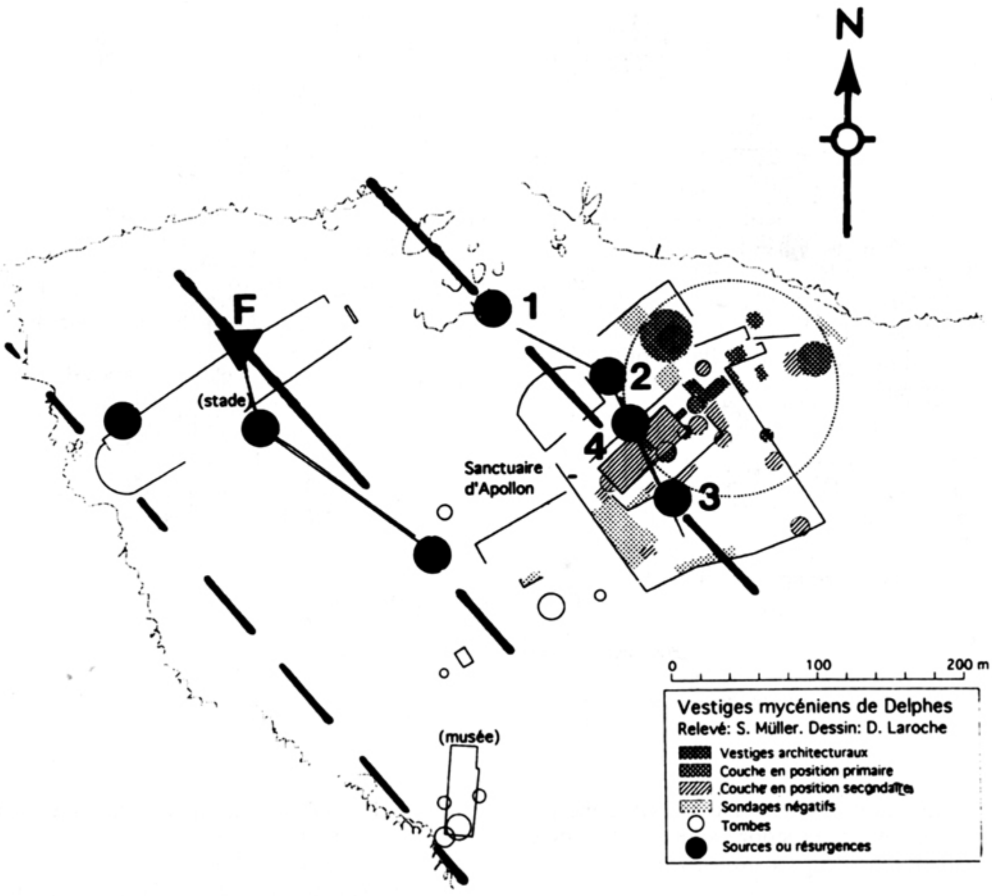

Fig. 7. Location of springs on the oracle site from Muller (1992). (1) Kerna spring; (2) unnamed spring house; (3) the well of the Muses; (4) location of thick travertine crusts on Iskhegaon wall (see Fig. 9). (F) Site of offset in stadium wall. Full lines, possible extent of NW (NNW) faults.

the (original) Cassotis well from which the Pythia drank before her mantic sessions. Additional evidence for the emergence of significant volumes of ground water along this lineament is provided by relatively thick encrustations of travertine (Fig. 9), which were deposited on the massive retaining wall (Iskhegaon) northwest of the Apollo temple (Fig. 8). These travertine crusts are clearly the result of a decrease in the solubility of calcium during cooling of ground waters, which splashed across the wall when earlier outlets further downhill (i.e. below the temple) were blocked. (This travertine deposit, which formed *in situ,* should not be confused with the travertine *[poros]* building blocks brought from the Kastri mill site near the Kephalovrisi spring.)

The presence of NNW–SSE faults and the NW–SE arrangement of springs and/or sites of ground-water emergence is too coincidental to be ignored. The waters of these springs probably accumulated on the plateau of Livadi, drained through fractures in the Phaedriades limestone massif, accumulated in the Delphi fault zone and rose along its intersection with a NNW–SSE fault, following this structure downhill.

Possible Presence of Gases in Spring Water(s)

Could gases have risen with the waters of the springs surfacing on the oracle site? Previous researchers are correct in stating that Delphi is not located in a volcanic region, hence no volcanic gases would or could be expected to have risen below the temple (Fig. 1). However, faults provide pathways for gases in both volcanic and non-volcanic regions. Dominant among the gases that surface in the eastern Mediterranean and Near East are carbon oxides and hydrocarbons.

The limestones below the oracle site contained (and possibly still hold) hydrocarbon gases, which formed during burial and diagenesis of its biogenic constituents. It is reasonable to assume that

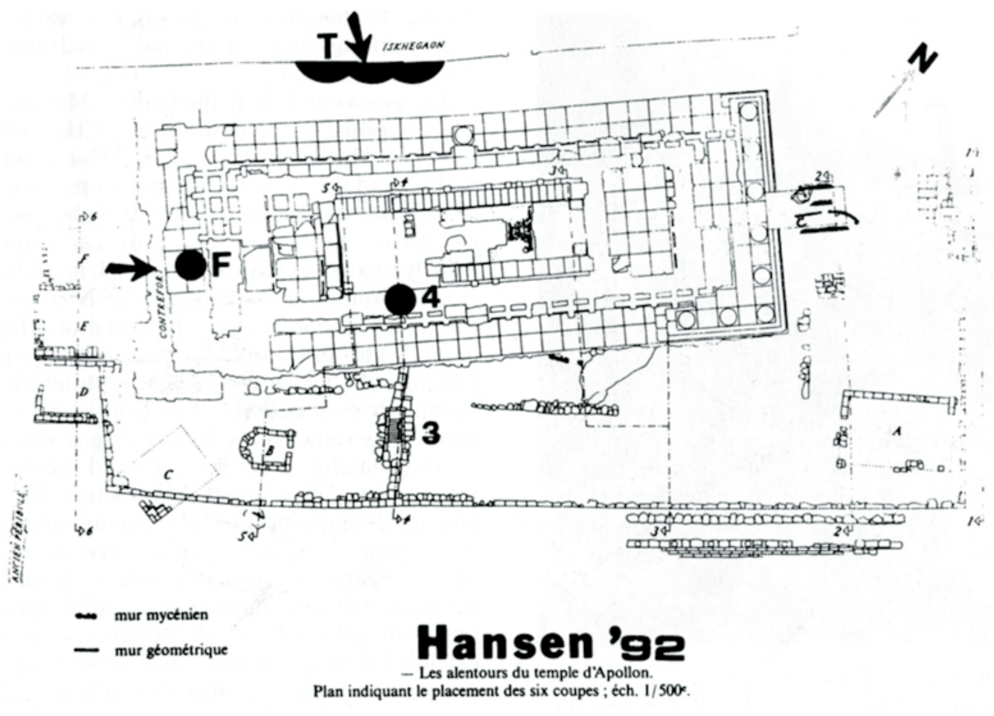

Fig. 8. Apollo temple by Hansen (1992). (3) The well of the Muses; (4) spring below temple. (F) Fractures in temple floor limestone blocks (see Fig. 10), and direction of responsible stress (arrow).

Fig. 9. Travertine deposits on lskhegaon wall. Note stalagtites and limestone block lodged in travertine after its décollement.

these gases rose along fault zones, especially in periods after seismic and tectonic agitation.

Oil and gas seeps along faults are common in the Near East, but also in the eastern Mediterranean and Greece. Tar pits occur on the Greek island of Zakinthos and in the Peloponnesos (Megalopolis) (Fig. 1).

Herodotus (c. 485-425 BC) wrote: "I myself have seen something similar in Zacynthus, where pitch is fetched up from the water in a lake. There are a number of lakes—or ponds—in Zacynthus, of which the largest measures seventy feet each way and has a depth of two fathoms. The process is to tie a branch of myrtle on to the end of a pole, which is thrust down to the bottom of this pond; the pitch sticks to the myrtle, and is thus brought to the surface. It smells like bitumen, but in all other respects it is better than the pitch of Pieria. It is then poured into a trench near the pond, and when a good quantity has been collected, it is removed from the trench and transferred to jars. Anything that falls into this pond, passes underground and comes up again in the sea, a good half mile distant." (Herodotus 1954)

If oil and hydrocarbon gases emerged along NNW–SSE trending fault zones on Zakinthos (and near Megalopolis) the same phenomena could have occurred in Delphi, given the similarities in geological stratigraphies and structure.

To understand what gases could have risen from the bituminous limestone below the oracle site, reference should be made to active gas seeps in the Gulf of Mexico. These gases originated in bituminous limestones and rose along faults in the form of gas hydrates. The geological and tectonic setting in this region is thus similar to that in Delphi except that the emissions occur at shallow depths below sea level.

Gas hydrate concentrations in the Gulf of Mexico act as a kind of pressure relief system, alternately checking and releasing the flow of hydrocarbons along localized vents (MacDonald et al. 1994). The accumulated volumes escape when the plug of gas hydrate either dislodges because of excess buoyant force or disassociates because the water temperature rises above the limit of hydrate stability (MacDonald et al. 1994). Seismic activity would or could trigger the former activity.

Gas release from a vent studied in detail was intermittent, and occurred only during periods of relatively elevated water temperature. With respect to this behaviour it is of interest to note that the mantic sessions at the Delphi oracle were never held during the winter months, when Apollo was believed to have gone north to the land of the Hyperboreans. This suggests that gas emissions at Delphi may have diminished during the colder periods when much of the water had accumulated on Parnassos as snow and ice, and groundwater temperatures were relatively low. As the temperature of the ground water rose during spring, more of the gas it had incorporated was released.

The gases emitted by the Gulf of Mexico vent are composed of methane (88% CH_4), ethane (*c.* 8% C_2H_6), propane (*c.* 2% C_3H_8), *n*-butane (*c.* 1%) and traces of iso-butane, iso-pentane and *n*-pentane. Methane, ethane and butane are colourless and odourless, and can produce (mildly) narcotic effects if inhaled in sufficient concentrations (Windholz 1983). No mention was made of the possible presence of ethylene (C_2H_4). This gas should be emitted by frictional heating of the bituminous limestone during seismo-tectonic activity. Ethylene is colourless and smells somewhat sweet. This gas was used by surgeons for anaesthesia around the turn of the century. When inhaled, induction is rapid, and not disagreeable mental clouding supervenes (Goodman & Gilman 1996). Assuming the adyton below the Apollo temple to have been a small, rather confined space, such gases if rising in relatively small volumes, but over extended periods of time, may have been able to accumulate in concentrations sufficiently high to induce mild narcotic effects. Of interest is the placing of the Omphalus next to the Tripod on which the Pythia sat. Could it have covered an opening in the fissure, holding back the gases to provide higher concentrations during monthly mantic sessions? Bituminous limestones also contain hydrogen sulphide (H_2S). This gas is colourless, but smells like rotten eggs. During seismic agitation of an area containing gas-enriched limestone, this is probably the gas that is emitted earliest, because it will not form gas hydrates. When Apollo occupied Delphi's oracle he had to slay a female serpent. Her name, Python, was bestowed on the site because he left her corpse to "rot." This myth suggests an early phase of H_2S gas emission, which probably followed a seismo-tectonic event along the Delphi fault zone.

Analysis of a piece of travertine collected from the Delphi fault zone north of the village (outside of the oracle site), showed traces of sulphur, indicating that sulphuric compounds did indeed rise along the fault. More analyses, however, are needed, especially of the travertine on the lskhegaon wall.

Could Seismo-tectonic Events Have Triggered Intermittent Release of Hydrocarbon Gases?

Plutarch drew the conclusion that the "exhalation is not in the same state all the time, but that it has recurrent periods of weakness and strength."

Phutarch's observation can be explained by short-term fluctuations in gas content during variations in ground-water temperature and/or dilution by heavy rains (increased ground-water flow). To continue gas emission over centuries it is necessary to evoke intermittent seismic agitation of its source. Plutarch's observation that earthquakes influenced the exhalations, clearly indicates that seismic activity played a major role in varying the volume (and site) of gas emissions.

Because of changes in the solubility of calcium in enriched ground waters that percolate through fractures and karst from the heights of the Phaedriades, spaces in the fault zone(s) will be slowly but inexorably filled with calcite. To reopen such pathways and increase both porosity and permeability, brecciation is needed, and such a process commonly results from motion along the fault(s). The Delphi fault is clearly an old structure, which possibly dates back to the early phases of subsidence in the Korinth rift zone. Strain release along this fault must have occurred intermittently, but information on such events is sparse. Sometime in the Bronze Age a goatherd Koretas, detected the presence of intoxicating fumes, when he noticed the aberrant behaviour of his goats. He may have witnessed seismic activity and found a fissure that had resulted from renewed tectonic activity. The earthquakes may have resulted from strain release (slip) along the Delphi fault zone and may have been responsible for a new phase in the release of gases from the underlying bituminous limestone formation.

Neeft (1981) believes that an earthquake destroyed the main part of Delphi's settlement around 730 BC. Delphi's period of highest prestige and wealth started around this time and lasted to the end of the fifth century. Activity along the Delphi fault in 730 BC reopened older fissure(s) and caused renewed emission of gases. Although it probably took only a few years before most of the H_2S had reached the surface, gas hydrate emissions lasted much longer.

Gases activated by the 730 BC event, however, could not have continued to surface for the 12 centuries during which the oracle "spoke." Renewed releases of the hydrocarbon gases must therefore have occurred when the Delphi fault was reactivated, but also when motion occurred along faults elsewhere in the western segment of the Korinth rift zone and strong earthquakes passed through the region.

The temple complex at Delphi was severely damaged in 373 BC, the same year in which Boura and Helice, small towns along the southern coast of the Gulf of Korinth, were utterly destroyed. These towns were located on the northern (hanging) block of a WNW–ESE trending fault zone, which had developed in the southern flank of the Korinth rift zone (Fig. 1). Downward slip of the hanging block presumably submerged part of Helice (Mouyaris et al. 1992; Lekkas et al. 1996) and destruction was completed by liquefaction of sediments and tsunamis. Contemporaneous destruction of the early temple complex at Delphi may have been due to severe shaking by seismic waves emanating from the reactivated Helice fault and/or related falls of rock masses shaken loose from the Phaedriades. However, it is equally possible that strain release along a major fault in the southern flank of the Korinth rift zone increased strain in and caused subsequent slip along the Delphi fault in the northern flank. An example of such a process was provided in 1861-1862. Motion along the Helice fault occurred on 28 December 1861. Surface rupture resulted, indicating downward slip of the northern (hanging) block. Damage as a result of liquefaction, tsunamis and structural collapse was considerable. A second strong earthquake followed on 1 January 1862. Its epicentre was located below the northern shore of the Korinth rift zone. Khoury et al. (1982) believe that slip along a southward dipping fault was responsible for this event. The seismo-tectonic sequence thus appears to have started with strain release along a north dipping normal fault and was followed

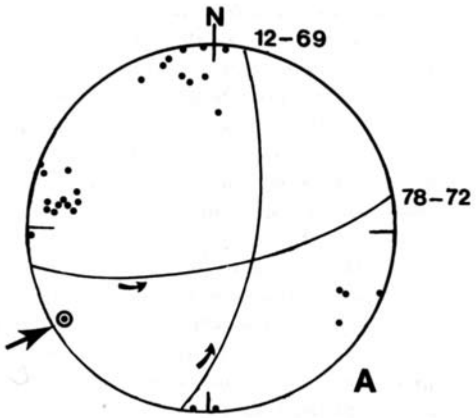

Fig. 11. Stereographic plot of shear fractures in limestone blocks of the temple floor. Dots represent normals to fractures and curved lines the mean fracture trends. Arrow indicates direction of principal stress component responsible for deformation.

Fig. 10. Conjugate set of shear fractures in limestone block of temple floor (see Fig. 8).

Fig. 12. Collapsed segment of SW part of the Apollo temple, which is also the area with the greatest density of shear fractures (Fig. 11). Collapse probably resulted from same stress field as that represented by the fractures and indicates the former presence of a space (adyton?) below the temple floor.

by strain release along its conjugate, a south dipping fault on the opposite side of the rift zone (Gulf of Korinth).

A similar earthquake sequence occurred in 1981 in the eastern segment of the Korinth rift zone (Alkionides Gulf). On 24 February, this region experienced an earthquake with magnitude M_s6.7. This quake was followed by a major aftershock (M_s6.4) 5h later. Elastic strain release responsible for the seismicity and numerous minor aftershocks was due to dip-slip along an ENE–WSW trending north dipping normal fault. The reactivated fault segment ripped upward from a depth of about 10 km and offset the surface on the Perachora peninsula (Fig. 1). The principal quake was felt over a region of about 250,000 km^2 and was responsible for generating intensity VIII effects within an area of 1400 km^2.

Ten days later (4 March 1981) an earthquake with M_s6.3 shook the same region. Its epicentre, however, was located further north (and east) than that of the previous event. It and a series of aftershocks were generated along an ENE–WSW fault zone that dips south and is located along the northern flank of the Korinth rift zone. The motion allowed for further subsidence of the crustal block in the axial zone of the rift. Strain release along the north dipping fault plane thus added strain to the south dipping fault(s) and triggered its subsequent reactivation. This pattern appears to be rather common for the tectonic evolution of a rift zone and probably was repeated many times in Greece's past.

Destruction of the temple complex at Delphi in 373 BC may therefore have been due to actual slip along the Delphi fault, which followed strain release along the Helice fault zone. Unfortunately, little historical evidence exists for the 373 BC events at Delphi. Information that does exist is indirect. Agathon and his brothers (acting as consultants for the Italian towns of Thourion and Tarenton) requested that their privileges for free access to the oracle be renewed. Their segment was inscribed on a stele, which suggests that the Alcmeonides temple was destroyed and had not yet been rebuilt. The request and permission thus were incised on a marble stele, rather than on the temple walls, and could be used for reference in the interval of several decades separating destruction and rebuilding of the temple.

Recurrence Interval of Seismogenic Events

Delphi's earthquake record is very incomplete and reliable evidence exists for the last century only. Ambraseys (1996) mentioned the occurrence of earthquakes near Delphi with $M_s > 6.0$ in 1580, 1769, and 1870 (two quakes). McKenzie (1978), Tselentis & Makropoulos (1986), and Hatzfeld et al. (1990) described events that shook the region in 1965 and 1970. Time spans between these quakes suggest a recurrence interval that varies widely. The Helice fault zone, the principal fracture on the opposite side of the rift zone from Delphi, was reactivated in 373 BC and AD 23. No data are available for the interval between the latter date and the early 18th century, but between 1748 and 1995 reactivation occurred five times (in 1748, 1817, 1861, 1888 and 1995) (Lekkas et al. 1996). Recurrence periodicity in this interval thus varied from 27 to 107 years. Tectonic activity along the Delphi fault probably occurred with similar frequency. During each of such events new pathways were created and additional volumes of gas may have been squeezed from the underlying limestone formation(s).

References to historical landslides may have been indicative of offsite seismic activity. The Persians in 480 BC, the Phocians in 354-352 BC, and the Gauls in 279-278 BC were thwarted in their attempts to ransack the temple complex because of rockfalls. Pechoux (1992) wrote: "Time and again earthquakes had rumbled here, frightening away the plundering Persians, and a century later the plundering Phocians, and a century later the plundering Gauls; it was the God protecting his shrine."

The oracle's ruins contain evidence for at least one such event, which caused significant damage. The limestone blocks that form the temple floor are locally intersected by a conjugate set of shear fractures (Fig. 10). The responsible force came from the SW (Fig. 11) and appears to have caused collapse of the southwestern temple section (Fig. 12). Such collapse can have occurred only if there was sufficient space below the temple floor. It appears possible therefore that this was the site of the adyton, the space into which the Pythia retreated for her mantic sessions.

This earthquake may have originated in the same fault zone (Patras-Nafpaktos area) as the one that occurred in AD 551. The latter quake was felt in all of central Greece, and caused major damage throughout the Korinth rift zone.

Gregor of Nazians (AD 329-390) told Emperor Julian that the Pythia spoke no more and that the Kastalian spring (Cassotis?) had been silenced. It appears logical to assume that the earthquake that did so much damage to the southwestern part of the Temple was also responsible for "silencing" the spring. The principal reason for such assumption is that the seismic waves originated in the southwest and travelled at right angles to the (NNW–SSE trending?) fissure in the adyton. They appear to have been strong enough to close it. The spring waters subsequently had no further outlet below the temple and were forced to emerge along a fault segment further uphill (to the north–northwest). After surfacing, these waters ran downhill and splashed across the Iskhegaon wall, leaving the thick coating of travertine (Fig. 9). This new spring (Fig. 7, no. 2) was also "silenced" in due time. Very little water emerges at present from the Kerna spring. In 1980 the remains of its spring house were severely damaged by offsite seismic activity, and flow appears to have been reduced even more.

Conclusions

The following conclusions can be drawn from geological observations on and near the oracle site at Delphi:

(1) The Delphi oracle site is intersected by a major WNW–ESE normal fault and a conjugate swarm of NNW–SSE trending fractures.

(2) Several springs emerged along the NNW fractures and one (possibly the ancient Cassotis) flowed below the Apollo temple.

(3) The oracle site is underlain by Paleogene calcareous shales, which in turn overlie a bituminous limestone formation of late Cretaceous age. Hydrocarbon gases emitted from the latter probably emerged locally along the NNW–SSE fractures.

(4) Seismic waves associated with an earthquake that most probably originated in the Korinth rift zone between Itea and Diakofto virtually closed a fissure(s) below the temple, caused local collapse of the temple floor, and resulted in the re-emergence of spring waters further uphill.

Note added in proof:

Chemical analyses of water samples and travertine deposits in the adyton (carried out in 1989) have shown that the springs on site have in the past and continue at present to emit small volumes of hydrocarbon gases (methane, ethane and ethylene). Light doses of ethylene were used during the early 20th century as a surgical anaesthetic.

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