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The Deep Earth Gas Hypothesis*

by Thomas GOLD[1]) and Steven SOTER[1])

Abiogenic gases, including methane, emerging from deep within the Earth appear to influence the earthquake process. A better understanding of the mechanism and pathways of the degassing process may lead to improved earthquake predictions and to the discovery of major natural gas reserves.

Volcanic eruptions are known to supply carbon dioxide, water vapor, and lesser amounts of other gases to the Earth's atmosphere. Over geological time this has undoubtedly been an important means of degassing the interior of the Earth to supply the volatiles that constitute the atmosphere and oceans as well as the carbon in the biosphere and sediments. But there is now evidence that such degassing also occurs in nonvolcanic regions, where deep crustal faults can provide a pathway to the surface. In such regions, the interior gases can migrate upward at a modest rate, punctuated occasionally by larger outbursts during major earthquakes. We believe that the movement of such gases is the primary phenomenon underlying a wide range of known earthquake precursory effects and that it plays a significant role in the actual triggering of earthquakes. Furthermore, there is reason to believe that a significant fraction of the gas emerging from the Earth's interior is abiogenic methane.

The composition of the emerging deep Earth gas is a difficult question, as the observational evidence is scanty and not easily interpreted. The gases observed in volcanic emissions are dominated by H_2O and CO_2, but CO, CH_4, NH_3, H_2, H_2S and others are frequently detected. However, it is not possible to deduce directly from such observations the initial gas composision at depth, because (1) an unknown proportion of the volcanic gas may consist of volatiles recycled from crustal sediments rather than juvenile gas arriving for the first time from the mantle; (2) hydrogen-rich (reduced) gases will have been mostly oxidized in the liquid magma on the way to the surface; and (3) most of the gas samples have been acquired during the more quiescent (and safer!) phases of activity, but these may be chemically unrepresentative of the greater volumes emitted in explosive eruptions.

Gases released during earthquakes are probably more accurate samples of those present in the deep crust and upper mantle. The sampling of such gases ist only just beginning, particularly in the Soviet Union, and it is too early to draw confident conclusions from the data. Undoubtedly, the composition of the deep Earth gases varies with geographical location, since the disposition of mineral deposits in the crust suggests substantial heterogeniety in the underlying mantle. Methane (CH_4) may be more important in this respect than previously realized. Because it is also the principal constituent of natural gas and, indeed, because there is the possibility that abiogenic methane may

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play an important role in the growth and maintainance of petroleum deposits, we will concentrate our attention on it here. But this is not to minimize the possible importance of the other deep Earth gases in the earthquake-related phenomena to be discussed later.

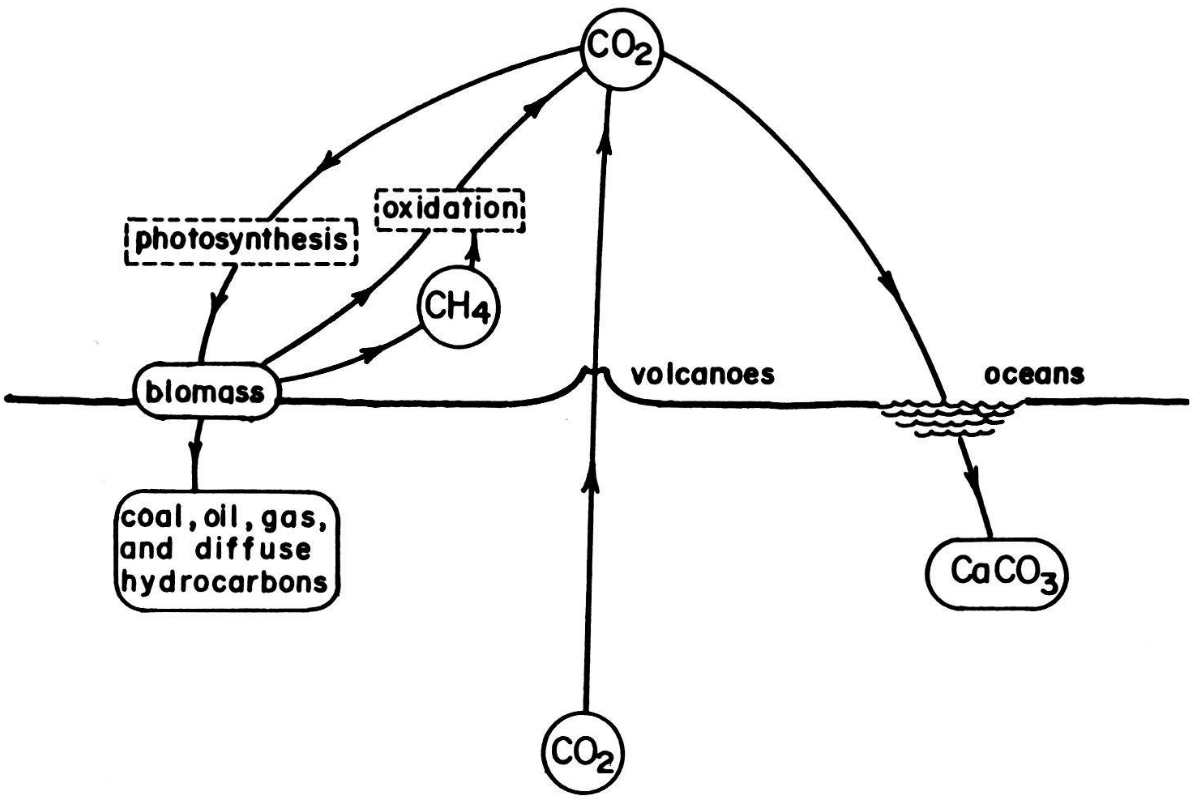
The notion of abiogenic methane runs counter to the prevailing view in petroleum geology that virtually all the oil and natural gas in the Earth is of biological origin. In that view, the carbon in the hydrocarbon fuels was all originally derived from atmospheric CO_2 and the energy to dissociate the CO_2 came from sunligth, in the process of photosynthesis by green plants. The burial of some of these organic compounds before they could become oxidized would then have provided the source materials for oil and gas. There ist little doubt that this process contributed to the genesis of much of the petroleum that has been recovered, but there may be more to the story.

The modern abiogenic theory of petroleum begins with the observation that hydrocarbons, rather than being exclusively biogenic, are the dominant carbon containing molecules in the solar system. The universe is made mostly of hydrogen, and the evidence of cosmochemistry suggests that the Earth originally condensed out of a hydrogensaturated solar nebula. Most meteroritic carbon is in the form of complex hydrocarbons having some chemical similarities to oil tars. The Earth may well have acquired most of its carbon in the form of such hydrocarbons. The primitive atmosphere was a reducing one and probably contained most of its carbon in the form of methane. The early stages of life on Earth are thought to have required such an atmosphere. With the subsequent production of oxygen by photosynthesis, the terrestrial atmosphere gradually attained its present oxygen-rich composition, and it is that fact which today makes hydrocarbons such a useful source of chemical energy, i.e., a combustible fuel.

What is the fate of the Earth's primordial supply of hydrocarbons? We can suggest the following hypothesis. Buried under conditions of elevated pressures and temperatures, these hydrocarbons liberate methane and this gas, often together with others, tends to migrate upward toward the surface, preferentially along zones of weakness in the crust, leaving the bulk of the heavy hydrocarbons behind. Where the pathway leads trough hot volcanic lava, the CH_4 will be oxidized to CO_2 just before entering the atmosphere. Where the pathway allows a pressure reduction in a cooler non-molten region (as along a cold fault), the gas can reach the surface in its original reduced state (although it will not survive as such for more than a few years in the oxygenrich atmosphere). Other pathways will cause some of the methane to be trapped temporarily beneath relatively impermeable strata, where it can contribute to the known deposits of natural gas. And, finally, some methane, on pathways diffusing it trough hydrocarbon deposits (including biogenic oils) may be trapped by a chemical augmentation (polymerization) to those hydrocarbons.

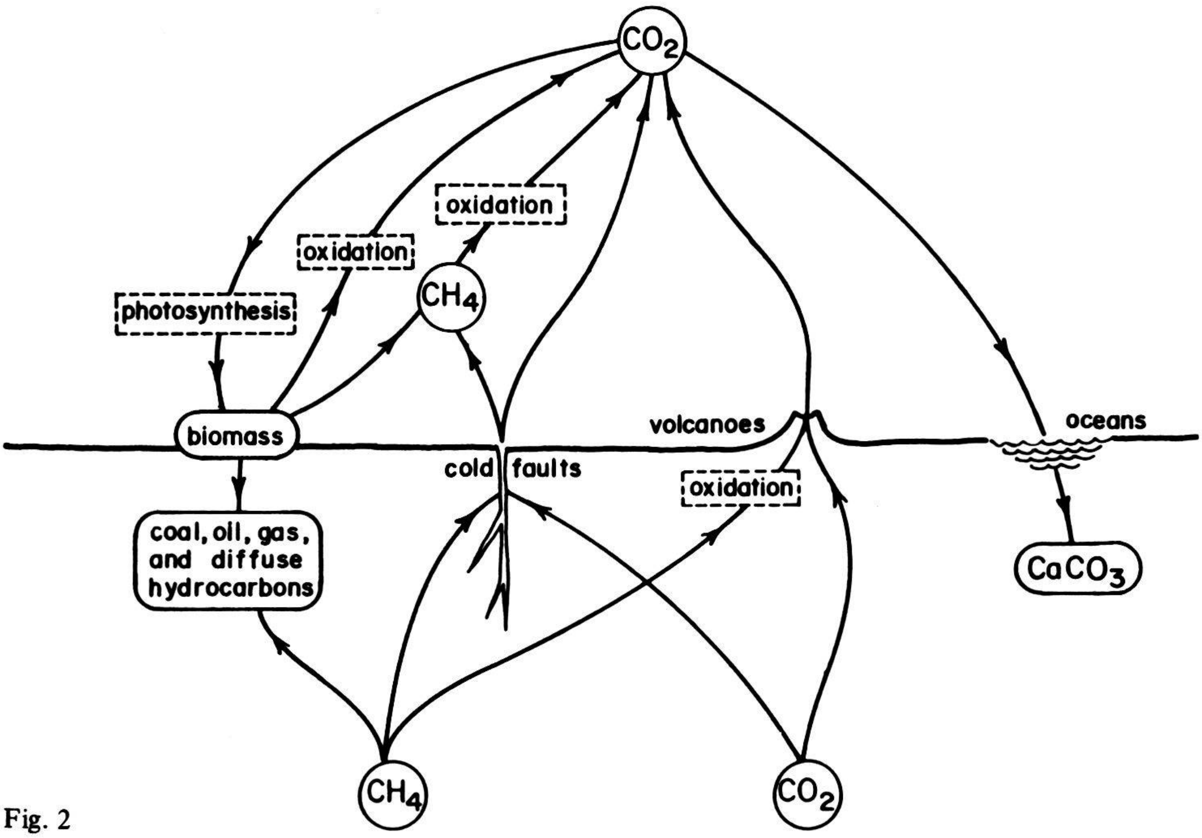
Fig. 1 Terrestrial carbon budget. The conventional view holds that all coal, oil, and gas is of biological origin, the product of photosynthetic reduction of atmospheric CO_2 into hydrocarbons which were buried before they could be fully oxidized. The initial source of the carbon is assumed to be deep-seated CO_2 which enters the atmosphere via volcanic emissions. The principal sink in the carbon cycle is precipitation through sea water into sedimentary carbonates, mainly limestone ($CaCO_3$). Almost all the atmospheric CH_4 is here assumed to be biogenic.

Fig. 2 The duplex origin theory assumes, in addition to the photosynthetic reduction of CO_2, that there is a deep source of abiogenic methane contributing directly to the growth and maintainance of coal, oil, and natural gas deposits. Some abiogenic methane is oxidized to CO_2 as it reaches the surface through hot volcanic lava at low pressure. But CH_4 can also enter directly into the atmosphere through cold faults, perhaps mainly during earthquakes, providing an abiogenic contribution to the atmospheric methane. Faults also provide a means for the seismic degassing of deep-seated CO_2 and other gases.



CO_2
oxidation
photosynthesis
CH_4
biomass
volcanoes
oceans
coal, oil, gas, and diffuse hydrocarbons
$CaCO_3$
CO_2

Fig. 1



CO_2
oxidation
oxidation
photosynthesis
CH_4
biomass
volcanoes
oceans
cold
faults
oxidation
coal, oil, gas, and diffuse hydrocarbons
$CaCO_3$
CH_4
CO_2

Fig. 2

Most of the carbon in the upward migrating methane will enventually enter the atmosphere, either directly as methane or oxidized as CO_2. From the atmosphere, the CO_2 will be dissolved and precipated throŭgh the oceans. The Earth's crustal rocks contain an enormous quantity of carbon, mostly in the form of sedimentary limestone. Carbon is much more concentrated in the sediments than in the igneous rocks from which the sediments derived; this „excess" carbon must have been brought to the surface in the form of CO_2 and CH_4 degassed from the interior, although in what proportion between these two gases we cannot say.

Table

Carbon and reduced carbon in the Earth's crust*

[in kilograms per square centimeter vertical column; to convert to global totals, multiply by Earth's surface area, 5 x 10^{18} cm^2]

CRUST OF THE EARTH		
Total Mass	5600 kg/cm^2	
Carbon content	17,5	(0,3% of crust)
Reduced carbon	3,7	(22% of the carbon)
IGNEOUS AND METAMORPHIC ROCKS		
Total mass	5100 kg/cm^2	(92% of crust)
Carbon content	2,6	(0,05% of these rocks)
Reduced carbon**	1,4	(54% of this carbon)
SEDIMENTARY ROCKS		
Total mass	470 kg/cm^2	(8% of crust)
Carbon content	15	(3% of these rocks)
Reduced carbon	2,3	(16% of this carbon)

* Data principally derived from J.M. Hunt (1972): Distribution of carbon in crust of Earth. Bull. Amer. Assoc. Petrol. Geol. 56, 2273 - 2277

** includes elemental carbon

We think that at least some of it originally came up as methane, and continues to do so. There ist no compelling reason to believe that the Earth is today completely degassed of its primary volatiles. If the amounts remaining below are comparable with those that have come up, there is the possibility of an enormous quantity of deep methane being present. The prime reservoirs would no doubt be too deep to drill, but one may be able to identify the formations that have guided some of this gas to more accessible levels where it can be reached.

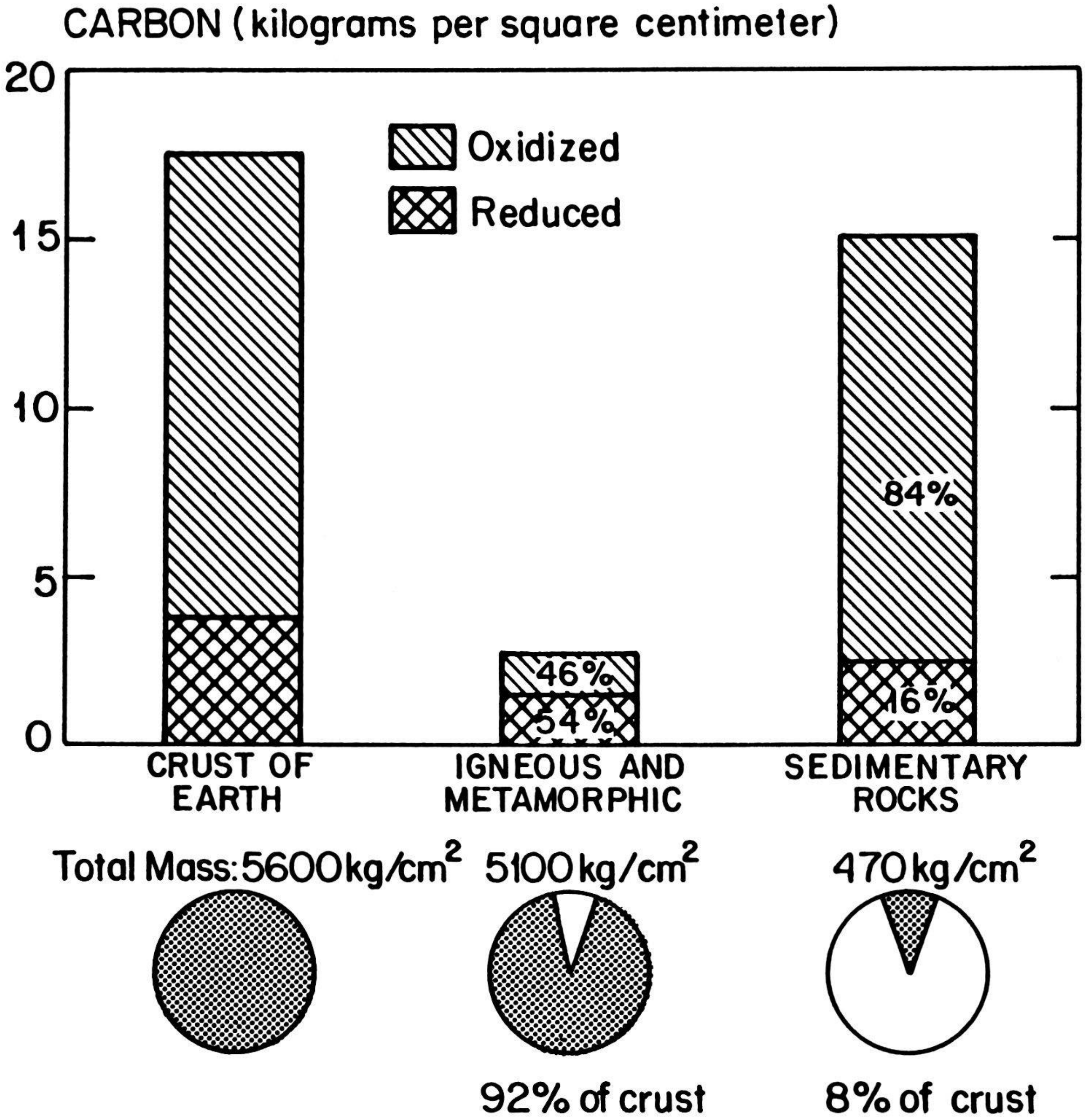


Fig. 3 Distribution of carbon in the crust of the Earth. In this figure, each bar shows the carbon content and how much of the carbon is in oxidized and in unoxidized form. The figure below each bar shows the total mass involved for each type of rock and the fraction of the crust that this represents. All the data are stated in terms of kilograms for a vertical column one square centimeter in cross section through the crust. The fact that carbon is much more concentrated in sediments than in the igneous rocks from which the sediments derived by weathering indicates that most of the carbon came to the surface as gas, presumably from sources deep in the Earth. The proportion of the carbon in unoxidized form is higher in the igneous and metamorphic rocks than in the sediments, contrary to what one would expect if all unoxidized carbon is derived from biological materials.

An objection sometimes raised against the viewpoint that inorganic hydrocarbons exist deep in the Earth is that such materials would readily be oxidized into CO_2 at the elevated temperatures found at great depths. But this argument neglects two important considerations. Firstly, the enormous confining pressures present even at modest depths favor the stability of methane and other hydrocarbons over CO_2 because they take up less volume in the chemical equilibrium. Secondly, even if the rocks contain oxygen in a form that could oxidize methane, it is only in liquid rock that this oxygen would be available in significant quantity. If the pathways of the gases are confined to fissures trough solid rocks, the accessible surfaces can yield only small amounts of oxygen, and for a large supply of methane there would be little loss to oxidation. Thus, the observation that most carbon in volcanic gases is in the form of CO_2 and not CH_4 does not tell us anything about how it originated, because methane bubbling trough lava at low pressures and high temperatures would readily be oxidized into CO_2 in any case.

Another objection often raised against abiogenic hydrocarbons is based on the ratio of the stable carbon isotopes. Of the two, ^{12}C predominates, but a small admixture (about 1%) of the heavier isotope ^{13}C is always present in terrestrial carbon sources. (The much rarer heavy isotope ^{14}C ist unstable and will be discussed later.) The precise ratio in the abundance of ^{13}C and ^{12}C varies somewhat among different kinds of carbon deposits, and this is often used in attempts to identify the sources. The carbon in the biomass is isotopically „light" compared to that in atmospheric CO_2, because photosynthesis selects against the heavier isotope when plants take up CO_2. The fact that carbon in petroleum is also depleted in ^{13}C relative to carbon in atmospheric CO_2 is often cited as evidence for the exclusively biological origin of oil and gas.

But this argument is not secure, because there are also several nonbiological processes that can sort carbon isotopes. For example, depletion of a stream of methane by oxidation enriches the light isotope; diffusion trough water enriches the heavy one. Complex hydrocarbons that chemically resemble those in oil tar and in carbonaceous meteorites are readily made, abiogenically, by a mineral-catalyzed reaction between carbon monoxide and molecular hydrogen. Significantly, the carbon in the resulting hydrocarbons is isotopically much lighter than that in the CO_2 produced in the same reaction. This process, known as the Fischer-Tropsch synthesis, very likely occurs under natural conditions deep in the Earth and may well contribute to some hydrocarbon deposits.

The relative abundance of ^{13}C in natural gas deposits shows a general increase the deeper the present depth of burial, regardless of the composition, age, or past depth of burial of the confining rock. This is true whether the gas is „free" or associated with petroleum. In the latter case, the isotopic weight of the methane bears no relation to that of the oil. These facts strongly suggest, as also noted by the Soviet geochemist E.M. Galimov, that all crustal gas deposits were emplaced only recently, that they are young relative to the age of the confining rock or the time for that rock to change its depth, and that the gas, even where it is found with oil, does not have a common origin with it. Galimov has suggested that methane deposits derive from dispersed sedimentary hydrocarbons and that temperature-dependent isotopic fractionation and continuous loss of methane would then lead to the observed ^{13}C depth dependence. But, in our view, a gas deposit could just as well be emplaced by an upward migrating stream of abiogenic methane which, with proper catalysts, would gradually be depleted of its ^{13}C by oxidation and isotope exchange on its way up. Unfortunately, not enough is yet known about the relevant processes; the complicated carbon isotope story can be interpreted in too many ways to decide whether or not some methane in natural gas deposits is abiogenic. But in any case, the depth dependence shows that the gas has only a short residence time in the crustal rocks, and that a much larger rate of outflow has to be supposed than was considered previously.

Finally, it is often said that the presence of porphyrins and other molecular residues of living organisms in many oil formations is proof that all the oil was derived from the decay of organic sediments. But many sedimentary rocks (in the porosity of which oil is most commonly found) are rich in biological residues. If such rock is invaded from below by abiogenic oil and is left to soak for a few million years at elevated temperatures and pressures, it would be difficult to prevent the contamination of that oil by biological substances derived from the sediments.

The chemist Sir Robert Robinson has written that „it cannot be too strongly emphacized that petroleum does not present the composition picture expected of modified biogenic products, and all the arguments from the constituents of ancient oils fit equally well, or better, with the conception of a primordial hydrocarbon mixture to which bioproducts have been added". Indeed, we do not believe that any of the evidence usually invoked in favor of an exclusively biological origin for petroleum is compelling. The picture that we favor is one of a duplex origin, with some petroleum made directly from buried organic sediments and a (probably larger) portion derived abiogenically.

The latter process may involve the chemical augmentation of existing hydrocarbon deposits from a stream of abiogenic methane. This is still hypothetical, but methane, usually assumed to be chemically inert, may well be able to polymerize into crude oil under suitable conditions of temperature, pressure, and catalytic action (including perhaps microbiology). If this indeed occurs, then an ascending stream of methane in a given geographical region could slowly augment existing hydrocarbon deposits (of oil and perhaps even coal) at different levels in that same region. The process need not be very efficient; even if most of the gas is not captured but goes on up to escape at the surface, still a modest flux persisting over geological periods of time could deposit an enormous mass of hydrocarbons. The process would resemble mineralization, in which high grade ore is precipitated out a long-lived stream of hydrothermal fluids.

The chemical augmentation of hydrocarbon deposits would have a positive feedback, because the larger the accumulation the more probable the capture of a rising methane molecule. This might help explain why the few largest petroleum fields are so enormous compared to all the rest. Of the many thousands of commercial oil fields, a mere 33 fields (25 of them in a single region the Middle East) contain about half of the world's known recoverable crude oil.

This process would further account for the presence of biogenic molecules in most crude oils. The primer deposits that commence the process are likely to be biogenic oily substances such as often occur in many sedimentary layers. Even a slight concentration of such hydrocarbons would favor the growth of a given layer over those adjacent to it, due to the positive feedback mechanism. Without the methane augmentation process, many such biogenic deposits would remain insignificant, but in areas where methane is flowing from deep sources they can grow into large oil fields.

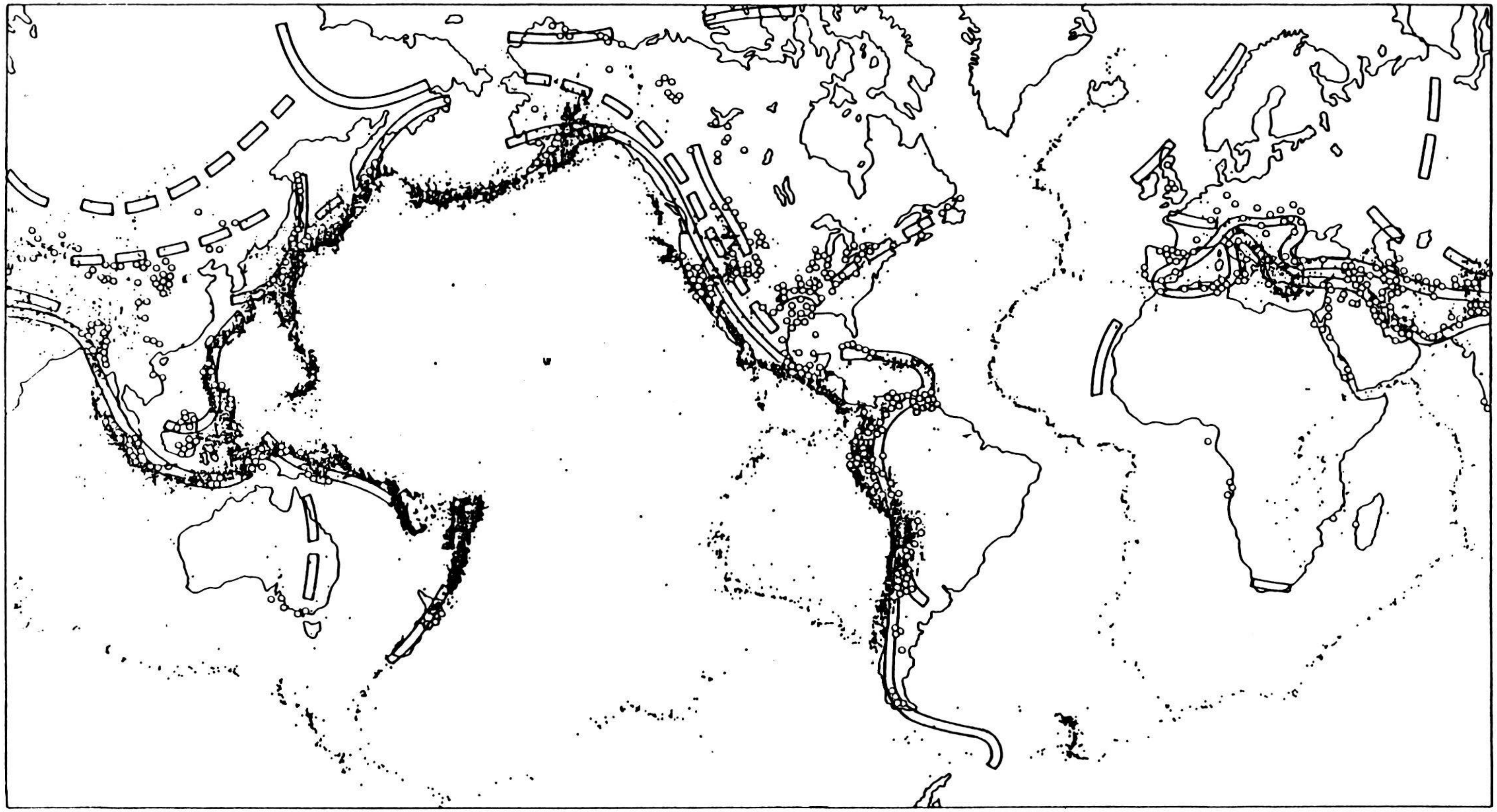
The upward streaming methane that is neither oxidized in volcanic regions nor entrapped in petroliferous deposits will enter the atmosphere, where it ought to be detectable. It will not contain any of the heavy carbon isotope ^{14}C, a fact that can help in distinguishing it from methane of recent biological origin. Atmospheric CO_2 contains some ^{14}C, which is produced when cosmic rays collide with atmospheric nitrogen. Trough photosynthesis, ^{14}C gets incorporated into the biomass. It is absent from oil and gas since it decays with a half-life on only 5800 years. Most of the atmospheric CH_4 is produced by known biological sources (microbial fermentation in paddy fields, swamps, and ruminants, with a turnover time not exceeding a few years); the known non-biological sources (mainly from industrial pollution) contribute much less. Thus, atmospheric methane ought to have nearly the same ^{14}C concentration as the biomass from which most of it is thought to be derived. Instead, there is some indication that it may be deficient by as much as 20%. If real, this depletion may be explained by the natural emission of deep methane both by gradual seepage and seismic eruptions. Atmospheric methane is present at about 1.5 parts per million and it is thought to have a lifetime, prior to oxidation, of about five to seven years. Careful monitoring of the global atmospheric methane concentration as well as of any changes in its isotopic abundances (for both ^{13}C and ^{14}C) would be most useful.

Let us now examine some of the more local evidence for the escape of such methane from the interior of the Earth. An important place to look is along the crustal faults and fissures of the tectonic plate boundaries; these ought to provide the best access to the deep interior. And indeed, hydrocarbons appear to be clearly associated with such places. For example, large concentrations of dissolved methane have been measured in waters overlying plate boundaries and rift zones. The deep brines of the Red Sea contain about 1000 times as much methane as normal sea water. Hydrothermal plumes found issuing from seafloor vents on the East Pacific Rise contain high concentrations of methane together with hydrogen and ^{3}He, indicating a deep abiogenic source for the gases. Lake Kivu, which occupies part of the East African Rift Valley, contains some 50 million tons of dissolved methane, for which there is no adequate microbial source. We suspect that these waters are all supplied by abiogenic methane seeping up through deep crustal fissures.

Another line of evidence connecting abiogenic hydrocarbons with such features is the striking correlation between major oil and gas producing regions and the principal zones of past and present seismic activity. Even on the local scale, oil fields often lie along active, or over ancient, fault lines. Most of the known natural seeps of oil and gas are found in seismically active regions. The most spectacular gas seeps are the so-called „mud volcanoes“, which are hills or sometimes substantial mountains of mud built up by the intermittant and sometimes violent eruptions of natural gas, often almost pure methane. There are scores of mud volcanoes known and almost all occur on or near plate boundaries, in places such as Trinidad, New Zealand, Indonesia, Burma, Pakistan, Iran, and Italy. In any one region, groups of them tend to lie along local fault lines. The world's largest active mud volcanoes are near Baku in Soviet Azerbaijan. One recent eruption there produced a flame that initially shot up to a height of several kilometers and burned some 200 000 tons of methane. Major eruptions of mud volcanoes frequently coincide with earthquakes.

In seismically active regions, many thousands of violent earthquakes are likely to occur in the course of a few million years. One might at first expect that the repeated fracturing of the rocks in such places would have released or strongly depleted any nearby accumulations of oil and gas in times short compared to the age of the confining strata. The fact that oil and gas fields show, on the contrary, a preferential association with such earthquake-prone regions suggests to us that the deep faults may provide a conduit for the continuous input of abiogenic methane streaming up from below. Furthermore, the upward migration of methane and other gases in fault zones may play an important role in the actual triggering of earthquakes.

An earthquake is due to the release of stress in the subsurface rock by a sudden brittle fracture, involving the rapid propagation of a crack, and the elastic rebound or slippage between the two sides. (The stress may accumulate due to slow viscous motions in the mantle, which are thought to generate all the phenomena of plate tectonics, including earthquakes.) Seismologists have long recognized a difficulty in accounting for deep earthquakes. At a depth of more than about five kilometers, the pressure due to the overburden of rock is so great that a crack cannot open up by itself. Instead of breaking suddenly by brittle fracture, rock at these pressures simply deforms when excessive shear is applied. At even greater depths, the increase in temperature further reduces the shear strength of rock. Continuous plastic flow would relieve the stress long before any



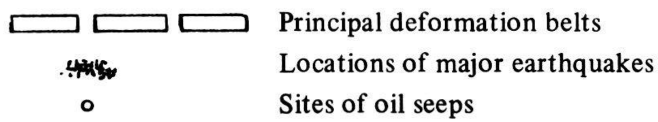


Fig. 4 Correlation between major regions producing oil and gas and zones of present and past seismic activity is indicated. The map shows the principal deformation belts, the locations of major earthquakes and the sites of a number of oil seeps. Many of the known hydrocarbon reservoirs, including those of Alaska, Texas, the Caribbean, Mexico, Venezuela, the Persian Gulf, the Urals, Siberia and Southeastern Asia, lie on deformation belts. The correlation is consistent with the view that hydrocarbons of nonbiological origin come up from deep in the earth through fissures in the crust. They may augment hydrocarbons of biological origin.

fracture could ever occur. And yet, earthquakes are known to occur at depths as great as 700 km, and their seismographic „signatures“ show that, like shallow earthquakes, they involve a sudden discontinuous fracture.

The presence of deep earth gas could resolve this contradiction. If the deep rocks in a region contain pores held open by gas at the ambient pressure, then the interconnection of these pores can lead to the formation of a crack that remains open. The gas effectively unburdens the rock along a nearly frictionless layer. Discontinuous slippage can then occur (as would be the case under low confining pressure), and the crack will propagate, releasing the strain energy and causing an earthquake.

If the shocks so created are strong enough to fracture the ground up to the surface, this same gas will find a rapid escape route, and will produce what we interpret as the gas eruption effects that are reported in many major earthquakes. These effects include: flames seen shooting from the ground; „earthquakes lights“; fierce bubbling in bodies of water; stifling or sulfurous air; loud explosive and hissing noises; and „visible waves“ seen slowly rolling along alluvial ground. We have collected hundreds of independent reports of such phenomena, spanning many centuries, and from all parts of the world, and these show a remarkable consistency. Only a small sampling can be given here. (Appendix III)

The flaming phenomenon indicates that some of the gas erupting during earthquakes is combustible, most likely methane or hydrogen. One of the more violent earthquakes ever recorded in North America occurred on February 5, 1663, along the St. Lawrence River in Quebec. French Jesuit missionaries reported that during the shocks, there emanated from the ground „fiery torches and globes of flame-now relapsing into the earth, now vanishing into the very air like bubbles“. Lest this be regarded as fantasy or exaggeration, there exist scores of similar descriptions from other earthquakes. Thus, according to contemporary newspaper accounts of the Owens Valley earthquake of March 26, 1872 (the most violent earthquake ever recorded in California), „Immediately following the great shock, men, whose judgment and veracity is beyond question, while sitting on the ground near the Eclipse mine, saw sheets of flame on the rocky sides of the Inyo mountains but a half mile distant. These flames, observed in several places, waved to and fro apparently clear of the ground, like vast torches; they continued for only a few minutes“.

Such accounts can readily be explained if these earthquakes liberated large quantities of combustible gas, under high pressure, through fissures in the ground. The gas will be self-igniting from sparks generated by the electrostatic charging of dust grains carried along in the flow. This is the same mechanism that causes eruptions of mud volcanoes to burst spontaneoulsy into flame. The reality of the flames in such earthquake reports is verified by the physical evidence sometimes left behind. For example, during the Sonora (Mexico) earthquake of May 3, 1887, there were many reports of flames, and afterwards burnt branches were discovered overhanging fissures in the ground.

The flaming phenomenon, when seen at a distance of a few kilometers, may also be responsible for some of the „earthquake lights“ which are frequently reported during seismic shocks occurring at night. These are usually described as hemispherical glows on the horizon; some of these have been photographed. Other kinds of earthquake lights, including sharp flashes, „fireballs“. and diffuse luminosity in the sky, may be due to electrostatic effects from the sudden emission of gas into the atmosphere.

There are a great many accounts of the vigorous bubbling of the sea or other bodies of water during major earthquakes. For example, during the great Chilean earthquake of May 22, 1960, observers on the shore over a range of 450 km reported that the sea appeared to be „boiling“. This is precisely what one would expect if large quantities of gas were liberated during the earthquake.

Frequently, a sulfurous odor is reported to linger in the air after a great earthquake. Methane itself is odorless, but hydrogen sulfide is a common constituent of natural gas. Since H_2S is soluble in water and highly toxic to fish, the eruption of natural gas containing it may account for some of the many reports of dead fish found floating on the water after major earthquakes at sea. For example, Capt. Fitz-Roy of the H.M.S. Beagle (of Charles Darwin fame), at Valdivia during the great earthquake of Feb. 20, 1835, reported that „the water in the bay appeared to be every where boiling; bubbles of air, or gas, were rapidly escaping. The water also became black, and exhaled a most disagreeable sulphureous smell. Dead fish were also thrown ashore in quantities; they seemed to have been poisoned, or suffocated".

There are also many reports of earthquakes accompanied by hissing and booming noises, of the sort that might be expected to accompany the eruption and/or explosion of confined gas. The explosions may in some cases be due to the physical impact of gases at high pressure with the air, as occurs with explosive sounds during conventional volcanic eruptions. During the New Madrid earthquakes of 1811 – 1812 (the most violent ever recorded in North America), loud roaring and hissing noises „like the escape of steam from a boiler" were heard, together with multiple explosions. Fires were reported in the sky and the smell of sulfur filled the air. The Mississippe River boiled up in huge swells and confined gas was seen to burst from its surface.

The phenomenon of „visible waves" is observed in many, perhaps most, major earthquakes that occur in alluvial ground. The solid surface of the earth ist usually described as rolling in waves resembling those at sea. A quite typical description of the phenomenon was given by a mining engineer who witnessed the Sonora earthquake of 1887: „These waves seemed to be two feet high, about twenty feet apart, and moved as rapidly as the incoming waves along the seashore". A police sergeant who saw the San Francisco earthquake of 1906 said: „The whole street was undulating. It was as if the waves of the ocean were coming towards me, billowing as they came". Waves of such small wavelength and especially with such low propagation velocities as to be clearly visible are not at all explained by conventional seismology. They are much too slow to be elastic waves due to the shock itself. But there is no doubt whatever as to their physical reality.

Perhaps the phenomenon is a kind of gravity wave, like waves at sea, but with the relevant fluid being compressed gas. As a result of a major fissure in the underlying rock during an earthquake, a large amount of gas shoots up with pressures that may be of the order of hundreds of thousands of atmospheres. The alluvial layers covering the fractured bedrock are less brittle and will not so readily open to large fissures. They act as an extra impediment to the outflowing gases, whose pressure is easily sufficient to lift them entirely by inflating the porosity. When so lifted from the bedrock, the material has a low rigidity and is quite unstable; it can then propagate gravity waves. (We find that a quite similar explanation for the phenomenon was given in 1760 by the English astronomer John Michell, who, incidentally, was also the first person to postulate the existence of black holes.)

If visible waves are produced by seismic gas eruptions on land, perhaps tsunamis are an analogous phenomenon at sea. It is usually assumed that the energy in such seismic sea waves is transferred by a sudden displacement of the seafloor over a vertical distance comparable to the observed height of the wave. However, this mechanism would require that a slab of rock extending from the seafloor down to the hypocenter of the earthquake (say 10 km) must all be raised through the height of the sea wave (say 1 m), which would in turn require many thousands of times as much energy as the potential energy in the sea wave itself. And yet, the total energy liberated in a tsunami earthquake (as calculated from its observed seismic magnitude) is usually found to be only an order of magnitude greater than the measured energy in the sea wave. A more efficient energy transfer mechanism seems to be required. A gas eruption would produce the required volumetric displacement of the water with much less energy. The sea wave volume will roughly equal the gas volume when the latter has expanded almost to atmospheric pressure. An earthquake energy only some ten times larger than the tsunami energy then appears to be a possibility.

There is as yet no proof that any of the above effects are due to gas eruptions during earthquakes, but at least for the flaming and bubbling phenomena it is difficult to imagine a likely alternative. Even in the conventional view, however, it might be argued that gas eruptions are occasionally to be expected during major earthquakes because the shattering of the bedrock ought to liberate any local pockets of confined gas derived from the adjacent strata. But there is evidence that the gas plays more than a passive role in the earthquake. We believe that most of the well-known earthquake precursory phenomena can best be explained in terms of an increase in deep gas pressure occurring well before an earthquake actually shatters the bedrock.

Many of the precursory phenomena have been detected by instruments. These include: changes in the velocities of seismic waves through the ground; in the flow of ground water; in the electrical conductivity of the ground; in the tilt and precise elevation of the surface; in the chemical composition of gases in the soil and ground water; and in the emanation of radon gas. The time interval between the onset of a precursor and an earthquake ranges from minutes to as long as years, depending on the phenomenon and the earthquake magnitude.

These precursors are usually discussed in terms of rock „dilatancy“, that is, the opening of microcracks in the rock as the shear stress approaches the critical value for fracture, as observed in laboratory experiments. We agree that an increased porosity and concomitant volumetric expansion of the rock would indeed contribute to most of the above precursory phenomena. But what has generally been neglected in these discussions is that at depths of tens of kilometers (where most earthquakes originate), the rock by itself would not have the strength to hold open such cracks against the enormous overburden pressure. Dilatancy could not even begin unless there were present a high pressure fluid to hold open the cracks.

We suggest that the deep earth gas does just that. In our model for brittle fracture at high ambient pressures, described above, there are two prerequisites for the occurrence of a deep earthquake: there must be a shear stress that would be sufficient to cause brittle fracture as if the same rocks were at a shallow depth, and there must be a high pressure gas to hold open incipient cracks and thereby mitigate the enormous friction due to the lithostatic overburden. It is the invasion of the rock by such a gas from below that changes it from a ductile to a brittle material, simultaneously causing its volumetric expansion and the associated dilatancy phenomena.

As the deep earth gas increases the porosity prior to triggering an earthquake, some of it may begin to find its way to the surface, disturbing the ground water, altering the electrical conductivity of the ground and the composition of the soil gases. The radon precursor effect seems, in particular, to require the presence of a carrier gas streaming through the ground. Radon is a minor trace gas produced chiefly by uranium ores at considerable depth. Since its half-life is only 3.8 days, it could not by itself diffuse more than a few meters through the soil porosity before decaying. And yet, substantial increases in the surface emanation of radon have been detected prior to some earthquakes, and at distances as great as 100 km from the epicenter. The simplest explanation is that the radon is merely a convenient tracer for a much more abundant gas that sweeps it along, an otherwise undetected gas with a sufficient flux to travel past the depths of the radon sources to the surface in only a few days.

Not all earthquake precursors require instruments for their detection. Some are so obvious to the senses that they have been recognized since ancient times. We believe that these effects are also due to an increased gas flux through the ground. Among these „macroscopic" precursors are: dull explosive noises of unknown origin: the bizarre behavior of wild and domestic animals; anomalous increases in local temperature; sulfurous fumes, sometimes accompanied by a peculiar fog; bubbling and other disturbances of well water; and flames from the ground.

Episodes of mysterious booming noises, resembling distant artillery over several days or months, were reported as preceding the great earthquakes in Charleston (1886), Assam (1897), San Francisco (1906), and East Anatolia (1976). Some of these noises, called „brontides" in the earlier earthquake literature, may have been due to the sudden release of high pressure gas into the air.

The most widely reported precursor is the anomalous behavior of animals. Farm animals often rush about in confusion and try to break out of confinement, dogs howl incessantly, burrowing animals are seen to leave their holes, and fish to come up to the surface, usually beginning some minutes or even hours before a major earthquake. Again, the reports are so widespread and consistent that there can be little doubt as to the reality of the phenomena. If the deep earth gas begins to force its way up into the soil prior to some earthquakes, it will tend to push out ahead of it the ambient soil-entrapped gases. The carbon dioxide normally present in the soil porosity will begin to invade the homes of burrowing animals, who will be driven to the surface to avoid asphyxiation. If the deep earth gas contains even small amounts of hydrogen sulfide, it will be dissolved upon entering the bottoms of lakes and other bodies of water, driving the fish toward the surface. Many mammals have an enormous superiority over humans in the detection thresholds of their olfactory organs, and for this reason the sense of smell appears to be the most likely explanation for their strange behavior prior to earthquakes. Although methane and carbon dioxide are odorless to humans, some of the soil gases are not. These, on entering the atmosphere, might well constitute an „olfactory cacaphony" with no discernable source-producing the kind of animal panic so often reported. In a few cases, the odors emanating from the ground prior to an earthquake are even strong enough to affect people, so it seems reasonable that in a great many cases only animals will notice them.

Such gas emission may also cause other peculiar effects in the atmosphere. For example, analysis of meteorological records has revealed that for several weeks before the earthquake of February 4, 1975 in Haicheng, China, communities along the entire length of the fault zone had recorded air temperatures systematically higher (by as much as 4 to 6°C) than in the surrounding region. A sulfurous odor was also intermittantly but strongly in evidence, occasionally driving people indoors. Bubbling was observed in ditch water. During this same period there were frequent reports of anomalous animal behavior: snakes were found frozen on the roads and rats acted as though dazed; farm animals showed clear signs of restlessness and alarm, which was a minor but contributing factor in the successful prediction of that earthquake.

One or two hours before the Haicheng earthquake, there appeared in the same region what people described as a low-lying „earth gas fog" with a peculiar smell. This phenomenon may have a simple explanation. During winter, the air temperatures are lower than the seasonal average found in the soil gases at depths of only a few feet. The soil gas can thus hold more water vapor than the air above. If suddenly expelled from the ground by the invasion of deeper gas from below, this CO_2-rich air will remain near the

Fig. 5 Hypothetical rise of gas from deep in the earth is depicted schematically. Gas liberated from the earth's original store of hydrocarbons diffuses slowly into pore spaces (a), which can be envisioned as bubblelike openings between grains of the rock. The pore spaces distent and become interconnected (b), creating a „pore-space domain" that, because of pressure instability, begins to ascend (c, d). As the pore-space domain reaches rock that is cooler and harder (dark band in e) its movement is arrested (f). The gas facilitates brittle fracture of the rock, and some of the gas leaks to the surface. Large amounts of gas can escape into the atmosphere through fractures created by an earthquake (g). Slow leakage of gas thereafter (h) gives rise to a widening area of aftershocks. Leakage during the last three steps may account for many precursors of earthquakes and phenomena associated with earthquakes.

ground despite its higher temperature and as it cools its water vapor will condense into a low-lying fog.

The connection between various gas-related precursory phenomena has been noted for centuries. We have, for example, the following account from the great Calabrian earthquake of 1783: „At the time of the earthquake, during the night, flames were seen to issue from the ground . . . exactly from the place where some days before an extraordinary heat had been perceived". Another account of the same earthquake reports: „The waters of the wells, of the sea, and also of the fishponds, a few hours before the earthquake of 5 February struck in Cosenza and neighbouring villages,was seen to raise its level, all foaming as though boiling, without being observed to have a greater heat than normal". According to Alexander von Humboldt, half an hour before the earthquake at Cumana (Venezuela) on December 4, 1797, a strong smell of sulfur was perceived, and at the same time flames appeared on the banks of the Manzanares River.

If the gases expelled from the ground as precursors to an earthquake make a combustible mixture in air, they can self-ignite electrostatically and give rise to the flaming phenomenon. An extraordinary account which we believe to be of this kind was recently reported from China by Lucile Jones of the Massachusetts Institute of Technology. Almost one month prior to the Songpan-Pingwu earthquakes of August 16, 21, and 23, 1976, Chinese seismologists observed fireballs rising from the fault zone some 150 to 200 km from the epicenters-to-be. The fireballs were about a foot or more in diameter, tapering toward the top, with the color of a „newly lit match"; they rose 10 meters above the ground, lasting only a few seconds; over 100 were seen in one night; they caused vines on the ground to be burned.

It might of course be argued that the occurrence of such gas-related precursory phenomena is simply due to the disengagement of gas from the expanding porosity of shallow rocks undergoing increasing strain prior to an earthquake. Some gas generation due to such dilatancy no doubt occurs but it seems unlikely to account for the fact that the characteristic precursory behavior is abrupt and irregular, at times while the measured strain is either steady or only gradually increasing and still far from critical. Furthermore the precursors are often prominent at great distances from the epicentral region where the strain ought to be highest.

The source of the gas responsible for the observed precursors is therefore more likely to be found at depths corresponding to the focus of the subsequent earthquake, where the strain is greatest. If we require a deep-seated gas both for the dilatation and for the subsequent triggering of an earthquake, it may well be that same gas which is detected in the macroscopic precursors. The flaming phenomenon then suggests that a combustible gas is being released, and deep-seated (abiogenic) methane is the most likely candidate.

It is often assumed that porosity cannot exist at great depths because it would be crushed out and the fluids expelled upward by the excessive lithostatic pressure. But this is not always the case. The porosity of the lithosphere falls into two quite different

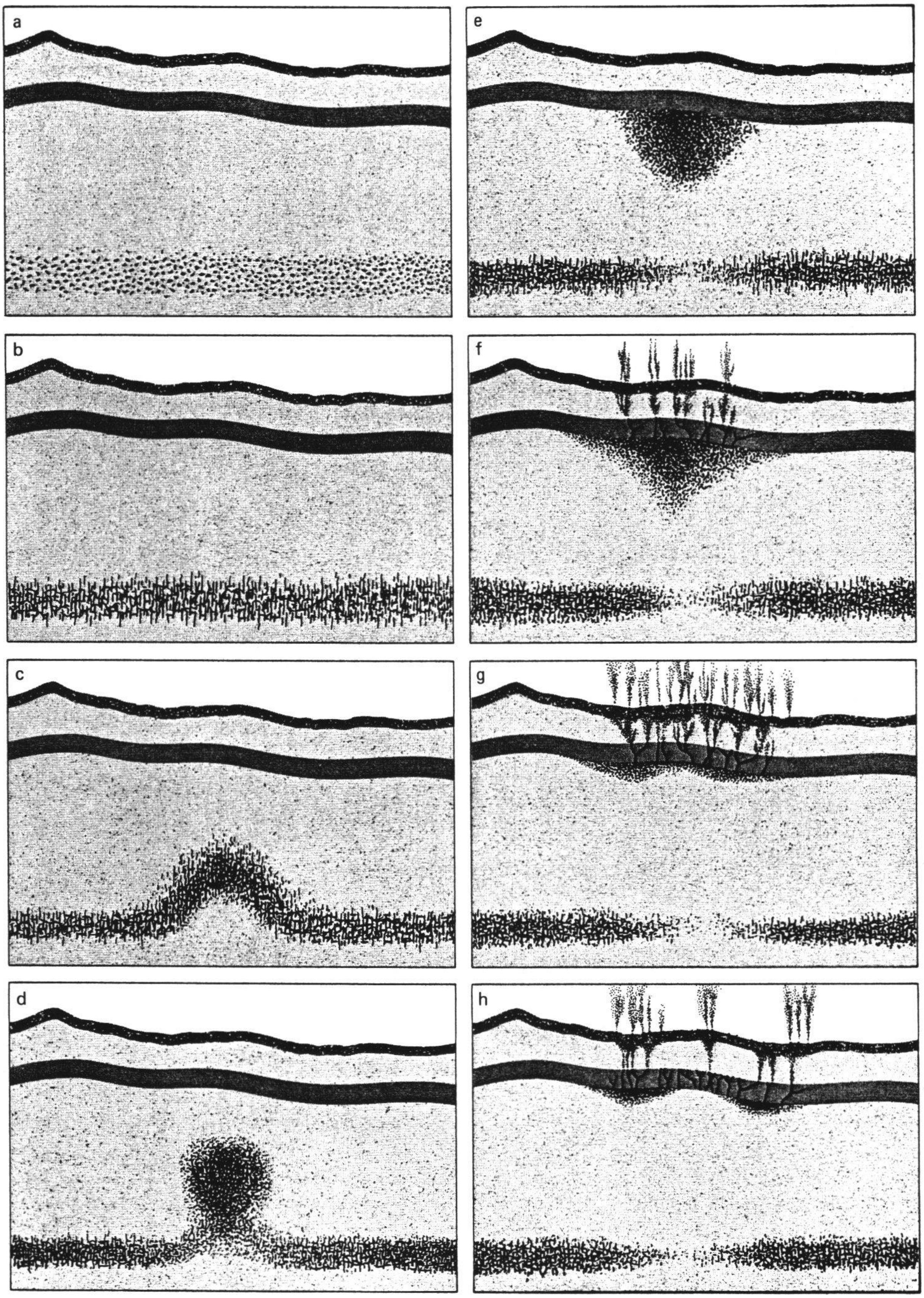


Fig. 5

regimes. As one drills down from the surface one generally encounters pore spaces in the rocks, usually interconnecting and filled with water. The pressure in them is that appropriate to the overburden of water, approximately three times less than the pressure within the adjacent rock. As one goes deeper the porosity slowly diminishes and eventually a level must be reached where the rock is no longer strong enough to support this differential pressure. Interconnected pore spaces there will indeed collapse, and whatever liquid or gas is in them will be expelled upwards. As one approaches this critical level, the porosity rapidly diminishes, but the pressure will still in general be given by the water overburden. However, beneath this level there can be another domain in which pockets of gas can again exist, but with the pore fluids now at the higher pressure approximating that in the rock. Of course if any connection ever establishes itself through the critical level, gas would rapidly escape and the connection would be crushed shut. The depth of this layer is dependent on the strength of the rock, but is usually between four and six kilometers.

We can assume that at great depths below the critical level, gas is generated at a rather steady rate, either by chemical reactions or by diffusion out of the solid. It begins to open pores. When a „pore space domain" becomes interconnected over a sufficient interval of height (probably several kilometers), it becomes hydrostatically unstable and will begin to ascend. This is because the strength of the rock is no longer sufficient to support the difference between the pressure gradients in the gas and in the denser rock. At this stage, the pores at the bottom will collapse and pores at the top will be opened up; the pore space domain as a whole will slowly migrate upwards. It probably requires some years to work its way from a depth of a few hundred kilometers to the surface. Since the average pressure in the gas decreases during the ascent, the volume of the pore space domain must increase. It is to this that we might attribute the gradual rising of the surface (of order 10 cm) that has sometimes been detected over a period of years preceding an earthquake. When the pore space domain penetrates the critical layer and enters the hydrostatic regime, rapid venting may lead to macroscopic precursors and shallow earthquakes.

Gases evolving from deep below will therefore exist in pockets left over in each case from the last venting episode, and such pockets must then be just a little smaller in vertical extent than the size that would drive upward migration and venting. But the amount of gas in such a region (with a vertical dimension of several kilometers) is probably much larger than that in most of the pockets trapped beneath impermeable layers in the upper hydrostatik domain, the conventional natural gas deposits.

If both the macroscopic precursors and those involving dilatancy are in fact merely secondary symptoms of a principal underlying cause – namely, the increasing gas pressure and porosity at depth – then it might be possible to monitor the primary phenomenon itself and thereby obtain a more secure basis for earthquake prediction. Perhaps it will be possible, by repeating seismic refraction profiles at the same location at intervals of a few months, to detect small changes in the seismic velocities due to changing porosity; we might then actually observe the ascent of a pore space domain. Efforts to monitor directly the subsurface gas composition and pressure in fault zones would be most useful. Several research groups in the Soviet Union are already engaged in substantial programs to observe changes in the chemistry and isotope ratios of ground gases, changes that are now known to occur prior to earthquakes. Much of this work is being done by that substantial minority of chemical geologists in the Soviet Union who have also taken an interest in abiogenic petroleum.

We believe that in addition to suggesting new approaches to earthquake prediction, the deep Earth gas hypothesis also suggests the possibility that truly large amounts of methane from internal sources have accumulated in regions where, on the basis of the conventional biogenic theory, they would never have been suspected. The upper domain in which gas is at the hydrostatic pressure has been extensively surveyed, but perhaps even that not well enough. The lower domain, however, where gas can exist only at lithostatic pressures, has as yet received little serious consideration. In a few places, deep „geo-pressured“ gas has been tapped, but in each case has been thought to be present only as a result of an unusual geological configuration. If it turns out, however, that this is a widespread phenomenon and that below the critical level of zero porosity there generally exists another regime of large porosity due to high pressure gas, then the whole outlook regarding the world's fuel supplies might have to be re-evaluated. The quantities of gas that have been associated with carbon degassing of the Earth as a whole have of course been enormous, and if methane has been a significant contributor, then even the fraction „temporarily“ caught in the high pressure domain on the way up may still be very large compared with all other known fuel reserves.

It is clear that we understand very little as yet of the degassing processes of the Earth. No one really has any secure evidence regarding the gas regime more than a few kilometers below the surface. Undoubtedly our model will turn out to be oversimplified and in places overstated. In this many-sided discussion, ranging from cosmochemistry to seismology, we have made a first attempt to formulate a relatively simple hypothesis to account for a large number of previously unrelated and sometimes anomalous facts. Further research leading eventually to the refinement or even the rejection of these ideas will, in either case we hope, help to enlarge our understanding of the Earth.

Appendix I - III p. 28 - 35 ▶

Appendix I:

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(by subject in order of presentation in text)

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Appendix II:

Hydrocarbons and the Mohorovicic discontinuity

The upward migrating gas, upon encountering the nearly horizontal layering of the base of the crust (the Mohorovicic discontinuity, or Moho), will not simply penetrate into the crust, but rather will more readily tend to be guided along the discontinuity in the direction of its upward gradient. The gas will thus migrate laterally until it accumulates in „pools" at those places where the Moho is most shallow, analogous to the stratigraphic traps of conventional petroleum geology. Any region of the Moho which maintains a relatively smooth upward gradient over an extensive area may thus provide an effective „catchment" surface for a large accumulation of gas.

It is therefore worth investigating wheter the locations that would be favored on such a basis are indeed regions of known hydrocarbon deposits. While the detailed topography of the Moho is not known in most areas, its relative depth can be crudely inferred from the isostatic flotation of the continental masses. Thus, in general, the Moho will be deep where the surface of the Earth is high, and its level will approximate an exaggerated inverted replica of the surface elevation.

The upper surface of the Arabian plate, for example, presents a smoothly sloping downward trend from the Red Sea coast to the Persian Gulf. Continuing eastward, the surface topography rises again. Presumably the Moho roughly mirrors this profile, with a stratigraphic high occurring under the Persian Gulf where the crust is thinnest. All the deep gas migrating upward under the Arabian plate would then tend to be channeled to the Persian Gulf region and its extension into the Tigris River valley, where is would give rise to the enormous petroleum deposits found there. Accurate seismic mapping of the topography of the Moho is required to understand this and other examples of deep gas accumulation in more detail.

Appendix III

Selected earthquakes showing gas eruption phenomena

Quebec Feb. 5, 1663

Sonds: „a rumbling like thunder. . amid a noise that made people think there was a fire crackling in their garrets".

Flames: „pikes and lances of fire were seen, waving in the air, and burning brands darting down on our houses-without, however, doing. . .injury"; „. . .from the earth. . . emanated fiery torches and globes of flame-now relapsing into the earth, now vanishing in the very air, like bubbles"; „a great section of the earth [was] borne upward and carried into the river; and, at the place whence it was separated by the yawning open of the earth, there burst forth globes of smoke and flame".

Sulfur and gas: „the river changed its color. . .for eight entire days, !it

Sulfur and gas: „the river changed its color. . .for eight entire days, [it] put on a sulphurous one"; „during the whole night, sweltering heat puffs exhaled from the soil".

Principal source: The Jesuit Relations and Allied Documents, Vol. 48.

Vosges (France) May 13, 1682

„Flames were also seen coming from the earth, without there appearing any opening, nor any other outlet, except in a single spot, where there opened a cleft, the depth of which could not be measured. . . The flames which issued from the earth, and which occurred most frequently in places that had been planted, such as woods, in no way burnt the objects they encountered; they gave off an extremely disagreeable odor, but one that hat nothing sulphurous about it. . .".

Claude Perrault, quoted in Galli's catalog #27, p. 266.

Lisbon Nov. 1, 1755

„The 1st of November, the day broke with a serene sky. . .but about nine o'clock the sun began to grow dim, and about half an hour after we began to hear a rumbling noise, like that of carriages, which increased to such a degree as to equal the noise of the loudest cannon; and immediately we felt the first shock, which was succeeded by a second and a third; on which, as on the fourth, I saw several light flames of fire issuing from the sides of the mountains, resembling that which may be observed on the kindling of coal. . .I observed from one of the hills called the Fojo, near the beach of Adraga [near Colares], that there issued a great quantity of smoke, very thick, but not very black; which still increased with the fourth shock, and after continued to issue in a greater or less degree. Just as we heard the subterraneous rumblings, we observed it would burst forth at the Fojo; for the quantity of smoke was always proportional to the subterraneous noise. . .".

Mr. Stoqueler, Phil. Trans. Roy. Soc. 49, 413 - 418 (1756).

Calabria Feb. 5, 1783

„At the time of the earthquake, during the night, flames were seen to issue from the ground in the neighborhood of the city towards the sea, where the explosion extended, so that many countrymen ran away for fear; these flames issued exactly from the place where some days before an extraordinary heat had been perceived. (emphasis added)

Francesco Ippolito, Phil. Trans. Roy. Soc. 73, Appendix i-vii (1783).

„The water of the wells, of the sea, and also of the fishponds, a few hours before the earthquake of 5 February struck in Cosenza and neighboring villages, was seen to raise its level, all foaming as tough boiling, without being observed to have a greater heat than normal". (emphasis added)

Nicolo Zupo, Riflessioni su le cagioni fisiche dei Tremuoti accaduti nelle Calabrie nell'anno 1783 (Naples, 1784), quoted in Galli's catalog, #57, p. 303.

Cumana (Venezuela) Dec. 14, 1797

An hour before the shock, a strong smell of sulfur was perceived, and before the earthquake flames appeared on the banks of the Manzanares.

Alexander von Humboldt, Personal Narrative of Travels to the Equinoctial Regions of America during the years 1799 - 1804, Vol. I, p. 163 (1889).

New Madrid (Mississippi Valley) Dec. 16, 1811 trough Feb. 7, 1812

Sounds: „distant rumbling sounds, succeeded by discharges, as if a thousand pieces of artillery were suddenly exploded"; „a loud roaring and hissing. . . like the escape of steam from a boiler, accompanied by . . . tremendous boiling up of the waters of the Mississippi in huge swells"; „explosions".

Lights: „many sparks of fire emittend from the earth"; „flashes such as would result from an explosion of gas".

Sulfur: „complete saturation of the atmosphere with sulphurous vapor".

Visible waves: „the earth was observed to roll in waves a few feet high with visible depressions between. . . these swells burst, throwing up large volumes of water, sand, and coal".

M.L. Fuller, USGS Bull. 494 (1912).

Callao (Peru) March 20, 1828

Water in the bay „hissed as if hot iron was immersed in it", bubbles and dead fish rose to the surface, and the anchor chain of H.M.S. Volage was partially fused while lying in the mud on the bottom.

Quart. J. Sci. Lit. & Arts, Jan.-June 1829.

Lima (Peru) March 1, 1865

The surface of the bay was agitated with jets of water 12 to 15 inches high, there was a strong odor of hydrogen sulfide, and the white paint on the U.S. Ship Lancastre was turned black.

Amer. J. Sci., 2nd Ser. 40, 365 (1865).

Arica (Chile) Aug. 13, 1868

„From every fissure there belched forth dry earth like dust, which was followed by a stifling gas. . . which severely oppressed every living creature, and would have suffocated all these if it had lingered longer stationary than it did, which was only about 90 seconds".

New York Tribune, Sept. 14, 1868.

Owens valley (Calif.) March 26, 1872

Sounds: „Several [shocks] were distinctly preceded by a dull, explosive sound, like the noise of the firing of a piece of heavy artillery at a great distance, or the letting off of a heavy blast. . . in several cases the explosive sounds were heard by our party when no subsequent vibration was perceived".

J.D. Whitney, Overland Monthly 9, 130 - 140, 266 - 278 (1872).

Flames: „People living near Independence. . . said [that] at very succeeding shock they could plainly see in a hundred places at once, bursting forth from the rifted rocks great sheets of flames apparently thirty or forty feet in length, and which would coil and lap about a moment and then disappear".

San Francisco Chronicle, April 2, 1872.

„Immediately following the great shock, men, whose judgment and veracity is beyond question, while sitting on the ground near the Eclipse mine, saw sheets of flame on the rocky sides of the Inyo mountains but a half a mile distant. These flames, observed in several places, waved to and fro apparently clear of the ground, like vast torches; they continued for only a few minutes".

Inyo Independent, April 20, 1872.

Charleston (S.C.) Aug. 31, 1886

Sounds: Heavy explosions were heard in Summerville (near the epicenter) on Aug. 27 and 28.

C.E. Dutton, Ninth Ann. Rept. USGS, pp. 270 - 272 (1899).

After the earthquake, in Summerville, „All during the day there was a constant series of detonations. . . from all possible directions. It resembled the discharge of heavy guns at intervals of about ten minutes, and was like the sounds of a bombardment at a great distance. . . it was only occasionally that the earth would quake from the subterranean discharges. . . Nearly all the wells had been at low water. There was a sudden rise in these wells. . . Just before any of the land detonations, [one could] see the water rise up the walls of the well and after the shock again subside".

Charleston News and Courier, Sept. 1, 1886.

Atmospheric effects: „Immediately after the great shock. . . a strong odor, remarkable for the presence of sulfur gases, permeated the atmosphere, and was perceptible throughout the night".

Dutton, op. cit.

A witness in Charleston reported that „It was terribly hot about 20 minutes before the shock. It was a peculiar scorching heat that I never felt before. I saw people on the streets taking off their coats and vests as they walked along. Then there was a rumbling noise". [note: the earthquake occurred at 9:51 p.m.]

New York Times, Sept. 4, 1886.

Visible waves: „The ground began to undulate like a sea. . . I could see perfectly and could make careful observations, and I estimate that the waves were at least two feet in height".

Eyewitness quoted by Dutton, op. cit. [Many similar accounts of visible waves were published by Dutton.]

Sonora May 3, 1887

Lights: Flames issued from fissures, in some cases scorching overhanging branches.

G.E. Goodfellow, Science 11, 162 (1888).

Visible waves: „seemed to be two feet high, about twenty feet apart, and moved as rapidly as the incoming waves along the seashore".

B. MacDonald, Bull. Seismol. Soc. Amer. 8, 74, (1919).

San Francisco April 18, 1906 [5:13 a.m.]

Lights: In San Jose, according to engineer J.E. Houser, „the whole street [was] ablaze with fire, it being a beautiful rainbow color but faint". Reports of blue flames also from Petaluma Creek and „hovering over the bases of foothills in western San Francisco".

E.L. Larkin, Open Court 20, 393 (1906).

Sounds: Healdsburg mining engineer George Madeira reported „Heavy detonations and rumblings were heard near the base of Mt. Tamalpais, Marin County, during the winter months and previous to the great earthquake which destroyed San Francisco. . . and have been heard up to this writing [May 5, 1908]".

T. Alippi, Boll. Soc. Sismol. Italiana 15, 65 (1911).

Visible waves: San Francisco police sergeant Jesse Cook said: „. . .I could see it actually coming up Washington Street. The whole street was undulating. It was as if the waves of the ocean were coming towards me, billowing as they came".

G. Thomas and M.M. Witts, The San Francisco Earthquake, p. 69.

Twenty-two similar accounts of visible waves, distributed over a 600-km span, were reported by the State Earthquake Investigation Commission in The California Earthquake of April 18, 1906, Vol. 1, Pt. 2, pp. 380 - 381 (1908). The amplitude most often reported was about a foot.

Swabia (South Germany) Nov. 16, 1911

Lights: „We saw a sea of flames, gas-like and not electrical in nature, shoot up out of the paved market street. The height of the flames I can estimate at 8 to 12 cm; it was like when you pour petroleum on the ground and light it".

„I observed very precisely how a bright fire, which had a bluish color, came up out of the ground in the meadow. The height of the fire might have been about 80 cm".

Eyewitness accounts, among many others, from A. Schmidt and K. Mack, Württ. Jahrbücher für Statist. u. Landeskde., Jahrg. 1912, Heft 1, p. 96 et seq (1913).

Gas: There are several accounts of people feeling giddy just prior to the earthquake, or noticing stifling air. After the earthquake, Lake Constanz appeared to „boil". The smell of sulfur was prominent in the air.

G. Rüetschi, Jahresberichte und Mitteilungen des Oberrheinischen geologischen Vereins Karlsruhe N.F. 3, 113 (1912).

Rumania Nov. 10, 1940

Flames: flames in rhythm with the movements of the soil"; „flames issuing from rocks, which crumbled, with flashes also issuing from non-wooded mountainsides"; „irregular gas fires".

Gas: „a thick layer like a translucid gas" above the surface of the soil.

G. Demetrescu and G. Petrescu, Acad. Roumaine, Bull. Sci. 23, 292 - 296 (1941).

Chile May 22, 1960

Observations of the sea having the appearance of „boiling" were reported over a range of nearly 450 km.

H.A. Sievers, Bull. Seismol. Soc. Amer. 53, 1125 (1963); W.M. Adams, Earthquakes (1964).

Haicheng Feb. 4, 1975

Earthquake lights were seen immediately before the shock.

C. Barry Rayleigh, personal communication, Dec. 1977.

Gas: The emission of „earth gas" and hot air preceded the earthquake. „Many areas were covered with a peculiar fog. . . just prior to the quake. The height of the fog was only 2 to 3 meters. It was very dense, of white and black color, non-uniform, stratified and also had a peculiar smell. It started to appear 1 to 2 hours before the quake and it was so dense that the stars were obscured by it. It dissipated rapidly away after the quake. The area where this 'earth gas fog' appeared was related to the fault area responsible for the earthquake. . . People in the quake area remarked that the air temperature was higher than usual during the days before the quake. Just before the earthquake many were not feeling well because of the warm weather. . . People. . . smelled this gas in an area measuring 15 x 5 km; one person fainted because of this. A certain commune member in Fung--hsing-hsein in fact saw gas bubbling out of a ditch. According to an incomplete survey, this 'earth gas' appeared quite a few times: it was noticed on Dec. 24, 1974, Jan. 14, 15, 22, 27, 30, Feb. 3, 1975, in many areas".

Acta Geophysica Sinica 20, 270 (1977).

East Anatolia Nov. 24, 1976

Booming sounds were heard several times in the two weeks prior to the quake; oil seepages were also noticed as a precursor. „Töksoz also interviewed villagers after a 6.7 magnitude quake in another part of eastern Turkey on Sept.5, 1975. He says that survivors of this quake reported . . . a brightening of the sky the night before the event. Some geologist 250 km away also noticed the brightening in the direction of the earthquake epicenter".

Science News 112, 408 (1977).