and the surface was established by drilling more than 450 wells (Fig. 3). Nearly 50 million barrels of oil were brought to the surface through these wells. Most was conveyed off-site to markets, initially in tanks and thereafter mostly by pipeline, but some was spilled and left in sump basins that were then a standard feature of the production system. By the 1930s, the urban development value of the land overlying the Salt Lake oil field exceeded its value as a production site for a declining oil field, and the field was largely abandoned. The legacies of a thirty-year oil boom included several large family and corporate fortunes, a few square miles of land where the natural upward hydrocarbon migration was complicated by the presence of hundreds of abandoned wells plus numerous filled sumps and covered-over spills, all underlain by a partially depleted hydrocarbon reservoir. Following the abandonment of most oil production, the area was rapidly covered by the homes, apartments, businesses and industrial facilities that exist today (Fig. 2). The remaining and most notable hydrocarbon presence is manifest in that popular and scientifically important exhibit of the "La Brea Fossil Pits" and Page Museum in Hancock Park on Wilshire Boulevard near Fairfax Avenue.

Meanwhile, beneath this urban environment, the underlying Salt Lake oil field was again tapped, in 1961, through skillful application of modern oil drilling techniques and production technology. This time, however, the entire surface installation was contained in an unobtrusive, screened complex covering only one acre. This compact facility included the heads of 43 wells which were slant-drilled to exploit several lease block holdings over an area of about a square mile (Figs. 3, 4), together with necessary equipment for separation of the well-head crude oil into oil, gas, and water components. The gas was disposed of by injection back into the Gilmore block of the field between 1961 and 1971. Salt water was initially disposed of by discharge into a local storm drain, but for environmental reasons was required to be injected back into the field, also in the Gilmore block, since 1964 (Crowder and Johnson, 1963; California State Division of Oil and Gas [C.D.O.G.], 1974).

AFTERMATH OF THE 1985 ROSS STORE EXPLOSION

After the flames subsided and the post-explosion exploration and gas-control drilling was completed, a special Task Force was convened at the direction of the Los Angeles City Council. The Council wanted to know what had happened and how future accidents could be prevented. The Task Force was made up of representatives from both City and State agencies and from industry, and it had available a Geologic Technical Committee which included experts in engineering geology and other relevant disciplines. Concurrent with the deliberations of the Task Force, the Senate of the California State Legislature enacted SB1458, the Roberti Bill, which required a study of the location of all abandoned oil and gas wells within the State of California.

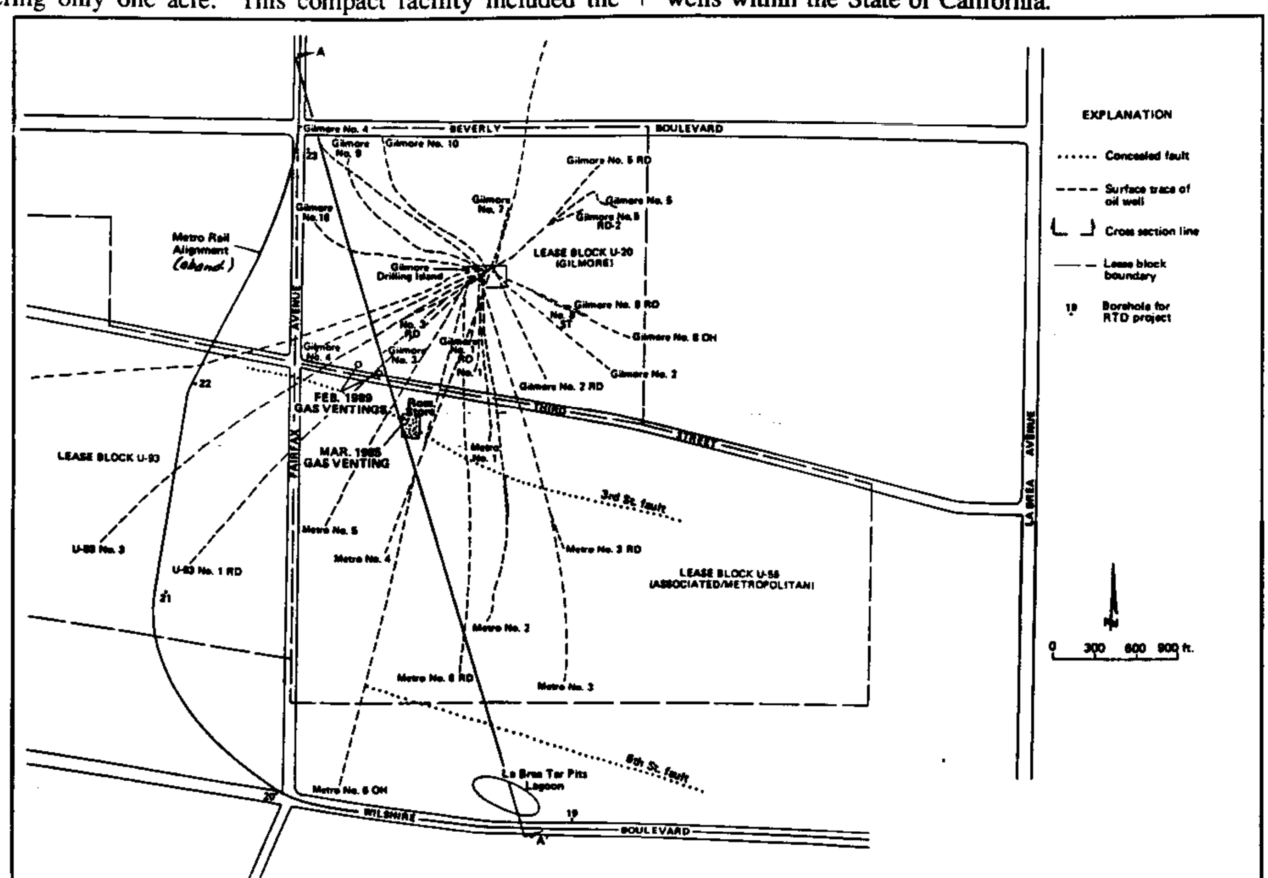

Figure 4. Surface plan of wells, faults and gas ventings, vicinity of Ross Store Site

Despite its own initial interest in abandoned wells as a potential source of the gas and the mandated purpose of the Roberti Bill to study such wells, the Task Force's surprising conclusion was that neither the existence of dozens of such abandoned wells, nor even the presence of the underlying oil and gas field which had been venting to the surface for a hundred millennia, had anything to do with the gas venting accidents. In fact, the oil field operation was not even mentioned as a possible agent in the Task Force report. Instead, a chemical analysis of a sample of the venting gas led the Task Force to conclude that the gas was of "biogenic" origin, presumably derived from near surface decaying of organic matter in the alluvial soil, rather than being of petrogenic or thermogenic origin, i.e., derived from rock-source hydrocarbon (oil field type) accumulations. The Task Force then went on to present a scenario of shallow "biogenic" methane being displaced and pressurized by a rising water table in the perched fresh-water aquifer beneath the Ross Store. It was an imaginative explanation: what school child is not aware of that primordial scene of mastodons thrashing about in a gassy swamp (as is artfully represented at full scale in the Hancock Park exhibit, only two blocks from the Ross Store). Troublesome legal issues were eliminated by this conclusion, the implication being that the methane hazard could exist virtually anywhere, so no human agency was at fault for its workings. The presence of the abandoned wells, the filled sumps, or anything else having to do with the past and current exploitation of the Salt Lake oil field evidently was considered no more than coincidence.

About a year after the issuance of the Task Force report, the results of two separate studies of the composition and indicated origin of near surface gas samples both at the Ross Store and elsewhere in the Los Angeles Basin, became available. One report was prepared under contract to the C.D.O.G., in response to the Roberti Bill (Geoscience Analytical, Inc., 1986). It presented the results of a study of eight selected urban areas sited over oil and gas fields where there were wells abandoned prior to 1930, and where there was a history of oil and/or gas seepage. This report concluded that with few exceptions, the methane present in these areas was, as at the site of the Ross Store building, of biogenic origin and thus unrelated to the underlying oil and gas accumulations. In their opinion it was essentially swamp gas. This remarkable conclusion was all the more interesting since it turned out that most of the areas sampled are local topographic highs. In any case, the results of this massive study assured the public the hazardous conditions identified by the Task Force as existing at the Ross Store, as well as "the vast majority of the high concentration gas samples" taken from the surface areas overlying oil and gas deposits throughout the Los Angeles basin, were also of purely natural swamp gas origin unrelated to human activities or oil field presence.

The other study, based on isotopic analysis of samples of gas at the Ross Store building escaping on the day following the explosion, concluded that the gas was of thermogenic origin, hence, came from an oil reservoir source (Global Geochemistry, 1986). These contradictory studies, one compatible with the Task Force's "rising ground-water displacing shallow biogenic gas" and the other clearly not, failed to elicit any notice outside of the groups of attorneys and technical consultants who were by then engaged in the inevitable legal maneuvering among the injured explosion survivors and the possible responsible parties.

Official disinterest continued into early 1989, when a second notable gas excursion occurred in the Ross Store neighborhood. This event, referred to officially as "Incident #113", is described in the subsequent "Task Force Report II on the Methane Gas Incursion" (1989) as follows:

"At or before 6 a.m. on February 7, 1989, an incursion of methane gas occurred within the K-Mart Store located at Third Street and Ogden Drive. The gas was detected on a portable unit which had detected near-explosive levels of methane within the store when employees entered the building. The Fire Department was notified and the employees evacuated the building. The responding Fire Department units observed a fountain of gas, water, and mud at the southwest corner of the Gilmore bank and additional emergency units were dispatched to the scene. Within 2 hours, explosive levels of methane were measured within the Gilmore Bank, K-Mart store, and in subsurface locations outside of these buildings including the Ross Dress-For-Less Store. The response team soon recognized similarities to the 1985 event in location and that the gas incursion was a higher-pressure type event. The area was then cordoned off to prevent ignition and explosion of the gas."

Fortunately, no explosion occurred this time and, as it had in 1985, the gas "incursion" dissipated within a few days time. The venting event did, however, trigger a reconstitution of the Task Force that had been convened following the 1985 explosion, and this body generated the "Task Force Report II" noted above. The 1989 Task Force had to grapple with the reality that there was no way the "rising ground water" component of its original (1985) position could account for the fountain of gas, water, and mud that occurred in 1989, while steadfastly maintaining that past and contemporary drilling and production in and from the Salt Lake oil field had nothing to do with the venting occurrences. Because the arguments and discussion in the 1989 Task Force Report II are distinct from those in the 1985 Task Force Report, those two reports are discussed separately in the following sections.

TASK FORCE REPORTS - DISCUSSION

The facts that established the point of departure for the 1985 Task Force's investigation were the following:

1) The explosion and ensuing fire were caused by ignition of methane gas venting from the ground beneath the site and vicinity, and

2) The methane gas did not originate within the utility distribution system. The latter point, as noted in the Task Force Report, was confirmed both by chemical analysis of the gas which showed it to be free of the tracer chemicals always added to commercial gas, and by the observation that the gas continued to vent after all pressure mains into the area were shut off.

Proceeding from these facts, the conceivable scenarios were the Task Force Report conclusion of gas of shallow biogenic origin displaced and pressurized by rising ground water (or a variation of this not given credence in the report), in which the gas originates in residual surface accumulations of crude left over from the early days of the Salt Lake oil field exploitation and subsequently buried during the course of urban development. The other scenarios addressed but rejected by the Roberti Bill Study were gas escaping from the underlying oil field via an inadequately abandoned well, to various possibilities of gas escaping from the underlying field, either as a continuation or resumption of the natural leakage that had previously characterized the field, or as a totally new process, related in some way to the current operation of the field. At the time the Task Force proposed it, there was no evidence to disprove the "shallow biogenic gas displaced by a rising water table" theory. Its plausibility, however, was another matter, especially in regard to the ability of a rising water table to pressurize shallow gas to the 28 psi found at 40 feet depth in the relief well drilled in the Ross Store parking lot the day after the explosion. The absence of this condition as a hazard in urban areas underlain by organic material and subject to variable water table levels raises some question as to whether it is a common condition, especially in semi-arid areas like Los Angeles, hardly known for extensive shallow organic soils.

The Task Force's biogenic gas theory would appear to have several requirements, as follows:

- The methane gas should be uniquely of shallow-biogenic origin, (hence have no possibility of having originated in the underlying oil and gas reservoir). This conclusion relied on the results and interpretation of the chemical test on a gas sample obtained following the explosion. The results of the Roberti Bill study in which application of the same chemical criterion to gas sampled from the soil overlying known gas-producing fields throughout the Los Angeles Basin yielded the same conclusion, i.e., that in "the vast majority" of cases the gas was also of shallow biogenic origin. This might be taken as overwhelming support for the validity of the Task Force Scenario. Alternatively, these results can be viewed as being so geologically implausible as to cast serious doubt on the validity of the chemical criterion to prove the origin of methane sampled from near-surface soil. In any case, the results of a different study employing isotopic analysis released by Global Geochemistry in June 1986, indicated that the Ross Stores gas was in fact of "thermogenic" (oil field) origin.
- The surficial deposits in the area should locally contain organic matter capable of generating methane gas upon decomposition. With regard to this issue, the data available to us are scanty, but offer no support for the biogenic gas hypothesis. Borings for the RTD line along Fairfax (Converse et al, 1981) yielded plenty of gas from soil samples but no organic matter. The soil encountered to a depth of 100 feet in these borings appeared to be of alluvial origin, and was of "rust brown" color indicating generally oxidizing conditions of deposition. Similarly, borings made for the Pan Pacific flood control basin by the L.A. County Flood Control staff (1977) encountered gassy soil, but no organic deposits. Turning again to the Roberti Bill study, one notes that many of the areas sampled were topographic highs, unlikely sites for geologically recent organic swamp deposits. Thus we find no plausible natural source for shallow biogenic gas in the Ross Store area.
- The mechanism for mobilizing and pressurizing the gas was identified as a rising water table, occasioned by cessation of pumping extraction of ground water from wells in the vicinity. This consideration can be examined from two standpoints: 1) whether such a rise in the water table of the perched zone actually occurred; and 2) whether the rise, either actual or postulated, could plausibly mobilize and pressurize shallow methane gas.

With regard to whether a rise in water table did in fact occur, as opposed to "should have occurred because extraction stopped in 1976," data from several wells located in the general area show no significant rise in the water table during the period 1976 to 1985. As with the issue of organic matter in the shallow subsurface, there may be other data that indicate some rise in the local water table did in fact occur between 1976 and 1985, but such information would be inconsistent with the pattern established by the data known to us.

With regard to the plausibility of the rising water table mechanism, we are unaware of a model which demonstrates how a rising water table displaces gas from natural traps beneath clay (or asphalt) caps in the soil section. Methane gas generated by decomposition of organic matter in a confined system can reach pressures above atmospheric. It is not so clear, however, how a rising water table could affect a pocket of gas that was confined effectively enough to maintain this excess pressure. The pressure effect of the water can be no more than hydrostatic unless the water itself is confined and pressurized. This does not occur under water table conditions.

The foregoing discussion simply addresses the position adopted by the Task Force in its' June 1985 report. As discussed below, the character of the 1989 venting incident led the subsequently reconstituted Task Force to abandon the "rising water table" mechanism, but to otherwise leave as open questions where the methane actually comes from and the means by which it is forcefully vented to the surface.

TASK FORCE REPORT II — DISCUSSION

The Methane Gas Task Force was reestablished by the Los Angeles City Council three days after the second major gas venting in the Fairfax District, which occurred on February 7, 1989. Its charge was again to report on the recent incident and "present recommendations necessary to protect health and safety within the area". The revived Task Force began its work with less urgency than had existed in 1985, since no actual damage had occurred in connection with the 1989 venting, but with a larger and more confusing data set. Some of the data that had accumulated since 1985 were simply contradictory, mainly the two different gas-origin studies. One indicated a shallow-source biogenic origin for the gas, the other indicated an oil field origin for the Fairfax gas, but the forceful ejection of gas, water, and mud during the 1989 venting clearly required a driving mechanism with more energy than a "rising water table". Faced with these contradictions and uncertainties, the 1989 Task Force elected to, in effect, throw up its hands with the following paragraph.

"*CONCLUSION ON ORIGIN — Obviously, the origin of the methane gas is complex and not clearly understood. Two reputable firms with qualifications and experience seem to have opposing opinions on the origin of the gas. But, if we intend to shield buildings or vent areas of probable methane gas seepage, the origin of the gas really does not matter. The most probable origin of the gas 'may' be a 'combination of' thermogenic and shallow biogenic sources with the high-pressure events from thermogenic (deep) sources and the low-pressure background gas from a combination of biogenic and thermogenic sources. So, in reality, the origin of the methane has its implications in the total understanding of the problem, but not in remediation or control. Methane gas produced within deep fields or in shallow marshes will not physically function nor react in the same manner. Both are capable of explosive conditions and both can be safely vented to the atmosphere.*"

Before going on to its recommendations for dealing with the problem, by a 3-point program comprising venting by relief wells, use of an area-wide monitoring survey team, and City inspection for Code compliance, the 1989 Task Force paused to provide assurance that neither past nor present activities related to exploitation of the underlying Salt Lake oil field had anything to do with the 1985 or 1989 gas venting incidents. With regard to the possibility that the gas might have escaped via one of the 400 plus abandoned wells that formerly tapped that field, the Task Force stated the following:

"*ABANDONED WELLS AS A SOURCE OF METHANE — The potential hazard imposed by old abandoned wells was not considered in the 1985 report because the gas was believed to have formed within the shallow biogenic areas above the production zone. However, the extent of chemical stripping of gas constituents and microbial alternations during migration probably could not occur within a gas bubble rising upward in a vertical shaft filled more or less with water or brine. These could, however, be the source of low-volume methane that mixes at the surface with ambient gas at low pressures. However all available chemical and isotopic information exonerates these abandoned wells as the source of the higher-pressure methane events.* (Underlining added for emphasis).

These wells are an entity to be considered in the future or as they are uncovered by area construction. But, even if the wells could be located, reabandonment to modern standards would be an expensive program."

The writers do not understand how the isotopic information reported by Global Geochemistry (1986), which indicated the Ross Store gas to be thermogenic, hence of oil field origin, in any way exonerates a potential conduit from the oil field to the surface such as an abandoned well.

With regard to the possibility that the problem might be related to disposal by pressure injection back into the subsurface of salt water stripped from the crude oil currently being extracted from the field, the Task Force stated the following:

"*PRESSURE INJECTION OPERATIONS — Within the Salt Lake field about 42 wells are currently producing from the "C" and "D" Production Zones. According to production records of the Division of Oil and Gas, more fluids are being withdrawn than are returned to the production zones. The type of injection used by McFarland Energy is a water disposal program that does not cause field repressurization. Current oil field operations within the Fairfax area, therefore, do not appear to have an adverse affect on the area methane seepage.*" (Underlining added for emphasis).

We address this latter conclusion in the discussions presented in following sections.

Although Task Force Report II explicitly "exonerated" past and present oil field operations from any role in the 1985 and 1989 gas ventings, it did, unlike the 1985 report, at least mention them. But, even this was evidently regarded as stepping outside of some kind of bounds by the Task Force member representing the C.D.O.G., since that member wrote a letter providing comments regarding the second draft of the Task Force Report II which seemed to generally take his fellow members to task for even mentioning oil field operations (Baker, 1989). This letter was provided as an attachment to Task Force Report II.

CAUSE OF THE 1985 ROSS STORE EXPLOSION AND OTHER GAS VENTINGS, FAIRFAX DISTRICT, LOS ANGELES

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INTRODUCTION

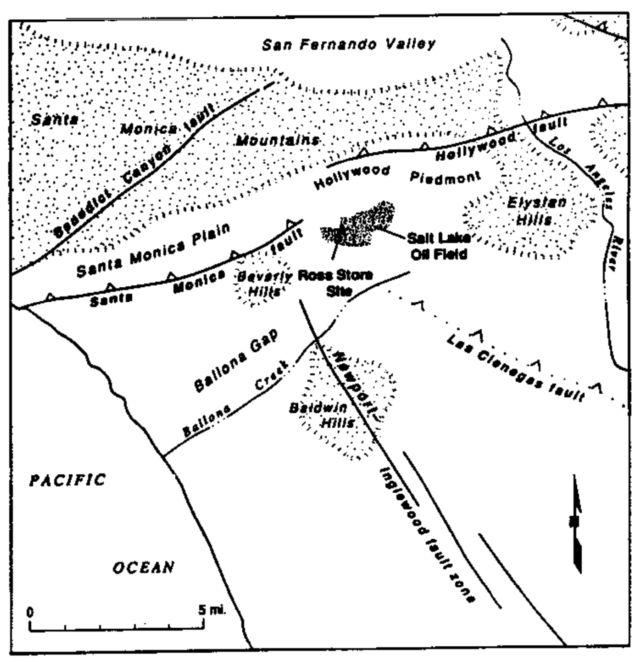
Late in the afternoon of March 24, 1985, methane gas that had been accumulating ignited in an auxiliary room of the Ross Dress-For-Less Department Store located on Third Street, in the Wilshire-Fairfax District of Los Angeles. The resulting explosion blew out the windows and partially collapsed the roof of the structure, reduced the store interior to a heap of twisted metal and resulted in injuries requiring hospital treatment of twenty-three people. Police closed off four blocks around an eerie scene of spouting gas flames that continued through the night.

In the following days, a drill rig brought to the site was used to test for possible gas accumulations in the alluvial soil beneath the store. A "pocket" of pressurized gas was encountered at a depth of 42 feet beneath the parking lot between the store building and Third Street. Gas was also encountered in several other borings at the site in smaller quantities and at lower pressures. Pressure gauges, control valves, and, on the hole where the high pressure pocket was encountered, a valved flare pipe, were installed. Following a brief period during which gas was flared and bled off into the air, the anomalous gas condition at the Ross Store site gradually declined to the normal gas concentrations characteristic of the local area. In 1989 another venting incident occurred, this time at several sites on the north side of Third Street. This second venting fortunately was detected in time, and did not ignite. In this case, water and silt were ejected from outdoor vents along with the gas, in addition to accumulation of dangerous levels of gas in several buildings. A blow-out crater several feet deep, from which dirt and small stones were ejected several feet into the air was formed during this episode which lasted about 24 hours.

The setting of the accident — an old-world Levantine market place a few miles from Hollywood; the famed tarry graveyard of the sabre-toothed tigers; pillars of fire dancing in the darkened streets — these biblical images attracted attention of the press, the bar, and local politicians. And yet, three months later when a hastily convened panel of experts announced that the event was caused by digestive rumblings of an ancient and invisible swamp the whole thing had been mostly forgotten, the explanation accepted as yet another production of Los Angeles' quirky environment. Outside of a lawsuit that was settled quietly in 1990, the possibility that the accident was caused by the knowing agency of Los Angeles' lesser known industry or that the official report of the experts, rather than being a serious statement of the scientific community, was a heavily edited script with a happily blameless ending, was not made known to the public, as we shall proceed to do here.

THE SETTING — TAR PITS AND OIL FIELDS IN THE URBAN ENVIRONMENT

The vicinity of the gas ventings lies within a sloping plain between the easternmost Santa Monica Mountains and the isolated topographic high of the Baldwin Hills (Fig. 1). The area drains via Ballona Creek, which cuts through Ballona Gap to the coastal plain fringing Santa Monica Bay. The Ross Store is in a neighborhood that has been attracting attention since the mid-Pleistocene on account of its hydrocar-



Note: Fault locations from Wright, 1991.

Figure 1. Location and Regional Setting

bon wealth; the La Brea tar pits are about two blocks to the south.

The old Salt Lake oil field, once the biggest producing field in California, directly underlies and extends west and east of the immediate neighborhood (Fig. 2). Methane gas has been a ubiquitous feature of this area so that urban engineering for both public and private facilities has required consideration of the hazards of flammable gas present in the soil. Examples include the excavation for the L.A. County Flood Control Pan Pacific storm runoff basin and park, the storm drain along Third Street, and the (formerly planned but since relocated) L.A. Metro subway along Fairfax Avenue.

Before the Ross Store explosion in 1985, there was general acceptance of the view that the hydrocarbon presence in the surface and shallow subsurface environment had its source in the underlying reservoir of the Salt Lake oil field. Upward migration of oil from parts of this reservoir was thought to be the source of the "breas" or tar accumulations that had trapped many of the Pleistocene residents of the area (Shaw and Quinn, 1986). Gas known to be present at shallow depth within the alluvial soil was likewise considered to have escaped from the reservoir and migrated toward the surface (Converse et al., 1981). The surface accumulation of the residual bitumin "breas" (Spanish for pitch) led to the discovery of the once-prolific Salt Lake oil field in 1902. As the field developed, mainly before 1917, further communication between the confined oil, gas, and water in the reservoir

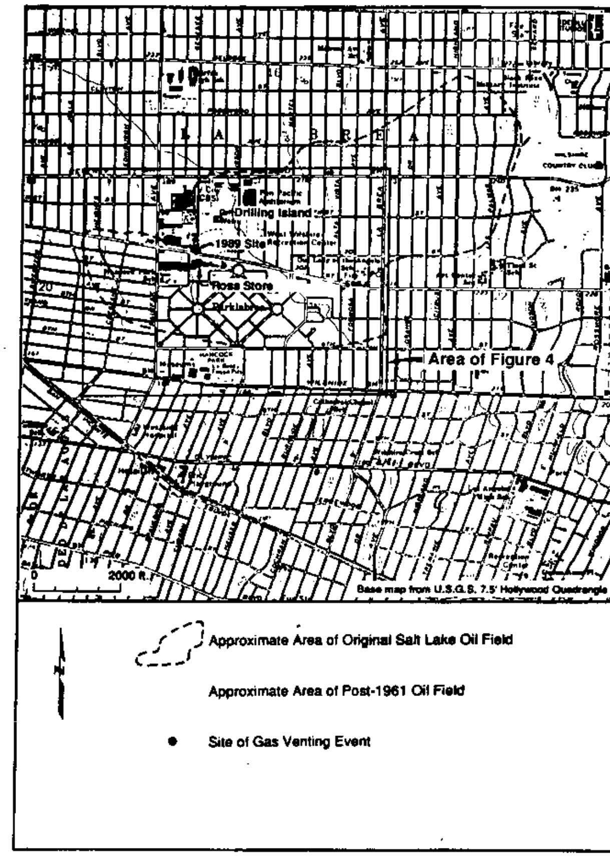


Figure 2. Wilshire-Fairfax area and the Salt Lake Oil Field

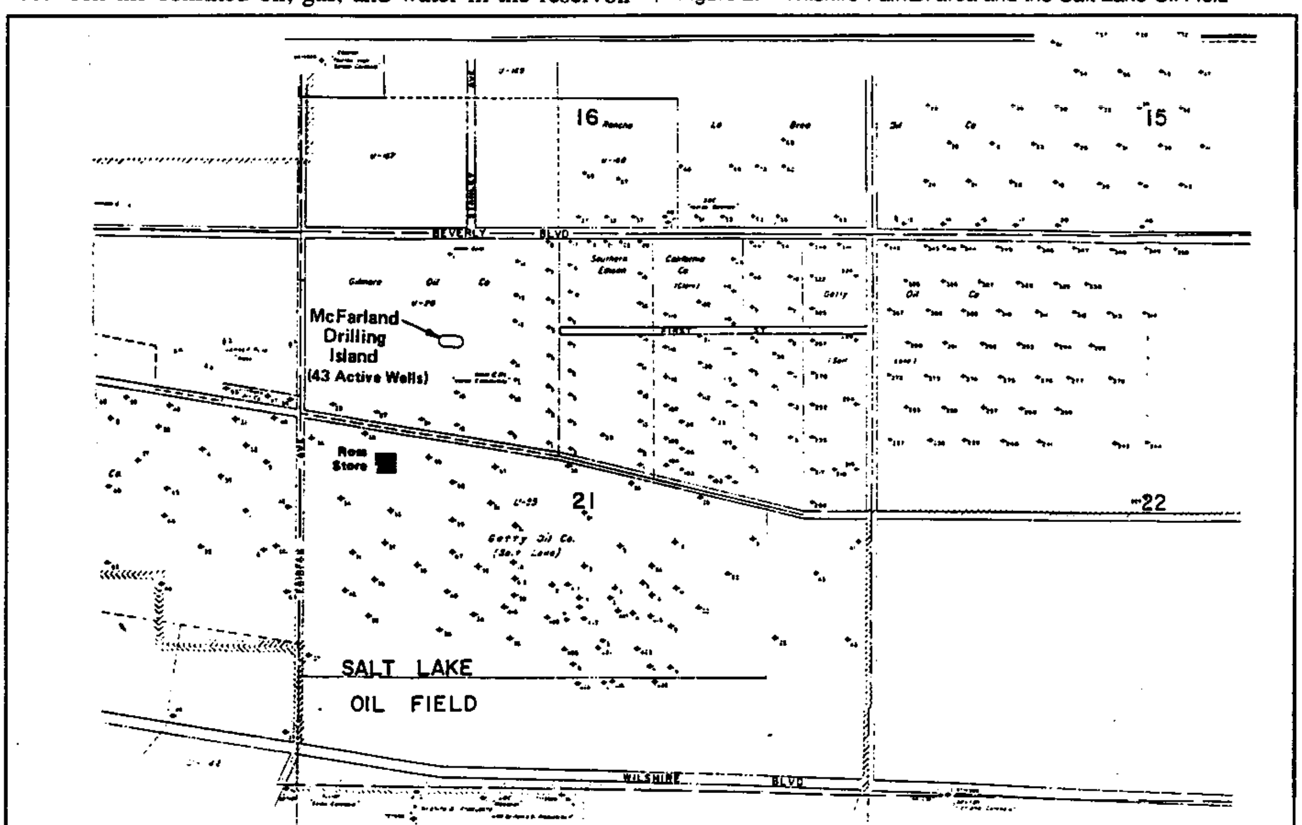


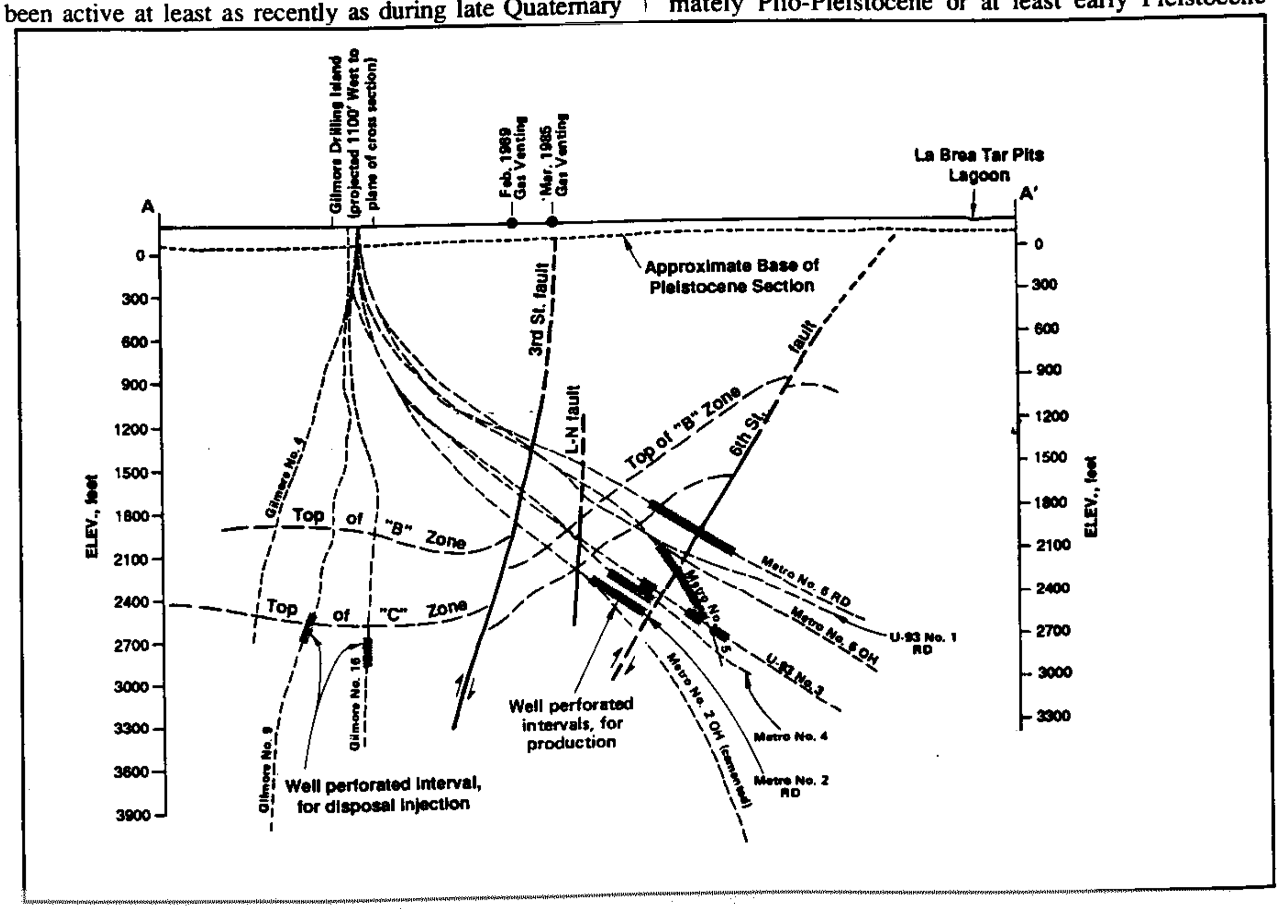
Figure 3 Abandoned and Active Oil Wells in the Salt Lake Oil Field

Source: C.D.O.G. Map 118

At the same time, a contradictory view was set forth in another letter, this from Dr. James E. Slosson, former California State Geologist and Consultant to the Task Force in both 1985 and 1989. In this letter, Slosson (1989) details his disagreement with virtually every point made in the Task Force Report II that dissociates the 1985 and 1989 gas venting incidents from the Salt Lake oil field. Unlike the letter from the C.D.O.G. member, Slosson's letter was not attached to or referenced in Task Force Report II, even though it was dated six weeks earlier.

GEOLOGIC SETTING OF THE FAIRFAX AREA

The geology of the Ross Store area has been studied and described in terms variously of surficial geology, emphasizing the formation of the La Brea tar pits (Shaw and Quinn, 1986), hydrogeology (DWR, 1965), neotectonics (Richards, 1973; Hill and others, 1979), engineering geology (Converse, 1981; L.A. County Flood Control, 1977) and petroleum geology (e.g., Hoots, 1931; Soper, 1943; Crowder and Johnson, 1963; Wright, 1991). To summarize, the area is situated near the northern edge of the Los Angeles Basin, and the central axis of the Salt Lake oil field nearly parallels and lies about 2 miles south of the Santa Monica fault. This fault forms the local boundary between the Western Transverse Ranges and the Los Angeles Basin. The Santa Monica fault is generally represented as a steeply north-dipping reverse fault, which has been active at least as recently as during late Quaternary time (Hill and others, 1979; Crook and Proctor in this volume). Hill and others (1979) based on data provided them by the City of Los Angeles Bureau of Engineering, and following Grant and Sheppard (1939), studied the surface subsidence in the region of the Santa Monica fault, including the Salt Lake oil field area. Although Hill and others (1979) viewed the results of analysis of recent micro-earthquake activity as suggesting that subsurface faults in the Santa Monica-Raymond fault zone are undergoing tectonic strain accumulation, the pattern of surface subsidence they mapped within a 5-mile wide zone along the inferred trace of this fault could be interpreted as indicating surface relaxation rather than compression (as well as indicating response to consolidation in the subsurface resulting from prior extraction of ground water). So it is not clear that the Santa Monica fault is contributing to any near-surface tectonic deformation in the area. Within the ground south of the Santa Monica fault, the folds and faults that form the structural trap of the Salt Lake oil field are the principal local geologic structures. This area is underlain by about a 200-foot thickness of Quaternary shallow marine and alluvial deposits, which overlie late Miocene and Pliocene age Repetto and Pico Formations (undivided) and late Miocene Puente Formation. The Tertiary strata are both tightly folded and displaced by steeply inclined reverse faults, but the overlying Quaternary strata are apparently undeformed (Fig. 5). Therefore, the tectonism that formed the compressional structure of the Salt Lake oil field therefore died out or has been quiescent since approximately Plio-Pleistocene or at least early Pleistocene time.



The pulse of tectonism which probably corresponds to the "Pasadenan Orogeny" (Stille, 1936 Wright, 1991), resulted in substantial north-south shortening, partly accommodated within anticlinal folds and partly along the several generally east-west aligned reverse faults. One of these, known as the Third Street fault owing to its location beneath the part of Third Street that extends east from Fairfax, locally divides the Salt Lake oil field into separate blocks with different production and pressure histories. Other faults also form boundaries of more or less isolated compartments within the field. Some of these breaks, notably the Sixth Street fault, may well have provided cross-cutting surfaces along which upward migration of oil and gas occurred from the reservoir to the overlying Quaternary capping deposits and ultimately to the surface environment. The Sixth Street fault breaches the crest of the tight anticline in the block south of the Third Street fault and is the closest recognized fault to the La Brea tar pits (Fig. 5).

The Salt Lake oil field comprises a succession of at least 6 producing horizons, referred to in order from shallowest to deepest as the A through F zones (Crowder and Johnson, 1963; Table A). The earliest oil production was from the A horizon but by the time the original development of the field reached its maximum in 1908, production was largely from the B and C horizons. The renewed production that was initiated in 1961 by wells slant-drilled from the "Gilmore Drilling Island", is altogether from the intermediate and deeper horizons. We have not had access to formation pressure data from the original period of exploitation of the Salt Lake oil field but Hoots (1930) mentions that some wells initially produced at a fairly high rate (up to 1000 barrels per day) and also that considerable gas was produced. From this we infer that the field started with a significant gas or solution-gas drive.

When the new development of parts of the Salt Lake oil field was started in 1961, a few wells flowed for a short time but all eventually required pumping; average initial tubing pressures were about 50 psi; casing pressures were approximately 100 psi (Crowder and Johnson, 1963). As of mid-1963, average daily production of the re-developed field, from an average of 13 production wells, was 650 bbl oil, 150 bbl water, and 270 MCF gas. In 1973, average daily production was 970 bbl oil, 1760 bbl water, and 686 MCF gas. Waste (i.e., salt water) disposal was discharged into the L.A. City sewer system (C.D.O.G., 1974); however, this was converted to subsurface injection back into the field starting in late 1973, through well Gilmore No. 16, completed in the "C" zone at about 2,900 feet in depth. By 1980, average daily production had declined to about 466 bbl oil and 200 bbl water. Oil production slipped gradually through the 80's reaching a daily level of about 340 bbl during our latest year of record, 1988, while water production rose, at least through 1984. Evidently, oil production was being limited by the available waste disposal options.

Production statistics for oil and water for the period 1980-1988 on record with C.D.O.G. are plotted in Fig. 6. This

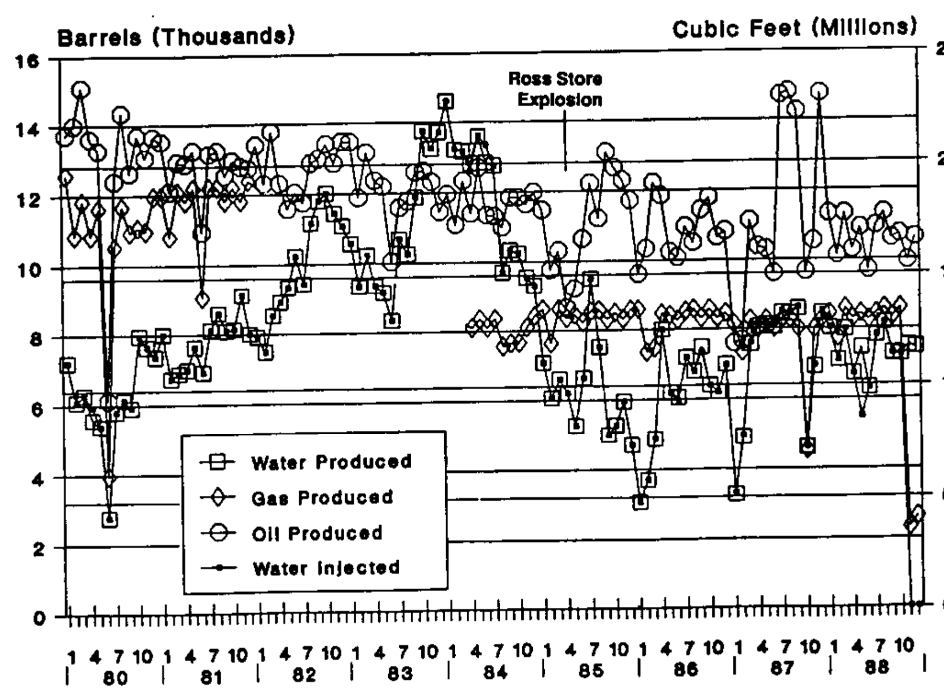


Figure 6. Reported monthly production/injection: all wells

plot shows the gradual decline in oil production noted above. Of particular interest in the context of the present discussion, however, is the history the production (and disposal) of water, brought to the surface along with the crude oil and gas hydrocarbon fluids. This is plotted separately in Fig. 7, showing monthly production and injection back into the field of the salt water byproduct of oil production. The indicated pattern is one of steadily increasing water production as oil production decreased, Fig. 6, from the beginning of 1980 through mid-1984. Between mid-1984 and about mid-1985, however, reported water production declined precipitously from around 14,000 to around 6,000 and less bbl/mo, the low being about 3,000 bbl in January 1986. A gradual upward trend in water production was re-established in 1985, so that average water production had increased to about 8,000 bbl/mo. by late 1988.

Taken at face value, the water production data shown in Figs. 6 and 7 would seem to indicate either a radical change in the oil-water ratio of the field's production, or a remarkably successful exercise in selective control of water production (for example, by shutting in certain wells or grouting off certain producing zones). In fact, however, well records on file with the C.D.O.G. show no evidence that anything like this occurred. What did happen, however, was that a second well, Gilmore No. 9, was reconditioned and converted from a production to an injection disposal well, in 1984. Meanwhile the operator, McFarland Energy, Inc., sought and received permission from C.D.O.G. to raise well head injection pressures fourfold from 200 psi to 770 psi. The workover records show that considerable effort was expended in the No. 9 conversion, including acid treatment with 5,000 gallons of hydrochloric acid and 2,500 gallons of hydrofluoric acid, in January, 1985. The well was then tested by injecting back into the C zone of the field at 475-500 psi. Thereafter, the C.D.O.G.-tabulated records of production for the Salt Lake oil field show Gilmore No. 9 as a disposal well, but no injection disposal is recorded for it prior to March, 1989. However the dramatic decrease in the quantity of water disposed of by injection into the original disposal well, Gilmore No. 16, coincided with the time Gilmore No. 9 was converted to a disposal well. Since the production of oil did not suffer a corresponding decrease, but instead actually increased by 3,000 to 4,000 bbl/mo. from early 1985, when the decrease in water disposal was most dramatic, to early 1986, the explanation for the pattern of water disposal must lie elsewhere. Given the generally constant (or at least only gradually changing) ratio of oil to water for production from this field, we suggest that the explanation may involve omission of data from the record rather than implausibly effective control of water production. According to this scenario, by mid-1984 water production would have exceeded the injection capacity of the only disposal well in the field, Gilmore No. 16, so work was begun to convert a second well, Gilmore No. 9, completed in the same lease and zone as No. 16, to function as a second disposal well; this was initially accomplished by late 1984, and an increasing percentage of the field's water production was diverted into the new disposal well through

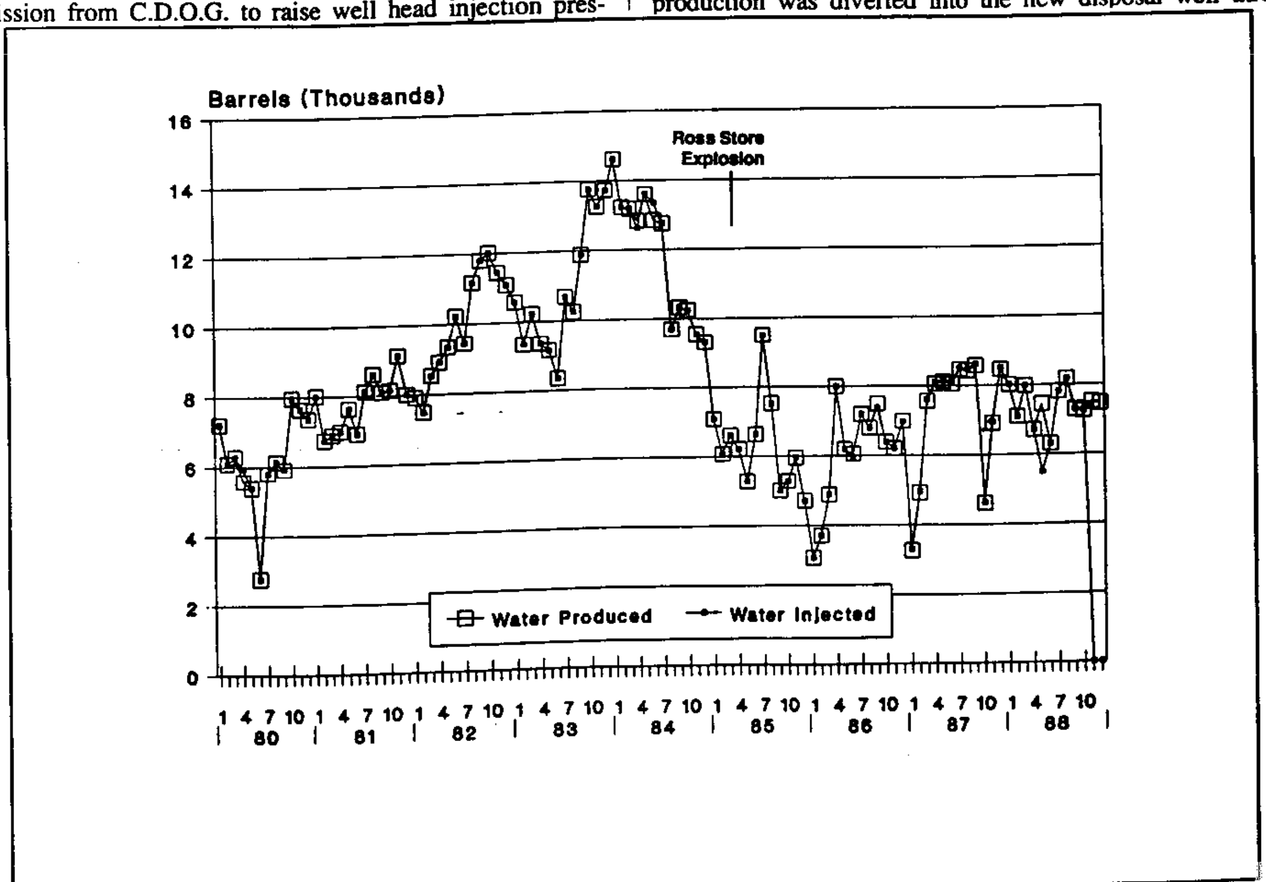


Figure 7. Reported monthly production/injection of water

mid-1985. Thereafter, we suggest that the water production may have been disposed of in both wells, probably in about equal quantities between them. For some reason, however, none of the (inferred) injection into Gilmore No. 9 was entered into the C.D.O.G. statistics, so C.D.O.G. records show only the production-injection volumes plotted in Figs. 6 and 7.

It is of interest to note that the gas venting that caused the Ross Store explosion (on March 24) occurred about two thirds of the way down the sharp decline in Well No. 16's recorded disposal history (Fig. 7). Declining injection into Well No. 16 seemingly would tend to decrease a tendency toward formation destabilization, if the factors of injection pressure and interference from recently established injection through Well No. 9 are neglected. However, it seems possible that one or both of these factors may have caused or contributed to an excursion or incremental buildup of formation pressure in the Gilmore Block "C" zone adjacent to the Third Street fault. If the injection performance of Well No. 16 is considered alone, the prior history of that well showed that the operator attempted to compensate for declining injection (due to clogging) by increasing the well head injection pressure as early as 1980. This would result in a corresponding increase in formation pressure, even if the actual amount of injection take did not increase (or continued to decline). The effect of transferring some of the injection to Well No. 9, located on the opposite side of Well No. 16 relative to the Third Street fault (Figs. 4, 5), would be to create a new pressure bulb which would form a barrier to the radial dissipation of pressure around Well No. 16, and would result in further concentration of pressure in the zone between Well No. 16 and the fault.

ALTERNATIVE SCENARIOS FOR EPISODIC GAS VENTINGS

There appear to be two basic scenarios that have been proposed, and one we propose, to explain the 1985 and 1989 gas ventings in the vicinity of the Ross Store near Third and Fairfax:

Scenario 1:	The 1985 Task Force biogenic gas/rising ground-water scenario;
Scenario 2:	The Roberti Bill oil field gas/abandoned well conduit scenario; and
Scenario 3:	The oil field gas/intermittent fracture conduit scenario.

Scenario 1 would be favored by the interpretation that the chemical composition of gas samples obtained following the March 24th explosion indicate the methane gas could not have originated under petrogenic or thermogenic (oil field) conditions, hence could not have had its source in the underlying oil field. This interpretation, of course, is contrary to the indication from the isotopic analyses that the gas in fact did originate under thermogenic conditions. Neglecting this, we believe that beyond this particular coincidence of a gas blowout occurring directly over a pressurized oil field but being completely unrelated to that field, the dubious conclusion of the Roberti Investigation, that the "vast majority" of gas above oil-gas fields in the Los Angeles Basin is unrelated to the underlying fields, effectively destroys the credibility of these "biogenic source" interpretations. Note that the 1989 Task Force abandoned the rising water table as a driving mechanism, while preserving the option that the gas might still be of shallow biogenic origin.

Scenario 2. The Roberti Bill "leaking abandoned well" scenario, corresponds to a recognized phenomenon, wherein pressurized gas and/or oil, water and entrained sediment escape via an abandoned well (or other conduit, including natural fractures and fault zones), either after the source is repressured, after the blockage or seal in the well fails, or after the fracture conduit is opened by some means. This scenario was dismissed by the 1985 Task Force on the basis of the "biogenic gas" analysis, since gas escaping from the underlying oil field would presumably be of "petrogenic" or "thermogenic" character. The 1989 Task force explicitly "exonerated" leaking abandoned wells as the source of either the 1985 of 1989 venting incidents even though the 1986 Global Geochemistry report had at least cast doubt on, if not, in the view of the Task Force, altogether disproved, a shallow biogenic origin for the gas. Endres and others (1991) on the other hand, cite leakage from naturally repressurized upper zones in the underlying oil field, most probably via old wells or well bores, as the probable source of the vented gas. We consider there to be three objections to the argument that abandoned wells are the cause, or at least the exclusive cause, of gas migration during the 1985 and 1989 venting events at Fairfax:

a) There is no known abandoned well within about 300 feet of the Ross Store building (nor within 100 feet of either of the 1989 venting sites), according to C.D.O.G. Map 118 (C.D.O.G., 1984);

b) The ventings were of brief duration — 24 hours or less, whereas an abandoned well blowout or fracture venting usually lasts longer and may continue indefinitely if not contained (a point also recognized in the Task Force Report II); and

c) The Ross Store site overlies Lease Block U-55 of the Salt Lake oil field. This block is isolated in the subsurface from the main part of the field to the north by the Third Street fault, but is undergoing active pumping extraction via wells slant drilled from the Gilmore Drilling Island. The abandoned original vertical wells in this lease block therefore bottom in a part of the field where oil, water and dissolved gas are being pumped out and pressure is thereby maintained below hydrostatic. Even in case the seal in one of these abandoned wells should fail, the ambient reservoir fluids should not have enough pressure to vent to the surface.

Endres (pers. comm., 1991) suggests that gravity drainage of oil down the steep north flank of the anticline in the Metropolitan lease block would leave a gas cap at the crest of the structure, and this together with a process of natural repressuring by access to high pressures from deeper within the structure means reservoir sands beneath the Ross Store would form a preferred source of gas. We believe, however, that in case repressuring (or some relict overpressuring) of the oil and gas-bearing zone beneath the site existed, the most likely route of fluid (especially gas) escape would be via the Sixth Street fault. This fault breaches the top of the tight anticlinal fold in the Metropolitan Lease Block (south of the Third Street fault - Fig. 5). Another route for gas would be via abandoned wells with inadequate or failing seals located in the area over the crest of this anticline. The crestal part of this structure, however, trends parallel to Third Street and lies about a thousand feet south of the Ross Stores site (Fig. 5). There would be required, therefore, for considerable lateral migration of pressurized gas (and water) for escaping oil field fluids to reach the Ross Store and Gilmore Bank venting sites.

Scenario 3. We propose a third alternative scenario, which we call the oil field gas/intermittent fracture conduit scenario. This scenario, not mentioned in the Task Force report nor set forth in the Roberti Bill charge, envisions a mechanism of intermittent releases of pressurized gas from the Salt Lake oil field, via passages temporarily opened along the Third Street fault, through the process of hydraulic fracturing. The fracturing would be triggered by buildup of fluid pressure caused by injection disposal of salt water in the Lease Block U-20 fault-isolated compartment of the field. This mechanism is similar to the fault activation process that occurred in the Inglewood Oil Field in response to pressure injection for secondary oil recovery, which in that case was instrumental in the breaching and ultimate failure of Baldwin Hills Dam in 1963 (Hamilton and Meehan, 1971). In that case, there was both escape of injected fluid to the surface along one or more fault conduits, and differential movement across faults. In the Ross Store explosion scenario proposed here, the Third Street fault fractured enough to allow upwardly migrating pulses of gas-pressurized water and free gas discharging into and through the overlying alluvial section, without detectible differential movement of the fault itself. With migration of the water upward, gas would be released either into the soil, or could vent directly to the surface.

THE OIL FIELD GAS/INTERMITTENT FRACTURE CONDUIT SCENARIO

The actual mechanism of fracturing and migration is indicated by the following calculations, in which the process is modelled by considering a fault which acts as a membrane separating adjoining fluid bearing zones within Production Zone C. We place our calculations at 3000-feet depth, roughly representative of the injection depth. This condition

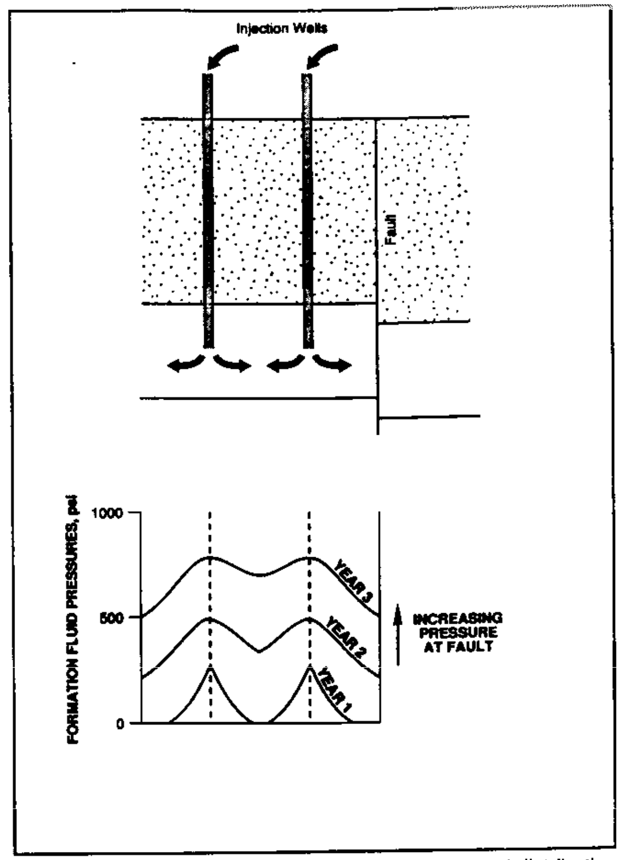


Figure 8. Diagram showing hypothetical evolution and distribution of pressure from injection wells

is shown on Fig. 8. We assume that the producing Zone C has the following history: fluid pressure initially hydrostatic, or 3000 x 0.45 = 1350 psi, with resulting partial buoyancy of sediments. Reduction of fluid pressure to about 200 psi, following extended periods of production causes compression (consolidation) of sediments with increases in both vertical and horizontal effective intergranular stresses. Assuming during this process zero horizontal strain, (the so-called "at rest" or Ko condition, in which the ratio Ko of horizontal to vertical intergranular stress is about 0.5), and a unit weight of sediments corresponding to 1 psi per foot depth (144 pcf), results in horizontal total pressure of (3000-200) x 0.5 + 200 = 1600 psi. Under this condition, any pressure, Px, from the injection side of the block acting on the fault membrane that exceeds the 1600 psi may cause incipient displacement or parting of the fault.

Now, with injection at X, fluid pressure will increase. Restoration of hydrostatic pressure in the X side of the producing zone will create original fluid pressure of 3000 x .45 = 1350 psi. This is 250 psi (at ground level) short of the fluid pressure that would equal the 1600 psi necessary to displace the fault membrane slightly. This incipient displacement condition would require an injector well head pressure of at least 150 psi, but in the short-term it would need more than 150 psi because of pressure loss in the well bore and time-dependent pressure loss between the well and the fault. This pressure decay process including both geometric and temporal decay factors can be simulated by modelling, as is routinely done by petroleum engineers. Even without doing so, however, it appears likely, based in part on other studies of the field, that the permitted 770 psi wellhead injection pressure would suffice to raise the formation pressure enough to displace the fault membrane. (Note that fracturing occurs at the fault discontinuity at some significant time after the well is pressurized, not at the well, therefore short-term hydrofracture tests of the well, which are sometimes required to check for hydrofracture hazards, would not indicate a potential for later hydrofracture at nearby faults).

Displacement of the fault membrane would permit opening of a parting lenticular fracture transmitting a mobile pulse of fluid which would migrate rapidly and upward (Fig. 9). Escape of gas from the mobile and increasingly less confined fluid into the alluvium (or into abandoned wells) would follow. The fracture opening, however, would collapse as the fluid pressure was released, and would remain closed until an adequate pressure gradient again built up in consequence of continuing injection into the formation. This would account for the episodic and brief character of the surface venting events.

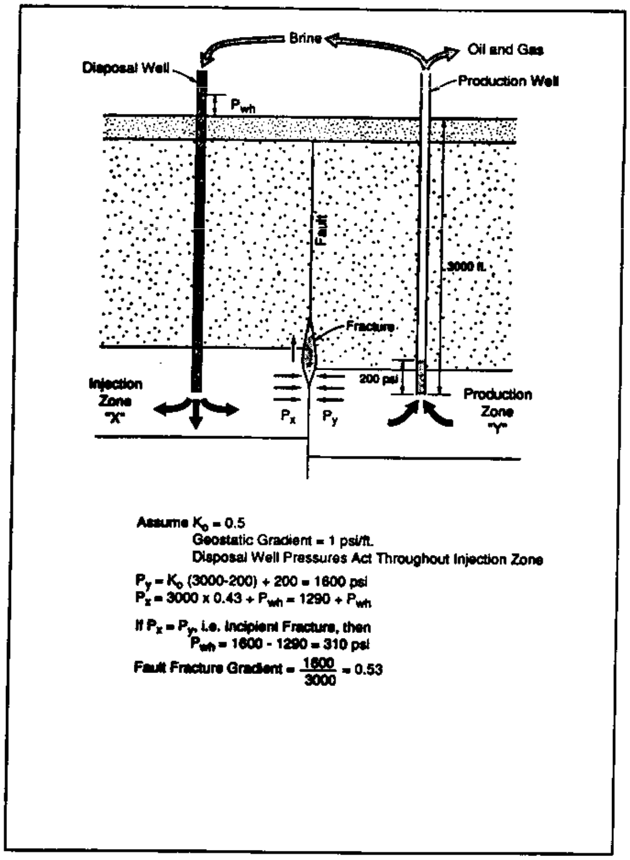


Figure 9. Fault injection pressure for case of long term injection

CONCLUSION

Our analysis indicates that the raise of well head pressures at Gilmore #16, sanctioned by C.D.O.G., from 200 to 770 psi was sufficient to fracture the formation at the nearby fault. This possibility is not recognized in current C.D.O.G. review of oil field operations, though the analytical techniques necessary for its consideration are certainly available in the oil industry. Moreover, there is evidence suggestive that additional injection, unreported in C.D.O.G. records, was taking place at the time of the disaster. It seems to us that future studies of the Los Angeles gas problem can hardly be considered complete without full investigation of these issues. Finally, our analysis suggests that the criteria currently employed by C.D.O.G. and industry may not adequately protect against formation fracturing and escape of formational or injected fluids and gas to the surface environment, resulting in disastrous consequences comparable to the 1985 Ross Store explosion.

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Each of the authors was involved in technical analyses of the causes of the methane gas ventings in the Fairfax District, in connection with the disputes that arose following the 1985 explosion. The views and interpretation presented in this article, however, are purely those of the writers and do not necessarily correspond to the views and interpretations of any party to these disputes, or to any other entity.

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