Environmental hazards posed by the Los Angeles Basin urban oilfields: an historical perspective of lessons learned

G.V. Chilingar · B. Endres

Abstract Urban encroachment into areas historically reserved for oil and gas field operations is an ever-present problem within the Los Angeles Basin. The recent frenzy in real estate development has only intensified what can be characterized as a conflict in land usage. Subsurface mineral rights are severed from surface ownership, often resulting in developments being approved without adequate consideration of the underlying oil and gas field consequences. Also, surface operations are frequently co-located within residential areas without consideration of the health and safety consequences of emissions of toxics to air. This paper presents a review of the environmental, health and safety hazards posed by urban oilfield operations, with an emphasis upon the lessons learned from the "L.A. Basin: Original Urban Oilfield Legend" (see Castle and Yerkes 1976; Denton and others 2001; Endres and others 2002; Kouznetsov and others 1994; Katz and others 1994; Schumacher and Abrams 1994; and Schoell 1983). The Los Angeles Basin has provided the authors with one of the largest natural laboratories in the world for studying the consequences of these issues. The results presented are part of a long-term research program based upon the application of geoscience and petroleum engineering principles in obtaining a fundamental understanding of the root causes of the environmental hazards posed. Topics addressed include: (1) vertical migration of gas to the surface along faults and improperly completed or abandoned wellbores (e.g., due to poor cementing practices), (2) subsidence caused by the fluid production and declining reservoir pressures, (3) soil and groundwater contamination resulting from historic oil and gas field operations, and (4) air toxics resulting from surface operations. A number of case histories are discussed that illustrate the seriousness of the problem. A clear case is made for the urgent need for closer coordination and education by the petroleum industry of the local government planning departments. These departments have the principal role in determining land use policies, acting as the lead agency in performing environmental site assessments (e.g., under the California Environmental Quality Act), and in establishing mitigation measures for dealing with the long-term environmental hazards. This paper establishes prudent practices on the part of oilfield operators for the monitoring and mitigation of these hazards.

Keywords Los Angeles oilfields · Gas migration · Toxic gases (hazard) · Subsidence-earthquakes · Methane

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Introduction

The environmental hazards posed to the urban development by oil and gas field operations are numerous. These hazards must be properly evaluated and mitigation measures implemented in order to protect public safety. These hazards are caused by gas migration along faults, subsidence caused by the fluid removal with consequent formation of faults and fractures, and by improperly maintained wellbores.

The Los Angeles Basin, California, has over seventy oilfields that underlie extensive urban development. This setting has provided the authors an opportunity to study the long-term environment consequences of this mixed usage. These environmental hazards are not unique to the Los Angeles Basin, but relate to fundamental principles of gas migration, along faults and fracture zones, subsidence, and outgassing of oilfield gases that must be properly evaluated. This paper provides a detailed insight into these hazards, as well as lessons learned from the numerous

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disasters that were not properly planned for. Methods for reducing risks and mitigation of hazards are discussed. Four aspects of these environment hazards are presented:

1. Oilfield gas migration into the near-surface deposits and aquifers.
2. Soil and groundwater contamination from upward migration of oilfields fluids, mainly gases.
3. Subsidence caused by oilfield fluid withdrawal and declining reservoir pressures.
4. Outgassing and release of air toxics from the oil- and gas-field operations.

These issues are interactive and must be evaluated in combination. Ignoring these issues could result in substantial legal liability upon the oilfield operator and upon those responsible for the public safety. Subsidence also reslults in the formation of faults and fracture zones, which are avenues for the migration of gases.

Gas migration in oilfield settings

The Los Angeles Basin has been plagued with numerous oilfield gas seeps that continue to present serious explosion and health risks to the residents. Oilfield gases have a propensity to migrate to the surface along faults and poorly completed and/or abandoned wellbores. Furthermore, the upward migrating gases will accumulate in the near-surface collector zones, often trapped and concealed within the permeable gravel and sand lenses.

The lower explosive limit (LEL) of the oilfield gases (composed primarily of methane) is approximately 5% by volume when mixed with 95% by volume of air. This translates into a serious explosion and fire hazard, especially where the gas is capable of migrating into a confined space such as a room or an electrical vault. In the Los Angeles Basin many homes and commercial structures have been constructed directly over old oil wells that have not been properly sealed, and no mitigation measures have been taken to seal out the seeping gases.

The March 24, 1985, Ross Department Store explosion

The first clear recognition of a very serious problem with oilfield gases migrating to the surface and causing an explosion hazard was the March 24, 1985, incident in the Fairfax area of Los Angeles which demolished the Ross Department Store and injured over 23 people (Cobarrubias 1985). Escaping oilfield gases burned for days through cracks in the sidewalks and within the parking lot surrounding the store located at 3rd Street and Ogden Drive, directly across the street from the Farmer's Market. Also, large quantities of gas were detected migrating to the surface under the Hancock Park Elementary School located on Fairfax Street near 3rd Street.

Near-surface soil gas studies revealed that the highest concentrations of gases were aligned in an elliptical pattern with the semi-major axis having an exact alignment with the Metropolitan Number 5 Slant Well operated from a nearby drilling island. A review of production records revealed that this well consistently produced the largest gas volumes of any operational well from the underlying Salt Lake Oilfield. Eventually, well records were obtained that revealed that the well casing had developed leaks as a result of corrosion holes located at a depth beginning at approximately 366 m, and extending deeper (Endres and others 1991; Khilyuk and others 2000).

Gas pathways to the surface included the 3rd Street Fault, that surfaced at the Ross Store location, and an old abandoned vertical well identified on the Division of Oil and Gas map for the area as Well Number 99. A vent well drilled into the parking lot of the Ross Store discovered a large pocket (collector zone) of trapped oilfield gas at a depth of approximately 15 m (Fig. 1). This collector zone had sufficient porosity and permeability to serve as a temporary trapping mechanism for the large quantities of upward migrating gases from the leaking wells to build to pressures of approximately 1.8 kg/cm^2. A clay layer served as a trapping mechanism until its threshold pressure was exceeded. Permanent soil gas probes were installed to a depth of approximately 4.6 m in order to perform ongoing monitoring of the upward migrating gases (Fig. 2).

Detailed gas fingerprinting, primarily utilizing isotopic gas characterization, was instrumental in providing 100% scientific proof (Fig. 3) that the explosion and fire were caused by the underlying Salt Lake Oilfield operations (Schoell and others 1993). Also, further investigation revealed that the gas seeps at the nearby La Brea Tar Pits result from upward migration of gases from the Salt Lake Oilfield along the 6th Street Fault (Jenden 1985). The 6th Street Fault slopes downward to the north and intercepts the oilfield reservoir at the location of the Metropolitan Number 5 well. Production Zone (viz., a very prolific gas zone). Gas fingerprinting has confirmed that the gas seeps at the La Brea Tar Pits match the leaking gases that caused the Ross Department Store explosion (Jenden 1985).

The City of Los Angeles methane ordinance

Following the Fairfax explosion and fires in 1985, the City of Los Angeles adopted a methane ordinance that was incorporated into the City of Los Angeles Building Code, Chapter 15, titled "Methane Seepage District Regulations." The stated purpose is for the control of methane intrusion emanating from petroliferous formations. These regulations apply largely to new construction, the boundaries of which are defined in the code, but are coincident with the boundaries of the Salt Lake Oilfield.

Existing commercial structures, including the Hancock Park Elementary School, were required to install gas detectors. These requirements for gas detection in existing buildings, however, were limited to the commercial

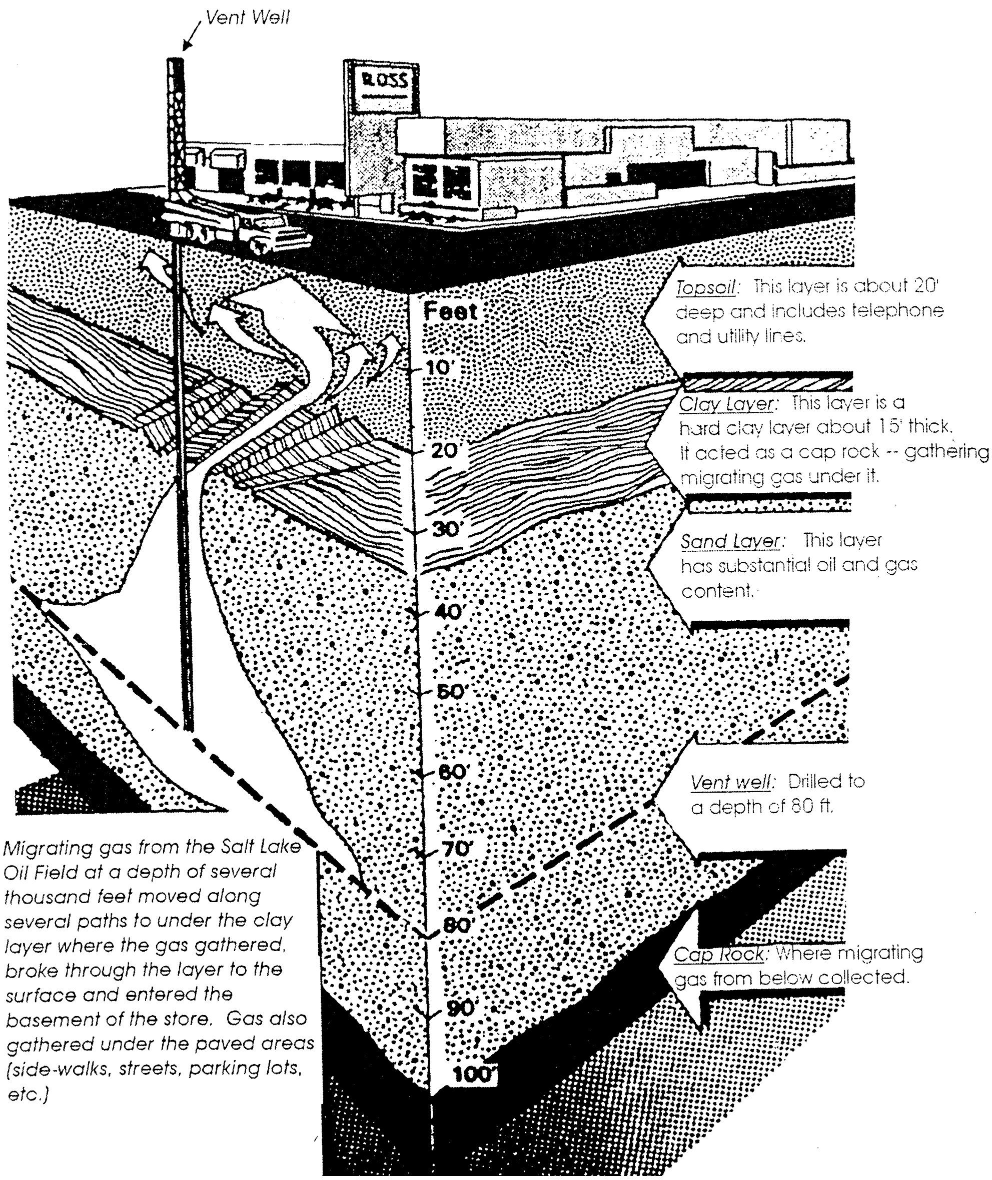


Fig. 1
Schematic showing how gas entered the basement of the department store and the surrounding area (modified after an article by George Ramos and Ted Thackery in the Los Angeles Times 1985; Illustration by Michael Hall

buildings in the immediate vicinity of the Third Street and Ogden explosion site. Additionally, these commercial establishments were required to share the weekly monitoring expenses associated with the permanent soil gas probes that are depicted in Fig. 2. Unfortunately, the Anthony No. 1 gas well (see Figs. 1, 2), that was installed to vent gas from the underlying formation, became plugged in the 1989 time period. Namely, the weekly monitoring of the soil probes failed to provide advanced warning of a near-disaster on February 7, 1989.

The near disaster of February 7, 1989

On the morning of February 7, 1989, a pedestrian who was walking by the Gilmore Bank building, located on the north side of Third Street and across the street from the 1985 explosion site, observed gas bubbling through the ground in a planter box. The fire department was called, which led to the discovery of area-wide gas seeps emerging from below the sidewalks and streets, a near repeat of the 1985 incident, but without an explosion.

It was discovered that the Anthony vent well had become plugged at the perforated intervals of the permeable sand zone depicted in Fig. 1. This condition was aggravated by the ground water movement existing at the depth of vent well.

The response team soon recognized similarities to the 1985 explosion and fires, and the area was immediately cordoned off to prevent ignition and explosion of the gas. In the wake of this near disaster, the City of Los Angeles undertook a second task force study. There is overwhelming scientific evidence that the gas accumulations were the direct result of ongoing oil and gas production, and leaking oil wells.

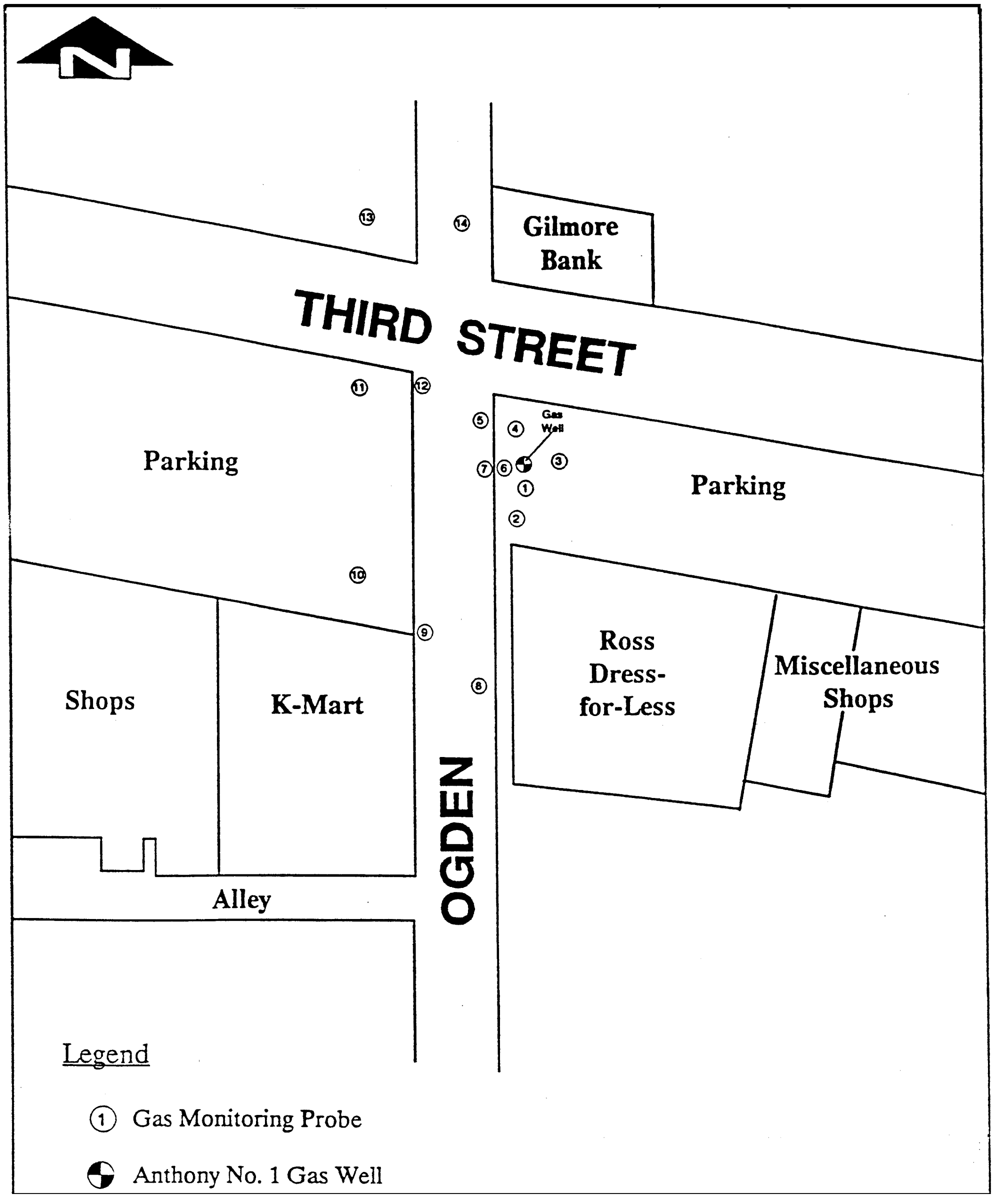


Fig. 2
Probe location map; 3rd St. and Ogden Drive, Los Angeles, California (courtesy of City of Los Angeles Fire Department)

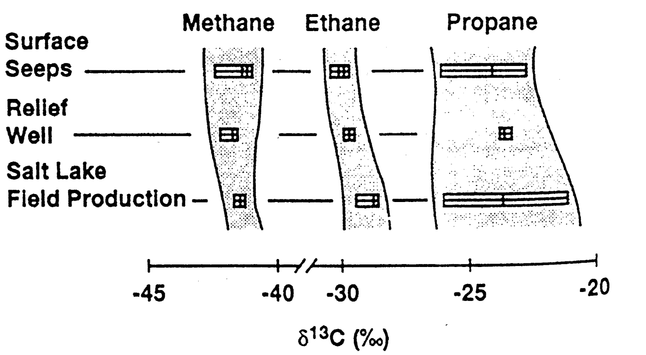


Fig. 3
Carbon isotopic fingerprinting of gas leaking from reservoir to the surface (after Schoell and others 1993, Fig. 8, p. 7)

Well records clearly demonstrate that the Metropolitan No. 5 well had developed serious corrosion leaks in the well casing. These leaks were ongoing, and caused large quantities of oilfield gases to leak into secondary collector zones below both the explosion site and under the Hancock Park Elementary School.

The gas fingerprinting experts (Schoell and others 1993; Jenden 1985) showed the match between the field production gases and the gas from seeps at the surface (Fig. 3).

There is an increased risk of a similar incident occurring somewhere else within approximately 70 oilfields within the Los Angeles Basin. The most important lesson to be learned from the Fairfax explosion is the need to carefully evaluate the integrity of the many old oil wells in the Los Angeles Basin that can serve as the primary source and/or the pathways for the oilfield gases to migrate to the surface. The authors have confirmed this enormous hazard by evaluating hundreds of documented well leaks, and identifying the causes of the leaks. Virtually all well leaks can be traced to the poor well completion and/or abandonment procedures (e.g., poor cementing practices).

Environmental hazards of oil well leaks

Wells that were drilled and completed many years ago are subject to ongoing corrosion and deterioration of both the steel casings and the cements.

Gas intrusion into cemented wellbores and the resultant leakage to the surface and porous formations below the wellhead have been persistent problems in the oil and gas industry for many years (Marlow 1989). Pressure and temperature cycling on the cement bonding characteristics, an acute problem in the gas storage industry, can give rise to shoe leaks and loss of bonding in the annular cement. To help quantify the annular leakage problem in gas storage wells, a survey was prepared and sent to the members of the American Gas Associations Pipeline Research and Storage Reservoir Supervisory Committees. The survey attempted to determine the magnitude of the annular leakage problem.

Tests showed that even when the most up-to-date cement types and techniques are used, leakage can and will occur in a significant number of cases (Marlow 1989 pp. 1147, 1148). For example, in a study of 250 casing jobs over a 15-month period with new cements, 15% of the wells leaked (Watters and Sabins 1980). Accordingly, the poor cementing and completion practices, typical of the many old wells located in the Los Angeles Basin, are giving rise to very serious environmental problems associated with gas leakage to the surface in the annular space, as discussed herein.

Numerous fields have accumulations of hydrogen sulfide that will eventually destroy the integrity of both the steel and cement relied upon to provide protection against gas migration, including abandonments performed to the current standards of the DOGGR. The corrosive conditions of hydrogen sulfide are well known, and have defied engineering solutions (Craig 1993).

Ongoing seismic activity in the Los Angeles Basin is also a major factor in contributing to a well integrity problem. For example, the 1971 Sylmar earthquake was responsible for causing well blowouts in the Fairfax (Salt Lake Oilfield) area (Khilyuk and others 2000).

Wilshire and Curson gas seep

A very serious gas seep at the intersection of Wilshire and Curson (directly across the street, and south of the La Brea Tar Pits) was discovered in 1999. This required the City of Los Angeles to install a vent pipe on the south-west corner of this intersection in order to direct the oilfield gases into the air above the adjoining three story commercial building. The odors from the gas emitted from the vent pipe are noticeable throughout the area.

The commercial office building to the immediate east of this seep location was experiencing gas migration through the foundation and into the building. A ventilation system is operating 24 h/day within the subterranean parking structure of that building in order to mitigate against the risk of an explosion.

Historical records of the area, reviewed by the writers, revealed that an old abandoned well had been drilled near the location of the seep. However, the high-density commercial development in the area has prevented finding the well.

South Salt Lake oilfield gas seeps from gas injection

In January 2003, serious gas leakage problems were discovered in the South Salt Lake Oilfield, located in a residential area near the Fairfax area (viz., in the vicinity of Allendale and Olympic Boulevard). The oilfield operator had been injecting natural gas into the South Salt Lake Oilfield for approximately two years, under elevated pressures to enhance recovery. However, gas began leaking to the surface along abandoned and poorly completed wellbores. In fact, the Division of Oil and Gas records reveal that numerous wells were drilled before the official records were maintained. Accordingly, the existence and abandonment status of some of these wells is unknown. High-density urban development, largely of apartment buildings has occurred directly over many of the old wells.

Montebello underground gas storage

The partially depleted Montebello Oilfield was converted into an underground gas storage operation. Natural gas was transported into the field through interstate pipelines and injected under high pressure (exceeding 105.6 kg/cm^2) into the 8th Zone at a depth of approximately 2,286 m. This storage gas was discovered leaking to the surface along old wellbores that had been drilled in the 1930s era. In some instances, homes had to be abandoned and torn down to provide access to drilling rigs in an attempt to repair and/or reabandon old wells. Studies revealed that the cement plugs used in well abandonment and the integrity of the well casings and cements were not adequate to seal off the high-pressure storage gas from migrating along the wellbores to the surface. This facility had to be abandoned because of the gas leaks. However, it will take many years to deplete the gas to pre-storage conditions.

These examples indicate the importance of a systematic examination of how wells leak, and the dangers posed by allowing residential construction to occur directly over old wells. If each well leak is evaluated in isolation of the long history of problems in an area, the true dangers may not be recognized.

Playa Del Rey underground gas storage

The Playa del Rey Oilfield, located in the Marina del Rey area of the Los Angeles Basin, was converted to an underground gas storage operation in the 1942 time period, and has been operated in that manner ever since. The Venice Oilfield adjoins the area to the immediate north. The gas storage reservoir has been leaking into the adjoining Venice Oilfield since the early years of operation (Riegle 1953). There are over 200 old and abandoned wells throughout this area, including wells that had to be abandoned in order to accommodate the construction of the Marina del Rey Boat Harbor (Fig. 4). For example, some old wells are located directly below the main channel that connects to the Pacific Ocean. Numerous gas seeps have been observed by the authors of this paper within the boat harbor, and within the Ballona Flood Control Channel that bisects the area and extends eastward along the old Los Angeles Riverbed alignment.

The Los Angeles River was responsible for depositing a massive gravel layer that extends eastward providing a highly permeable zone for leaking oilfield gases to collect and migrate easterly, including under the influence of tidal forces. The gravel zone begins (viz., below surface sediments) at a depth of approximately 15 m (referred to as the "15-meter Gravel") and extends to a depth of several hundred feet. This gravel zone interconnects many of the old wells in the area, and serves to conceal the identity of wells that are experiencing the worst leakage. Gas fingerprinting has established that the leaking well gases match the gases seeping to the surface along the flood control channel and into the surrounding residential areas.

This gravel zone is saturated with oilfield gases, which becomes additionally pressurized during the heavy rains as a result of the shallow aquifer being recharged. Surface gas seeps become very pronounced because of this pressurization, and can be observed bubbling through standing water during rains. Probes placed into the 15-meter Gravel Zone have measured gas flow rates as high as 20–30 l/min. Also, drilling rigs have experienced blowouts as a result of encountering the high-pressure gas zone when penetrating to 15 m.

These examples, including the Ross Department Store explosion and vent well histories, reveal the importance of understanding the underlying hydrology in the identification of hazardous oilfield gas seeps to the surface (also see Toth 1996). These studies have confirmed that the underlying permeable aquifers can act to conceal the true magnitude of the gas migration hazards. Accordingly, soil gas studies must include determination of the magnitude of dissolved oilfield gases contained in the near-surface aquifers. This may include multiple zones, requiring the use of deep soil probes.

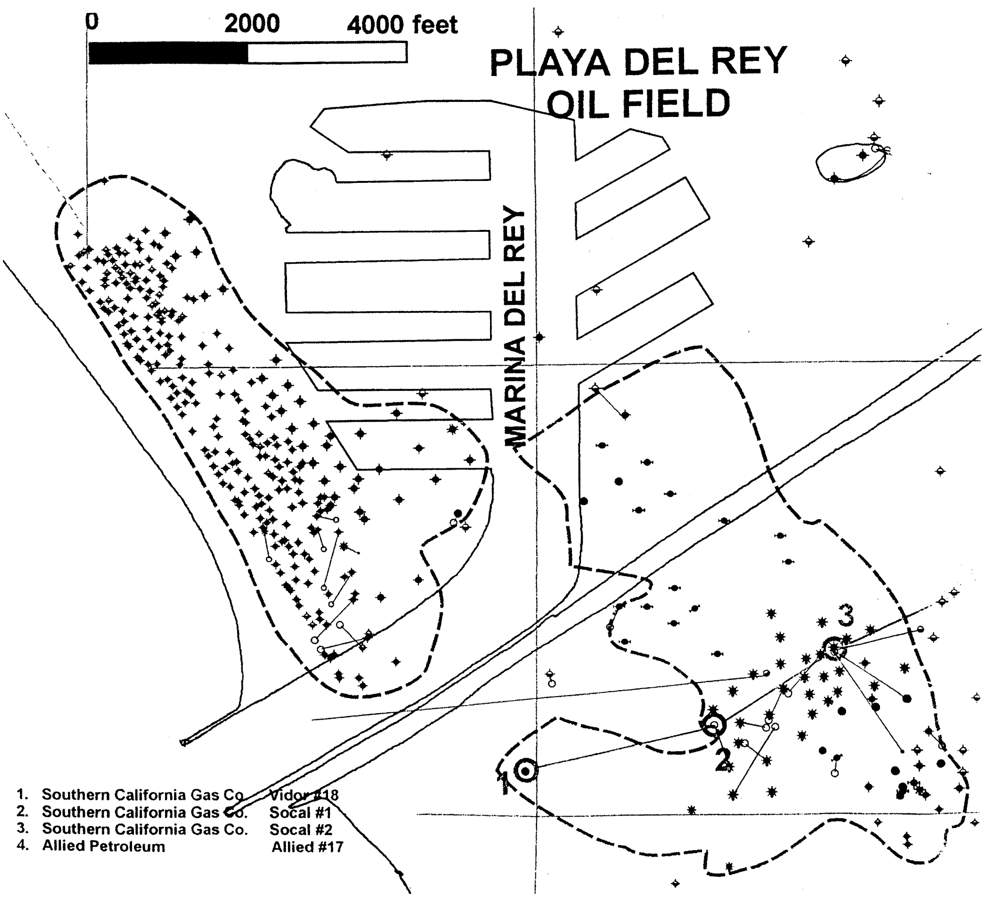


Fig. 4
Playa Del Rey oilfield (courtesy of Jack West, petroleum geologist, Fullerton, California)

A review of well abandonment records for the Playa del Rey and Venice oilfields has revealed very serious leakage problems. Leakage within the annular space between the casing and drillhole, because of poor cementing (see above), is a serious problem. Most of the wells depicted in Fig. 4 were drilled in the 1930s, before prudent cementing practices were used. For example, wells that had been abandoned as recently as 1993—to make way for housing developments—were found to be leaking when excavations were begun for the actual construction. In each case, homes were constructed directly over the old wells after minimal efforts were taken in an attempt to reseal the wells. Because of the small lots and high-density construction, there will be no room for reaccessing the wells using conventional drilling rigs.

Most of the construction in the Playa del Rey and Venice oilfield areas has failed to provide gas detection or other mitigation measures (e.g., as required by the Methane Ordinance) in order to deal with these gas migration hazards. For example, the underground gas storage operations at Playa del Rey involves injection of storage gas under high pressure (approximately 120 kg/cm^2). Gas inventory studies (Tek 1987) have shown that leakage is directly proportional to the reservoir pressure maintained for gas storage (see Fig. 5). This raises serious questions about the appropriateness of locating gas storage fields in highly populated urban settings, especially where many homes have been built directly over poorly-abandoned wells. It is paramount that a fundamental understanding of how wells leak and proper procedures for monitoring are developed. Gas storage pressures are typically selected by the gas storage operator to maximize the storage volume, and to enhance retrievability of the gas when market demands dictate recovery (usually during cold spells when usage skyrockets). Also, cyclic operations associated with gas injection and withdrawal may create fractures.

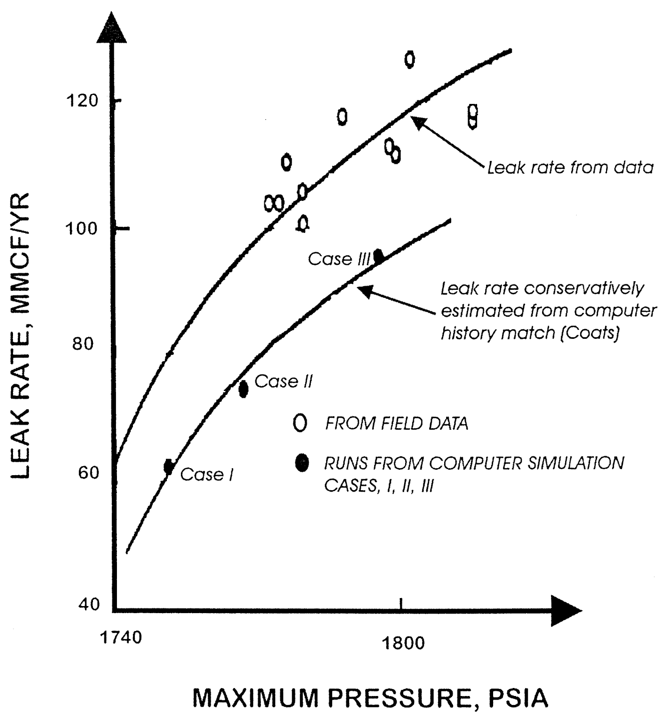


Fig. 5
Gas leak rate for various maximum reservoir pressures for Leroy Gas Storage project, Wyoming (modified after Tek 1987, Fig. 11–16)

Fig. 6
Los Angeles City oilfield (after California Division of Oil and Gas 1991)

Hutchinson, Kansas, gas storage leaks, explosions and fires of January 17–18, 2001

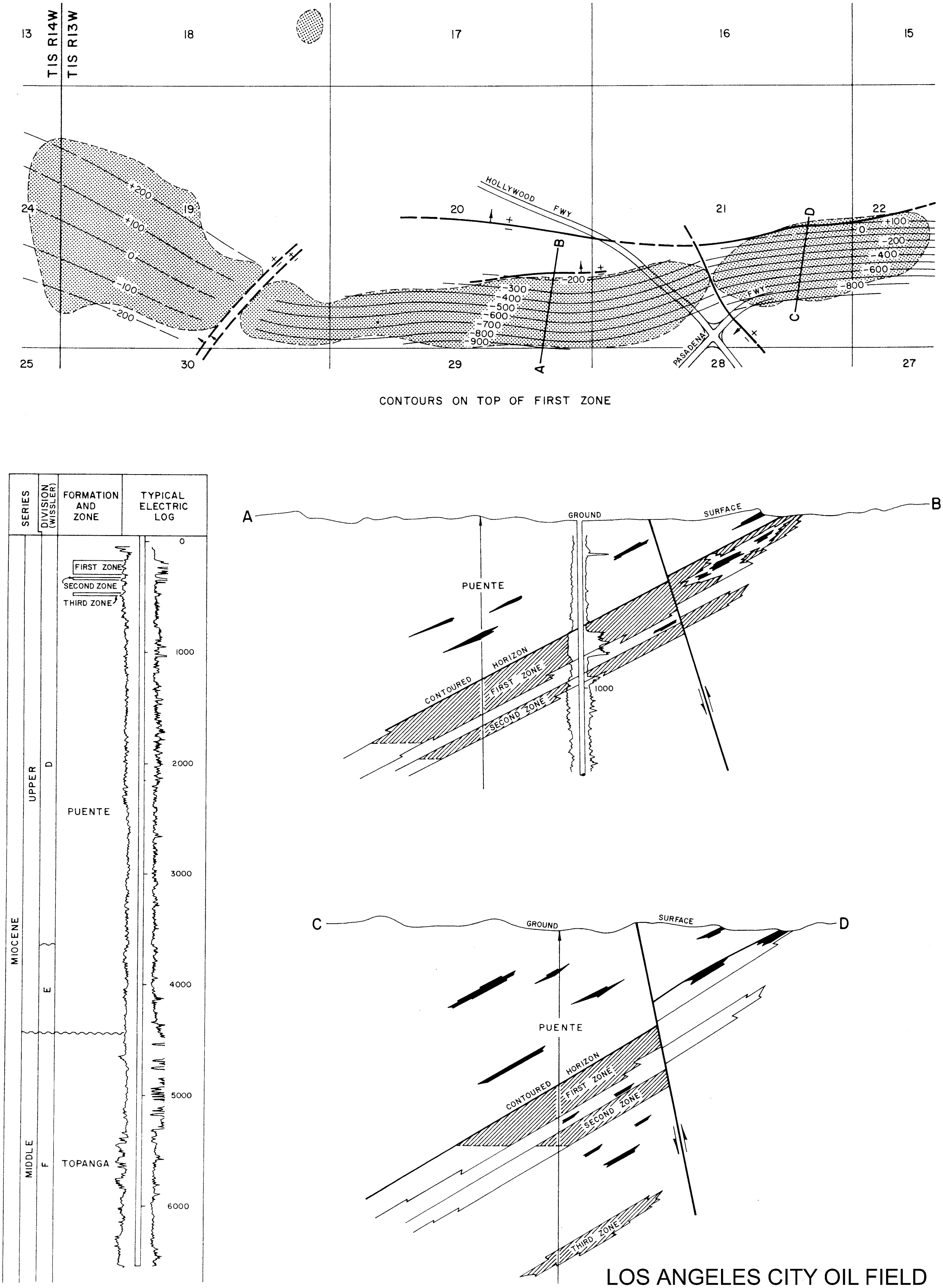
Underground gas storage leaks caused a devastating explosion and fires in the downtown area of Hutchinson, Kansas, on January 17, 2001 (Allison 2001). There was a release of natural gas from the ground water under several stores. Upon ignition, windows were blown out, and within minutes two businesses were ablaze. The fire department was unable to extinguish the flames because of the ongoing migration of gas into the area.

On the following day, leaking gas migrated into a trailer park on the outskirts of the town, causing a second explosion, and killing two people. The gas leakage was traced to a leaking storage gas reservoir about 7 miles from the town. Possibly, gas migrated along the fractures, formed as a result of subsidence, into the aquifer, and the water carried this gas to the sites of explosions.

Santa Fe Springs oilfield

A study was undertaken by the authors to determine the integrity of operational oil wells in the Santa Fe Springs oilfield. To facilitate this review, a time period was selected after heavy rains in which the well cellars were partially filled with water. This allowed observation of gas bubbles seeping to the surface along well casings. Results were systematically recorded for more than 50 wells, some of which were used for waterflooding operations at pressures approaching 84.4 kg/cm^2. Approximately 75% of the wells were found to be leaking.

The waterflooding for enhanced oilfield recovery can be a dangerous practice due to hydraulic fracturing which could create avenues for the migration of gas to the surface creating an explosion hazard. Pressurization of an oilfield by way of water injection or gas injection requires careful attention to the integrity of the wells throughout the oilfield, and should not be undertaken until a soil gas monitoring program has been implemented in the vicinity of each well and fault to detect the potential leakage of gas to the surface. This is also necessary to determine the need for well repairs and/or well reabandonment.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LOS ANGELES CITY OIL FIELD

Belmont school construction on an oilfield

The Belmont Learning Center, a proposed high school in downtown Los Angeles, was in the process of being constructed over the Los Angeles City Oil Field before being abandoned. The site chosen was on a 0.14 km^2 parcel of land bounded by 1st Street to the south, Temple Street to the north, and Beaudry St. to the east. This location is over a shallow oilfield that has an outcrop to the surface just north of the building site. Furthermore, major faults criss-cross the area as illustrated in Fig. 6 (California Division of Oil and Gas 1991). The area is also part of the Elysian Park blind thrust fault system that has a generally east-west trend, which helps explain the uplifting and tilting of petroliferous formation depicted in Fig. 6.

Oil wells in the area continue to produce from shallow oil deposits at a depth no greater than 213 m. Most of the wells were drilled in the early 1900s, and continue to produce. All of the oilfield production gases are released to the atmosphere in the residential areas surrounding the wells. This includes four operational wells at the northwest corner of the school property.

Environmental studies, undertaken only after construction was undertaken, have revealed oilfield gas seepage to the surface over most of the 0.14 km^2 parcel, including the area directly under the school buildings. The project was abruptly halted when gas seepage was detected in the main electrical vault room of the project, just before the power was to be energized.

Soil gas studies revealed that methane (explosive levels) and other gases are migrating to the surface, including hydrogen sulfide. Measurements at the wellhead, and at other seep locations, revealed releases to the air of over 300 parts per million (ppm) of hydrogen sulfide. At depth, hydrogen sulfide was measured at over 3,000 ppm. These alarming results were extensively evaluated by the authors herein, and commented on during the many environmental reviews for the project (Endres 1999, 2002).

Over $175 million has been spent on the project by the Los Angeles Unified School District. At least $20 million has been spent on environmental site characterization alone. A double passive membrane has been proposed to be installed over the entire 0.14 km^2 site. One expert proposed drilling of a slant well to intercept the main avenue of gas migration (fault) and, thus, divert the direction of gas movement.

A recent discovery of surface faulting extending under several of the school buildings has placed a further halt on construction, and may doom the entire project.

This case history clearly identifies the extreme caution needed in evaluating the environmental suitability of sites located over oilfields, especially for school construction. The State of California has passed recent legislation that requires direct participation by the Department of Toxic Substances Control (DTSC) in the future school site selection process in order to avoid a repeat of the Belmont failure.

Subsidence problems caused by oilfield fluids production

One of the most serious environmental problems caused by oilfield operations within the Los Angeles Basin has been subsidence (Chilingarian and others 1995). Subsidence exists in virtually every oilfield within the Los Angeles Basin (Wentworth and others 1969). Subsidence is caused by the reduction of pore pressure within the reservoir resulting from fluids production. The resulting increase in the effective stress causes compaction which is propagated to the surface, typically causing a bowl-shaped subsidence at the surface, centered over the oilfield (see Fig. 7). The subsidence area is approximately twice the size of the oilfield itself (Khilyuk and others 2000). The enormity of the problem is well known for the Wilmington Oilfield that reached approximately 8.5 m before corrective action was taken by implementing a massive water injection program. This required legislative action in order to bring about a unitization of the oilfield to allow the flooding water program to be implemented. It has also become the public policy of the State of California to arrest subsidence, especially in coastal areas, through the use of water injection.

Minimizing the consequences of subsidence requires implementing a subsidence-monitoring program. The standard in use today in oilfields throughout the world (Endres and others 1991) is the Global Positioning Satellite System (GPS). The disasters of the past can be directly traced to the failure to perform adequate monitoring for subsidence. Conventional surveying and now satellite geodesy, permit determination of vertical and horizontal movements of the land surface above oilfields with great accuracy and at relatively minimal cost.

The Baldwin Hills reservoir failure of 1963

On December 14, 1963, at about 11:15 a.m., an unprecedented flow of water was heard in the spillway pipe at Baldwin Hills Dam in the Inglewood Oilfield area of Los Angeles. A short time later water broke violently through the downstream face of the dam, causing massive property damage to homes located below the dam and five deaths. The owner, the Los Angeles Department of Water and Power, had operated the dam continuously from July 1951 until its failure on December 14, 1963. Although an ongoing surveillance for leaks within spillways was carried out, no monitoring for oilfield subsidence was undertaken. The Inglewood Oilfield, discovered in September 1924, lies under the western half of the Baldwin Hills area. It covers about 4.9 km^2 and in 1963 had more than 600 producing wells (see Fig. 8). The field adjoins the reservoir site on the south and west, the nearest reported production at the time of the reservoir failure being from three wells within 213 m of the south rim.

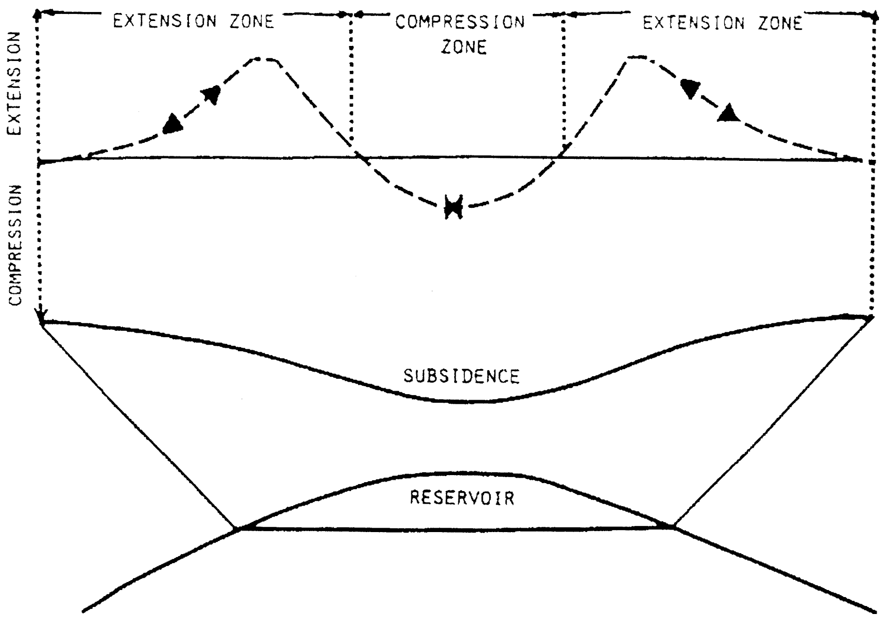


Fig. 7
Schematic diagram of compressive and tensile stress distribution in subsizing formation (modified after Gurevich and Chilingarian 1993, Fig. 1, p. 244)

Analysis of failure revealed ground movement that correlated directly with the Inglewood Oilfield fluids production (see Fig. 9). The total area of subsidence resembled an elliptical bowl with its center about 805 m west of the reservoir and centered over the oilfield. Subsidence at the reservoir site was about 0.9 m, compared to nearly 3.4 m at the subsidence bowl. Noteworthy was the fact that the southwest corner (viz., direction of maximum subsidence) had dropped more than the northeast corner, resulting in differential settlement across the dam of approximately 0.15 m. Furthermore, a review of survey data from 1934 to 1961 and 1963 showed lateral movement in the direction of subsidence depression.

The Inglewood-Newport Beach active strike-slip fault also bisects the area (see Fig. 8), with numerous faults branching off of the main fault in the area. Drilling records clearly reveal these many branching faults, indicating the enormous potential for differential movement along individual fault blocks. Indeed, a post-accident investigation revealed that differential fault block movement had caused rupturing of the asphaltic membrane used as a water seal over the floor of the dam.

Although fluid extraction and resultant subsidence were the prime contributors to the rupture of the reservoir, there is substantial evidence to indicate that water injection to stimulate oil production was also a contributing factor (Hamilton and Meehan 1971). Increased fluid pressures in the reservoir resulting from secondary recovery were sufficient to force brine water to the surface along faults. These forces, along with the lubricating influence of the water exacerbated differential movement along the individual fault blocks.

Recently, a large housing development was proposed for the Baldwin Hills area, virtually over the above described subsidence area. Large retaining walls (exceptionally high) were contemplated to enhance views (and presumably to add value to the individual lots). These retaining walls would have been extremely vulnerable to geologically active and subsidence-prone area. When the developer became aware of the history of land movement in the area from ongoing oilfield production, the property was sold to the State for use as a public park.

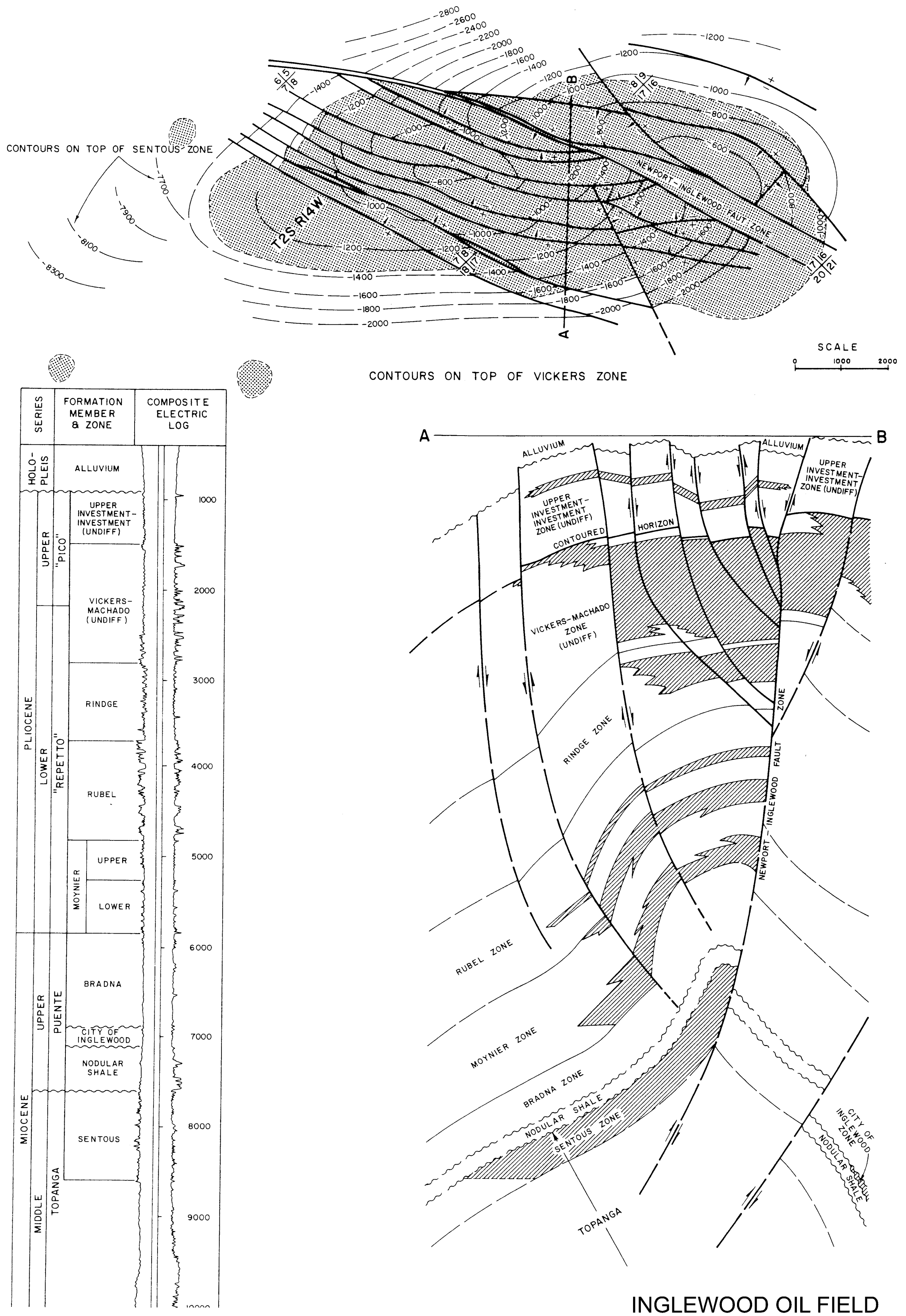
This case history highlights the importance of proper planning and monitoring of the land movement in an area that has been heavily impacted by major faulting, oilfield subsidence, and secondary recovery.

Redondo Beach, King Harbor subsidence

During a winter storm in January 1988, waves overtopped the breakwater constructed by the U.S. Army Corps of Engineers in order to protect the Redondo Beach King Harbor Boat Marina and surrounding commercial structures. Enormous damage resulted, including the destruction of the Portofino Inn. King Harbor is located at the northwest end of the Torrance Oil Field, directly over the Redondo Beach Oilfield (which is considered an extension of the Torrance Oilfield). The City of Redondo Beach had granted permission for offshore drilling from slant wells in that city.

The heights of benchmarks (used by the U.S. Army Corps of Engineers to construct the breakwater) were based on a U.S. Coast and Geodetic Survey of 1945. These benchmarks were assumed fixed, because the Corps of Engineers did not suspect subsidence until 1985, when surveys showed the breakwater crests to be as much as 0.6 to 0.9 m above the original design elevations. Apparently, nothing was done to protect the harbor, or to warn the commercial establishments prior to the storm of January 1988.

Investigation following the disaster revealed that nearly 0.6 m of subsidence had occurred under the breakwater as a result of oil production beginning in 1943, but with



INGLEWOOD OIL FIELD

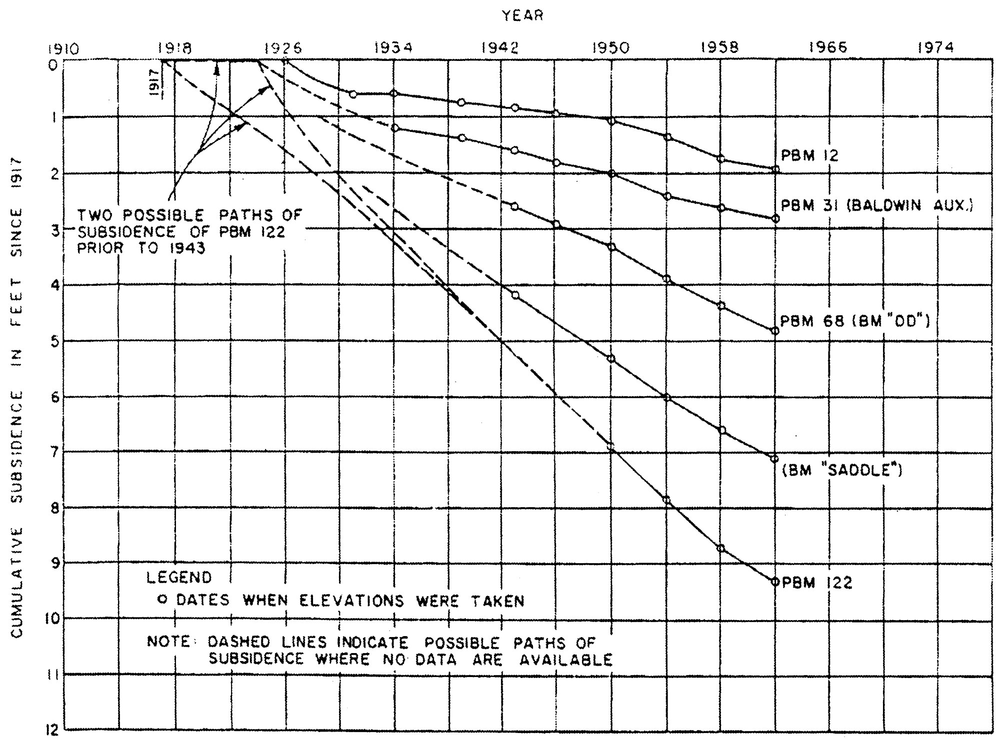


Fig. 9
Subsidence of benchmarks, Baldwin Hills area, Los Angeles, California (after California Department of Water Resources, Baldwin Hills Reservoir, Apr. 1964)

accelerated subsidence occurring after the approval of tideland oil production in 1956.

A jury trial in the Torrance Superior Court resulted in a multi-million dollar judgment against the U.S. Army Corps of Engineers and the City of Redondo Beach. Several oil companies involved in the oil production settled prior to the case going to trial.

The main lesson to be learned is that this disaster could have been averted if proper monitoring for subsidence had been undertaken. It is important to note that the judgment was upheld on appeal, in which the Appellate Court found that undertaking oilfield production in such an urban setting constituted an ultra hazardous activity, requiring the utmost standard of care. Virtually every oilfield in the Los Angeles Basin has experienced subsidence as a result of fluid production. Accordingly, an appropriate standard of care for all oilfield operators should be to undertake monitoring from the onset of production.

Playa Del Rey/Marina Del Rey subsidence

Historical measurement data regarding subsidence in the Playa del Rey/Venice oilfield areas reveal almost 0.6 m of subsidence from the time that oil production began in the 1920s and through 1970. However, no subsidence monitoring has occurred since 1970, despite the fact that fluid production has continued to the present. The Marina del Rey breakwater is vulnerable to subsidence, as is the coastal area.

The most vulnerable are the old wells that were drilled and completed in the 1930s. Any damage to the oil wells (including cements) due to movement along faults present the potential for increased gas migration to the surface. This is especially critical because the oilfields underlying the area are being used to store high-pressure gas transported in from out of the State of California. Figure 10 is presented to illustrate the interrelationship among earthquakes, gas migration, and subsidence resulting from oilfield production (Chilingarian and others 1995; Gurevich and others 1993).

Clearly, these oilfield operations required the utmost degree of vigilance in order to protect the high-density urban development in the area. Monitoring for subsidence and gas migration is essential in order to meet this standard of care.

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Fig. 8
Structural contour map of the Inglewood Oilfield, Los Angeles, California. Contours are on top of the Vickers Zone (after California Division of Oil and Gas 1991)

The release of air toxics from surface operations, wellheads and pipelines

The Federal Environmental Protection Agency (EPA) has determined that the primary hazardous air pollutants (HAP) emitted from oil and natural gas transmission and storage facilities are (see Federal Register, Volume 63, No.25/Feb.6, 1998):

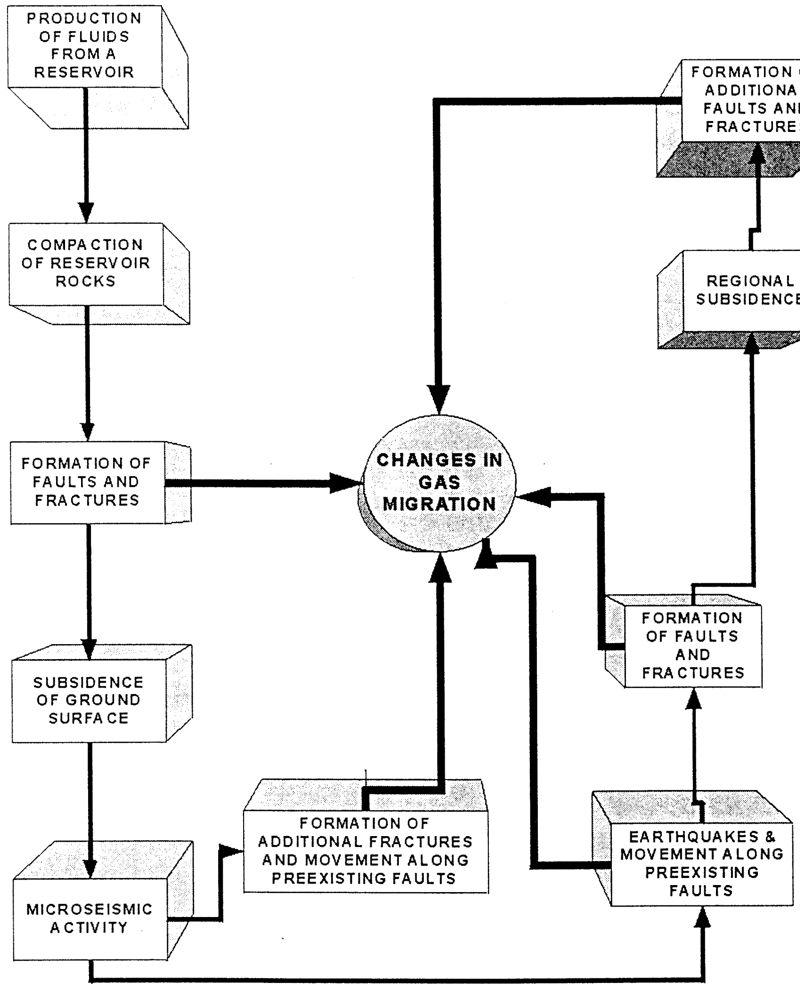

Fig. 10
Schematic diagram of system relationships among the production of fluids, compaction, subsidence, and seismic activity (Modified after Chilingarian and others 1995, Fig. 1, p. 41)

1. Benzene
2. Toluene
3. Ethylbenzene
4. Xylenes

These compounds are collectively referred to as the BTEX chemicals. The BTEX chemicals are the aromatic components of crude oil. For a further discussion of these hazardous components of crude oil see McMillen and others (2001). Although crude oil has variable contents of aromatic hydrocarbons, depending upon the origin, the API rating of the crude oil can be a good predictor of the content of aromatics, especially benzene (see Fig. 11). The higher the API gravity of the crude oil, the higher the percentage of aromatics in the crude oil.
Tissot and Welte (1978) found that 95% of the crude oils produced around the world fell into the distribution pattern shown in Fig. 12. As an example, the composition of a 35^0 API-gravity crude oil is as follows (Hunt 1979):

Molecular type	Weight percent
Paraffins	25
Naphthenes	50
Aromatics	17
Asphaltenes	*8*
Total	100

The majority of crude oils have been reported to contain 15 to 40% aromatics. The aromatics are characterized by a double carbon bond, which has been directly linked to the health hazards posed by these chemicals. Benzene, a known human carcinogen, has been linked in the medical literature to leukemia, aplastic anemia, lymphomas and a variety of other cancer related ailments.
Oil and gas production facilities are required to provide warnings to the public regarding certain hazardous oilfield chemicals, including benzene and toluene, under California Health and Safety Code Section 25249.6 (otherwise known as Proposition 65).
Most facilities are not required to identify the amount or the specific types of chemicals being released to the atmosphere from their operations. The Federal EPA has identified dehydration equipment as a major source of benzene and toluene air toxics emissions, and has proposed legislation to curtail such emissions, especially in residential areas.
Venting of oilfield gases to the atmosphere must be viewed as a hazardous activity, because the oilfield gases can contain appreciable levels of benzene. Oilfield gases and condensates have the highest contents of benzene. A typical content of benzene in the oilfield gases can vary between 30 parts per million (ppm) to over 800 ppm. For this reason, the natural gas should be carefully tested for its benzene content before venting of large quantities of

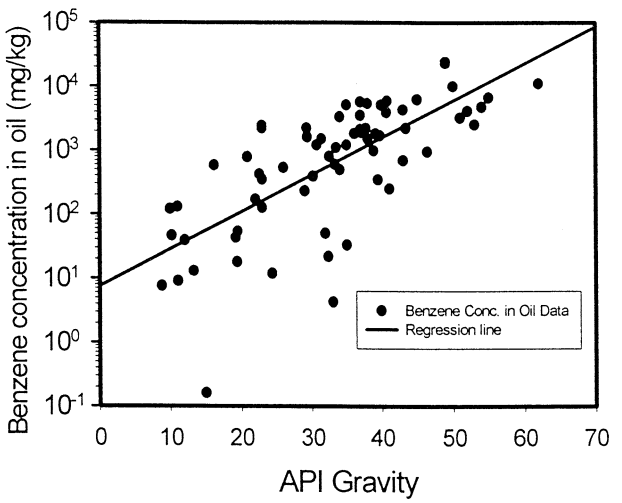

Fig. 11
Benzene concentrations versus API gravity for 61 crude oils and 14 condensates (API gravity data were unavailable for eight crude oils) (after Rixey 2001)

gas is undertaken. Also, vent stack emissions should be carefully monitored. Additional concerns and precautions must be taken in and around sour oilfield operations. Hydrogen sulfide, even in small quantities, can be hazardous to the health. The research conducted at the University of Southern California Medical Facility (Kilburn 1998, 1999) has established central nervous system damage from the neurotoxin effects of hydrogen sulfide even at concentration in air as low as 1 ppm. This is much lower than the workplace standards that have been considered safe in the past. This also highlights the importance of not relying upon workplace standards regarding air toxics emissions in the case of residential areas and school sites. Safety, health, and environmental considerations need to be made a top priority in the land use planning where urban development coexists with the oil- and gas-field operations.

Conclusions

The history of the Los Angeles Basin oilfields has demonstrated the need to exercise a high degree of vigilance regarding the environmental hazards posed by these operations. Land use planning and governmental entity decisions regarding allowing massive real estate development over and adjacent to these operations sometime ignored the health and safety risks posed by these operations. The primary purpose of this paper has been to show the importance of reviewing a long history of environmental problems created by this mixed land usage, and to identify what steps need to be taken to avert future disasters. This includes the necessity of taking the following steps:

Gas migration monitoring: Much closer attention must be given to the need to perform ongoing monitoring for gas migration into the near surface soils in areas heavily impacted by historical oil production, and where there are many old and abandoned wells. It is very important to monitor gas migration near the fault zones.

Subsidence monitoring: Monitoring for subsidence in the oil and gas producing areas is necessary in order to protect against the undermining of foundations and highly sensitive changes in elevation (especially in coastal areas), and to reduce the risk of gas migration hazards. Subsidence gives rise to faults and fractured zones, which are avenues for gas migration.

Air Toxics monitoring: The release of air toxics from surface operations, wellheads and pipelines must be carefully monitored in order to protect the public health, especially from the release of such chemicals as benzene, toluene, ethylbenzene, xylene (viz., the BTEX aromatic hydrocarbons) and hydrogen sulfide. Great caution is required in the operation of vapor recovery equipment and in the monitoring of toxic emissions in order to take corrective action.

Soil and groundwater monitoring: Soil and groundwater must be carefully evaluated for petroleum and drilling

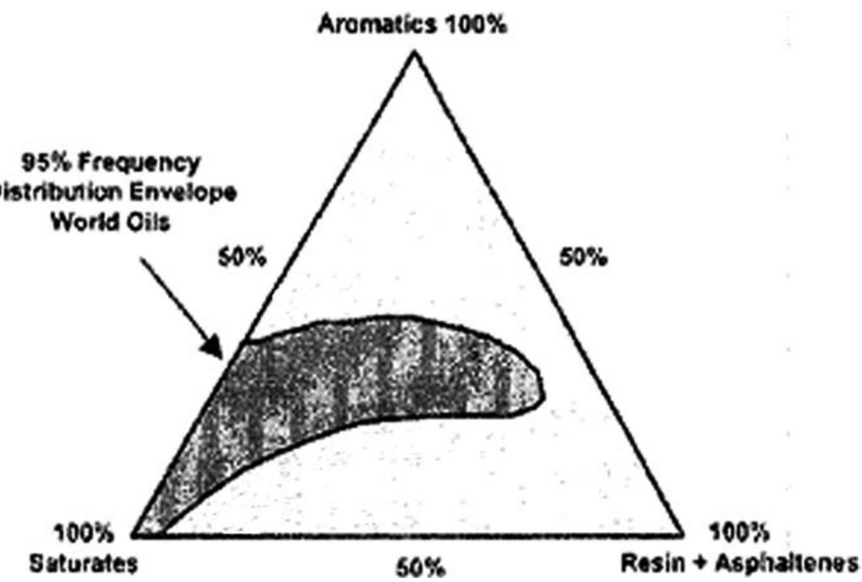

Fig. 12
Ternary diagram showing the class composition of crude oils (after Tissot and Welte 1978)

mud contamination, and appropriate steps must be taken to remediate the soil and water contamination before development is allowed to proceed. This requires an evaluation of the underlying aquifers, which become a ready target for the oil and gas migration hazards.
Soil gas monitoring: Soil gas monitoring is an essential step in the evaluation of soil and aquifer contamination by historic oil and gas field operations. It is also necessary to determine what mitigation measures may be necessary to protect against migration of explosive and toxic oilfield gases into residential and commercial structures. This will be an ongoing problem in many areas that must employ gas detectors, vent pipes, membrane barriers and ventilation systems in order to protect against the gas migration hazards.
Oil and gas well leaks and ongoing monitoring: Oil and gas wells must be carefully evaluated, and old wells must be reabandoned to protect against the risk of oilfield gases migrating up the old wellbores and entering the near-surface environment. There has been a long history of this very serious problem, establishing that the prior well abandonment procedures have been often inadequate in dealing with this extremely dangerous problem.
Building over abandoned wells: Land planning and issuance of building permits should require adequate room to provide access for a drilling rig to reenter old wells, when they begin leaking.
As a final conclusion, the authors would like to quote the editorial of Professor George V. Chilingar, Founder of Journal of Petroleum Science and Engineering and Managing Editor (J Petrol Sci Eng 9:237): ".... Underground gas storage and oil and gas production in urban areas can be conducted safely if proper procedures are followed."
"After recognition of the existing problem, proper safe operating procedures can be easily developed."

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