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ENVIRONMENTAL HAZARDS AND MITIGATION MEASURES FOR OIL AND GAS FIELD OPERATIONS LOCATED IN URBAN SETTINGS

by:

George V. Chilingarian, Ph.D.
Professor of Civil and Petroleum Engineering
University of Southern California

Bernard Endres, Ph.D.
Oil and Gas Environmental Consultant
Los Angeles, California

Prateep Pokinwong, Ph.D. Student
University of Southern California

ABSTRACT

This paper presents a methodology for evaluating the environmental hazards posed by gas migration from oil and gas reservoirs, or underground natural gas storage facilities, and into the near-surface environment. Geological faults and improperly completed or abandoned well bores (e.g., due to poor cementing practices) are described as the primary pathways by which the gas can reach the surface. Furthermore, the gas migration problem can be exacerbated by such factors as subsidence, earthquake activity and well corrosion.

Soil gas monitoring, geochemical gas fingerprinting and geological profiling are used in order to identify the magnitude and location of the environmental risks. Shallow and deep soil probes are used in order to characterize the near-surface hydrology, and to identify possible collector zones where gas concentrations can build to dangerous levels.

These techniques have proven to be important in the planning for and design of mitigation systems necessary to protect residential and commercial properties from the migrating gases. For example, some jurisdictions have imposed regulatory controls and design requirements regarding the installation of gas mitigation systems. Also, these methods are important in establishing safe procedures for the operation of oil and gas fields, or underground natural gas storage facilities.

A number of case histories are discussed that have been used by the authors to validate the methodology, and to illustrate the seriousness of the problem. A clear case is made for the need to perform ongoing monitoring for these conditions, especially in an urban setting.

INTRODUCTION

The major paths for vertical migration of gas are formed by natural faults and fractures in the rock formations that overlie the reservoir. Natural lithification processes and tectonic activities formed these breaks or channels. These are illustrated in Figure 1 as subtending zones I, II, and III. However, in many geological settings, these fault zones can be discontinuous, but still allow the gas to literally hopscotch from one fault to another, or to act in conjunction with leaking wellbores in the same manner.

Wellbores of operational, idle or abandoned wells often result in literally pipeline flow of large volumes of gas to the surface. This is an especially serious problem where the well, usually in the annular space between the drill hole and the casing, was not properly sealed with cement. Also, the wellbore may have been hydraulically fractured during the cementing phase of well completion. Vertical fractures may extend for tens of feet from the wellbore depending upon the characteristics of the formation and the injection pressures used for placement of the cement. The cement will fill some of the larger fractures surrounding the casing, but the cement particles cannot enter the smaller fractures away from the wellbore.

SOURCES OF GAS FOR MIGRATION

During the course of oilfield production, fluid is produced from the reservoir causing a drop in pressure. This liberates the gas held in solution, and allows the gas to migrate. The free gas can migrate upward due to differences in the specific weight between the gas and the surrounding fluids (viz., upward buoyancy forces). Figure 1 illustrates the migration of gas from the reservoir to secondary collector zones, and eventually to the surface.

Initially, the gas is trapped below the caprock within the reservoir, forming a free gas zone. However, this free gas can escape through the caprock due to natural fractures in the caprock or man-induced fractures. Man-induced fractures include: wellbores penetrating the caprock during drilling, fracturing pressures occurring during oilfield operations, or by subsidence resulting from production of fluids from the reservoir.

Well completion practices rely upon squeezing cement slurry into the annular space between the drillhole and the steel casing. However, the inevitable movement of the rock formation resulting from the subsidence can destroy the intended sealing joint at the caprock interface. Once through the caprock, the gas can follow faults and fractures, as illustrated by Zone III, in Figure 1. In Zone III, secondary gas traps can often be found where layers of shale or other impervious layers slow down the upward migration of gas and permit it to gather in pockets. Figure 2 is presented to illustrate the interaction between subsidence and gas migration.

In secondary and tertiary recovery operations, water is often injected under high pressure into the reservoir to increase the production of oil. This water displaces the free gas in the reservoir, forcing the gas to migrate under this pressure influence. This free gas is then able to migrate along the paths described above, toward the surface.

The 1985 Fairfax Explosion and Fires

The phenomenon of natural gas migrating to the earth's surface from oil and gas field reservoirs via geological faults, fractures and well bores is a serious environmental problem. An explosion hazard is created if the gas collects in a confined space and reaches a five percent (5%) mixture ratio with air (viz., the lower explosive limit for natural gas). The Ross Department Store in the Fairfax area of Los Angeles, California exploded on March 24, 1985, seriously injuring 23 people. Fires burned for days through cracks in the sidewalks and parking lots until a vent well was drilled to relieve the pressure build-up. Extensive investigations, including gas fingerprinting, confirmed that the gas had migrated to the surface along faults and poorly maintained well bores. Shallow soil gas probe holes were installed to monitor any future build-up of gas. In 1989 these gas monitoring wells indicated that large volumes of gas were again building up under the site. Fortunately, the area was evacuated immediately. It was discovered that the single vent well, that had been installed to vent the gas, had become plugged with silt at the slotted interval depth of 80 feet.

Other serious gas seeps have occurred in this area over many years. It is also the location of the famous La Brea Tar Pits where gas and oil continually migrate to the surface along the 6th Street Fault. This site has been used by the authors as a large "natural laboratory" to study and research the phenomenon of gas migration discussed in this paper. Over the past 15 years, this research has been expanded to address similar gas migration problems located in many parts of the world. This paper will provide an overview of these findings. References 1 through 5 provide a detailed treatment of these topics, including an analytical formulation of the gas migration mechanisms.

THE 2001 HUTCHINSON, KANSAS EXPLOSION AND FIRES

Research on these topics is continuing at the University of Southern California, including at the graduate student level. This is expected to contribute important new information to the understanding of the geological, geochemistry and hydrogeology principles that control gas migration. The most recent incident that is under investigation is the natural gas explosion that destroyed the downtown area of Hutchinson, Kansas on January 17, 2001. The next day, natural gas exploded under a mobile home park outside of the city, killing two people. Gas and water geysers reached heights of 30 feet. The gas leaks were traced to an underground natural gas storage field located nearly seven miles from the explosion sites. The gas had migrated through geological faults and permeable formations from leaking well bores at the storage site. Investigation has revealed that virtually no monitoring was in place in order to prevent this disaster. Worse yet, the emergency response teams had no clue as to the cause of the disaster. For example, the fire department was unable to extinguish the flames, illustrating the lack of preparedness for such an event. In the case of the 1985 Fairfax explosion, the fire department had been called, and had responded to gas odors in the area 30 minutes before the explosion. Because of their lack of preparedness, they mistakenly believed it was sewer gas, and returned to the fire station. Shortly thereafter, the alarm was sounded to respond to the explosion and fire that devastated the area that they had just returned from.

ENVIRONMENTAL HEALTH HAZARDS OF CERTAIN OIL FIELD CHEMICALS

Additional concerns regarding the environmental hazards of oil and gas migration in urban areas are the carcinogenic, toxic and neurotoxin constituents that are contained within the oil field gases. These include the so-called BTEX chemicals comprising benzene, toluene, ethylbenzene and xylene. For example, benzene and toluene are contained on the so-called Governor's List of toxic chemicals within the State of California, and require a posting of warning signs to the public under the Proposition 65 environmental laws. Benzene is a known human carcinogen, and can cause blood disorders, including aplastic anemia and leukemia, as well as cancer. Benzene and toluene can cause birth defects. Both chemicals are highly volatile, and can easily transform from the liquid crude oil state into the natural gas state (e.g., associated gas), especially under reservoir pressure conditions.

This also becomes a serious problem in partially depleted oil fields that have been converted to underground natural gas storage operations. The storage gas is pumped into the oil field reservoir under high pressure. Frequently, 60% to 70% of the original crude oil still remains in place. When the storage gas comes in contact with the crude oil, aromatic hydrocarbons are transferred from the crude oil to the natural gas stream, enhancing the presence, particularly, of benzene and toluene. When the storage gas is retrieved to the surface for customer delivery, the gas must be processed through scrubbers and dehydration surface equipment. This provides an opportunity for these chemicals to escape into the atmosphere as fugitive emissions, or intentional releases. As a minimum, vapor recovery systems are necessary to control fugitive emissions. Billions of cubic feet of storage gas can be withdrawn from inventory over a short period of time, increasing the health hazard risks to the surrounding community.

Furthermore, the natural gases that escape to the surface along well bores, faults and pipeline leaks will contain these health hazard chemicals. Also, workers need to be protected against these hazards, especially from long-term exposure.

HYDROGEN SULFIDE ENVIRONMENTAL HAZARDS

Another serious problem is caused by the hydrogen sulfide formation that can occur when the leaking natural gas stream interfaces with high sulfate levels in the near-surface water table. This can give rise to the perpetual generation of hydrogen sulfide through microbial alteration under anaerobic sulfate to sulfide reducing conditions. Hydrogen sulfide is not only highly corrosive, but is a neurotoxin, that must be considered a health hazard even at levels as low as 1 ppm (Kilburn, 1998; Kilburn, 1999).

The corrosive conditions of hydrogen sulfide on both steel casings and cement are well known (Craig, 1993). However, oil field operators, especially regarding the longevity of well completions and well abandonments, often ignore the long-term consequences of hydrogen sulfide, and other corrosive soil conditions. Namely, the steel casings and cement completion practices can be expected to develop gas leaks to the surface as a result of future aging. Accordingly, it would be ill advised to allow building over abandoned well bores, regardless of how carefully they were abandoned with cement seals and plugs. Also, access to the wells with oilfield drilling rigs would be necessary in order to repair leaks that could develop at any time in the future.

Although this research has been devoted to evaluating the environmental hazards of gas migration, these same topics are important regarding near-surface exploration for oil and gas. In fact, the research methodology – especially soil probe studies – evolved originally from this exploration technology point of view. Namely, near-surface exploration for petroleum is based on the detection and interpretation of a great variety of natural phenomena occurring at or near the land surface or sea floor and attributed, directly or indirectly, to hydrocarbons migrating upward from leaky reservoirs at depth. Development of surface exploration methods began in the early 1930's with chemical analysis of gaseous hydrocarbons in soil air. It has since expanded to include a wide range of geochemical, geophysical, mineralogic, microbiological and other types of anomalies (Toth, 1996).

MITIGATION SYSTEMS OVERVIEW

Mitigation systems, both passive and active, have been developed in recent years in an attempt to cope with the gas migration hazards discussed in this paper. Many of these remain unproven. For example, the most common procedure is to install a geomembrane or plastic liner under the footprint of the structure being built in order to capture the upward migrating gases. Perforated pipes are installed in a gravel blanket located under the membrane in order to vent the gases that are collecting below the structure. These systems have demonstrated a high failure rate. The membranes can become punctured during installation, and/or develop leaks around the multiple penetrations that must accommodate utility and electrical lines, elevator shafts and pilings used for foundations. Gas detectors, used in conjunction with the membranes, require ongoing maintenance and calibration.

These mitigation systems have typically not been designed to deal with the health hazards of the migrating gas, but only to prevent a catastrophic explosion. This is a serious oversight, since the most dangerous chemical constituents of the leaking gas are heavier than air. For example, benzene, toluene and hydrogen sulfide are all heavier than air, and will tend to concentrate at ground level, and lower elevations, creating an inhalation hazard to those living and working in the area.

In summary, ongoing monitoring for the prevention of explosions and fires is essential, along with monitoring for health hazard conditions. The latter requires, at least, an order of magnitude lower threshold detection limits to protect against an inhalation health hazard.

NATURAL GAS STORAGE FIELDS

It has become common practice to utilize depleted oilfields for the purpose of storing large volumes of natural gas underground. It is more economical to store gas in underground reservoirs than construct large delivery lines, typically from out-of-state sources, that would be capable of satisfying peak demands. Gas is purchased and delivered to the storage field during non-peak demand periods, and retrieved from the storage field during high demand periods, such as during cold spells.

Underground gas storage facilities utilizing old, depleted oil and gas fields are subject to the same gas migration hazards as discussed above, but are often times more serious. The existing wellbores and well completions were not designed to withstand the high pressures that most gas storage facilities are operated at, nor the cyclical variations in pressure experienced by the seasonal high and low operating pressures. For example, during inventory draw-down the cement seals at the bottom of the casing can fail, causing shoe leaks and other seal damage.

Abandoned wells associated with the prior oil or gas field usage, are difficult, if not impossible to reenter and seal in order to prevent gas leakage. Also, since these wells do not allow direct monitoring, gas seepage can be detected only at the surface. However, the leaking gas can spread out and migrate along fault planes, and/or experience lateral migration within the shallow water table, before ever reaching the surface. This can act to conceal the true dangers of the leaking wells. These problems require the placement of deep soil probes, positioned immediately adjacent to the well bores. Also, gas levels within the near-surface water table require monitoring. Field experience has demonstrated that the near-surface water table can serve as a temporary barrier for the upward migration of gas. Often, the gas will collect below the water tale, and spread out laterally before eventually reaching the surface.

For these reasons, it is important to perform a detailed characterization of the near-surface hydrology, including gas concentrations, free gas volumes and water movement directions. The individual gas constituents (e.g., methane, ethane, propane, etc.) have different solubility levels, and must be accounted for when attempting to characterize the origin of the leaking gases.

Gas fingerprinting studies must account for a number of near-surface gas alterations in order to properly interpret the source of the leaking gas. The primary adjustment factor is to account for the mixing between the native oilfield gas and the gas storage gas during migration using a so-called mixing line. Also, near-surface mixing with biogenic gas can alter the characterization of the gas.

Underground gas storage facilities are frequently located in urban areas where gas, migrating to the surface can cause serious environmental problems. Examples include the following:

(1) MONTEBELLO GAS STORAGE FIELD, CALIFORNIA

The Montebello Oilfield, located in Southern California, was utilized by a gas company to store large volumes of natural gas in a partially depleted oilfield. Prior to converting the Montebello field to a gas storage facility, many oil wells had been abandoned using standards that were based on 1930's vintage technology. The old oilfield also contains several fault planes that are potential paths for gas migration.

The gas company began storing gas in a portion of the Montebello Oilfield in the early 1960's. By the early 1980's, significant gas seepages were discovered at the surface within a residential housing area. The gas seepages endangered homes, requiring evacuation of families. Some of the homes had to be torn down in order to provide access to leaking wells, that were attempted to be reabandoned. Monitoring of the near-surface water table for gas concentrations was undertaken on an emergency basis. Also, gas was found leaking up under the City Hall front lawn.

Because of the endangerment to the homes, and the huge economic losses suffered by the gas company from the lost gas, this storage facility has been closed.

(2) PLAYA DEL REY GAS STORAGE PROJECT

The Playa del Rey Oilfield was converted into a gas storage field in 1942. Shortly thereafter, storage gas was discovered migrating into the adjoining Venice Oilfield at the reservoir level of approximately 6,000 feet. Gas began migrating when the differential pressure reached approximately 300 psi. The storage field has been operated continuously to the present time, with storage gas pressures reaching approximately 1700 psi. A study, performed by the gas company in 1953, estimated that 25% of the injected gas was migrating to the adjoining Venice Oilfield. The operational procedure is based on capturing as much of the leaking gas as possible, and returning it to the primary storage field on an ongoing basis. This requires numerous old oil wells to be used as recapture gas wells, in order to return the leaking gas.

Over 200 abandoned oil wells are in the area, which used 1930's era technology for the well completions. High-density housing has been built throughout the area, with many homes constructed directly over the old abandoned wells. Virtually no mitigation measures have been provided to deal with the gas migration hazards.

Recent soil gas studies have revealed gas concentrations as high as 90%, within the near-surface soil conditions. Soil probes and vent wells that have been drilled into the near-surface aquifer have measured gas flow rates as high as 25 to 30 liters per minute. One soil gas measuring expert has characterized the area as having the largest gas seep to be found anywhere in the world.

The City of Los Angeles has only recently begun to require mitigation systems to be installed in new construction, but only in the extremely high gas zones. The lessons learned from the Fairfax gas explosion, and the more recent Hutchinson, Kansas gas explosions have been largely ignored.

CONCLUSIONS

If future disasters are to be averted, careful attention must be given to the monitoring for oilfield gas migration hazards. Furthermore, addressing the health hazards posed by certain chemical constituents such as benzene, toluene and hydrogen sulfide requires much lower detection thresholds to be used for monitoring purposes: within the 1 ppm range. Mitigation systems have not proven to be capable of dealing with these extreme hazards.

The main conclusions to be drawn from this paper can be summarized as follows:

1) The primary force controlling the migration of gas to the surface is the difference between the specific weight of water and that of gas (viz., the buoyancy force).

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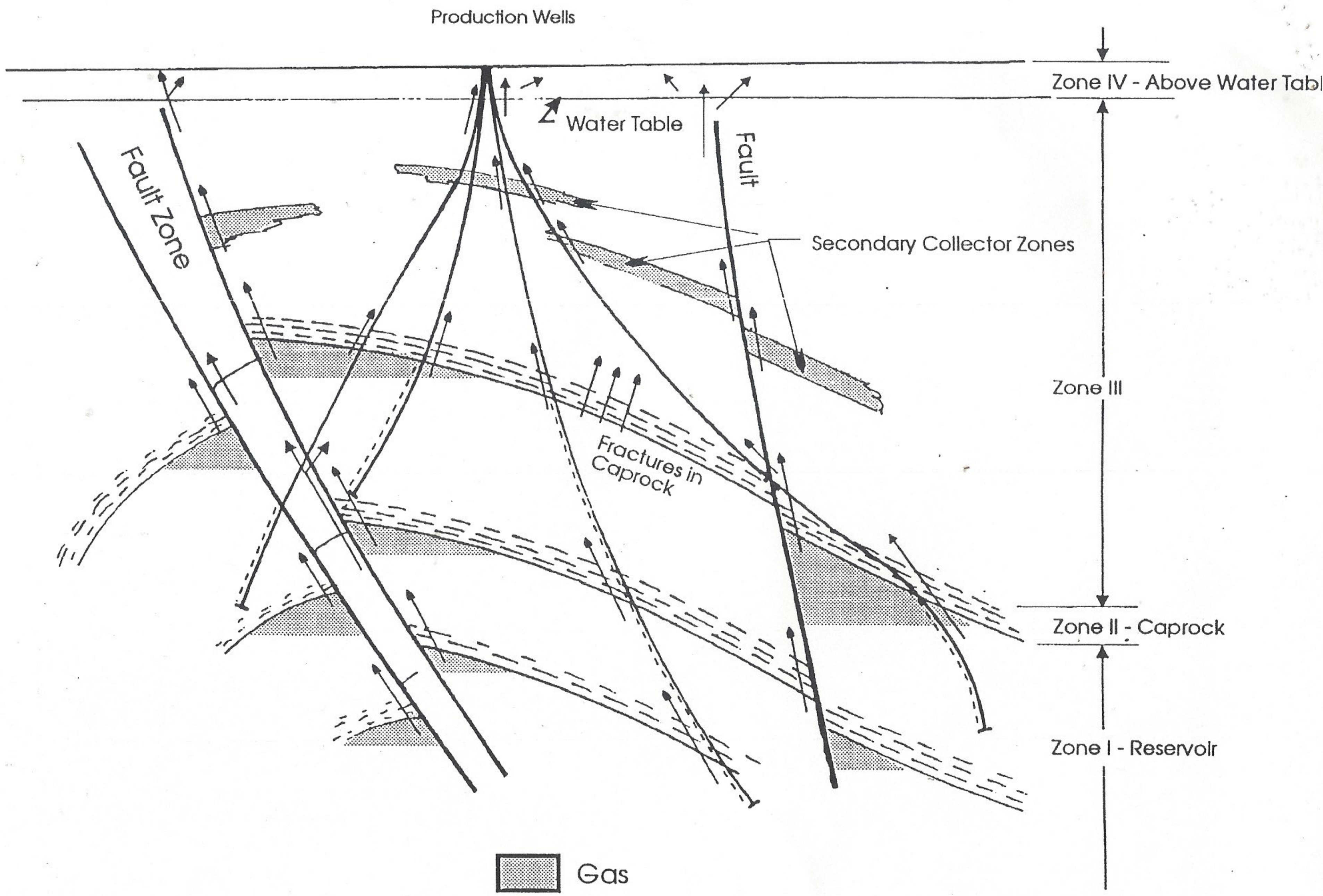

POTENTIAL PATHS OF GAS MIGRATION

FIGURE 1.

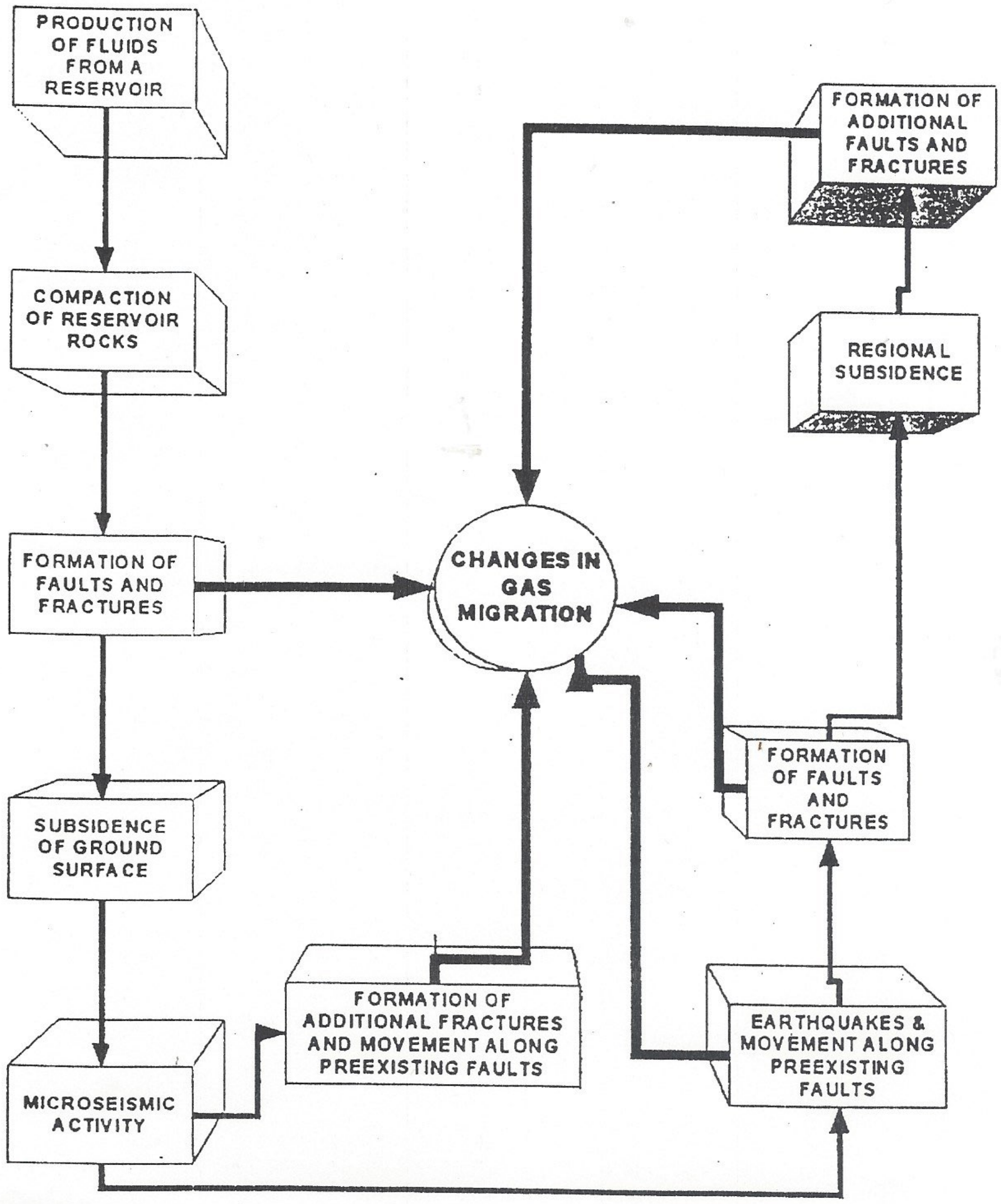

FIGURE 2. Schematic diagram of system relationships among the production of fluids, compaction, subsidence, and seismic activity.