23 April 1971, Volume 172, Number 3981 SCIENCE

Ground Rupture in the Baldwin Hills

Injection of fluids into the ground for oil recovery and waste disposal triggers surface faulting.

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On the Saturday afternoon of 14 December 1963, water burst through the foundation and earth dam of the Baldwin Hills Reservoir, a hilltop water storage facility located in metropolitan Los Angeles. The contents of the reservoir, some 250 million gallons of treated water that had filled the artificial, 20-acre clay- and asphalt-lined basin to a depth of 70 feet, emptied within hours onto the communities below the Baldwin Hills, inundated a square mile of residences with mud and debris, and damaged or destroyed 277 homes *(1)*. Fortunately for those in the path of the flood wave, indications of imminent failure had been observed by a reservoir caretaker several hours before the final breach occurred; even so, police evacuation teams had barely sufficient time to clear the area. Consequences of the disaster were minimal compared with what would have occurred if no warning had been provided, but they included five lives lost, $12 million in property damage, and loss of the reservoir itself.

The remains of the Baldwin Hills Reservoir stand empty today, the northern rim of the bowllike structure having been gashed from crest to foundation by the escaping water (see cover). A linear crack issuing from the base of this gap can be traced across the asphalt floor of the reservoir. It reappears as a slight buckling of road pavement on the far side of the reservoir basin and thence becomes a faint, discontinuous break in the ground surface, which trails off south of the reservoir into the brush-covered and excavation-scarred terrain of the Inglewood oil field.

Since 1963 geologists and engineers have been intensively investigating this crack and several similar ones nearby, all known to be surface expressions of deep, near-vertical faults of Pleistocene or greater age. For there is no doubt that the disaster occurred as a result of displacement along faults in the unconsolidated sediments that underlie the reservoir. These displacements led to rupture of the protective clay lining that covers the floor of the bowllike structure, which had been constructed in 1951. Ironically, the 10-foot-thick (3-meter) lining and its underdrain had been especially designed and constructed to isolate the soft, sandy foundation rock from leakage of the reservoir water, thus providing what was thought to be a margin of safety against *piping*, a process characterized by gradual development of eroded subsurface cavities and channels. What the designers evidently had not thought possible were offsets along one or more of the buried faults great enough to destroy the lining.

On the day after the failure, it was apparent that major offset had occurred along what was to become known as the "Reservoir fault," the west side of the fault having moved relatively downward with respect to the east side (Fig. 1). The offset was sufficient to crack the lining all the way across the floor of the reservoir, and surface displacement of as much as 6 inches (15 centimeters) was created. The crack line was punctuated by several ragged, cavelike sinkholes, which marked the points of water entry that had led, possibly over a period of hours or days, to the deterioration and eventual destruction of the reservoir foundation.

Responsibility for the disaster has never been formally fixed. Insurance carriers for the Los Angeles City Department of Water and Power, constructor, owner, and operator of the reservoir, promptly paid for flood damages. A report on the results of an investigation carried out by the State of California's Department of Water Resources *(2)* provided a taut narrative of events on the day of the disaster and a cool appraisal of failure as the result of an unfortunate combination of physical factors: "Sitting on the flank of the sensitive Newport-Inglewood fault system with its associated tectonic restlessness, at the rim of a rapidly depressing subsidence basin, on a foundation adversely influenced by water, this reservoir was called upon to do more than it was able to do."

Two lawsuits filed in 1966 by the city and its insurers against the oil companies active in the Inglewood oil field at the time of dam failure charged that the oil field operations had led to the events directly associated with breaching of the dam. These suits were settled out of court for nearly $3.9 million dollars, thus disposing of the immediate financial issues that arose from the ground rupturing beneath the reservoir. Origin of the ruptures is a question that remains unadjudicated.

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Geologic Setting

The Baldwin Hills, site of the Inglewood oil field and the failed reservoir, form part of an interrupted chain of low hills that rise in striking contrast to the surrounding flat terrain of the Los Angeles basin (Fig. 2). Processes of both folding and faulting have contributed to the uplift of this chain (*3, 4*). In the Baldwin Hills, the primary anticlinal fold structure has been much modified by faulting, especially by lateral and dip-slip displacement along the Inglewood fault, which bisects the hills. Many unnamed subsidiary faults, apparently related genetically to the Inglewood fault, are present throughout the hills and are especially numerous in the vicinity of the reservoir.

Moody and Hill (*5*), among others, consider the Inglewood anticline to have developed as a drag fold during deformation of the thick, plastic sedimentary section overlying the Newport-Inglewood zone of basement right-lateral transcurrent faulting. The anticlinal folding began and continued while marine sedimentation was still going on, as evidenced by thinning and lateral discontinuities in the stratigraphy of the overlying section of late Tertiary and Quaternary strata. As movement continued along the Newport-Inglewood zone, the deformation exceeded the capacity of the overlying strata to adjust by folding, and failure was propagated through the section as normal and strike-slip faulting. The surface strain pattern associated with this tectonic deformation (*6*) is illustrated in Fig. 3, and the subsurface structure is shown in Fig. 4.

The near-parallel, north-striking faults that splay outward from the Inglewood fault south of the Baldwin Hills Reservoir (Fig. 3) were probably formed as an array of tear faults developed in response to strike-slip displacement along the dominant Inglewood fault. The Reservoir fault is a member of this family of steeply dipping faults, all of which intersect the Inglewood fault at depths of no more than a few thousand feet.

The apparent sense of displacement on these secondary faults is largely vertical. At the time of construction of the Baldwin Hills Reservoir, vertical stratigraphic separation of as much as 26 feet was noted at surface excavations across what became known as the Reservoir fault; lesser apparent vertical displacement was recorded for several related faults beneath the reservoir. Some

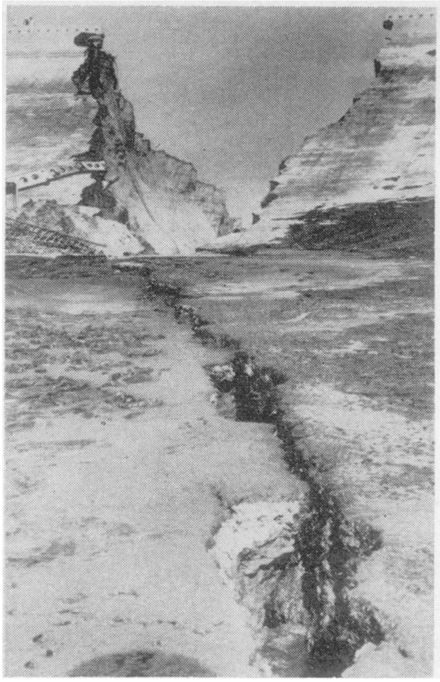

Fig. 1. Baldwin Hills Reservoir. Seepage through the ruptured reservoir lining (foreground) undermined and then breached the Baldwin Hills dam embankment (background). The relatively downward displacement of the ground surface to the left of the crack is clearly visible in the photograph. [Wide World Photo]

horizontal displacement on the Reservoir fault was inferred on the basis of observed striations on the fault surface. However, the significant vertical offset component that is evident along these faults clearly places them in the category of normal (gravity) faults.

Inglewood Oil Field

The Inglewood oil field occupies an irregularly oval area that extends diagonally across the trend of the hills along the axis of the faulted Inglewood anticline (Fig. 3). The field is localized by the anticlinal structure and by the distribution of its sedimentary strata. The extensive breaking associated with the Inglewood fault has disrupted the original fold structure, so that it now has the form of a series of slices translated successively downward toward an axial trough along the west side of the Inglewood fault (Fig. 4). The Inglewood fault forms a structural break between the east and west blocks of the field and effectively isolates the two producing blocks hydraulically from each other. Some subsidiary faults within both blocks are also fluid barriers, as was confirmed by changes in reservoir pressure with time and in response to both production and water flooding. The barrier effect of many subsidiary faults in the east block may be local, however, and may not extend the entire length of any given fault.

Although oil production has been primarily through solution gas drive, a peripheral water drive exists along the northeast margin of the east block and also along the west margin of the west block. The edgewater condition of the east block encroaches from the area of artesian formation water in the northerly extension of the permeable oil sand horizons, beyond the area of petroleum entrapment where the groundwater formerly existed at or near hydrostatic pressure.

Exploitation of the Oil Field

The Inglewood oil field was discovered in 1924. It was explored and developed so rapidly that its period of greatest yield occurred within the first 3 years of production. Although the fluid pressure in the oil field reservoir was at hydrostatic levels under preexploitation conditions (570 pounds per square inch in the east block), fluid pressures measured in wells declined through the years to about 50 pounds per square inch in the early 1950's (*2, 7, 8*). Castle and Yerkes (*4*) have suggested, however, that blocks of higher pressure may have persisted after the general pressure declined, owing to fault compartmentalization of the reservoir. In any case, production and development, mainly by "infill" drilling between wells, has continued steadily to the present.

A significant modification of the extraction program was started in 1954, when the Standard Oil Company initiated a pilot "water-flood" program of secondary recovery in its east block leases. The history and technical development of this program were well described by Oefelein and Walker in 1963 (*9*). They also presented detailed information on the structure and stratigraphy of the main producing horizon, known as the Vickers zone, of the Inglewood field east block. The pilot water flood involved the injection of brine in selected intervals from two arrays of four wells each, generally at pressure gradients in the range of 0.5 to 0.9 pound per square inch per foot of depth.

Results of the pilot program were sufficiently encouraging to prompt a full-scale program in 1957. The east block secondary recovery program has been expanded by increments since its inception, with a general pattern of increasing numbers of injector wells and increasing volume and pressure of injection (Fig. 5). Although the program has been successful, it has involved many technical difficulties, including maintenance problems in the wells (*7*). Problems such as loss of major amounts of injected fluid in narrow intervals, sudden increases in formation "take" with concomitant loss of injection pressure, casing failures, "breakthroughs" to producing wells, and surface leaks of injected fluid seem to have increased as greater numbers of injection wells, operating under increasing pressure, have been brought into service. Such problems frequently have occurred after significant raising of injection pressure in specific wells, and some have been severe enough to cause abandonment of the injection well. However, techniques of sealing damaged intervals and repairing wells have often been effective in restoring wells to injection after each episode of failure, and the overall injection program has been progressively expanded.

Subsidence and Ground Rupture in the Baldwin Hills

Although the phenomenon of "earth crack" ground rupturing may not have been definitively observed in the Baldwin Hills prior to 1957, the existence of a more widespread and larger-scale form of ground surface movement was recognized by engineers of the Los Angeles Department of Water and Power as early as 1943, when comparison of leveling surveys indicated that elevation changes were taking place in the area (*10*). The ground subsidence was

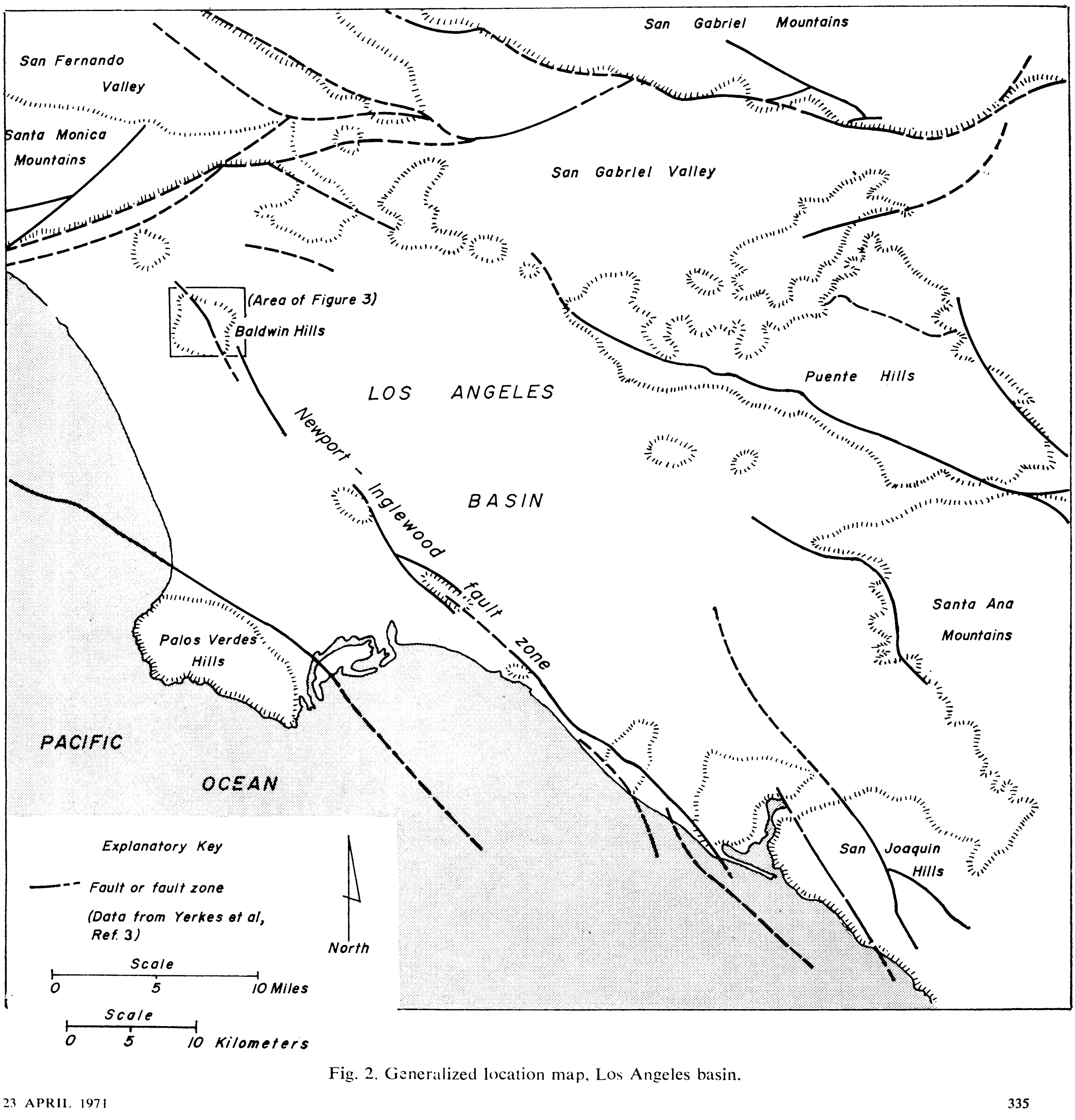

Fig. 2. Generalized location map, Los Angeles basin.

of concern to the department because of its plans to construct and operate a reservoir, but it was not known by the community at large. Not until 1955 were sufficient data available to establish that the changes in elevation defined a bowl-shaped area of subsidence (the outline of which appeared to coincide with the outline of the Inglewood oil field) (*10*). In 1957, 6 years after the reservoir had been put into operation, the beginning of surface cracking and faulting in the vicinity of the intersection of Stocker and La Brea streets, southeast of the reservoir, attracted the attention of public officials.

The spatial relations among patterns of ground deformation in the Baldwin Hills, preexisting geologic structural features, and the area of production in the Inglewood oil field are illustrated in Fig. 6. Table 1 summarizes the sequence of ground-rupturing events.

The principal features of contemporary ground subsidence and surface rupture are clearly established. They have been thoroughly documented by the U.S. Geological Survey (*4*), the Los Angeles Department of Water and Power (*10, 11*), the State of California Department of Water Resources (*2*), and by several consultants (*12, 13*) and other investigators. Some interpretations have differed slightly from others as to the exact pattern, magnitude, and history of this deformation. Explanations for the origin of the deformation have, in contrast, been sharply segregated into two categories: (i) response to lowering of fluid pressure, fluid withdrawal and injection, and related phenomena and activities associated with operation of the Inglewood oil field; and (ii) deformation largely or wholly of tectonic origin.

Tectonic theory. This theory is based on records of recent surface rupturing along known "active" faults and on indications that the sense of the contemporary movement appears to be indistinguishable from that of prior displacements. It is argued that vertical offset along the family of faults in the east block has occurred in recent geologic time as a result of lateral displacement along the Inglewood fault or as part of the process of anticlinal folding, or both, and that it may be reasonably assumed that the tectonic environment that created these structures, relatively recently and rapidly, persists today. The tectonic theory is offered by some geologists as an explanation of

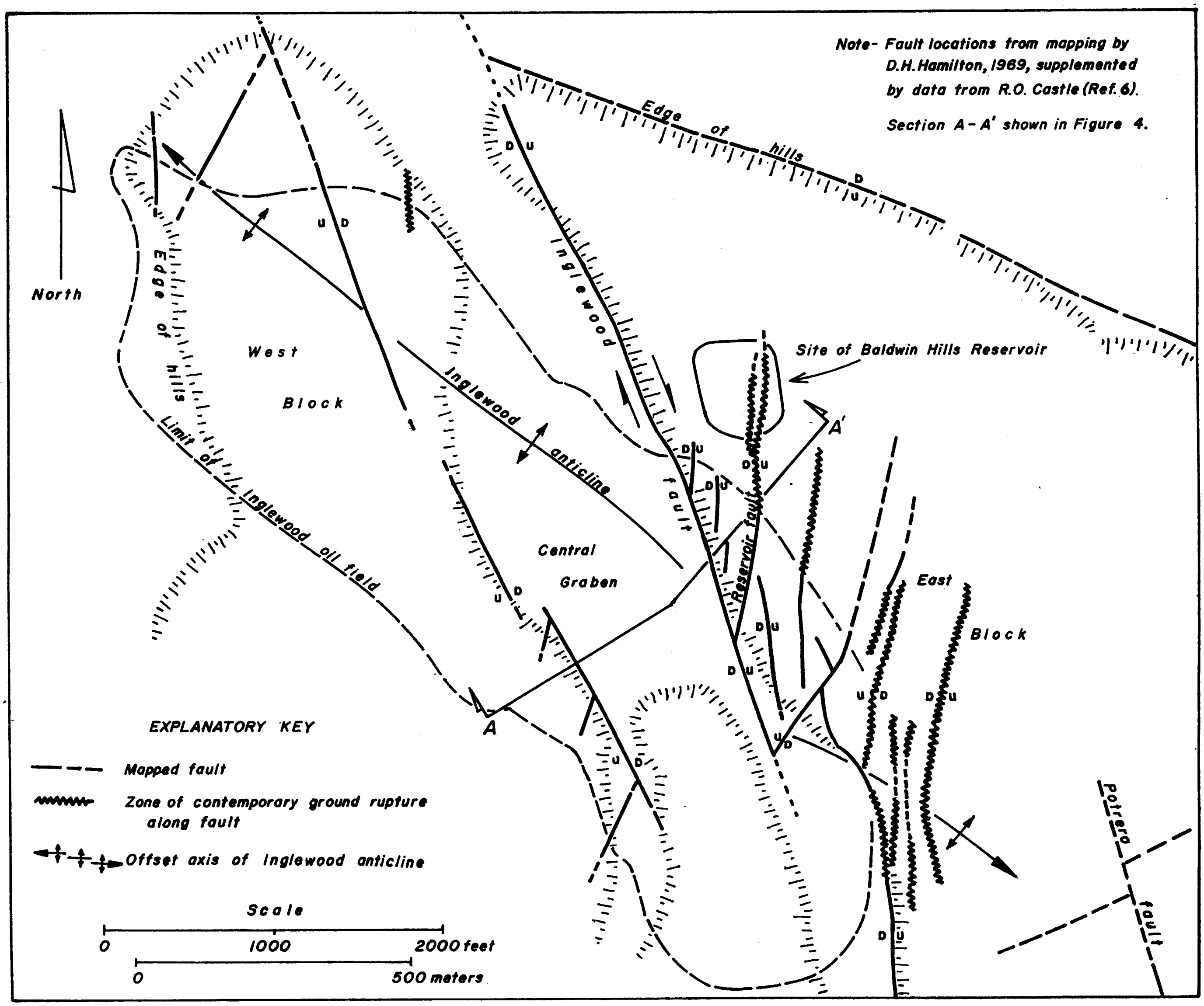

Fig. 3. Geologic map of the Baldwin Hills.

the subsidence in the Baldwin Hills as well as the cause of the ground rupture in the east block area.

The tectonic theory is open to objections of several kinds. First, and most important, displacement along subsidiary faults generally occurs in response to a relatively greater displacement along the principal fault, which in the Baldwin Hills is clearly the Inglewood fault. Yet relatively large offsets have occurred on the subsidiary faults in the east block, whereas no evidence has been produced to indicate related creep, rupture, or crustal strain that would give rise to displacement along the Inglewood fault or nearby major faults in the Baldwin Hills or adjacent area.

Continued upward warping of the Baldwin Hills might well lead to the observed normal faulting, but detailed analysis of survey leveling data by Hayes, Castle, Leps, and others indicates that little or no such regional uplift has occurred during the past half-century for which data are available. Further, the margins of a near-surface, upwarping, anticlinal fold should move outward, away from the fold axis, but surveys of four bench marks situated on the flanks of the anticline show the ground to be moving toward the anticlinal axis (and radially toward the center of the subsidence bowl) (Fig. 6). Moreover, offset of the folded formations by the Inglewood fault demonstrates that the major episodes of folding must have predated much of the faulting. This suggests that faulting has superseded anticlinal folding as the dominant style of tectonic deformation in the Baldwin Hills.

Finally, the shape of the subsidence bowl does not correspond to the shape of the "central graben," as would be expected if the subsidence were caused by further downfaulting.

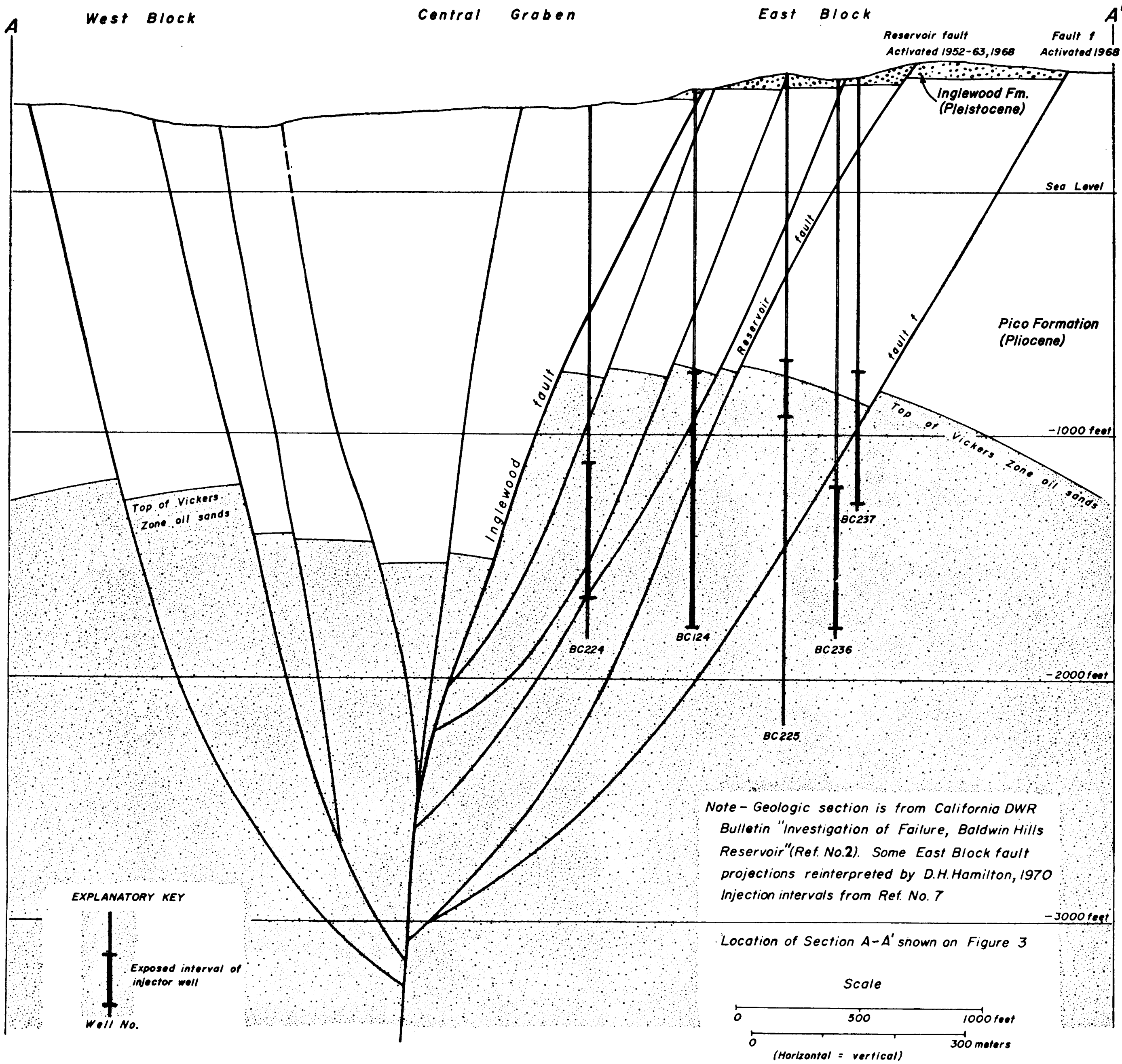

Fig. 4. Geologic structure section through the Baldwin Hills–Inglewood area and the Inglewood oil field.

Table 1. Sequence of ground rupturing along earth cracks in the Baldwin Hills, 1957–68. For location of cracks, see Fig. 6.

Crack No. or name	Occurred or first observed (date)	Length (feet)	Cumulative length (feet)
1	May 1957	2,600	2,600
3, 4	Jan. 1958	1,900	4,500
2	Mar. 1958	600	5,100
5a	Before 1961	400	5,500
5	Feb.–Mar. 1963	400	5,900
1a	1962–1963 (?)	800	6,700
8	Feb. 1963	400	7,100
Wilson's fault I*	Aug.–Dec. 1963	2,000	9,100
Wilson's fault V	Aug.–Dec. 1963	800	9,900
Wilson's fault I	1968	Recurrent movement (2,400)	
Wilson's fault V	1968	Recurrent movement	
Hamilton's fault f	1968	1,400	11,300

* Wilson's fault I is now identified as the Reservoir fault.

Subsidence theory. Advocates of the subsidence theory argue that the 6 feet or more of ground subsidence in the Inglewood field is clearly related in space and time to the net withdrawal of some 67,000 acre-feet (*14*) of oil, water, and sand from shallow producing horizons, a contention supported by theoretical mechanics and by analogous experience in other areas (*4*). Almost all the observed surface rupturing has occurred on the edge of the subsidence bowl; stretching on the rim of the sagging ground surface is an obvious and mechanically proved consequence of subsidence [demonstrated by Grant (*15*), Deere (*16*), Lee and Strauss (*17*), and others], and tension cracking of the near-surface materials is one result (illustrated diagrammatically in Fig. 7). Subsidence also exerts a downward drag on the sediments that rim the subsidence bowl, and, where faults or other established surfaces of weakness are present, accumulating elastic strain may be relieved by upward "popping" of the ground on the edge of the bowl.

Two objections might be leveled at the subsidence theory as an explanation of ground rupture in the east block. First, ground rupturing was not directly observed prior to 1957, and the only positive evidence of drag or tension-induced failure before 1957 is a record of continuous extension of the rupture caused by movement since 1952 of the Reservoir fault under the Baldwin Hills Reservoir inspection gallery. However, most of the ground subsidence between the early 1920's and 1963 had already occurred by 1957, and the rate of subsidence in the east block had slowed markedly in the late 1950's and early 1960's. Why then should intense surface faulting suddenly begin to occur as late as 1957?

The other possible objection to the subsidence explanation is the local distribution of ground rupturing. The downward drag and stretching presumably would be distributed around the rim of the subsidence area, but almost all the rupturing has occurred in one limited sector of the bowl circumference (Fig. 6).

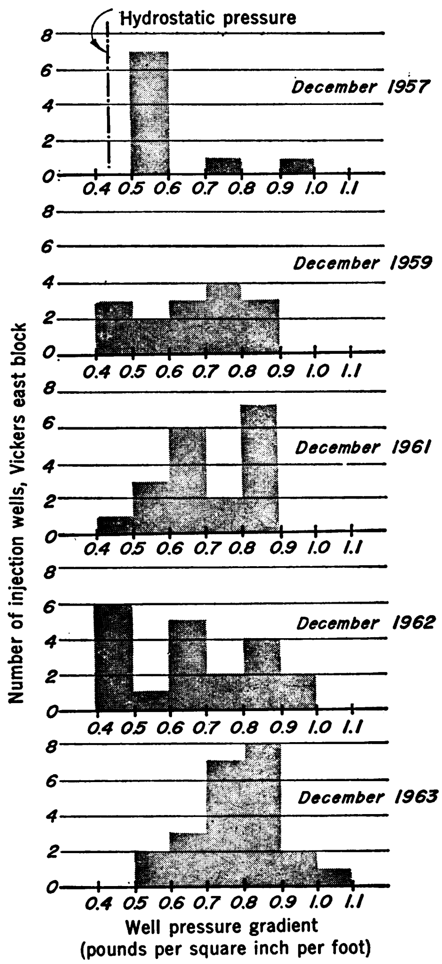

Fig. 5. Injection history for Vickers east block, 1957–63.

Influence of Secondary Recovery Operations

Recognition of these two serious objections, and further recognition that the procedure of exploitation in the Inglewood field changed from simple extraction to extraction combined with injection, has led to modification of the subsidence theory. As here presented, it eliminates the objections noted above, is supported by striking correlation of water-flood events and episodes of fault movement leading to ground rupture, and provides a satisfactory mechanical basis for the observed history of ground rupture. The revised theory may be referred to as the "subsidence fluid injection" theory. In substance, it specifies that injection of fluid into the ground under pressures only slightly greater than normal hydrostatic pressure will reduce and may, in areas subject to normal faulting, eliminate shearing resistance along potential failure planes. When this activity is carried out in ground earlier affected by faulting, and where additional stresses have been set up by differential subsidence, reduction in shear strength will give rise to movements that will be concentrated along preferred surfaces of weakness such as preexisting faults. According to this theory, fault activation and consequent ground rupturing should develop preferentially in an area being affected by fluid injection. This prediction is verified by the localization in space (Fig. 8) and time (Fig. 9) of earth-crack ground rupturing in the Baldwin Hills in and adjacent to the area of fluid injection for secondary recovery, which began almost simultaneously with the initiation of the "full-scale" water-flood program. The correlation of fluid injection events and surface rupturing is even more striking when it is examined in detail.

One of the first of the full-scale injector wells was placed in operation in May 1957. In that same month, a fault, the probable subsurface projection of which lies within or very near the injection interval of this well, was activated and became the first recognized earth crack in the east block area. Injection was started in 21 additional wells in that area between 1957 and 1963 (Figs. 5 and 8), during which time at least eight more faults were activated. The relation of injection intervals to the east block subsurface structure is illustrated by the geologic cross section in Fig. 4. This section passes through two of the east block faults, each of which had been related to surface rupturing by 1969.

The history of contemporary movement along the Reservoir fault (beneath the east side of the Baldwin Hills Reservoir basin) is known from monthly readings taken on strain gauges extending across a crack in the concrete inspection gallery beneath the reservoir and across the fault. The opening of the crack, which reflected displacement along the underlying fault, began in 1952 and was monitored until the time of reservoir failure in 1963. The history of crack activity (Fig. 10) shows three stages of progressively accelerating movement, upon which are superimposed individual jumps that reflect events of larger fault movement. These stages correspond to episodes of surface rebound or uplift, identified by Leps (*13*) from records of comparative leveling of bench marks at and south of the reservoir.

When the history of movement along the Reservoir fault is compared with the operational history of injector wells located in the vicinity of the fault's southerly subsurface projection, the evident influence of pressure fluid injection on fault activity can be recognized. The earliest stage of crack extension began prior to the initiation of the water-flood program and continued until just after the third of the first three injectors along the fault was brought into service. This stage may therefore represent ground movement attributable to differential subsidence with little or no effect of pressure injection. Then, in late 1957, a jump in the crack extension was followed by a doubling in the rate of extension and also by the first episode of surface rebound. This level of activity then continued for 3½ years, until 1961. At that time, three more injector wells were activated in the area. This increase in injection was followed several weeks later by another fault jump and a further increase—a tripling—in the rate of crack extension. Mid- and late 1963 was a period marked by intense activity in injection operations. Injection was started (or restarted) in four additional wells close to the reservoir, and severe and unusual operational problems were occurring in those wells (now nine) near the fault. Uncontrolled loss of fluid occurred in five injectors. One well appears to have been

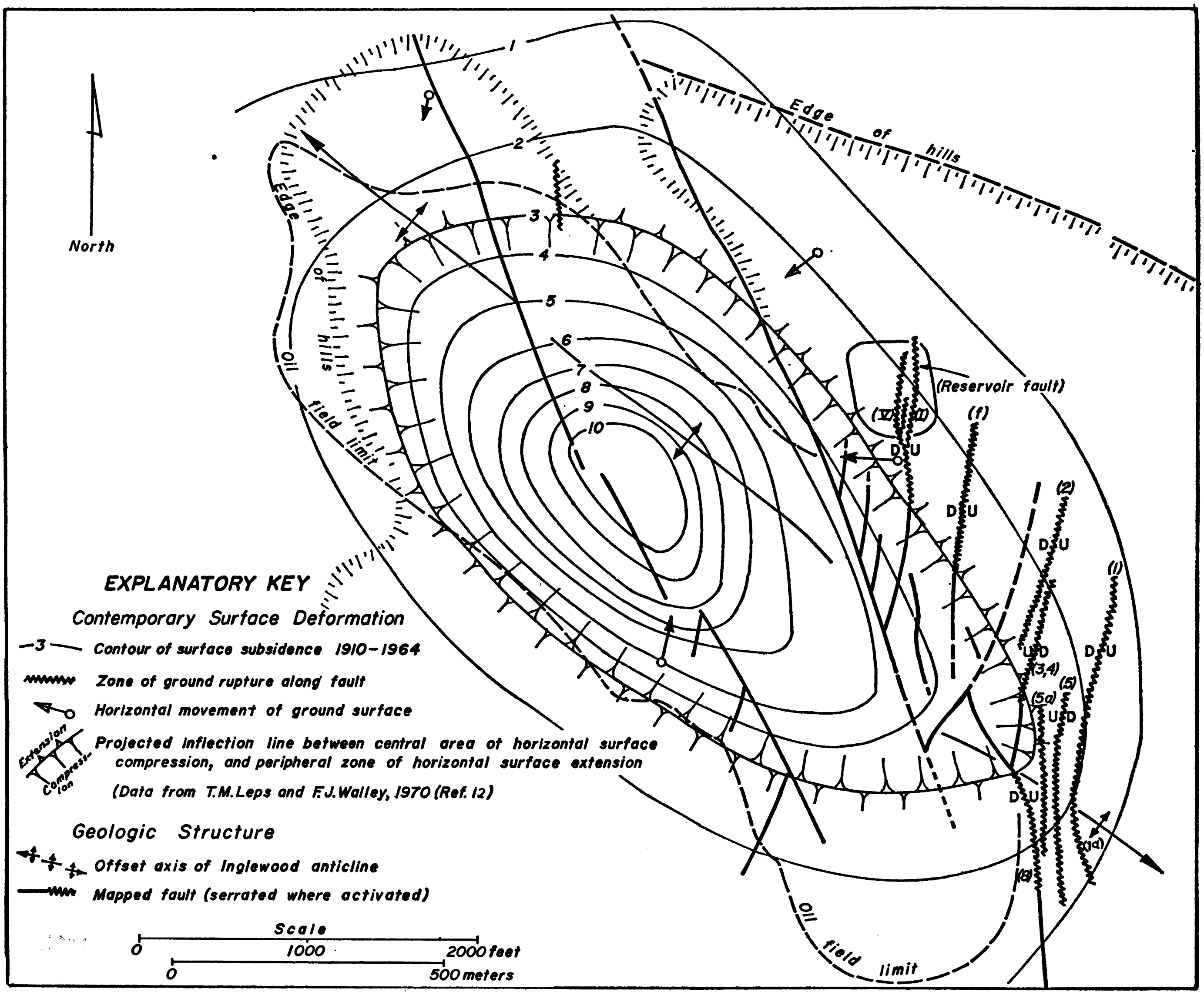

Fig. 6. Contemporary surface deformation, Baldwin Hills–Inglewood area.

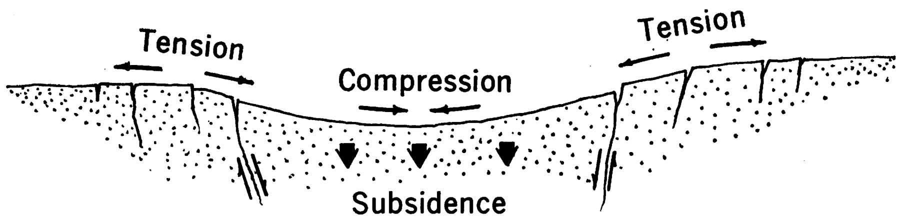

Fig. 7. Diagrammatic representation of fault activation attributed to subsidence.

pinched or sheared off at depth. In May, 6 months before the reservoir failure, brine was observed seeping from cracks in the ground surface south of the reservoir and on the trace of the Reservoir fault. Wellhead injection pressures during 1963 were erratic, but pressures in excess of 400 pounds per square inch were common; 400 pounds per square inch creates a gradient of 0.73 pound per square inch per foot at a depth of 1200 feet, the top of the injection interval. Late in 1963, an episode (or episodes) of movement occurred along the Reservoir fault. which culminated in failure of the reservoir. This fault movement, though apparently normal in sense of displacement, actually involved upward movement of the footwall block and was therefore distinctly related to the earlier episodes of surface rebound in the area.

In considering the possible cause-and-effect relations among injector activity, subsurface problems, and fault movements, it seems significant that all recorded episodes of fault movement since 1957 have occurred *after* one or more of the following: initiation of injection in nearby wells, increases of injection pressure, or problems such as dropping of fluid pressure concomitant with increases of fluid take, loss of fluid in narrow zones, and so on. The sequence of events suggests that the injection caused or contributed to the movement.

As is evident from Fig. 7, most of the ground cracking occurred in and beyond the outer margin of the injec-

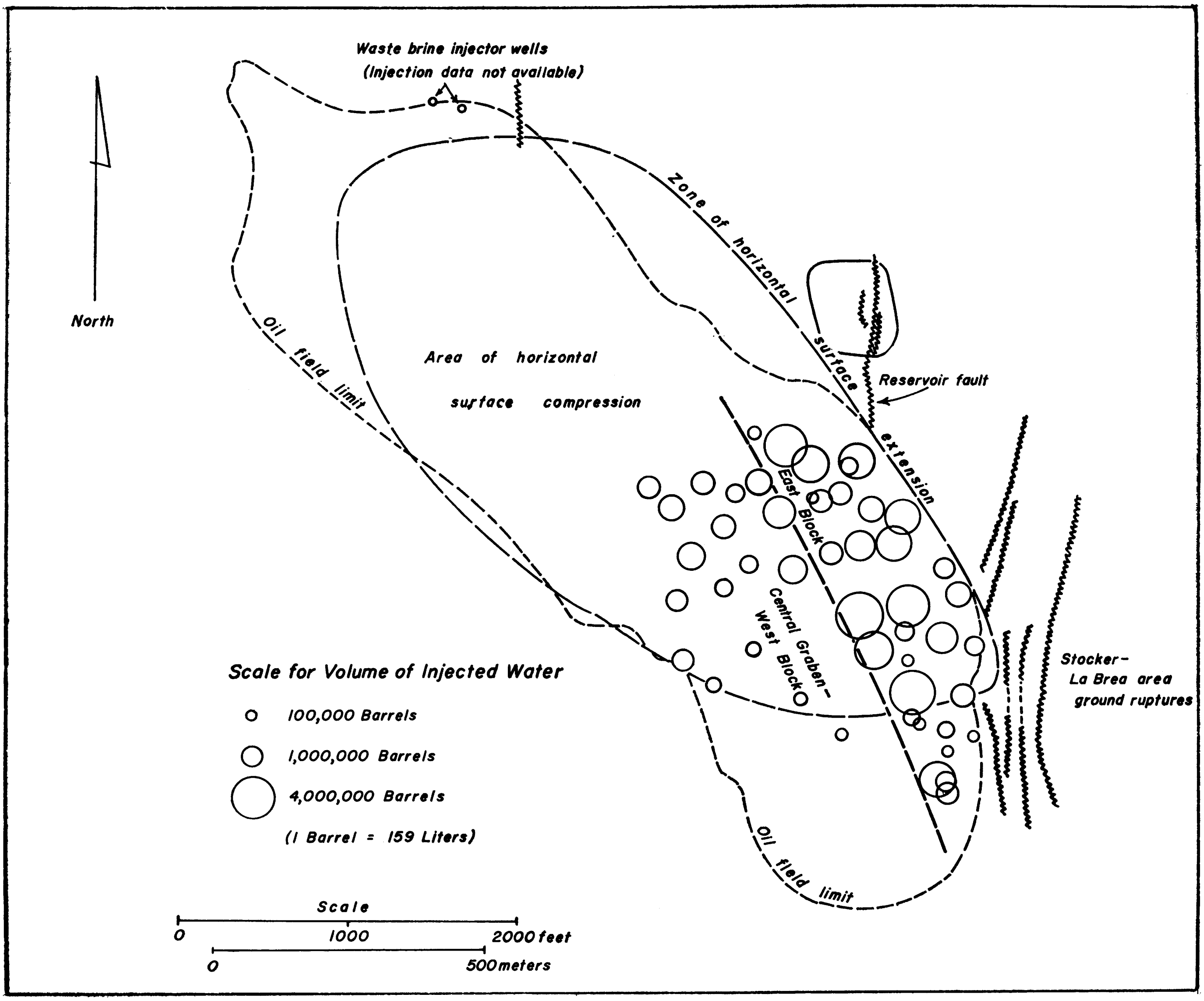

Fig. 8. Zones of ground rupture and cumulative amounts of injected water, Baldwin Hills–Inglewood oil field, through 1963.

tion area. The explanation for this condition lies in the three-dimensional geometry of the faults, and also in the relation of the area of surface rupture to the area of ground surface extension and compression induced by subsidence. Both projection of fault plane dips measured at the surface and reference to the cross section constructed from subsurface data (Fig. 4) indicate that most of the east block faults dip to the west. Consequently, fault planes in the immediate vicinity of injection intervals reach the ground surface, 800 to 1500 feet above, some hundreds of feet to the east. Faulting initiated at depth and propagated to the ground surface would therefore result in surface rupturing hundreds of feet to the east of the subsurface point of origin. Also, reference to the map of surface deformation (Fig. 6) shows that the surface rupture has occurred in the zone of ground surface extension but that it dies out as the faults enter the zone of surface compression. The surface compression evidently "clamps" the fault surfaces together, whereas the extension is associated with a pulling apart.

The only active ground rupturing known to us outside the east block area in the Baldwin Hills is a north-south zone of cracking at the north margin of the Hills (Fig. 8). This cracking reportedly began to develop about 10 years ago, well before the time of any secondary recovery operations in that vicinity. However, the rupturing is very near two fluid injection waste disposal wells, which probably have affected the strength of the subsurface in the same fashion as the pressure fluid injection for secondary recovery of oil.

Although water flooding was under way in 1970 throughout most of the Inglewood oil field, no ground rupturing other than that just noted has been recognized in the field's central area, or around its north, west, and south margins; it still continues, however, in the east block area. The absence of fault activation within other parts of the field can be explained by the "clamping" effect of surface compression in the ground there. The west margin of the field is probably in surface extension; unlike the faults in the east block, however, most of those in the west block die out upward at points beneath the ground surface. Consequently, even if fault activation has occurred at depth, it evidently has not propagated upward through the unfaulted shallower ground.

Fluid Injection Causes Faulting

The mechanical behavior of systems that consist of solid particles with fluid-filled voids has long been investigated experimentally by workers in the field of soil mechanics, who have derived mechanical principles that have been of great practical use in the design of civil engineering works. Changes in volume and in strength of soil and rock materials with fluid-filled voids have been shown to be fundamentally related to change in stress within the solid skeleton. An increase in stress in the solid skeleton produces a decrease in its volume, owing to elastic deformation of the skeleton and, in the case of uncemented assemblages, to closer packing of particles. For liquid-saturated systems, stress within the solid skeleton is generally expressed in terms of effective stress $\bar{\sigma}$ (*18*), given by the expression

$$\bar{\sigma} = \sigma - u \tag{1}$$

where σ is the total stress acting across some plane within the system and u is the fluid pressure in the region of the plane. This relation is more complex for a solid-liquid-gas system, but it holds approximately if the liquid and gas pressures are approximately equal. It follows from the effective stress principle that a decrease in fluid pressure produces a like increase in effective stress and therefore a decrease in volume of the solid skeleton.

The principle of effective stress provides a reliable theoretical basis for the prediction of settlements caused by changes in either total stresses or fluid pressures, if the compressibility of the solid phase is known from laboratory

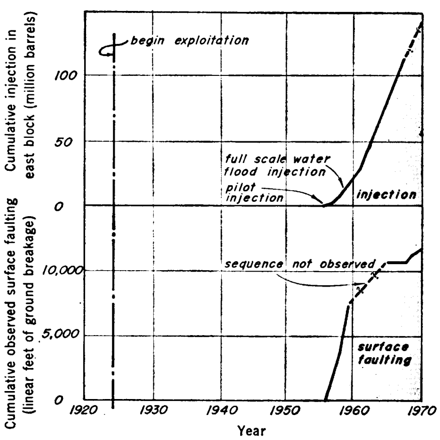

Fig. 9. Time relationship of ground rupturing and east block injection, Baldwin Hills and Inglewood oil field.

tests. No laboratory testing of the Inglewood oil sands has been performed, to our knowledge, but an a posteriori theoretical analysis of subsidence in the Inglewood oil field has been made by Castle and Yerkes (*4*), who used reasonable compressibility data for the oil sands. Their analysis indicates that increased effective stresses accompanying fluid withdrawal and decreasing fluid pressure will lead to subsidence of the same order of magnitude as that shown in Fig. 6.

Subsurface fluid *injection* has been practiced less widely than fluid withdrawal, and theoretical and empirical understanding of the mechanical effects of high-pressure fluid injection has lagged accordingly. Such injection into the subsurface has many practical applications, among the most important of which is water (and steam) flooding of oil-producing zones, with the object of enhancing production by maintaining hydraulic pressure and flushing oil toward producing wells. This process is known as secondary recovery.

Secondary recovery is now widely practiced by the oil industry, and an advanced technology has been developed to service these operations for production enhancement. The economic feasibility of production in many older oil fields now depends on this technology.

The mechanical effects of high-pressure fluid injection on the volume of sediments may be described by the principle of effective stress in a fashion corresponding to that for withdrawal. It is apparent from Eq. 1 that an *increase* in fluid pressure, induced perhaps by pumping fluid into the ground at depth, would be accompanied by an equal decrease of the quantity described as the effective stress. This would result, in accordance with experimental results, in an expansion of the soil element subjected to the increase in fluid pressure. Pressure injection over a wide area might then be expected to result in a rise of the overlying ground surface, or, in the case of formations that had previously been compressed through reduction of fluid pressure, restoration of former higher pressures could result in rebound of the compressed sediments. Results of laboratory tests suggest that the amount of rebound may be roughly equal to or, under the less usual but predictable situation of rebound from virgin compression, substantially less than the compression accompanying a like decrease in fluid pressure.

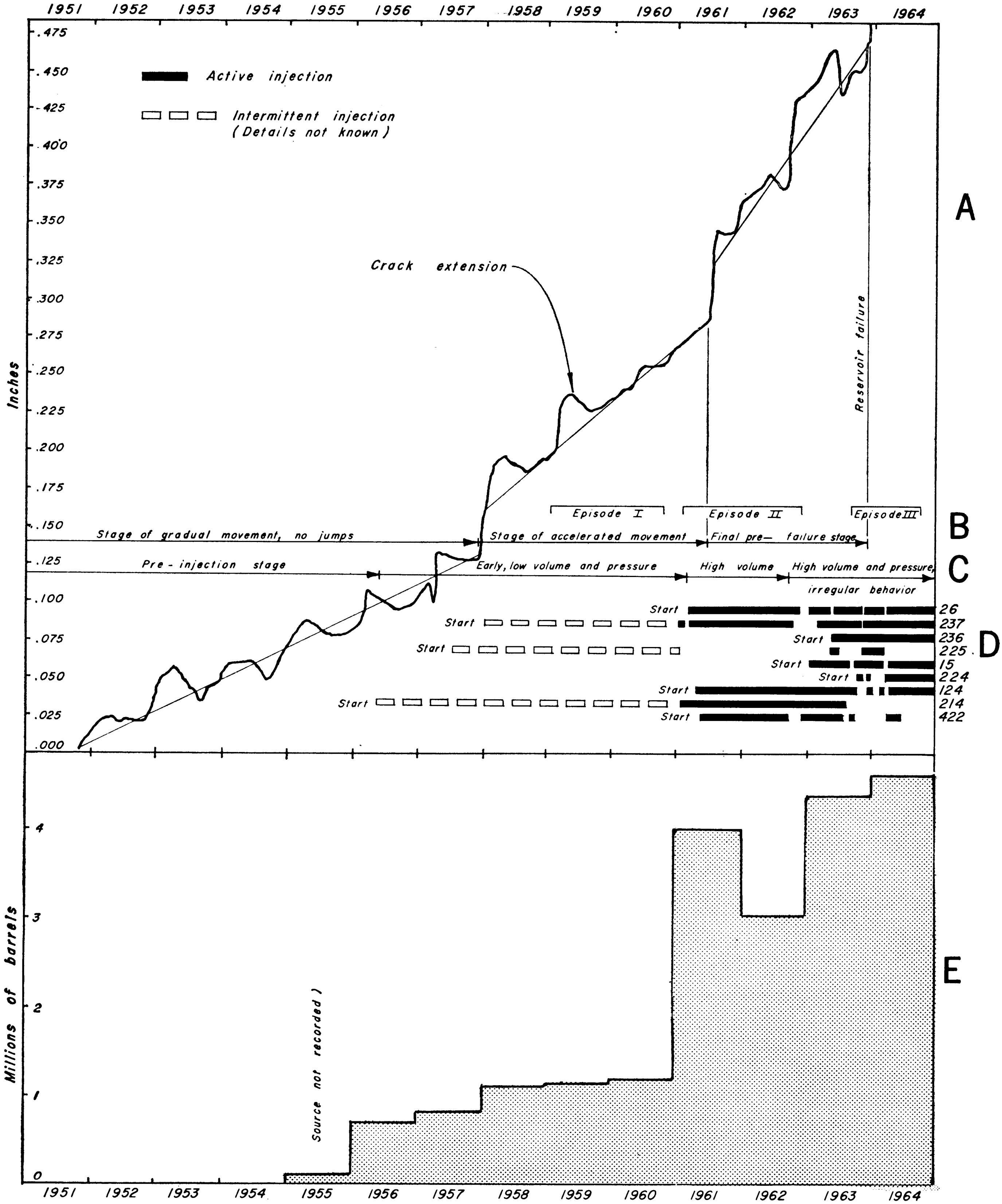

Fig. 10. Extension of Reservoir fault crack in inspection chamber of Baldwin Hills Reservoir as related in time to episodes of surface uplift, activity of injector wells, and volume of injected fluid near Reservoir fault. (A) Extension of crack over Reservoir fault in Baldwin Hills Reservoir inspection chamber (data from Los Angeles Department of Water and Power). (B) Episodes of surface uplift east of Reservoir fault (identified by T. M. Leps) and stages of crack extension activity. (C) Stages of injector well activity. (D) Times of operation of indicated injector wells located near the Reservoir fault. (E) Volume of fluid injected in wells located near the Reservoir fault.

Ground heave attributable to injection-induced volumetric expansion of substrata apparently has not generally given rise to secondary problems, perhaps because injection programs usually involve relatively small quantities or, not infrequently, are carried out in areas simultaneously or previously affected by subsidence and perhaps lacking structures such as reservoirs that could be seriously damaged. However, another side effect of high-pressure injection is the weakening of substrata that inevitably accompanies artificially induced increases in fluid pressure. This will occur in both cemented and uncemented rock materials; it can be more easily visualized in the case of uncemented sediments such as those in the Baldwin Hills.

The shear strength of unconsolidated sediments is mainly frictional and can be related to the quantity previously described as the effective stress. This can be shown experimentally by confining a sand specimen in a box (or flexible membrane) and then causing the specimen to fail by shearing. The shear stress on the failure plane at failure will be, for a typical sandy sediment, about 0.6 times the normal stress on the failure plane (Fig. 11A). This relation holds in a simple solid-fluid system, if the effective stress is taken as the normal stress. It can also be demonstrated theoretically and experimentally that the relation between major and minor principal stresses (effective stresses) at failure for the same material will be approximately as shown in Fig. 11B.

Subsurface stresses in relatively unconsolidated sediments under conditions of normal (gravity) faulting are approximately as shown on Fig. 11B. The major principal stress is vertical; expressed in terms of effective stress, it is equal to the pressure exerted by the weight of the overburden less any fluid pressure. The faulting is by definition a shear failure of the material, from which it may be deduced that the horizontal effective stress is at or near one-third the vertical effective stress.

Figure 12 illustrates the fluid pressure on a hypothetical system at a depth of 1600 feet—the depth of intensive injection activity in the east block—and initially in a state of incipient normal faulting. A geostatic pressure gradient of 1 pound per square inch per foot is assumed; thus, total vertical stress is 1600 pounds per square inch. The hydrostatic fluid pressure gradient is 0.43 pound per square inch per foot of depth, or 690 pounds per square inch at a depth of 1600 feet. From Eq. 1, effective vertical stress is then 1600 less 690, or 910 pounds per square inch. Horizontal stress includes a fluid stress component, equal to the assumed hydrostatic fluid pressure of 690 pounds per square inch at a depth of 1600 feet, and an effective stress component that, under the assumed state of limiting equilibrium, is about one-third of the vertical effective stress, or 303 pounds per square inch.

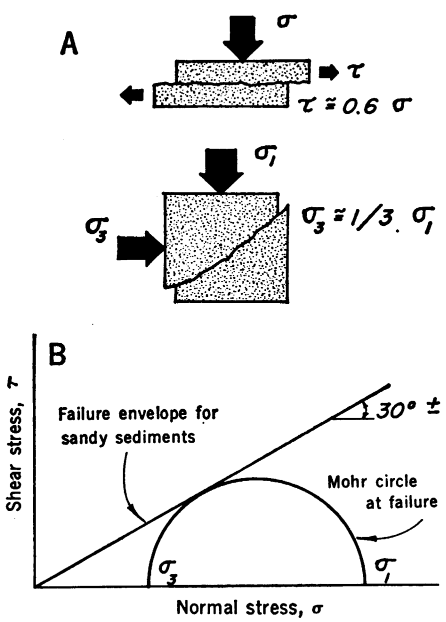

Fig. 11. Typical failure conditions in uncemented sediments: (A) as determined by laboratory tests; (B) Mohr failure criterion.

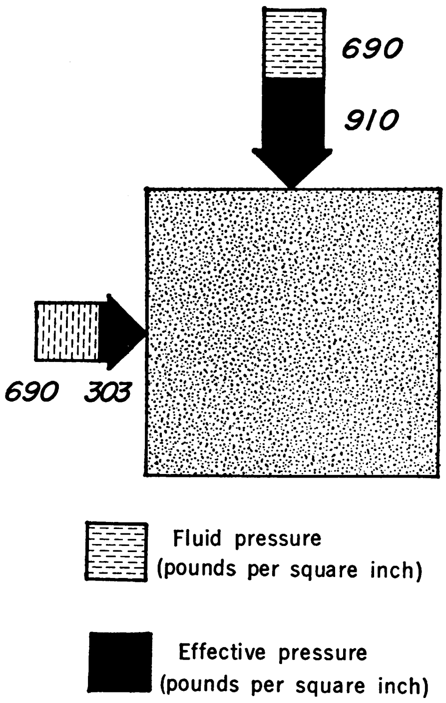

Fig. 12. Hypothetical natural stress conditions in element at a depth of 1600 feet. Normal faulting is imminent.

Reduction of fluid pressure increases both major and minor principal stresses, produces compression of the element, and, by reduction of the ratio of principal stresses, "backs away" from the critical state of shearing equilibrium.

Increase of fluid pressure has an opposite, destabilizing effect. If the fluid pressure is raised beyond the natural hydrostatic condition, the principal stress ratio will tend to increase, a condition not compatible with the previously defined state of limiting equilibrium; shearing will then occur and will continue until some readjustment of stresses restores equilibrium.

If normal faulting had occurred in the distant geologic past but a readjustment of stresses had since provided a margin of safety against reactivation of existing normal faults, and if subsidence were not contributing to disequilibrium, then the initial stress condition in the east block area might be somewhat different from the postulated condition of limiting equilibrium. However, unless a recent and major change in orientation or magnitude of principal stresses in the vicinity of the east block is postulated, it is reasonable to assume that the ratio of horizontal to vertical effective stresses across the recently active, normal fault planes would be no greater than about 0.5, a typical ratio obtaining in "normally consolidated" sediments under tectonically quiescent conditions. In this case the initial horizontal effective stress would be 455 pounds per square inch for the example in Fig. 12, and a fluid pressure increase from 690 to 915 pounds per square inch (gradient increase from 0.43 to 0.57) would be required to reestablish the limiting principal stress ratio of one-third; hence, faulting would be activated in the ground affected by such a pressure increase. It would thus appear that only a small increase in fluid pressure (a gradient of 0.6 or less) should be sufficient to trigger at least local shear failure in the east block, even if the material was not stressed to the point of failure by subsidence or active normal faulting.

The relation of fluid pressure to formation fracturing has been treated by Hubbert and Willis (*19*), who show that hydraulic fracturing will occur in tectonically relaxed regions at injection pressure gradients of less than 1. In the above example, the reduction of horizontal effective stress (455 pounds per square inch) to zero should result in fracturing along vertical or near-vertical planes and would occur at an injection pressure gradient of 0.62. As demonstrated above, this hypothetical fracture condition is statically inadmissible, given the shear failure criterion adopted for the material, without readjustment of stresses, which could arise only through shear deformation. The history of difficulties with injectors in the east block and comparison of injection gradients with fracture gradients in similar tectonic environments leave little doubt that fracturing could (and did) occur in the east block at injection gradients well below 1.0. Fracturing would and doubtless did result in extension of the effects of a single injector to points hundreds or thousands of feet away from the injection interval, thus exposing large volumes of sediment to the elevated injection pressures soon, or perhaps immediately, after the raising of pressure at the wellheads. Moreover, fracturing must have been accompanied by shear deformation, unless initial horizontal and vertical stresses in the injection zones were equal, which was certainly not the case in the recently faulted sediments comprising the east block.

In the Baldwin Hills east block area, injection pressure gradients of as much as 0.9 were employed, and relatively large bodies of ground, including an extensive reach of the Reservoir fault, were subjected to pressure gradients greater than 0.7. The history of casing failures in injection wells, sudden injection pressure losses, uncontrolled major entries of fluid at the tops of injection intervals (leading in at least one incident to discharge of injection fluid at the ground surface), all indicate that injection pressures were high enough to markedly reduce, or, in some areas, locally to eliminate the shear strength along preexisting fault surfaces and, also locally, to "fracture" the formation hydraulically and to create new fracture surfaces. The weakened zones must have been confined initially to the immediate vicinity of the injection wells, but subsequently, as new injectors were put into operation, relatively larger volumes of material became affected. In the case of the Reservoir fault, significant shear displacement probably had occurred along much of the break by mid-1963, and, at the end of that year, rupture propagating to the ground surface was of sufficient magnitude to shear the clay lining of the Baldwin Hills Reservoir and cause its failure.

Conclusions

That the earth-crack ground rupturing of the Baldwin Hills was genetically related to high-pressure injection of fluid into the previously faulted and subsidence-stressed subsurface seems established beyond reasonable doubt. The fault activation appears to be a near-surface manifestation of stress-relief faulting triggered by fluid injection, a mechanism identified as being responsible for the 1962–65 Denver earthquakes and for generation of small earthquakes at the Rangely oil field in western Colorado (*20*).

These examples of fault activation through the response of stressed ground to artificially induced increases in subsurface fluid pressure demonstrate some of the mechanically predictable consequences of injection of fluid into the ground, a practice that is becoming increasingly widespread not only in secondary oil recovery operations but as a means of industrial waste disposal and groundwater management.

Experience in the Baldwin Hills suggests that, although fluid injection operations may be carried out for beneficial purposes, the effects of such injection on the geologic fabric can be serious and far-reaching.

References and Notes

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21. We thank T. M. Leps, R. H. Jahns, and others for suggestions and criticism.