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Case Histories of Induced and Triggered Seismicity

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1. Introduction

The study of anthropogenic seismicity began when earthquakes were first felt in Johannesburg in 1894 (McDonald, 1982); by 1908 these events had been attributed to the Witwatersrand gold production, which had commenced in 1886 (Cook *et al.*, 1965). Mine seismicity began to be recognized in Europe in about the same era. The first seismological observatory for monitoring these phenomena was established in Bochum in the Ruhr coal basin, Germany, in 1908 and the first seismic network was installed in the Upper Silesia coal basin, Poland, in the late 1920s (Gibowicz and Kijko, 1994).

Since then, many other types of induced and triggered earthquakes have been either recognized or, at least hypothesized. Seismicity associated with petroleum production became apparent in the early 1920s, with reservoir impoundment in the late 1930s, with high-pressure liquid injection at depth in the mid-1960s, and with natural gas production in the late 1960s. Currently debated is the possible connection between major petroleum or natural gas production and large earthquakes at midcrustal depths.

As used here, the adjective "induced" describes seismicity resulting from an activity that causes a stress change that is comparable in magnitude to the ambient shear stress acting on a fault to cause slip, whereas "triggered" is used if the stress change is only a small fraction of the ambient level (e.g., Bossu, 1996; McGarr and Simpson, 1997). By "stimulated" we refer generally to seismicity either triggered or induced by human activities. As will be seen, most of the case histories reviewed here entail triggered rather than induced seismicity.

Our assumption is that a wide variety of examples of stimulated seismicity can provide independent perspectives regarding the essential problem of the causes of earthquakes (Simpson, 1986). Accordingly, we review case histories exemplary of a broad spectrum of causative mechanisms and ranging from obvious to speculative in the correlation between earthquakes and specific human activities. Hopefully, by surveying a representative cross section of such earthquakes we can gain general insights. To this end, it is important to establish the similarities and differences in the mechanisms responsible for the various types of stimulated earthquakes. Thus, progress in understanding one type of artificial earthquake can be of use in understanding other types and perhaps interactions between natural earthquakes as well (see Harris, 1998; Chapter 73 by Harris).

The mechanisms that have been invoked to account for anthropogenic seismicity include changes in the state of stress, pore pressure changes, volume changes, and applied forces or loads. These mechanisms, of course, are not all independent. Often, for a particular case, the analysis of several mechanisms can provide different perspectives regarding the resulting seismicity. Ideally, if we understand these mechanisms well enough and we also know the background crustal state (tectonic setting), then we can forecast both where triggered seismicity will occur and the maximum likely earthquake magnitude.

Figure 1a,b introduces the types of seismicity reviewed here starting with mining-induced earthquakes, for which cause and effect are established, and ending with large-magnitude seismicity at midcrustal depth whose association with shallow-level hydrocarbon production is only speculative. In general, triggering is a plausible explanation for earthquakes if the corresponding perturbation can be shown to have shifted a fault toward failure at a time that can account for the onset of seismicity. This task is easier where natural seismicity is low and a chance correlation in time and space between a possible trigger and seismicity is unlikely.

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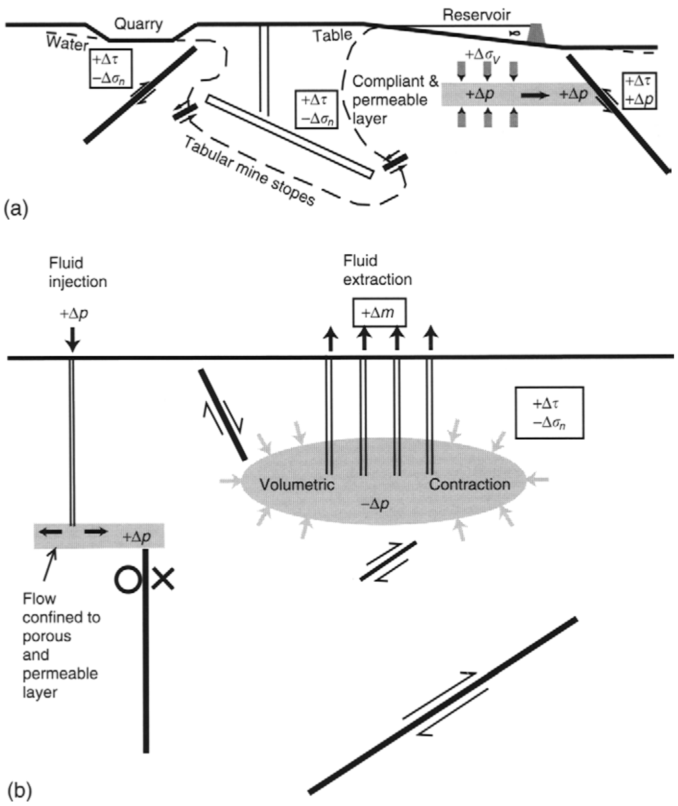

FIGURE 1 (a) Schematic view of seismicity stimulated by quarry, deep mining, and reservoir impoundment. For each case, the important mechanisms for causing seismicity are indicated. Quarries and deep-level mining cause the water table to be depressed because of pumping operations to prevent flooding. (b) Schematic view of seismicity stimulated by liquid injection at depth, which can raise the pore pressure on faults in the environs, and earthquakes caused by the exploitation of major oil and gas fields. Oil or gas production reduces the pore pressure within the reservoir, causing contraction and induced stress changes in the environs. These stress changes can result in a variety of focal mechanisms as indicated. On a larger scale, production can change the crustal loading substantially resulting in major earthquakes at midcrustal depths. A thrust faulting earthquake tends to thicken the crust so as to offset the vertical force imbalance due to production.

2. General Considerations

2.1 Ambient State of Stress and Pore Pressure

In situ stress measurements made in a variety of tectonic settings, both active and inactive, indicate, almost invariably, that the ambient state of stress in the continental crust is quite close to the depth-dependent strength of the crust estimated from laboratory experiments (e.g., Zoback and Healy, 1984; Brudy *et al.*, 1997). Moreover, these same investigations reveal that the ambient pore pressure is nearly always close to hydrostatic. Laboratory estimates of crustal strength (e.g., Brace and Kohlstedt, 1980) are based on stick-slip friction experiments as extrapolated to conditions anticipated at depth in the crust. That is, if the upper seismogenic crust is pervasively faulted then frictional sliding across these faults [Byerlee's (1978) law] will limit the strength of the crust.

The strength of a fault, or the shear stress τ required for failure, can be expressed as

$$\tau = \tau_0 + \mu(\sigma_n - p) \qquad (1)$$

where τ_0 is the cohesion, μ is the coefficient of friction, σ_n is the normal stress across the fault and p is the pore pressure within the fault zone. Laboratory measurements of μ are generally in the range 0.6–1.0 (Byerlee, 1978; Dieterich, 1979). Thus, for a given state of stress, the strength of a fault would depend on its orientation, pore pressure, and cohesive strength. In estimating crustal strength it is often assumed that (1) faults exist in the crust that are optimally oriented for failure, (2) the water table is at the surface (hydrostatic pore pressure), and (3) the cohesive strength can be neglected.

2.2 Stress and Pore Pressure Changes Required to Cause Earthquakes

Triggered or induced seismicity occurs when the mechanical state of the seismogenic crust is sufficiently perturbed to cause a fault to fail. As indicated by Eqn. (1), failure can occur either because the stress τ loading the fault increases or the strength of the fault is reduced due to a decrease in the normal stress σ_n or an increase in the pore pressure p.

Figure 2 shows a ternary diagram in which these three components (σ_n, τ and p) form a field in which can be placed different types of induced and triggered seismicity, depending on the dominant cause. In some cases, the isolation of a single mechanism is simple (e.g., increases in pore pressure cause injection-related seismicity). In others (e.g., reservoir triggering) the relationship is more complex. More than one parameter may be involved (shear stress and pore pressure) or parameters may be coupled (e.g., stress and pore pressure). While care should be taken not to oversimplify what is often a complex process, this figure can help as a reference in the following discussion to identify the dominant factors influencing failure.

For a number of the case histories to be discussed here, the stress changes required to trigger seismicity, as well as the corresponding seismic stress drops (of the order of 1 MPa), are small fractions of the shear stress acting to cause fault slip (e.g., McGarr and Simpson, 1997); indeed, numerous studies, some of which are reviewed here, lead to the conclusion that stress changes as small as 0.01 MPa [Eq. (1)] may trigger earthquakes. This general observation is consistent with the idea that the crustal state of deviatoric stress tends to be nearly as high as the crustal strength (e.g., Zoback and Harjes, 1997; Grasso and Sornette, 1998). The exception to this

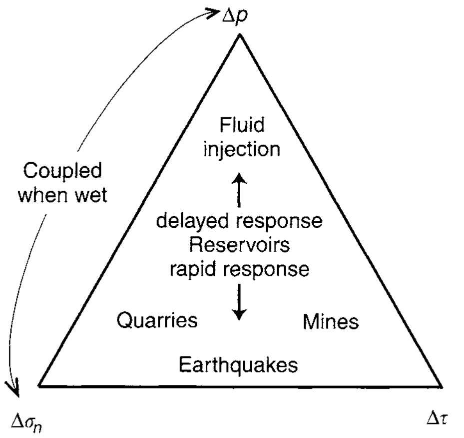

FIGURE 2 A simplified classification of three of the mechanisms controlling stimulated seismicity [see Eq. (1)]. Surface quarries, deep mines and regional earthquakes cause increases in seismicity primarily through modifications to the elastic stress field. Increased pore pressure is the dominant factor for liquid injection at depth. Reservoir loading can entail changes in all three parameters to stimulate earthquakes. Oil and gas field compaction primarily results in changes in the state of stress within the seismogenic rockmass surrounding the reservoirs. (Adapted from Figure 1 of McGarr and Simpson, 1997.)

generalization is mining-induced seismicity (Fig. 1) for which the stress changes causing the earthquakes are of the same order as the ambient crustal stresses loading the mine workings, as will be described.

2.3 How Much Seismic Deformation?

Given that seismicity occurs in response to specific changes in stress or pore pressure [Eq. (1)], then the next question entails the amount of seismic deformation that results. This is an important question because both the maximum magnitude and the seismic hazard are well correlated with the total seismic deformation.

Perhaps the most straightforward factor influencing the potential for seismic deformation is the size of the region over which an activity (e.g., gas production) takes place, as will be illustrated later. Volume changes associated with mining, liquid injection at depth and petroleum exploitation (McGarr, 1976; Pennington *et al.*, 1986) provide another means of estimating the potential seismic deformation. Similarly, large-scale oil and gas exploitation can remove mass and thereby change the crustal loading resulting in an isostatic imbalance; it is straightforward to calculate the seismic deformation needed to restore isostatic balance to the region (McGarr, 1991).

It is important to note that we can only estimate the potential for seismic deformation resulting from a particular human activity, which is not the same as predicting the ensuing seismic deformation. There are, needless to say, many activities that have the potential for producing sizable earthquakes (e. g., large impounded reservoirs) that, in fact, result in little or no detected seismicity. This issue is returned to later.

2.4 Triggered Seismicity in Stable Continental Regions and in Tectonically Active Regions

Even though deformation rates in stable continental regions within the plates are so low that they cannot yet be measured with the current $\approx 10^{-10}$ geodetic resolution (Argus and Gordon, 1996), earthquakes nonetheless occur there which suggests that deformation rates are finite and perhaps coherent over large regions of the continents (Sbar and Sykes, 1973). Faults that can be associated with this seismicity tend to be small and to have little accumulated displacement (Adams *et al.*, 1991; Crone *et al.*, 1992; Machette *et al.*, 1993; Seeber *et al.*, 1996). Geologically, they do not stand out from many other faults scattered over these stable regions. Seismicity and geology, therefore, suggest that potential sources of earthquakes are ubiquitous in these areas in spite of their tectonic stability (Seeber *et al.*, 1996). This is consistent with many sets of *in situ* stress data (e.g., Brudy *et al.*, 1997) indicating states of stress close to the failure state for both stable and tectonically active regions.

Although anthropogenic seismicity in different tectonic environments has not been rigorously compared, it seems higher in stable continental regions because of the combination of low strain rate, which yields a low level of natural seismicity, and a near-failure state of stress, which is the key factor in the occurrence of triggered earthquakes. Assuming that all other factors are equivalent, including the average proximity of the stress to failure, similar absolute levels of triggered seismicity are expected in tectonically stable regions and at plate boundaries. Because of the vast difference in rates of natural seismicity, however, artificially triggered seismicity appears to be far more significant in stable regions than in plate boundary settings.

The tendency of many natural earthquakes in stable tectonic settings to nucleate in the upper few kilometers of the crust (e.g., Ungava, 1990; Adams *et al.*, 1991; Mekering, 1968; Vogffjord and Langston, 1987; Tennant Creek, 1988; Choy and Bowman, 1990; Marryat Creek, 1986; Fredrich *et al.*, 1988) is another factor that may contribute to the relative importance of artificially triggered earthquakes in these areas. Presumably the seismogenic crust in these tectonically stable regions extends to shallow levels and thus may be relatively close to engineering activities that might cause seismicity, such as quarry operations. In contrast, most significant earthquakes in active areas tend to nucleate below the upper few kilometers of the crust which are thought to be too fractured and weak to accommodate significant elastic energy (e.g., Scholz, 1990). Thus the near-surface perturbations from engineering activities may coincide more closely with the seismogenic crust in stable than in active tectonic settings.

2.5 Monitoring Induced and Triggered Earthquakes and their Causes

In contrast to poorly understood natural seismotectonic processes, mechanical changes caused by engineering operations in the seismogenic depth range of the crust can be assessed in some detail in terms of their potential for induced and triggered seismicity. The predictability of triggered seismicity offers the opportunity for a systematic approach to designing seismic experiments that can provide unique insights regarding the earthquakes, their causes and their effects, particularly in areas where natural seismicity is low. Monitoring should start before the perturbation so that an onset of unprecedented seismicity, if it occurs, can be recognized and compared to the evolution of any forcing function. Furthermore, the monitoring needs to continue after the end of the engineering operation because the strongest perturbation may stem from a delayed rise in fluid pressure. Additionally, these observations need to include not only high-resolution earthquake ground motion data, but also geodetic, pore pressure, and water level data, as well as pertinent industrial and engineering parameters.

In many of the early cases of earthquakes triggered near dams, some ambiguity existed because of the lack of detailed monitoring before impounding of the reservoir (e.g., Lake Mead, Roeloffs, 1988). As the possibility of triggered seismicity has become more widely appreciated and acknowledged, it is becoming more common to have seismic stations installed and operating during the early development stages so that a clear picture of background seismicity is available.

2.5.1 Earthquake Monitoring

The instrumentation and techniques for observations of induced and triggered earthquakes are similar to those for any local, shallow seismicity (Chapter 17 by Lee). Dense networks of seismometers are required to determine both the temporal evolution of seismicity, including the time-dependent spatial patterns of earthquake locations. Because the onset of triggered seismicity may involve subtle changes in microearthquakes, it is important to have a monitoring system with adequate sensitivity and high location accuracy, so that low-magnitude events can be well recorded. To avoid the signal degradation associated with near-surface site effects, borehole recording using three-component seismometer packages having wide dynamic range and broad bandwidth is highly recommended (e.g., Malin *et al.*, 1988; Abercrombie, 1995).

With regard to data analysis, precise hypocentral locations and magnitude assignments are essential, but there is much more that can be gleaned from the seismograms. In particular, seismic source parameters including source dimension, seismic moment, stress drop, and radiated energy (e.g., Spottiswoode and McGarr, 1975) can provide useful insights for relating industrial operations to the resulting seismicity. For instance, seismic moment tensors have revealed key information regarding energy budgets of earthquakes and their relationship to mining operations (McGarr, 1992).

Triggered seismicity tends to be close to major engineered structures (dams, wells, mines) and may include damaging earthquakes. Seismic instrumentation deployed on these structures can provide valuable detailed knowledge of their response to strong ground motion.

2.5.2 Monitoring the Causes of Induced and Triggered Earthquakes

If the relationship between the stimulated seismicity and its cause is to be established and understood, it is essential that there be detailed monitoring of the causative agent itself (e.g., water level in reservoirs; pressure and volume of fluids injected or extracted). These data need to be available as time series with sufficient resolution to be compared to the time and size of earthquakes. Measurements of crustal deformation generally have played key roles in relating various human activities to corresponding induced or triggered earthquakes. Such measurements include trilateration, leveling, tilt, and borehole strain. Airborne or space synthetic aperture radar (SAR) interferometry offers new opportunities for detailed monitoring of strain.

2.5.2.1 Reservoirs

To first order, the most obvious parameter to measure at a reservoir is the depth of water at the dam (usually the deepest part of the reservoir). Because of its importance in operation of power plants or irrigation, this parameter is measured precisely and frequently by the dam operator. Daily measurements with a precision of centimeters are usually available. Water volume in the reservoir is also estimated, usually through knowledge of the basin geometry. Often overlooked in studies of reservoir-triggered seismicity is the growth of the reservoir over time and the influence of the reservoir on the regional water table. Less frequently, deep piezometer wells are drilled as part of the assessment of the regional groundwater regime and these may continue to be monitored during exploitation of the reservoir.

2.5.2.2 Liquid or Gas Injection and Extraction

The pressure and volume of fluid in or out of the rock are the key parameters. They are also of prime concern to the facility operator and are carefully monitored. These data are often considered proprietary, however, and so are difficult to obtain because they may have direct economic and liability implications.

2.5.2.3 Mines and Quarries

In cases of seismicity associated with mining or quarrying, the mass of extracted material and the geometry of the excavations are important. In deep mines the opportunity exists to compare seismicity directly with *in situ* stress measurements. Some large mines now include extensive seismic systems as a safety measure for monitoring rockbursts. In addition to being an important part of the mine operations, the data from these systems can provide information of direct relevance to the nature of induced seismicity and earthquake sources in general. Most mines and quarries require continuous pumping of water to prevent flooding. After they are abandoned, pumping ceases, allowing the water table and pore pressure to rebound to original levels. But, the stress is permanently altered by the mining, leading occasionally to triggered seismicity; we review in the next section a case history of this. It is useful, therefore, to continue monitoring seismicity, water level, and pore pressure after the facility is shut down.

2.6 Can Triggered Earthquakes Be of Use?

Earthquakes can be helpful in several ways. For instance, harmless small earthquakes can give information about large potentially damaging ones. In situations where earthquakes are triggered by known hydromechanical changes, analysis of these events can improve our general understanding of processes leading to earthquakes. As an example, the nucleation process, whereby friction on a fault changes from static to dynamic, is recognized as a key to understanding earthquake physics and to make progress in earthquake prediction (e.g., Dieterich and Kilgore, 1996). In the natural laboratory provided at sites of triggered earthquakes, the nucleation process that occurs between the time of the triggering perturbation and the occurrence of the earthquake can be studied in some detail and the dependence of the nucleation time on the characteristics of the earthquake and of the stress perturbation can be explored (e.g., Harris and Simpson, 1998).

Earthquakes can provide information about the changes in hydromechanics that triggered them. Engineering projects that alter conditions in the crust may consider earthquakes as a threat to the integrity of the operation and as a potential liability, but they may also use them for remote monitoring of physical parameters in their field of operation. Applications of modern seismology to engineering problems may include monitoring stress parameters including pore pressure effects (e.g., Reasenberg and Simpson, 1992), illuminating the structure and kinematics of active faults (e.g., Seeber and Armbruster, 1995) and resolving bulk properties such as anisotropy and anelasticity (Hough *et al.*, 1999). Earthquakes may also illuminate flow paths as shear failure tends to increase permeability on joint or fault surfaces (Brown and Bruhn, 1996). Thus seismology is becoming a tool for monitoring hydrocarbon fields, hydrothermal energy recovery systems, and waste-fluid disposal in deep wells. Finally, we note that monitoring of microearthquakes in mines provides information that can influence management decisions regarding production operations so as to enhance underground safety by taking seismic hazard more fully into account.

2.7 Liability for Induced and Triggered Earthquakes

From a scientific perspective, the liability aspect of induced or triggered earthquakes largely entails disadvantages to anyone trying to understand these earthquakes (in contrast to someone seeking to assign blame for them). In most cases, sincere efforts to work closely with professional staff at an engineering operation that could cause or is experiencing triggered or induced seismicity will result in productive cooperation. In some cases, however, especially in areas of high risk, concerns over litigation can stifle cooperation. For example, the potential for litigation may cause industry to be reluctant to release data that, although scientifically valuable, might be used in a court of law to establish liability. Similarly, industry may hesitate to even record data (e.g., seismic) that could be used for purposes of litigation. Moreover, collegial relations between scientists may be compromised by legal proceedings and the exchange of scientific information curtailed. Although self protection by private enterprise is understandable, society in general and the scientific community in particular suffer the disadvantage of being denied potentially beneficial information. Such situations can be mitigated by government regulatory agencies which can apply both "carrot" and "stick." For instance, industrial activities that tend to cause seismicity might be required to collect and release pertinent data. The "carrot" may entail a broader distribution of responsibility for the seismic risk involved in engineering operations which are vital to society. Scientists can also offer a "carrot" to industrial management in the form of improved understanding of the interaction between natural processes and engineering operations that would improve the basis for production decisions from both the economic and the liability standpoint. For the reader interested in a comprehensive discussion of legal issues associated with anthropogenic earthquakes, we recommend the article by Cypser and Davis (1994).

3. Case Histories of Stimulated Seismicity

The following examples have been chosen from many different regions to illustrate various mechanisms that relate human activities to stimulated seismicity. These case histories begin with mining-induced earthquakes for which the relationship between mining and earthquakes is unequivocal, and end with major earthquakes at midcrustal depths beneath oil and gas fields where a connection between the production and the seismicity is controversial.

3.1 Mining Seismicity

We review here five examples of mining seismicity, selected so as to illustrate the effects of factors such as depth, scale, state of stress, pore pressure, and mining technique. A vast literature has accumulated in the last four decades about mining-induced earthquakes (e.g., see bibliography in Gibowicz and Kijko, 1994). This type of seismicity is arguably better understood than other types and, thus, is of particular interest regarding insights into the causes and mechanisms of natural earthquakes. That is, earthquakes caused by mining appear to be largely the same phenomena as natural crustal earthquakes but, as reviewed here, can be analyzed more confidently in terms of causative forces, energy budgets, and hypocentral circumstances.

3.1.1 Deep-level Gold Mining in South Africa

The Witwatersrand gold fields, where the study of induced and triggered earthquakes began early in the 20th century (e.g., Cook *et al.*, 1965), currently involve gold production at depths between 2000 and 4000 m in an extensional, but inactive, tectonic setting. In these mines, gold production is achieved by excavating subhorizontal tabular stopes, with initial widths a little greater than 1 m and lateral extents generally in the range of 100 m to several km. The high level of seismicity, typically within several hundred meters of the active mine faces, is associated with the substantial stress changes in the brittle strata abutting the stopes. The source of energy for this process is the collapse of the tabular voids due to the considerable overburden stress (Cook, 1963; Cook *et al.*, 1965, McGarr, 1976, 1993); magnitudes occasionally exceed 5 (Fernandez and van der Heever, 1984) and levels of ground velocity, especially in the hypocentral environs, can be in excess of several meters per second and highly damaging (Wagner, 1984; McGarr, 1993; Ortlepp, 1997).

The rate of seismic deformation, as measured by estimating seismic moments, has been related quantitatively to the rate of ore production and the attendant stope collapse (McGarr, 1976). Maximum magnitudes or moments, however, are influenced by the mining techniques. Irregular mine geometries give rise to the largest earthquakes (e.g., McGarr and Wiebols, 1977; Gay *et al.*, 1984), a point which is returned to later.

The stress changes that cause the seismicity often involve increases in the shear stress as well as decreases in the normal stress acting on the fault plane and can be estimated using various methods (e.g., Cook, 1963; Cook *et al.*, 1965; McGarr *et al.*, 1975; McGarr, 1993). These changes are substantial, of the order of 25 MPa, which is about an order of magnitude greater than typical stress drops of 0.5–5 MPa for these events (Spottiswoode and McGarr, 1975; Spottiswoode, 1984). Accordingly, these earthquakes are induced, not triggered.

Similarly, volumes of stope collapse associated with mining-induced earthquakes can be used to calculate the energy released by these events for comparison with the energy radiated seismically. It turns out that at most a few percent of the released energy appears in the seismic radiation, which implies that nearly all of the available energy is consumed in overcoming fault friction (e.g., McGarr, 1976, 1994; Spottiswoode, 1980).

The largest mining-induced earthquake recorded in the South African gold fields occurred in 1977 in the Klerksdorp mining district and was assigned a magnitude of 5.2 (Fernandez and van der Heever, 1984; Gay *et al.*, 1984). At that time this district included four large mines covering an area approximately 27 km in extent (Gay *et al.*, 1984), with gold-bearing reefs at depths somewhat in excess of 2000 m; in this district, mine layouts tend to be somewhat irregular because preexisting normal faults offset the gold-bearing horizons often by several hundred meters.

3.1.2 Underground Research Laboratory (URL), Canada

The URL, situated in southeastern Manitoba within the Lac du Bonnet precambrian granite, was established to test the feasibility of nuclear waste storage. This facility, involving a shaft more than 400 m deep and horizontal tunnels extending out at several different levels, has been the site of intense geotechnical and seismological monitoring (Talebi and Young, 1992; Martin and Young, 1993). This example provides some interesting contrasts to that of the deep mines in South Africa with regard to depth (400 m vs. several kilometers), tectonic setting (compressional instead of extensional), and scale (several meters vs. several hundred meters or greater). The seismicity is tightly coupled to the excavation of both shaft (Gibowicz *et al.*, 1991) and tunnels (Martin and Young, 1993). Small events, with magnitudes in the range -4 to -2, are located near the advancing shaft bottom and tunnel faces (Feignier and Young, 1993). In the vicinity of the seismicity caused by shaft development at depths near 400 m (Gibowicz *et al.*, 1991), the ambient principal stresses $[(S1, S2, S3) = (55\,\mathrm{MPa}, 48\,\mathrm{MPa}, 14\,\mathrm{MPa})]$ are oriented approximately northwesterly, southwesterly, and vertically (Martin and Young, 1993). The seismogenic zones are within several meters of the shaft sidewall where S1 has been amplified by a factor of about 2, from 55 to 110 MPa (McGarr, 1994). Thus, the shaft, with a diameter of 4.6 m, interacts with the horizontal principal stresses to produce earthquakes with magnitudes as high as -1.8 (Gibowicz *et al.*, 1991).

3.1.3 Exceptionally Large Events Caused by "Room and Pillar" Mining

An association between irregular mine geometries and large magnitude events was mentioned above. The 1989 Volkershausen, Germany, rockburst is a spectacular illustration of this effect. This event, with a magnitude of 5.4 (Knoll, 1990; Bennett *et al.*, 1994) occurred in the Ernst Thaelmann Potash Mine and entailed the collapse of about 3200 pillars in the depth range 850–900 m.

Similarly, the 1995 Solvay Trona Mine, Wyoming, event, with a magnitude of 5.1, involved the collapse of pillars at a depth of 490 m over an area of about 1 km by 2 km (Pechmann *et al.*, 1995); the lateral extent of the mine is somewhat greater than 4 km. In both the 1995 Solvay and 1989 Volkershausen earthquakes surface subsidence and waveform modeling indicated a substantial implosive component to the seismic source (Bennett *et al.*, 1994).

These two examples illustrate the importance of mining method (room and pillar in both cases) in determining the maximum event. The unmined pillars are intended to inhibit stope collapse and the attendant seismicity. If one pillar fails, however, many others can fail in a cascade and the result is an exceptionally large earthquake. In contrast, if pillars are not left, stope collapse and seismicity, localized near the advancing face, occur steadily. Thus, the rate of earthquakes is higher but maximum magnitudes are smaller (McGarr and Wiebols, 1977).

3.1.4 Seismicity Caused by Quarrying or Surface Mining

Pomeroy *et al.* (1976) associated an earthquake sequence in 1974, including a mainshock of magnitude 3.3, with open-pit quarrying operations near Wappingers Falls, New York. The mainshock and aftershocks show very shallow hypocenters (0.5–1.5 km deep) with thrusting mechanisms, directly beneath the quarry. The quarry, which has a long dimension of about 1 km, has been excavated since the early 1900s to a depth of 50 m, providing a total stress change, albeit distributed over many decades, of 1.5 MPa near the surface. Studies of stress direction and magnitude (Sbar and Sykes, 1973) have shown southern New York to be a region of high horizontal compression. In such an environment, the removal of surface material decreases normal stress and increases shear stress on an underlying thrust fault so as to bring it closer to failure.

Pumping operations to prevent quarry flooding can have two opposing effects regarding triggered seismicity. First, these operations lower the water table, reduce the pore pressure and, thus, strengthen the fault and suppress earthquakes. Second, the removal of water reduces the effective overburden load on any subjacent fault thereby weakening the fault and encouraging seismicity. These two effects are sufficiently complex that it is difficult to predict, without substantial additional information, which will dominate. In the case of Wappingers Falls, it appears that dewatering was of little consequence whereas in the following example, fault strengthening due to dewatering predominated until the pumping ceased.

The 1992–1997 sequence of earthquakes centered in the Cacoosing Valley near Reading, PA, originated on a well-identified shallow fault located directly below a quarry and appears to have been triggered by it (Seeber *et al.*, 1998). The damaging January 1994 $M_w = 4.3$ mainshock ruptured an oblique-reverse fault in the upper 2 km of the crust. The excavation of an 800 m-wide quarry centered directly above this fault presumably brought the fault closer to failure due to the removal of substantial overburden. This unloading effect, however, had started several decades earlier and had ceased in December 1992, 5 months before the onset of seismicity. Evidently, the unloading effect of the quarry operations was offset by a near simultaneous reduction in pore pressure in the seismogenic zone as the quarry was dewatered to allow production [Eq. (1)]. After the quarry operations ceased, however, the original water table was rapidly restored. Pore pressure on the fault 0.5–1 km below the quarry probably rose almost as fast because permeability of the subjacent Cambrian–Ordovician carbonates is high. The strengthening effect of the lowered pore pressure disappeared leaving the effect of the unloading unmitigated and bringing the fault to failure. Seismicity started in May 1992, and included a damaging $M = 4.3$ event.

Other examples of earthquakes triggered by surface unloading are from the Belchatow region in Poland, where events up to magnitude 4.6 have been related to open-pit coal mining (Gibowicz *et al.*, 1981). The excavation in this case was 1 km by 2 km in area and about 100 m deep.

Finally, at the Lompoc diatomite mine, California, surface mining caused at least four events, with magnitudes up to 2.5, between 1981 and 1995 (Yerkes *et al.*, 1983; Sylvester and Heinemann, 1996); the long dimension of this mining operation is about 1000 m. These Lompoc events differ in several respects from their counterparts in stable continental region settings. First, coastal California is an active tectonic setting. Second, the events at Lompoc produced very distinctive fault scarps on the quarry floor (e.g., Sylvester and Heinemann, 1996), whereas surface faulting was not found at Cacoosing or Wappingers Falls.

3.1.5 Pumping and Flooding in Mines and Quarries

Wetmiller *et al.* (1993) outlined the seismicity history of the Falconbridge, Canada, Mine that was closed in 1984 and then allowed to flood in late 1990. The strong correlation reported between the renewed seismicity and the flooding constitutes quite a credible argument that increasing crustal pore pressure tends to stimulate earthquakes, presumably by reducing the effective normal stress [Eq. (1)].

The Cacoosing Valley sequence, just described, is a shallower example of this. The quarry operations were the essential cause of the seismicity but this only occurred after the quarry was abandoned and the attendant flooding restored the pore pressure in the seismogenic zone to its ambient hydrostatic state.

Finally, pumping to prevent flooding in the deep mines of the South African gold fields has strengthened the surrounding crust by drastically reducing the pore pressure from its ambient hydrostatic state (e.g., McGarr *et al.*, 1975). In the ambient state, the minimum horizontal principal stress is typically about half the vertical overburden stress, the water table is near the surface and pore pressure is close to hydrostatic (McGarr and Gay, 1978; Gay *et al.*, 1984). Based on laboratory evidence, this state of stress and pore pressure is close to failure (Brace and Kohlstedt, 1980). The Witwatersrand tremors, described earlier, occur in spite of the strengthening effect of the large decrease in pore pressure because the change in state of stress from the extensive tabular stopes is sufficient to counteract this effect locally.

3.2 Seismicity Caused by Liquid Injection

3.2.1 Rocky Mountain Arsenal Well

One of the earliest and most spectacular examples of seismicity related to fluid injection occurred near Denver, Colorado in the 1960s (Evans, 1966; Healy *et al.*, 1968). Hazardous wastes were being injected under high pressures at a depth of 3.7 km at the Rocky Mountain Arsenal. Soon after injection started, earthquakes began to be felt in the Denver area, a region that previously had experienced little or no earthquake activity. The seismicity was initially concentrated near the bottom of the injection well, but eventually spread along a linear zone for about 8.7 km. The fault plane solutions for the largest events indicated normal faulting. Of particular interest, however, is that the largest earthquake, of magnitude 4.85 (Herrmann *et al.*, 1981) occurred more than a year after injection had ceased. The injection pressures were of the order of 10 MPa above the initial formation pressure of 27 MPa. Hsieh and Bredehoft (1981) showed that increases in fluid pressure of only 3.2 MPa were sufficient to stimulate activity on favorably oriented faults.

3.2.2 Ashtabula, Ohio

Liquid waste was injected into the 1.8 km deep basal Paleozoic formation of the Appalachian Plateau near Ashtabula Ohio. A magnitude 3.6 mainshock occurred in 1987 a year after the onset of injection and more than 30 km from any other known earthquake. Accurate aftershock hypocenters showed this event to have ruptured, left-laterally, a vertical west-striking fault just below the Precambrian–Paleozoic unconformity (Nicholson and Wesson, 1990; Seeber and Armbruster, 1993). The sequence started where the fault was closest to the well, i.e., 0.7 km from the injection point, and migrated westward about 2 km. The 35 accurately determined hypocenters all cluster along the fault; none are detected at the injection point. This example shows that preexisting structure can play a key role in the spatial distribution of triggered seismicity.

3.2.3 KTB, Germany

By far the deepest example of seismicity caused by liquid injection occurred when 200 m^3 of brine were injected into the 70 m open-hole section at the bottom of the 9.1 km main borehole of the KTB (German Deep Drilling Program) (Zoback and Harjes, 1997). This experiment resulted in several hundred microearthquakes, close to, but somewhat above, the point of injection. The largest event, which occurred 18 h after the start of injection, had a magnitude of 1.4, whereas, for all the remaining events, the magnitudes were less than zero. These KTB events evidently occurred in response to pore pressure changes of 1 MPa or less (Zoback and Harjes, 1997), which is about 0.01 of the ambient pore pressure. The state of shear stress near the bottom of the borehole was estimated, from an extensive set of measurements, to be about 100 MPa (Brudy *et al.*, 1997), which is close to the predicted failure stress at that depth. The results of this experiment in the tectonically stable region of eastern Bavaria is consistent with other measurements in similar settings showing stress levels close to failure. It also suggests that the high deviatoric stress is not limited to near the surface where most of the measurements are taken, but that it extends through the seismogenic part of the crust.

3.2.4 Control of Seismicity

Following the Denver observations, Raleigh *et al.* (1976) performed a partially controlled experiment in Rangely Colorado where water injection for secondary recovery in an oil field was producing low level seismicity ($m < 3.1$). Injection was in a number of wells with depths of up to 2 km. The formation pressure was of the order of 17 MPa. During the experiment, earthquakes could be turned off and on by varying the pore pressure about a critical value of 26 MPa.

Water injected for solution salt mining in Dale, New York (Fletcher and Sykes, 1977) provides another example of a partially controlled experiment, in this case with lower pressures at shallower depths. Earthquakes of magnitude -1 to 1.4 formed a cluster about 650 m across near the bottom of a 426 m injection well. The earthquake activity ceased abruptly when the top hole pressure dropped below 5 MPa.

3.2.5 Summary of Liquid Injection Effects

Earthquakes associated with liquid injection show the following characteristics. First, the seismicity tends to be triggered along preexisting faults that are hydraulically connected with injection points. The earthquake activity is usually concentrated on the portion of the fault with the least hydraulic resistance from the point of injection. Second, there is also evidence of time dependence in injection-related seismicity. Initially, seismicity tends to be concentrated near the injection point and to respond rapidly to changes in injection pressure or rate. As injection proceeds, the zone of influence increases, the upper limit of earthquake magnitudes increases and the response to input pressures becomes more sluggish and subtle. This response tends to lag changes in injection parameters. Activity close to the injection point usually stops immediately after the injection ceases, whereas farther from the injection well earthquakes may continue for some time afterwards.

An excellent review of many more case histories of seismicity related to liquid injection can be found in Nicholson and Wesson (1990).

3.3 Seismicity at Large Impounded Reservoirs

Over the past six decades, numerous cases of seismicity associated with reservoir impoundment have been reported. We briefly describe three examples of reservoir-related seismicity, chosen to highlight different aspects of this complex phenomenon. Koyna produced the largest earthquake associated with reservoir impoundment and presents a clear example of activity lasting for decades. At Aswan, the seismicity was surprisingly deep. At Nurek, detailed observations show how very minor changes in water level can be sufficient to modify the seismicity.

3.3.1 Koyna

The Koyna, India earthquake of 10 December 1967 is the largest earthquake associated with reservoir loading (Gupta and Rastogi, 1976). The earthquake of magnitude 6.5 occurred at the western edge of the Deccan traps, in a region of low natural seismicity. The mainshock was at a depth of less than 5 km, within 10 km of the dam and involved predominantly strike-slip faulting. The water level in the dam at the time of the mainshock was approximately 75 m and the impounded lake was about 52 km long (Gupta *et al.*, 1969). Seismicity continues at Koyna today and a number of significant events since 1967 have been associated with seasonal changes in the reservoir water level (Gupta, 1985). A magnitude 5.2 event in 1973 occurred when the water level in the reservoir had exceeded its previous maximum by only one meter. The seismicity at Koyna – a "main event" of magnitude 6.5 preceded by at least one year of seismicity and followed by persistent activity for more than 30 years – does not fit the usual mainshock–aftershock pattern for tectonic earthquakes. Clearly, the Koyna reservoir has not simply acted to trigger the release of tectonic stress in a normal earthquake sequence. Instead, the reservoir and its annual cycles in water level, continue to interact with the tectonic stress field in a complex manner and is continuing to trigger earthquakes.

3.3.2 Aswan

Lake Nasser, impounded by the 110 m high Aswan dam on the Nile River, Egypt, is one of the largest artificial lakes in the world. A magnitude 5.3 earthquake in November 1981 occurred 60 km upstream from the dam, directly beneath a large embayment that extends west of the former Nile channel (Kebeasy *et al.*, 1987; Simpson *et al.*, 1990). The earthquake was widely felt in upper Egypt, where there is no evidence of prior seismicity of this magnitude in spite of the long historical record. Aswan reservoir is relatively shallow by world standards, with water depths of greater than a few tens of meters being confined to the narrow channel of the Nile River. The water level in the embayment where the earthquake occurred is less than 10 m, but the groundwater level in the epicentral area prior to impoundment is known from well data to be more than 100 m below ground level. Simpson *et al.* (1990) suggest that the flooding of the porous Nubian sandstone beneath the embayment created an effective load whose impact greatly exceeded that of the reservoir itself.

The Aswan earthquake and the long sequence of earthquakes that followed are unique among cases of reservoir-triggered earthquakes in terms of the depths to which they extended. The main shock was well recorded by regional stations and the aftershocks were intensely studied by a local telemetered seismic network (Simpson *et al.*, 1990). The mainshock was located at a depth of 18 km. The earthquakes located with the local network showed two distinct clusters of seismicity: one extending from near the surface to 10 km; the other centered about the mainshock depth and extending from 15 to 25 km. The mainshock and many aftershocks were spatially correlated and show the seismicity to be related to the Kalabsha fault, an ancient right-lateral, strike-slip structure which extends west from the Nile channel and controls the topography in the epicentral area.

3.3.3 Nurek

At 315 m, the Nurek dam, on the Vakhsh River, Tadjikistan is the highest dam in the world and is situated in the Tadjik depression, a region of moderately high seismicity. The reservoir filled in stages, with the first major increase in water level to 100 m occurring in 1972. Two earthquakes of magnitude 4.6 and 4.3 occurred beneath the 50 km-long reservoir, immediately after the water level abruptly stopped rising after reaching the 100 m level in November 1972 (Simpson and Negmatullaev, 1981). Long-term monitoring of the regional seismicity for 20 years before construction of the dam clearly shows the activity following impoundment to be anomalous. Detailed monitoring of the postimpoundment seismicity with a local network revealed a close association of the rate of seismicity with minor changes in both the depth of water in the reservoir and changes in the rate of filling (Simpson and Negmatullaev, 1981). Similar effects observed at Lake Mead (Carder, 1970), on the Arizona–Nevada border, were analyzed by Roeloffs (1988).

The second stage of filling the Nurek reservoir, to over 200 m in 1976, was carried out much more smoothly than the first stage of filling in 1972. A strong burst of low magnitude activity accompanied a rapid, but minor fluctuation in water level, when a tunnel was tested part way through the filling cycle. The maximum level of 200 m was reached gradually, however, and no significant earthquakes or increases in activity accompanied the final filling stage. The seismicity at Nurek is especially sensitive to a sudden drop in water level or a rapid decrease in the filling rate. Simpson and Negmatullaev (1981) showed that water-level changes of a few meters (few × 0.01 MPa) and changes in the rate of filling of as small as 0.5 m day^{-1} can influence the rate of seismicity.

3.3.4 Triggering Mechanisms

The mechanism of earthquake triggering by large reservoirs is more complex than most other types of triggered seismicity. This is partly a consequence of scale – the mass of water impounded in a large reservoir is typically orders of magnitude larger than in an injection project, for example. The area affected is also much larger and can cover extensive changes in geology and fault structure. In addition, reservoir-triggered seismicity can involve a complex interaction between all three of the factors indicated in Figure 2. The weight of the reservoir can influence both shear and normal stress. Pore pressure increases instantly from the compaction of pore space due to the reservoir load and then from the raised water column with a delay due to diffusion. Because of temporal differences in the response to load and pore pressure, Simpson *et al.* (1988) showed that reservoir-triggered seismicity can be divided into two types: a rapid response related to instantaneous elastic response and a delayed response related to fluid diffusion.

Reservoir loading differs from injection- or mining-related seismicity in that the triggering agent (water in the reservoir) is remote from, and in some cases isolated from, the fault zones on which the triggered activity occurs. The pressure change at the bottom of a 100 m deep reservoir is 1 MPa. In a simple elastic medium, only a small fraction of this stress is propagated to hypocentral depths (Gough, 1978; Bell and Nur, 1978).

If the triggering mechanism is an increase in pore pressure from diffusion of water into permeable zones intersecting the reservoir, the influence at depth is also attenuated, and delayed as well. The amount of attenuation depends on rock properties and geometry of the reservoir, but simple elastic models show that stress at depths of a few kilometers can only be about 10% of the surface value (Bell and Nur, 1978). Under these conditions, a 100 m deep reservoir would thus increase the stress at hypocentral depths by, at most, 0.1 MPa. This is considerably lower than the stress changes we have shown to be acting in cases of mining seismicity, but is of the same order as the stress changes in simple elastic modeling for earthquake–earthquake triggering (e.g., Harris, 1998). For such small changes in stress to be sufficient to initiate failure, the preexisting state of stress needs to be much less than one stress drop away from failure. This condition is statistically possible on a subset of the potentially seismogenic faults. The relatively common occurrence of seismicity triggered by small stress changes would require many such faults, even in areas where natural seismicity is low (Seeber *et al.*, 1996). Alternatively, the stress change may be locally amplified on the affected faults. Simpson and Narasimhan (1990) have proposed that structural or lithological inhomogeneities can provide one mechanism to produce the necessary stress amplification.

3.4 Hydrocarbon Reservoir Compaction

Seismicity associated with fluid extraction was first recognized in the oil field at Goose Creek, Texas, in 1925 (Yerkes and Castle, 1976). In the meantime, numerous other examples of this phenomenon have been recognized, with the oil field at Wilmington, California producing the most spectacular effects of compaction-caused subsidence, horizontal deformation and attendant earthquakes (Kovach, 1974; Yerkes and Castle, 1976). Yerkes and Castle (1976) demonstrated that differential compaction at depth, due to liquid extraction from the producing formations, could lead to shear failure, including earthquakes.

As reviewed by Segall (1989), the phenomenology of earthquakes associated with hydrocarbon production includes:

1. Seismicity in the immediate environs of a reservoir commences when the pore pressure reduction reaches a level of the order of 10 MPa.
2. The earthquakes tend to occur either immediately above or below the reservoirs and are most prevalent in strata that are especially strong with a tendency toward brittle, rather than ductile, failure.
3. For earthquakes above and below the reservoir, the most common focal mechanisms indicate thrust or reverse faulting; normal faulting mechanisms have been observed for events located in the peripheral region.
4. Earthquakes located in the weaker strata tend to be slow, i.e., the source duration is quite extended compared to that of a typical crustal earthquake of similar magnitude (e.g., Kovach, 1974).

Noteworthy among many examples of seismicity triggered by hydrocarbon extraction are the earthquakes located in the environs of the Rocky Mountain House gas field in Alberta, Canada (Wetmiller, 1986). The substantial reverse slip accumulated on a surface fault at the Buena Vista Hills oil field, in the San Joaquin Valley, California, was aseismic (Kock, 1933; Nason *et al.*, 1968).

Grasso and Wittlinger (1990) described earthquakes triggered by natural gas production in the Pau basin, near Lacq in southwestern France. The gas field, about 10 km in extent with production from depths near 4 km, triggered an exceptionally high level of seismicity for this type of operation, with earthquake magnitudes ranging up to 4.2. These are, so far, the largest events unequivocally associated with reservoir compaction.

Pennington *et al.* (1986) described earthquakes triggered by fluid depressurization in oil and gas fields of south Texas. Earthquakes of $M = 3.9$ in July 1983 (largest) and $M = 3.4$ in March 1984 were located in the Imogene oil field near the town of Pleasanton and in the Fashing gas field adjacent to the town of the same name, respectively. The Imogene field has a long dimension of about 13.5 km whereas that of the Fashing field is about 7 km (Pennington *et al.*, 1986, Figure 1 of that report).

To understand these effects more quantitatively, Segall (1985, 1989) modeled the hydrocarbon reservoir as a poroelastic medium (Biot, 1941) embedded in an impermeable elastic half-space for purposes of calculating the deformation and stress changes due to fluid extraction (see also Geertsma, 1973) assuming a plane strain geometry. Essentially, hydrocarbon production removes fluid (oil, water, or natural gas) from the reservoir, which responds by contracting. This contraction induces both deformation and stress changes in the strata surrounding the reservoir. The calculated deformation can be compared to geodetic measurements of surface subsidence (e.g., Segall, 1985) and horizontal crustal deformation (Yerkes and Castle, 1976). Similarly, calculated stress changes can be compared to focal mechanisms of nearby earthquakes (e.g., Segall, 1989).

Solutions to the linear poroelastic equations for axisymmetric reservoirs, developed by Segall (1992), were applied to the analysis of subsidence and earthquakes associated with the Lacq gas field by Segall *et al.* (1994). Good agreement between computed vertical displacement and geodetically observed subsidence confirmed that the linear model was realistic. Interestingly, the stress changes, computed from the same model, indicate that the earthquakes at Lacq (Grasso and Wittlinger, 1990) are occurring in response to changes of about 0.2 MPa, or less.

Generally, the deformational response of the crust, at least at the surface, to fluid extraction from oil or gas reservoirs seems to be reasonably well understood judging from the success of linear poroelastic models for replicating geodetically measured subsidence (e.g., Segall, 1985; Segall *et al.*, 1994). Such models have, so far, proved to be of more limited use in understanding earthquakes stimulated by oil or gas extraction, partly because the seismic response to hydrocarbon production is highly variable from field to field (e.g., Doser *et al.*, 1992). Evidently, the mechanical characteristics of the strata above and below the producing formation play substantial roles in the seismic response (Volant, 1993). In fact, no seismicity is observed in the vast majority of producing gas and oil fields. Even in cases for which a rich seismic sequence is associated with hydrocarbon production, as in the Lacq field (e.g., Grasso and Feignier, 1990), this seismicity accounts for only a small fraction of the crustal deformation measured geodetically.

3.4.1 Large Midcrustal Earthquakes Beneath Oil and Gas Fields

3.4.1.1 California Earthquakes

Although the 1983 Coalinga earthquake occurred beneath a major producing oil field, the likelihood of a connection between oil production and the earthquake sequence was considered by most seismologists to be quite small, primarily because of the eight vertical kilometers separating the hypocenter from the producing formations (Segall, 1985) and because of the relatively high level of natural seismicity in the area. But the ensuing occurrence of large earthquakes directly beneath two other oil fields from which exceptional amounts of liquid had been extracted, i.e., the 1985 $M = 6.1$ Kettleman North Dome and the 1987 $M = 6$ Whittier Narrows earthquakes, generated renewed interest in a possible link between oil production and large, midcrustal earthquakes. McGarr (1991) noted that the dimensions of the oil fields, 13 km for Coalinga, 23 km for Kettleman North Dome, and 6 km for the Montebello field above the Whittier Narrows earthquake, are similar to the dimensions of the respective aftershock sequences.

Of particular interest, though, is that the ratios of net liquid production to total seismic moment are nearly the same for all three events. This last observation suggests the following mechanism relating the earthquakes to oil production. Because oil production results in a net removal of mass from an oil field (extracted oil + water − injected liquid), the isostatic response of the crust to this mass removal is to thicken so as to restore the vertical force equilibrium. This crustal thickening can be accommodated by thrust faulting, in a region of compressional tectonics, and so the total seismic deformation can be related to the corresponding liquid production (McGarr, 1991). As presented by McGarr (1991, see Table 1 of that report), the agreement between the seismic deformation and expectations based on liquid production is quite good. This proposed mechanism remains speculative, nonetheless, for a number of reasons including several discussed in the next example.

3.4.1.2 Gazli

The region surrounding the desert town of Gazli, Uzbekistan, was relatively aseismic until April 1976, when a $M = 7$ earthquake occurred. This was followed by two more $M = 7$ events, one in May 1976 and another eight years later in March 1984, together with a rich sequence of small events spanning an arcuate region, elongated in the east–west direction (Simpson and Leith, 1985).

Simpson and Leith (1985) noted the possibility that this impressive earthquake sequence was related to the enormous natural gas field immediately to the south. They remarked that (1) this area had no history of large seismic events before the gas extraction operations, suggesting that this sequence of $M = 7$ events is anomalous and (2) the persistent high level of seismicity, including three $M = 7$ events does not form a typical foreshock–mainshock–aftershock pattern. Of particular interest, the arcuate region of seismicity is approximately the same size as the gas field, whose long dimension is about 49 km in the east–west direction (Bossu, 1996).

After numerous recent investigations near Gazli (e.g., Grasso, 1992, 1993; Amorese *et al.*, 1995; Bossu *et al.*, 1996; Bossu and Grasso, 1996; and summarized most recently by Bossu, 1996) more information with which to decide whether the gas field and the earthquakes are related is now available than when Simpson and Leith wrote their report. With depths of 20, 13, and 15 km, in order of their occurrence (Bossu *et al.*, 1996), and with focal mechanisms that largely involve thrust faulting on fault planes that do not extend to the surface (Bossu, 1996), the three Gazli $M = 7$ events are similar to their counterparts beneath the three California oil fields, of the preceding example. If these large-magnitude earthquakes, located at midcrustal depths, are connected to gas production, limited to depths only slightly greater than 1 km, the responsible mechanism is likely to involve the entire upper brittle crust. Might crustal thickening in response to an isostatic imbalance due to production, proposed for the three California earthquakes, also apply to the events at Gazli?

From some of the gas field production information presented by Bossu (1996), one could argue either way. On the one hand, Grasso (1992) noted that either the mass of gas produced from the reservoirs at Gazli or the mass of water infiltrating the reservoirs as gas is produced suffices to account for an appreciable fraction of the seismic deformation (McGarr, 1991). On the other hand, Bossu (1996) pointed out that these two contributions to the crustal load, extracted gas and infiltrated water, tend to cancel one another; in fact, the mass of the infiltrated water apparently predominates. In this way Bossu (1996) concluded that the earthquake sequence and gas production are probably unrelated to the restoration of isostatic equilibrium because gas production added, rather than subtracted, mass to the local crustal load. According to Bossu (1996) about 300 million metric tons of gas was

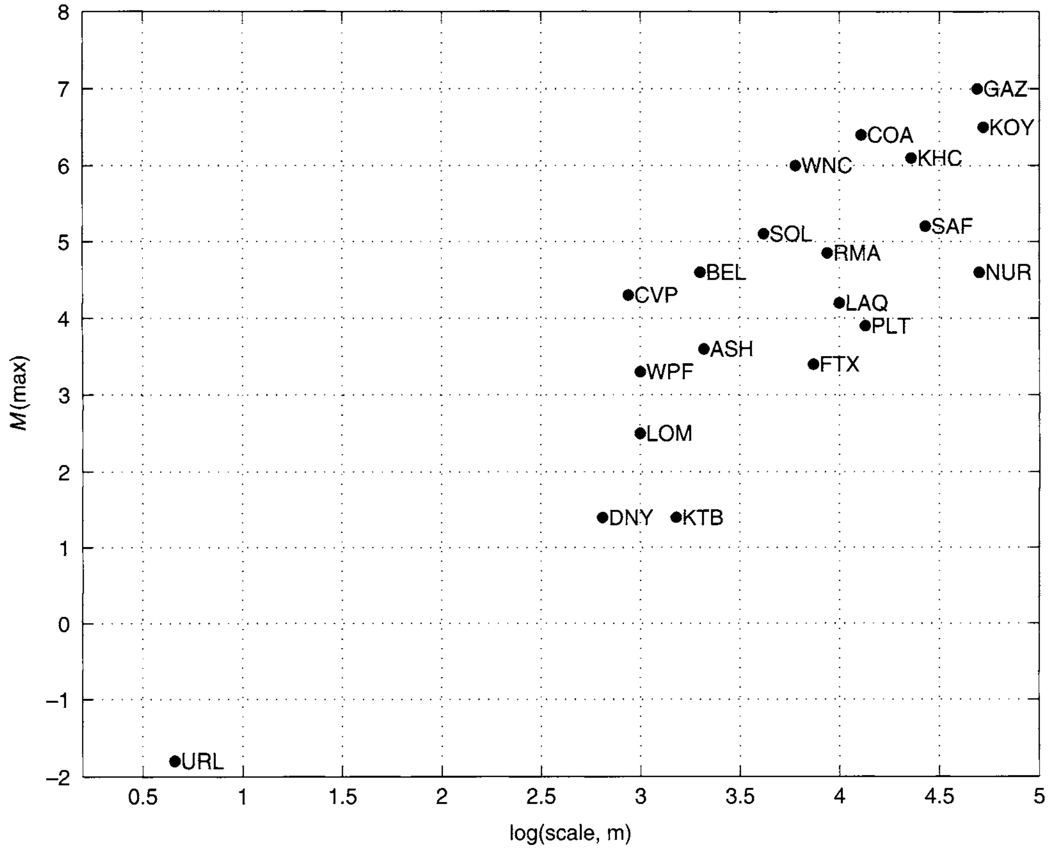

FIGURE 3 Maximum magnitude as a function of scale for 20 case histories. The scale is the maximum dimension of the causative activity as explained in the text. The letter identifications for the case histories, in the same order as they appear in the text, are: underground mining: SAF, deep gold mines in South Africa; URL, Underground Research Laboratory; SOL, Solvay Trona; quarry and surface mining: WPF, Wappingers Falls; CVP, Cacoosing Valley; BEL, Belchatow; LOM, Lompoc Diatomite; Liquid injection: RMA, Rocky Mountain Arsenal; ASH, Ashtabula; DNY, Dale NY; KTB, KTB, Germany; reservoir impoundment: KOY, Koyna; NUR, Nurek; Oil/gas production: LAQ, Lacq; PLT, Pleasanton TX; FTX, Fashing TX; COA, Coalinga; KHC, Kettleman North Dome; WNC, Whittier Narrows; GAZ, Gazli.

extracted whereas, about 1200 million metric tons of water infiltrated the gas field.

4. Effects of Scale

An important question regarding induced or triggered seismicity involves the maximum magnitude earthquake that might result from a particular human activity. For instance, if a dam that impounds a large reservoir is built, what is the maximum credible earthquake that might result?

As described in previous sections, there are several measures of any particular activity that can be related to the total seismic deformation, which, in turn, can be used to estimate the maximum credible earthquake for that activity. Examples include volumes of stope collapse in deep mines (e.g., McGarr and Wiebols, 1977) and the crustal load changes associated with large-scale oil and gas production mentioned in the previous section.

Here, however, we use the maximum dimension of an activity as a simple metric that can be compared to the corresponding maximum magnitude. As described for the case histories reviewed in previous sections, it was straightforward to estimate appropriate maximum dimensions for 20 of them, and Figure 3 shows that the long dimension of an activity correlates fairly well with the corresponding maximum magnitude.

Interestingly, the upper-bound envelope to the data of Figure 3 has an average slope close to 2, suggesting that for an activity of a given size there is an upper limit to the magnitude of the corresponding maximum credible earthquake. For instance, if an activity were 10 km in extent the maximum credible earthquake would presumably have a magnitude near 6. It is important to note, however, that no seismicity is recorded in many instances where human activities affect the stress over large areas, such as below many impounded reservoirs.

5. Conclusions

The case histories reviewed here help to support the following conclusions.

1. The seismogenic continental crust is in a state of stress close to failure, whether the tectonic setting is active or inactive. Because of this, perturbations of the state of stress toward failure [Eq. (1)], even as small as 0.01 MPa, may trigger seismicity. One implication of this is that, for a given activity, triggered earthquakes are as likely in stable as in active tectonic settings, but within stable regions such events are more obvious because the background seismicity is comparatively low.
2. Among the case histories of induced and triggered seismicity reviewed here, perhaps the only examples of induced seismicity (requiring stress perturbations of the order of the ambient deviatoric stress) are from underground mining. This is because pumping operations to prevent flooding strengthen the rock mass by reducing the pore pressure. Extensive mine excavations, especially at depths of several kilometers, amplify the ambient stresses substantially so as to bring the strengthened rock mass back to the point of failure in localized regions. All of the other case histories seem to involve triggered earthquakes inasmuch as the stress perturbations promoting fault slip are tiny compared to the ambient stress level and, in most cases, are much smaller than a typical earthquake stress drop.
3. The size of an activity that perturbs the crustal state of stress appears to be a good predictor of the maximum credible earthquake for that operation. This is evidently the case for all types of induced and triggered earthquake sequences reviewed here including those due to mining, quarries, liquid injection, large reservoir impoundment, and oil and gas exploitation. It is important to note, however, that many large-scale activities result in little or no recorded seismicity.

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Due to space limitations, references with full citation are given in the file McGarrFullReferences.pdf on the Handbook CD, under the directory \40McGarr. Please see also Chapter 32, Rock failure and earthquake, by Lockner and Beeler; Chapter 33, State of stress within the Earth, by Ruff; and Chapter 34, State of stress in the Earth's lithosphere, by Zoback and Zoback.