TECHNICAL REPORT

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Seismic effects on bedrock and underground constructions. A literature survey of damage on constructions; Changes in groundwater levels and flow; Changes in chemistry in groundwater and gases

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June 1989

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SEISMIC EFFECTS ON BEDROCK AND UNDERGROUND CONSTRUCTIONS
A LITERATURE SURVEY OF DAMAGE ON CONSTRUCTIONS; CHANGES IN GROUNDWATER LEVELS AND FLOW; CHANGES IN CHEMISTRY IN GROUNDWATER AND GASES

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ABSTRACT

This report is a literature review of direct and indirect effects of earthquakes on underground constructions as tunnels, caverns and mines. The direct damage will cause vibrations, shaking and displacements, which may lead to partial or total destruction of the underground facility.

The damage effects, reviewed in Chapter 2, on underground constructions are either caused by displacement along an existing fault intersecting the underground facility or by shaking. A third type of damage observed mainly for shallow tunnels is ground failure or landslides which will damage the tunnel portals.
Damage caused by shaking has been reported in several studies, and several hundreds of events have been reported both from mines and tunnels.These reports are mainly from active earthquake areas.

There are very few reports of damage caused by displacements on an existing fault.
The damage, which may be severe, is generally concentrated to the vicinity of the fault zone.

The report also includes a review of the effects caused by earthquakes on groundwater level, flow, pressure, chemistry and constituents in the ground. Such changes are mainly reported from studies in wells near active faults. The interesting coupling of changes in groundwater characteristics around an underground construction is,unfortunatly,very seldom reported.

The ground water level and pressure changes are discussed in Chapter 3. The bases for this part of the review is taken from the Alaska earthquake 1964, which turns out to be the most recorded and studied single seismic event in relation to a world wide ground water change. Still further work and analyses can be expected from this event. Other observations are reported from wells and reservoirs located near existing faults. Water level changes have in a few cases been correlated with aseismic creep events, but the normal case as an earthquake.

Changes of the geochemistry in ground water and soil gases are reviewed in Chapter 4. The mechanisms of seismochemical anomalies are discussed and examples of short and long term monitoring are given from USA, Soviet Union and China.

Gases in ground water and soil is reported in Chapter 5. Radon is so far one of the most studied species and its variation in short, medium and long term with seismic activity is rather well understood. Other gases or isotopes that have been studied include helium, carbon dioxide, hydrogen, argon and methane, radium and uranium.

The paper also includes same statements for repository design based on the result of the review.

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SUMMARY

This report is a review of damage effects caused by earthquakes on underground constructions and on changes of ground water level, pressure and flow, changes in chemistry in ground water and soil gases. The reported investigations are mainly from active earthquake areas as the west coast of North America , Japan, parts of China and the Soviet Union.

Earthquake damage to underground constructions is either caused by shaking or displacements on old faults.
Underground constructions located a few tens of km from the epicentral area may suffer damage due to shaking, however, constructions located away from the epicentral region will very likely suffer any damage if located in rock.
Minor damages on superficial underground constructions are reported at estimated ground accelerations between 0.2-0.5g. Significant damages are recorded at an ground acceleration above 0.5g. These damages will in general only effect the portals of the tunnels.
There is no report of total collapse caused by only shaking.

Local damage on underground constructions is reported in a local fault region if the fault intersects the tunnel or mine. The damage includes offsets, destruction of concrete lining, local collapse of roof and walls and changes in ground water inflow.

There are sparse reports regarding amount and type of changes on the ground water inflow. Reported increase of inflow varies from about 40 to 300% but the inflow may also cease.

The response of ground water level and pressure changes have been studied in wells and different types of reservoirs. Normally the water level increases prior to the earthquake and in 20-30% of the wells will not recover to pre-seismic levels after the earthquake.
Also the piezometric levels will change and about 30% of the wells in an seismic area will stay anormal as observed from the Alaska earthquake 1964.

Changes in chemistry of ground water and soil gases are site specific depending of the local geology. They are also dependent of environmental factors as rainfalls, barometric and temperature changes and other local factors. A number of different elements have been used and the most reported ones are:

Ion cations : Na, K, Ca, Mg
Anions: SO_4, Cl, F, CO_3
Trace elements: Hg, Rn, U, F, Li, Sr, Ba
Dissolved gases: CO_2, H_2S, CH_4, He, Ne, Ar, N_2, H_2,Rn

Dissolved ions normally indicate anomalies at magnitudes greater then 4. There is however no common trend of behaviour as decrease or increase prior to, under and after a seismic shock. Continuous monitoring of Rn is becoming an accepted method for long term monitoring.

Radon, hydrogen and helium have been used as indictor samples in soil gases. Radon and hydrogen are reported to increase prior to an seismic event while helium is observed to decrease.
The environmental factors are reported to be of significant importance.

In conclusion can be stated that

- Underground superficial constructions will sustain damage due to shaking up to a level correlated with a surface acceleration of 0.5g. The damage will be less with increasing with depth and rock quality

- Underground constructions intersected by a fault(s) may suffer severe local damage due to fault displacements. The amount of displacement will decrease with depth.

- The groundwater in-flow to an underground construction may increase or decrease due to seismic activity. There is a lack of data regarding amount and duration of these changes.

- There are changes in chemistry of groundwater and soil gases caused by seismic activity. There is however little agreement of their significance, mechanism and stability with time.

1 INTRODUCTION

This report is a literature survey on published direct and indirect effects of induced seismic events on underground constructions as tunnels, caverns and mines. The direct effects on a construction includes vibration, shaking and displacements on an intersecting geological structure (fault). The result will be an increasing level of damage.

Indirect effects are changes in the environment surrounding the construction especially of the groundwater level, pressure, groundwater chemistry and volatile emanations.

In general there is quite good information available of direct effects on tunnels and caverns. There are much less data for mines. Very little information has been found on groundwater changes in relation to an underground construction.

Physical and chemical changes in groundwater and gases have in this report therefore been concentrated on such changes observed and measured in wells near active faults, where at present the best information can be found.

The report is subdivided into five parts. The first part, Chapter 2, deals with the direct effects of an earthquake namely damage to underground constructions. The second part, Chapter 3, includes water level anomalies. Chapter 4 describes geochemical changes of groundwater and volatiles related to earthquakes. Gases in groundwater and soils are surveyed in Chapter 5.
Conclusions and discussion of the relevance of these effects with respect to repository design are found in Chapter 6

2 THE DAMAGE EFFECT OF EARTHQUAKES ON UNDERGROUND CONSTRUCTIONS

The effects of damages on shallow tunnels have mainly been based on the summerized reports made by Duke and Leed 1959, Rozen 1977, Stevens 1977, Dowding 1978, Dowding and Rozen 1978, McLure 1982, Carpenter and Chung 1986.

2.1 PLATE TECTONICS

The crust of the earth is subdivided into a number of plates of various dimensions. These plates are moving in relation to each other due to active forces, mainly ridge push forces. The rate of the movement for each plate is up to 100mm per year. These movements are fairly well understood and they are the fundamentals in the concept of plate tectonics.

There are three dominating types of plate boundaries. The spreading type boundary, where the two adjacent plates are moving away from each other perpendicular to the spreading axes, the subduction zone where the plates are moving against each other and the transform faults where the plates are sliding horizontally in relation to each other.

In all three cases the relative movement of the plates will induce shear forces along the boundaries. The energy built up may be released locally in the form of sudden displacements, earthquakes, or as continuous displacements with time , creep. In most cases there is a combination of these two types of displacements . Some creep is often observed prior to a main seismic event.

Active earthquakes areas are mainly localised along these boundaries of which the subduction zones contain the most active and dangerous earthquakes. There also occur earthquakes inside the plates, intra-plate earthquakes. These have normally lower intensity.

2.2 ENGINEERING CHARACTERISTICS OF AN EARTHQUAKE

An earthquake is characterised by the following parameters

1. The geometry of the fault as length, depth and amount of displacements.

2. The strength of the earthquake expressed as magnitude, local magnitude, surface and body wave magnitude or seismic moment.

3. The dynamic parameters measured as acceleration, frequency, durability or intensity.

Damage within earthquake engineering is measured by the peak ground acceleration while the peak particle velocity is used for express vibrations caused by blasting. Structural damage is caused by and is a function of the number of cycles or duration of shaking, ratio of structural frequency to input frequency and structural damping as well as peak acceleration (Dowding and Rozen 1978).

Duke and Leeds (1959) have summerized the effect with depth.

1. At short periods, surface displacements are larger than underground displacements

2. The ratio of surface to underground displacement depends on the type of ground. It is greater for alluvium than for weathered rock. It might reach a value of at least 10.

3. For wave period over one second, the ratio becomes comparatively small, approaching unity as the period increases.

4. There is a particular average period of incoming waves for which a given type of ground will provide a maximum ratio of the surface to underground displacement. If the average period of incoming waves is not approximately equal to this particular period, the ratio will be materially small.

It has been proven from observation and measurement data that the seismic ground motion generally decreases with depth (Kanai and Tanaka 1950). A generalised attenuation curve of the intensity for the Tangshan earthquake 1976 is illustrated in Figure 1.

Iwasaki et al (1977) have monitored the maximum accelerations (gal) in a series of earthquakes in the range of M=4.8-7.2. They found that ratios of the surface accelerations to accelerations at depths (110-150m) varied from 1.5 in rock to 3.5 in clayey ground.

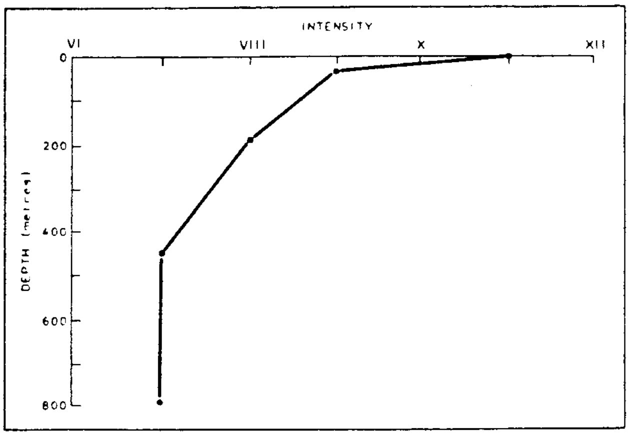


Figure 1. Generalized attenuation of intensity at the Tangshan mine

Owen (1982) reports that there are recorded data which indicate peak amplitudes at depth that are greater than those at the surface. In general the changes with depth are greatest for acceleration and least for displacement. According to Vortman (1982) nuclear weapon tests have indicated that for all measured parameters including acceleration and displacement the amount of difference between surface and subsurface is very site dependent.

Pratt et al (1982) has summerized the observed permanent displacements on a fault plane (Figure 2). Surface displacements due to shaking range from at least 1 to 10m depending on geology, magnitude etc but decreases markedly with depth. Displacements < 25cm have been measured at 100m level. Data from levels below 500m is almost negligible.

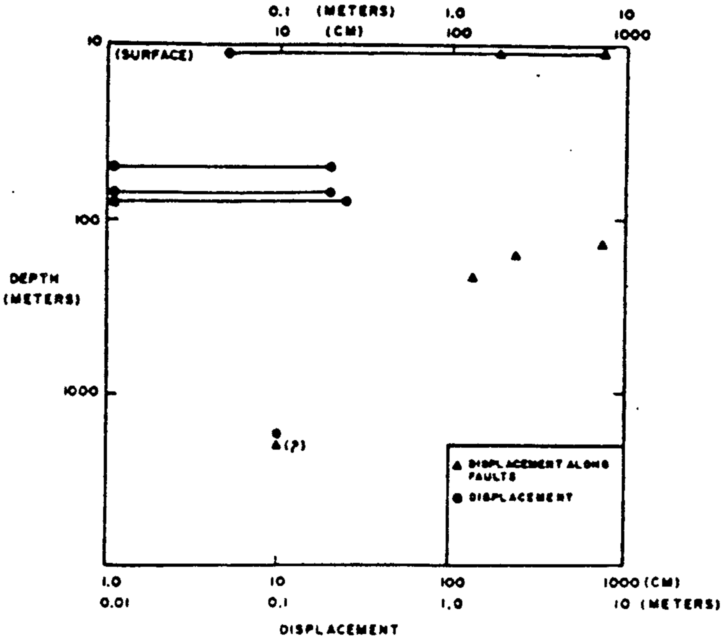


Figure 2. Measured range of displacements as a function of depth

Pratt (1978) has summerized in Figure 3 the variation and attenuation curves of peak surface acceleration from different sources for a 6.5 magnitude earthquake . The frequency is not given.

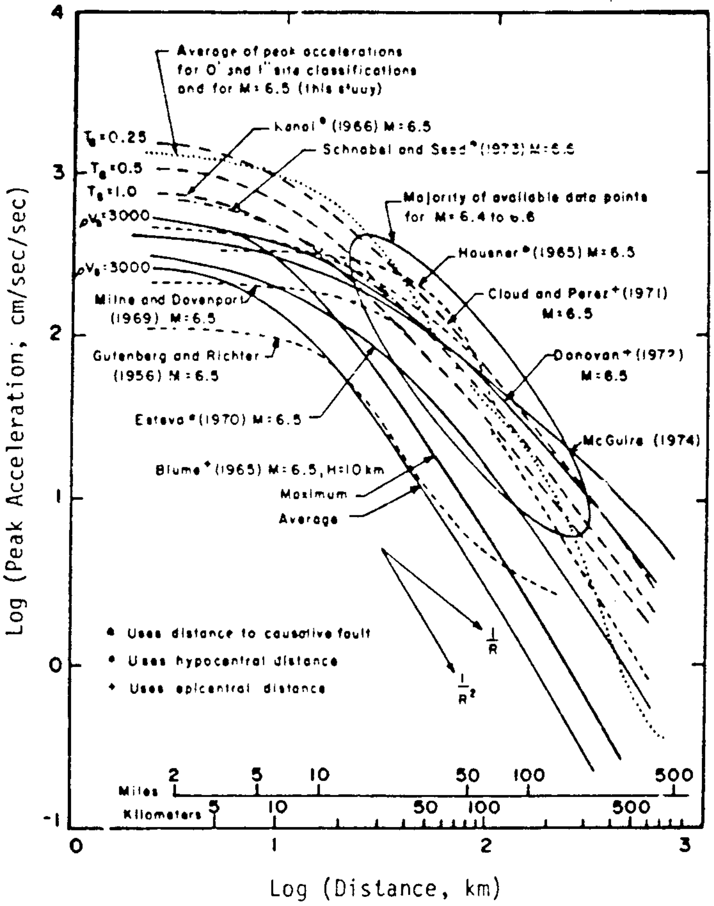


Figure 3. Various relationships between peak acceleration and distance from source for magnitude 6.5 earthquake

Rozen (1976) has summerized the relationship between velocity and damage level in Figure 4 . Strong tensile and some radial cracking was noted at surface velocities of 1.52 m/s which could occur at distances of 7-8km at a magnitude of M=6.5 . Even at this level the seismic damage would be negligible in competent rock.

2.3 TYPES OF DAMAGE

Earthquake effects may be classified as primary and secondary processes. Faulting is a primary process due to instantaneous slip along the fault plane. Secondary processes are caused by the passage of elastic waves generated by the primary process like vibration and shaking.

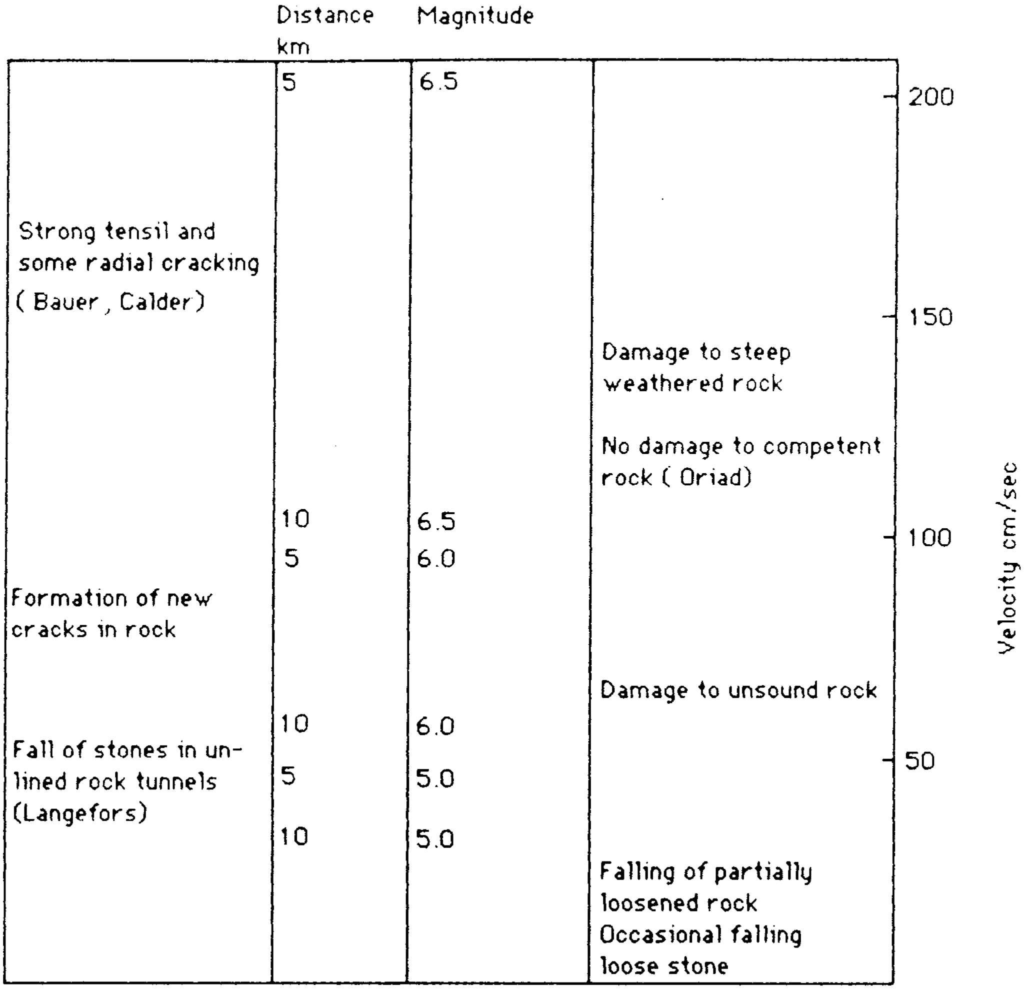


Figure 4. Summary of damage levels

Three modes of main damage have been reported.

1. Damage caused by movement on a fault plane
2. Damage causing ground failure as liquefaction or landslides at tunnel portals
3. Damaged caused by ground vibration

Combinations of these three will occur.

Displacements along a fault plane usually result in serious damage. The damage will normally only affect limited areas around the intersection between fault and tunnel. Damage caused by ground vibration will normally affect a larger segment of the tunnel.

Damage on the portals are normally caused by slope failure near the portals.

Damage in poor ground conditions is caused by shaking of poor rock or soil surrounding the tunnel.

Damage may also be associated with shallow cover and unsymmetric load on the construction.

Dynamic stress concentrations are caused by waves impinging on the tunnel periphery and are expected not to be more then 10-20% greater then the static load.

2.4 EFFECTS DUE TO FAULTING

Very few examples are reported on damage caused by displacements on a fault intersecting the excavating room.
Bonilla (1967) has summerized historic surface faulting events. Reports of damage to mines as a direct result of faulting are absence.

Below is a short description of published data.

San Francisco earthquake,1906

Earthquake with magnitude M=8.3. Rock type is sedimentary rock mainly sandstone
Two tunnels were damaged during the San Francisco earthquake 1906 (Stevens 1977).
One tunnel at a depth of 213m and 1.8km in length was offset 1.37m where it crossed the San Andreas fault. The tunnels were also damaged by caving in the roof and sides, the breaking of flexure of upright timber and upward heave of the rails.
The second tunnel, at depth 206m and 1.7 km long, did not cross the fault, and therefore was less damaged due to shaking. Timber was broken and roof caved which caused blocking of the tunnel.

The Izu earthquake in Japan, 1930

Earthquake with magnitude M=7. Rock type at 140m depth is volcanic andesite.
The Izu earthquake in Japan occurred along the Tanna fault, which was intersected by a drain tunnel. The tunnel was offset 2.29m. The village 160m above the tunnel was destroyed to 55%. Surface displacement occurred along the fault for a distance of 24km.

Kern Country earthquake, 1952

Earthquake with magnitude M=7.6. Rock type is decomposed diorite.
Four tunnels which crossed the White Wolf fault were greatly damaged at the Kern Country earthquake. One tunnel 213m in length was collapsed at one end for a length of 61m. Another tunnel was totally collapsed for its full length. The third tunnel got cracks and holes formed in the ground above. The roof collapsed at several places. The fourth tunnel suffered displacement along a fault and was daylighted.
These tunnels were located in the epicentral region, but the damage was caused by their location in the fault zone. Displacements at depth exceeded those at surface.
The tunnels are located shallow, 45-70m below surface and lined with timber and 12-24 inches of concrete.

Aseismic creep

Blanchard and Laverty (1966) reports on displacement in a tunnel not associated with direct seismic events. The displacement was probably caused by gradual creep. The tunnel is 45.7m below ground and intersects the Hayward fault near Berkeley, California. Since 1950 the tunnel show a right lateral offset. The total offset was 1966 in the order of 168mm.

The Izu-Ohshima-Kinkai earthquake

Earthquake of magnitude M=7.
The Izu-Ohshima-Kinkai earthquake occurred in 1978 causing damages mainly on the east part of the Izu Peninsula. Hypocenter was located 3 km from the tunnels and the hypocenter at 3km depth.

Damages of tunnels were reported as:

a) Strike slip fault intersected the Inatori railroad tunnel. The concrete lining was destroyed at the fault, causing a gap in the roof. Rails in the neighbourhood came off 0.5m from ground.

b) Cracks were also observed. Expansion and contraction in the longitudinal direction which caused the rails to meander near a portal

c) The side walls of the Ohigawa River tunnel were thrusted and displaced. This caused arch roof to crush and exfoliate. Similar damage phenomena was observed in two other tunnels.

d)Three road tunnels collapsed near the portals due to large scale sliding on slopes.

2.5 EFFECTS DUE TO SHAKING

2.5.1 Mines

Reports on damages in mines are in general of qualitative nature.

Stevens (1977) has summerized the historic records on the effects of earthquakes in underground mines. Sparse information was found to relate effects to distances to epicentres or mine condition. He reports on a number of earthquakes strongly felt on ground but were little noticed in the mines.

Some of the reported earthquakes close to mines are described below. Further description is given in Röshoff 1989 .

There is a general conclusion that the effects of earthquake shaking is less in mines or caverns then on surface constructions. Most mines are located in solid rock at great depth. Here the rock is a good transmitter and the wave energy is passed with a minimum decrease in speed and the smallest possible displacement (Steven 1977).

Pratt et al (1978) report that at their investigation from Europe, they were unable to find any significant reports of damage to deep underground structures or mines due to earthquake. Their concern was mainly Central Europe.

Chilean earthquake 1960

The report is from a coal mine located 4.8 km from the epicentre and below the ocean. There were several old faults in the mine but no movements were observed or any damage (Stevens 1977).

The very large underground copper mine in Braden, Chile, was affected by violent shocks in 1924, 1927, 1928 and 1938. One of the the events was so strong that it generated tidal waves, which destroyed one coastal town and damaged two others. The 1928 event destroyed a tailing dam at the mine, no other damages were reported.

Montana earthquake 1925

Earthquake with magnitude M=6.7.
The workings in the mines in the area were not damaged and the shock was not noticed by the miners.
Miners in a shaft, 76m deep, did not feel the shock.

Idaho earthquake, 1944

This earthquake with intensity MM =VI caused shocks in a stope at the 1345m level in the Morning Mine. One worker was buried to his knees in muck, while two other workers were peppered by popping rock. There were no cave-ins or loss of ground.

The Alaska earthquake 1964.

No significant damages to underground constructions as tunnels and mines were reported for the event of M=8.5. Sedimentary and metamorphic rocks are predominating. The observations include the coal mines at Matanuska Valley, rail road tunnels near Whittier, tunnel and penstocks at the Edlutna hydroelectric plant and the Chugach Electric Association tunnels at Copper lake. The surface damage was extreme for this earthquake.

The Peru earthquake 1970

This earthquake with a magnitude of 7.7 did no damage to 16 railroad tunnels of total length of 1.740m under little cover in zones of class MM=VII and VIII intensity.

South Africa ,1976.

A damaging earthquake with M=5.0-5.5 was recorded at the Welkom mine. The surface damage was extreme. Displacements < 10cm were measured at a depth of 2km. The focal depth was approximately 6km.

China, 1976

The earthquake in Tangshan had the epicentre in a coal area district south of the city. Several coal mines of which 8 are underground mines are located south of the city. The mines have a depth of 500-800m. The mines are supported with timber and steels set, occasionally with wire mesh, rock bolts, shotcrete and masonary. The roof often consists of sandstone.

Surface constructions above the mines were stronger destroyed if they were founded on alluvial deposited compared to solid rock foundation (Lee 1987).
The earthquake had a magnitude of 7.8 with a focal depth of 12-16km. About 11600 aftershocks were recorded with magnitudes between 3 and 6. Two of them exceeded magnitude 7.
Figure 1 shows the variation of intensity based on reports from about 2000 miners.

The intensity gradually decreases from XI at ground to VII at 450m level.
About 10000 miners were underground at the time of the earthquake. Most of them survived.
The groundwater inflow rates increased with 40-300%. There is no information if the increase was persistent or not.

Kanai and Tanaka (1951) measured accelerations at depths down to 600m in a copper mine located in Paleozoic rocks in Japan. The recodings were made from small earthquakes. The ratio of the surface maximum displacement to that at 300m depth was about 6:1.

Stevens (1977) make the following conclusions about reported damages in mines.
- Effects on mines are less serve then surface effects
- Damage to mines is most insignificant when they are located in highly competent, unweathered rock. Greatest damage occurs in mines found in loose unconsolidated or incompetent rock.

2.5.2 Tunnels and underground constructions

This section includes reports from tunnels and underground constructions and some mines. In most cases the reports includes comprehensive summaries of reported damages. Detailed information is found in Röshoff 1989.

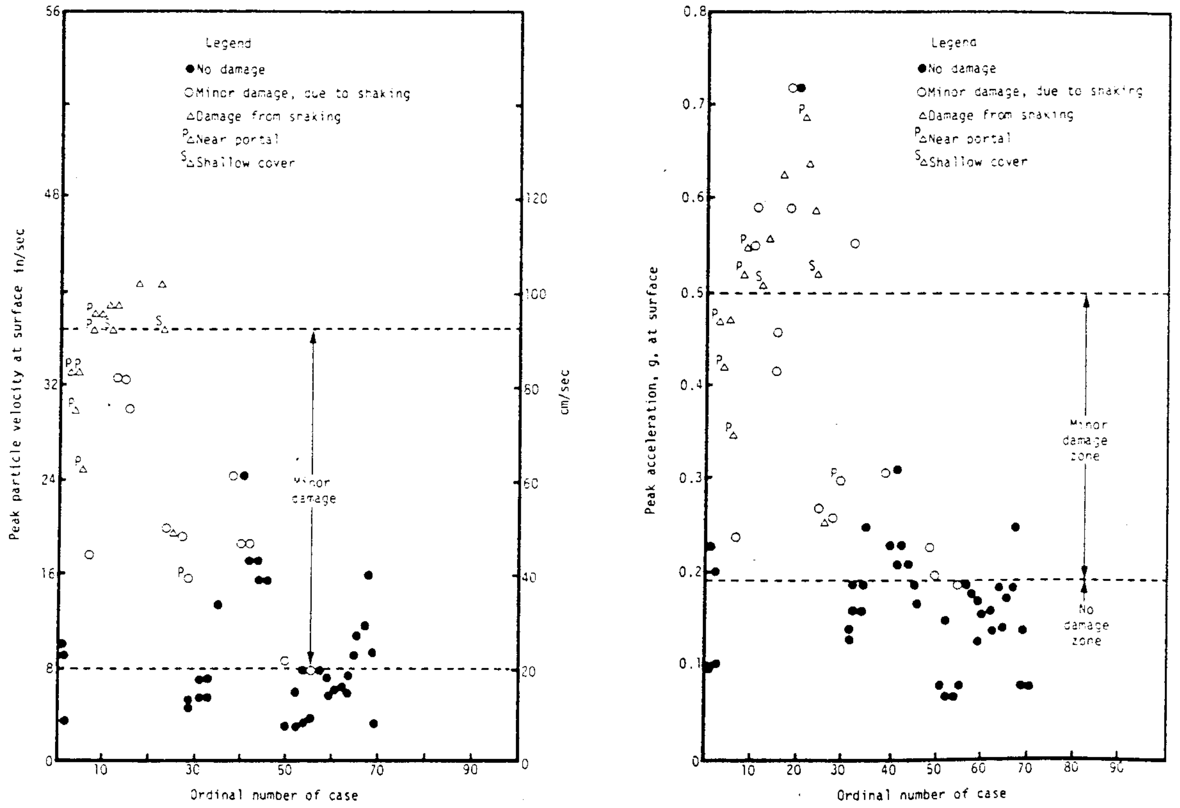
In the paper by Dowding and Rozen (1978) and Dowding (1979) 71 tunnels were studied, which were subjected to shaking and distortion. They served as railway and water tunnels. The diameter varied from 2m to 6m. Three tunnels were located in soil and 12 tunnels in hard competent rocks. The constructions of the different tunnels were made from 1800 to present with a variety of reinforcement types. Thirteen tunnels were fully concrete lined, two were unlined, seven were lined with bricks or masonry and two tunnels with timber. Average depth for the tunnels are 100 meter.

The tunnels were located in active earthquake areas in California, Alaska, and Japan and subjected to 13 different earthquakes with magnitudes varying from 5.8 to 8.3. The focal depth varied between 13 and 40km, where depths of 15-20km are dominating.
Six earthquakes occurred in California, six in Japan and one in Alaska.

The result of the study is found in Figures 5, where the 71 one earthquakes are plotted against peak acceleration (g) at surface (5a) and peak particle velocity at surface (5b). The surface peak acceleration was calculated for the surface above the tunnel.
Three levels of damage response were observed. "No damage" implies no new cracking or falling stones, " Minor damage" includes fall of stones and development of new cracks and " Damage" includes major rock falls, severe cracking and closure.

The three level of damage response correlates with the calculated peak acceleration in the following way.

There is no stone fall or cracks in unlined or lined tunnels up to a peak acceleration of 0.19g (20cm/s). Only a few cracks are reported up to 0.25g (40cm/s) in concrete lined tunnels. There is one collapse reported between 0.25g to 0.52g.



5a

5b

Figure 5. Calculated peak acceleration (5a) and particle velocity (5b) at surface and associated with tunnel damage

Figure 6 summarizes two relationships regarding tunnel damage. Observed damage is compared to Modified-Mercalli (MM) Intensity levels for ground structures. The damage level is also correlated to the Richter magnitude and distance between epicentre and tunnel location.

The 0.19g level of acceleration (No damage zone) correlates with MM level of VI-VIII and the 0.5g level is equivalent with MM VIII-IX. From this diagram it can be seen that the peak surface acceleration,which will cause heavy damage to on ground structures (MM VIII-IX) only will cause minor damage to the tunnels. However, damage resulted from fault displacement must still be considered.

The reported modes of damage are summerized in the following

The results of the analysis show that most of the damages were caused by slope instability near the portals. Damage of portals may be significant at ground accelerations of 0.25, but most damage occurred at accelerations above 0.4g.

In a few of the reported tunnels the damage was caused by poor soil or rock quality. The shaking damage can be eliminated if the soil or rock ground is stabilized.

Deep tunnels seem to be safer and less dependent to earthquake then shallow tunnels. Tunnels also seems to be more stable under symmetric then asymmetric load.

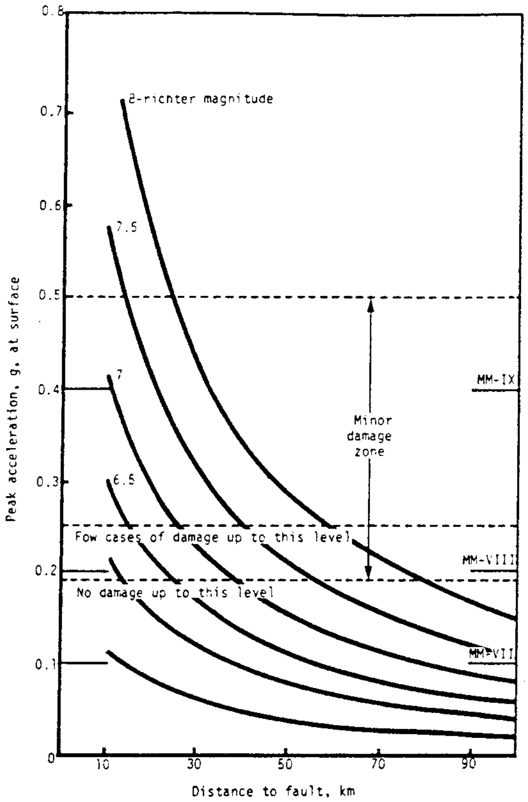


Figure 6. Modified -Mercalli intensity of surface motions and associated damage for superficial tunnel. Tunnel data from Figure 5 (Dowding and Rozen 1978).

The report of McClure (1982) includes 107 reports of damages from tunnels, excavation rooms, power stations and 43 mines located in rock . Earthquake damage in unconsolidated materials is not included thus only excavation rooms in rock are considered. The information covers eight countries. The damage considered is only for shaking ground and not displacement along faults crossing the tunnel.
Table 1 is a summery of the conclusions drawn from that report.

Table 1 Underground openings in rock with respect to damage

Number of earthquakes	Total number of openings	Damage			
		None	Slight	Moderate	Heavy
46	72	51	13	6	2

McClure makes the following design criteria for underground constructions within active earthquake areas:

1) The facility should be located in rock with a minimum shear wave velocity of 900m/sec. The shear wave for competent hand rock is normally in the order of 3000-4000m/sec.

2) The overlying bedrock thickness should be at least 150m. The underground construction should not be located in the immediate vicinity of today active or potential active faults.

If the data presented in Figures 5 are considered in the light of these design criteria then most of the cases showing damage would be eliminated. This is illustrated in Figure 7.
The description of each site is found in Röshoff 1989.

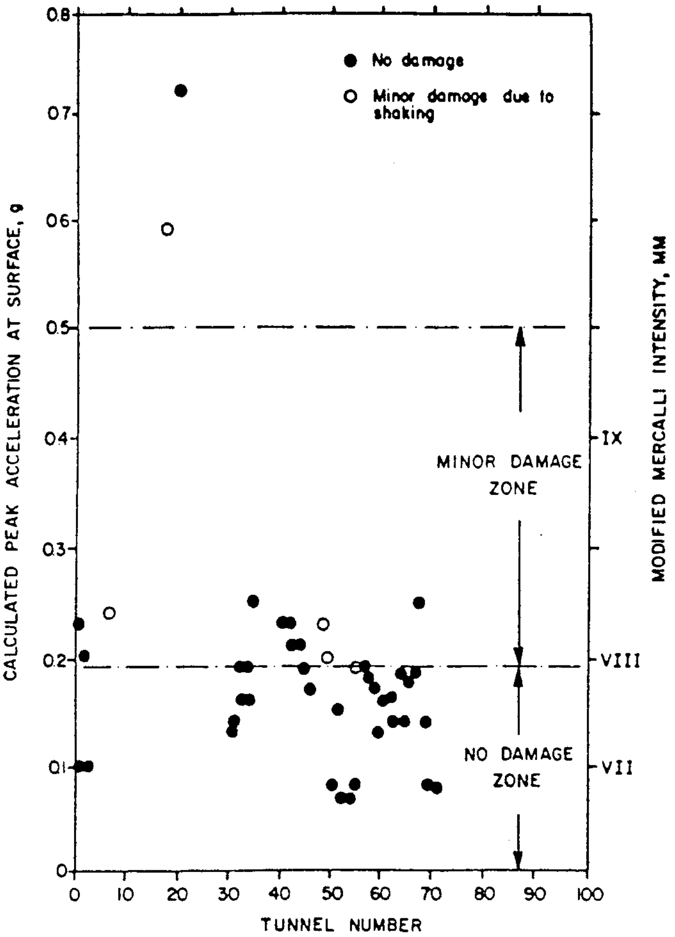


Figure 7. Diagram of damage observations considered only tunnels meeting siting criteria proposed by McClure (1982).

Murano and Takewaki (1984) present 26 references from Japan covering earthquake damage and earthquake observations in power stations and rock caverns. They also present analytic studies of the dynamic stability around rock caverns.

Three earthquakes causing damages are reported.

1. The Great Kanto earthquake
2. Kita Mino Earthquake
3. Izu-Ohshima-Kinkai Earthquake

The Great Kanto earthquake occurred 1923 with a hypocenter depth of 0-10km and with magnitude of M=8.16.
The following reports are made of damage in tunnels:

a) Among 116 railway tunnels, 82 were damaged by portal collapse, cracking in linings both transverse and in vertical directions, rock falls and rock deformation. Thicker lining was more damaged then thinner.

b) Tunnel damage occurred mainly near the epicentre and was mainly caused by slides of mountain sides near the portals and the resulting portal collapse and cracking in the linings.

c) Lining damage away from the portals occurred at places where the cover was thin or exposed to eccentric earth pressure

The Kita Mino earthquake (1961) had the hypocenter at 25km depth and a magnitude of about 7. The tunnels in the area reported are water tunnels located in jointed sandstone of Mesozoic age. The power station was located 20km from the epicentre. The dimension of the cavern is 77m in length, 42.8m high and 22.5m in span. There is no information about the depth of the cavern.

The report of damages states:

a) The damage in the tunnels was mainly cracking in lining. Most lining was not reinforced.

b) Thicker lining was more damaged then thinner

c) No damage was observed in the power station

The authors make the following conclusions:

1. Tunnel portals are more susceptible to earthquakes then central parts of the tunnel

2. Damage of tunnels is closely related to the properties of rock surrounding the tunnel and the lining thickness. The more inferior the properties of rock are, the greater will the damage be if the lining is thick.

3. Damage in the lining is dominated by cracks in the longitudinal and transversal directions

4. A tunnel that transverse an active fault, may be severely damaged due to displacements on the fault during an earthquake. It is therefore advised that location of a tunnel across a fault should be avoided.

2.6 ROCK BURSTS

There are a number of cases, especially from mines,in which underground mining excavations have been damaged due to nearby rock bursts. Rock bursts are similar in character to tectonic earthquakes, although the shaking is much shorter in time.

The best documented case is from South African gold mines (St John and Zahrar 1987), where rock bursts have been trigged as a result of the mining operation giving rise to body wave magnitudes up to 5.2. Experiences indicate that rock bursts with energy corresponding to magnitude 2-2.75 ,occasionally, will cause damage if they are associated with a major fault within about 30m of the mine workings.

The mines at the Rand Gold and Orange Free State district are 4 km deep. Shear displacements of 5-10cm were recorded in association with rock bursts of magnitudes 2-3 (McCarr in Carpenter and Chung 1986)

2.7 ARTIFICIAL EXPLOSIVES

According to the report by U.S Army Waterways Experiment Station, Vicksburg, DNAPR (Charpenter and Chung 1986) the peak velocity or strain are the best parameters to be used for correlation of damages with ground motions. Four damage zones are recognized

Zone 1	Complete damage	(particle velocity 120cm/s)
Zone 2	Rock breaking	(60 cm/s)
Zone 3	Continuous slabbing	(15 cm/s)
Zone 4	Discontinuous slabbing	(4.5 cm/s)

These values are minimum values and dependent of the rock type.

The ground motion for a blast is different from an earthquake out to the limit of zone 3-4. Thus to use blast damage as a criteria should be a conservative design.

The requirement for minimize the damage in the rock due to blasting is for unlined tunnels suggested to a particle velocity of 30cm/s, which will result in rock fall while a velocity of 60cm/s will cause new fractures.

Very large charges of high explosives were detonated in the UET(Underground Explosive Test Programme, St John and Zahrah 1987). Damage consisting of spalling was observed at a particle velocity of 90cm/s and continuous damage at a velocity of 180cm/s.

From these tests and from underground nuclear tests the threshold for damage of unlined tunnels is in the order of 180cm/s. Tunnels reinforced with rock bolts and light shotcreting will stand peak accelerations of up to 900cm/s.

Dowding et al (1983) have, on the other hand, commented that the number of stress cycles are critical in revealing the critical acceleration and therefore artificial explosive tests data can not be directly compared with earthquake loading.

3 EARTHQUAKE HYDROLOGY

3.1 INTRODUCTION

It has been known for centuries particularly in China and Japan, that earthquakes are commonly preceded and accompanied by changes in the groundwater. At present field data and observations within these field are mainly recorded in USSR, Japan, China and USA. Smaller programmes are also undertaken in Egypt and India.

Changes in pressure, flow rate, colour, taste, smell and chemical composition of surface and subsurface water in relation to a seismic event are called hydrological precursors. Hydrological effects from earthquakes have mainly been studied from wells and surface water stations. Special studies have been made to correlate the type of seismic waves that produce these hydrological effects. The Richter scale of magnitudes have been applied to correlate the hydroseisms. However, due to the many variables related to a well and the earthquake waves and their travel paths an application is at present not available.

The subsurface fluids show great changes in response to crustal strain changes. Many examples of water level fluctuations in artesian wells indicate that confined groundwaters can sensitively respond to changes in crustal strain as small as 2×10^{-8} of volume dilatation induced by earth tides (Melchior 1983)

This chapter consider the correlation of changes of water level, fluid pressure and hydrochemistry due to seismic events.

3.2 GROUNDWATER LEVEL CHANGES

3.2.1 Recordable information

Vorhis (1967) point out the following recordable information from a well or surface station:

1. Depth of water in the well at the start of the seismic recording

2. The maximum seismically caused water level rise

3. The maximum seismically caused water level decline.

4. For the largest seismic events, some wells record a coda portion during a period of 1-2 hours following the maximum fluctuation during which the fluctuations decrease to static level.

5. The surface wave that took the long way around the world, only registered in sensitive wells, was recorded as a distinct fluctuation, and likewise, the wave travelling i opposite direction was record as a still smaller but distinct fluctuation. These waves have been identified for the first time at the Alaska earthquake 1964.

6. A change in water level trend due presumably to seismically caused changes in the aquifer such as increase or decrease in transmissivity and enlargement or contraction of fractures

7. The approximate time of the disturbance.

Figure 8 shows a very typical and detailed recording from the Alaska earthquake 1964. (Waller 1966). According to the author many wells tend to have a water rise equal to the decline he assumes that the water in this well fluctuated more then 7 feet.

In most cases the studies have been performed in one single well but studies have also included the hydroseisms effect geographically spread and recorded from one single earthquake.

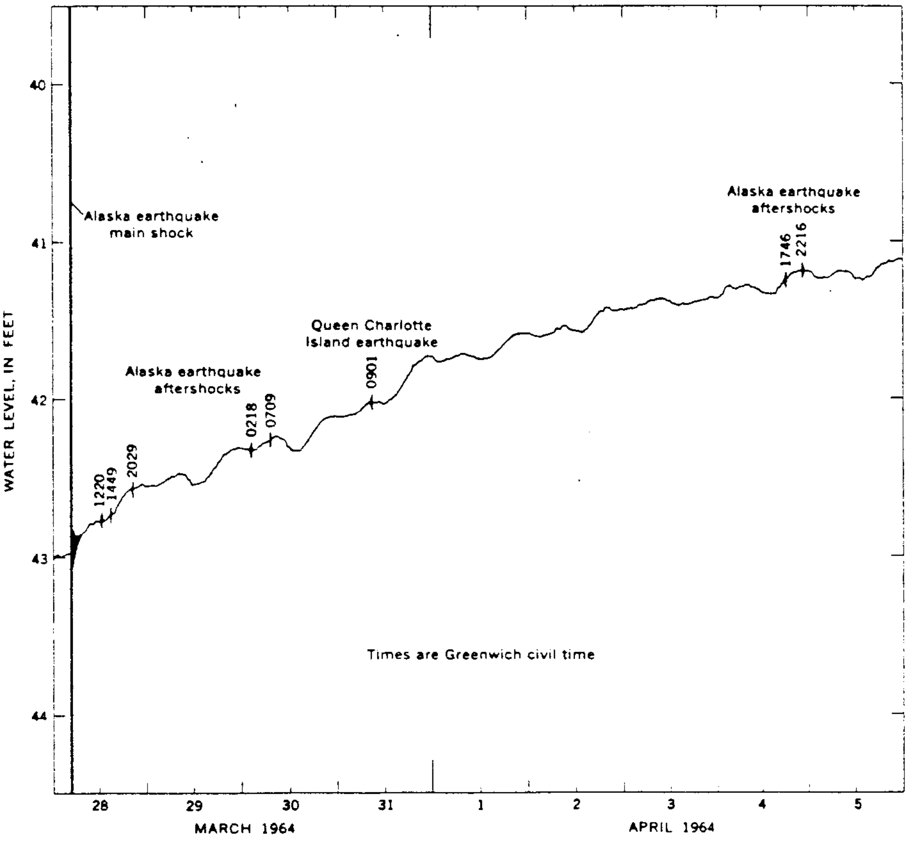


Figure 8. Typical hydroseismic registration of main and aftershocks from the Alaska earthquake 1964 (Waller 1966).

3.2.2. Seismic causes of level changes

The theories of aseismic, preseismic deformation, falls into three categories. The first theory is that irreversible fracturing occurs throughout the volume containing the future hypocenter. The second theory postulates the existence of propagating deformation fronts that can trig earthquakes. The third class suggests that a precursory slip will occur in the plane of the fault that will fail in the future earthquake.

I many cases the water level change is thought to be due to the opening of fresh fractures especially where there is a drop in water level. The water level is recovered shortly before the earthquake starts. A fracture volume is opened caused by dilatance of the rock. The objection to this theory is that the response to increasing stresses will more likely be expressed as a slip on the preexisting fractures. As the fracture zone undergoes extensional strain , dilatation, it will create forces on the surrounding rock material that would cause a rise in the water level in those areas.

The second theory, propagating deformation fronts, are possible mechanisms for water level anomalies that are distant from the epicentre especially for anomalies that propagate towards the epicenter. Migration of earthquakes and creep along the fault plane are good evidences. Scholtz (1977) has suggested that migrations of epicentres, microseismicity etc are manifested by a deformation front at a speed of 110km/year. This trigged the Haicheng earthquake in China 1975. If the front takes the form of a propagating dislocation distribution, travelled as kinematic waves, then it can be expected that the water level can either rise and fall after passage of the front. According to Roeloffs and Rudnicki (1985) the size of an anomaly is dependent on the propagating speed, the distance of the well from the path of the front, the diffusivity of the crust between well and the path of the front.
The volume strain from this model has been estimated by Roeloffs (1988) based on observed water level changes (Figure 9).

The third theory is based on slip-rate and rate-history dependent friction laws. The slip instability is always preceded by an accelerated stable slip over a patch of the fault, which may give rise to signals 10days-10min before the earthquake. The displacement in the patch will increase rapidly. The increase of the displacement will in this case be detected in wells over time at increasingly greater distances from the nucleation patch. Thus the anomalies in water level would appear to emanate from the epicentre.

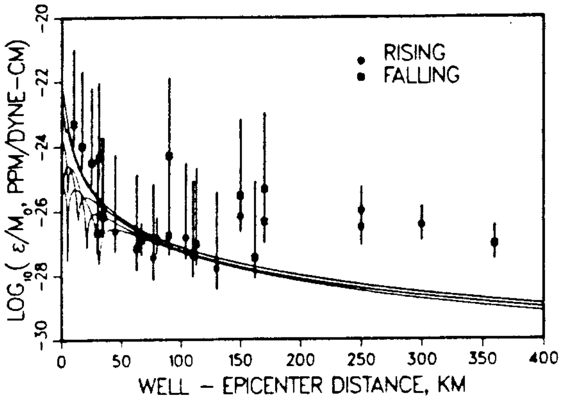


Figure 9. Comparison of strain represented by water level anomalies with predicted maximum coseismic strain. Curves: Absolute values of volume strain as function of distance along the azimuth of maximum volume strain for several source mechanisms. Curves represent strain per dyne-cm of moment. Shear modulus: 3×10^{11} dynes/cm^2
1 dynes/cm^2 = 0.9×10^{-6}atm

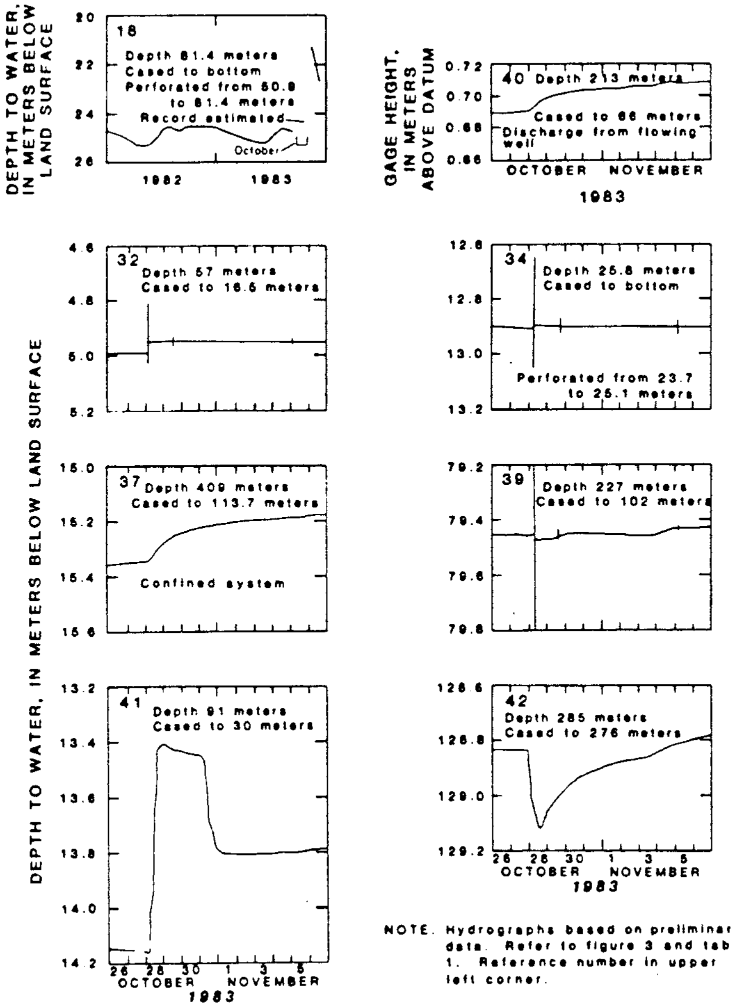
3.2.3 Recorded level changes

This section describes some typical recodings connected to earthquakes. For more details see Röshoff 1989.

The Idaho earthquake, October 1983

Significant hydrological changes were observed after the Idaho earthquake with magnitude 7.3 (Whitehead, et al 1984/85). This is the strongest continental earthquake during the last 25 years in USA. A 37 km long fault was formed and the vertical displacement was up to 3 m. US Geological Survey made the recording by a hydrological monitoring network. Water levels were measured in 69 wells and water samples were collected from 40 sites for chemical analyses.

The most significant hydrological changes occurred near the epicentre .
Changes were noted as far away as 700 km. These changes are recorded in Röshoff 1989 . Water level changes are recorded for some wells in Figure 9.



NOTE. Hydrographs based on preliminary data. Refer to figure 3 and table 1. Reference number in upper left corner.

Figure 10. Hydrographs from some selected wells showing level changes after the Idaho earthquake 1983

In general the water levels near the epicentre rose rapidly after the earthquake. The water was in many cases muddy and damaged some pumps.

Changes in the water level were recorded in numerous wells mainly in southern Idaho but also wells north of the epicentre in Montana declined after the earthquake.
Figure 11 shows the water level monitoring from one well located 8km north of the epicentre. This well is 409m deep in a confined system. The water level rose nearly 4 m. and then declined steadily until January 1984 when it levelled off at about 1.5m above its pre-earthquake level.

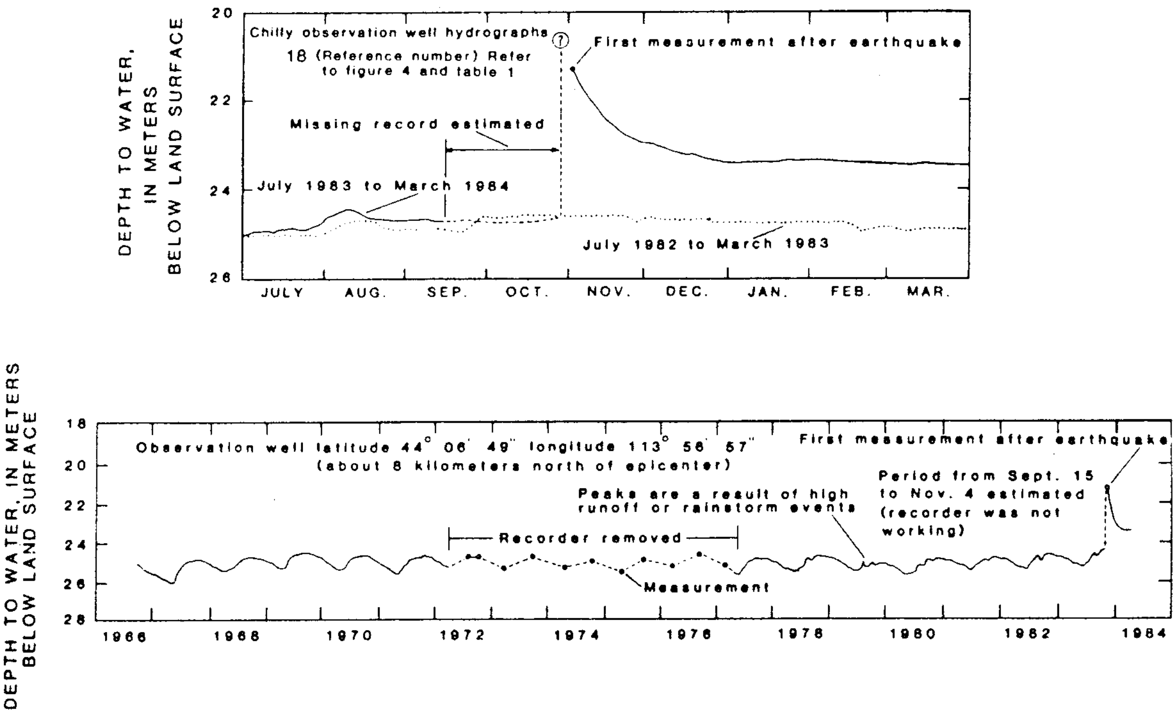


Figure 11. Hydrographs of observation well 8 km north of epicentre, showing short and long term water level changes in relation to the Idaho earthquake 1983

Figure 12 illustrates another well located 210km southwest of the epicentre. In this well the water level became steady at a higher level then before the earthquake.
It was also observed an increase of discharge in many springs. The most significant was the Warm Spring at Challis. Pre-earthquake discharge was 170 l/s. The spring ceased after the earthquake but began to flow in November with an increase of the flow with a peak of 1640 l/s. The flow in May 1984 was 1300 l/s.

Recordings was also made in some mines. The 330m deep Clayton Silver Mine, located in quartzites and dolomite, 45km west of the epicentre pumped out 62 l/s from lower levels of one of the workings but had to increase the pumping to 126 l/s after the earthquake. In February 1984 the pump out water amount was 96 l/s.

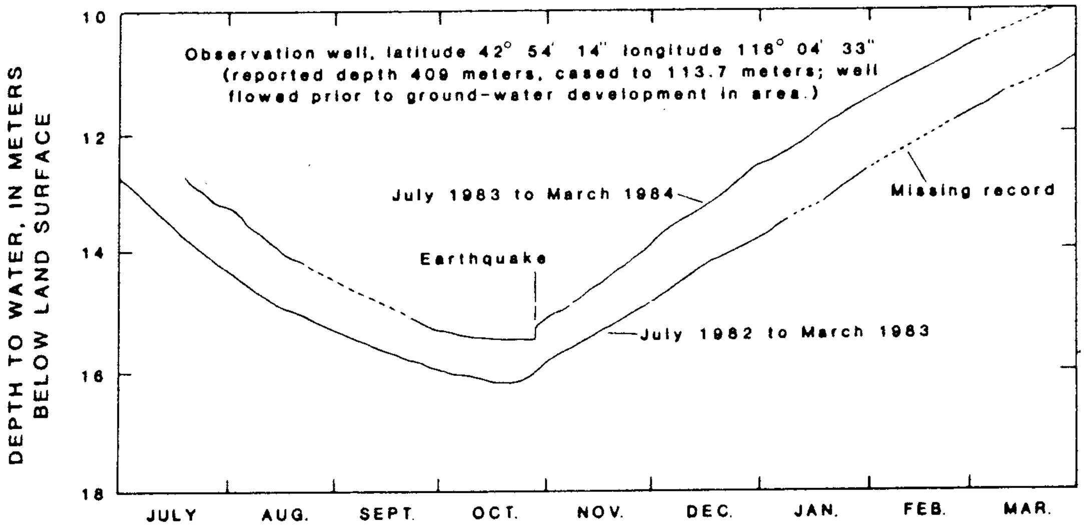


Figure 12. Hydrographs from a well located 210 km from the epicentre, showing comparison of water level changes after the earthquake with previous records

Flow rates and pressures reportedly increased in numerous locations in the 240m and 330m levels, while the 150m level produced water for the first time in several years. The inflowing water was clear.

A similar behaviour with increase of water in-flow was observed in the mine at the 1959 Hebgan Lake earthquake, 150 km northeast of the Idaho earthquake epicentre. At that event the water in-flow returned to normal after about 8 months.

Barton (1986) made the following comment of the subsequently reduction in flows observed at the Clayton mine, that it is probably a function of local drawdown of the groundwater table due to the increasing permeability of the rock mass.

The Alaska earthquake March 1964

The Alaskan earthquake 1964 is one of the strongest earthquakes of all time (Eckel 1964). The Richter magnitude is 8.3-8.7. Displacements of the surface occurred in two arcuate zones parallel to the continental margin 1080km long and 450 km wide. The land and the sea-bottom surface to north and west of the isobase subsided on average 0.75m and maximum 2.25m. The land south of the isobase was uplifted 1.8m on average and as maximum 11.4m. The maximum horizontal movement was measured to 21m. The earthquake produced two main surface faults. The lengths are 66km and 51km with reverse vertical movements of 6m and 4.8m respectively.

The groundwater affect was also recorded in about 700 wells in Europe (England, Belgium, Denmark,) , Asia, Africa (Libya, South-West Africa) , Australia and in 46 states in USA. About 716 wells in USA recorded water level fluctuations. Important response was also registered as fluctuations on streams, reservoirs, ponds and lakes (Vorhis 1967). In most cases the water level recovered to normal after a few minutes.

The recordings of the groundwater level in wells penetrated the shallow groundwater table and deeper aquifers.
The general effect on the the groundwater was that many shallow wells surged with or without permanent changes in level. In some cases sea water entered into the wells. Most of these effects were temporary, but some were permanent or semipermanent.
Records of five wells in Anchorage area show an immediate increase in level when the seismic waves induced pressure in the aquifer. The other immediate effects include reported failures of well systems, muddy well or spring water. Generally the ground water levels were residually lowered after the initial fluctuation.
Many artesian wells were greatly affected with pressure level drops of 4.5m either permanent or for several months.

Most records indicated only brief fluctuations of the water level but about 25% of the wells showed a lasting rise or decline suggesting that the earthquake caused a redistribution of the strain within North America. Some wells as far as in Georgia, USA, were muddy.

The hydroseismic effect in USA were felt throughout the country. However the states east of the Appalachians did not register many events. The most numerous and largest effects were recorded in southeastern States most distant from the epicentre.
The recordings from USA are listed in Röshoff 1989 . There is at present no interpretation of the data recorded from the Alaska earthquake.

About 100 wells were selected for mapping the earthquake effect. The wells range in depth from 5m till 162m. About 70% of the wells were effected in some other way then just water fluctuation. These wells were effected by the earthquake independently of well depth. Type of lithology was not a significant factor.

The groundwater was also ejected in south-central Alaska whenever the water table was close to land surface. It is thought that the shallow water table aquifers were confined at the time of the earthquake due to the frost layer. Therefore the shallow aquifers responded in the same way as deeper confined aquifers.

The piezometric levels were measured at about 50 points starting a few days after the earthquake. In some wells recordings were made before the earthquake. Nearly all the data show that the artesian-pressure surface was lowered due to the earthquake , locally as much as 7.2m. Recovery started immediately and that within 6 months the water levels either had recovered to their former level or stabilized at a different level (Figure 13). The piezometric level is as much as 4.5m lower than before the earthquake in 30% of the wells. Almost in all observations indicate changes in the artesian-aquifer system in the glaciofluvial sediments.

The cause of the residual changes in water levels in aquifers are discussed by Waller (1966). Possible causes are tectonic lowering of the land in relation to the sea, a change in recharging the aquifers, changes in the porosity as a result of seismic strain, openings and closing of fractures. The tectonic lowering of the land should have caused a rise in general of the water level. Only one well of about 50 shows an increase in water level.
A straining and/or rearrangement of the grains in the aquifer are generally accepted as the causes.

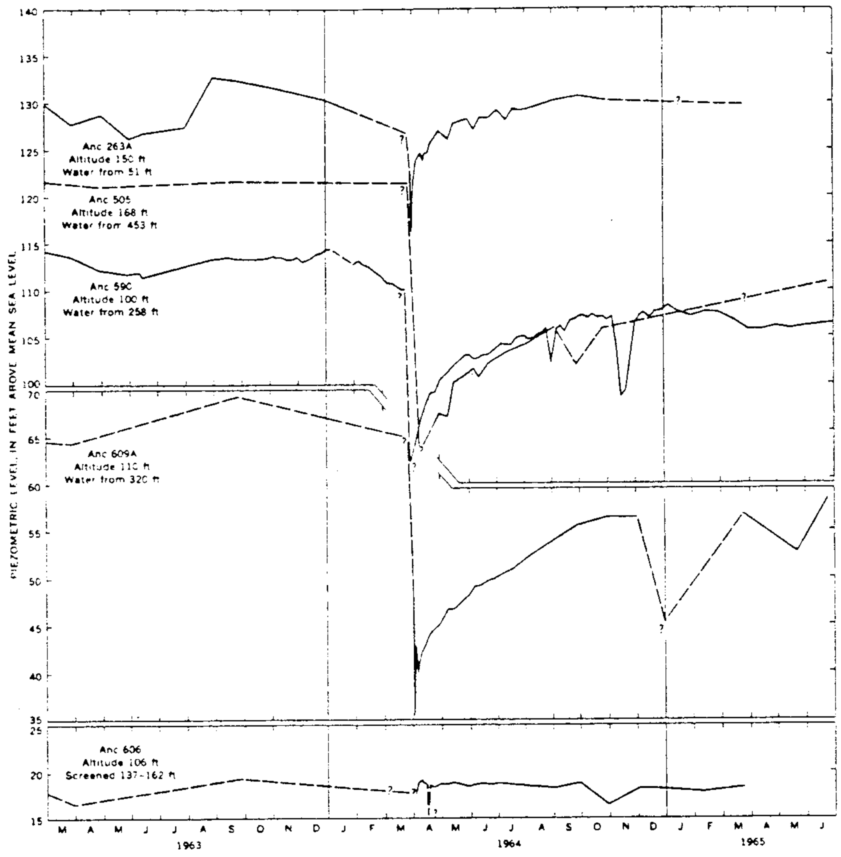


Figure 13. Hydrographs 1963-65 of five wells in the Anchorage area. The graphs show, by yearly comparison, the residual changes of the artesian water level after the Alaska earthquake 1964

Studies of earthquakes in USSR

In all seismic studied areas in USSR (Barsukov et al 1984/85) an extensive investigation has been undertaken for the hydrogeodynamic precursor parameters in artesian water, water level in non flow wells and gas yield. Water level changes are characterized by bay-like anomalies, whose amplitude and durations depend on the earthquake magnitude and epicentral location. The hydrogeodynamic geographical sensitivity range up to 500km or more.

The described examples for such anomalies are the earthquakes in Ashkhabad 1948 and Gazli 1976 located in the same seismic region, where both events were preceded by a drop in groundwater levels 1-2 years before and then 1.5-2 months prior to the main event.
The total drop was 19m with baylike drops of 10-15cm about 10 days before the earthquake. A recovery of the water level took place at the time or after the event. There is no information if the recovery was partial or total.

Studies in China

Ground water level observations are an important part of earthquake research in China for prediction of seismic events (Chengmin 1984/85). At present more then 4000 wells are continuously under control. Of these wells about 300 are included in a professional network. They are deep confined wells with a measurement accuracy of +/- 5mm. These deep wells have a relative stable water level and respond sensitively to stresses associated with earth tide, barometric changes, seismic waves and fault creep.

Anomalous water changes before an earthquake show that normally the water level will drop. The relation between time, location and magnitude to a corresponding earthquake are very complicated. Water levels at wells in the epicentral areas often recover shortly before the earthquake. Sometimes a migration pattern is observed. In some cases the migration is towards the epicenter before the earthquake and back again after the seismic event.

3.2.4 Correlation of earth tides and well response

Merifield and Lamar (1981,1985) have studied thirteen wells since 1977 in the San Jacinto fault zone in California and found that wells responsive to earth tides maybe detectors for crustal strains changes. The largest earthquakes within the 30km shear zone during the period were of M=5.5 in 1980, M=4.8 in June 1982 and M=4.5 in March 1982.

The most significant water level change occurred at the earthquake 1980 in well 3N4 a well located 31 km from the epicentre (Figure 14). The water level rose 4cm, 88 hours before the earthquake, but returned to normal level before the earthquake. The smaller water level fluctuations, about 1 cm with a period of less then 24 hours, are caused by earth tides.

The rise and fall 88 hours before the earthquake are anomalous and possibly caused by creep along the fault plane.

Water level response to a propagating creep may produce water level curves showing rapid increase or decrease and gradual return to normal levels (Wesson 1981).

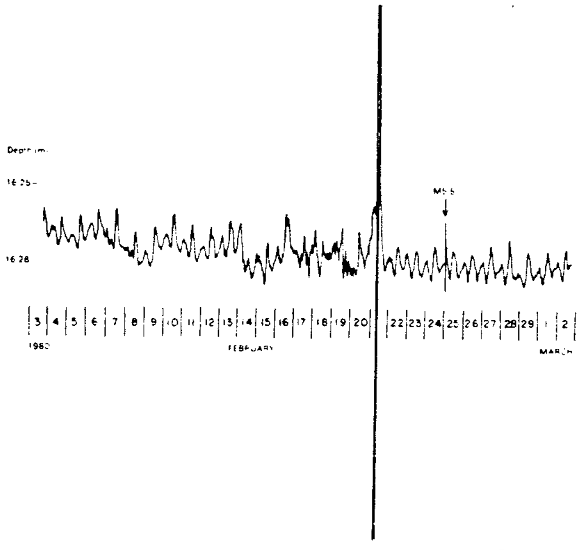


Figure 14. Water level recorder chart for the well 11S/6E-3N4

Marifield and Lamar (1984/85) conclude that the observed anomalous up and downward spikes have a period shorter and the anomalies are more spike like than in water level changes measured in days associated with creep. The spikes occurred over shorter time but are similar in shape to those reported by Lippincott et al (1983), which are believed to be creep events. Water level changes due to creep should vary with geology, well characteristics and the nature of the event; thus different anomalies are not surprising. Well 13D5 is 25m deep and penetrates granitic rocks (Figure 15) and is located 13km from epicentre. According to the authors this well shows no apparent effect of the earth tides.

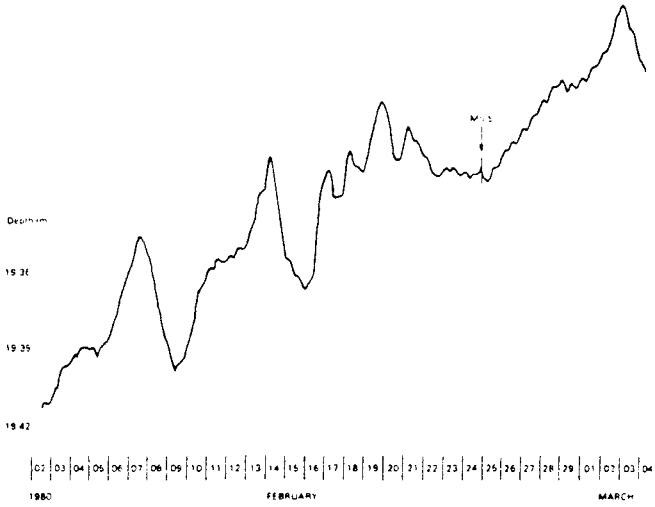


Figure 15. Water level recorder chart for well 13D5, 1980

The authors make the following note that the apparent water level anomalies correspond roughly in time to changes in the strain pattern, radon activity and other geophysical phenomena, which have also been observed in southern California during 1979. The radon and other anomalies returned to normal in early 1980. This has definitely occurred in only two wells. Two other wells have shown some return to normal. Levels in the other wells (4) have remained anomalous up to fall 1980. Thus some wells appear to consistent with changes in the crustal strain pattern in 1979, those in other wells did not. Five of eight wells with possible anomalous water level changes were identified as good strain meters based on the response to earth tides.

3.2.5 Correlations between creep and water level changes

Simultaneous recordings of water levels and fault creep along the San Andrea fault indicate that episodic creep can be accompanied by water level changes (Johnson et al (1973).

Roeloffs and Ridnicki (1984/85) reports of a study regarding water well fluctuations with episodic creep. They suggest that coupled deformation-diffusion effects can be significant in the interpretation of water well fluctuations due to creep. The response of a water well to periodic fluctuations of stress and strain at the boundary of an aquifer has been studied by Johnson and Nur (1984). To produce creep related water fluctuations the critical frequency of the well response must be high enough to overlap pore water pressure fluctuations.

Simultaneous water level and creep is reported by Johnson (1973) at wells in Hollister, California. The creep was detected by creep meter monitoring. At one event the water level dropped 4.1cm at a well located 10m from the fault and 300m from a creep meter. He also estimated that the level change corresponded to a stress drop to 150kPa on the fault.

3.2.6. Time migration

There are different opinions regarding where the groundwater anomalies should first be observed. Wang and Li (1976) report that the anomalies, before the Haicheng, Tangshan and Songpan-Pingwu earthquakes first appeared at large distances from the epicenter and then gradually migrated towards the epicentre, especially along old faults or faults parallel to older fault directions. This migration occurred over a distance of 150-200 km within a 3 months period.

Sadovsky et al (1979) think that the water level anomalies begin sooner and close to the epicentre area and then migrate away.

Similar behaviour occurred for the Oshima-Kinkai earthquake in Japan , where the anomalies started 3-5 weeks before at a distance 50 km within the epicentre, but only several days before at a distance 50-150km from the epicenter.

3.2.7 Changes in fluid pressure and flow rate

It is assumed that the saturated rock of a fluid reservoir behaves as a porous media. Fluid pressure changes caused by volume strain changes in confined reservoirs is described by the equation (Rice and Cleary 1976)

$$\Delta P=-(2GB/3)\{(1+v_{\mu})/(1-2V_{\mu})\}\Delta æ \qquad (1)$$

where

ΔP is the change in reservoir fluid pressure

$\Delta æ$= the increment of volume strain in the reservoir.

G= shear modulus

B= Skempton´s coefficient

V_{μ}= undrained Poissons Ratio

For example in a porous elastic reservoir with G= 3 GPa, B=0.8 and V_{μ}=0.3. The equation predicts a pressure change of 52cm of water per microstrain. Fluid flow is neglected.

Earth tides and barometric changes are usually expected to produce uniform volumetric strain in fluid reservoirs. For earth tides it is also assumed that they impose horizontal strains with no change in vertical stress. The pressure changes in the reservoir due to tidal volume change are derived from equation (1). Such a relationship is given by Bodvarsson (1970).
The change in pressure will be smaller in most cases if the flow is not negligible.

The following equation is applicable to an open unconfined well

$$\Delta h=-(H/n)\Delta æ \qquad (2)$$

where

Δ h= water table change

H= saturated thickness

n= porosity

For a 100m saturated interval of rock with 2% porosity the rise will be only 0.5cm per microstrain. Thus the confined reservoir is much more sensitive.

The ability for the fluid level to track the pressure changes in the reservoir depend on the rate of changes, as any changes in water level require flow of water in and out of the well.
Bodvarsson (1970) observed that the water level response decreases rapidly for fluid pressure changes having frequencies greater then a critical frequency; thus for sandstone this critical value ranged from cycles of per minute to cycles per day while crystalline rocks had less than a cycle per month.

Roeloffs and Bredehoeft (1985) report one of very few events of water level drops, in four wells in California, coseismic with the North Kettleman Hill earthquake 1985, M=5.5. The drop after correction for earth tides ranged from 2.1 to 7.8cm. This drop correlated within 50% with calculated elastic strains produced by the earthquake.

Most other observations of coherent water level changes with seismic events for strain evaluation show too large level changes to be explained by volume strain dependency only.

The author also give approximate strain sensitivity data based on well data. Measured amplitudes (M_2) from wells is given in Röshoff 1989. The amplitudes corrected are plotted against depth in Figure 16. It is suggested that deeper wells are more sensitive to tidal strain and a crude bound can be defined for the amount of strain required for producing a given change in water level at a given depth. This equation is:

$$\Delta h/\Delta æ=-(77d +90 +/- 142) \text{ cm/microstrain} \qquad (3)$$

where d is depth

Δ h= change in water level

Δ æ= change in strain

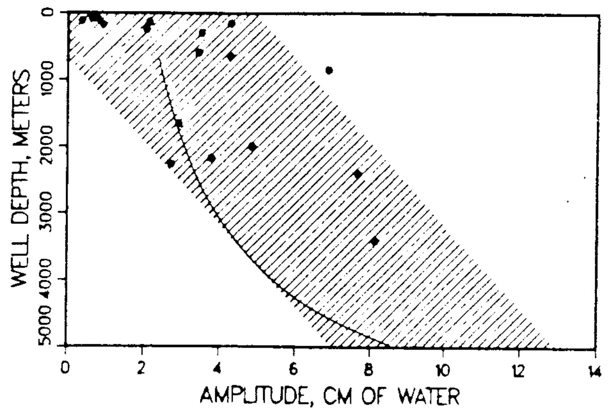


Figure 16. Amplitude of M_2 tidal constituent versus well depth for wells listed in Röshoff 1989. The shaded area represents the relationship given in equ. (3).

4. CHEMICAL CHANGES IN GROUNDWATER AND SOIL GASES

Groundwater anomalies have been among the first and most frequent reported phenomena to be observed in conjunction with seismic events. Groundwater monitoring programs consist of sampling of wells or springs at intervals of weeks or months and the analysis of selected ions and constituents.

The most frequent monitored ions are group I and II cations (Na, Ca,K and Mg), major anions (SO_4, Cl,F, CO_3) and less frequent of trace elements (Hg, Rd,U,F, Li,Sr and Ba). Dissolved gases includes CO_2, H_2S, CH_4, He, Ne, Ar, N_2, H_2 and Rn.

Deep wells, mineral springs and thermal springs are preferred as sources as they are less influenced from environmental effects or seasonal changes.
The studies so far have mainly been concentrated on anomalies occurring coseimic with intermediate and large earthquakes ($M>4$).

Among the more intensively investigated geochemical phenomenas are

a) changes in the concentration of dissolved ions and gases in ground water

b) variations in concentration in crustal and mantle volatiles in ground gas.

The tectonic correlations with the changes of dissolved ions are known from intra-plate earthquakes in China and USSR (Barsukov et al 1984/85) subduction zones (Wakita 1981) and inter-plate, strike-slip earthquakes in USA (King et al 1981).

Changes of gas emissions from wells and springs have been reported for more then 100 years. The primary component is often CO_2 but also CH_4 and H_2S are reported.

There is a correlation between geology and type of gas. Thus CH_4 and H_2S are typically reported from areas of known coal and organic rich strata and petroleum deposits (Kawabe et al 1981). Discharges of CO_2 have been observed in limestone formations or shallow alluvial deposits (Li et al 1985).

The monitoring of soil-gas include mainly Rn and H_2 but He is also of great interest.

4.1 MECHANISMS OF SEISMOCHEMICAL ANOMALIES

Many different mechanisms have been suggested to account for the geochemical anomalies related to seismic events. The primary cause of observed geochemical anomalies is a long term effect of strain changes induced by the earthquake's starting processes. Five models have been proposed for the processes (Thomas 1988) :

1. Physico-chemical release by ultrasonic vibration (UV-model)

2. Chemical release due to pressure sensitive solubility (PSS-model)

3. Physical release by pore collapse (PC-model)

4. Chemical release by increased loss from or reaction with freshly created rock surfaces (IRSA-model)

5. Physical mixing due to aquifer breaching/fluid mixing (AB/FM-model)

The chemical components are suggested by the UV-model to be mechanically freed by ultrasonic vibrations prior to the seismic event (Barsukov et al 1985).

It is known that ion and gas solubilities changes with change in fluid pressure (PSS-model). Therefore it has been suggested that the precursory stress changes can increase the concentrations of the dissolved compounds in groundwater. However, it is unlikely that stresses of such high magnitudes will be transmitted to the fluid phase namely magnitudes of 10-100 bars.

Jiang and Li (1981)proposed the pore collapse model (PC-model). At increase of stresses prior to the earthquake the pores in the rock will collapse and chemical compounds will be squeezed out into the ground water. Field evidences supporting this model includes cycling changes in inert gas ratios associated with tidal strain variation. According to Thomas (1988) this model is not likely to be a major mechanism for expelling chemically anomalies.

Several investigators have proposed the IRSA-model (Thomas 1988). Exposed fresh silicated rock surfaces are believed to both increase the rate of alteration reactions with groundwater and escape trapped gases. Field studies report coincident trends of regional stress changes and groundwater radon concentrations (Wakita et al 1985).

Precursor changes in groundwater chemistry are often reported by mixing of fluids from two or more aquifers(AB/FM -model). This model explains both increase and decrease in concentrations of the compounds and also changes in temperature in the groundwater flows (King et al 1985). Fluid flows through shear zones in the bedrock is suggested by McCaig (1989) to be entered and the result of such seismic pumping. Compare also page 18. During this process fluids are sucked into the highly stressed areas due to volume increase caused by increase in pore volume when micro-cracks develop.

The gas associated with artesian well water is a mixture of atmospheric air dissolved in rainwater and different gases. The gas components coming from the underground are added to the water percolating the stratum. The anomalies are assumed to be made by changes in mixing ratios due to strain changes in the bedrock. This means that the subsurface gas rich for example in CH_4 and He is pressed out from pores, cracks and mineral grains and mineral boundaries of the rock into the circulating groundwater by the deformation of the aquifer.

The mixing of gas into groundwater is thought to be a very complex transport process in the fractured rock. It should be explained and described as an adequate gas-transport equation, consisting of several parameters including advective transport, molecular diffusion, production and reaction rates. Differences in transport characteristics between the different gases then explain why the anomalies of for examples the CH_4/Ar ratio are much higher then for example He/Ar ratio.

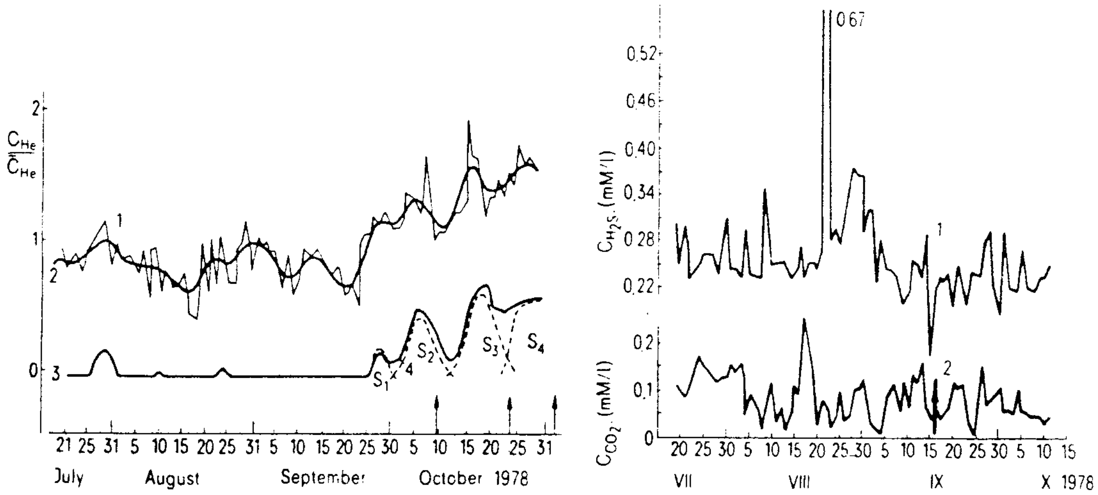
4.2 HYDROCHEMICAL INVESTIGATIONS IN USSR

A state of the art paper is presented by Barsukov et al (1984/85) comprising the last five years hydrochemical studies in 83 stations located in all the seismic regions in USSR. Data of more then 40 parameters are included. The main purpose for these studies are for earthquake predictions. On the basis of statistical treatment it has been possible to attain major principles of the seismic events and the hydrochemical anomalies prior to an earthquake depending on the nature of precursor, geological conditions in a region and seismic features as focal depths, intensity and epicentral distances.

The gaseous components He, Rn, CO_2 and H_2S have been most informative for earthquake prediction. These components have a geographically large sensitivity (300-500km or more). The anomaly duration and amplitude are observed to be related to the magnitude and epicentral distance.

Measurements of He in a flowing well (Figure 17a) have shown that the strong earthquake in the region was proceeded by "bell-shaped" anomalies with peaks 4 or 5 days before the event.

A number of large seismic events in the USSR Central Asia were correlated with minima of "bay-like gas anomalies. Three to four weeks before the Iranian earthquake 1978 there was a pulsed increase of H_2S and CO_2 concentrations with a gradual decrease of these elements after the seismic event (Figure 17b).



a

b

Figure 17. Variation in concentration in He (17a) and CO_2 and H_2S (Figure 17b) in Yavroz flowing well waters. Recordings for 17a for earthquakes 8 October, 24 October and 2 November 1978 and for 17b before the Iranian earthquake 16 September 1978 S1-S4= "bells" for estimating earthquake intensity and time.

Radon is one of the most informative gas components in groundwaters. Normally there is a sharp anomaly of radon manifested 1-15 days before the seismic event. Strong local and remote earthquakes were occasionally preceded by an increase in radon content in the water.
In areas with repeated seismic events or fore-shocks, the radon may be absence due to gradual " exhaustion" of available radon gas before the main shock.

Mercury is an imminent component for earthquake prediction. During seismic silent periods the mercury content in water and soil air is fairly stable, but in a period several hours or days before a shock the content increases by one or two orders of magnitude.

Observations of major ion contents as Ca, Cl, F and SO_4 ions all indicate sharp increase with duration of anomalies of a 24 hours period. Numerous data indicate that major ion precursors occur mostly in the epicentral zones. The geographical sensitivity will not exceed 50-100km.

Successfully investigations were also made in the study of anomalous isotopic ratios which show pulses or bay-like curves. These ratios are $^{13}C/^{12}C$ in CO_2 and CH_4, $^{3}He/^{4}He$, $^{40}Ar/^{36}Ar$ and $^{4}He/^{40}Ar$.

4.3 HYDROCHEMICAL INVESTIGATIONS IN CHINA

Several geochemical anomalies were measured before the Haichen 1975(M=7.3), Longling 1976 M=7.4), Tangshan 1976) (M=6.9) and Songpan 1976 (M=7.2) earthquakes.
The analysis of the chemical composition of ground water include the ions of Ca, Mg, Cl, SO_4, F and HCO_3. Normally also the conductivity , pH and Eh are measured. Some anomalous changes were observed and coincident with the aftershocks of the Tangshan event (Jiang and Li 1981). Most geochemical anomalies are found to increase.
The observed anomalies prior to a strong earthquake depend on the tectonical , geological, lithological and hydrogeological conditions at the monitoring site.

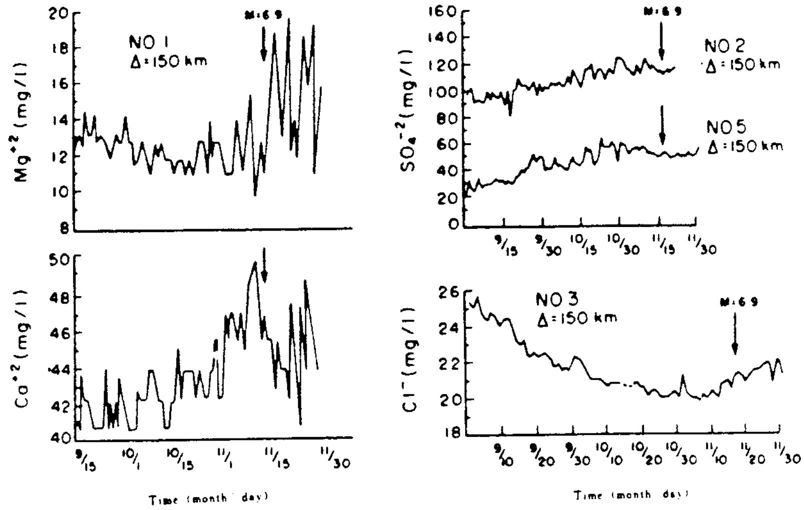


Figure 18. Anomalous changes in ionic composition of water before the M=6.9 Ninghe earthquake, November 1979

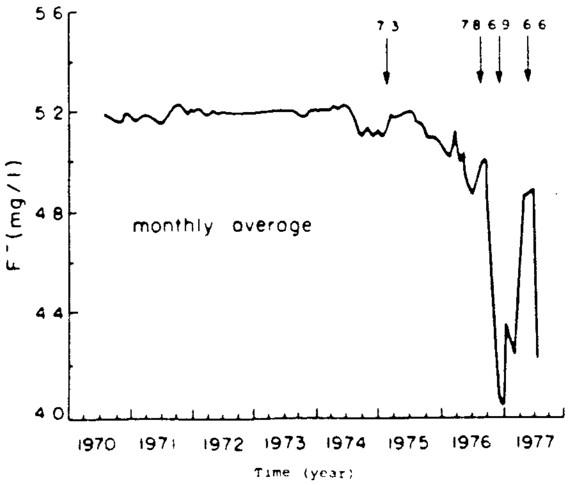


Figure 19. Significant decrease in F^- content in water recorded before the Haicheng and Tangshan earthquakes

Figure 18 shows the changes in groundwater chemistry of some ions that occurred before the Ninghe earthquake, a strong aftershock of M=6.9 of the Tangshan earthquake 1976 (Guiru 1984/85). There is also a significant decrease in F ions before the Haicheng and Tangshan earthquakes (Figure 19).

4.4 HYDROCHEMICAL INVESTIGATIONS IN USA

Chemical changes i well water prior to an earthquake have been studied by King et al 1981.
The samples were taken from three wells located along the San Andreas fault. The water level, temperature, salinity, electrical conductivity and pH have been measured for several years. Chemical analyses of the water were made for the following ions Na, Ca, Mg, SO4 , HCO_3, F and Cl. Sudden changes in the ion concentration occurred with the beginning of an seismic period starting in May 1980, with a magnitude of 4.8.

It is thought that these changes are the result of mixing of waters from different aquifers. One well (CW) is 152m deep and located 10-20 m north of the fault plane. The second well (SFR) was originally 152m deep but could only be penetrated to 80m. This well is located a few meters from the fault. The third well (MFC) is located a few meters southwest of the fault and is only 30m deep at present. The fault is described to be impermeable across the fault plane at this well.
The fault is characterised by small to moderate earthquakes and by fault creep with a rate of 12mm/y at CW and 9mm/y at MFC.

The observed changes (Figures 20 a-d) coincided approximately with the onset of increasing seismic activities. Chemical changes were observed in Ca, Na, Mg, F, Cl and HCO_3 in the SFR well as well as changes in conductivity, salinity and water level. In the MFC well the conductivity and salinity increased rapidly from a previous stable background.

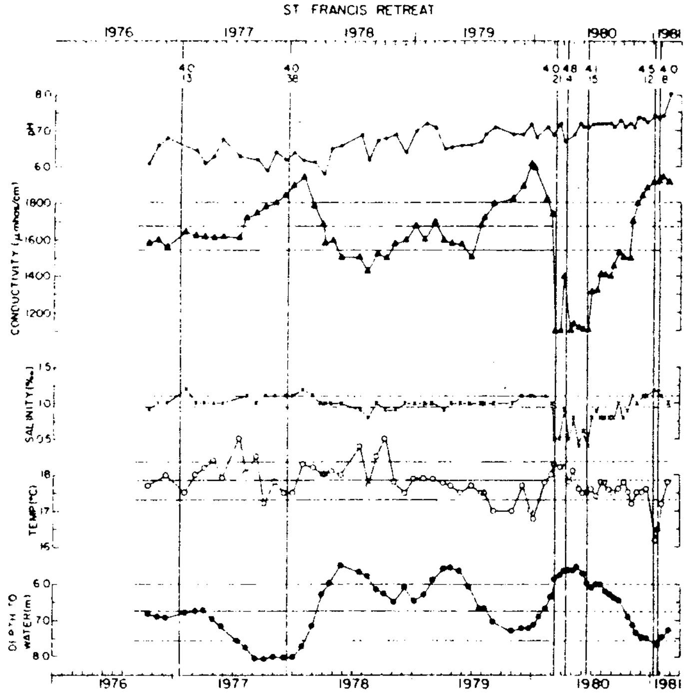


Figure 20 a. Time series of water level, temperature, salinity, electric conductivity and pH at the SGR-well.
Horizontal lines indicate pre-anomaly mean value +/- one standard deviation. Vertical lines indicate earthquake of M>4. Epicentral distance labelled.

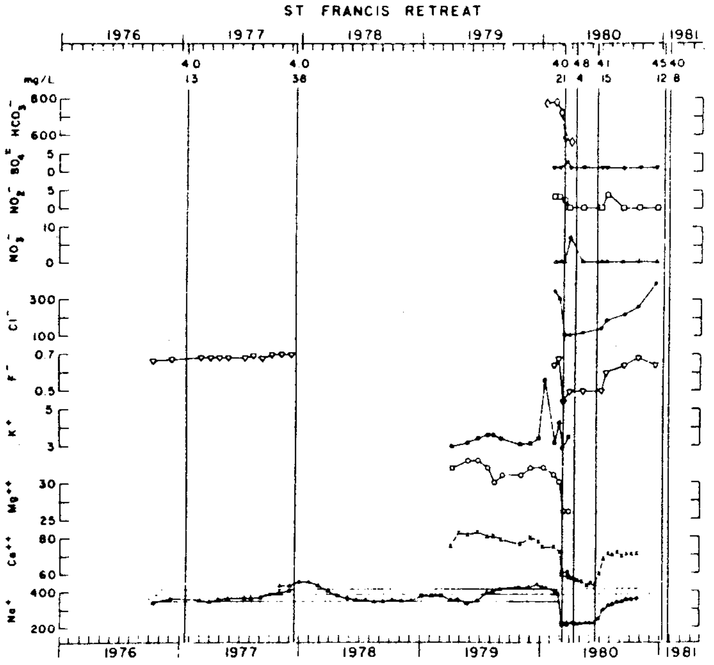


Figure 120b. Time series of ion concentration in water samples from SFR well. Horizontal lines indicate pre-anomaly mean value +/- one standard deviation. Vertical lines indicate earthquake of M>4. Epicentral distance labelled.

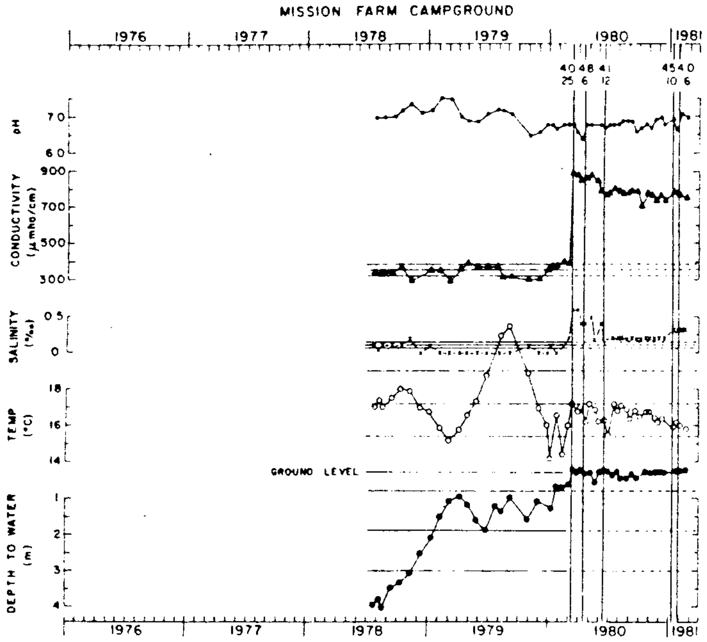


Figure 20 c. Time series of water level, temperature, salinity, electric conductivity and pH at the MFC-well.
Horizontal lines indicate pre-anomaly mean value +/- one standard deviation. Vertical lines indicate earthquake of M>4. Epicentral distance labelled.

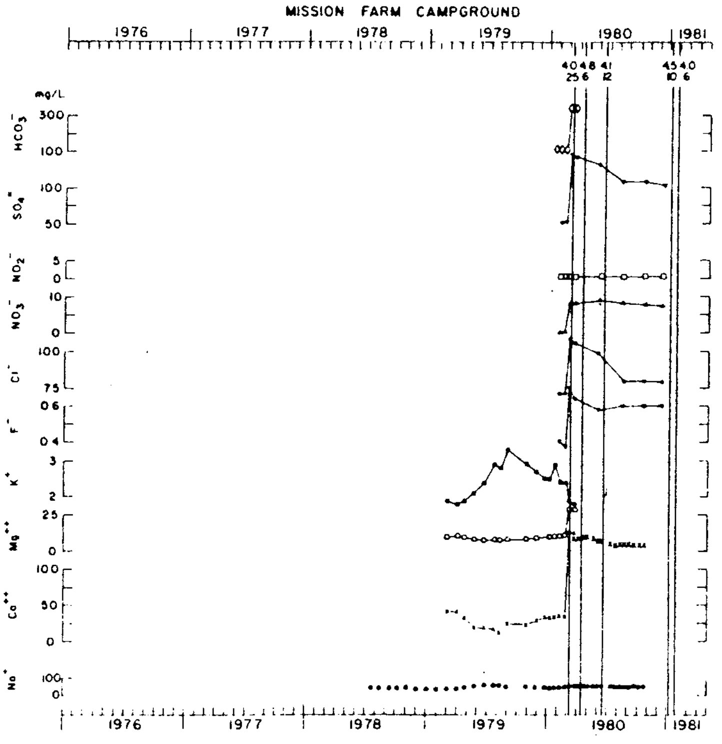


Figure 20 a. Time series of ion concentration in water samples from MFC well. Horizontal lines indicate pre-anomaly mean value +/- one standard deviation. Vertical lines indicate earthquake of M>4. Epicentral distance labelled.

previous stable background. These changes were only partly recovered during the following period. Similar changes also occurred in the chemical data especially for Ca, Mg, F, Cl, NO_3 and SO_4.
The interpretation of the changes in SFR and WFC wells is that a mixing of waters occurred from different aquifers normally not in connection. The increase of NO_3 in the MFC well is thought to be caused by mixing of irrigating water.
Both the groundwater changes and the increased seismicity are probably caused by an increase in strain. A compression of the crust by 2μ was measured across the fault. The radon concentration increased with 25%.

5 GASES IN GROUNDWATER AND SOIL

The soil gases are measured by sensors buried in the soil cover close to a well or fracture. Gases dissolved in groundwaters are sampled directly from the water.

5.1. RADON GAS CONCENTRATION AND ISOTOPES

Radon isotopes have been monitored extensively in many earthquake areas since 1966, when observations was made by Ulomov and Mavashev (1966) that the radon content in groundwater showed an anomalous increase before the Tashkent earthquake. Since then radon has been extensively monitored in relation to seismic events with the purpose to predict earthquakes.
Radon is detected from groundwater in wells or springs or in soil gas.

The observed radon anomalies (King 1978, Birchard and Libby 1980, Jiang and Li 1981) indicate that the radon anomalies have a wide range of duration from a few hours to several years depending mainly on the earthquake magnitude and epicentral distance. The radon anomalies may also be caused by other factors as weather changes and ground water pumping.
The physical processes that have caused radon changes due to earthquake is not well understood at present.

5.2.1 Heterogeneity in emanation of gas

Monitoring of radon at two stations along the San Andreas fault, King (1984/85), showed great background variations even at the same station, where measurements where taken at several spots only separated by meters or tens of meters. The average radon level at the same site differed as much as a factor of 5. The lower radon recordings occurred within the fault plane probably due to lower permeability of the clayey filling material within the fault zone.
This difference was not caused by local uranium content in the soil.

5.2.2 Daily variations

Daily variations have been observed by several authors (Ball et al 1983). These variations have mainly been thought to be caused by variations in temperature and

barometric pressure changes. These pressure variations may exert a pumping effect on the soil gas.
Recordings during rainy or cloudy days normally will give a less daily variation. There is a distinct increase of radon emanation after a period of several days of rainfalls.

Recordings at spots at the San Andreas fault (King 1984/85) outside the main fault zone during sunny days clearly showed daily variations. These variations were about +/- 30 % of the average values and usually with a peak in late afternoon , when the barometric pressure was at minimum. Similar variations within the fault zone were small or out of phase.

Barometric changes of longer time periods were not correlated with similar changes in radon changes.

The pumping effect can however not explain daily variations when the correlations are out of phase with variations with other nearby recording stations. King suggests that crustal fluid convection induced by uneven solar insulation may have a strong affect on the radon variation.

In the paper of Klusman (1981) a study was made to investigate the causes of variation in gas emission . The gases investigated were radon, mercury and to some extent helium.The study was made in an aseismic area in Colorado. The result of his work is that measurements indicated considerable influences by meteorological and seasonal parameters on the gas emission. The gases were influenced by their individual physical and chemical characteristics as well as they were site specific.

5.2.3 Sudden radon increase

Impulse radon increases were recorded by King (1984/85) independently of weather conditions (Figure 21 a and b). Such increases suggest to be caused by crustal disturbances, sudden bursts of ground gas along fractures into the atmosphere. Such outbursts may be trigged by crustal deformation during seismic events. King also suggested that degassing may occur when enough pressure have been built up in a reservoir after a gradual accumulation.The mechanism of crustal outgassing is not well understood. Both outgassing processes will increase the radon content with or without earthquakes or creep events.

The briefness of the sudden increase of radon may suggest that they partly were caused by short lived Rn-isotopes thoron and actinon.

A creep along the San Andrea fault of 2.3mm was monitored by King (1984/85). This event did not give any significant radon changes while other seismic events gave impulses. Increasing radon contents were associated with earthquakes magnitudes 3-4 located 20-40 km from the measuring stations.
A 2.6mm creep was recorded on all four stations when scanning time was on hourly intervals. Some sharp pulses were recorded during an hour or less. The creep took place within a day.

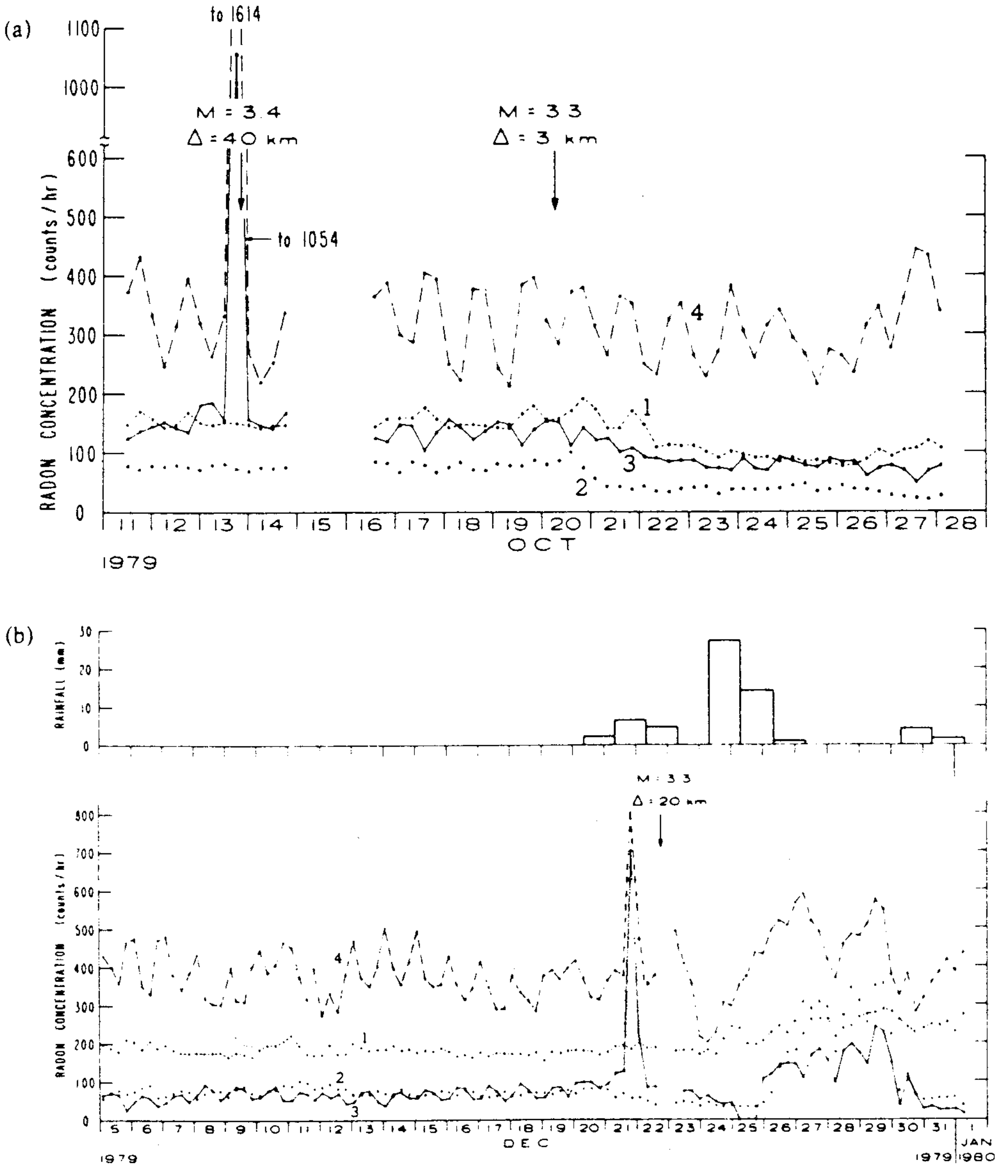
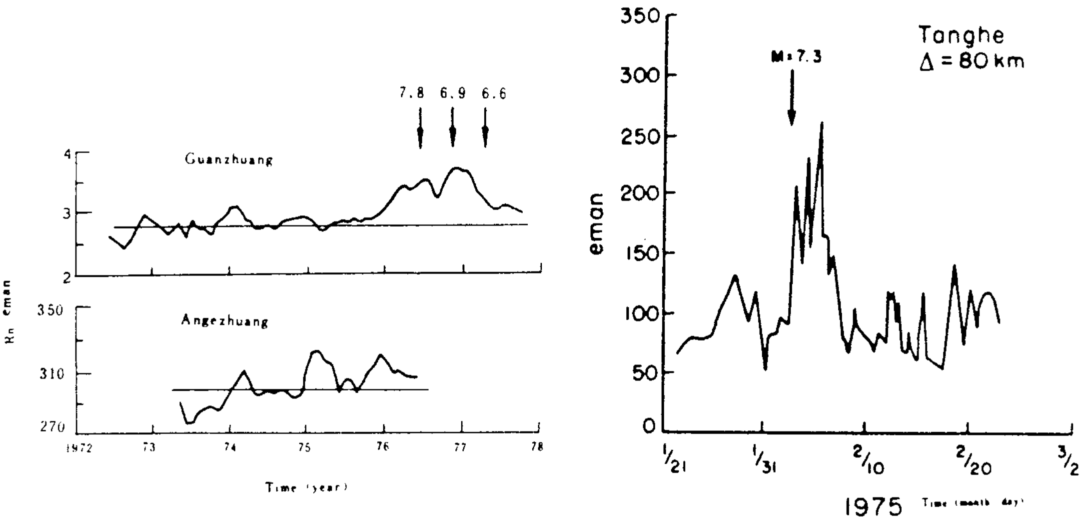


Figure 21. Impulsive radon increases at Melendy Ranch. Data recorded every 6 hr. Solid arrows : earthquake labelled with magnitude and distance.

According to Jiang and Li (1981), Li et al (1984/85) the radon measured in groundwater in China falls into two groups; long term anomalies and short term anomalies. The long term built-up time is a few months to more then a year. In most cases there is an increase trend before the large earthquake. The amplitudes of these anomalies are 10-30%.

Prior to the Tangshan earthquake the long term radon anomalies were observed in 25 of 65 sites within a 200km radius of the epicenter.



a b

Figure 22. a) Characteristic patterns of long term radon anomalies at two wells before the Tangshan earthquake 1976.
b) Peak-like radon anomaly before the M=7.3 Haicheng earthquake 1975.

Short term anomalies appear to be more important for prediction. The amplitude will be in the range 35-140% (Figure 22 a).
Figure 22b shows a typical radon anomaly measured before the Haichen event. At this station the sampling was once a day but the sampling interval was shortened to 30 minutes when there was a rapid increase of radon content. This made it possible to observe the major radon spike which began only 30 minutes before the earthquake.
Sampling of radon in soil gas also gave indication of increasing content of radon before the same earthquake.

5.2.4 Long term monitoring of radon

Thirteen sites have been monitored from 2 to 7 years in southern California for radon (Hammond et al 1981). Besides , concentrations of Na, K, Mg, and Cl were included in the study. The sites were located close to major faults covering an large geographical area. The paper describes four wells. An index has been used in order to illustrate the seismicity in the area and to index the likehood of observing a radon anomaly.

Index $P= A^{\exp(3.4M/R\times R)}$

where

R= separation of monitoring sites and epicentre (km)
A= a normalization factor chozen to 10^{-3}

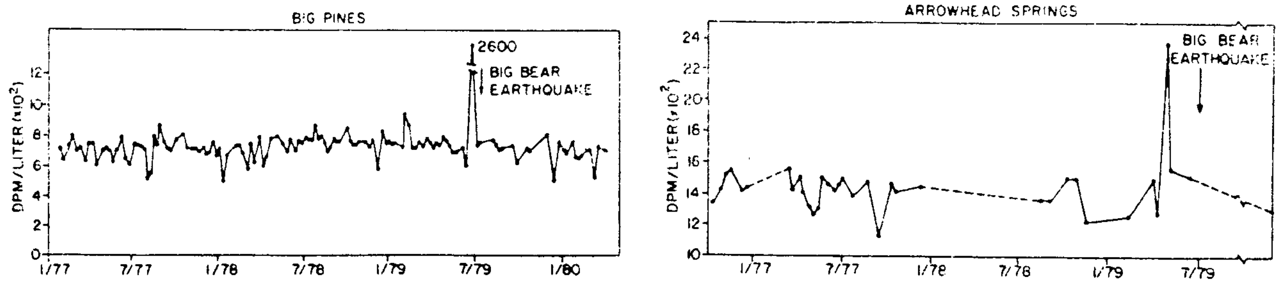
The index was chosen so that it increased with a factor of 30 for each unit of magnitude increase.
The index was calculated for all earthquakes with M>3.5.

At the ARP well the radon concentration showed close relationship to rainfall. The concentration was low during rainy periods and high when it was dry. The ionic components did not indicate any cycling with the rainfalls. The authors suggest that the radon fluctuation was due to changes in ground water flow rate.
Even at the Big Pines site the radon correlated with rainfalls, but here the ionic constituents decreased in concentration with rainfalls. This site was located 70km from the Big Bear earthquake, M=4.9, P=3.5. A small radon anomaly was detected 8 days before the event.
The Seminole Hot spring well showed radon to be uniform. Values ranging from 0.4 to 4 times the average were observed prior to the Malibu earthquake, M=5.0, P=60. The ionic parameters did not show any fluctuations during the period.

Teng et al (1981) and Chung (1984/85) describe correlation of groundwater radon anomalies with earthquakes from southern California. The samples were taken from hot and cold springs, deep artesian wells and irrigation wells. The wells had a depth of more then 100m.
The result of the study is that the sites fall into three types:

1. Meteorologically affected sites
2. Non-responsive sites
3. Sensitive sites

Wells of the first category are affected by rainfall, temperature, pressure and artificial pumping. Wells of category 2 showed that the radon concentration was not affected by the meteorological conditions. The long term monitoring indicated a rather constant mean value.
The interesting wells in category 3 were those which appeared to have radon anomalies associated with a nearby major earthquake event. Figure 23 shows the measuring result from two sites observed during the Big Bear earthquake (M=4.8).



a b

Figure 23. a) Radon graph from the BP well and b) from the AS well
Big Bear earthquake M=4.8

The BP site was located 60km from the epicentre. The peak occurred one day before the event. The radon concentration did return to normal after the seismic event.
Site AS is a hot spring about 35km from the epicentre. A similar peak was observed prior the Big Bear earthquake. This peak is 50% higher then the long term mean.

The peak for these wells were observed within a few weeks prior to the earthquake. Also He showed a similar behaviour as radon (Chung 1984/85) for the Big Bear earthquake.

Radon concentrations in geothermal waters and cold springs were samples and measured in Taiwan from 1980 to 1983 at four sites (Lui et al 1984/85). Seven peak anomalies were observed at three stations. An earthquake of magnitudes > 4.6 occurred 4 to 51 days after the peaks. The epicentral distances were from 14 to 45km , with focal depths less then 10km. The duration of the peak was in the order of one week.

The distribution of seismic events are reported to be skewed into certain directions from the sampling stations. Earthquake occurring in other directions did not give radon anomalies.
Radon concentration in one hot water well was measured both in the water as well as in gas. It was observed that the gas contained higher concentrations.
Radon will be rapidly lost in water when it is exposed to the atmosphere. Similar results are also reported by Chung (1984/85). He found that only 5% of radon was distributed in the liquid phase.

5.2.6 Environmental caused variations in radon

Shapiro et al (1984/85) used four techniques to investigate the non-tectonic environmental factors which can effect radon concentration in water. It was found that for some wells there were several factors as air temperature, rainfall, water level, CO_2 in the water and barometric pressure that correlated with the level of radon. At one site about 60% of the variance in concentration was of non-tectonic causes. Anomalies which appear to have tectonic origin seem to have a sudden onset and slow decay during the initial part of the anomaly. That feature was not identified when the anomaly was caused by environmental effects. According to Shapiro radon from groundwater data must be be treated with caution. It is however possible to recognize environmental causes and changes due to tectonic origin when good baseline data are available.

5.2.7 Correlations with earth tides, strain and stresses

Wollenberg et al (1984/85) found at their study in the Long Valley Caldera in California daily and semi-daily variations of radon in springwater correlated with earth tides. The authors suggest that these variations are responding to small stress changes in the rock of the caldera.
Steele (1984/85), interprets a very strong radon anomaly in the New Madrid Seismic zone in central Mid-continent of USA as due to significant changes in the state of stress or strain. The anomaly was followed by an earthquake (M=4.0) one month later. The detection of radon was made from soil gas during seven years starting 1977.

Steel et al (1982) showed that sudden increases in the range of 5-6 times the base line were related to changes of stresses in the ground. These anomalies were recorded prior to four events, several magnitude with 20-320km distance from epicentres and three events, several magnitudes at epi-distances of 20-90 km.

The following general conclusions are made.

- Larger earthquakes, M=4-5, show soil-radon anomalies with higher amplitude then those before the M=3 events. The radon activity has normally been longer before a larger seismic event.
- The tectonic structure of the fault zones also seems to influence the radon emissions. The strongest anomalies occurred at four sites which were close to fault intersections.
- The occurrence of a regional scale strain events prior to the some of the larger earthquakes are suggested from the following observations

a) Relative large distances between several anomalies and followed by seismic events

b) Widespread and synchronous radon anomalies before one of the largest earthquakes in the region

c) Synchronous seismic pulses at regional distances and at continental seismic distances

5.3. HELIUM CONCENTRATION AND ISOTOPES

Helium gas is a noble gas and has unique characteristics for measurements and interpretations as it is chemically inert, radioactive stable, non-biogenic and highly mobile. Both bulk and isotope measurements have been reported for use of earthquake related investigations.

5.3.1 Helium in gas concentration

Reimer (1981) describes the monitoring of helium concentration in soil gas along the San Andreas fault. The study was made for monitoring long term seasonal variations. The sampling instrument was buried 2 m in the ground in order to avoid meteorlogical effects on the gas concentration.
During the time of monitoring several helium anomalies were observed, which not could be explained by any seasonal or daily meteorological reasons. All these anomalies preceded a moderate earthquake by several weeks. During the monitoring period 8 earthquakes of M>4 occurred and located within 160km of the centre of the monitoring stations. The helium content in soil gas decreased in all stations at least for six of the seismic events. In all cases the helium content recovered to pre-quake levels either shortly before or after the earthquake.

Reimer (1984/85) has observed short time variations of He soil-gas concentration along the San Andreas fault in central California and has tried to correlate this variations with seismic activity. Ten stations were built along a 15km long segment of the fault.
Figure 24 is a plot of the average soil gas concentrations from May 1979 to December 1983. The dots represent earthquake events and shaded areas indicate periods of helium decrease. There has been 25 seismic events excluding aftershocks where M=4 is cut off limit for gas earthquake comparisons and earthquake events.
There are 15 decreases that match the 25 subsequent earthquakes. If several earthquakes clusters are considered one event the 15 helium decreases match 18 seismic events. There were 6 false alarm and 3 earthquakes without preceding decrease.

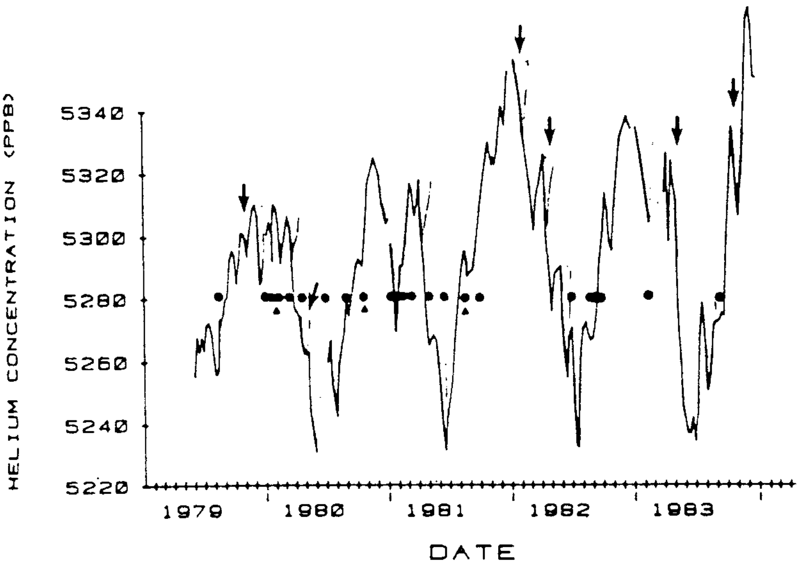


Figure 24. Helium gas concentrations California ; May 1979 to December 1983.
Dots are earthquakes of M>4. Arrows indicate decrease without an earthquake. Triangles indicate earthquake without preceding decrease in helium concentration.

The author has not a satisfactory model to explain the observed helium soil gas decreases. The helium-earthquake correlation is 83% but the number of events are few. Questions regarding magnitude, lead time and epicentral depth remain unanswered as well as the understanding of the mechanism of helium gas changes to geophysical changes in the crust. The correlation between helium gas decreases and earthquakes is reported to be very positive.

5.3.2 Helium isotopes

Very high ratios of $^3He/^4He$ have been measured from 115 wells and hot and mineral springs in Japan in an anomalous area away from volcanic activity (Wakita et al 1987). The area is characterized by seismic swarms. These swarms are however normally associated with areas of volcanic activity.
The ratio is almost as low as atmospheric values, 1.4×10^{-6}, transverse the island arc system, but increases at the volcanic front and remain high at the back arc. The highest value is 9.69×10^{-6}. This high ratio is interpreted to reflect the presence of a magma source in the crust (deep gas system).

The seismic distribution is characterized by a three layer structure

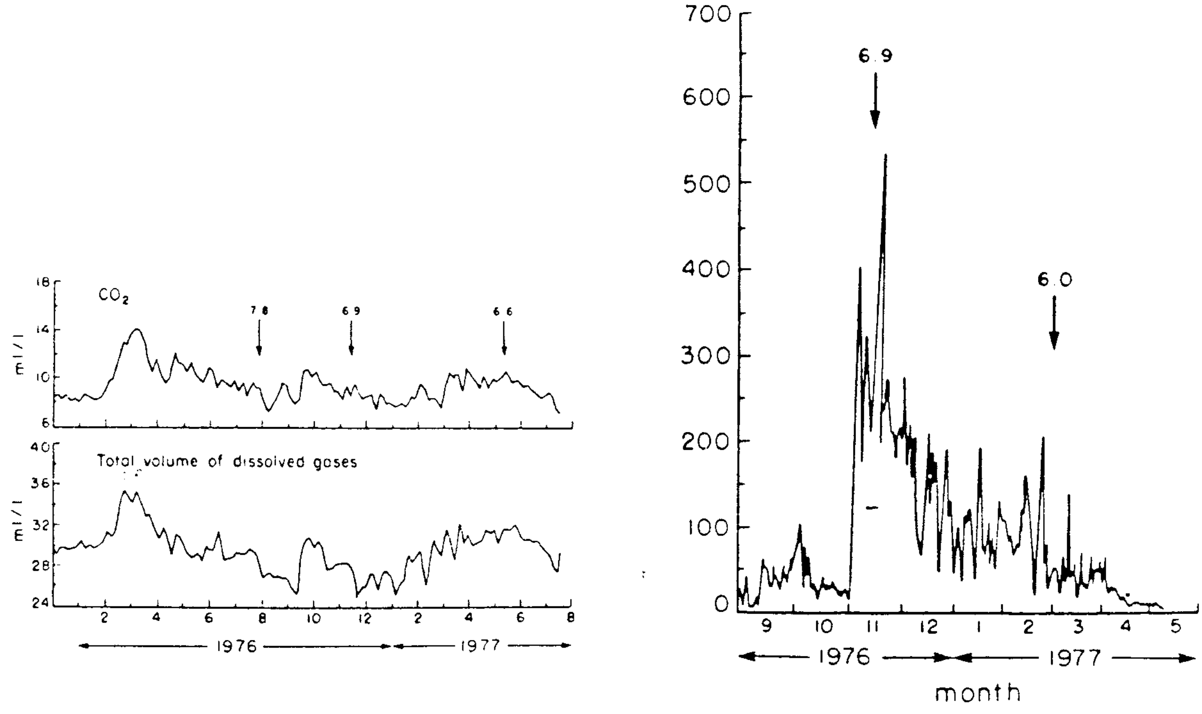
1. Earthquakes in the upper 10 km of the crust
2. Earthquakes associated with descending plate at depths greater then 25km
3. Earthquakes in an intermediate zone.

The focal mechanism in the intermediate zone is normal faulting. Normal faulting indicates extensional tectonics and opening of vertical cracks.
The He-flux along the fault caused by earthquakes is 10^4 times greater then average for the crust. The flow of the groundwater in the fault is significant and the chemistry of the water is different from that of surface water. The water contains chlorine and calcium ions at concentrations thousands of ppm and is super-saturated with carbon dioxide. The ratio of ${}^3He/{}^4He$ was as high as 8.9×10^{-6}.

5.4 GASES OF CO_2, H_2, Ar AND CH_4

The report by Jiang and Li (1981) shows observations of anomalies of the CO_2 and H_2 gases and total dissolved gas measured in China. Changes in CO_2 content and total volume of dissolved gases were observed before the Tangshan earthquake (Figure 25 a).

The gas H_2 is reported to be sensitive for tectonic events. This gas is very light and most mobile and is related to igneous rocks underlying the measuring station in Guanghua.
The well is 1000m deep. It was observed that the H_2 content increased rapidly nine days before the Ninghe earthquake (M=6.9) with a peak anomaly 10 times the ambient level (Figure 25 b)
The anomaly continued for several months.



a

b

Figure 25. a) Anomalies of CO_2 and total dissolved gases observed at the Jin-er prior to the Tangshan earthquake. 23b) Spike like anomaly in H_2 content recorded in water prior to the Ninghe earthquake 1976.

Sugisaki 1984/85 has reported on H_2 gas measurements from a mineral spring at Yuya Spa located close to the Median Tectonic Line, the longest active fault in Japan. Observed concentration of H_2 from active faults associated with historical earthquakes usually get concentrations of several percent, while concentrations from Quaternary faults not associated with earlier seismic activity amounts to most 100ppm Sugisaki (1983).

Sugusaki et al (1980) classified the gases along the faults of central Japan into two types. Gases from fault gouges (type 1) are found to contain high concentrations of H_2 or CO_2 and lack of CH_4. Gases of type 2 occur as bubbles in flowing mineral waters from fault zones. They show high concentrations of He and CH_4 and lack of CO_2.

The H_2 concentration of type 1 varies extremely, while gas from type 2 fluctuates greatly even within a day. The fluctuation is about two orders of magnitude compared to other gases as He, Ar, N_2 and $CH_{4,}$ which are rather stable. The fluctuation of H_2 is not related to meteorological or other near environmental causes. It is thought that H_2 is produced by reaction of pulverised rock with water (Sugisaki et al (1983). The correlation between seismic events and emission of gas is shown in Figure 26.

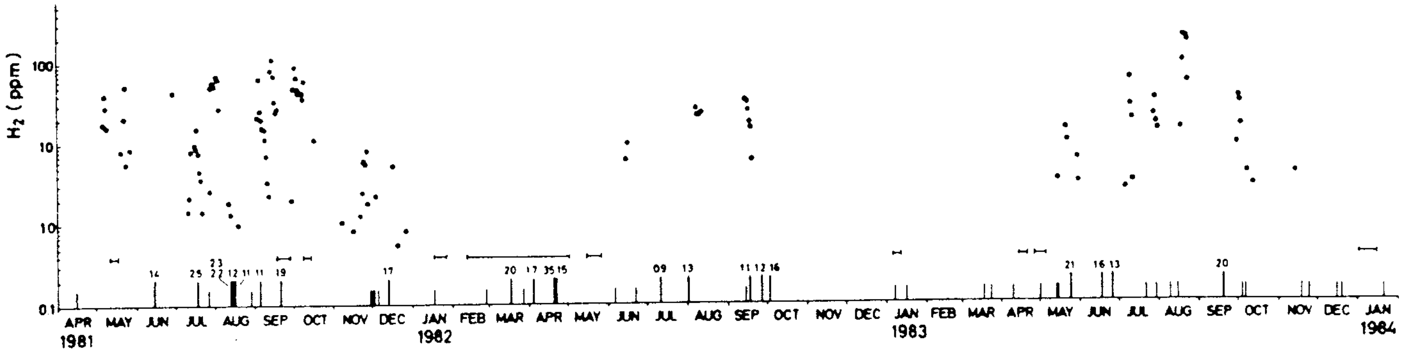


Figure 26. Temporal variation of daily average H_2 concentration. Horizontal lines: data gaps. Vertical lines : occurrence of earthquakes that might have had an effect on the monitoring station.

The gas is probably derived from deep sources near the hypocenters of the seismic swarm. The measured concentration of H_2 shows fluctuations from 0.5ppm to 200ppm during the Ohno earthquake swarm. The magnitude of the swarm ranges from 0.9 to 2.5. The figure shows that higher concentrations are correlated with lager magnitudes. It is proposed that the release of H_2 is proportional to the energy release according to Figure 27. Thus the H_2 gas is thought to be directly produced during the seismic event when the rock starts to break up (Wakita et al 1980). Other gases monitored simultaneously did not change in concentration.

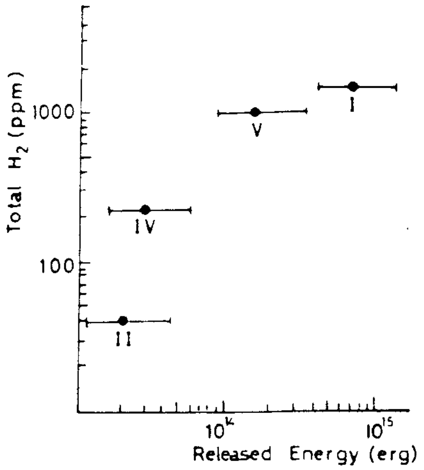


Figure 27. Relation of total concentration of H_2 and sum of energy released by earthquakes in each period in figure 24.

According to experiments by Kita et al (1982),Sugisaki et al (1983) the reaction between rock powder and H_2 is dependent on temperature and type of rock material and the type of atmosphere; more H_2 is produced if more rock powder is used Sugisaki (1984/85).

The time of the increase of the gas anomaly did not correspond to individual seismic events and high concentrations did not correlate with larger events. It is suggested that the cause is due to the migration paths and rates in the ground.

Giardini et al (1976) suggests that H_2 could be used to serve as an indicator of stress changes.

Ware et al (1984/85) has tested H_2 and CH_4 in soil as a tool for mapping of fault systems. Eleven faults where tested in active fault areas in California, Colorado, Greece and Japan. The faults were of normal type, strike-slip faults and thrust faults. From the preliminary result published it is not clear weather the presence of H_2 is correlated uniquely to locations of faults or whether it occurs randomly.

Ware et al (1984/85) suggest the following sources for H_2:

1. Purely mechanical by release of hydrogen from rock that is crushed

2. Chemically, involving rock surfaces exposed, that react with or act as a catalyst for dissociation of ground water

3. Chemical reaction of water with FeO in magmas and rocks

4. Deep source in the mantle that produce hydrogen and methane.

Satake et al (1984/85) have measured H_2 in soil gas weekly at five stations at two active faults near central Main Island, Japan since 1981.

The authors found that in general

1. The H_2 gas varied greatly from 1ppm to 5000ppm in space

2. The H_2 concentration in soil gas was strongly related to the local geology

High concentrations , > 1000ppm, were observed in boreholes located in breccias or fault gouge, in fine-grained rock material, while low concentrations < 100ppm, were measured in holes in hard rock, soil, sand and fault gouge without fine rock fragments.

3. The H_2 content showed large temporal variations

The lateral displacements along the two active faults as described by Satake et al are in the order of 1-3m/1000 year and 0.8-1.5m/1000 years respective. Many small earthquakes, approximately 1000 per year, with magnitudes of 0-3 occur along the faults. The depths are less then 15km.

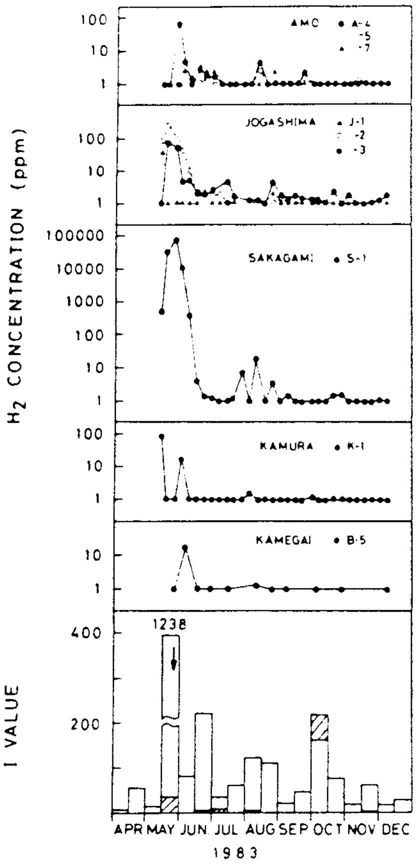


Figure 28. Measurements of H_2concentrations at five different stations. I-value for earthquakes with magnitudes M>4.

Figure 28 shows the measured H_2 concentrations at five stations during 1983. The earthquake frequency and occurrency are expressed as and index I. The largest seismic event had a magnitude of 7.7 and located 485km from Amo station. This event happened in May 1983. High concentrations were recorded at all stations about the same time. The other periods of increasing H_2 seemed also to coincide with peaks in I-values from major seismic events. The recorded H_2 concentrations have not shown any correlation with I-values derived from minor local earthquakes. Here the seismic events (M) were less then 3 and probable not able to fracture sufficient rock material.

Sato et al (1984/85) describe a continuous monitoring of H_2 concentration in soil along the San Andreas and Calaveras faults in central California. Ten monitoring stations were established and monitored from 1980.

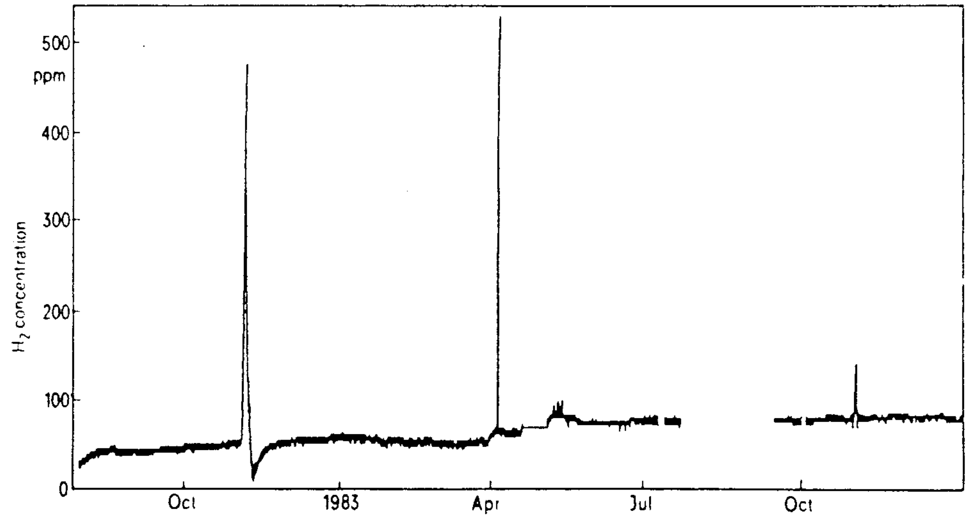


Figure 29. Plot of H_2 data from Cienega Winery from 30 July 1982 to 31 December 1983.

The result from the measuring data indicates that each site had some characteristics probably caused by the local geomorphology and geology. These site characteristics must be considered in the interpretation. Anomalous H_2 emissions were clearly observed in many cases. The best results were from the site Cienega Winery site. Figure 29 shows the results after removal of back ground noise. The daily changes at this site was very small, less then 10ppm. After installation of the sensor there was an gradual increase of concentrations within about 7-10 days.

During the monitoring period 3 distinct peaks were indicated, one in November 1982 which lasted for 2.5 days and a second in April which lasted for 4 days. Much of that peak (60%) may be due to telemetric noise. A third peak was observed in November 1983.

The correlation with earthquakes during the monitoring period is limited to earthquakes within a 50 km radius except for those larger then M=5. A time series of energy released earthquakes, within 50km from the Cienega Winary site, for seismic events larger then M=2, indicted that the three large H_2 anomalies took place during intervals of a very low seismic energy release. The same result was given when the radius was decreased to 2km, 5km and 10km radius from the site. It was not possible to analyse if the H_2 peaks were precursory, post-seismic or unrelated to seismic events.

Kawabe (1984/85) has reported about long term monitoring of subsoil gas associated with groundwater from deep boreholes. These were located in the Matsuyama area in an active seismic belt in southwestern Japan. Seven earthquakes of M>7 have here occurred since 1600.
The test was performed in two wells, which were weekly sampled. The tests started in June 1982 and continued to December 1983. The water from the two wells were from different aquifers as they differed in temperature and flow rate.

The variation of the ratios CH_4/Ar, He/Ar, N_2/Ar and H_2/Ar have been compared with seismic events. During the test period thirteen events occurred with a magnitude variation of 6.8 to 3.5 within an epicentre radius about 80 km. The earthquakes had there focal locations close to the subcrustal high seismic layer.

The ratio CH_4/Ar showed a very large variation up to more then 100%. The ratio was constant higher for one well by a factor of 7 (Figure 30). The Ar concentration was almost constant ranging from 0.9 to 1.0%. Thus the variation is totally due to variation in CH_4. It is thought that the difference in bedrock type causes the level offset in ratio between the boreholes. The variation pattern is equal so the changes is suggested to be of a common origin.
The curves show a gradual change superimposed with sudden changes. These increases correspond rather well with seismic events. Three peaks were correlated with earthquakes of magnitudes M=4.2-4.9. The epicentres were located within 50km. The ratio begun to rise at least a week before the main shock. The variation in ratio showed no evidence of any significant effects from meteorological or tidal phenomena. However, there is a seasonal change in the ratio as it found to be higher in the winter than in the summer. period.

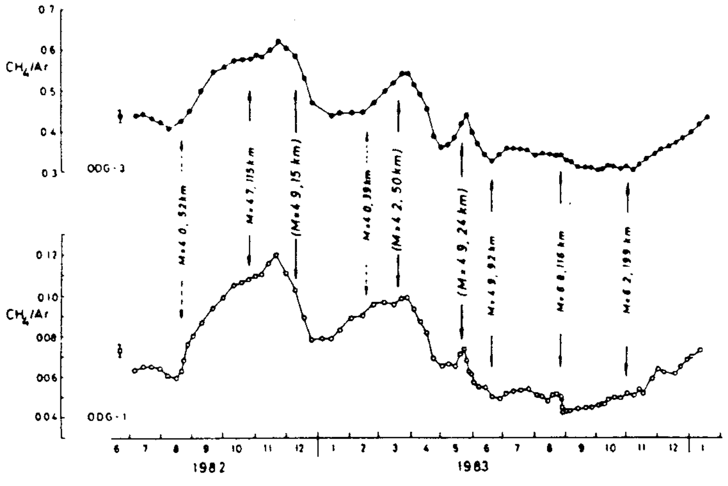


Figure 30. Four-point moving averages of mean gas CH_4/Ar ratio. Earthquake (M) with labelled distance to epicentre.

The ratios He/Ar and N_2/Ar show less variations then the CH_4/Ar ratio. There was small changes that are suggested to be real changes in the gas concentration. The He/Ar ratio in the atmospheric air is 72 and 112, values that indicate that almost all He is derived from gases from radioactive elements in the subsurface rock. The ratio was in one well higher in the winter then in the summer time.

The ratios He/Ar and N_2/Ar were not sensitive ratios in the monitored wells.

Variations of oxygen and hydrogen isotope (D) ratios of natural water are quite regular and fairly well understood (O'Neil and King 1981). The isotopic ratio might change in response to forces prior and subsequent to a seismic event. If dilatation occurs during the faulting process groundwater can invade the dilatant zone and mixing of waters can take place. With respect to the stable-isotope ratios the invading water will be either "heavier" in both in ^{18}O and D, "lighter" in both ^{18}O and D or have approximately the same ratio as the original water.

O'Neil and King 1981 give the possible changes in ^{18}O and D of ground water in seismic active regions in table 2.

Table 2

Process	^{18}O	D
1. Mixing with "heavier" water	Increase	Increase
2. Mixing with "lighter" water	Decrease	Decrease
3. Mixing with "^{18}O-shifted" water	Increase	Constant
4. Exchange between rock and water	Increase	Constant
5. Exchange with oxygen containing gas	Decrease	Constant
6. Exchange with hydrogen containing gas	Constant	Increase

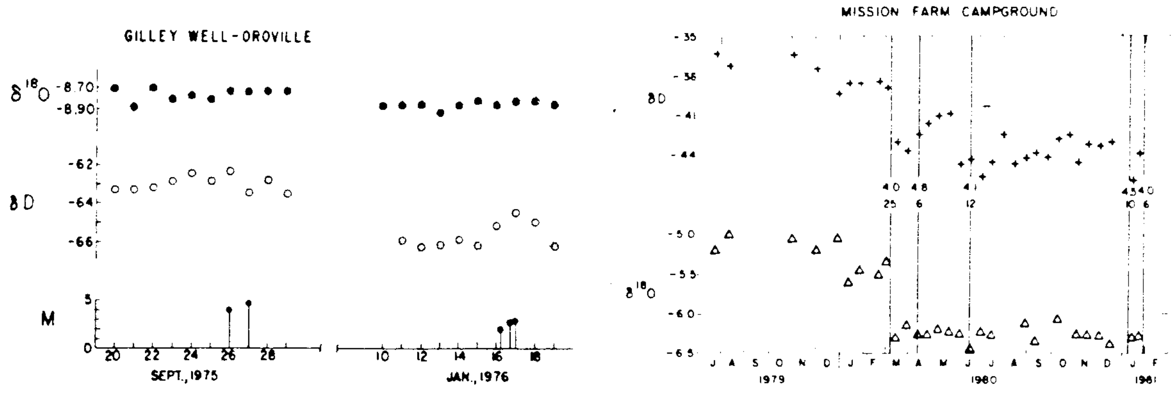
Three factors control the direction and magnitude of changes as a result of exchanges (4-6 in table 2)

a) The rate of exchange.
The nature of the gas is important . Gas like CO_2 exchange fast compared to H_2

b) The fractionation factor
The temperature fractionation factors is well known. For example at low temperature CO_2 is enriched in ^{18}O.

c) Gas/water ratio.
Depending on the magnitude of the fractionation factor the amount of gas has to be enlarged enough to effect a change in the isotopic composition of the water.

The authors give an example of process no 6 from Oroville Dam from north California. An earthquake of M=5.7 occurred in the area. Isotopic analyses were made on groundwater to study the effects from the aftershocks. Figure 31a clearly shows an increase in deuterium shortly after the shocks, ^{18}O remained constant during the period.



a

b

Figure 31. a) Time series of ^{18}O and D of waters and magnitudes of aftershocks of the Oroville earthquake 1975.
b) Time series of ^{18}O and D from MFC well. Vertical line occurrence of earthquake M>4.

It is thought that the increase in deuterium was caused by exchange reactions between water and hydrogen-containing gas.

Similar measurements from the San Andreas fault indicated no correlation between the stable isotopes and seismic events.

Better correlations were attained from three other wells located in San Juan Bautista at wells MFC, SFR and CW. These wells were monitored during 2 years. Several earthquakes with magnitude >4 occurred. In all wells there were a clear cut in both ^{18}O and D-values from about one month prior to the event (Figure 31 b).

As both isotopes decreased in well MFC another ground water must have entered the system. The ^{18}O isotope did not recover even after a year but the D value dropped significantly after about 2 weeks.

The SFR well, sited 3.5km from the MFC well, showed a different picture. The D and ^{18}O values were constant until one month before the earthquake of M=4.8, when both values increased. The data suggest a slight increase in the D content after the event. The ^{18}O recovered after about 2 months.

5.5 RADIUM CONCENTRATIONS AND ISOTOPE5

Radium ^{226} has been monitored in southern California along a major fault (Yy 1981). Radium was measured in order to obtain information about its spatial variation as well as baseline level.
Besides the measurement of radium also radon, temperature and conductivity were measured .

The radium levels varied by a factor of 4 magnitudes. The radon/radium ratio varied from 10 to 10^5. Thus the radon is in excess over radium in groundwaters. The spatial variations are thought to be due to different chemical and physical properties of the rocks. It appeared that radium increased in general with conductivity but not always with temperature.

5.6 URANIUM CONCENTRATIONS AND ISOTOPES

Uranium concentration and $^{234}U/^{238}U$ activity ratios have been measured in 24 deep wells in southern California (Finkel 1981).

Uranium concentrations in groundwater are influenced by the source rock composition, aquifer chemistry and inter-aquifer mixing, by Eh and pH of the water and presence of adsorptive minerals. Especially important is the oxidation state of uranium.

The result of the investigation shows that the uranium concentration varies more then three orders from 0.002ppb to 9.4ppb. There is a regional correlation between site and concentration. At most sites there also is a monthly variation not correlated to water temperature, conductivity or tectonic activity.

The $^{234}U/^{238}U$ activity ratio range from 0.88 to 5.4.

During the time of monitoring 11 earthquakes with $M>4$ occurred. Nine of these had $M<5$, one $M=5$ and one $M=6.6$. The effect of these events as measured with uranium , was only observed in one well located 70km from the epicenter.
The uranium concentration value increased just before the event ($M=6.6$) and returned to normal 3 months later. The activity ratio dropped with a factor of 3, but was normal again after 4 months.

6 CONCLUSIONS

6.1 EARTHQUAKE DAMAGE TO UNDERGROUND CONSTRUCTIONS

The intensity of shaking is commonly much less severe underground then on the surface.

Mines and tunnels near the zone of energy release of a strong earthquake (a few tens of km from the epicentral region), but not intersected by a fault, may suffer damage due to shaking. This damage is more attributed to tunnels located in less competent material and/or superficial (< 100m).

Tunnels and mines away from the epicenter region and away from faults will very likely suffer little or no damage from a strong earthquake. The damage will be negligible for tunnels and mines located in competent rock.

There is no record of a total collapse of a tunnel or mine in rock due to only shaking.

Severe local damage may occur if a fault intersects the mine or tunnel and if there is displacement along the fault during an earthquake. Bedding planes and other discontinuities may also serve as local fault planes for close earthquakes.
The damage includes offset of the fault, destruction of reinforcement, collapse of roof and walls and an increasing /decrease of in-flow of groundwater as joints are opened and interconnected or closed.

The data of damage for superficial underground constructions compared to estimated surface acceleration indicates that minor damage in tunnels is reported for accelerations of 0.2-0.5g. Significant damage is recorded above 0.5g mostly only effecting the portals of the tunnels.

Seismic data are mixed but there seem to be a reduction in amplitude of motion with depth. The ratio of surface to underground seismic wave amplitudes depends on the type of ground. It is greater for soil then for hard rock. Attenuation with depth is in the order of 1.1-1.7 for rock.

Frequency most likely to cause damage to subsurface constructions is much higher (50-100Hz) then frequency causing damage on surface (2-10Hz).

Shafts and wells are not as susceptible to damage as are the surface constructions. However, vertical openings are reported less stable then horizontal openings.
Wells are normally not effected by shaking below a depth of 100m , unless they are not intersected by a fault.

6.2 GROUNDWATER FLOW

There are very spare observations and published data regarding the change in water inflow and in water in-flow rates into tunnels and mines due to earthquake effects.

The data published indicate that there are changes, that inflow amount and rates have increased and mining levels that earlier not were subjected to groundwater inflow suddenly have been flooded. The increase of in-flow is reported to vary from 40-300% in the surveyed examples. There are also examples of a reduction and even cease of the in-flow.

The response of water level changes in wells, ponds,reservoirs etc to seismic events is evident. Numerous observations and measurements clearly show that the water level normally will rise prior to the event, due to pressure increases in the deep reservoirs. The records from the Alaska earthquake, which is the most studied example, show that about 75% of the water level recovered shortly after passage of the seismic waves. The rest of the wells showed a lasting anomaly either with higher or lower level then pre-earthquake.
Most wells will not be destroyed by shaking and it seems that wells deeper then 100m will be much less effected then shallow wells.

The piezometeric levels measured on the aftershocks at the Alaska earthquake showed that the pressure surface was lowered and that the recovery started directly after the seismic event. After 6 months about 30% of the wells had a lower level then pre-earthquake.

There are reports that the water level fluctuations will correlate with strain changes in the crust as correlations are found between level fluctuations and earth tides within in some seismic areas.

Episodic creep has also been identified in recordings of water level changes.

The water level changes show a significant environmental dependency from effect of barometric pressure changes and rainfalls.

6.3 GROUNDWATER CHEMISTRY

It is general agreed that earthquakes are preceded by different types of geochemical anomalies. But there is little agreement of their significance and mechanism to an earthquake. At present these anomalies consist of a diverse group with a few common characteristics which will not allow the estimation of their physical and chemical nature. However, there are several reports clearly indicating an association of an anomaly e.g. changes of chemistry in groundwater and soil gases, with a specific seismic event.

The most used dissolved ion cations are: Na, K, Ca, Mg
The most used major anions are: SO_4, Cl, F, CO_3
The trace elements includes: Hg, Rd, U, F, Li, S,r Ba
The dissolved gases contain: CO_2, H_2S, CH_4, He, Ne, Ar,N_2, H_2, Rn

The dissolved ions indicate anomalies typically when the earthquake magnitude is more then 4. They show anomalies at intra-plate earthquakes in China and USSR and at subduction zones in Japan and at inter-plate earthquakes in USA.
There is no common trend identified of the behaviour as decrease and/or increase prior, under and after a seismic event.

There is no indication of a pattern regarding magnitudes of the earthquake and anomaly amplitude. A random distribution around the epicentre or along the fault system is the most common situation.
Anomalies based on dissolved gases seem to be site specific and dependent on the local geology. Methane and hydrogen sulphides anomalies are found in regions with coal, petroleum and organic strata, while carbon dioxide is more connected to limestone ground.

The concentration of the gas may increase or decrease prior to the seismic event.
The gas anomaly seems to be concentrated close to the epicentral area.

Helium (He) has been used both as a earthquake precursor and as a trace element for mapping faults.
Ratios of gas concentrations of He/Ar and N_2/Ar have indicated a decrease prior the earthquake, but there also are reports of no or very little changes.
It has been argued that the origin of the gas could be traced by using the isotopes. At present no trend in this work is published.

Continuous monitoring of radon (Rn) is now becoming an accepted method for long term monitoring. The first well documented trend comes from the Tashkent earthquake, 1966, with samples from deep groundwater.

Radon anomalies are reported to have short term, intermediate term and long term durations. The concentrations normally increase prior to the seismic event, but decreases are also observed in short term durations.

The occurrence of hydrogen (H_2) anomalies along fault system were recently discovered. The result so far has shown that there is a variable hydrogen enrichment. There is little agreement regarding the timing or amplitude of the anomalies and the associated seismic event.

There is a common difficulty with all investigations of elements in groundwater namely to discriminate between true earthquake and background noise. The environmental factors are very important as they causes large seasonal variations. Barometric changes, rainfalls, artificial pumping are the most important factors.

6.4 SOIL GASES

During the last years several reports include the sampling of gases in soil and air. Radon and hydrogen are so far the most studied species. A few studies have been made on helium.

The reports of radon indicate that there is an increase in concentration prior or coseismic. Some investigators have suggested that radon anomalies will decrease with increasing distance from the epicentre and with decreasing magnitude of the event. Others have found no linear correlation.

Studies of hydrogen in fault gases have shown that the concentration increases about four orders over the fault compared with air. It has also been suggested that there is a correlation between fault age and concentration.

Helium has been reported to decrease prior to seismic events.

Also the soil gas concentrations are dependent on the environmental conditions. It has been found that the soil permeability, frozen soil, wet soil will effect the concentrations. There is no general agreement of the relative importance of the environment.

6.5 RELEVANCE TO REPOSITORY DESIGN

Based on the published damage data on underground constructions the depth of a repository location should be at least 150m below the surface.
Data indicate that only minor damage occurs to openings with moderate cover even at particle velocities exceeding 900mm/sec.

Of great importance is the quality of the rock material. However, there is not enough data to assess the exact influence of rock type.
The facility should be located in competent rock material e.g. the shear wave velocity should be greater then 900m/sec. Normal granite is in the order of 3000-4000 m/sec.

The facility should not be located in the immediate vicinity of today active or potential active faults. It is impractical to attempt to design a cavern to withstand a potential offset at an active fault.

Vertical constructions as wells and shafts are less susceptible to damage then surface facilities.

St John and Zahrah (1987) suggest that peak velocity is used as a design criteria instead of peak acceleration. They also suggest a simple emperical design threshold point of about 200 mm/sec.

Low frequency vibrations are generally more damaging to flexible structures, whereas high frequency vibrations are more likely to effect rigid structures and components.

Long tunnels in section may cause out of phase motions of the tunnel during an earthquake. A diagonal transverse shear wave will develop a compression-dilation wave, which may open existing joints along the tunnel axis.

For the design of the reinforcement system the dynamic amplification may be taken as equal to the ratio of the effective seismic acceleration to gravity.

The effect of an offset on a fault and facilitate post-earthquake repairs should be incorporated in the design. Such typical features are

- excavation of an oversize section through the fault zone and use a flexible support system
- incorporate of a flexible coupling if the tunnel is lined
- flexible joints are also required at interfaces between geological and tectonic boundaries
- the design of portals includes slope stability, soil liquefaction and differential settlement analyses

The hydrogeological network around a repository must be known in detail in order to avoid permeable faults and shear zones intersecting the facility. Seismic activity may cause pressure changes, hydraulic pumping, which could change the water pressures which in turn can modify the chemical compositions of the ground water around the repository. The in situ recordings indicate that these changes may either be temporary or permanent.

There is today sparse knowledge of the long term in situ effects of such changes on the bedrock.

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