Monitoring Reservoir Containment in Thermal EOR

Prepared by M. B. Dusseault, University of Waterloo,
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Monitoring Reservoir Containment in Thermal EOR

Report to the Energy Resources Conservation Board

March 31 2013

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Executive Summary

A limited number of suitable monitoring options exists for caprock and overburden integrity surveillance at an intermediate time scale (1-10 days) or for identifying incipient breakthrough of fluids on a short time scale (< 24 hr) during shallow steam injection processes. At the short time scale, there appears to be no method that guarantees a high probability of detecting an incipient breakthrough event under all conditions. Nevertheless, there are methods that can help in the tracking and analysis of processes at depth, and some of them are amenable to the detection of subsurface activity related to incipient breakthrough.

For "alarm" purposes (< 24 hr), steam chamber pressure and surface deformation measurements are the most suitable methods to help assess if incipient caprock breakthrough is developing. Deformation measurement methods for alarm purposes may include angular measurements using tiltmeters or inclinometers, uplift and lateral movement measurements using Differential Global Positioning System (D-GPS), or surface deformation scans using Light Detection and Ranging (LIDAR), Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR), or other automated ground-based scanning techniques. Close sensor or measurement point spacing is necessary to achieve adequate coverage of the area at risk. For some methods, such as deformation measurements, software advances are needed to provide useful results in a short time frame so the technology can be used for alarm purposes. Updated analyses every 1 – 6 hours are required for alarm purposes to allow comparison of results and evaluate changes over time.

A deformation monitoring array will permit mathematical inversion of data so that regular images of volume change and shear distortion at depth can be generated, preferably on a short time scale. In addition to deformation, other monitoring data (chamber pressure, ΔT, 3-D resistivity changes…) can be collected and used synergistically to aid interpretation for safety, process control optimization, and to aid model development and calibration. Deformation measurements are not intended to fully replace other types of monitoring systems (groundwater quality monitoring, microseismic monitoring, p&T measurements…). In principle, although challenges remain, methods such as microseismic and electrical resistivity monitoring could provide highly useful data, and could even generate useful information for alarm purposes once the methods are better understood and more widely used.

For intermediate-time scales (1-10 days), several methods can give a picture of deep processes; if changes are gradual, comparison of sequential process images (time-lapse imagery) can allow the changes to be spatiotemporally quantified and tracked. Methods that have promise include repeated 3-D seismic surveys with permanent geophone locations, and more detailed mathematical analysis of deformation data to resolve shear and volume changes at depth. Microseismic monitoring and various electrical techniques should be further investigated with a view to achieving general use as methods to study changes with a view to integrity assurance through better understanding.

The following table summarizes key information for various monitoring methods, in particular the suitability of using the method to provide an alarm of an impending caprock breach.

Summary of Methods for Monitoring Reservoir Containment

Method	Comments	Relative Costs*
Deformation Methods**		
Level survey – Δz at many monuments	• Unsuitable for alarm use • Precisions of 1 mm over 100 m, very straightforward technology • Realistically, repeated surveys every 3 to 8 weeks can be used to track processes, measuring relative changes between two surveys • Unsuitable for short term deviation detection under any scenario	Medium, 2-days needed, plus analysis, usually taking at least several days total
Aerial photos	• Unsuitable for alarm use in any realistic scenario • Short turn-around of the photo analysis is not a realistic option • Measures relative deformation changes between two surveys • It is impossible to determine any short-term deviation from the interval average if no other data sources are available. • Precisions several mm over 100 m, straightforward technology	Medium to high, and analysis is lengthy
Satellite InSAR	• Unsuitable for alarm use or even intermediate time scale use in most scenarios because of large time intervals between images • Measures relative deformation changes between two surveys. • Impossible to determine any short-term deviation from the interval average if there are no other data sources available. • Images usually 4-12 weeks apart, but more satellites becoming available in the future means the availability of more frequent images	Medium to high depending on frequency of images
Borehole or surface linear extensometers	• Likely not suitable for alarm use in general, because many wells per km^2 needed to have a high probability of detecting an event • However, extensometers are easy to use as alarm devices because of a straightforward output signal (a direct measure of deformation) • Sensor stability over many years remains to be explored • Immediate response in some systems, others use readout devices. • Not used by the oil industry; little relevant experience exists • Recent fiber-optics gauges grouted into suitable boreholes (without casing) should be evaluated for deep deformation measurements	High cost if many sites and deeper boreholes are used, well-understood technology in the mining industry
Tiltmeter arrays (and other digital inclinometers)	• Immediate response, but generating a surface deformation image in “real-time” plus quick analysis provision to the client remain issues • As better software is developed, the value of tilt measurements as a potential short-term monitoring approach will increase substantially	High cost, many expensive sites needed
Ground-based InSAR – GB-InSAR	• May be suitable for alarm use if a ground-based system is used, giving radar image series over short time intervals • Requires vertical tower placement to get adequate Δz resolution repeatedly over short time intervals in a fully ground-based system	Medium-low for Δx, Δy measurements, medium to include Δz
Light-based ranging – LIDAR	• With automatic sampling systems, ground based (i.e. not airborne), could be used as an alarm system for measuring surface deformation • As for GB-InSAR, it requires an appreciable height component to achieve good Δz resolution but gives excellent Δx, Δy resolution (millimetric) with a flat array of sensors and emitters	Medium-low for Δx, Δy measurements, medium to include Δz

Method	Comments	Relative Costs*
Differential Global Positioning – D-GPS	• Provides continuously updated map of surface heave – Δz(X,Y) – in quasi-real time using satellite technology (global positioning system) • Information content for critical areas can easily be increased by adding more antennae. • Recent developments mean that good quality information about Δx and Δy for the sensor sites can be obtained as well as vertical resolution • D-GPS is suitable for short-term deformation measurements, as there are always enough satellites visible to give precise positioning • Software is needed for rapid mathematical inversion of D-GPS to give a picture of reservoir deformation in a short time is lacking	Medium-low for Δz, medium for Δx,Δy data
Geophysical Methods		
Borehole logging approaches	• Not considered as suitable for short term alarm methods because of deployment time of measurement equipment (logging equipment) • Cannot detect changes in the acoustic, electrical, magnetic resonance response and other properties strata except very locally, directly behind the casing, thus no chance of caprock integrity assessments • Radioactive bullets (ΔL) and other cased-hole log methods may be suitable to resolve strains over a sampling distance • Vertical monitoring wells with multiple sensors (Δz, T, p) are considered highly valuable to help calibrate models that may be used to interpret the deformation fields, the flow fields, etc.	High for many repeated logging assessments because of deployment costs and the large number of boreholes needed
3-D, 4-D (time-lapse) seismics	• It is not likely that these methods will evolve to the state where they become suitable for alarm purposes; at present, the “turn-around” time is well over 10 days for a fully analyzed image, and these methods cannot be deployed quickly to evaluate anomaly evolution • Inadequate resolution for caprock integrity issues because the size of the acoustic anomalies (e.g. velocity contrasts) is likely small in most cases (e.g. the thickness of a shearing zone may be < 1 m)	High if short Δt needed between surveys such as every 2 weeks
MS - Micro-seismic monitoring	• MS monitoring is not a technology suitable for short-term surveillance of processes for purposes of alarms at this time because a strong relationship between MS activity and a caprock or overburden breaching processes is not evident • Much work has to be done before microseismic methods can be used with confidence as a means of continuous evaluation of the region in and around thermal processes. • Understanding what MS is telling us still remains a challenge in the short term and even the longer term (evolution of MS response over days or weeks), but the method holds promise and should be developed	Medium-high, depending on the number of triaxial geophones and accelerometers installed in boreholes (surface sensors are far less desirable)
Electrical methods	• Changes in fluids composition and rock temperature cause large changes in rock conductivity, and these are highly detectable in practice, but rarely used in the oil industry • Emerging experimental methods, not proven in practice, but it deserves attention and may prove of considerable value in conjunction with other methods to reduce the chances of mis-interpretation of anomalous responses • Recent developments in electrical resistivity tomography in a short time interval should be field tests with permanent electrode arrays	Medium-low

Method	Comments	Relative Costs*
Gravimetric arrays	• Limited experience in practice, largely unknown as a method, likely impractical	High, many expensive sites (protected gravimeters) needed

Method	Comments	Relative Costs*
Other Monitoring Methods		
Temperature in caprock and overlying beds	• Temperature sensors are not capable of detecting changes remotely, they must be in direct contact with the site where ΔT is taking place • Because of geological complexity and the slow movement of heat, to reliably detect a breakthrough in the caprock and the overburden from ΔT measurements would require a huge number of sensors, making this approach impractical • Of value in the steam chamber region to calibrate models and relate ΔT zones to other system changes (e.g. seismic or electrical changes)	Medium-low (many wellbores required but readout is trivial)
Pressure in monitor wells <u>outside steam chamber</u> in the overburden	• Because the well must be in contact with the ΔP location for successful detection, and because there is no guarantee of hydraulic pressure communication between a breakthrough event and a monitor well, the utility of ΔP measurements remains weak in practice for caprock and overburden monitoring • In real cases of geological stratification, vertical and lateral strata heterogeneity may make good interpretation impossible • Risk management using pressure measurements in the overburden is not considered a viable approach	Medium-high (many geotechnical style wellbores required, but read-out can be automated)
Pressure <u>in the heated volume</u> (chamber) *in situ*	• These are vital measurements for thermal process management, and any sudden unexpected changes may be diagnostic of breakthrough events which are almost certainly accompanied by a sudden pressure-rate response in the injection wells and steam chamber • Of great value in steam chamber control and management, as well as useful in model calibration and to aid interpretation of other data sets by relating responses to pressure changes in the heated zone • Pressure records are needed for regulatory purposes to demonstrate compliance with maximum operating pressure requirements if these have been stipulated for a particular project	Medium-low: a T-resistant bubble tube or optical fiber measure needed. Most SAGD wells have heel ΔP sensors, and they are easy to install in dedicated ΔP monitor wells
Volume rates	• Metering of materials going in and coming out is a valuable management tool, particularly when combined with p, T, Δz, and other measures to maintain a clear assessment of volume balances at the overall process scale • In particular, short-term changes in injection rates when maintained at constant P (or vice-versa) are considered to be a crucial indicator of general chamber response. Realistically, integrated pressure-rate analysis is the only way to tell in the short term if a chamber has developed a leak	Low, but threshold values, reliability, and other issues arise during the 5-10 year evolution of a steam chamber or well array

Groundwater well monitoring	• Standard groundwater monitoring methods involve water level monitoring in wells, water sampling and analysis, gas sampling and analysis, and so on. • Water levels and other changes in groundwater wells, even if they can be detected within a few seconds, are difficult to link to any processes involved in caprock integrity deterioration, so the data are no more valuable in the overburden than pressure data (above) • Groundwater well monitoring has no role to play in early detection of caprock integrity impairment	Low, and levels can be monitored electrically in all wells

* There are few low-cost alternatives because of the number of sensor sites required to achieve sufficient areal coverage, or because of the nature of various methods which may require extensive analysis (e.g. 3-D seismic inversion or deformation field inversion). Costs are relative only; low costs generally involve simple monitoring of an array of economical sensors with direct GUI (Graphical User Interface) display; medium costs involve an array of more expensive sensors (GPS, tilt…) or a system that has to be manually surveyed, but the analysis is easy; high costs generally refer to methods that require dense arrays of sensors that are each relatively costly, or methods that require extensive analysis or other personnel time (tilt, repeated 3-D seismic methods, many short time interval satellite InSAR analyses).

**A number of methods require extensive analysis before the data can be presented in a useful form to the engineering team that must make decisions. For example, the surface deformation data from LIDAR, D-GPS, and GB-InSAR can be presented as a pseudo-3D surface map, likely every hour or so (the time interval is a flexible factor, and images of deformations that took place between different times give a quantitative picture of the rate of deformation). Comparison of such surface deformation maps in a time-sequence gives valuable decision-supporting data to the engineering team. However, to relate this deformation quantitatively to subsurface processes that have taken place in the reservoir at depth requires a mathematical process of analysis called “inversion”. In "inverting" data to give information about the processes at the reservoir level, short turn-around times (less than 1-4 hours for example) seem not to be commercially available at present, but this is a limitation that will disappear quickly as the demand for deformation services increases. Hence, mapping surface deformation at different times (e.g. every 1 to 6 hours) is a highly useful decision-supporting tool, but the value will be greatly enhanced when more rapid analysis provides 3-D images of the subsurface deformation.

1 Monitoring Purpose and Time Scales

1.1 Reasons for Monitoring

Monitoring of *in situ* thermal and non-thermal oil production processes takes place for various social and technical reasons, among which the major ones are defined here, along with examples. The focus in this report on monitoring is on thermal viscous oil recovery processes involving steam injection, and particularly shallow[1] SAGD (**S**team-**A**ssisted **G**ravity **D**rainage) processes. The observations and comments in this section may also be considered appropriate for a variety of steam injection processes such as steam flood, steam drive, or cyclic steam injection. Furthermore, these injection processes may be implemented through vertical, inclined or horizontal wells.

- **REASON 1**: To advance understanding of the physical processes taking place.
  - Early SAGD pilot projects such as the Underground Test Facility (UTF) northwest of Fort McMurray were carefully monitored to learn about the stability of the process and the sharpness of the thermal front, verifying hypotheses developed from laboratory physical simulations
  - New approaches such as air injection methods, cyclic steam/solvent injection, and new well configurations are carefully monitored to gain understanding of the physics and chemistry of complex *in situ* processes to aid commercialization decisions
- **REASON 2**: To verify and calibrate conceptual, empirical or mathematical models so that predictions can be made and future projects more rationally planned.
  - Before shear dilation was recognized as an important physical process in thermal methods, the increase in permeability was (and largely still is) handled empirically by calibrating models to real cases, developing pseudo-relationships to achieve history matching, then using these "calibrated" models to make heuristic predictions
  - Just as some flow rate data, perhaps combined with pressure data, are required to calibrate reservoir flow models, deformation measurements are needed to calibrate stress-strain models
- **REASON 3**: To optimize a process over time, using the monitoring data as metrics of performance to guide control values.
  - Steam injection rates and steam-oil ratios are monitored during production to optimize a control function based on oil production rates and thermal energy expenditure (these functions change with time as the value of oil and the cost of heat vary)

[1] "shallow" is a relative term that defies rigid definition, especially for different technologies operated at different pressures. It is best to avoid specifying a value to define "shallow" without the full context of the operational plans. As an example, for cyclic steam injection the minimum depth should be higher than for low-pressure SAGD, therefore "shallow" would mean different depths in these different technology contexts.

- Different combinations of condensable vapors (aliphatic hydrocarbons) and steam are injected during a typical Solvent-Assisted-SAGD process, and data are collected to optimize the steam/HC ratio

- **REASON 4**: To assure health, safety and environmental security (HSE).
  - Air quality (particulates, SOx, NOx…), pressure variations in steam lines (perhaps indicating leaks), water chemistry, and other site and process metrics are collected regularly or continuously to achieve mandated and corporate HSE targets
  - Monitoring data are used for alarms related to unacceptable conditions, such as H_2S gas concentrations, CO concentrations, or sudden high temperatures related to steam leaks

- **REASON 5**: To satisfy regulatory policy or to meet specific conditions laid down by the owners of the resource (e.g. as represented by government agencies in Alberta and Saskatchewan).
  - Water, oil and gas injection and production rates are collected and reported monthly to the ERCB in Alberta.

Monitoring of thermal processes can be undertaken to satisfy any or all of the reasons above, but specifically, the issue of caprock integrity above shallow thermal projects involving steam injection is the context of this report. There are two dominant questions that have guided the report content:

a. Are there techniques that can give an alarm (minutes to hours in advance) of an impending breakthrough event?

b. Are there techniques that can track a shallow steam injection process, generally a SAGD or a CSS (**C**yclic **S**team **S**timulation) process in the cases of Canadian viscous oil recovery projects, reliably enough over time to permit the study of the evolution of the caprock integrity so that an assessment of the probability of a future breakthrough can be made?

1.2 Defining an "Alarm"

Each reason for monitoring has its own rational and guiding principles. Monitoring may be required by law in order to protect persons and property, or it may be installed by a company in order to improve the management of the process. Each monitoring method will provide a specific measurement such as a temperature, a length, a pressure, a voltage, a volume change, and so on, but more usually an array of measurements is provided, such as pressure or temperature data along the exterior of a cased monitoring well. Some forms of data need to be collected (or are possible to collect) only at long intervals, perhaps over several months, such as changes in seismic attributes; some data are best collected in "**real time**"[2], such as changes in pressure or flow rate. Some data are collected continuously and stored in great detail, such as temperature or pressure data from electronic sensors, whereas other

[2] "real time" may be interpreted in different ways, from seconds to perhaps as much as an hour, depending on the characteristic time of the process. Here, "real time" generally means "within a few minutes", so that the data show up on a computer monitor soon after they have been recorded, perhaps after a short period of analysis.

data are collected only episodically, such as satellite-based InSAR survey deformation data or 3D seismic imaging data.

The nature of the data and the goals of analysis guide its use as well. Any genuine "alarm" use of data must be based on information that is changing in a relatively short time frame. If the process being monitored is characterized by gradually changing or steady values of pressure or ground movement, then data that represents an "alarm" must be characteristic of a short-term process superimposed on the longer term changes. In the extreme case, such as for toxic gas level monitoring (CO, H_2S), there may be a low but constant background concentration (or a detection level in the equipment), and an "alarm" consists of a deviation from that level to exceed a **threshold value.** In the case of a toxic gas or an escape of steam, the time lag between a measurement that exceeds the threshold value and the sounding of an alarm must be only seconds.

In many cases, it is not the absolute value of the metric that dictates the need for an alarm; it is the rate-of-change that will serve as the trigger. For example, in the use of ground deformation measurements as a potential alarm for a caprock breakthrough, slow steady changes in surface uplift are not a reason for an alarm because those accompany any thermal steam injection process; rather, it is a sudden departure from a "typical" or "acceptable" or "characteristic" rate-of-change that has been determined for the process. In such cases, base-line monitoring information is important to choose a suitable "typical" behavior pattern from which a deviation can be quantitatively defined; this base-line is almost always determined by the early life of the monitoring array itself.

In many cases it is necessary to define a **characteristic time** of the process in order to decide on an acceptable time frame for setting an alarm. In cases of extremely slow movements, such as glacier velocity, the time scale of an alarm that a glacier is accelerating or decelerating anomalously is on the order of months to several years. If the characteristic time of the process is unknown or ill-defined, as in the case of shear breaching or hydraulic fracture breaching of a thermal well array, then a cautionary principle is to use a short time scale for the measurements to be used for purposes of an "alarm" until the characteristic time is well-calibrated to processes in the field so that the **characteristic rate-of-change** is well defined.

To summarize, the development of a monitoring system that is capable of serving as an alarm for a process such as a caprock breakthrough must be based on the physics of the process, experience, site-specific history (base-line or calibration), and a clear definition of the purpose for an alarm and the response to it. Factors such as the nature of the expected event (magnitude, distribution, location…), its characteristic time, its inherent detectability within a noisy dynamic environment, suitable threshold values for alarm purposes, and even response protocols to a positive alarm must be analyzed before an alarm system is designed, installed and used. Addressing these issues carefully is not a trivial task, but it is necessary to give assurance that the system will be functional and cost-effective.

1.3 Report Scope

This report addresses various characteristics of data collection, with a view to identifying data types and analyses that could "warn" of a possible or probable future caprock breaching event so that mitigating or preventative actions can be taken. If the time available after a warning is not adequate for mitigating or preventative action, it may still be adequate for personnel safety purposes. In the case of a caprock breakthrough event, a breakthrough may have been unavoidable, but if a breakthrough is detected at an early stage, an alarm can reduce risk to personnel and perhaps restrict damage to the process.

If more time is available during a process, or if the measurements are only collected episodically (monthly or even annually), it is feasible to carry out more detailed analysis of the measurements and to take advantage of different types of information so that the steam injection process can be studied as it evolves over time and interacts with the overlying fine-grained strata that form regional low-permeability seals and are considered as caprocks guarding against porous medium flow. Thus, data can be used for different ends, depending on how soon it is available, what it measures, how much and how fast it can be analyzed, and the reliability of the measurement for the purpose intended.

Many methods are not described in detail in this report because they remain poorly developed for thermal process monitoring (electrical methods in general, although in the writer's opinion they hold great promise) or are likely to be impractical (gravimetric arrays). Nevertheless, there are many measurement methods that may not be amenable to an alarm system and cannot be used to give short- or intermediate-term interpretations, such as 4-D (time-lapse) seismic or satellite InSAR methods, but these have profound value in helping to understand the process in general, as well as the degree of heterogeneity and scale of changes that are occurring. Then, this information guides the interpretation of short-term variations in other metrics such as sudden changes in pressure or ground tilt.

Technical developments are continuous and will change the value of a method for shallow thermal processes, or allow it to be combined synergistically with other methods. For example, electrical resistivity methods using a fixed electrode array provide a means to do tomographic reconstruction of subsurface electrical impedance structure as it changes over time. At the present time, the measurement methods and analysis tools for electrical impedance tomography are poorly developed and thus take too much time, but in principle they could be improved greatly. Once 3-D electrical impedance maps become available on a routine basis, they can be used synergistically with the 3-D volume change map that can be reconstructed from deformation methods, or could be used as an independent measure to help interpret the reasons for changes in the surface tilt field.

Finally, there are some methods discussed briefly in this report that are unlikely to give easily interpretable information at their current state of technical development, such as microseismic (MS) monitoring, but which are promising for further development. Rapid development of MS methods in the last few years has been driven by mining engineering and hydraulic fracturing technologies, but the specific value of MS monitoring for steam injection operations remains ill-defined. It is widely thought that the method has promise, but it is not clear at the present time if further developments could make MS methods suitable for caprock integrity monitoring.

2 Monitoring Issues: Scale, Errors, Types

2.1 Relevant Time Scales

There are two time-scales of monitoring that must be considered in the assessment of whether a caprock breaching event is likely to occur:

a. Short-term monitoring system responses that are strongly anomalous and take place on the order of minutes to perhaps several hours can, if detected and appropriately interpreted, be used as “alarms” indicating an incipient breakthrough or breaching of a caprock seal.
    i. Among parameters that might have applications in this time scale are ground tilt or other short-response deformation measurements, temperature and pressure.
    ii. However, there are serious shortcomings with the use of T&P measurements in the overburden, and this will be discussed at length later in the report.
b. Intermediate-term monitoring systems can provide “snapshots” or “pictures” of some characteristic of the process at depth; these can be examined serially to assess evolution and departures from expected behavior.
    i. Significant departures from expectations based on previous history will trigger more detailed analysis, more frequent sampling, or a modification of the process itself (e.g.: reduction of steam injection rate, changes in steam/solvent ratio, etc.).
    ii. Intermediate-term time scales are not viewed as suitable for purposes of “alarms” that can trigger an immediate response.
    iii. Among methods which have application to the intermediate time scale are microseismic monitoring, electrical impedance tomography, and a number of different ground deformation monitoring approaches such as airborne LIDAR, which could be used episodically every 5 to 10 days if necessary.

Long-term monitoring systems are also useful to maintain scientific and engineering understanding of the changes in a process zone, but are impractical or currently too expensive to be used to track changes over a time scale less that 10 days. Such long-term methods include, for example, 4-D seismic methods, borehole geophysical logging (assuming many boreholes to be logged), leveling survey, satellite InSAR methods, aerial photogrammetry, and other longer-term episodic methods.

For this report, several time-scale definitions are laid-out. The choice of interval for these definitions is somewhat arbitrary, but based on an understanding of the various technologies available.

a. A monitoring method that can give updated information on a time scale that allows decision-making in less than 24 hours from the beginning of the anomalous behavior is called “short-term”.

b. An “intermediate-term” monitoring method refers to provision of updated data (or imagery, or interpreted data…) on a time scale longer than 24 hours, but less than 10 days.

c. A "long-term" method is one that gives updates on some parameter (e.g. seismic attributes distribution in the subsurface, surface deformations using satellite InSAR methods…) at time intervals greater than 10 days.

It is assumed that data collected at time scales greater than 10 days will not be of significant use in identifying caprock breaching soon enough or with enough certainty to allow corrective responses. Thus, periodic provision of certain types of data at time intervals greater than 10 days are deemed to have marginal value for this purpose, although they remain of great value in understanding the scientific and engineering nature of the processes and optimizing operational practices in general

2.1.1 Short-Term Alarm Time Scale

Measures such as pressure, temperature, changes in the chemistry (e.g. salinity or acidity) or composition (oil-water-gas fractions, gas compositions) of produced fluids, injection rates, and so on, can be collected continuously using direct measurements in real time. The information stream from such sensors is often referred to as time series data, and time series data can be metered and analyzed in real-time for sudden changes. However, because a large number of measurement points, closely spaced, is required to give a high confidence of being able to successfully identify the beginning of a caprock breakthrough event, it is not practical to rely on a dense array of these types of measures within the caprock and overburden for alarm purposes. Changes can be taking place that are not picked up by the sensor array, even if it is densely distributed. For example, a hydraulic fracture propagating through shale may give no short-term T or P response at sensor sites that are just a meter away. Even if changes are detected, it is uncertain how large and how widespread a change is needed to give a high probability of success in identifying an incipient breaching event.

The processes involved in caprock integrity impairment or loss (breakthrough) as the result of hydraulic fracturing, shear breaching, or some combination of mechanisms, are accompanied by significant deformations at depth (volume changes, shear distortions). A volume change at depth – ΔV – associated with steam processes and breakthrough will always be positive (an increase in volume); therefore it will be associated with a surface uplift. If shearing along a planar surface is taking place at depth – ΔS – the surface displacement field generated will be mainly positive (uplift), but will show geometric features characteristic of shearing (discussed later).

Because of the elastic behavior of the overburden, these ΔV and ΔS deformations at depth give rise to a surface (X,Y) and subsurface (X,Y,Z) deformation field that includes vertical heave – $\Delta z(X,Y,Z)$ – and lateral deformations – $\Delta x(X,Y,Z)$, $\Delta y(X,Y,Z)$. The physical nature of the transmission of these distortions at depth to the sampling point at the surface (X.Y) or in a wellbore (X,Y,Z) is reasonably well understood and is amenable to mathematical analysis. In principle, therefore, if the deformation field can be sampled with sufficient precision and at enough points spread over an appropriate area, it is possible to reconstruct a reasonable image (3D map) of the magnitude and location of these distortions at depth.

Figure 1A conceptually shows what happens when surface deformation measurements ($\Delta z(X,Y)$, $\Delta x(X,Y)$, $\Delta y(X,Y)$) are analyzed through some mathematical model based on the transmission of strains through the overburden. Because it is generally impractical to measure shear distortion (ΔS) or volume change

(ΔV) at depth directly, it is necessary to estimate these mathematically by calculating the most probable distribution of volume changes and shear distortions that gave rise to the surface deformation changes. Currently, this type of calculation cannot be undertaken in a short time period (less than one hour), but improvements in tilt and deformation analysis are being made. It appears that there are no intractable theoretical or computational barriers that exist for development of rapid calculation methods; therefore in the future it is reasonable to assume that rapid, appropriate software will be developed to do this.

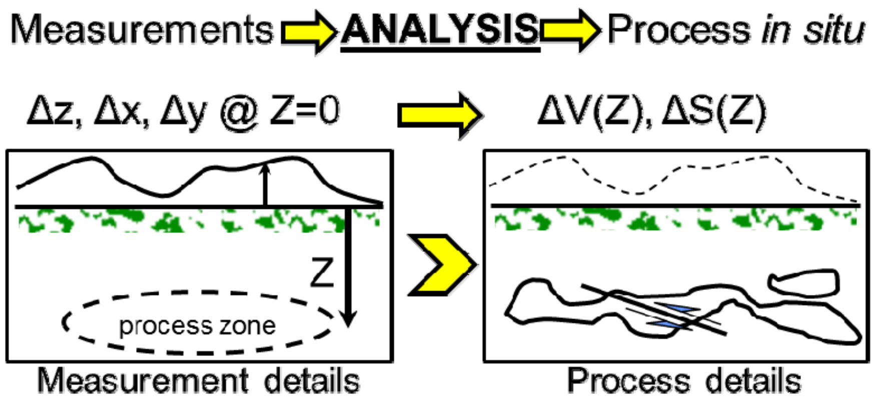

Figure 1A: Measurements, properly analyzed, can help track process evolution.

Δx, Δy, Δz = displacement measurements at the surface

ΔV(Z), ΔS(Z) = volume changes and shear displacement at depth

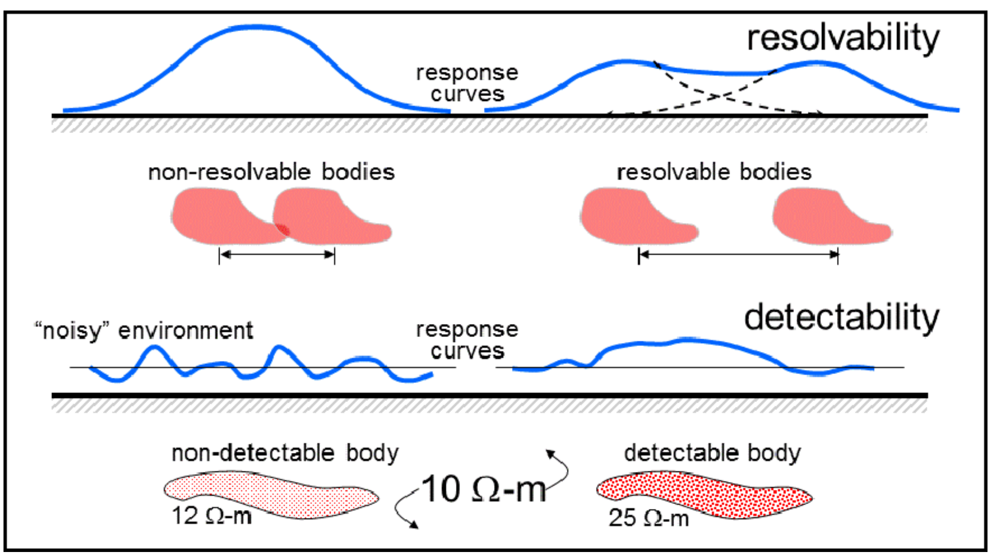

Figure 1B: Monitoring anomalies requires addressing many issues including resolvability and detectability in conditions of signal noise and limited numbers of data points. For example, a 12 ohm-m anomaly in a 10 ohm-m background will not be detectable, but a 25 ohm-m anomaly is highly detectable (providing it is of sufficient volume as well)

Figure 1B shows some of the concepts that must be quantified in a monitoring and analysis system. The lower issue is detectability. As an example, two bodies of different resistivity are shown, but the contrast between each body and the local resistivity is different, only 20% in one case, 250% in the other, making one highly detectable, the other not. Furthermore, the measured response curve may be plagued by large amounts of noise or spurious signals of different frequency. The upper part of Figure 1B shows another issue, the ability to resolve anomalies spatially. Suppose two events happen during a time period between surveys; both events are then affecting the data, but they may not be resolvable if they are too small, too close to each other, and so on. All of these issues, including precision, repeatability, data density, and so on, must be addressed in monitor system design.

Given a suitable monitoring system with adequate data, surface deformations can be used directly to make primary inferences about the processes at depth without a detailed mathematical analysis. For example, if there are anomalously sudden changes in Δz in a particular region, this can be identified as an "event" through the alarm system that continuously takes the deformation data and analyzes it in terms of the magnitude and the rates at which these are taking place, and comparing this data to historical data or expected rates. An event, once identified, can then be analyzed further, either mathematically, statistically or through the judgment of an experienced person, to make operational decisions. As a simple example, if a significant uplift at the surface is observed to be taking place over a small area only, one may be certain that the source is shallow; if the uplift has a lower magnitude and is spread over a large area, one may be certain that the source is deep. Mathematical methods exist to quantify these interpretations.

What technologies can provide data about such changes in deformation so that they could be used as the basis of an alarm system to help identify active or impending caprock integrity impairment that might lead to unacceptable steam and gas breakthrough at the surface? The major candidate technologies are introduced below, and discussed in greater detail later in the report.

TILT

Tilt measurements at many points using precision inclinometers will delineate a surface tilt field. Tilt - $\Delta\theta/\Delta r$ - is the spatial differential of the surface Δz field and α is the direction of the maximum tilt, and the combination of the two is the tilt vector measured at a point. Just as shown in Figure 1 for direct displacement measurements Δx, Δy and Δz, analysis of tilt vectors ($\Delta\theta/\Delta r$, α) also allows estimates of volume changes and shear distortion that are taking place at depth. Changes in tilt, and in fact all changes in surface deformation are almost instantaneously transmitted to the surface from depth, and the nature of the surface deformation is directly linked to the deformation changes at depth. Because of instantaneous transmission and direct linkage, these changes are of potential value as an alarm measure if they can be reliably collected with sufficient spatial density. Deployment and use of spatially dense arrays of tilt monitoring sites could give not only alarm capacity, but also allow much greater insight into the nature of the processes at depth.

It is assumed that tilt data can be used for short-term alarm purposes because the tilt is being measured in real time and can be provided electronically to any user. However, generating a complete surface deformation image and an interpreted sub-surface distribution of ΔV and ΔS from tilt measurements in a consistent time-frame that is on the order of an hour or less may not be an available service at the present time. This is largely a software issue, and as soon as such software is developed, short-term tilt response analysis will be feasible, and the value of tilt measurements as an alarm-type monitoring approach will increase substantially.

LIDAR

Continuously operating LIDAR (LIght Detection and Ranging) and similar ranging methods usually use a fixed emitter site and radiation (e.g. laser, radar or infrared source) to precisely measure distance. These methods require installation of a number of permanently fixed reflectors in line-of-sight communication with the emitter and can be used to monitor changes in deformation at time scales from 1 minute to 60 minutes, depending on the number of stations to be scanned and the time required for analysis (usually very rapid). No analysis is required to give the precise distance between the emitter site and the reflector, but to generate a deformation map requires a scan of many reflectors followed by some straightforward computer analysis. Furthermore, to measure $\Delta z(X,Y)$, it is necessary that the emitter be located some distance above the ground surface (e.g. 50-100 m) in order to achieve adequate resolution in measurements of vertical movements at a distance from the emitter (e.g. 1000 m).

GB-InSAR

GB-InSAR (Ground-Based Interferometric Synthetic Aperture Radar) is a scanning method that takes precise mono-frequency radar images and thus can generate a deformation image over time between two scans, giving information about rate-of-change as well as absolute change, including both vertical deformation and horizontal deformation. To fully resolve horizontal deformations requires two emitter sites and more analysis. Time scales to provide the differential deformation between two sequential GB-INSAR scans is on the order of minutes to an hour. Similar to LIDAR methods, it is necessary to have the emitting antenna located some distance above the ground in order to achieve sufficient resolution in the $\Delta z(X,Y)$ map, but it is straightforward to obtain high precision measurements of changes in the horizontal plane ($\Delta x(X,Y)$ and $\Delta y(X,Y)$).

D-GPS

Differential GPS (Global Positioning System) approaches measure the differences in surface elevation (Δz) between a “mother” station and a number of “daughter” antennae. D-GPS data provide a continuously updated map of surface heave – $\Delta z(X,Y)$ – in quasi-real time, the method does not require clear line-of-sight, and the information content for critical areas can be increased by adding more antennae to better cover the critical area. Recent developments in D-GPS also mean that information about Δx and Δy displacements for the sensor sites can be obtained. In principle, this additional information can be included in the mathematical analysis to give a more precise picture of the volume changes and shear distortions at depth.

Thus, all four of these monitoring methods (tilt, LIDAR, GB-InSAR, D-GPS) can be used as alarms in various ways. For example, trigger limits can be set on the magnitude of deformation at each target, site or specified location, and a minimum number of locations triggered can be specified to raise an alarm, such as requiring three or four spatially close locations to exceed the trigger limit. Also, maps of surface deformation (Δz, but also Δy and Δx in most cases) can be generated from each of these methods at precisions adequate to provide ongoing assessment of changes happening at the ground surface and at depth. As with tilt array measurements, software developments are needed to more rapidly generate surface deformation maps – $\Delta z(X,Y)$, differential deformation maps between specified time intervals – $\Delta z(X,Y)/\Delta t$ – for rate-of-change presentation, and other useful information to allow the interpretation and decision-making team to assess the progression of deformation and make well-informed judgments.

2.1.2 Intermediate-Term Time Scale

The intermediate time scale is taken to be more than one day but less than 10 days between the time that an anomalous event occurs and is reliably identified as such by a sensor system (likely backed up by analysis). If the characteristic time of a caprock breakthrough event is on the order of several days, which is thought to be the case,[3] intermediate time scale measurements and analysis cannot be used as the basis of alarm systems. If the analysis process is too lengthy, for example, the time from data acquisition to the time of provision of a suitable interpretation may be more than a day, even though the data collection may have taken only a few minutes. Intermediate-term time scales deal with changes in rate and magnitude and interpretable data provided to the operator to allow decisions about rates and processes to be made, but not at the time scale of an alarm.

Approaches that are of intermediate time scale usually require a mathematical model that takes the data changes between two times and interprets this information in terms of changes that are taking place at the reservoir level (see Figure 1). An example might be electrical impedance surveys based on measurements of voltage drops or electromagnetic measurements using surface surveys; these methods cannot be done instantaneously unless there is a permanently installed array and an automated excitation method. Furthermore, the models that must be used to analyze the data may be complex and cannot (at this time) give results in a short time frame.

Similarly, a 3-D seismic survey could, in principle, be repeated at a short time interval such as daily or weekly (in practice, such a short time span between seismic surveys is unrealistic). Then, the new seismic “image”, usually an image constructed from the differences between the two images (e.g. the **<u>changes in</u>** wave velocities, amplitude and frequency content over the time interval) is subjected to further analysis or interpretation. This process takes several days using current methods of analysis, and the results may also require verification by experienced persons. Thus, it is assumed that the “turn-around time” for 3-D seismics is typically greater than 2-3 days, and more likely to be greater than a week. Until specialized software is developed to give rapid updates to the “image” with a time lag of

[3] Only one unequivocal caprock breach and breakthrough to surface is well-documented at the present time – the Joslyn site north of Ft. McMurray. A general lack of information related to this class of events means that their physical characteristics remain ill-constrained, which is a handicap for the design of an alarm system.

minutes to hours after data acquisition, time-lapse 3-D seismic methods will remain a long-term monitoring method, not able to contribute to assessing changes on a weekly or bi-weekly basis.

Other intermediate time-scale methods could be, for example, those that require a lengthy survey time (e.g. manual laser leveling or surface resistivity surveys that require persons walking over a site carrying an antenna for several days), deployment of specialized equipment (e.g. geophysical logging of observation wells or using a large moving coil antenna to collect induced magnetotelluric currents), or windows of opportunity that do not arise except at time intervals greater than a few days or more (e.g. satellite-based InSAR images or conventional 3D seismic surveys).

If the deformation field at the surface – $\Delta z(X,Y)$, $\Delta x(X,Y)$, $\Delta y(X,Y)$ – is appropriately sampled by the methods discussed in the previous section or by other means, mathematical analysis can be used to generate the most probable interpretation for the volumetric and shear deformation changes $\{\Delta V, \Delta S\}$ taking place at the reservoir level. This requires sufficient quality of data and a sufficient number of data points. For a shallow process, where a developing deformation anomaly might be relatively small, this will require a proportionately greater number of sensor locations on the surface to give a high detection probability.

In most cases, there are additional constraints that apply to the analysis, but in general, the deep deformation field can be resolved in terms of volumetric and shear deformations, and the evolution of these responses can be tracked over time as a series of short time interval (differential) images. If these images can be developed only on time basis greater than a day or two, they cannot be used as alarms, only as means of establishing baselines and studying the physical evolution of the process. Deviation from baseline expectations (e.g. sudden appearance of a large amount of shear displacement or an unexpected volumetric inflation at depth) and other anomalies that may appear over time then can be analyzed in greater detail, at a shorter time scale, or specific ancillary investigative surveys can be carried out. In other words, intermediate term (and long term) methods are vital parts of understanding what is going on, but are insufficient for alarm purposes.

Other fields can be measured and analyzed in a manner similar to the deformation field:

a. Gravimeters can be used to delineate changes in density and vertical deformations at depth that affect the micro-gravity response.
b. Electrical measurements (of various types) can be used to delineate changes in the electrical conductivity at depth that arise from spatial changes in fluid salinity and temperature.
c. Seismic surveys can be used to delineate changes in seismic characteristics at depth by analyzing only the changes that have occurred over the time interval between surveys.
d. Microseismic emissions can be collected using a 3D sensor array, and the MS events provide sources for tomographic reconstruction of the seismic attributes.

Surveys based on gravimetric response, electrical impedance or electromagnetic measurements leading to tomographic delineation of resistivity changes (3D images), active seismic surveys for time-lapse images of seismic attributes' changes, and passive seismic data (MS event characteristics mapping) each have substantial potential. But, for better delineation of the processes that are going on at depth, in the steam chamber and caprock environment, the use of two or more independent methods gives synergetic possibilities that increase the odds of a correct interpretation. For example, MS techniques can provide information about the shifting loci of shear events, although at shallow depths and in soft weak rocks the magnitude of these events is not large. If the dominant event loci changes and indicates potential localization in a specific area above a SAGD or CSS operation, it might be related to the beginning of shearing or fracture propagation. If this is clearly identified, then a specific investigation can be carried out to better understand the linkages and thus better interpret the overall system response. These may include deformation co-analysis, a 2-D seismic line survey, a 2-D electrical resistivity line measurement, or other short-term data collection and analysis to confirm the primary interpretation.

Many opportunities exist to develop novel integrated monitoring methods, such as using the microseismic sensor array to build up a tomographic image of the three-dimensional seismic attributes of the structure of the rock mass between the events' loci and the sensors. Then, changes in this seismic structure can be linked to alterations in the state of the caprock, such as pressure and temperature increases.

Similarly, electromagnetic methods have great potential. These approaches include electrical impedance tomography (EIT), controlled-source excitation methods (magnetotelluric effects), and 2-D and 3-D surface electrical surveys. Each of these, or combinations of them, can be used to determine changes in electrical properties in the subsurface. In principal, this should be functionally and explicitly linked to spatial changes in resistivity because of the process. For example, condensed steam or inert gases are far less electrically conductive than natural saline pore water; therefore the displacement of saline pore water by steam will be detectable using electromagnetic methods.

In summary, for these intermediate time scale methods:

a. Survey methods, methods involving the redeployment of specialized equipment, and methods requiring lengthy and detailed mathematical analysis and interpretation to yield useful results for engineering decision making cannot realistically be used at a time scale short enough to be used as alarms.
b. Methods that can be applied at intermediate or long time scales remain of great interest to the understanding of the process because:
    i. They provide baseline data which are used to assess and set the trigger limits of the alarm system.
    ii. They are of value in providing more insight as to the physical nature of the processes taking place at depth, so that alarm decisions can be made on a more scientific basis.
    iii. Software and hardware developments will, in some cases, move intermediate time-scale technologies into the 24-hour limit for an alarm system.
c. These methods are often synergetic: combined, they give far more information than any method alone, especially if different fields are measured, such as the changes in seismic attributes combined with the volume changes at depth.

2.2 Alarm Errors

An issue that arises in any technology is the probability of making an error. In the case of thermal process monitoring for purposes of identifying potential impending breakthroughs into the overburden or to the surface, there are two types of error, the missed alarm and the false alarm:

a. Type I error: The missed alarm, comprising a failure to successfully identify a breakthrough event in a time interval where it can be acted upon.

b. Type II error: The false alarm, comprising raising an incorrect alarm of an impending breakthrough event, and particularly, acting upon it.

Clearly, each of these has economic consequences. The first may be considered as far more costly than the second, but to reduce the probability of the first necessarily means increasing the probability of Type II error, the false alarm.

Only one example is given here. Suppose that the criterion of a sudden chamber pressure drop, measured with a continuously reading pressure gauge at the heel of a horizontal well, is chosen as the most reliable alarm measure. At the present time, we do not know *a priori* how big a pressure drop and over what period of time it should take place in order to constitute a genuine alarm. The ability of the engineering community to simulate a breakthrough event is not well-developed, and setting specific values of ΔP in order to trigger an alarm still involves conjecture as to the actual mechanism involved in the breakthrough.

Another difficulty in specifying alarm settings is that it is extremely risky, even impossible, to try and determine or verify these measures through experience in the field because of the catastrophic nature of a breakthrough; we do not have the luxury of an extended period of trial and error because the consequences of an error are extremely costly. The previous shallow SAGD breakthrough event that took place in 2006 was not extensively monitored for deformation or other measures, only for temperature and pressure (and not in the overburden), so it is difficult to use that lone case for purposes of calibration of an alarm approach. Additional complexities are related to heterogeneity in the nature of the caprock and overburden, and to the existence of features associated with karst dissolution processes which may have given rise to anomalous stresses or unexpected pathways for fluid escape.

On the other hand, in the absence of a breakthrough, there will always be some engineers who will argue that the pressure criteria are too conservative, therefore the temperature of the steam is too low to give the maximum process efficiency, and a substantial economic opportunity is thus impaired. This conflict remains a serious dilemma that can only be partially resolved, and only through the use of integrated monitoring methods that are complementary in nature. To date, in thermal extraction processes such as shallow SAGD, this has not been accomplished for purposes of alarm-type surveillance. Whether the degree of uncertainty as to the physical nature of a caprock breaching process can be mitigated so that the frequency of a Type I error (missed alarm) can be reduced to a very small value without generating a large number of Type II errors (false alarm) remains a topic in need of careful study, new developments (in analysis software speed for example), integration of monitoring methods that are synergetic (electrical plus deformation plus MS for example), and the development of better mathematical modeling methods and understanding of the physical processes taking place at depth.

Although the physical processes involved in steam injection technologies are becoming better understood, much remains to be done. Several critical areas where additional knowledge and development seem to be needed are listed here.

a. Shear dilation accompanies all steam injection processes in oil sand, changing transport properties and inducing large surface displacements. The general uplift measured at the surface above SAGD or CSS projects is ≈80% the result of shear dilation, and this deformation component develops gradually over time, without sudden jumps in deformation over periods of a few days.

b. Non-condensing gases are released during steaming of oil sands, even shallow oil sands. Methane dissolved in the bitumen has been noted at depths as shallow as 15-30 m in open-pit mining, and this gas exsolves under heat, does not re-dissolve, and migrates to the top of the steam zone where it accumulates as a non-condensing gas cap.

c. Mathematical simulation models are based on assumptions that may be inappropriate. For example, shallow SAGD simulation may use dead oil models (no gas in solution) because they are mathematically simple, or the rock transport properties (hydraulic or thermal conductivity) may be assumed to be constant over time, which is known to be incorrect.

d. Rock mechanics parameters such as rock unit stiffness are based on laboratory tests or correlations with other physical parameters such as seismic properties. Sample damage and inappropriate laboratory methodology in testing are severe problems in oil sands, and historically have led to poor-quality data. Also, there have been no published cases found involving direct verification of rock behavior through back-analysis of detailed deformation measurements taken during a thermal steam injection process; hence, values being used in mathematical models remain un-verified in practice.

e. Mathematical models that are used to analyze thermal processes may not be fully-coupled flow-stress models; they may be only partially coupled, or fully uncoupled, such that there is inadequate or no explicit accounting for the effect of pressure and temperature changes on stresses. Because the breakthrough processes associated with caprock integrity breaching are almost certainly associated with large stress changes triggered by ΔT and ΔP, incomplete or inadequate models may lead to predictions that are simply wrong.

If these and other areas are clarified, it would not mean that errors would be eliminated, but it would mean that the probability of errors would be diminished.

2.3 Critique of Pressure and Temperature (P & T), and Seismic Measurements

2.3.1 Are Caprock and Overburden P & T Measurements Useful for Alarms?

Because P & T measurements and seismic techniques are so widely used as aids to petroleum reservoir engineering, it is necessary to be clear as to their use in active caprock assessment methods. Issues with caprock integrity and the possibility of gas (non-condensable gas and steam) breakthrough are almost certainly related to one of two mechanisms (or a combination of the two):

a. Breaching of the overlying rocks and seal through the generation of a large (laterally extensive) low-angle shear plane along with high pressure propagation along the shearing plane; and,

b. Hydraulic fracturing by steam or non-condensable gas at a pressure that exceeds the local minimum horizontal stress (σ_{hmin}), leading to vertical migration of the gas.

Figure 2 shows the two mechanisms, low angle shearing on the flanks of the expanding SAGD zone, or vertical hydraulic fracturing above the SAGD zone; some combination of the two – as in Figure 3 – is feasible; a rising shear plane may lead to a hydraulic fracture at shallow depth.

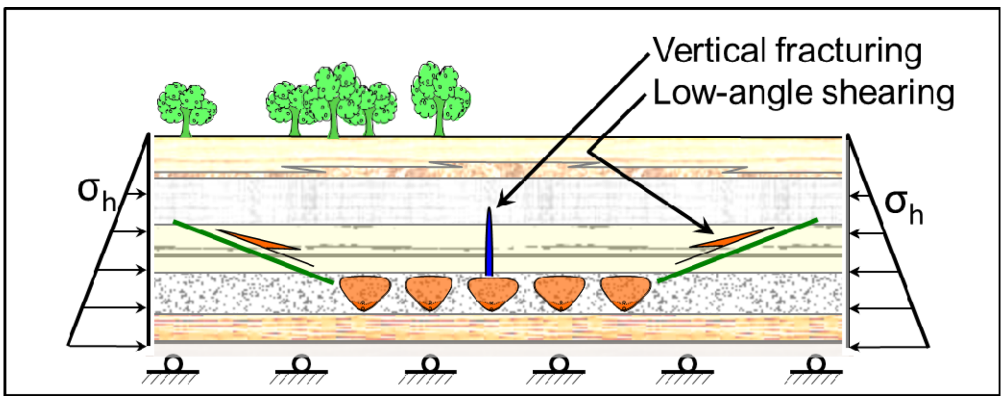

Figure 2: Caprock breaching mechanisms in shallow SAGD operations

Both of these thermal – flow – geomechanical mechanisms can be mathematically simulated for simple conditions, but the computational effort is substantial, even for a typical two-dimensional cross-section, and the uncertainties discussed at the end of the previous section (shear dilation, dead oil assumptions, constant properties…) mean that predictions are also uncertain. There have been no detailed assessments of the combined effects of uncertainty and heterogeneity on the validity or quality of the predictions that are made using mathematical models. In fact, because the modeling is laborious, parametric variation modeling to assess the effects of uncertainty is computationally demanding, and may not be fully explored. Mathematical models need to be calibrated using real data to be useful and to give reasonable predictions. Monitoring of deformations and other physical changes at the intermediate and long time scales is necessary to calibrate these models. This is a vital aspect of monitoring, and it helps to manage the process as well as to provide a physical mechanisms context that is useful for alarm purposes.

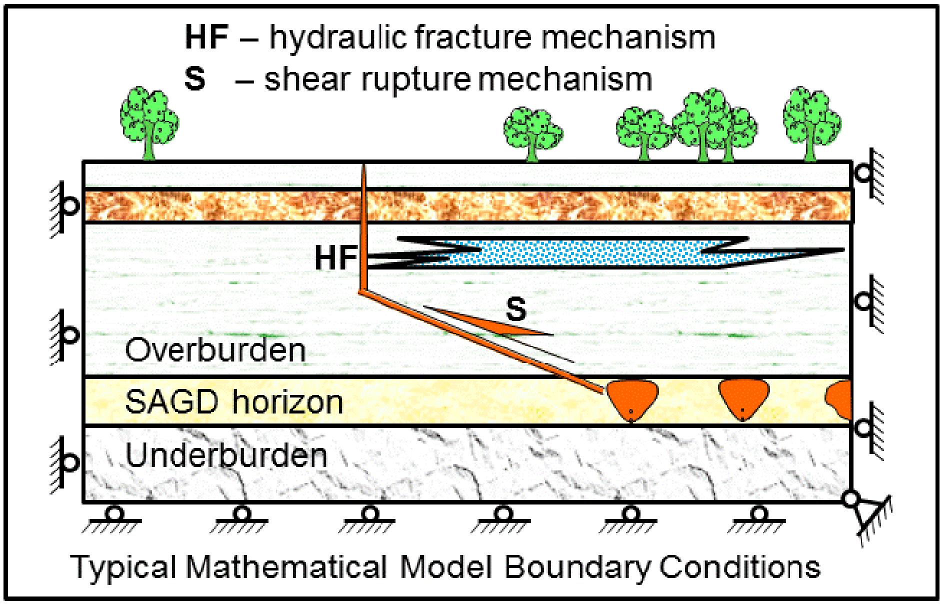

Figure 3: Combined shear and fracture breaching mechanisms in shallow SAGD operations. (The diagram also shows typical boundary conditions used in 2-D plane-strain mathematical models used to analyze stresses and deformations around a SAGD array)

The different overburden breaching mechanisms shown above each lead to different physical effects: shear distortion versus volumetric distortion, MS emission differences, differences in the changes of electrical properties, and so on. Thus, they may require different methods or different spatial deployment of sensors to adequately monitor them. A serious issue for monitoring is that these breaching mechanisms are not spatially wide-spread processes, they tend to be strongly localized, and it takes only one breakthrough location for a serious event to ensue. The shear or fracture plane does not extend all the way along the SAGD well length, which can be perhaps 800 m long; it can be localized and of limited areal extent, especially a hydraulic fracture.

Because of these local effects (a breakthrough is a local event) and their nature, pressure and temperature data collected in the caprock region and the overburden over a steam-injection region are not highly useful as alarm indicators. In order to detect ΔP or ΔT anomalies related to a progressing breakthrough event, the T or P sensor must be directly exposed to a change; it is not possible to measure changes in T or P remotely. Thus, at least one sensor must intersect or be close to the actual pathway of fluids breaking through in order to give an indication of an event. However, the actual (or most probable) pathway for the fluids that may be involved in a breakthrough is not known in any specific steam injection project, and it may be very narrow. This means that to achieve a high probability of detecting a developing event, a very close spacing of T and P sensors is required, on the order of perhaps a few meters vertically or horizontally; this is not possible in practice.

T and P data are taken at a single point, and a change in value at a single sensor gives no information about what direction the change came from or how strong the source was. Even if several sensors show changes, interpolation of these changes to the region between the sensors is usually not possible. This is very different from a deformation field. Because of the solid nature of the overburden, if a Δz of +20 mm is measured at a point at the surface over a 24 hour period, there is absolute certainty that the ground surface surrounding this point for some distance has also experience uplift. Furthermore, if this uplift field can be specified, it is possible to calculate where the original source of the uplift was, and how large the volume change or shear displacement was. Because P & T values represent point measurements with no guarantee of interconnectedness, severe issues arise in interpretation. A number of examples are given here, using the examples of shearing or fracturing of caprock.

a. If a breach involves a hydraulic fracture driven by non-condensing gas rising from the top of a steam chamber during a SAGD process or a Cyclic Steam Stimulation (CSS) process, will there be a temperature anomaly of any significant size laterally from the fracture plane? (This is unlikely because of the low specific heat of gases.) In such a case, T measurements fail to identify a breaching event.
b. If a hydraulic fracture plane is passing through ductile shale, will there be a significant pressure response some distance away? The extremely low permeability of ductile shale would shield a pressure sensor even one meter away, therefore overburden ΔP measurements may fail in practice.
c. If a breach involves progressive growth of a local gently inclined shear plane, as in Figure 2, can an array of pressure and temperature sensors give any indication that such growth is taking place with a reliable degree of certainty?
d. Can anyone predict with reasonable certainty where above an array of SAGD wells is a breaching event most likely to occur?
e. Because non-condensing gas tends to generate capillary blocking against finer-grained sands and silts, will there be a significant pressure response in sensors some distance away? How far away and how quickly?
f. How many boreholes instrumented with P & T sensors are necessary to give a high probability of detection of an anomaly? What level of probability of detection is needed?
g. If there is a sharp anomaly from one P & T sensor, is it indicative of a general breakthrough? How many sensors would have to register anomalies, and how would these sensors have to be deployed in the complex subsurface geology in order that an interpretation can be made with a high degree of certainty?

If the pressure and temperature measurement sensors in the overburden are carefully placed in permeable zones, detection of a pressure anomaly at a distant (tens of meters) breakthrough site may be possible, as long as there is a reasonable chance that an incipient breakthrough will lead to a wide-spread pressure increase in the permeable zones. Hence, p-measurements may detect an event in progress, but more likely, P & T responses will be detected well after caprock breakthrough has occurred and sufficient volumes of leakage have occurred to affect a large volume of the permeable zone. Placing P & T sensors in shale sections of caprock is likely to be of little use because the low permeability inhibits temperature and pressure migration. To give a high probability of anomaly detection, P & T measurements above the caprock would have to be extremely densely spaced, and even then, because of the local nature of the breakthrough process, the level of certainty would be difficult to quantify.

Because of heterogeneity in the overburden stratification, there is no guarantee of pressure communication between the location of the breakthrough mechanism and a particular P or T sensor, even if the sensor is in close physical proximity to the breach. If the overburden is mostly fine-grained strata, pressure response of a near-by sensor is not guaranteed if a short-term breakthrough event develops. If the breakthrough is associated with or caused by a gas that does not condense, such as methane from the gas dissolved in the viscous oil that accumulates at the top of a SAGD chamber, a capillary barrier to flow is generated against the porous strata. If the pressure sensor is located in fine-grained sand or silt, there may be no detectable response because of capillary blockage of the material from the surface tension effects between the immiscible fluids (this is a well-known pressure blockage mechanism in tight gas sands).

Clearly, with the combined effects of geological heterogeneity, low permeability and capillary blockage, an inordinately large number of pressure measuring points in the overburden would be required to give sufficient spatial coverage to have a high probability of identifying a breakthrough before it reaches the shallower surficial sediments. Whether this is attainable in practice appears unlikely.[4] Even with a large number of sensor points and assuming that a response is detected, pressure anomalies in the overburden are difficult to interpret in terms of the actual events happening. For example, if a P response is noted, where is the source of the breakthrough, and is it too late to take any action?

The potential for temperature anomaly use as an alarm metric is far worse than for pressure because the rate of transmission of temperature in sediments is either through conductive (low permeability) or advective (high permeability) heat transfer, processes that are inherently local in nature. An influx of fluid at some distance can create a sudden pressure response, but not a temperature response. Furthermore, the breakthrough may be led by a non-condensing gas driven off by the higher temperatures applied to the bitumen, so a breakthrough may potentially be initiated without a local temperature anomaly if the gas has already been cooled during transit through the underlying strata. Because any induced shear plane or fracture plane is relatively narrow, on the order of centimeters in width, there is a low probability of temperature migration into a large volume where it could be detected by a temperature sensor. For temperature sensors to have a chance of detecting a hot fluid breakthrough, which would require direct contact with a locally induced temperature anomaly, an extremely dense network would be required, far beyond practical limits.

Because the answers to these and other similar issues are not known, ill-understood, or likely to be negative in terms of their value, overburden P & T measurements are considered to be inadequate for alarm purposes. Nevertheless, because of their low cost relative to other methods and the value of P &

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[4] Little is known about SAGD breakthrough events because only one incident – Joslyn – has been carefully analyzed. Thus, factors such as pressure transmission rate, rise rate of a shear or hydraulic fracture plane, accumulation of non-condensing gas in the fracture, and many other factors remain unquantified or speculative.

T data in a general sense (and for post-analysis of events, groundwater monitoring, and so on), P & T sensors in the overburden are of general value if installed in permeable zones.

2.3.2 Are Chamber Injection Rates and Pressures Useful for Caprock Breaching Analysis?

The critique of T & P data value in the overburden does not mean that they are of little value elsewhere; in fact, chamber T & P data are critical for control purposes, and may play a significant role in alarm strategies in the future, most likely in combination with other measures.

Pressure measurements in the chamber (e.g. at the heel of the SAGD wells), temperature measurements in the injection and production wells, and P & T measurements in wells above and around SAGD arrays are essential to monitor the chamber and to provide additional information for understanding, controlling, and optimizing the SAGD process in practice. Just as measurements of deformation are necessary to calibrate and develop geomechanics models, measurements of P & T are necessary to refine and calibrate fluid flow models associated with thermal processes. Since these models are used to aid important economic decisions and are part of the general analysis process, it is essential that they be developed and refined through collection of relevant data.

The standard approach for monitoring a SAGD project independent of the caprock integrity issue might include the following methods:

a. The pressure is monitored at the wellhead and at the heel of the well (injection or production); more recently but more rarely, fibre optics pressure sensors can be installed to measure the pressure at points along the wellbore.

b. The temperature is measured using distributed sensor cables such as thermistors or thermocouples along the wellbore length.

c. The injection and production rates of the various phases (steam, non-condensable gas, oil, water) are monitored.

d. A few small diameter vertical wells are installed to measure P & T at various locations along their axes. These wells may be placed in various locations above the steam injection sites, in adjacent strata, at different depths, and so on, depending on the perception of the process physics, how the project will proceed spatially and temporally, and how much model calibration is desired.

e. Episodically, perhaps each 3-8 months, a surface deformation map from InSAR technology is obtained, and a 3-D seismic survey repeated. These provide more spatially and temporally integrated data for model calibration and verification and for generally tracking the process for management purposes.

Injection and production rates may be collected for each individual well, or there may be a proration approach applied if pad-wide measurements are used. In this case, allocation to individual wells is made through the use of test separator data taken for a limited time period for each well (e.g. 1 day per month). Detailed measurements for each well are preferable because a breakthrough event is almost certainly associated with one chamber only, therefore prorated production allocation and pad-level measurements only have little use in short- and intermediate-term monitoring.

The chamber pressure should show a response if an active breaching process is developing through the caprock and into the overburden. The expected response in the injection well would be a pressure decrease combined with a rate increase as a channel (shear plane or fracture) is opened to shallower strata where the fluid pressure is lower and where the pressure is more easily dissipated through flow. This is why chamber pressure is a vital alarm measure, especially for post-analysis and process control (e.g. maintaining a maximum chamber operating pressure). However, it is not likely that there is a different and detectable temperature response to a breakthrough event. In the chamber, the temperature and pressure are thermodynamically linked because steam and water are both present, but pressure is transmitted through the porous medium in the chamber more rapidly than a temperature change, therefore chamber pressure monitoring is far more valuable than temperature monitoring for alarm purposes.

Although injection and production rates are vital for process management and integrated pressure-rate methods and differential analysis techniques for well monitoring and process monitoring are widely used, defining how to use these measures for caprock breaching events remains a challenge. Some of the difficulties are related to uncertainty as to what the breaching process is and its regional extent (highly localized or over a large volume), the volume of the chamber and compressibility effects, the volume of a propagating fracture (perhaps too small to generate a detectable pressure-rate response), the possibility of little to no volume change associated with a shear fracture, and so on. Furthermore, above a typical steam chamber 800 m long and 100 m wide, if a breach occurs and a chamber pressure-rate response is detected, there is no means of determining where it is taking place (in contrast, for example, to deformation or electrical measurements).

For example, under conditions of constant steam injection rate into a chamber, a breakthrough of fluids to a higher elevation without a change in liquids production rate should be accompanied by some combination of a rate increase and a pressure drop. However, the magnitude of the response depends on at least the following parameters: the steam chamber volume, gas/liquid volume fractions, current pressure and temperature. Differential pressure-rate responses at early stages of a process where the gas volumes are small may be sharp and easily detectable, but when steam chamber volume becomes large after several years, the compressibility effect, gas volume, and permeability effect will severely dampen the magnitude of a response. The nature of the differential pressure-rate response therefore changes with chamber maturity, and this means that threshold values of pressure, rate, or rate-of-change are not constant with time and with chamber volume.

A hydraulic fracture breach of the caprock should lead to a sudden surge of fluid through the fracture, causing the pressure to drop in the short term. Similarly, if a shear fracture ruptures the cap rock and allows a sudden surge of fluids to escape to lower pressure regimes in the overburden, a response should occur. But, in both of these scenarios, there is little possibility of detecting the caprock rupture in advance of it taking place; it is only after breakthrough that a significant change in pressure can be detected. Hence, pressure-rate methods are critically important for process management and post-analysis of an event, particularly in combination with other data such as deformations or changes in electrical conductivity, but may not be valuable as a precursor metric, and are therefore not to be relied on alone to give insight into the processes taking place in the caprock and the overburden.

2.3.3 Are Seismic Methods Useful as Alarms for Caprock Integrity?

Finally, it remains appropriate at this stage of their development for thermal process monitoring to remain suspicious of seismic methods as means of detecting an incipient breakthrough for a number of reasons. Active seismic methods, including cross-hole seismic methods, time-lapse 3-D seismic methods, and so on, may fail to detect a breakthrough process unless the surveys are carried out frequently, analyzed in the higher frequency domain (to give better resolution), and interpreted correctly. Large changes in material acoustic properties as the result of temperature and pressure changes, effective stress changes, formation shear dilation, and massive alteration of phase saturation make the inversion of active seismic data singularly difficult, even for shallow processes. Because of the local nature of an incipient breakthrough event, a detailed coverage 3-D seismic survey would be necessary, and the survey would have to extend beyond the flanks of the SAGD chambers (Figure 2).

Currently, there is no assurance that the development of a local event could be easily identified by any seismic method (active or passive) in the midst of the other temperature and fabric changes taking place. Even if an anomaly is detected, it is not clear if it could even be related to an incipient breakthrough process with a high degree of probability. The significant changes in porosity, saturation and temperature taking place during SAGD chamber growth mean that an anomaly would have to be significant in scale, and stand out clearly from the background changes. Changes associated with fracturing and shearing, although more rapid than chamber growth, are small in the context of the overall changes at the chamber scale.

Even if it were possible to detect seismic anomalies and to interpret them correctly, 3-D seismic surveys would have to be repeated at time intervals small enough so that the development of an anomaly could be tracked reliably. This would require 3-D seismic surveys every few days or once a week so that the anomaly could be seen and interpreted correctly on at least two sequential surveys, giving at best about two-week detection reliability when analysis time is taken into account. This is not practical in large SAGD field cases; time-lapse surveys each 4 to 8 months are far more likely. For 3-D seismic survey technologies, it is not likely that they will evolve to the state where they become suitable for alarm purposes.

It has not yet been demonstrated that the low-angle shearing events which have been repeatedly confirmed world-wide by many low-angle casing shear occurrences in steam projects (for example, AMOCO Gregoire Lake, Imperial Oil Cold Lake, BP Wolf Lake…) are accompanied by MS emissions that could be useful for engineering purposes (detectable, reliable, mappable, interpretable…). Nevertheless, years of monitoring at Peace River and Cold Lake projects show that a great deal of MS activity is occurring in and around steam zones, and that the location of the events and their magnitude evolves in space and in time. In other words, there is a great deal of detectable and mappable activity occurring, but it is not clear how this may be used in practice for alarm purposes.

The spatial migration of MS activity above steam chambers could be an indicator of impending caprock breakthrough, if the event is localized and consistent and if there is a clear physical link to the breakthrough process (MS activity is almost exclusively the result of small shearing events), but shallow depth tracking of such activity means using a relatively dense array of buried geophone sites. If this could be achieved and if a clear link to physical processes can be demonstrated, MS monitoring may become useful, but again, spatial localization of breakthrough events and the unknown response of MS emissions during a hydraulic fracturing caprock breach may serve to confound interpretation. It remains completely unknown whether shallow vertical hydraulic fracturing by steam or by non-condensing gas generates detectable MS events. At this time, MS monitoring as an alarm approach is not considered reliable, and it remains to be demonstrated that MS mapping is useful for intermediate-term scales. Experience in Cold Lake (IOL) and Peace River (Shell Oil) to date has not been highly positive in terms of developing a powerful MS monitoring capability for managing thermal injection processes, either in the long-term or the short term.

At this stage in their evolution, seismic methods cannot be relied on to serve as alarms for caprock breakthrough events. They have value in mapping processes over time, in correlating to other measures (electrical conductivity, deformation), and in understanding the physical nature of processes, but not in short-term alarm systems. It is well to note that the cross-hole seismic testing carried out in the original UTF monitoring scheme proved to be of no value, and that the deformation data proved to be the most technically valuable. Similar statements have been made by engineers at Shell Peace River for their CSS and SAGD work at depths of 480 m. It seems that, for shallow SAGD operations, short-term deformation measurements may be the only realistic method of getting data that could be linked to incipient fluids breakthrough in an alarm mode (<24 h).

2.4 Types of Monitoring

2.4.1 Active or Passive Monitoring

Monitoring may be active or passive. Active methods involve the deliberate generation of specific acoustic, electromagnetic, or other types of sensing energy fields through active generation of a change such as applying a step-function electrical potential, vibrating the ground surface, or other change. The evaluation of the response of the subsurface to these changing fields over space and time are then measured, and suitable analysis is implemented. Passive methods measure changes in properties (acoustic velocities, ground movements, compressibility) or state parameters (p, T) generated or altered by the process itself and do not require an active excitation field.

Examples of data types that are active include most monitoring approaches carried out as specific survey methods at chosen intervals:

a. Active seismic methods, including VSP, cross-hole seismic, 3-D seismic methods

b. CSAMT – controlled source audio-frequency magnetotelluric measurements
c. EIT – Electrical Impedance Tomography
d. Various electrical methods involving different arrays such as the Schlumberger or Wiener array performed on a surface survey basis

Passive monitoring methods do not actively generate a field, but simply collect data related to the process without using a specific excitation. This usually implies the permanent installation of an array of sensors to execute the measurement. Many of the standard, well-understood monitoring methods are passive, including:

a. Passive seismic methods which measure the acoustic emissions associated with the thermal process itself – induced microseismic activity – or collect emissions generated by other processes for analysis and interpretation
b. Pressure, temperature and flow rate monitoring are passive by nature
c. Changes in the gravity field can be passively measured using carefully installed precision gravimeters in a designed array
d. All deformation measurement approaches such as level surveys, LIDAR, tilt vector collection, InSAR, GB-InSAR, D-GPS and wellbore techniques are passive methods because they do not involve measuring the response of the system at depth to a deliberate excitation

2.4.2 Remote or Proximal Monitoring

Monitoring efforts for thermal project surveillance can be remote or proximal. Remote methods can be applied or used from a distance in order to collect information that can be analyzed to give information about the process zone. Proximal methods usually involve data that can only be determined by a direct measurement at the point at which the data are needed. Also, in many cases, it may not be technically feasible to install proximal measurement devices because of the elevated temperatures; for example, geophones and various other sensor types that contain electronic circuitry cannot in general be installed in regions where the temperature will exceed 110-140°C.

Remote monitoring may involve using a remote measurement platform technique, such as airborne or satellite methods to determine precise ground surface elevation without direct contact, or the measurement of a set of data that have to be analyzed mathematically to infer the changes in or around the process zone. Examples of remote monitoring include:

a. All surface and subsurface deformation measurements made outside of the zone of volume change are by definition remote, and mathematical models must be used to analyze the data to determine the deformation of the zone of interest.
b. All seismic methods, passive or active, are by definition remote because the changes in the seismic attributes of the rock mass are back-calculated at a specific point only through the use of acoustic waves that have travelled through that specific point from a distant source to a distant receiver.
c. Gravimetric measurements are remote, taken at the surface generally, distant from the deep-seated location where the density changes are occurring.

Proximal monitoring is necessary when measuring various types of scalar quantities. In these cases, the probe is measuring a specific change in the energy level or state at a point. Proximal monitoring examples include:

a. Temperature and pressure measurements
b. Changes in rock density behind casing, as measured through density log methods, because the log has to be within 10-20 cm of the zone where the density is to be assessed (indirectly, through the adsorption of ionizing radiation such as gamma radiation).
c. Alterations in fluid salinity, flow rate, and density. (although some inferences can be made in some cases by remote methods, such as using EIT to track fluids or gravimetric methods to track changes in saturation)

Remote monitoring has, in principle, no capacity to change the physical properties of the rock mass, proximal methods require access to the point, and usually this is a borehole or a shallow installed sensor at the surface. In some cases the borehole or installation configuration can change the response of the sensor or the system. For example, pressure transmission behind the casing along an inadequately sealed well will give responses to transducers that may actually have been hydraulically isolated initially. Also, if there is only one sensor (e.g. one pressure measurement point), there is no way of knowing where the pressure came from; this lack of directionality is characteristic of scalar measurements at a point (density, temperature, pressure, geochemistry…).

2.4.3 Continuous or Discontinuous Monitoring

Data can be collected in a discontinuous manner, with a periodic "survey" or "snapshot" acquired at regular intervals, or when considered necessary. Alternatively, there are methods which provide continuous monitoring, although in many cases data are only collected and stored occasionally.

Examples of continuous monitoring include:

a. Electronic tilt meter measurements, which can be sampled at very high frequencies (albeit not into the dynamic range)
b. MS monitoring is continuous, even though the events that are recorded are episodic in nature.
c. Temperature, pressure and flow rate measurements are continuous in nature, although only episodically recorded (perhaps the rate of recording is a function of the rate of change, easily programmed into an electronic acquisition system).

Discontinuous monitoring methods include:

a. All active seismic methods such as 3D seismic surveys, cross-hole seismic methods, or VSP approaches
b. All deformation methods that are acquired at a point in time such as a leveling survey data set, a D-GPS or InSAR data set, etc., are discontinuous in nature. Of course, with some of these approaches, such as ground-based InSAR, the time interval between scans can be only a few minutes.

c. Borehole geophysical logs or any methods requiring the lowering or use of a sonde, or the short-term application of specialized equipment, are inherently discontinuous in nature.

Some parameters can be measured in either way, depending on the technology used. For example, pressure measurements are continuous if certain types of fiber optics cable are used, or they may be discontinuous if a level has to be read or if a manual measurement such as activating a bubble tube is required. Some types of physical extensometers provide continuous electronic read-out, others have to be manually checked or episodically excited to get a reading.

2.5 Other Factors

Various other issues have to be considered in implementing and integrating a monitoring system. As mentioned above, a single pressure point in a well gives no directionality of the source of the pressure change; it is a scalar quantity only. Similarly, a measure of vertical movement – Δz – only gives a scalar value. In contrast, GB-InSAR methods can, in principle, give data on Δz and Δr, as the vertical and radial distances are precisely measured from the emitter point. This is far more valuable data because it contains a great deal of information about the surrounding deformation field, and thus constrains the mathematical solution in a far better manner than purely scalar data. For example, tilt is vectorial in nature (tilt magnitude and the direction of the maximum tilt), and is therefore superior in delineating (constraining) the deformation field than a Δz measurement at the same point. To obtain a local value of tilt from surface heave measurements requires a minimum of three properly spaced points (e.g. in a triangular configuration). Of course, the two measures taken together are yet more valuable than either of them alone. If a LIDAR or a GB-InSAR system is established using two or more independent sites for the emitting devices, then the full (Δx, Δy, Δz) deformations can be determined. In general, this is rarely done in practice, and there may be technical limitations to the precise determination of some data. For example, horizontal-plan ground surface mounted LIDAR systems cannot measure Δz values; to achieve a capability to detect Δz, some vertical height between the emitter and the sensor is needed. This could be achieved by airborne LIDAR, or by emitters mounted on a guyed tower, etc.

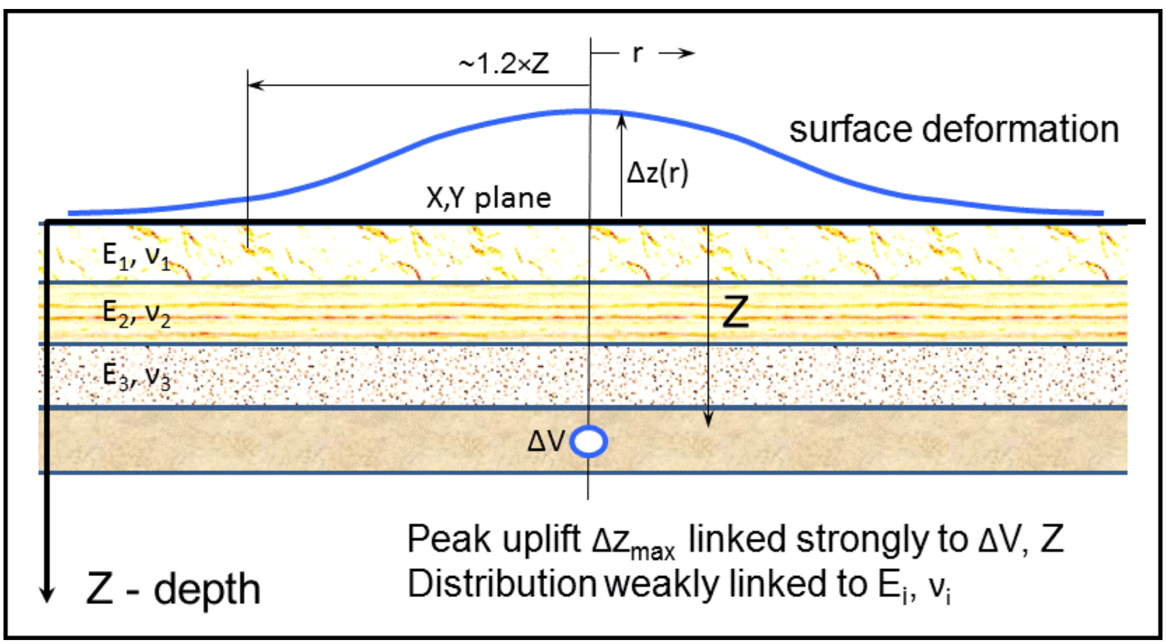
3 Deformation Measurement Issues

Because it appears that deformation measurements are among the most important approaches for surveillance of SAGD chambers for caprock integrity (see the Summary Table at the beginning), and because these methods are poorly understood by the petroleum industry, much of the rest of the document deals with deformation. A number of these comments will nonetheless have relevance to more general issues arising in monitoring strategy delineation.

Deformation measurements of thermal projects in Alberta essentially started in the original UTF, where civil engineering style extensometers and inclinometers were installed and the region around the wells was heavily instrumented with survey points, pressure measurements, thermocouple strings, cross-hole seismic arrays, and so on. A great deal of valuable data was generated, and there have been a few publications of analyses of this information. [5]

3.1 Characteristic Scale of Deformations and Potential Errors

A deformation field generated by a source function (a volume change or shear distortion in the ground) exists throughout the continuum and in principle can be measured anywhere. In practice, it is easiest to measure at the surface. A point-source of volumetric deformation at depth Z will give rise to a significant deformation ($\Delta z(r)$) at the surface over a radius of approximately 1.2-1.3×Z at the surface (i.e. ≈ at 10-15% of Δz_{max}), and the deformations are negligible (<1%) at distances somewhat larger than 2×Z. The specific distribution of the surface deformation pattern depends weakly on the distribution of the elastic properties of the individual strata in the overburden).



[5] Unfortunately, the UTF data have not been publicly released because of claims that a SAGD license must be purchased to get access to the data. This is quite unfortunate because this is perhaps the only source of high quality deformation data that could be made fully available for others to assess and evaluate.

Figure 4: A point source of volume change, or any deformation, will generate a surrounding deformation field that can be measured at some level of precision.

The value (magnitude) of the peak uplift (Figure 4 – which is conceptual and not based on a specific calculation) is strongly related to the magnitude of the volume change and the depth at which it is taking place. For example, consider only the depth of a 1 m^3 volume change occurring in a limited region. If the depth is doubled, the surface Δz distribution from this volume change is spread out over an area that is four times as large, and therefore the magnitude of the peak response (Δz_{max} at the midpoint in the figure) is greatly diminished, in theory, by as much as a factor of 8 (2^3). Thus, a given volume change is more difficult to detect with greater depth.

Now, consider the magnitude of the volume change at a fixed depth. Because all the physical parameters in the system remain the same, and the overburden is being lifted, not stressed, the Δz_{max} response at the midpoint in the figure should scale directly to the value of ΔV. Note that the shape of the deformed surface shown in the diagram above is exaggerated by many orders of magnitude; typically, the Δz changes are on the level of millimeters per day, and are spread out over the area of the pilot. This means that the distortions (the compressive and bending strains) within the overburden are extremely small (unless a massive volumetric event or a shearing event is propagated through the rock of course).

Thus, the deformation curve is scaled to the volume change directly, but drops off sharply with depth for a fixed volume change. A point ΔV at a depth of 2Z gives a Δz_{max} only ⅛th the magnitude as the same ΔV at a depth of Z. The magnitude of the surface uplift shape – $\Delta z(X,Y)$ – is only weakly dependent on the stiffness of the rock mass above the point of volume change – the overburden, for the reasons stated above: the distortions (compressive and bending strains) are extremely small. There is a small effect of Poisson's ratio, but in most cases the elastic stiffness of the overburden rock does not have a major impact on the magnitude and shape of the surface deformation shape.

Even if the overburden is highly heterogeneous, it has been found that this has only a secondary effect on the surface deformation shape because the strains imposed onto the overburden are extremely small (no stress change therefore no strain), although the displacements can be significant. In other words, at a point in the overburden, there may be a considerable amount of movement (translation), but no stress change and therefore no strain (internal deformation). Under such conditions, deformations are transmitted quite faithfully to the surface.

In a typical process case at depth, there is a region that is experiencing deformation, and in Figure 5, this is assumed to be a case of absolutely uniform heave over a defined zone for illustrative purposes. This would correspond only to theoretical cases of perfectly uniform heating or pressurization. This uplift gives rise to a surface curve, the solid red line, and therefore there are regions of large tilt (highest slope), generally different from the regions of large Δz in the centre of the surface uplift shape. This leads to a simple but important observation: the deformation measurement devices must be placed in the areas where the response is the largest. In the very centre, the magnitude of tilt (the slope of the red curve) is small; the tilt measurements will have the largest values on the slopes of the uplift curve.

On the other hand, using leveling survey sites to measure Δz will give the largest responses in the centre of the heave bowl. The angle θ is called the “angle of draw” in mining engineering subsidence work. Note that in the centre of the heave bowl the vertical movement is very close to the value of the uniform heave at depth because the width of the zone is greater than the depth Z, for the reason discussed above: the overburden is subjected to movement, but not to significant strain.

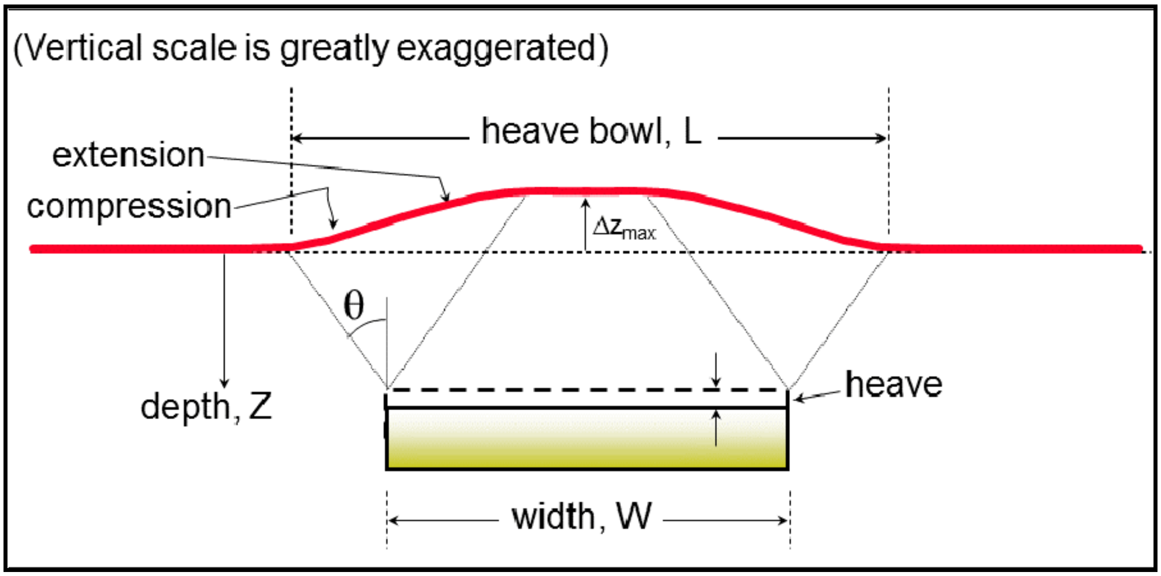


Figure 5: The heave bowl above a uniform reservoir displacement at depth

There are also surface horizontal movements that are generated by the deformations that take place at depth. There will be no horizontal movement directly above the reservoir, but on the slopes, there will be a significant outwardly-directed movement, and this will decay to almost zero at a distance about 3-4 times the depth of the reservoir. This horizontal movement is usually about ⅕th the magnitude of Δz, and in many technologies (InSAR, leveling, tilt) it may not be measured although horizontal movements have value in mathematical analysis to determine the volume changes and shear distortions at depth. Technologies such as GB-InSAR, D-GPS and LIDAR, however, can give high precision information about the magnitude of the horizontal movements. It is also well to remember that deformations can in principle be measured in the entire rock mass, and it is important to know where to place instruments in order to get maximum value. For example, if an array of tilt meters were to be placed in a vertical borehole directly about the center of the reservoir, the response would be minimal; far better to place a tilt meter borehole through the region of greatest tilt, to the side of the peak Δz values.

Figure 6 shows a cross-sectional picture of the deformed surface for a single SAGD chamber with a length far greater than its depth. Much of the surface deformation that can be detected is from the general shear dilation that accompanies high-temperature steam injection; in most shallow SAGD projects, it is estimated that from 75% to 85% of the deformation at the surface arises from the general shear dilation that is taking place at depth in response to the high shear stresses induced by the differential thermal expansion. In quartzose viscous oil sands, the dense packing is perturbed (dilated) by the small-scale but general shearing that takes place. Dilation ($+\Delta V$) is additive to thermoelastic and pressure-related ΔV, and the total volumetric response in the reservoir leads to the ground surface uplift. The uplift curve is shaped like an upside-down plate, similar to point-source ΔV effects shown in Figure 4. Because of the smoothing effect of the rock mass between the region of volume change and the surface, little can be said about small-scale spatial variations in volume change at the reservoir level. With excellent surface measurements, mathematical modeling (inversions) can give a spatial resolution of ≈5% of the depth. In other words, details of the volume change zone (magnitude and location of ΔV) can be mathematically determined (i.e. "resolved") only to a certain degree. Small deformations cannot be detected and located if they are below some limit in their size (area or volume) and the magnitude of the deformation field that they generate.

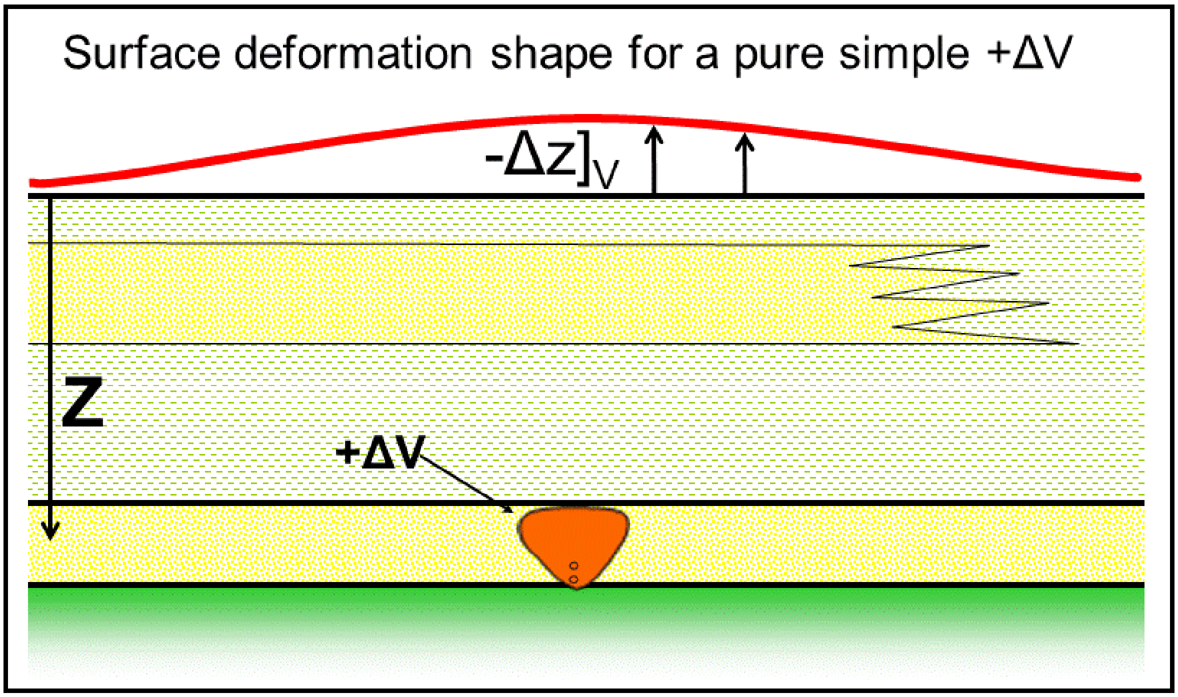


Figure 6: Surface uplift for a SAGD chamber characterized only by volumetric dilation (thermal and shear dilation leading to generalized ΔV)

For example, surface tilt deformations are used to map hydraulic fractures at great depth, but only down to 3 km, and only if the hydraulic fracture is large enough. The resolution precision for the length, height and aperture of the hydraulic fracture is a function of the depth because of this upward spreading of the deformation field. If the depth is 0.5 km, it may be possible to say that the length is 100 m ±10 m with a probability of 95% (P = 0.95). If the depth is 1 km, the resolvability is greatly reduced, and one might only be able to say that the fracture length is 100 m ±**<u>25</u>** m with P = **<u>0.90</u>** (this is a conceptual statement only and has no quantitative link to actual tilt analysis). If the fracture is vertical, it is easy to determine its azimuth because the tilt field is anisotropic, but details such as the fracture height, length, and open aperture width can only be estimated to some level of accuracy.

Issues of resolvability, detectability, precision, measurement stability, and many other related factors must be included in the design and operation of a deformation monitoring system. If the subsurface distribution of deformation is complex and spread over a wide area, a large number of measurement points will be required to mathematically estimate what is happening at depth.

The deformation shape in Figure 7 is quite different from that in Figure 6. Figure 7 shows a dipole displacement at the surface in response to a pure shear (no ΔV)[6]. A dipole means that there is a region of +ve ΔV and a region of –ve ΔV in specific locations. A dipole shape is shown in the small inset, an InSAR image of the ground movement associated with a thrust fault earthquake. The lower part moved upward over the upper part, so the thrust fault must be dipping gently to the south. The additional weak dipole to the left of the major dipole shows that the fault has a small component of strike-slip movement as well as thrust movement.

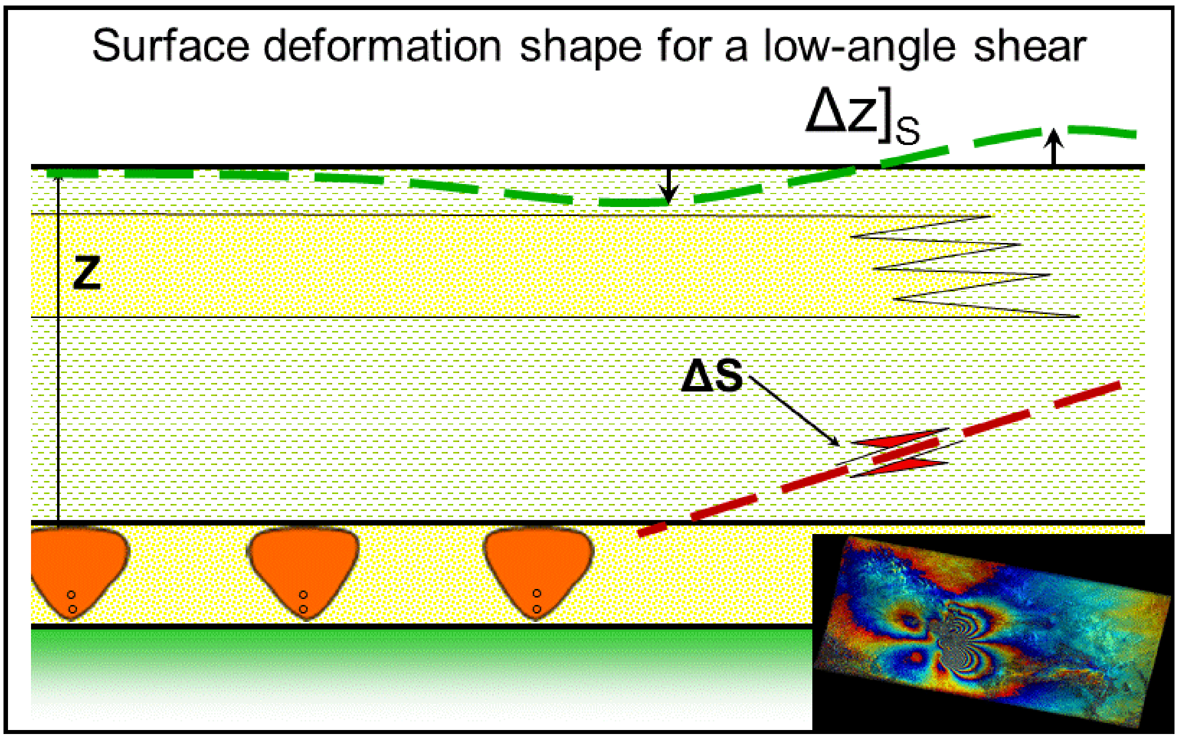


Figure 7: Surface deformation shape for a pure planar slip without volume change

The magnitude of the Δz response and the locations of the dipole centers are strongly dependent on the depth, as well as the area and magnitude of the slip S. The deformation field is somewhat more affected by the elastic properties of the overburden than in the case of the pure volumetric dilation shown in previous figures. This is because a large shear slip pushes and pulls the rock, propagating compressional and extensional strains into the overburden and underburden of the shear plane.

In this case, if there is a great deal of heterogeneity in the material properties above the shear surface, and if the shear plane is of a significant size with respect to the depth (e.g. 0.3 - 0.4 x Z), the details of the surface deformation patterns are more difficult to predict than for the case of pure volumetric

[6] The specific location of the slip surface S on the diagram is not intended to represent the most critical slip surface in actual SAGD projects, it is illustrative only.

dilation. Similarly, mathematical analysis of surface deformations involving large components arising from large-scale slip movements at depth are far more challenging than the simple nucleus-of-strain models that are widely used to analyze surface deformation information in a simplistic manner.

The issue of heterogeneity is illustrated in part by the geological cartoon shown in Figure 8. The sedimentary environment shown reflects an accreting sedimentary sequence associated with a transgressive estuarine accretion plain, an environment thought to be roughly what was responsible for the deposition of the oil sands in the area of Alberta where shallow SAGD is being considered. What are the differences in the mechanical properties of the different lithotypes? Will this have a large or a modest effect on the mathematical analysis of the surface deformation measurements? Heterogeneity confounds pressure measurements so that a detailed pressure sensor array still possesses great uncertainty. Can this be resolved in any way? These are questions that can only be answered by modeling and measurements to calibrate the models quantitatively.

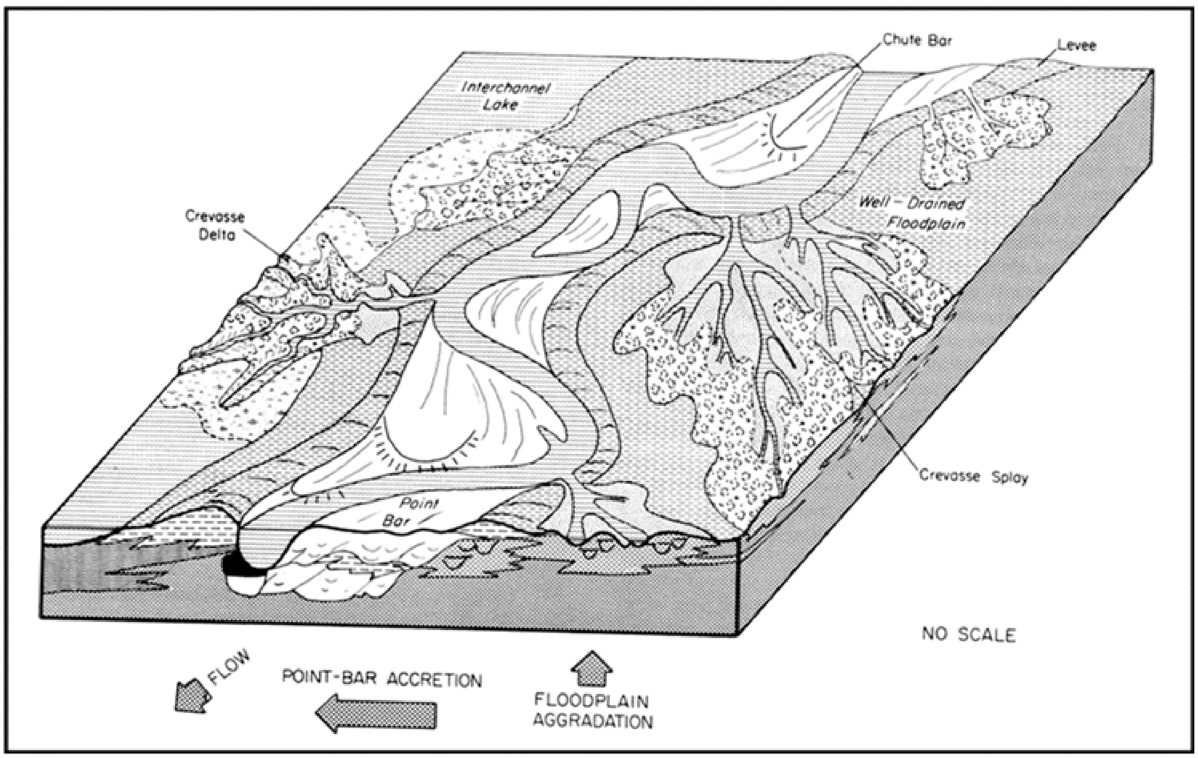


Figure 8: Estuarine accretion plains are formed by meandering rivers, and the degree and scale of lateral and vertical heterogeneity can be appreciable. This is the sedimentary environment in which most of Alberta's shallow SAGD assets were laid down

3.2 Sources of Errors and Signal Filtering

3.2.1 Systematic and Random Errors

Most sources of non-reservoir surface movements have different characteristics (Figure 9) that allow them to be removed from a data set through filtering techniques. These are systematic errors, and they are not thought to be of any consequence in the relatively short time frame of a typical SAGD project when the issue of caprock integrity is being examined. For example, regional subsidence or permafrost may, in some areas (such as the Mackenzie Delta), be an issue.

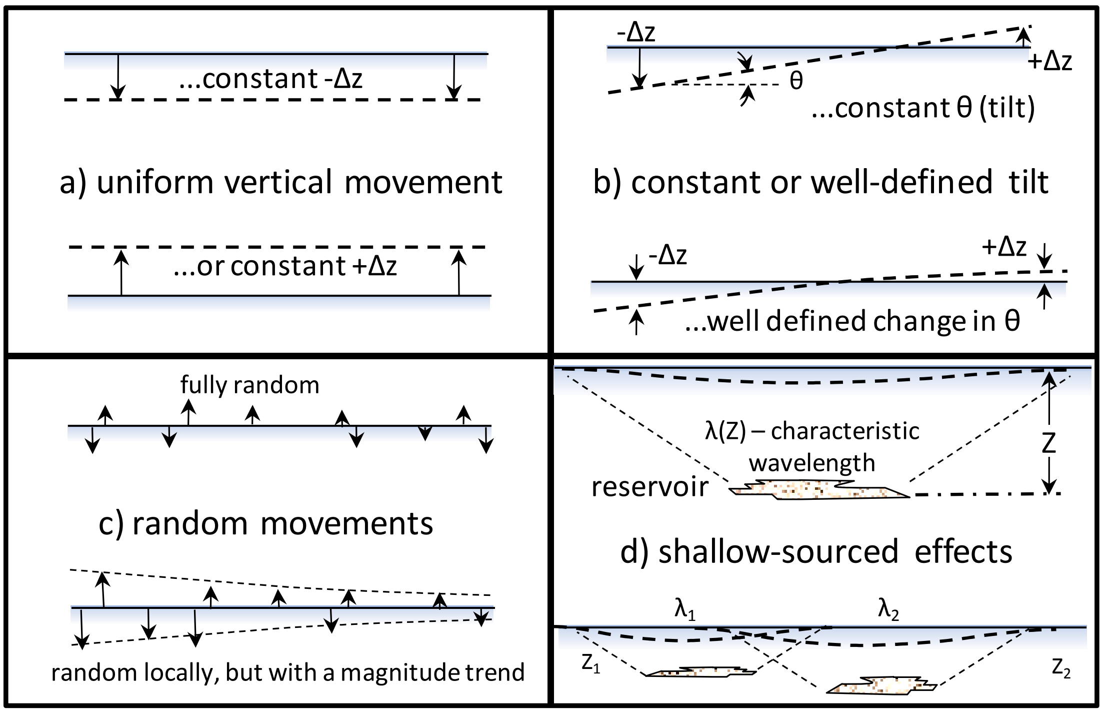


Figure 9: Types of systematic error

In Figure 9a, the source of error arises from a process such as a wide-spread and uniform change in ground surface elevation, but on land this happens only at scales of hundreds to thousands of years, and the same may be said of the systemic tilt in Figure 9b. This type of error has a wavelength that is extremely long (~infinite) whereas the reservoir-sourced subsidence has a definite wavelength related to the depth of the volume change. Thus, it is a simple matter to subtract any constant (systematic) error from a surface subsidence data base, and this is facilitated if the surface survey stations are planned to extend some distance beyond the edge of the subsidence bowl.

In some regions there may be a ground uplift and decline seasonally associated with freeze-thaw effects. Random error, either the randomness associated with the measurement method, or small random movements from seasonal effects, have little effect on the analysis of deformation as long as the errors are truly random in space and in time and are of a magnitude less than perhaps 20-30% of the characteristic amplitude of the ground movement at the surface. It is not widely understood that fully spatially random elevation variations where the statistical distribution of the errors is genuinely

Gaussian in nature (Figure 9c) do not contaminate the information content that is imbedded in the $\{\Delta z\}_N$ data vector, providing the mean magnitude of the random variations is small enough that the underlying subsidence bowl data from the reservoir compaction can be easily identified mathematically. An example of Gaussian error is the standard process error that arises as a network of leveling of GPS stations is surveyed. Because of the limitations in precision of an instrument and standard human error, such variations tend to be truly random. Far more difficult to account for is the case shown in the bottom part of Figure 9c where there is a locally random process that also has a spatial component of variability. This might arise, for example, if there is a laterally changing intensity of permafrost alterations consisting of both upward and downward components. These cases create difficulties in filtering because they can be hard to identify and specify quantitatively, particularly if the lateral variability is also neither Gaussian nor systematic (i.e.: not definable).

Figure 9d shows the concept of different subsidence profiles (or heave profiles in the case of SAGD processes) with different wavelengths arising from deformations at different depths or of different widths. The upper sketch represents the case of surface subsidence arising solely from a deep reservoir source. The lower sketch shows shallower compaction cases; clearly, the shallower the source, the less is the width of the side of the subsidence bowl; a source only 100 m deep will generate a side slope about 200 m wide, a source 3 km deep will generate a side slope width of about 6 km. The extent (length) of the side slope of the bowl is a function of the reservoir geometry as well as the depth to the source. However, the magnitude of the slope is a function mainly of the magnitude of compaction at depth, as discussed above with respect to Figures 4 and 5, as well as the shape of the zone at depth (sharp edges or diffuse edges). For an elastic response of the overburden, there is a maximum slope that can be generated for a particular value of compaction at depth, and there is a characteristic width of the side slope of the bowl.

3.2.2 Cyclic Processes and Time-Series Filtering

In technologies such as SAGD, the pressure is kept constant, so there is realistically only the possibility of volumetric expansion at the reservoir level, which is equal to the sum of the thermal expansion and the shear dilation associated with large shear stress changes. Similarly, steam-drive and steam-flood approaches are generally operated at approximately constant pressure conditions, and, providing the formation is a quartz-rich sandstone of porosity less than 32%, heave will take place, without any significant compaction (in California, the 50-60% porosity Diatomite evidences massive collapse when contacted by steam).

In CSS – cyclic steam stimulation, vertical surface movements are positive (heave) during the steam injection cycles, but subsidence occurs during the production phase. This subsidence is the consequence of the compaction taking place in the reservoir during the pressure depletion phase, and it has been called recompaction drive because the loss of porosity helps squeeze oil out of the porous strata to the production well. It is an important drive mechanism in cyclic processes, and is measured and correlated to injection periods to aid in calculating volume balances and process progression. Figure 10 is a representation of the ground heave occurring during cyclic steam injection. Initially, little Δz recovery occurs because the dilation is limited and not reversible. In later cycles, the dilated region is large and most of the deformations induced during the injection cycle are recovered. Calculations show in such cases that the vertical movements overall are dominated by dilation, and only 0.05 – 0.10 m of vertical movement can be ascribed to temperature effects alone (thermoelastic strains).

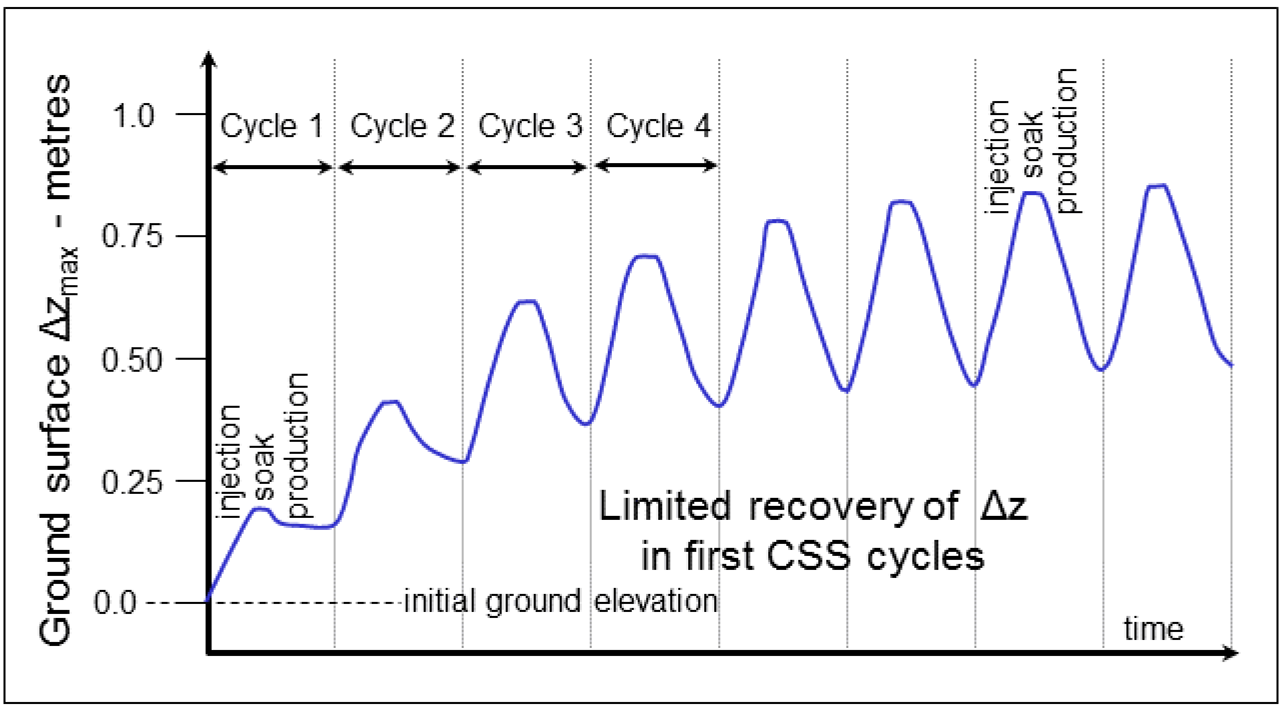


Figure 10: Vertical ground movements above a cyclic steam injection process

Figure 11 is vertical heave above a shallow SAGD project after a particular time. In this case, several years later (after the time at which the figure was drawn) the vertical movements had locally exceeded

600 mm, despite the process being maintained at a constant pressure of less than 2 MPa. Companies who have systematically measured the ground movements above thermal processes have found that the methods are extremely valuable in determining what is happening at depth.

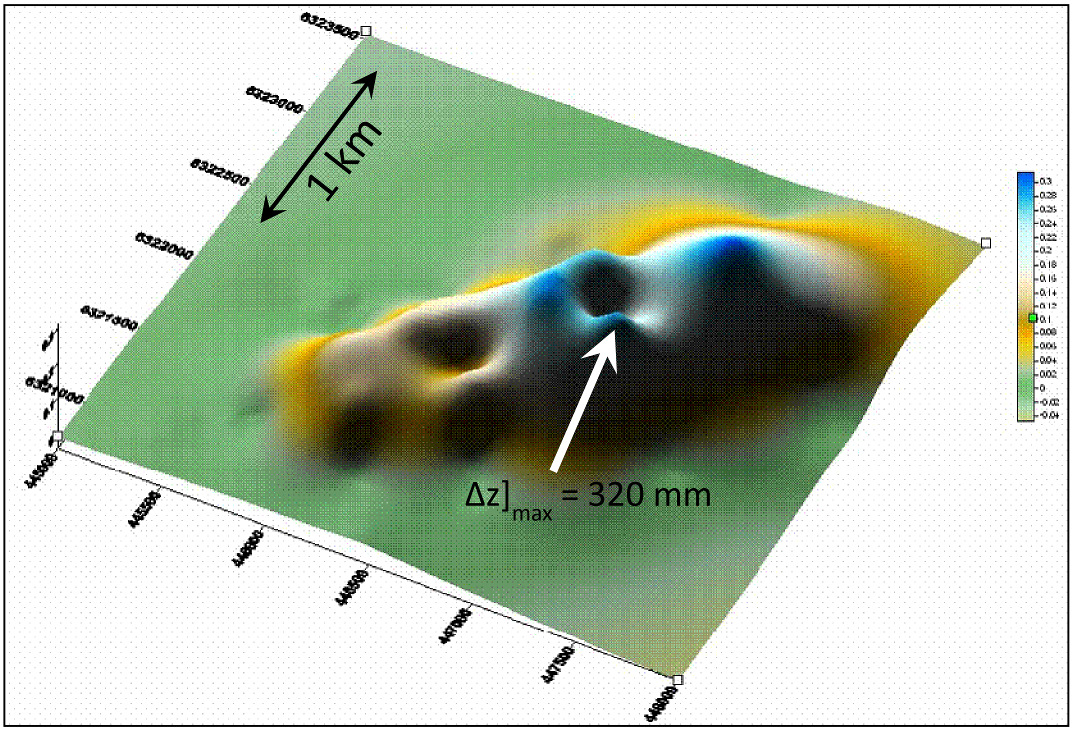


Figure 11: Vertical ground movements above a shallow (<200 m) SAGD operation

Sources of subsidence or heave generally also have characteristic temporal effects that appear in time-series plots of surface elevation. In the case of SAGD these can be linked directly to the evolution of the chamber size in space and in time. Suppose that information from a surface elevation array is collected on a daily basis and plotted versus time. However, because of changes in fresh water zone thickness and other effects arising from seasonal wetting and drying, perhaps combined with freeze-thaw effects, the change in elevation relative to the local base line should show some annual effect superimposed upon any gradual trend that may exist (the latter is thought to be zero for SAGD time periods). Similarly, the surface elevation may show relatively sudden changes that arise from events such as freezing or thawing, and these processes also have a characteristic time (Figure 12).

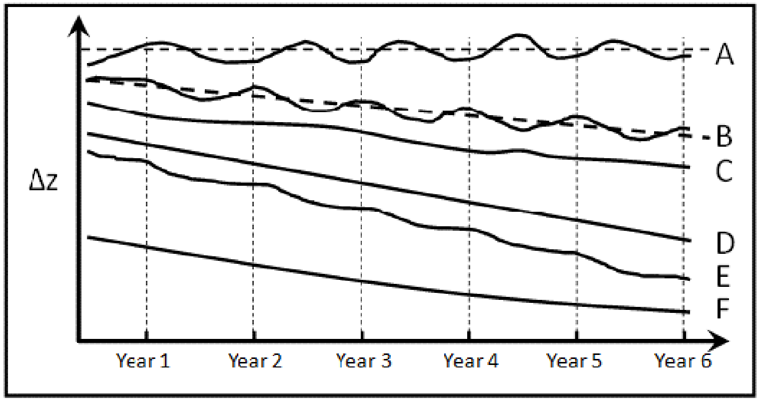


Figure 12: Time-series plots of surface monument behavior in a deltaic region experiencing annual effects (different locations)

If injection rates are known and the chamber growth is predictable, then it has a strong temporal signal that progresses with time; it may be abstracted from any cyclic seasonal changes. This is done with filters that have certain wavelengths in time and are referred as Fourier filters. The method is to identify the wavelength of a cyclic signal (e.g. 365 days for seasonal changes) and then filter out all deformations in the data that have a wavelength of, for example, 340 to 390 days. In the case of SAGD deformations, any cyclic surface movements are expected to be small in any case because the pressures are maintained constant, and their presence may not degrade the analysis of surface movements. Also, there is probably not a significant annual variation associated with the SAGD process itself (this is not necessarily the case for all oil fields: many heavy oil fields in the Lloydminster area in the period 1970 – 2000 showed consistent annual variations in production rate, and hence reservoir deformations). Also, CSS processes are cyclic in nature, but there is always excellent information about the injection and production periods, so it becomes an easy manner to eliminate extraneous signals.

3.3 Deformation Measurement Array Characteristics

A high-quality surface ground movement measurement array is needed for each thermal project (each combined SAGD pad or CSS pad, accounting for spatial overlap and other related issues) if there is to be any realistic expectation of the data having use for purposes of alarm for risk mitigation. The use of survey monuments alone is not sufficient because of the large time lapse between data acquisition and the deformation map (or deformation-rate map). Thus, in general, this discussion focuses on an array of reflectors for LIDAR technology, subsidence or total stations for D-GPS, shallow buried tilt meters, or the environment for GB-InSAR. Nevertheless, because there are also longer-term purposes for the surface movement data, an array must serve the dual purposes of giving sufficient information for an alarm, and being of suitable design for more detailed mathematical inversion of longer term information. Perhaps in all cases, if the array is designed to give good short-term data, it will also give good long-term data, unless there is a problem with calibration drift over time.

This array must be designed on the basis of a number of principles:

a. The array must extend beyond the geographical extent of the subsurface reservoir to capture the subsidence bowl. Specifically, it should extend laterally from the edge of the reservoir a distance 2·Z (where Z is the depth to the reservoir).
b. Surface leveling stations, GPS sites, tilt boreholes, and so on, should be anchored well below present and expected future depths of surface effects to eliminate shallow diurnal and seasonal effects and to prevent interaction with equipment or vandals.
c. Leveling and tilt stations should be placed more densely in regions of higher information content with respect to the reservoir heave expectations.
d. Because infrastructure (buildings, roads, wellheads…) can lead to effects on the ground level (re-gravelling a road for example), leveling stations for the most part should be placed away from infrastructure to reduce data contamination risks.
e. A sufficient number of leveling (or GPS or LIDAR or tilt) sites should be included to be able to perform spatial filtering of the data so that short wave-length (definitely not reservoir-sourced) and extremely long wave length sources can be easily discriminated.
f. If concern exists over the presence of local heave or subsidence contributions that are cyclic in nature or limited in depth, the array of leveling or GPS points should be measured frequently so that anomalous responses can be easily identified.

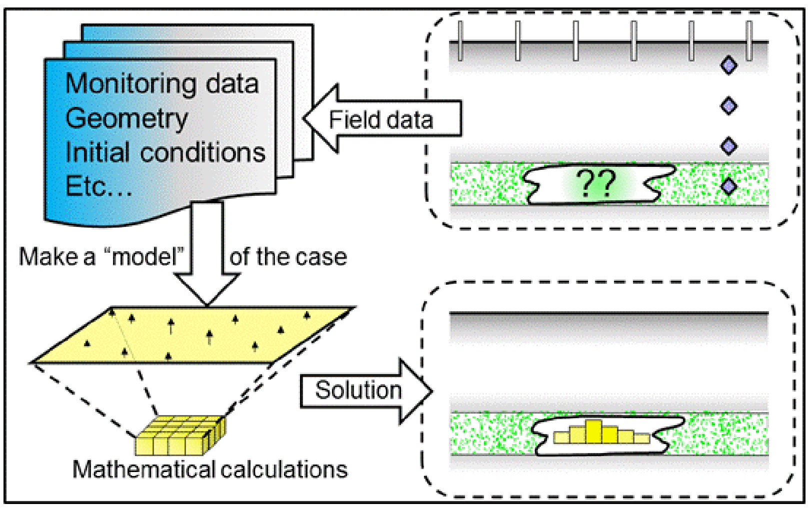


Figure 13: Inversion of the surface data to give volumetric changes at depth

3.4 Nature of the Surface Movement Data

Some minimum criteria are needed for surface movement data suitable for use in mathematical analysis, and these are listed below. Here, the discussion is presented in terms of a number – N – of vertical deformation (subsidence or heave) – $\{\Delta z\}_N$ – data points deemed to be located on a flat horizontal plane representing the surface of the earth. The N (or more) data points are located at a specific number of locations defined by points (x_i, y_i) in a surface Cartesian coordinate system (X, Y), and these points are not uniformly spaced for various reasons (accessibility, inversion needs…). The data have been collected by one or more technologies that may include survey leveling methods, inclinometers, GB-InSAR, LIDAR, satellite methods (InSAR, D-GPS), aerial photography, and so on.

The data is deemed to have been collected using best reasonable practices, and it is assumed that no systematic operator error has entered the data set (systematic error from external sources is another issue). In the points below, the focus is on points of measurement of Δz, and similar guidelines can be developed for other technologies and measurement methods. For example, if tilt or $\{\Delta x, \Delta y, \Delta z\}_i$ are measured, then fewer data points are required to achieve an acceptable mathematical inversion.

a. The surface data must be sufficiently dense (enough reliable data points) to allow a statistically acceptable mathematical inversion that provides a means of clearly understanding the spatial distribution of deformations at depth. This is estimated to be approximately 150-200 reliable sites for a one square kilometer SAGD well pair array at a depth of 150 m. Because cyclic steam operations will in general be taking place at depths greater than 250-300 m, details of the array must be modified to account for the spreading of the deformation bowl (see Figure 5).
b. The (x_i, y_i) locations of $\{\Delta z\}_N$ cannot be placed wherever desired at the surface. In typical operations there are regions that are inaccessible to monument installation because of swamps or infrastructure. In general, the pattern of sites cannot be highly regular. It is also not appropriate to place any ground deformation targets near to or onto any thermal well or heated structure because of expansion of the steel.
c. The specific (x_i, y_i) locations of the $\{\Delta z\}_N$ points is amenable to mathematical optimization, with locations chosen to provide maximum value. Placement of tilt measurement systems on the steepest parts of the deformation surface, sparser placement in the flat part or on the flanks beyond the $0.20{\cdot}\Delta z_{max}$ subsidence contour, and so on.
d. Some of the surface Δz or tilt points must extend out to the edges of the subsidence bowl (preferably beyond the $0.10{\cdot}\Delta z_{max}$), two lines are recommended in general. Such ground truthing is valuable even if satellite technologies are used to guarantee calibrations and consistency. Accurate deformation measurements along these lines extending away from the central part of the subsidence bowls help the analysis in several ways.
    i. The nature of the decay of the $\Delta z(r)$ away from the central subsidence bowl can be well-defined and thereby be used to help identify regional subsidence effects.
    ii. The data from the extended lines can be used to mathematically constrain the inversion analysis so that the results are more likely to be physically correct (less uncertainty).

Generally, tiltmeter sites or monuments for precision leveling surveys are designed to be placed below a depth of about 5-8 m to ensure stability. Tilt meters do not require sight lines and can be fully isolated. There are few environmental issues with the shallow holes needed for installation of tilt locations or monuments, except that cutlines must be installed for small track mounted rig installation access.

4 Techniques for Deformation Monitoring

4.1 Conventional Leveling Surveys

Leveling surveys were used in Alberta in the period 1985 -2005 to measure Δz above steam injection projects, including several SAGD projects, as well as CSS projects. Measurements using level surveys continue to be used, but they suffer from the following deficiencies:

a. Leveling is performed at intervals of at least several weeks, so the Δt interval is typically in the range 20-50 days, perhaps less in the winter
b. Survey monuments have to be seated at depth (4-6 m) to be independent of seasonal effects and shallow surface effects – Figure 14. (Note that any Δz measurement technology, including LIDAR and GB-InSAR, tilt and D-GPS, has to address this issue.)
c. Monuments must be protected from equipment
d. Lines of sight must be cleared through woods
e. Interpretation of the data may take several weeks once the data are available

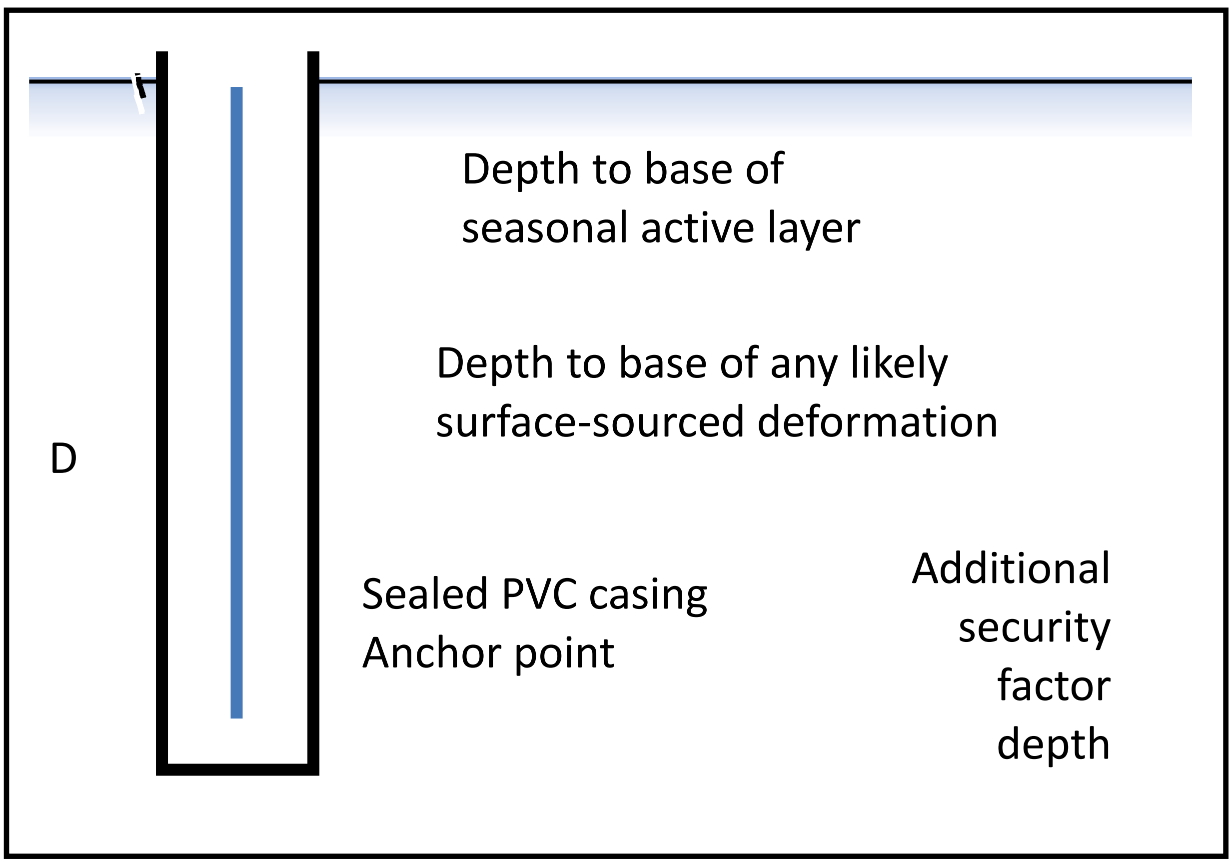


Figure 14: A typical design for a monument location for leveling. Similar well-anchored systems are recommended for all methods requiring fixed stations.

These issues make level surveys useful for tracking long-term movements over minimum time intervals of weeks to months, suitable at best for intermediate-term monitoring of about a one-week interval in practice.

Figure 15 shows a typical leveling survey arrangement of benchmarks. Sub-centimeter precision in Δz is feasible over distances of several hundred meters using standard optical leveling methods. Although it is possible to use precision distance ranging in combination with leveling to obtain the pattern of (Δx, Δy), this is generally not done because it required carefully fixed reflectors at the monument sites as well, and the magnitude of (Δx, Δy) is usually far less than the magnitude of Δz. A sufficiently dense areal coverage is necessary to achieve a reasonable degree of accuracy if such data are used for mathematical inversion to estimate the regions of volumetric expansion or contraction in the reservoir, and it is also possible to analyze good quality data in terms of general shear distortion at the reservoir level.

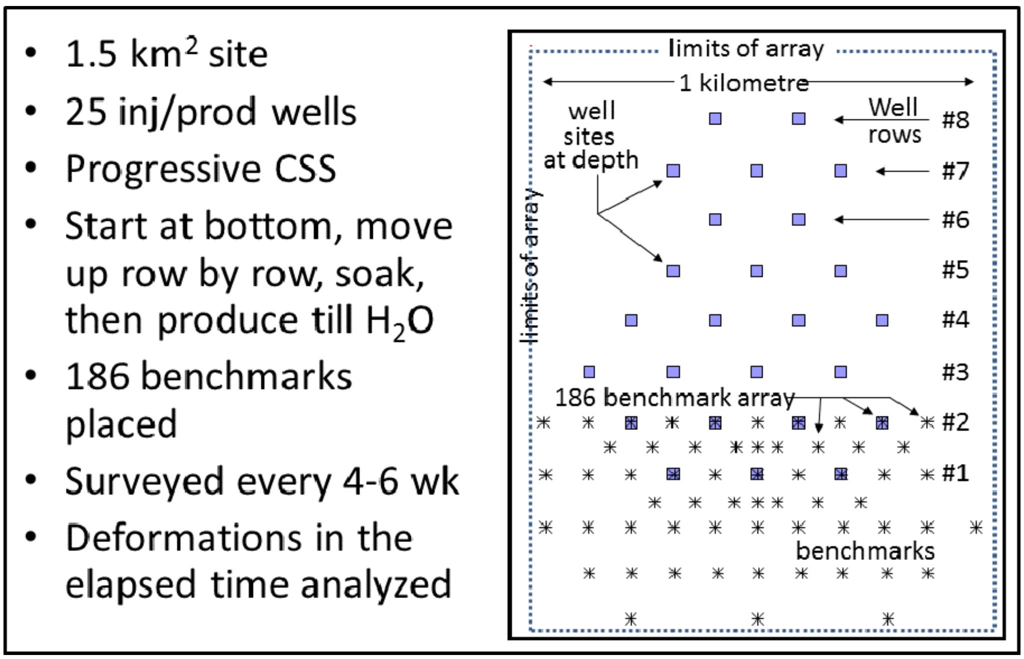


Figure 15: A leveling survey array above a sequential cyclic steam injection site. Each benchmark is a leveling site, and production from a row was maintained until the H_2O production level exceeded 95% of the total oil + water rates

4.2 Aerial Photography, InSAR Surveys

Aerial photography was developed in the 1990's into a precision areal measurement of the changes in elevation Δz(x,y) over time. The method is based on automated photogrammetric methods using high-resolution aerial photographs with multiple overlap. Each point on the ground is located in multiple overlapping photographs taken from a low-flying aircraft (300-1500 m elevation); up to 9-fold overlap has been used. The differences between surveys taken at different times are determined and presented as a precision contour map on the horizontal plane (X,Y). Precisions can easily be at sub-centimeter levels with good targets, although issues such as snow cover and dense forest cover create problems. Placed targets that are easily visible in the overlapping photographs facilitate the analysis.

Figure 16 shows the concept. A low-flying aircraft takes a series of photographs, and because of the changing location, parallax differences develop, and these can be measured with automated digital photogrammetric methods. As with any similar survey method, short turn-around is not a realistic option.

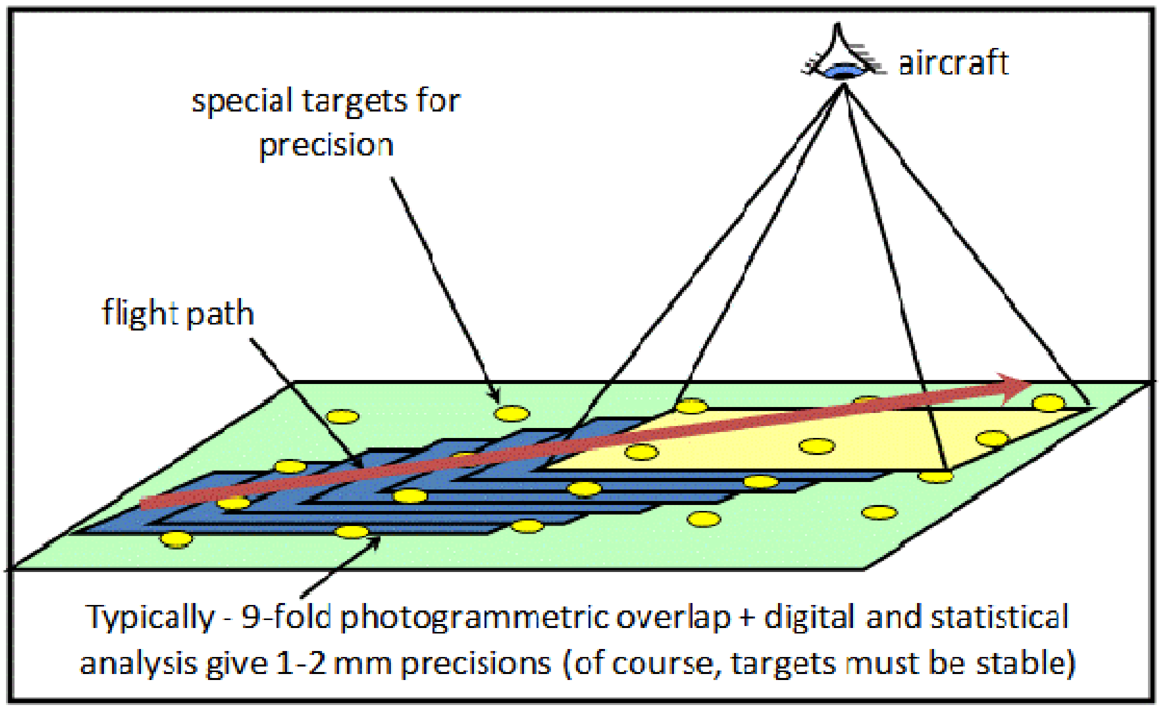


Figure 16: Aerial photogrammetry acquisition

The advent of Interferometric Synthetic Aperture Radar (InSAR) scanning from satellites in the 1990's has been a seminal development in large-area measurements of Δz and has been widely applied to analysis of tectonic movements (fault slip analysis), subsidence of large regions, and heave (or subsidence) above steam injection projects in Canada and the USA. The process involves obtaining a reflection from the ground surface from a scanning with a monochromatic radar frequency, and subtracting the data from that of a previous InSAR survey. Then, residuals give an interference pattern that is converted into a Δz(X,Y) map projected onto a horizontal plane. Precisions at sub-centimeter levels is feasible, and thick forest cover or wet snow degrade precision analysis of the ground surface movements (dry snow is transparent to radar frequencies). InSAR can also be based on airborne or ground-based episodic measurement methods.

Figure 17 shows the Δz distribution over a wide area above a cyclic steam project at IOL Cold Lake over 86 days. The diffuse regions are because of tree cover, but excellent Δz data are available, showing the vertical ground heave above the injection rows, and recompaction during the production phase over the production rows. Sub-centimeter resolution is possible, but sequential InSAR surveys are needed to delineate changes because the approach is a differential calculation based on the interferometric analysis of two images taken at different times. In other words, InSAR (and aerial photogrammetry and surveying…) are snapshot methods and can only be used if there are two or more snapshots.

InSAR and aerial photo surveys provide changes in elevation over a discrete time interval – $\Delta z/\Delta t$ – between two specific times – $\Delta z_i = z_{t2} - z_{t1}$, or $\Delta z/\Delta t = (z_{t2} - z_{t1})/\Delta t$. The absolute values of the elevations involved are not known, only the relative changes that have occurred between the two snapshots. The rates are averaged over the entire time interval, so it is impossible to determine any short-term deviation from this long-term average if there are no other data sources available. This issue, combined with the time required for an analysis to be completed, makes all snapshot methods such as level surveys, InSAR, and aerial photogrammetry unsuitable for any alarm use. They remain of great value as means of regionally quantifying long-term ground movements, estimating large-scale volume changes, reservoir volumetric balance, identifying where fluids in the subsurface are flowing, and so on.

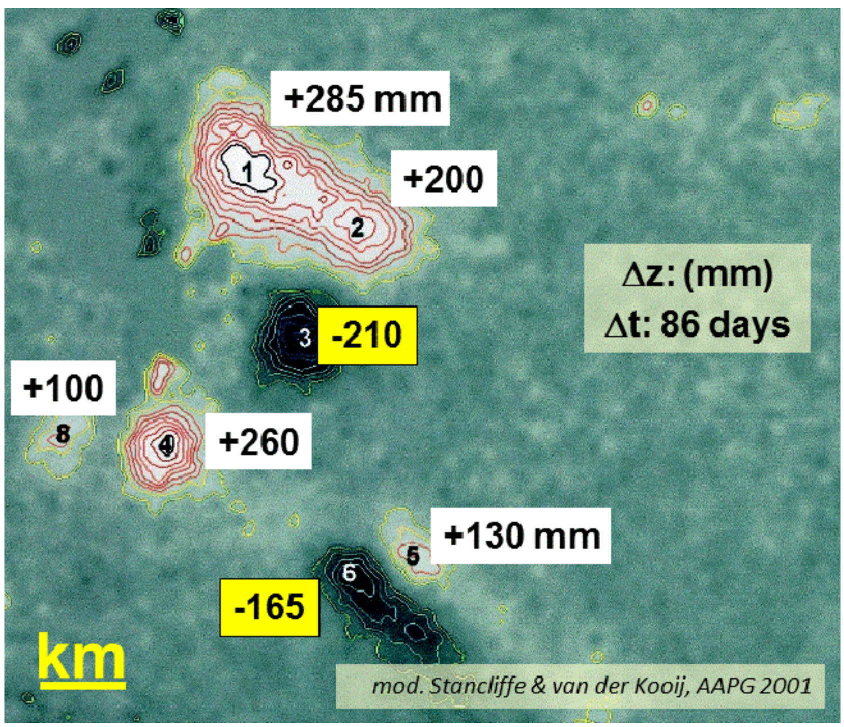


Figure 17: Interpreted InSAR Δz map, IOL Cold Lake Project

In order to better understand the changes in absolute elevation over time, which can help identify any systematic non-random subsidence or tectonic tilt, the local data need to be tied into a stable benchmark system that is occasionally surveyed as well. This typically will involve one or two level survey lines going from the project area to a distance at which there is minimal effect on the elevation from the process. For a project 200 m deep for example, the calibration level monument line should extend about 500 m beyond the edge of the ΔV region at depth in the reservoir.

Figure 18 is another InSAR map above a region of the IOL Cold Lake Project, and the product can be easily understood. The time interval is relatively short for InSAR imagery, from September 08 to October 02, 2000, just over three weeks. Nevertheless, about 15 cm of vertical motion took place above steam injection rows, and far lower recompaction rates were observed over regions of production.

Satellite availability, although better now than at that time, limits images to certain times so that the feasible frequency of snapshots remains in the range of weeks. The analysis takes time, so that the lag from acquisition to provision of the product (Figure 18) remains too long for any reasonable use as an alarm. One advantage of InSAR is that the satellite corporations store image data even though the data have not been specifically purchased by a client, so it is feasible to “go back in time” about 10-12 years and obtain surface movement rate information averaged over time scales typically of several months. Thus, an operator such as Cenovus at Foster Creek can purchase vertical ground movement history and use this to help understand the nature of the process, to quantify shear dilation, and so on.

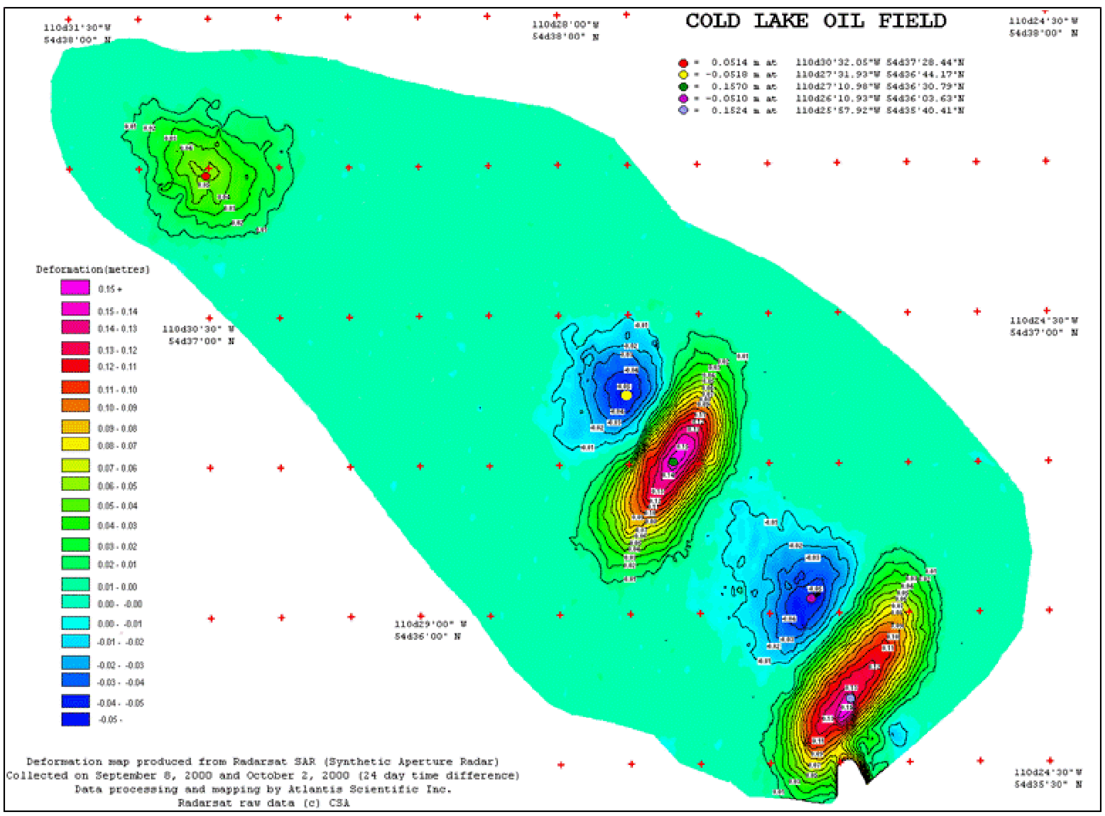


Figure 18: Interpreted InSAR Δz map, IOL Cold Lake Project; Megarow steaming leads to red-orange areas of uplift, and production to blue areas of re-compaction

As mentioned above, using aerial photogrammetry and InSAR to monitor shallow SAGD operations is similar to the process of obtaining a level survey data set: the data are converted into images which are “snapshots” of the deformations that have occurred between two data acquisition times which may be weeks or months apart. Though the data are extremely valuable to understand the details of the ground deformation over long time intervals (generally months), the analysis of the data currently takes at least a week under typical conditions, therefore the methods are not suitable for detection of anomalies on a time scale less than a month or two.

Use of small programmable drones is an alternative to satellite or airborne methods and this type of service is now available commercially.

4.3 Surface and Wellbore Extensometers, Strain Gauges

Direct measurements of changes in length of casing in boreholes have been used many times in various applications in mining and civil engineering, but far less commonly in the oil and gas industry, and generally in much shorter wellbores. Furthermore, there is often a question as to whether the casing is deforming along with the rock mass in a fully bonded manner, or whether there is shear slip that is taking place between the casing and the rock mass. This arises in all cases where the casing itself is being measured, or some instrument bonded to the casing is being used. Anyone who has worked in thermal recovery of heavy oil is familiar with the vertical movements of wellheads in cyclic steam technologies, and this is unequivocal proof that the rock is not moving directly along with the casing, but it must be moving nonetheless. Therefore, any use of an extensometer is limited to monitoring wells or other wells that are not experiencing large thermal effects.

It is also possible to use surface extensometers to measure local ground extension or compression. Figure 19 shows images of just a few of dozens of configurations available.

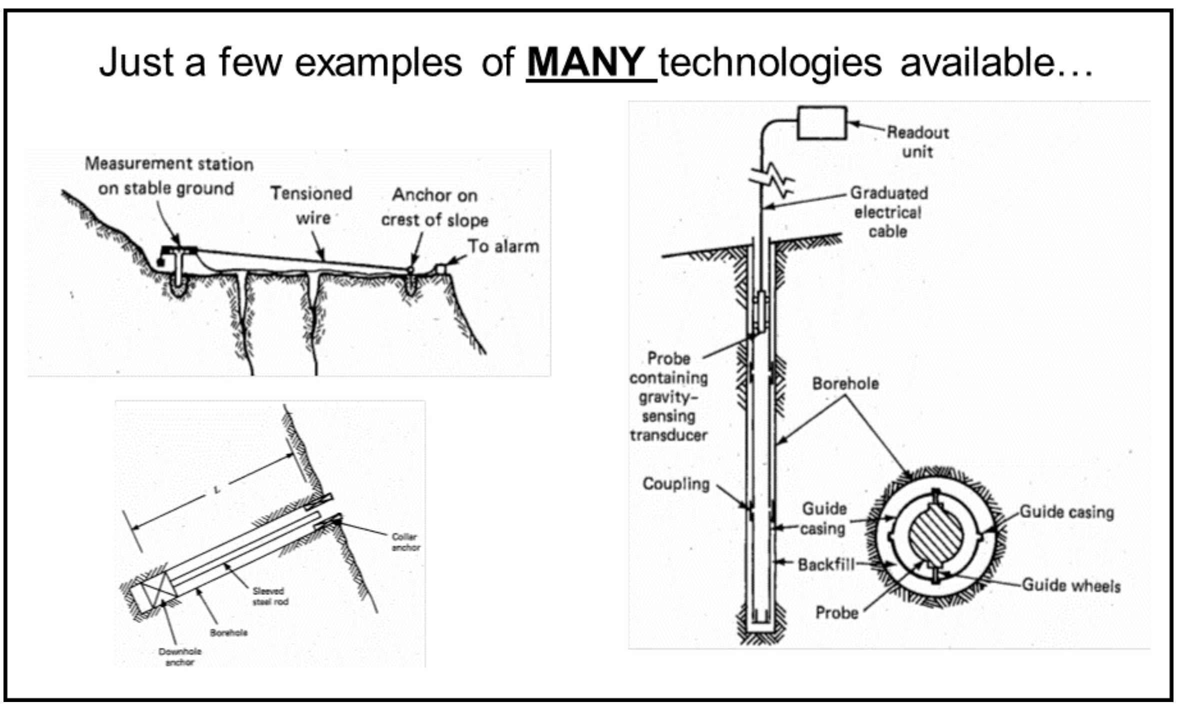


Figure 19: A diagram of a few extensometer technologies

On the surface, different linear extension devices ranging from a tensioned wire to a fibre optics device a kilometer long and buried a meter deep can be used. The readout sensitivity is high, better than one part ΔL in 10,000 in fibre optics devices. Other methods include vertical shallow well inclinometers (a form of tilt meter) such as those installed at the original UTF site (Figure 20), vibrating wire strain gauges, and so on. This entire area is worthy of revisiting for any project to assess whether such measurements could serve as a valuable means of understanding ground movements in real time because all of these methods are amenable to electronic readout. It is important to remember that the placement of these devices usually has to be far from active wellheads, away from roads, and so on.

At this time, surface extensometers and shallow borehole extensometers have not been used in monitoring steam projects in any systematic manner. Extensometers within the wellbore (Figure 21 shows a schematic view of a mechanical extensometer in a dedicated well) have been used in the Imperial Oil Cold Lake project, and in many applications for relatively deep groundwater withdrawal subsidence studies (as well as numerous civil and mining engineering projects). There are various designs available including extensometers that are directly linked to the surface, others that are installed within the well and give electronic readout data.

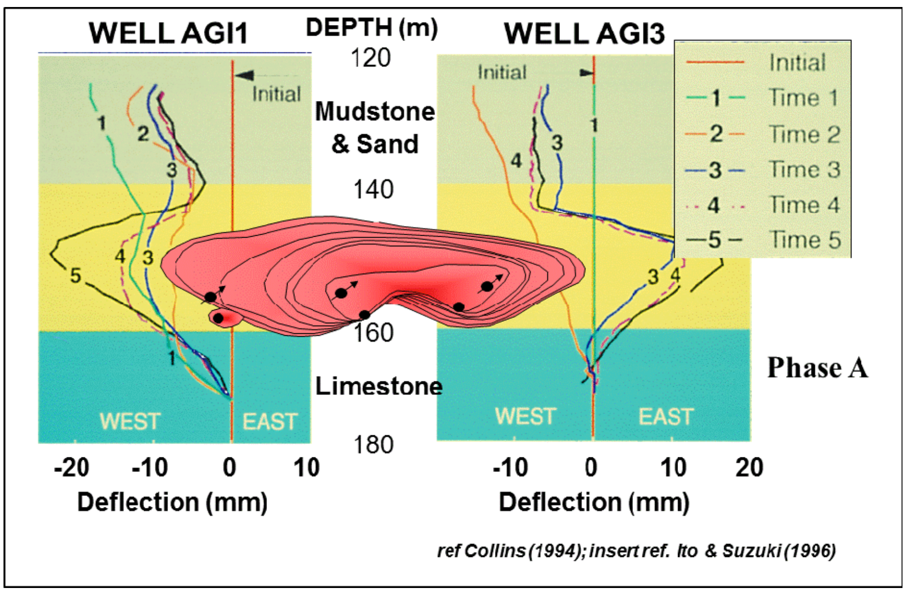


Figure 20: Schematic showing deformation measurements using borehole extensometers and inclinometers at the original UTF experiment

An important development in displacement measuring devices has taken place in the 2005-2010 period. It is now possible to use fibre optics devices with continuous measures of deformation or Bragg grating optical devices or Brioullin-scattering techniques (other approaches as well) with measurement points every 50 cm to 5 m in wellbores hundreds of meters long. These systems can be temperature compensated, but are not suitable for cases of large temperature changes which would impair their ability to sense changes in length or bending strains along the fiber length. To implement this approach in a SAGD case, the following approach would be taken:

a. The location and orientation of the fibre optic cable is chosen based on a strain-deformation analysis (just as tilt meters are placed at locations of maximum expected tilt, fibre optics deformation cables should transit zones of expected larger linear deformations).

b. A surface casing is installed to protect shallow groundwater, and a small diameter hole (100 mm) is drilled to the desired depth. The installation borehole may be vertical, inclined or curved.

c. The cable is installed with centralizers and grouted into place continuously along its entire length using a suitably designed cement grout to reduce relative stiffness compliance issues between the rock mass and the grout and the cable so that formation deformations are faithfully transmitted to the cable.

d. After setting and baseline establishment, the deformations along a cable averaged over each meter of length can be measured using a specialized readout device (not automated at the present time).

e. Elongations (ΔL) and shear distortions (ΔS) of the cable at specific locations can be determined with precisions exceeding 1 part in 20,000 with a typical installation.

An advantage of this type of installation is that electrodes for electrical impedance tomography could be installed in the grouted borehole along with the fibre optics cable, and there would be no negative effects from steel casing, and the two methods would be non-interfering and complementary.

The negative aspects of direct within-the-wellbore installations of extensometers are the following:

a. There is no extensive experience that exists for the installation of direct extensometer devices such as linear strain gauges at the surface or at the depths of shallow SAGD applications.
b. Because of the short wave length of deformation, if steamed intervals are shallow (Figure 9d), it is necessary to install many extensometer wells to have a high probability of detecting an event as an alarm.
    i. This is similar to tilt, but because deformations can be measured continuously along fibre optics cables, this type of deformation measurement is continuous along the axis of the cable, so a single borehole has a much greater amount of information than a tiltmeter site.
    ii. Thus, a few wells (8-20), judiciously placed, can help calibrate and confirm other measurement devices, and allow spatial combination of deformation data.
    iii. Also wells can be instrumented with many other types of sensors – Figure 22 – to generate high-utility monitoring wells.
c. There is no experience found in the literature that suggests that wellbore extensometers can be stable over a time period of years. Installations in most engineering applications have been in far less difficult conditions, and usually intended to measure deformations for the period of project construction and for a few years thereafter, to confirm design assumptions.

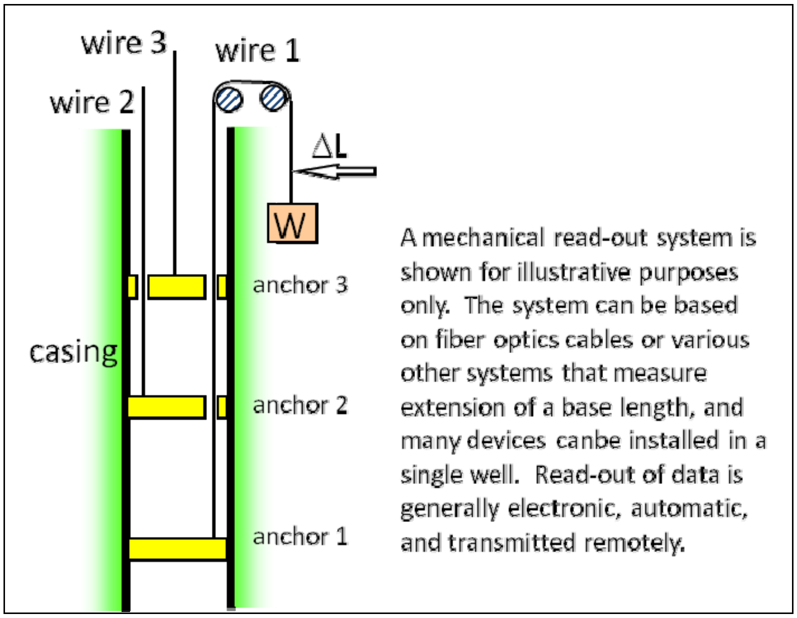


Figure 21: Extensometer installation in a vertical or inclined well

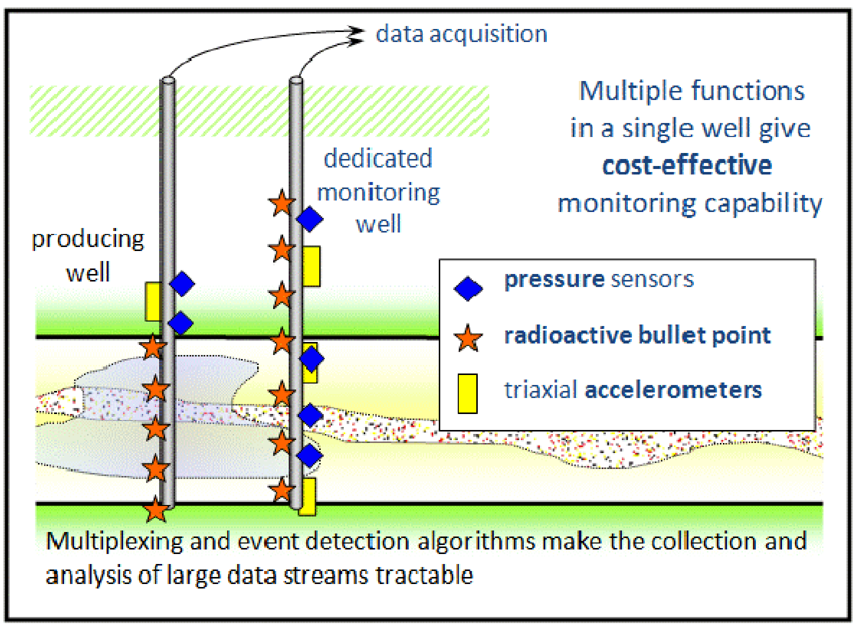


Figure 22: Multi-purpose monitoring wells

Strain measurement devices can be attached to the outside of casing, connected to the surface through use of an armored cable placed outside the casing, with the system cemented into place as the casing is emplaced. Outside-the-casing approaches are not recommended for the following reasons:

a. Corrosion of the strain gauges or other devices, zero-base drift (deterioration of calibration or baseline), and other processes acting on the time scale required (up to 30 years) will degrade the usefulness of the sensors. Replacement is often not possible.

b. Failure of the electronic devices in downhole applications in a few years is the norm, and a mean life expectancy of even 10 years would be optimistic.
c. The issue of casing slip versus rock deformation remains a concern, especially with a strong steel casing passing through soft sediments.

Specific installations of within-the-well extensometers for deformation tracking are of interest to shallow SAGD operators as well as other thermal project operators and should be investigated. Monitoring wells should be designed for multipurpose measures (including P & T). On the injection and production wells themselves, no realistic deformation monitoring can be carried out.

4.4 Casing Collar Logs, Radioactive Bullets

Figure 23 shows the principle of a casing collar or a radioactive bullet log.

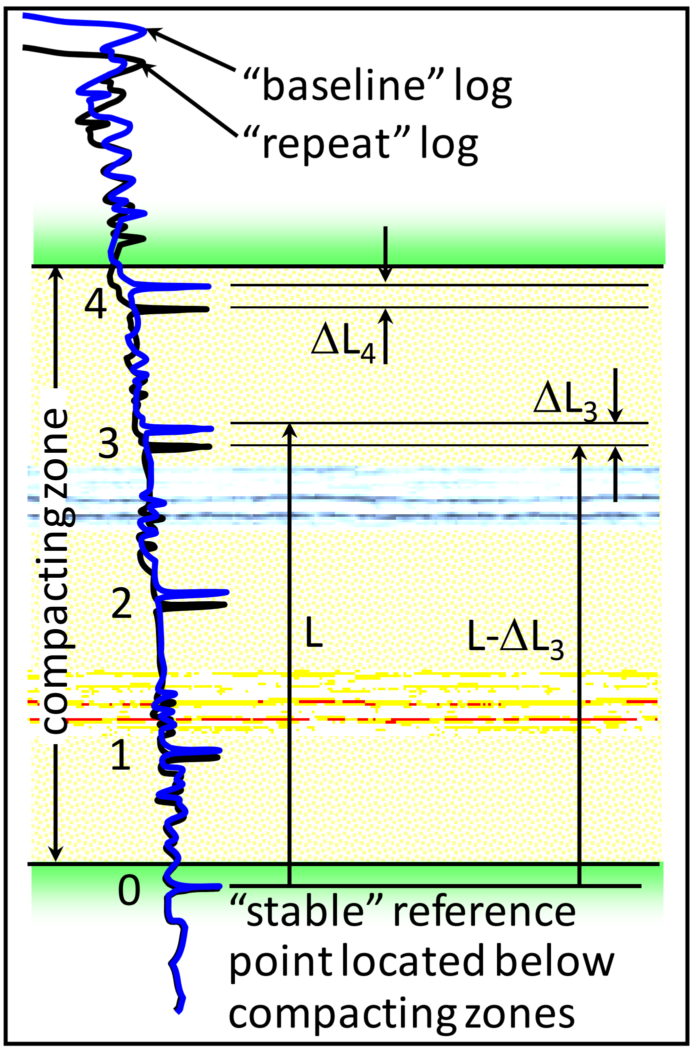


Figure 23: Measuring ΔL in or around the reservoir

The thickness of steel in the threaded casing collars linking joints of casing, generally spaced at 10 m or 13 m along the casing string, is easily detected using a precision magnetometer. If the well is near-vertical and the formation around the well is contracting in length because of reservoir compaction, the casing is carried along with the formation if no slip occurs, and the casing collars come closer together. This change in length between collars can be measured with high precision and used to allocate average strains within the reservoir intervals bounded by the casing collars.

It is necessary to first have a high-quality baseline of magnetometer information; then, repeated surveys carried out each year (for example), will allow the changes in length between collars – ΔL – to be quantitatively measured to within a few millimeters. The logging approach is useful in many applications such as radioactive bullet placement and formation interface behind-the casing log detection.

Deformation surveys based on casing collar logs are best used in wells that do not deviate from vertical by more than 10°, although up to 20° can be considered. Issues such as friction of the tool against the casing during logging (a value that may change with time and corrosion), calculations of Δz from highly deviated wells, tool precision, and other factors must be evaluated in the context of repeatability and reliability of data. These issues are well-understood by the logging corporations.

The issue of thermal effects and slip of the casing relative to the formations exists in the use of casing collar log data, and if there are processes that lead to slip along bedding planes (wellbore shear), or that lead to any axial distortion of casings, casing collar log data can be significantly degraded in terms of reliability or utility. Figure 24 shows, purely for illustrative purposes, the shapes of distorted casings from the processes of axial wedging and shear displacement along a formation interface, respectively.

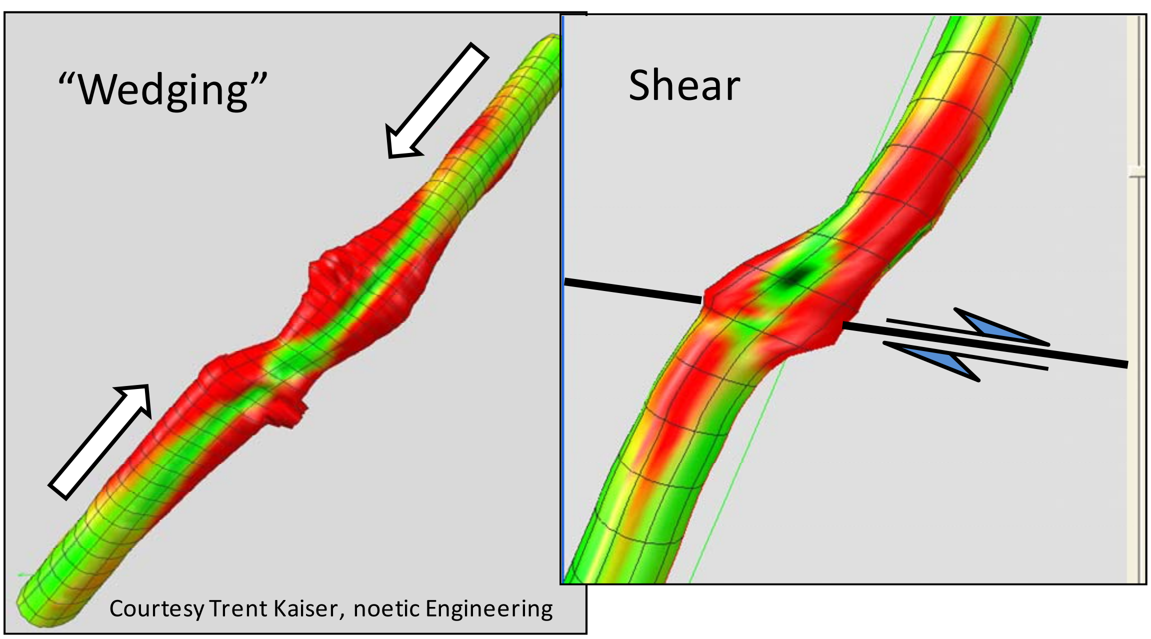


Figure 24: Examples of casing distortions in large deformation cases

Casing logs may be of some interest for shallow applications; in particular, radioactive bullets placed into the formation in vertical monitoring wells before casing and cementing may have some merit, but not for short-term alarm purposes. In comparing the nature, density and value of the data from a fibre optics cable extensometer to the data provided by radioactive bullet logs, it is clear that the costs are lower and the data of far greater use for the fibre optics alternative.

The most direct and reliable method of measuring the deformation across and above the reservoir zone is the installation of radioactive bullets into the formation rocks before an observation well is cased (steel cemented casing is necessary because the well will be intersected by hot fluids during its life). Bullets are fired into the strata at selected locations (chosen based on open-hole geophysical log data), penetrating a few cm deep, then the well is steel cased and cemented. The radioactive substance behind the casing gives a sharp spike on a natural gamma ray log, standing out sharply above background, and the spike is analyzed to determine the peak, which is compared to the peak location on a previous logging episode. Accuracies of the scale of millimeters (1-3 mm) over the baseline (distance between bullets) are feasible but logging has to be done slowly so that a sufficient density of digital data points is available for analysis. One deficiency is that it is not possible to determine exactly where between the two points the deformation is taking place. This can be partly addressed by installing more bullets, but each installation requires another wireline run, which takes time.

The figure in the section on casing collar logs is applicable to radioactive bullet logging. The spikes on the traces in this case represent the peak in gamma radiation detected by the natural gamma ray log.

The advantages of radioactive bullets are the following:

a. It is possible to place bullets exactly where desired (e.g. to straddle a reservoir interval), something that is more difficult with casing collar logs and some other methods.
b. Bullets are bonded into the formation and move with the formation, not the casing.
c. The method is completely non-interfering so the well can be used as a monitoring well for many other processes.
d. The bullets will not interfere with any other use of the well, and the bullets are not affected by perforation activities through the casing.
e. Issues such as loss of bonding (strain gauges), galvanic reactions, geochemical corrosion, and so on, do not affect the radioactive bullet method.

In the limit, the well could even be used for some technologies linked to production, such as inert gas control at the top of the SAGD chambers or episodic solvent injection. Installation of radioactive bullets into near-vertical monitoring wells only is recommended. A sufficient number of bullets should be installed to allow discrimination among the deformations in the reservoir zones (upper McMurray, lower McMurray), especially the vertical deformations taking place in the shaley sections at the top of the intervals in the shallow SAGD region. The minimum number of bullets will include one or two below the productive zone, and one just at the upper and lower interfaces of each producing horizon, plus one (or more) placed 10 m above the top of the last perforated zone. Typically, this will require on the order of 10 radioactive bullet placements.

However, as for other methods, these approaches are not continuous enough at the present time to be used for short term alarm methods, but should be revisited as technologies improve and more and more electronic read-out systems become available. Even if it is not suitable for alarm purposes, vertical monitoring wells with multiple sensors (Δz, T, p… Figure 22) are considered highly valuable to help calibrate models that may be used to interpret the deformation fields.

4.5 Behind-the-Casing Geophysical Logs

In the last 20 years, geophysical logging companies have developed a sophisticated capability to "see" behind the casing and the cement of a completed well to detect changes in the rocks (e.g. changes in porosity, density, conductivity…), or to precisely locate a sharp change in physical properties. If "behind-the-casing" logs are used to measure formation deformations, high-quality open-hole baseline data are needed, and sharp property contrasts in the formations must be identified. This straightforward process is based on conventional logging carried out during field development. However, if the potential for higher precision requires more carefully obtained baseline logs in appropriate near-vertical wells, operating companies should be encouraged to collect such logs during the field development stages.

Reference to the previous figure for Casing Collar Logging shows the principle of repeated behind-the-casing logging to identify the precise location of a strong contrast in physical properties. The most reliable contrasts are a sudden change in natural radioactivity (detected using a natural gamma log – sometimes called a lithology log) between shale and clean sand, or a sudden change in density associated with a concretionary bed (e.g. a thin carbonate-cemented band).

These methods, although they may help in delineating the general distortion fields, are not considered to be of high utility for shallow SAGD monitoring because of the high cost of logging, the inability to really use such data as short-term alarm indicators, the perturbation in the system caused by the wellbore itself (pressure migration behind poorly cemented casing for example), the small region around the wellbore that is sampled, and so on. Perhaps such data could help refine mathematical models that are used to analyze the short term deformation changes, but they are not amenable to short-term monitoring for the possible detection of incipient breakthrough events.

4.6 Tilt Meters

Tilt meter information can be obtained through a series of rock mechanics and petroleum technology articles, available at a Halliburton web site. This company is the largest provider of tilt meter services in the oil industry. http://www.halliburton.com/ps/default.aspx?navid=2450&pageid=5097

Tilt meters are geophysical precision inclinometers that provide electronic output of tilt magnitude and tilt azimuth at a spatial point – $\theta(x,y,z,)$ and $\beta(x,y,z)$. This is a vectorial quantity equivalent to the measures of dip and dip direction to specify the spatial orientation of a plane. Because the vectorial nature of the tilt output specifies the change in inclination and the direction of change, it provides information about the shape of the surrounding deformation field, not just a scalar quantity at the (X,Y) point. Hence, a single tilt datum is about three times more valuable to mathematical analysis than a scalar datum such as a single level survey value (Δz), and the surface deformation field can be delineated with about one-third of the number of sites, compared to level survey data.

4.6.1 Near-Surface Tilt Measurements

Tilt meters are sensitive to inclinations, not to vertical movements. For example, if there is a general uplift or subsidence of 3-4 mm/yr in the shallow SAGD areas for some reason, as long as it is constant over the instrumented area, it will not appear as a signal on the tilt meters. However, it will appear as a systematic 3-4 mm uplift or subsidence on the Δz survey points, if they are linked to appropriately stable regional benchmarks. This invariance to regional movements (Figure 25) makes tilt a powerful monitoring tool in conjunction with vertical movement measures.

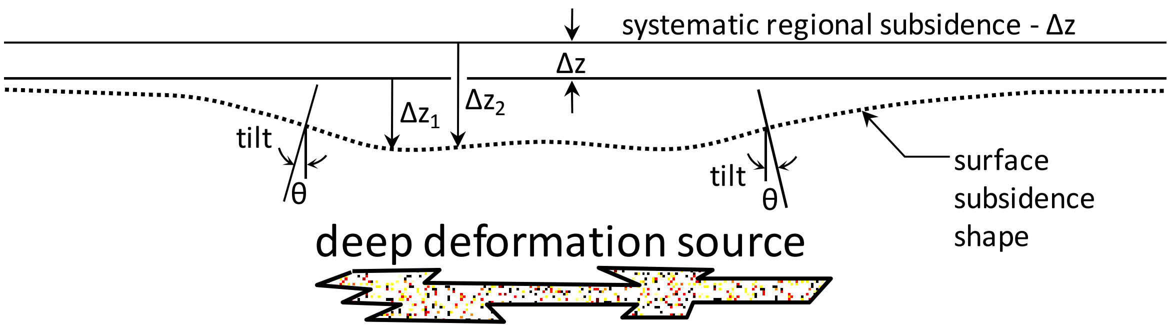


Figure 25: Change in tilt is unvarying with a systematic subsidence or heave

Figure 25 illustrates the concept. Because Δz is linked directly to a stable benchmark system, it will reflect the sum of the systematic subsidence plus the local subsidence (reservoir deformation + other local causes). However, the tilt will not register the effect of a constant Δz, therefore it is largely immune to the effect of regional systematic deformation. This is an important strength that separates the nature of tilt data from other sources that give only measurements of Δz.

If it is considered vital that the effects of the reservoir deformation be separated from the regional subsidence or uplift possibilities, tilt measurements are likely to provide that discriminatory capability. High-precision geophysical tilt meters are widely used, although they may not be the most suitable technology in all cases, and the use of other long-life inclinometers such as civil engineering type inclinometers should be evaluated.

However, there are disadvantages associated with the acquisition of tilt deformation data:

a. Each tilt station is approximately 4 to 8 times more expensive than a survey (Δz) station.
b. Geophysical and other electronic tilt meters are designed to give continuous readouts (e.g., data every 10 seconds), and they are generally not designed to be stable monitoring sites for years (although this deficiency has largely been eliminated in newer sensors).
c. A monitoring strategy for the SAGD cases has to have many sites to give a high level of probability of detection of any incipient breakthrough, and the data have to be read and

interpreted on a quasi-continuous basis, converting to reservoir deformation (Figure 26). Likely, 150-200 sites per square kilometer will be needed.

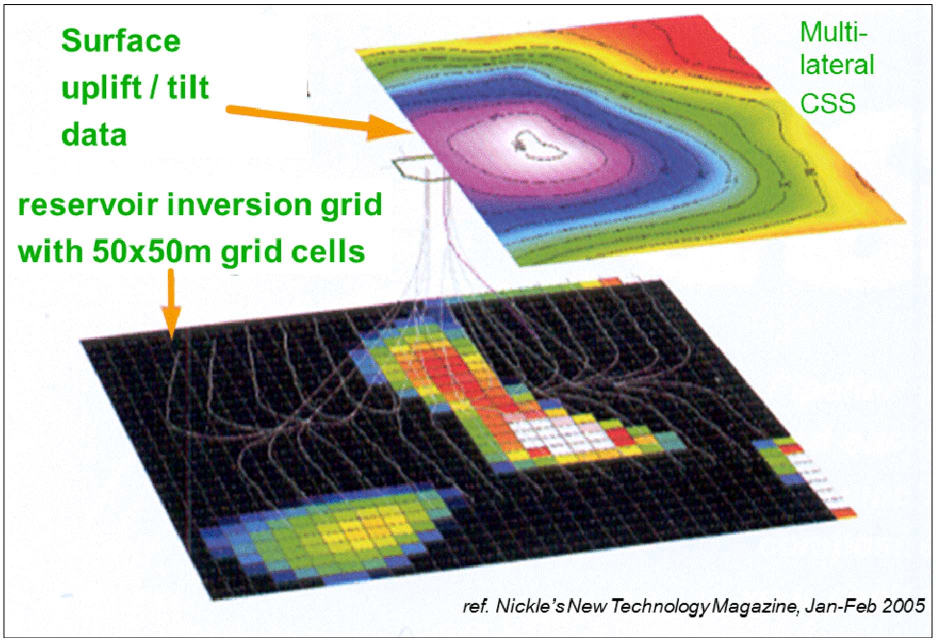


Figure 26: Shell Peace River deformation measurements and mathematical analysis

d. Tilt meters may suffer from zero base drift in the long term. In other words, their calibration baseline may not be stable over time scales of years. This means they are most valuable in conjunction with a technology such as leveling surveys or occasional InSAR surveys to ground truth the absolute elevation changes.

4.6.2 Downhole Tilt Meters

Deep tilt meters arrayed in vertical wells have been installed in cases where there was a great deal of interest in deformation measurements in order to understand technical processes at depth (e.g. hydraulic fracturing). It is not necessary for the well to penetrate the reservoir, as the tilt meter array can precisely sample the induced deformation (tilt) field above the reservoir.

Tilt meters have shown to be able to give high precision data that have proven useful in processes such as tracking volume change regions associated with steam flooding (Shell Peace River).

It is suggested that the use of Civil Engineering inclinometers be more carefully examined for possible use in shallow SAGD. Extreme precisions are not required for shallow SAGD operations, and if many sites are needed, a more economical inclinometer with electronic readout would make monitoring more economical. (e.g. http://www.geodaq.com/inclinometer.html?gclid=CP7JuLjoirECFWaFQAodaHjcFw)

4.7 Differential GPS Approaches

The standard GPS position locator gives an absolute positioning accuracy on the order of 20-30 cm, even using multiple-satellite triangulation, because of uncertainty as to the speed of signals travelling through the ionosphere. Differential GPS is not based on absolute accuracy, but on the differences in the arrival times of the various signals at pairs of close antennae (a remote antenna and a "mother" site). Because in terms of scale (100's of meters distance between antennae) the signals are passing through essentially identical atmospheric conditions in the atmosphere and ionosphere, it is possible to measure and compute with great precision small changes in the elevation between the two antennae. In other words, it is the difference that is determined, not the absolute elevations, hence the term Differential-GPS (D-GPS), which is not subject to the same level of imprecision as the absolute position locator algorithms.

Because the differences in elevation at various times are calculated, the stable mother site does not have to be remotely located, but must be protected and well anchored to avoid seasonal effects. Deep anchoring using a concrete pillar that is decoupled from the surface 5 m and anchored only at 5 to 6 m is a method of doing this, and there are many alternative methods. The daughter stations are distributed throughout the region to be monitored and also stably anchored at depth, perhaps using a method similar to the survey station sketched previously. The fact that both antennae are stably anchored allows a precision much better than the technique involving a stable site and a "roving" antenna.

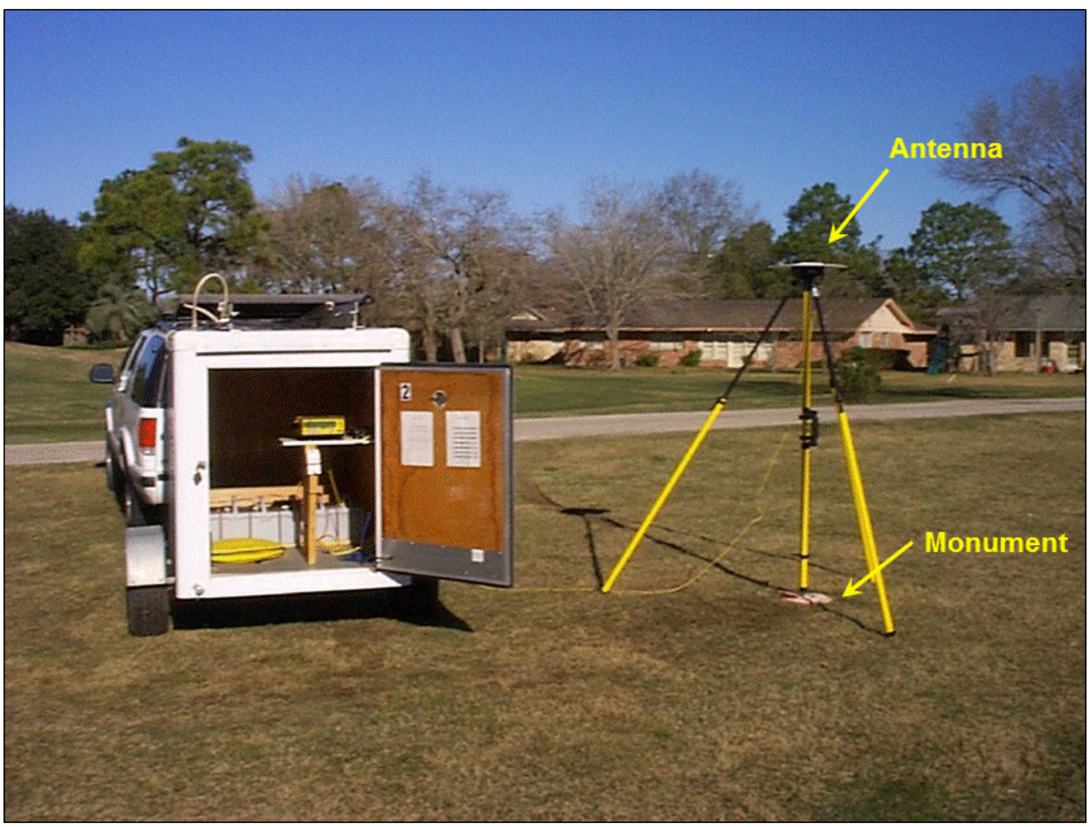


Figure 27: A D-GPS mobile system showing the reference antenna set-up.

Figure 27 shows a set-up for a mobile GPS system where the reference antenna is set up and positioned on a permanent monument. The roving antenna is not shown in Figure 27, but the principle is straightforward: a person moves to various sites using the roving antenna, setting it up identically from one survey to the next, using installed benchmarks (or survey points anchored at depth, as was discussed in the section on level surveys). Then, thousands of differential distance determinations are taken automatically and averaged over the time of sampling to give the difference in elevation to precisions on the order of 10 millimeters (better if the sites are all guaranteed to be stably anchored at shallow depth).

D-GPS with permanent antennae locations is illustrated in Figure 28. This array is designed for areal measurements at a mine site, where quasi-real-time data is needed for detection of potentially dangerous ground movements. Again, the issue of the stability of the anchor points is important, and in many circumstances it will be necessary to have a significant number of points anchored at a depth below seasonal for short-term changes in elevation.

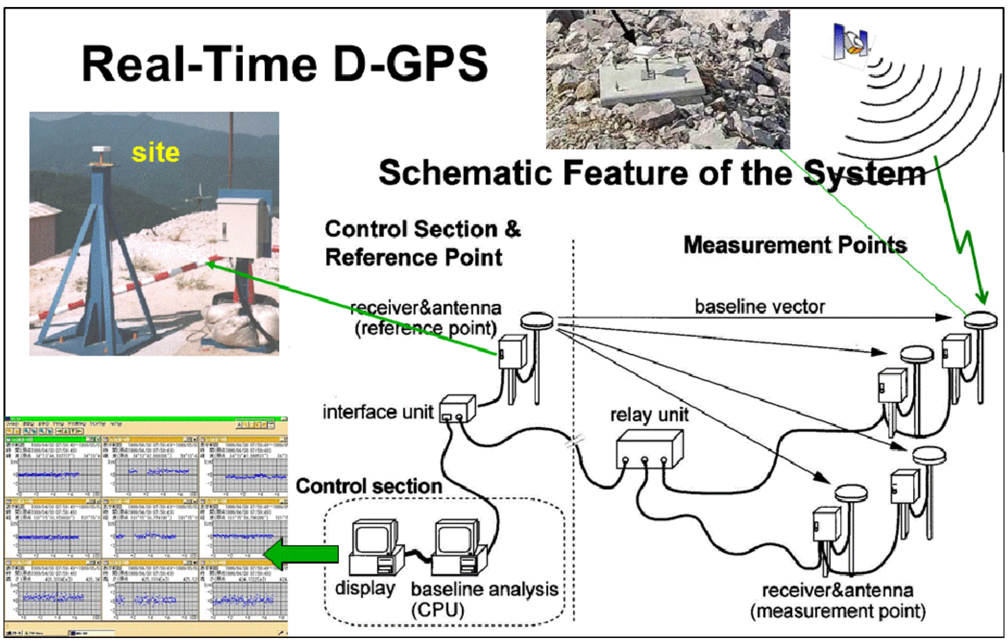


Figure 28: A D-GPS system designed for mining (or petroleum) applications

The system sketched in the figure is relatively straightforward. The reference antenna is stably mounted and the daughter antennae are shown in the figure as also stably mounted, in this case using rock bolts on the surface. Co-axial cables form the connections, although large bandwidth Supervisory Control And Data Acquisition (SCADA) links suffice as well. D-GPS is most commonly used for vertical movements – Δz – but because the satellite signals used for the triangulation involved are generally at low angles to the ground surface (many satellites are used in this process), it is also possible to take measurements of Δx and Δy with respect to the mother antenna. The capability for acquisition of precision Δx and Δy data has greatly improved since the year 2000.

Some of the advantages and disadvantages of the D-GPS system include:

a. No direct line-of-sight between the daughter and the mother antennae is required.
b. Antennae can be located and anchored at depth or on any surface such as the top of a building or operations equipment (e.g. separator tanks, wellheads, etc.)
c. Differential deformation data between the mother and daughter antennae are quasi-real time, although the results have to be subjected to calculations to provide a map of the movements.
d. Precisions of perhaps 5-8 mm in the distance differences with time are realistically obtainable.
e. One disadvantage is that each remote antenna must be self-powered and self-transmitting (in contrast to LIDAR methods for example where all sites are passive reflectors).

4.8 LIDAR Systems

There are many different technologies based on monochromatic light (lasers, infrared signals), usually combined with interferometry to give high precision distance data. More-and-more, such systems are completely automatic so that continuous updates of ranging distances are available. Achieving high precision requires the use of reflectors fixed to solid surfaces or monuments, in a manner similar to leveling survey methods. Precisions for x,y locations of a millimeter over baselines of 100 m or more are realistic. Commercial information may be found on many webpages (e.g. http://www.soldatainc.com/)

Typically, a central stable monument for automatic scanner location is established, and line-of-sight placement of reflectors is carried out. The scanner, essentially a theodolite emitting a laser beam or two closely tuned laser beams to allow interferometric measurements, is permanently mounted. The scanner is aimed at various reflectors in turn and the positions of the reflectors are stored in the computer memory so that for all future scans the process is automatic. During a scan, the scanner sequentially points at the various reflectors, storing the distance measurements. Measurements of Δx and Δy in an absolute sense and with high precision requires two or more stations, and if there are many reflectors with line-of-sight issues (buildings or traffic in the way), then it may be necessary to set up several (3-5) central stations. If a large area is to be monitored (several square kilometers together), a system with a similar number of central stations can be established. Each central station is protected from the environment and has line-of-sight to as many reflectors as possible. Figure 29 shows the principle of a distributed network of central stations.

Figure 30 is a general view of different instrument technologies to measure response (mainly deformations) around a tunnel. Many of these are not suitable for application to oil and gas field conditions, but the diagram shows an important principle of LIDAR. Because the beam is direct to a reflector, a single measurement can only give information about movements along the line of sight, and a single such measurement only indicates that the reflector location is moving directly toward or away from the central station. Thus, if the central stations and the reflectors are in the horizontal plane, it is impossible to resolve Δz values, although high resolution of Δx and Δy are straightforward using two or more central stations. To achieve Δz resolution, it is necessary to have the reflectors in a plane above or below the central stations. Hence, in practical terms, at least one of the central stations has to be suspended some distance above the surface, but this is not as easy as it sounds. The greater the distance above the ground, the better the Δz precision, but if the area to be monitored is, for example, 4 km^2, the distance to the most remote reflectors from the vertically suspended central station is about 1400 m. Assuming that the device is at the top of a 100 m tower, this gives a weak vertical angle, only 4.1°. Vertical movements on the order of 1-2 cm will be difficult to precisely detect under such conditions.

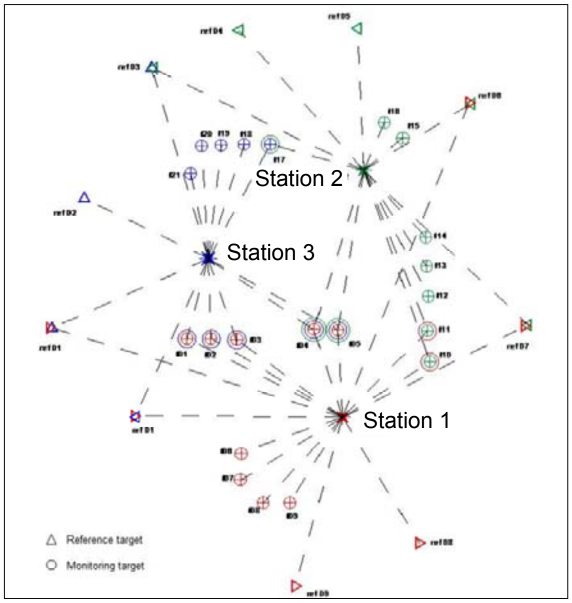


Figure 29: Multiple LIDAR stations improve coverage, precision, and line-of-sight issues[7]

[7] Poitrineau N, Gastine E, El Gammal M-L. 2009. Safe Tunnelling Involves Real Time Accurate Monitoring Systems. Downloaded from www.ctta.org

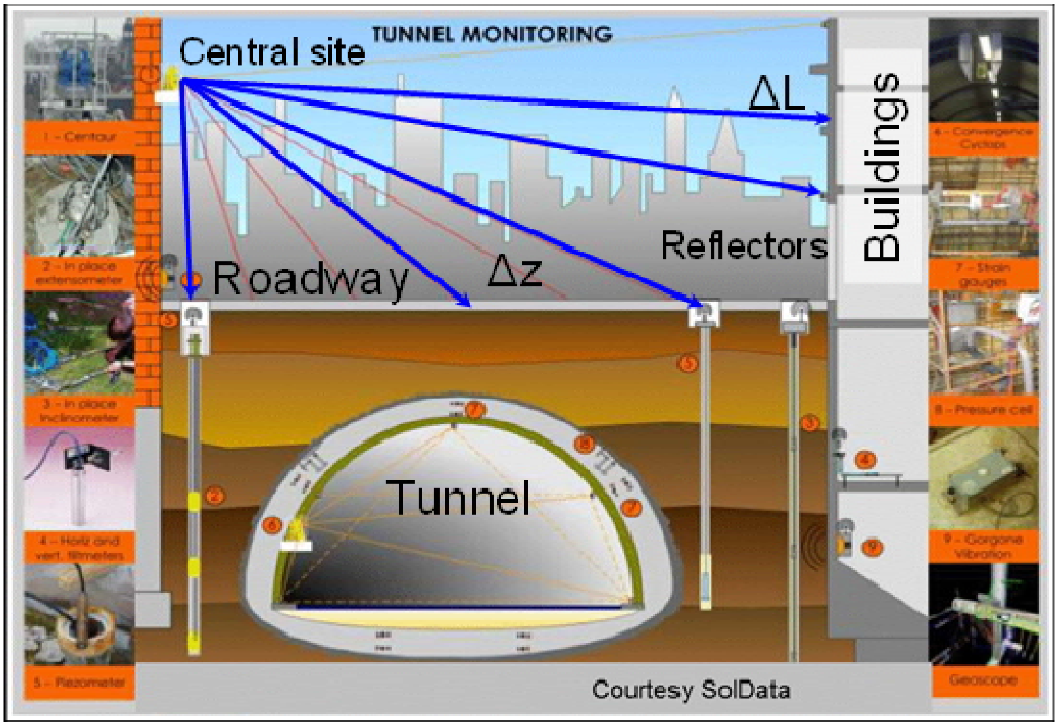


Figure 30: The issues of vertical and horizontal movement resolutions in LIDAR methods

Mounting the stations on the tops of buildings is recommended, but the height of buildings in oil sands SAGD and CSS areas will be limited to perhaps 20-40 m maximum.

Airborne LIDAR measurements are common and available generally as a service used for detailed topographic reconstruction, and hand-launched retrievable drone technology for precise LIDAR surveys is now available (http://www.sisb.my/index.php/services/uav). Drone use is limited to good weather and mild wind conditions, so survey data are not "on demand" as would be the case for a fully land-based installation.

Hence, LIDAR methods have severe disadvantages as well as some definite advantages, and an attempt to list these here is made:

1. Passive reflectors are extremely cheap and easy to set up in a relatively dense array, as there are no transmission requirements.
2. Line-of-site between at least two stations and each reflector is necessary, and at ground level, this would mean clearing sight lines through forest in many situations.
3. Because of the problem with the vertical angle of sighting, it may be impractical to achieve sufficient precision in vertical movements – $\Delta z(X,Y)$ – using LIDAR.
4. Sites suitable for good Δz measurements would have to address issues of vertical stability, just as for leveling surveys, tilt, or D-GPS methods, if high precision Δz measurements are deemed necessary.
5. LIDAR methods can give very high precision measurements of lateral displacements (Δy and Δy), and a minimum of two (preferably three or more) stations is necessary to achieve this. This also

suggests that LIDAR in combination with tilt measurements or D-GPS measurements may be synergetic if sophisticated mathematical inversion methods are used which incorporate both vertical and horizontal movements.

6. Hand-launched pre-programmed flight path drones can conduct LIDAR surveys and are of interest to obtain vertical deformation data at higher precision, and daily or weekly drone flight pattern LIDAR surveys could be implemented.

In conclusion, LIDAR methods are probably the best approach to the measurement of horizontal movements to high precisions, but LIDAR may have to be combined with some technology that gives a high precision measure of $\Delta z(X,Y)$, such as D-GPS.

4.9 Ground-Based Interferometric Synthetic Aperture Radar

InSAR techniques were discussed in the context of episodic satellite images used to develop a Δz map for the time interval between images. This gives data about the rate of change as well as the change itself, but is inappropriate for any alarm method. Some of these limitations can be overcome by ground-based radar – GB-InSAR – achieved through scanning from a ground-based emitter-receiver system.

The article by Rott *et al*. (2003) introducing the subject is still an excellent if brief introduction to GB-InSAR. GB-InSAR is a scanning method giving a ground surface image calculated from time-of-travel of a monochromatic radar frequency beam. If two high quality radar images are taken some time apart, an interferometric calculation can be done, and because the monochromatic radiation wavelength is small (26 mm is common), a high precision interferometric image of movements can be made. Using GB-InSAR, it is possible to take several images from different positions of the scanner (the antenna) and to combine the results mathematically, to give a high-quality image of velocities (Figure 31).

Radar will reflect from any hard surface, is absorbed by water (including wet snow and somewhat by vegetation in the summer), but is unaffected by dry snow, fog and mist. From rough hard surfaces, such as a coarse-grained gravel surface, reflections are of lower quality and precision is degraded. Radar results will be substantially more precise if a number of stably anchored radar corner reflectors are used to give targets of extremely high reflectivity, as this allows more precise distance change measurements and therefore can also be used to calibrate the rest of the image.

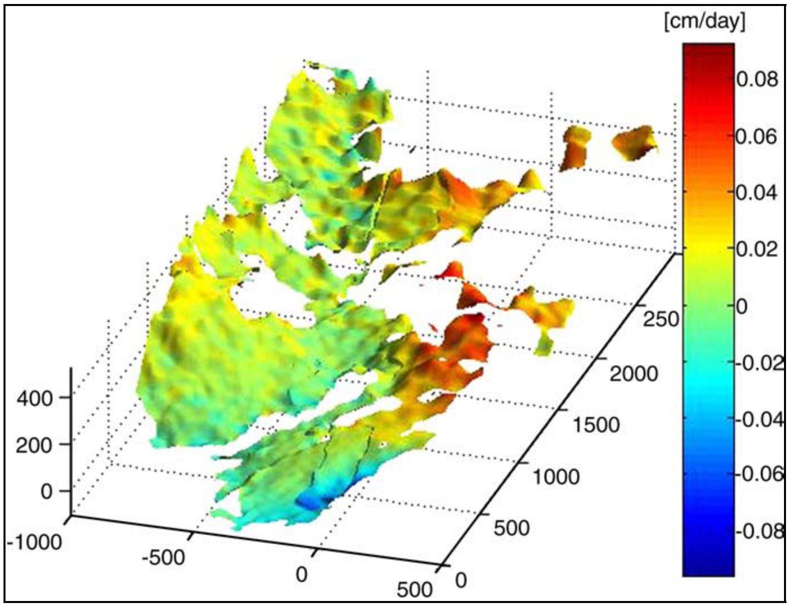


Figure 31: A map of velocities of ground movement from interferometric radar analysis. Millimeter level precisions can be achieved with systems including reflectors.[8]

Figure 32: An interferometric radar scanner used in a mining slope stability application

Because of the location of the scanner, a satellite scan is not the same as a ground-based scan. From a satellite passing roughly overhead (±45°), the vertical changes –Δz – are easily detected between sequential images, but the lateral movements are less easily measured precisely. For GB-InSAR, it is the opposite; horizontal movements can be tracked at great precisions, but vertical movement precision

[8] Noferini L, Mecatti D, Macaluso G, Pieraccini M, Atzeni C. 2009. Monitoring of Belvedere glacier using a wide-angle GB-SAR interferometer. *Journal of Applied Geophysics* 68, 289-293.

depends on the same factors discussed in the section on LIDAR above. Thus, to achieve vertical movement resolution, there must be a vertical angle between the location of the radar image and the scanner. For mine-wall or landslide monitoring, it is easy to set up an array or to locate the scanner so that vertical movements are precisely measured interferometrically. For a flat surface, some vertical distance must be incorporated just as for LIDAR. In other words, in a flat area the GB-InSAR has some limitations that are similar to LIDAR, but some strengths as well, being less sensitive to climate conditions, giving a full scan instead of measurements only at reflector locations, and so on. Because of the difficulty in obtaining precise Δz data, as with LIDAR, there is merit to combining GB-InSAR with another technique that is more sensitive to vertical movements, such as tilt or D-GPS methods.

4.10 Microseismic Monitoring

Thermal processes are accompanied by a great deal of seismic noise. There are a number of mechanisms involved, but in all cases the seismic energy emission is associated with sudden shear slip, referred to as Mode II fracturing (in-line shear, such as the possible case shown in Figure 7). The amount of energy emitted by tensile rupturing is negligible by comparison; in particular cases such as the strata surrounding Cretaceous oil sands, the tensile strength of the rocks is very low as well, so there is no mechanism for tensile energy emission through Mode I fracturing (parting). However, the materials involved are relatively dense, so that the materials are strain-weakening and dilatant, and therefore weaken and slip in an episodic manner. Figure 33 is a stress-strain-dilation plot of a typical geological material showing the strain-weakening behavior. Because the peak strength is larger than the ultimate strength, elastic strain energy is stored through compression, and when failure is reached, this energy is suddenly released, giving a burst of acoustic frequency (10-500 Hz) energy.

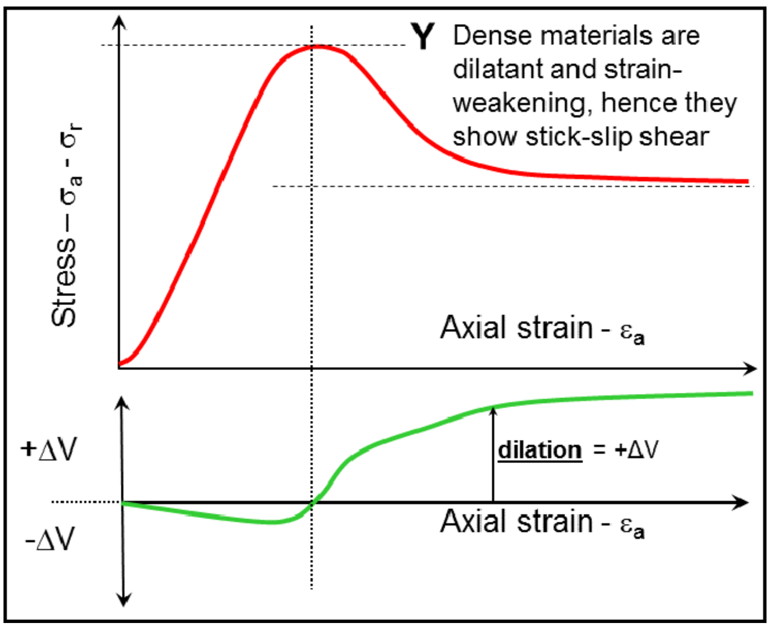


Figure 33: Dense geological materials (sands and shales) show dilatancy and strain weakening when subjected to an increasing shear stress

Figure 34 shows some of the sources and locations of shear slip in a heated case where a large volume change is taking place. Note that the combination of ΔT and dilation is critical to calculate these effects, it is not sufficient to account only for the thermoelastic expansion effect, which is usually on the order of 15-25% of the total volumetric expansion effect. Furthermore, a coupled model is necessary to do this because the vertical volumetric expansion component shows up as vertical displacement, whereas the horizontal strain tends to be suppressed and shows up as large increases in the horizontal stress component.

Shear takes place along the interface between the heated reservoir and the low-permeability cap rock as the thermal zone expands and the differential expansion overcomes the shear strength of the shale-sand interface. This process is noted in all thermal projects, and leads to large numbers of shear wells each year (e.g. IOL Cold Lake project loses many wells each year through shearing at the upper interface, and these have to be sidetracked).

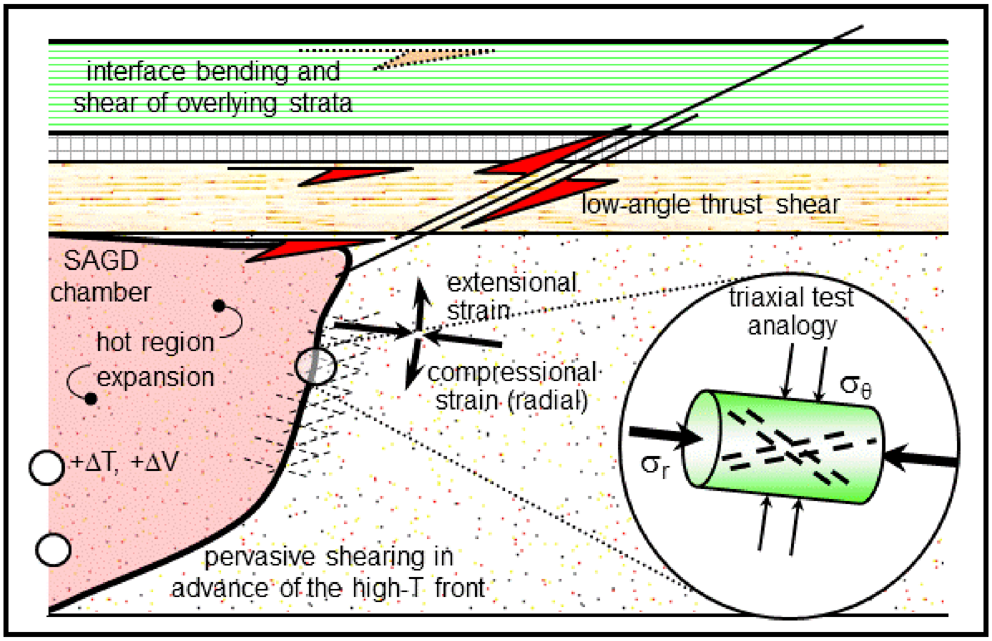


Figure 34: Shearing associated with a thermal process

The steam chamber is expanding because of thermal expansion and shear dilation, and thus lifting the overlying strata; but, away from the chamber, there is no expansion and shear, and hence no uplift. This differential uplift causes bending of the overlying strata, and slip along interfaces between rocks of different stiffnesses (as bending a sheet of plywood causes delamination because of high shear stress between layers). This type of shearing is most severe near the edges of a steam chamber group, and attenuates upward and away from the chamber shoulder because the bending curvature is lower farther away. Low-angle thrust faulting arising because of uplift and outward expansion is another mechanism related to these movements in the region of the chamber shoulders (the same applies for an array of chambers).

Important for SAGD and any thermal process is the general shear that takes place in the region of the thermal front. This leads to dilation, with porosities increasing from 30% to values of 33-35%. This general shearing, which is not just a single plane but pervades the sand in front of the SAGD chamber, is acoustically noisy, but is characterized by a large number of small events that are difficult to separate from one another and which may be affected by the strong spatial heterogeneity in seismic properties generated by the dilation itself.

All of these shearing processes lead to acoustic emissions because shearing in geologically old materials does not occur smoothly; it takes place in short jumps (stick-slip behavior). This shear slip radiates a sudden small mechanical strain impulse (a seismic event) that is not symmetric. With an array of geophones or accelerometers, the characteristics of the radiated seismic energy can be sampled. Then, amplitude, location, direction of motion, and other parameters can be calculated. Figure 35 shows where the concentrations of acoustic emissions might be expected, although insufficient information has been published to date to verify this diagram.

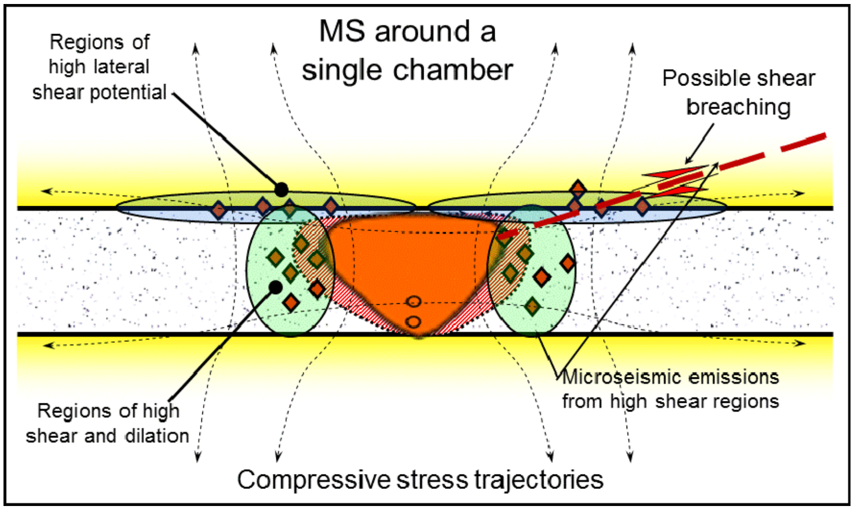


Figure 35: Shearing and microseismicity associated with a thermal process

In principle, if the physical processes were all well-understood and enough data available, MS monitoring could be used to clarify the locations of the shear slip, the length of the slip and orientation of the slip plane, and these could be tracked almost in real time (as is done in mining microseismicity). In practice, this is possible, but there are complications, including the density of the array needed to collect the events, what the events and clustering are indicating, huge inhomogeneities in acoustic velocities, and attenuation generated by the steam process itself (especially in CCS when pressures are high), and other complications.

Even if a number of these issues could be overcome, the specific physical links between the processes involved in an impending or ongoing caprock breaching and the nature of the microseismic emissions associated with that type of event remain ill-defined.

MS monitoring at the present time is not a technology suitable for short-term surveillance of processes for purposes of alarms or indicators of impending breakthrough. Much work has to be done before microseismic methods can be used with confidence as a means of continuous evaluation of the region in and around thermal processes.

Below, two diagrams are included to show some of the principles involved in a microseismic monitoring exercise. In Figure 36, a number of issues are illustrated, including:

a. The MS sensors must be placed at depth in dedicated monitoring wells to avoid issues associated with waveguide effects, excessive attenuation, reflections and refractions from large-scale heterogeneity, and so on.

b. No work station is powerful enough to carry out computations in real time for a large number of 3-component accelerometers (plus a precise timing channel). A distributed computational network is needed with local high-speed microprocessors.
c. A central work station is needed to govern the system and do the plots and analysis to give quasi-real time output of event locations and characteristics.

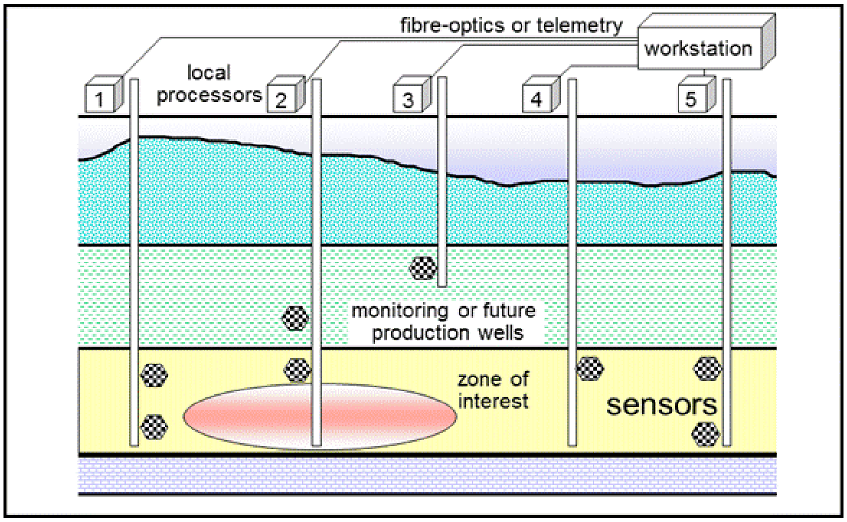


Figure 36: A distributed sensor array and computational capability for MS monitoring

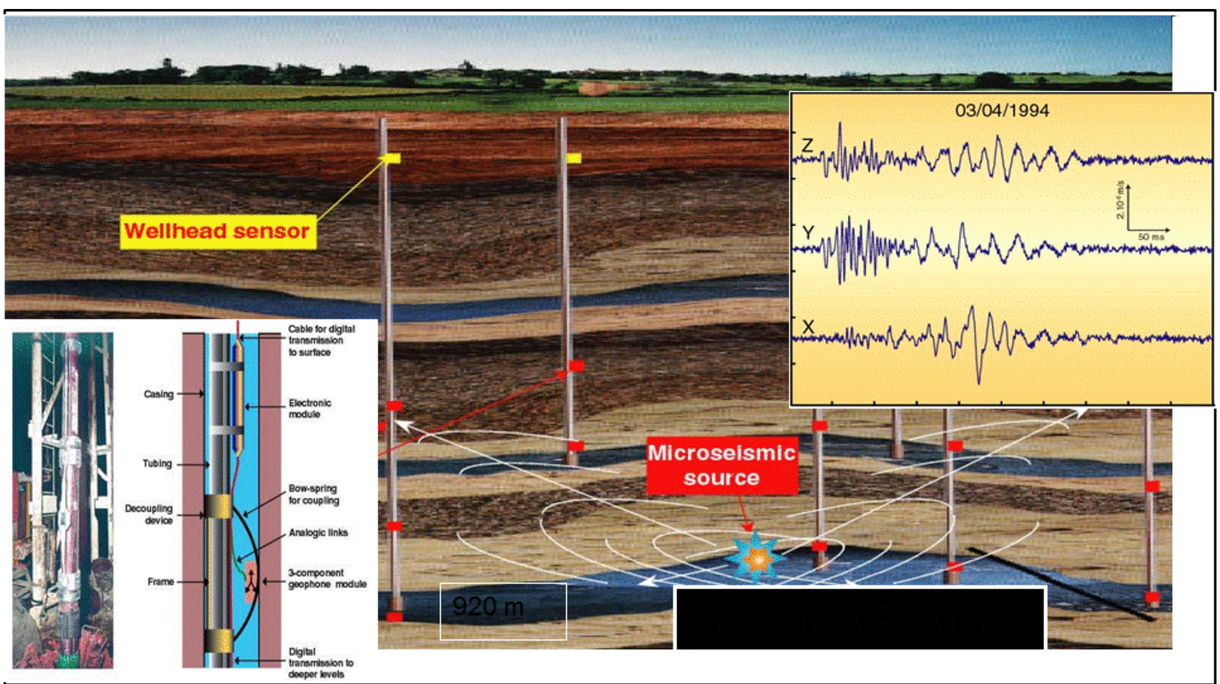


Figure 37: The MS concept in practice in the oil industry

Finally, Figure 37 shows the concept of MS monitoring with the nature of the wave train recording at each sensor. These data are analyzable in quasi-real time to yield information about the nature of the individual events, so that evolution of the processes at depth may be better understood.

Nevertheless, MS monitoring remains an interesting technique that has not developed to the point where it can be explicitly linked with processes of interest in thermal stimulation methods. It is not yet clear if MS monitoring will progress to the point where it can be of value in real-time surveillance strategy of *in situ* thermal processes.

5 Conclusions

a. For alarm purposes related to caprock integrity and potential breaching of the overburden, a short term alarm system allowing detection and decisions in 24 hours or less is needed. This restricts methods to those allowing rapid (electronic) readout methods where the results can be analyzed and displayed quickly to the engineering team.

b. For alarm purposes, methods that can give rapid and reliable information over large areas (volumes) are necessary, as SAGD pads generally involve about a km^2 at depth (800 m wells, 120 m spacing, 8 wells per unit).

c. Pressure and temperature measurements are of limited utility for overburden monitoring, although of great utility for chamber monitoring for potential impairment of chamber integrity.

d. Seismic methods are of value for intermediate- and long-term monitoring to understand the evolution of the processes at depth, but

    i. Active seismic methods (e.g. 3-D seismic surveys) are far too protracted in time to ever serve as a short-term or even intermediate-term (<10 days) monitoring approach.

    ii. Passive seismics (MS - microseismic monitoring) may prove useful in the future, but at the present time, there is no clear physical link between MS activity and breakthrough processes (fracturing, shear of ductile caprock), so MS monitoring cannot be used reliably to manage and mitigate risks of process destabilization. MS may, however, be used in conjunction with better methods to give more complete interpretations of breakthrough processes.

e. Borehole geophysical techniques requiring logging truck use (T logs, gyroscopic logs, acoustic casing deformation logs, etc.) are not suitable for alarm purposes, nor are other methods that required the deployment of large equipment. These methods may be highly valuable for other purposes such as casing integrity management, behind-the-casing leak detection, etc.

f. Because breakthrough events are associated with deformations (volumetric & shear) that develop before rupture, during breaching, and continue massively after breakthrough (overburden deformation), continuous monitoring of deformations is potentially a means of developing an alarm capability to manage and mitigate risk (including HSE risks) of caprock breaching by bringing important time-dependent data to the engineering team.

g. A number of deformation monitoring methods are long-term "snap-shot" approaches that may be highly useful for long-term process tracking, but cannot provide short-term alarm capacity because of the time involved to acquire the data, or the time involved to provide suitable interpreted data to the engineering team. Methods not suitable for such alarm purposes include leveling surveys of large numbers of survey monuments, satellite InSAR surface deformation images, aerial photogrammetric methods, and borehole geophysical logging.

h. Deformation measurement technologies at specific locations include many types of extensometers, inclinometers, stain gauges, and so on. Among all of the specific deformation methods available, the most valuable are those that give integrated readings and can also give an automated or electronic read-out. Inclinometers (tilt-meters) and fibre optics deformation monitoring systems are available, and tilt is a mature and widely used approach to measure the deformation field. Exploration of the utility of fibre optics methods (perhaps other similar methods) in long grouted boreholes should be undertaken as this area is undergoing rapid technological development.

i. The deformation monitoring systems that can give “maps” of the changes in the deformation field over a short time frame (minutes to a few hours) to the engineering decision makers are likely suitable for alarm purposes, and there are four identified methods that are commercially available:

    i. Tilt meter array of surface (5-10 m deep) and perhaps subsurface tilt measuring devices spread over an area and spaced to allow local deformation events to be detected. Each tilt meter site provides a real time measurement of tilt (maximum inclination change and its direction).

    ii. A Differential Global Positioning System (D-GPS) of appropriately spaced antennae can give near-real time measures of the changes of deformation of the ground surface, including Δx, Δy and Δz movements at each antenna location.

    iii. Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR) is based on the same technology as satellite InSAR, but using ground-based systems to take images and analyze them to give changes in the ground surface (Δx, Δy, Δz), although the vertical resolution is less easily achieved than the horizontal movements.

    iv. Similarly to GB-InSAR, light incidence methods (LIDAR) can be used to give short-term maps of surface deformations, and high quality reflective targets are needed.

j. All short-term deformation methods involve provision of a “map” of the surface deformation shape to the client. This map may be provided at relatively short time intervals, such as a few minutes for a LIDAR or a tiltmeter system. The data from one image time to another can be subtracted to show the changes in deformation over various time intervals, and it is even possible to display deformation maps sequentially to give a short “movie” of changes. These tools and quality image provision are of great use in decision making.

k. For the engineering team that must make decisions, what is potentially of far greater value is the provision of a 3-D image of the deformations in the ground, in and above the thermal reservoir region. Provision of a 3-D subsurface deformation image requires mathematical analysis (inversion) of the surface deformation data, a process far more complex than just the provision of the surface deformation image. The 3-D image provides more specific information about the depth, magnitude and nature of the deformation event. This mathematical analysis capability seems not to be available for the alarm time-frame at this time (early 2013), but continued software development will move this capability into an alarm capacity in the near future.

l. Many other techniques are unsuitable for the purpose of caprock integrity, an exhaustive list would be too lengthy, but, for example, these unsuitable methods include conventional groundwater monitoring and geochemical methods, gravimetric methods, magnetotelluric surveys or airborne electromagnetic techniques, and so on.

m. One method that seems to be suitable for alarm purposes as well as general utility in tracking and understanding processes but which has not been well-developed to date is electrical impedance monitoring using a 3-D array of installed fixed electrodes to track changes in subsurface resistivity. Short-term changes in the resistivity of the subsurface strata in response to changes in fluid nature and temperature could be assessed in the short-term. This method can be combined with episodic (e.g. monthly) electrical surface surveys using special antennae, magneto-telluric approaches, and EM methods to refine the analysis models. Resistivity mapping has the advantage of being highly synergistic with deformation and other methods (if gives entirely different data, so there is strong synergism between methods).

n. In addition to choosing the most appropriate technology for monitoring the caprock and overburden condition, a large number of issues must be evaluated and incorporated in the design of such a system. Among these issues are:

    i. Improving the understanding of the physical processes involved in SAGD and thermal processes, especially those processes related to deformation changes and fluid and pressure migration events. The science and engineering of this area is in very early stages.

    ii. Spatial deployment strategy of sensors or sites over a large area in order to give a high probability of detection.

    iii. Evaluation of the financial and HSE impact of Type I and Type II errors (detection failure and false alarms respectively).

    iv. Development of protocols for reaction to alarms of various certainty (reacting to a tentative alarm versus a strong alarm versus a risk of impending blowout, for example).

    v. Shortening the time span of the analysis used to give images of the subsurface (inversion or tomographic reconstruction) so that better quality information is provided to the decision makers as quickly as possible.

    vi. Exploring the synergism among different methods to mitigate and manage risk, such as integrating an electrical impedance array with a deformation array as well as some microseismic sites, so that a deformation event can be quickly studied by other means.

o. Although the remit of this report is not to make specific recommendations, there seem to be several obvious recommendations of a broad nature that should be made because actions in this direction will help the industry and the regulatory framework in general.

   i. Joint-industry cooperation to help understand the processes at depth and how best to monitor, assess and analyze them to meet the various goals outlined in Section 1.

   ii. Development of rapid analysis methods to shorten the alarm time and increase the probability of a correct interpretation of the events is also an area for cooperative investments by the industry.

   iii. Public sharing of data and developments so that the larger skill set of academic and research organizations can be brought to bear to foster rapid development of better monitoring and interpretive methods. In this domain, confidentiality seems counter-productive to the HSE, process optimization, and resource management goals of the industry and society.

   iv. Foster development of specific technologies that promise to give new or better metrics for thermal process integrity risk management; specific technologies identified in this report for development include electrical impedance tomography, fiber optic extensometers, and there will be others that have value for further development.

6 Some References

This list is not intended to be an exhaustive bibliography, nor are the articles listed here referred to explicitly in the text. The list is intended to serve as an introduction to some of the relevant literature in this vast subject area.

Alnes, H., Eiken, O. and Stenvold, T. (2008). Monitoring gas production and CO_2 injection at the Sleipner field using time-lapse gravimetry. *Geophysics* **73(6)**, WA155-WA161.

Bilak, R., Rothenburg, L. and Dusseault, M.B. (1991). Use of Surface Displacements to Monitor EOR Projects, Proceedings 5th International Conference on Heavy Crude and Tar Sands, Caracas, Venezuela.

Bruno, M.S. and Bilak, R.A. (1994). Cost-Effective Monitoring of Injected Steam Migration Using Surface Deformation Field. *Proceedings Western Regional Meeting of the Society of Petroleum Engineers,* March, 397-411.

Bruno, M.S. and Bovberg, C.A. (1992). Reservoir Compaction and Surface Subsidence above the Lost Hills Field, California. *Proceedings 32nd US Symposium on Rock Mechanics*, June, Santa Fe, 263-272.

Doornhof, D., Kristiansen, T.G., Nagel, N.B., Pattillo, P.D. and Sayers, C. (2006). Compaction and Subsidence. *Schlumberger Oilfield Review*, Autumn, 50-68.

Dusseault, M.B. (1986). Monitoring In Situ Processes, *Proceedings, 37th Annual Technical Meeting, Petroleum Society of CIM*, Calgary, **Paper #86-37-63**, 351-365.

Dusseault, M.B. (2007). Monitoring and Modeling in Coupled Geomechanics Processes. *Proceedings Canadian International Petroleum Conference*, Calgary, **Paper 2007-028**, 10 p

Dusseault, M.B. and Rothenburg, L. (2002). Deformation analysis for reservoir management. In *Oil & Gas Science and Technology - Revue de l'IFP*, **v 57, N° 5**, 539-554.

Dusseault, M.B., Bilak, R. and Rothenburg, L. (1993). Inversion of Surface Displacements to Monitor *In-situ* Processes. *Proceeding 34th United States Rock Mechanics Symposium*, Madison, WI

Friedrich, J.T., Arguello, J.G. Thorne, B.J., Wawersik, W.R., Deitrick, G.L., de Rouffignac, E.P., Meyer, L.R. and Bruno M.S. (1996). Three-Dimensional Geomechanics Simulation of Reservoir Compaction and Implications for Well Failures in the Belridge Diatomite. *Proceedings 1996 Society of Petroleum Engineers Annual Technical Meeting*, Denver, 195-209.

Grasso, J.R. and Wittlinger, G. (1990). Ten Years of Seismic Monitoring over a Gas Field. *Bulletin of the Seismological Society of America* **80(2)**, 450-473.

Kooi, H. (2000). Land subsidence due to compaction in the coastal area of The Netherlands: the role of lateral fluid flow and constraints from well-log data. *Global and Planetary Change* **27**, 207-222.

Macini P., Mesini, E., Salomoni, V.A. and Schrefler, B.A. (2006). Casing influence while measuring in situ reservoir compaction. *Journal of Petroleum Science and Engineering* **50,** 40– 54.

Macini, P. and Mesino, E. (2002). Measuring Reservoir Compaction through Radioactive Marker Technique. *Journal of Energy Resources Technology***, V. 124**, 269-274.

Mayuga, M.N. and Allen,D.R. (1969). Subsidence in the Wilmington Oil Field, Long Beach, California, USA. *Proceedings of Tokyo Symposium on Land Subsidence*, **v 1**, 66-79.

McGillivray, P.R., Brissenden, S., Bourne, S., Maron, K. and Bakker, P. 2006. Making Sense of the Geomechanical Impact on the Heavy-Oil Extraction Process at Peace River Based on Quantitative Analysis and Modeling. Society of Petroleum Engineers Annual Conference, San Antonio TX, USA. 5 pages. SPE#102876 .

Mousavi, M. S., Shamsai, A., El Naggar, H.M., and Khamehchian, M. (2001). A GPS-Based Monitoring Program of Land Subsidence due to Groundwater Withdrawal in Iran. *Canadian Journal of Civil Engineering*, **28(3)**, 452-464.

Patel, P.R. and Kulkarni, M.N. (2008). Preliminary Results of GPS Studies for Monitoring Land Subsidence over the Shallow Gas Reservoir in India. *Survey Review* **40, 310**, 356-365.

Rothenburg, L., Dusseault, M.B., Bilak, R.A. and Bruno, M.S. 1994. Waste Disposal Monitoring Using the Surface Displacement Field. *Proceedings EUROCK '94*, Balkema, Rotterdam, 739-745.

Rott, H. (and seven other authors) 2003. InSAR techniques and applications for monitoring landslides and subsidence. In *Geoinformation for European-Wide Integration*, editor Tomas Benes; Millpress, Rotterdam, 25-31.

TRB (2008). Use of Inclinometers for Geotechnical Instrumentation on Transportation Projects. Transportation Research Board of the National Academies, *Transportation Research Circular* **#E-C129**, October, 92 pp.

USGS (2000). Measuring Land Subsidence from Space. *United States Geological Survey Fact Sheet*-**051-00**, April, 4 pp.

Yin, S., Dusseault, M.B. and Rothenburg, L. (2007). Coupled Multiphase Poroelastic Analysis of Reservoir Depletion Including Surrounding Strata. *Int. Journal of Rock Mechanics and Mining Sci*, **44**, 758-766

Yin, S., Dusseault, M.B. and Rothenburg, L. (2007). Analytical and numerical analysis of pressure drawdown in a poroelastic reservoir with complete overburden effect considered. *Advances in Water Resources* **30**, 1160-1167.

Yin, S., Rothenburg, R. and Dusseault, M.B. (2008). Analyzing Production-Induced Subsidence using Coupled Displacement Discontinuity and Finite Element Methods, *Computer Methods in Engineering Science*, **469(1)**, 1-10

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