GEMS: the opportunity for stress-forecasting all damaging earthquakes worldwide

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Strange as it may seem, we understand the distribution of matter in the interior of the sun far better than we understand the interior of the earth.

(Feynman 1995)

ABSTRACT

The logical extension of a single or small network of three-borehole Stress-Monitoring Sites (SMSs) (Crampin & Gao 2010) is GEMS, a Global Earthquake stress-Monitoring System deploying a world-wide network of SMSs. GEMS would need a network of perhaps 200 three-borehole SMSs on a 1200 km-grid in seismic regions and a 5000 km-grid elsewhere. Recent technological and internet developments could control and monitor both onshore and offshore SMSs. Not only would GEMS stress-forecast all damaging earthquakes ($M \geq 5$) worldwide, the range of benefits would include: a long-term stress forecasting service analogous to weather forecasting; control for mitigating seismic hazards; sites for other geophysical instruments; and a better understanding of the evolution of the interior of the solid Earth.

Key words: earthquake stress-forecasting; GEMS; Global Earthquake stress-Monitoring System; New Geophysics; shear-wave splitting; Stress-Monitoring Sites (SMSs).
1. INTRODUCTION

Despite two hundred years of geology and a century of geophysics, we know remarkably little about how rocks deform a few meters beneath our feet. This is partly because rocks at depth are extraordinarily remote. We cannot access the behaviour directly without destroying in situ conditions by the severe traumas of partial de-stressing, partial cooling, and fluid disruption.

This lack of understanding has serious consequences for earthquake hazard. The 1995, $M_{\text{7.2}}$, Kobe Earthquake in Japan killed 6,000 people and caused an estimated 250 billion dollar damage. Earthquakes such as Kobe; 1999, Izmit, Turkey, 17,000 dead; 2001, Bhuj, India, 40,000 dead; 2003, Bam, Iran, 34,000 dead; 2008, Wenchuan, China, 70,000 dead; 2009, Haiti, 230,000 dead; occur frequently, indiscriminately, and cause incalculable suffering and loss. Those were all earthquakes with magnitudes between 7 and 8. The largest earthquakes, such as the 2004, $M_{\text{w}} = 9.2$, Sumatra-Andaman earthquake, whose tsunami killed over 250,000, release two to three orders of magnitude more energy (but fortunately are two to three orders of magnitude less frequent). Currently there is no effective earthquake prediction programme and we may be fatally surprised.

Recent advances in understanding and modelling fluid-rock interaction (Crampin 2006) lead to a New Geophysics, and a paradigm shift in forecasting earthquakes (Crampin et al. 2008). Large earthquakes release enormous amounts of stress-energy which, since rock is comparatively weak to shear stress, necessarily accumulate over very large volumes of rock before large earthquakes can occur. The paradigm shift for earthquake forecasting is to ignore the earthquake source which is deterministically unpredictable and chaotic (Geller et al. 1997), but monitor stress-accumulation in the rock mass surrounding the impending earthquake by analysing shear-wave splitting. The evidence shows that the approach to fracture-criticality, when the microcrack distributions are so closely spaced they lose shear-strength and fracture in earthquakes, can be monitored at substantial distances from the eventual source zone (Crampin et al. 2008).

A combination of three recent developments provides the opportunity for the paradigm shift to be exploited in GEMS: a Global Earthquake Monitoring System. The first is the recognition that almost all in situ rocks, certainly in the crust, and the seismogenic parts of the mantle, are pervaded by self-organised scale-invariant systems of fractures ranging from open fluid-saturated grain-boundary microcracks and preferentially-oriented pore space in sub-millimetre to millimetre scales to plate-boundaries at scales of thousands of kilometres (Crampin & Peacock 2008; Heffer & Bevan 1990). In the crust, the fluids are usually water-based salt solutions, but may be hydrocarbons, and in the upper mantle, the ‘fluids’ are likely to
be intergranular films of hydrologised melt (Crampin et al. 1986; Crampin 2003). Shear-wave splitting shows that the fluid-saturated microcracks are so closely spaced they verge on fracturing and are critical-systems (Crampin 2006), and hence are a New Physics (Davis 1989), and a New Geophysics. The criticality, particularly of small-scale microcracks, is the underlying reason for rocks’ extreme sensitivity to small disturbances.

The second development is that we now know that details of stress-induced low-level deformation of crack distributions can be monitored by shear-wave splitting (seismic birefringence), so that the accumulation of stress before earthquakes can be monitored and the release of stress in earthquakes “stress-forecast” (Crampin et al. 2008).

Finally, and crucially important, recent advances in borehole instrumentation and technology allow polarized shear-waves to be monitored by repeated crosshole shear-wave transmission measurements at borehole Stress-Monitoring Sites (SMSs) (Crampin et al. 2003), which may now be both onshore and offshore.

2. STRESS-MONITORING SITES (SMSs)

The prototype SMS, developed by the European-Commission-funded SMSITES Project in Iceland used wells, previously drilled for geothermal purposes, adjacent to the Húsavík-Flatey Transform Fault of the Mid-Atlantic Ridge where it runs onshore in Northern Iceland (Crampin et al. 2003). The well geometry was not optimum for SMSs and signals were restricted to horizontal propagation at 500 m-depth between wells 315 m-apart. Never-the-less, despite non-optimal geometry the records were spectacularly sensitive to small disturbances of stress.

In what was intended to be a source calibration test of the borehole source (the Downhole Orbital Vibrator, DOV, Leary & Walter 2005a, 2005b), the DOV was pulsed every 12 to 20 seconds for 24 hours for 13 days, yielding over 40,000 records at each of four downhole three-component geophones 1 m-apart. Hundred-fold stacking gave travel-time accuracies of ±0.02 ms. Fortuitously, the recordings coincided with a burst of low-level seismicity, 70 km NW of SMSITES on another transform fault, the Grímsey Lineament, and remarkable anomalies were recorded (Crampin et al. 2003). The variations in seismic travel-times between the two wells and the shear-wave anisotropy also correlated with NS and EW Global Positioning System (GPS) variations, and with changes in level in a water-well on the Island of Flatey immediately above the fault. This sensitivity to low-level seismicity (equivalent energy to one $M \approx 3.5$ earthquake) at 70 km distance at hundreds of times the conventional source dimensions is far greater than would be expected in a conventional sub-critical brittle-elastic crust and is another
demonstration of the crack-critical nature of the Earth’s crust of the New Geophysics of critical-systems of closely-spaced fluid-saturated microcracks throughout the crust (Crampin & Gao 2010). These observations confirm the science, technology, and sensitivity of SMSs for monitoring changes of stress in the Earth’s crust and stress-forecasting the times and magnitudes of impending earthquakes. Although the experiment was designed to monitor small changes, we were surprised by the sensitivity actually recorded. Well-level changes and GPS variations have previously been observed by several authors at substantial distances from earthquake epicentres, but this was the first time that variations in four seismic measurements, vector GPS, and water-well levels have been observed simultaneously before earthquakes.

3. ADVANCES IN BOREHOLE TECHNOLOGY

The operation and recording of permanent installations of seismic receivers and energy sources within deep boreholes is now well-established in oil industry seismic surveys. Borehole seismic recorders routinely operate at several kilometres depth at temperatures up to 150ºC. The most significant advance has been in controlling the DOV source and understanding the behaviour and characteristics of propagating polarised seismic signals (Leary & Walter 2005a, 2005b).

New developments of this seismic source provide the means to reliably control the source, record observations, and process signal measurements by satellite technology both onshore and offshore. This means that the whole shear-wave monitoring operation could be controlled and processed remotely via Internet technology, so that a global network of SMSs (GEMS) could be managed effectively on a continuous real-time basis both onshore and offshore.

4. THE GEMS GLOBAL NETWORK OF SMSs

The concept of Stress-Monitoring Sites is believed to be a significant advance. For the first time there is the opportunity for controlled-source operations to monitor stress-induced changes to microcrack geometry by non-invasive seismic techniques at depth in in situ rock. The power of a single SMS is that it can monitor very subtle changes in behaviour by time-lapse techniques. In very quiet conditions, preferably at or below 1000 m-depth, records of the highly-repeatable DOV signals can be differenced to monitor the effects of very small changes in rock mass
Section D. Anisotropic rock physics and related studies

Anisotropic rock physics and related studies. The measurements allow exceptional accuracies of ±0.02 ms (±20 μs) over 315 m (Crampin et al. 2003).

Note that although not specifically addressed by the discussions in this paper, the accuracy of SMSs would also be valuable for investigating the frequency dependence of seismic velocities. Such dispersion is currently of interest to the oil industry as a means of investigating the dimensions of the cracks that cause shear-wave splitting in hydrocarbon reservoirs.

The seismic measurements in the SMSITES experiment were clearly not at the limit of their range. Conservative extrapolation suggests that a single SMS would be able to monitor changes induced by $M \approx 3.5$ earthquakes to 100 km, and correspondingly $M 5$ to ~1000 km, say, and $M 8$ and greater earthquakes to the scale of tectonic plates, if not worldwide.

This suggests that GEMS, a global network of SMSs, would be able recognise stress accumulation and stress-forecast the times and magnitudes of all earthquakes with magnitudes greater than $M 5$ worldwide. In particular, what would be guaranteed is that the accumulation of stress before all damaging earthquakes would always be recognised. No change would indicate no impending large earthquake and security. However, if changes were observed, the estimate of the time of occurrence would depend on the rate of the tectonic stress accumulation which may vary from place to place, and possibly from time to time.

The suggested GEMS network of a 1200 km-grid in seismic areas and a 5000 km-grid elsewhere would lead to some 200 SMSs, after adjusting distributions for stable (lower concentrations of SMSs) and unstable (higher concentrations) regions. There are large stable areas both onshore, such as the Canadian Shield, and particularly offshore as in oceanic basins, which are believed to be almost completely aseismic and would probably show little variation in stress, although this would be open to confirmation. Note that routine drilling of deep wells offshore is only now becoming feasible as the Riser Drillship 'Chikyu' of the Integrated Ocean Drilling Program, IODP, now becomes available. Riser technology allows deeper and more easily re-enterable wells to be drilled offshore. Indeed, networks of borehole seismometers across ocean floors have been proposed to record and analyse earthquake data (Suyehiro 2002). A 1000 km grid was suggested, filling in the largest gaps in the worldwide network of seismic stations, and would be passive, monitoring earthquakes as they occurred. Because of the sensitivity of SMSs to changes of stress, a lower concentration of SMSs would be appropriate for GEMS.
5. **A STRESS-ForeCASTING SERVICE**

Monitoring stress changes and directions at a single SMS would be analogous to a single weather station, where the principal measurements are changes in air pressure, and wind speed and direction. Such patterns of behaviour can be used to estimate, particularly the stability of the weather, and the likelihood of storms. (One of us finds it useful to look at a barometer and a wind vane each morning before stepping into Scottish weather!) The power of weather forecasting comes from networks of such weather stations, where recognising areal and temporal patterns of behaviour allow relatively accurate local forecasting. However, weather is another critical system so that weather forecasting has all the uncertainties and sensitivity inherent in critical systems of complicated heterogeneous interactive phenomena.

It is anticipated that identifying previously unrecognised patterns of behaviour with GEMS would allow a stress forecasting service analogous to weather forecasting. Such stress forecasting should provide some predictive capability over longer-term estimation (we guess at five to ten years) of earthquake scenarios, so that long term preparations for earthquake hazard could be instituted. Currently, such questions are not even raised by the scientific community, because there is no means of acquiring relevant information. Stress forecasting with GEMS would open this new capability.

It is worth pointing out that GEMS would provide the data for new investigations of Earth deformation that have not been previously available. Earthquake forecasts would be by investigations of stress and crack evolution, and provide information for stress modelling and some new understanding of the phenomena. This is in contrast to probabilistic statistical predictions, which even if they were accurate would provide no increased understanding of earthquake occurrence and Earth deformation.

6. **LOWERING THE POTENTIAL FOR LARGE EARTHQUAKES**

As the accumulation of stress before large earthquakes is so extensive any large-scale increases of stress or, more generally, any other changes of stress, could be recognised at substantial distances and times before the impending earthquake. Consequently, if accumulating stress is believed to be threatening a large city or other vulnerable location, in principle, the accumulating stress could be diminished almost anywhere within the larger stressed volume, by inducing small earthquakes, and the potential for city-threatening earthquakes reduced. The most direct way to release stress would be by hydraulic pumping operations in non-vulnerable
areas nearby, within 500 to 1000 km, say, of the threatened city. Hydro-fracturing is a routine oil-company operation. Stress release by hydraulic fracturing could be sited in areas of low population and infrastructure such as amongst mountains or deserts, or even offshore, with suitable allowance made for tsunamis.

However, this is an untested procedure and the effects are currently not known. The great advantage of GEMS would be that the effects of such hydraulic pumping could be monitored so that the results of tests could be optimised. The intention would be to release stress by exciting small earthquakes in areas within the larger stressed volume where earthquakes would be less destructive. The seismic (acoustic) events as oil reservoirs are depleted demonstrate this possibility.

Such hydraulic fracturing operations would need to be massive, extensive, and costly. However, the 1995 Kobe earthquake has been estimated as costing $250 billion dollars U.S. Had the accumulation of stress been recognised by GEMS, a premium of 0.5% would provide $1.25 billion for hydraulic fracturing if a city such as Kobe was shown to be threatened by a large earthquake. This would not be a blind investment. The GEMS SMSs would allow the effects to be monitored and the stress release optimised. If hydraulic fracturing at one location was not proving effective in lowering stress, hydraulic fracturing could be relocated within the stressed volume until an effective relaxation regime had been established.

Note that lowering the risk of large earthquakes on specific faults by hydraulic fracturing on the actual fault was suggested many years ago (Raleigh et al. 1976). At that time, the major disadvantage was that such operations might excite the event they are designed to prevent and the experiments were abandoned. The advance now is the recognition that the stress accumulation is so extensive that hydraulic-fracture-induced events could be triggered at substantial distances from any vulnerable location, and that any such changes would be monitored by GEMS.

7. **GEMS AS A NEW TOOL FOR MONITORING EARTH EVOLUTION IN THE 21ST CENTURY**

Apart from the earth tides, ocean tides, and other astro-geophysical influences, the major driving force of Earth evolution is the generation, spreading, and subduction of tectonic plates at plate margins. We do not know, and currently have no means of assessing, the dynamics of plate motion and the way stress is distributed, except by modelling based on inadequate information. The two year relaxation stress implied from the decrease in time-delays following the 1996
Vatnajökull eruption in Iceland (Volfi & Crampin 2003) suggests that these movements are highly episodic. It is well known that earthquake occurrence is fractal and varies over scales from minutes to millions of years. The reasons for this are likely to be the interaction of the dynamics of the core with flow in the mantle and movements of oceanic and continental plates, but we currently have minimal information. Consequently, there are many comparatively simple questions that are currently unanswerable: whether plates are pushed by ridges or pulled by subduction zones; and the underlying reasons for cycles of greater or lesser seismicity. But the major questions are what drives the plates and how and why they vary with time. Currently we have no means of acquiring such information which is crucial for understanding the evolution of the Earth. GEMS by monitoring stress deformation over the near-surface of the Earth would provide for the first time the means of investigating the dynamic evolution of the interior of the crack-critical Earth.

It is perhaps worth noting that over 70% of the surface of the Earth is water beneath which lie some 50% of all earthquakes. This means that wholly satellite-based Synthetic Aperture Radar (SAR), Global Positioning System (GPS) displacement, or other similar measurements which are confined to observations of the solid surface, cannot monitor approximately 50% of all earthquakes. Only an onshore and offshore borehole-based system such as GEMS would be able to monitor the approach of all earthquakes.

8. CONCLUSIONS

The effects of changes of stress on shear-wave splitting are comparatively subtle and easily overlooked or misunderstood (Crampin & Peacock 2005, 2008). Consequently, interpretations of temporal changes in shear-wave splitting are sometimes claimed to be controversial. We suggest that the evidence supporting APE modelling and temporal changes is vast (Crampin & Peacock 2005, 2008) and is confirmed by the unique observations from the SMS in Iceland (Crampin et al. 2003). The observed sensitivity to remote seismicity is remarkable and marks a new property of the in situ rock mass. Despite not knowing exactly how stress behaves before earthquakes, though previous stress monitoring experience provides indications, the New Geophysics, the new sensitivity, and the state-of-the-art technology are all proven attributes, although not necessarily wholly understood. GEMS would have the capability of monitoring stress changes and stress-forecasting all damaging ($M \geq 5$) earthquakes worldwide.
TABLE 1. The benefits of GEMS.

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<th>Benefits</th>
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<tr>
<td>1</td>
<td>Provide data to stress-forecast of times and magnitudes of all damaging earthquakes worldwide with magnitudes greater or equal to $M \geq 5$ (and many greater than $M \geq 4$).</td>
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<tr>
<td>2</td>
<td>Provide data for a stress-forecasting service, analogous to weather forecasting, which would give longer-term estimates of earthquake occurrence and hazard, as well as Earth evolution.</td>
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<tr>
<td>3</td>
<td>Provide facilities to monitor the effects of massive hydraulic fracturing operations to optimise stress release to mitigate earthquake hazards threatening vulnerable locations.</td>
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<td>4</td>
<td>Provide a network of deep boreholes for passive monitoring of broadband seismics, gravity, resistivity, magnetism, etc., in exceptionally-quiet environments for time-lapse monitoring of the dynamics of Earth evolution.</td>
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<td>5</td>
<td>Provide a new controlled-source tool for monitoring the evolution of the crack-critical Earth to stimulate solid-earth geoscience at the beginning of the 21st century.</td>
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The benefits of Global networks of SMS are summarised in Table 1. GEMS at the suggested grid size of 1200 km in seismic areas, and 5000 km elsewhere, and the establishment of regional processing centres, could stress-forecast the times and magnitudes of all damaging earthquakes, $M \geq 5$, worldwide. The greatest advantage may be peace of mind. The absence of change would mean there could not be an imminent large earthquake nearby.

Secondly, GEMS would provide the data for a stress-forecasting service, similar to the familiar weather forecasting, for the longer-term estimation of stress and earthquake occurrence.

Thirdly, GEMS would provide monitoring for deterministic control for lessening the potential for a large earthquake by mitigation methods such as massive hydraulic fracturing operations. These would be practical advantages for understanding and mitigating earthquake hazard and would place mankind for the first time in some control of damaging earthquakes worldwide.

Fourthly, GEMS would provide a network for other borehole instrumentation for passive geophysical monitoring, where very quiet locations would allow time-lapse monitoring of other geophysical phenomena and open up a whole new range of geophysical investigations.

Finally, providing a tool for investigating the dynamic evolution of the Earth on which our lives depend would provide an enormous intellectual stimulus for understanding the Earth in the 21st century.

GEMS, estimated as a five to ten billion U.S. dollar development, is matched in Earth Science only by the scale of oil industry investments. However, multi-billion dollar decisions need to be made. For example, the question of whether new buildings in the New Madrid Seismic Zone, USA, which has occasionally suffered very large earthquakes, should have the same earthquake resistant designs as coastal California, which more frequent but smaller earthquakes. The argument between Frankel (2003), Project Chief for the U.S. Geological
Survey, for seismic hazard maps for different designs and Stein et al. (2003) for the same designs, has multi-billion dollar implications for the cost of new buildings. In the absence of real information, the answers depend on “…essentially philosophical differences about how to forecast and prepare for future natural hazard about which much is not well understood” (Stein et al. 2003). GEMS would eventually (it would need several years to accumulate sufficient data) provide real factual information on which to base such costly decisions.

In contrast, a few billion dollar investment in GEMS would, for the first time, place man in some control of earthquake hazards, as well as providing the intellectual stimulus for investigating the dynamic behaviour of the solid Earth on which we are totally dependent every day of our lives. GEMS would provide the basic factual information for informed decisions about the future behaviour of the stressed crack-critical Earth.

Although the cost is likely to be too great for current geophysical research monies, the benefits of forecasting all damaging earthquakes worldwide should attract funding from the World Bank, the World Health Organisation, UNESCO, insurance companies, earthquake vulnerable cities, cities vulnerable to volcanic eruptions, and others.

REFERENCES


*Papers available at www.geos.ed.ac.uk/homes/scrampin/opinion.*